EMOTION SIGNALLING IN MULTIPLE INTELLIGENT VIRTUAL AGENTS FOR BELIEVABLE ARTIFICIAL ANIMALS.

Carlos DELGADO-MATA

Centre for Virtual Environments

Information Systems Research Institute.

University of Salford, Salford, UK

Submitted in Partial Fulfilment of the Requirements of the Degree of

Doctor of Philosophy, May 2004

Contents

List of Tables

List of Figures

Abstract

Current Virtual Environment technology is capable of recreating virtual scenes with an impressive degree of realism. However users often lose their interest very rapidly in these types of virtual environment because they are empty and static, lacking 'life'. One way to address this is to add virtual creatures (artificial animals) to the virtual world. But this is very challenging as they have to give the 'illusion of life'. To achieve this, animals must have convincing behaviour, and if this is to be autonomous, each animal requires an action-selection mechanism allowing their behaviour to be generated in real-time.

This thesis describes an ethologically inspired architecture for self-animated artificial animals (agents) that communicate emotions amongst each other, influencing each other's behaviour. Artificial Pheromones are signalled amongst conspecifics. These are sent when an emotion is 'felt' (like fear) and an apocrine gland is thus excited resulting in the pheromones being exuded to the virtual environment. The animals have an artificial olfaction sense. When they perceive the pheromone, then can 'feel' the emotion that is being communicated and hence alter their behaviour. This mechanism was found to produce a more believable group behaviour than with traditional flocking algorithms. In this thesis a mechanism for measuring collective behaviour is also presented and results obtained show that emotion can act as an organiser of complex behaviour, that is a mediator between two vital behaviours: collective (flocking to avoid predators) and individual act of grazing.

Declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institution of learning.

Copyright

Declaration of honesty

I declare that this thesis is work carried out by me. Some of the work reported herein has been previously published.

Carlos Delgado-Mata, 31 March 2004.

Acknowledgements

I am deeply indebted to Ruth Aylett, for her incredible support and guidance, for believing in me, and giving me this amazing opportunity. I am also grateful to Jesus Savage, my MSc supervisor in UNAM, who helped me to discover an appetite for research.

I appreciate Jesus' assistance with the flocking algorithm. I also long for those tea breaks. Also, I am thankful for Simon's assistance, specially with Statistical Analysis and very useful comments, and Rocio who created the beautiful Mayan Virtual Environment. Fred for proof-reading this work and several papers.

I would like to express gratitude to all my friends in the Centre for Virtual Environments who have made working here really enjoyable. Fred, the first person I met in Salford and now a great friend. Prasad and family, thank for being with us in the most testing of times. Kevin always willing to help. Sandy, Paula and little Jules, great French-Brit friends. Khalid and family, we miss those excellent BBQs. Gary, we sure enjoyed a lot of footy together. To Linda, Sue, Stacey and Michelle who helped me dealing with the administrative stuff. Nick, Karen, Miguel, Jose, Nikos, Norman, Simon C, Nav, John, Michael, Luis, Hissam, Kuo-Chen, Dulcidio, Neil, Yannis, Amir, Ying, Mei and all the rest of the CVE.

I also appreciate all the team-mates and (most) opponents I encountered whilst playing football, table-tennis, squash and badminton I surely blew steam off by kicking or hitting a ball, instead of the monitor.

I am grateful to Conacyt, Bonaterra and my parents for believing in me and sponsoring me during this adventure. Thanks very much indeed.

Thank you dear God, my Lord, for my being. I can see You through your creatures in nature.

Publications

The following refereed publications have been published. They account for work carried out in this thesis.

1. Carlos Delgado-Mata and Ruth S Aylett. Emotion and Action Selection: Regulating the Collective Behaviour of Agents in Virtual Environments. *In International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2004).* New York, 2004. ISBN 1-58113-864-4. To appear.

2. Carlos Delgado-Mata. Characterising Emotion Signalling and Affected Group Behaviour in Virtual Mammals. *In Intelligent Virtual Environments and Virtual Agents, IVEVA 2004*, ITESM CCM, México, 2004. CEUR Workshop Proceedings (Vol. 97), ISSN 1613-0073,. To appear.

3. Jesus Ibanez, Carlos Delgado-Mata, Ruth S Aylett, and Rocio Ruiz. Don't you escape! I'll tell you my story. *In MICAI 2004, LNAI 2972*, Springer-Verlag, April 2004, ISBN 3-540-21459-3. To appear.

4. Jose Perez, Carlos Delgado-Mata and Ruth S Aylett. Giving Embodied Agents a Grid-Boost. *In Intelligent Virtual Environments and Virtual Agents, IVEVA 2004*, ITESM CCM, México, 2004, CEUR Workshop Proceedings (Vol. 97), ISSN 1613-0073. To appear.

5. Carlos Delgado-Mata, and Ruth S. Aylett. Emotion Signalling in Virtual Agents.*In Evolvability and Interaction: Evolutionary Substrates of Communication, Signalling, and Perception in the Dynamic of Social Complexity*, Queen Mary University of London, England. Technical Report No. 393, Poster, 2003

6. Carlos Delgado-Mata, Jesus Ibanez, and Ruth Aylett. Let's run for it: Conspecific emotional flocking triggered via virtual pheromones. In Andreas Butz, Antonio Krüger, and Patrick Oliver, editors, *In Smart Graphics 2003, LNCS 2733*, pages 131–140, Heidelberg, Germany, 2003. Springer-Verlag. ISBN 3-540-40557-7

7. Carlos Delgado-Mata, Ruth S.Aylett, Rocio Ruiz and Marco A. Perez. Emotional Ruins:Communicating Emotions inside a Virtual Environment for Cultural Heritage, *In Proceedings of the Eight International Conference on Virtual Systems and Multimedia*, Korea, pp 1024-1033, 2003, ISBN 89-952475-1-7.

8. Carlos Delgado-Mata, and Ruth S Aylett. Virtual Odours to Transmit Emotions in Virtual Agents. *In VRAI 2002 Hangzhou*, China, April 2002.

9. Carlos Delgado-Mata, Rocio Ruiz-Rodarte, Ruth S Aylett, M A Perez-Cisneros, and P A Cook. Illusion of life in palenque: Communicating emotions inside a virtual environment for maya cultural heritage. In Helmut Prendinger, editor, *PRICAI: Seventh Pacific Rim International Conference on Artificial Intelligence*, Tokyo, Japan, 2002. PRICAI. ISBN 4-915905-07-1

10. Carlos Delgado-Mata, Jesus Savage and Rocio Ruiz. Adding intelligent agents to a virtual archeological environment, *In Workshop on Intelligent Virtual Environments*, Merida, Mexico, 2002.

11. Carlos Delgado-Mata, and Ruth S Aylett, Emotional Sheep: An Emotional Behavioural Architecture, *In ENC'01, Aguascalientes*, Mexico, 2001.

12. Ruth S. Aylett and Carlos Delgado-Mata, Emotion and Agent Interaction,*In 2001 AAAI Fall Symposium, Emotion and Cognition: A Tangled Knot II*, November 2-4, North Falmouth, Massachusetts, 2001. ISBN 1-57735-136-3

13. Carlos Delgado, and Ruth S Aylett, Communicating Emotion in Virtual Environments through Artifical Scents, *In Intelligent Virtual Agents, IVA 2001* LNAI 2190,Springer-Verlag, Madrid, Spain , 2001. ISBN 3-540-42570-5

14. Daniel Ballin, Ruth S Aylett, and Carlos Delgado: The Development of An Architecture For Interactive Autonomous Children's Television Characters. *In Intelligent Agents, Mobile Media and Internet Applications*, Bradford, U.K. 2001.

15. Carlos Delgado-Mata and Ruth Aylett. From robots to creatures: Extending a robot behaviour based architecture to create virtual creatures. In Rene Mayorga, editor, *Proceedings of ISRA 2000*, Monterrey, Mexico, 2000. IT Monterrey.

16. Carlos Delgado, and Ruth S Aylett. BAMUVA: A Robot behaviour based architecture to create virtual creatures, *in UKVRSIG 2000*, Glasgow UK

Dedication

In memory of my beloved sister Laura E. *Porque tambien somos lo que hemos perdido* (Because we are also what we have lost).

All my love and gratitude to Cecilia, my wife, partner, companion, best friend and wonderful mother of my children for all her patience, love and support. To Carlitos Antwan and Rowan Sebastian (future ones ?); you bring happiness to our home.

To my wonderful parents, Carlos and Laura, because this is also fruit of your love, example and incredible support throughout my life. *Gracias Dios mio por darme a unos excelentes humanos como mis padres.*

To Adriana, my sister, whom with I have shared so many memories. You know me better than most. To Jorge, my brother-in-law, whose generosity knows no bounds. To Jorgito, who is a reflection of my departed sister Laura E. To my *abue*, Elena; *Siempre fueron ejemplo para mi. Gracias por su amor.* To my parents in law and to my *cuñados.* To all my family and friends.

Chapter 1

Introduction

Writing is a struggle against silence.

– *Carlos Fuentes.*

Virtual environments are often visually compelling but static and empty of life. In this sense, Hoorn et al. [Hoorn *et al.*2003] argue that a Virtual Reality experience gains more from increased emotional relevance than from a more graphically realistic representation. Further, we argue that the lack of life eventually undermines the sense of physical presence for the user. This thesis discusses work to include animals in a virtual environment, taking a multidisciplinary point of view. Theories and techniques from ethology, virtual reality, graphic simulation, artificial intelligence, artificial life, robotics, and software agents (among others) are all seen as relevant. Although it is useful to model the behaviour of individual autonomous animals, in nature animals often behave as part of social groups. Therefore, if we want to populate virtual environments with believable virtual animals, we need to visualise the behaviour of animal groups. Furthermore, our assumption of life and smartness in real animals derives from our perception of their reaction to the environment, and in particular, to their reaction to perceived actions. For example, if one runs through a flock of animals, we expect them to move in order to avoid us. This reaction seems driven by emotional stimulus (most likely fear), and is communicated amongst conspecifics at an emotional level. Thus, believable virtual animals should display this kind of emotional response and communication. In this work, an architecture is described to model and simulate animals that not only 'feel' emotions, that affect their decision making, but are also able to communicate them through virtual pheromones. The virtual animals also show group behaviour, in particular a flocking behaviour based on the boids algorithm [Reynolds1987] modified so that it takes into account the animals' emotions. In this sense, the emotional communication "drives" the emergence of flocking.

1.1 Summary of Main Contributions

The work presented herein in the thesis describes three main contributions:

- The first of these is an novel emotional communication system via virtual pheromones in an artificial environment. In this it includes the development of an artificial nose and particles in a free expansion gas to simulate the pheromones.

- The second contribution is the mechanism to mediate between group behaviour (like flocking) and individual behaviours (like grazing) as these two behaviours are vital for grazing mammals.

  Other secondary contributions include the results obtained with real users when they observed the environment. These results are discussed in chapter 6. Similarly, the results of an experiment which involved measurement to characterise group behaviour is presented and discussed in chapter 6.

  Another secondary contribution is a modular toolkit to develop emotional animals in a very configurable way using XML (eXtensible Markup Language. A text markup language for interchange of structured data) files to define each of the animal's brain parts; like Amygdala, Hypothalamus, Basal Ganglia and Sensorial Cortex. More contributions will be discussed in chapter 7

1.2 Emotion

Over the last years, there has been increased interest in the development of computational models of emotion. These models have been integrated into architectures for development and control of a number of agents, in a variety of embodiments and environments. Work in emotion has come a long way since late ninetieth century with work carried out by Darwin [Darwin1872] and James [James1884]. This document presents a review of relevant Emotion Architectures. It presents relevant emotion theories that can be classified in neurological and cognitive (appraisal) theories; some theories span both fields. Representative of the former are Damasio's [Damasio1996] and LeDoux's [LeDoux1995] models of neural circuitry of emotions, where they show the importance of different systems that play a role in emotion of animals and humans, one such system is the amygdala and its relation to memory and perception. The most representative example of the latter is the Ortony, Clore and Collins model [Ortony *et al.*1988] (hereafter OCC) which has been used in different emotional architectures, one example is Elliot's Affective Reasoner [Elliot1992] ; another example of a cognitive approach to emotions is Frijda's appraisal theory. Izard's [Izard1993] and Smith's [Smith and Kirby2001] model of emotion use both a cognitive and a neurological or direct approach.

It has been proposed that there is a set of basic emotions [Ekman1992] [Panksepp1994a] [Damasio1996] [Sloman2001], one of the most popular basis for its classification is those that are thought to be universally portrayed across different cultures, through facial expressions [Ekman1993]; for some the basic emotions are anger, disgust, fear, joy, sadness and surprise; there are theories that include more emotions like guilt.

To work with emotion architectures of emotion a broad range of knowledge is needed in different fields, such as neurology, psychology, ethology, and robot-based action selection. In this review, the aim is to cover some of the most relevant work in each of the mentioned areas of knowledge, but we do not intend to provide an in-depth review of all these areas. Our aim is to provide sufficient knowledge to create an architecture based on emotions for action selection that could be biologically-plausible, like the architecture proposed in this work.

1.3 Methodology

As already said, this work has several sources of inspiration, namely ethology, emotion, group behaviour, signalling, computer graphics.

The goal that was defined at the start of research was to achieve group behaviour in a believable manner. To achieve this, a design was created to achieve the aim.

An iterative process was chosen to develop the architecture. To start the process, a reactive architecture was selected and applied. This architecture had been developed for mobile robots [Barnes1996], and later for autonomous agents [Aylett *et al.*1999]. This architecture was implemented to include several behaviours, like moving toward a beacon, and used to test the switching of scripts via pre- and post conditions [Delgado-Mata and Aylett2000]. But this architecture was found (as it was designed to be) rather task oriented, and not flexible enough to perform autonomous behaviour in a changing environment. Thus Action Selection Mechanisms inspired in ethology were looked at. Later, it was found that emotion had been used to improve action selection mechanisms and so we envisaged the system to include an emotional mechanism.

It was not seen as desirable to model emotion as an optional add-on but rather as an integral part of the 'brain'. Hence the path-ways in the brain that involve an emotional experience were considered, as they affect the behavioural response. To achieve this, a high-level functional model of the brain was investigated [LeDoux1995]. It is important to notice that when doing this work, it was never the aim to completely simulate the brain; such a gargantuan task (if at all posible) can not be accomplished in the time-frame of a PhD thesis. Instead the aim was to produce a higher level view of the functions of the brain to grasp a better understanding of it.

To study intelligence several approaches are proposed [Minsky1985] [Sloman1993] [Nilsson1998] [Russell and Norvig2003], though when designing the methodology used in this work we concur with [Pfeifer and Scheier2001]. He proposes two basic approaches: The analytic approach and the synthetic approach. The former is used when studying natural systems. The latter is used when studying artificial systems. A third approach is the intersection of both and it is named synthetic modelling.

Because this work was developed to obtain more believable behaviour in artificial animals, it is positioned in synthetic modelling, see figure 1.1. This work overlaps with the analytic approach (ethology and neurology) but also uses synthetic approaches (group behaviour, autonomous agents). The reader must be aware that it is not the intention to replicate the behaviour of real animals. Any real animal does it better! As stated before the aim was to produce more believable behaviour, and in doing so acquire a better understanding of the pathways in the brain, certainly in the case of emotional experience.

To design the architecture "The three amigos" Unified Software Development Process [Jacobson *et al.*1999] was chosen. This method was selected because of its iterative nature and because of its relation to the Unified Modelling Language (**UML**) [Booch *et al.*1999], which has emerged as the standard for modelling Object Oriented Analysis and Design.

As stated before AI systems and synthetic modelling can be used to obtain a better understanding of natural systems. By carrying out an iterative process (see figure 1.2) a system can be tested when it reaches a major milestone, or it can be used to test a partial

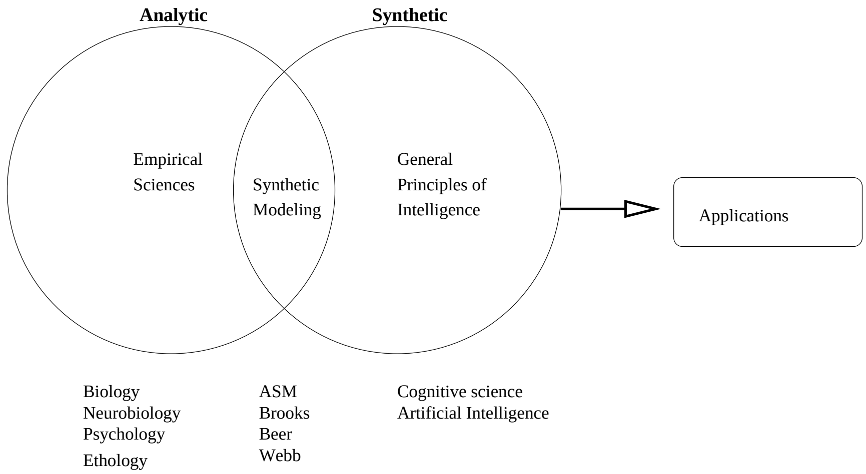


Figure 1.1: Approaches to study of Intelligence. Modified from [Pfeifer and Scheier2001]

function of the system. This has several benefits that can be found in the case of modelling a behaviour that is inspired in natural systems, whence a feature is improved, added or removed depending on the resulting behaviour compared with the expected one.

The overall process is shown in figure 1.2. According to the Process, there are four Phases.

1. Inception
2. Elaboration
3. Construction
4. Transition

In the work presented in this document an emphasis is placed on the first three phases because in this thesis, we will not replace an existing system that is used by lay people; therefore, a transition phase is not necessary.

On each iteration, several steps can be carried out, but as seen in figure 1.2 the emphasis shifts depending on the phase. Namely, in the Inception and Elaboration Phase

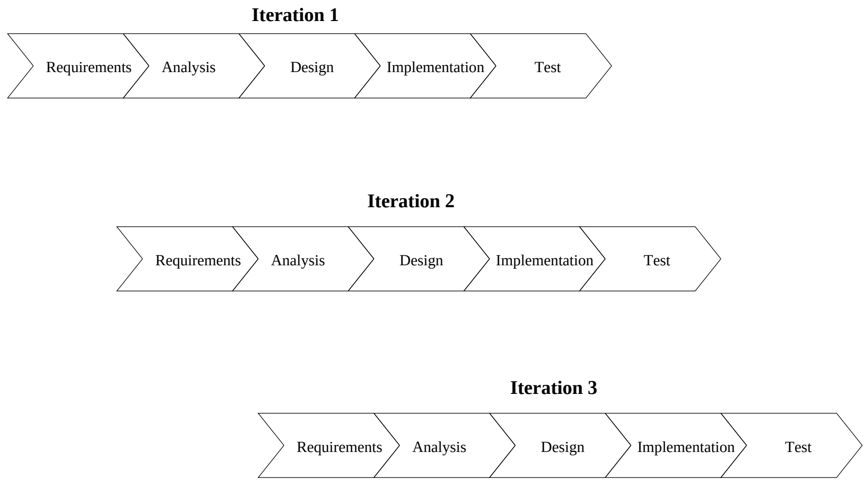


Figure 1.2: Iterations sweep through the workflows from requirements capture to test. After [Jacobson *et al.*1999]

the emphasis is on Analysis, whereas, in Construction the emphasis is on Design and Implementation.

Another idea from Software Engineering, embraced throughout the development of the architecture and related to the iterative process mentioned above, is that of having a running version at the end of each day. That is, when a set of features are developed and tested they are left in the source code tree and an executable is made. If the features are not functioning then the previously successful executable built is left.

1.4 Overview of the Thesis

The rest of this thesis is split into six chapters, which are outlined herewith:

- Chapter 2 reviews some of the literature on action selection. The review pays attention to ethology and computational action selection mechanisms.

- Chapter 3 reviews some of the existing literature on emotion. The review pays attention to the approaches that are low level, that is, non-cognitive.

- Chapter 4 reviews signalling (communication) and group animation.
- Chapter 5 presents the architecture of the proposed solution. As this is a computational solution, mathematics is used to describe the algorithms used.
- Chapter 6 discusses results and details the implementation, illustrating the discussion with appropiate graphs.
- Chapter 7 offers conclusions on the work described in this thesis and gives some possible directions for future research.

Chapter 2

Action Selection Mechanisms

If we had more time for discussion we would probably have made a great many more mistakes.

–Leon Trotsky

The great end of life in not knowledge, but action.

– Thomas Henry Huxley

I used to be indecisive, but now I'm not so sure

Bascoe Pertwee

Fast, Cheap, Good: Choose any two.

–anonymous.

Action Selection has been quintessential in fields like simulation of adaptive behaviour. Applications are constantly developed in Robotics, Intelligent Agents, and lately in Virtual Agents populating Virtual Environments, that is embodied virtual agents. Or as it can be put forward, to have it all 'The looks (3D graphics) and the Brains (Do something interesting)'. Historically there have been two approaches for selecting actions: the reactive [Tyrrell1993] and the deliberative [Nilsson1998]. The advantages of the former [Brooks1986] are that they are computationally cheap and can adapt better to a changing environment. The advantages of the latter are that they can hold in memory a representation of the world and thus they -in theory- could accomplish a more informed and better solution than their counterparts. They do not suffer from the local minima problems inherent in local decision making.

In this chapter we will consider different theories, with special interest in those related to the one proposed in this work. It will be argued which one is best suited for our aims.

According to [Arkin1999] some authors state that animal behaviour can be roughly categorised into three major classes:

Reflexes are rapid, automatic involuntary responses triggered by certain environmental stimuli. The reflexive response persists only as long as the duration of the stimulus. Further, the response intensity correlates with the stimulus's strength. Reflexes are used for locomotion and other highly coordinated activities. Certain escape behaviours, such as those found in snails and bristle worms, involve reflexive action that results in rapid contraction of specific muscles related to the flight response.

Taxes are behavioural responses that orient the animal toward or away from a stimulus (attractive or aversive). Taxes occur in response to visual, chemical, mechanical, and electromagnetic phenomena in a wide range of animals. For example chemotaxis is apparent in response to chemical stimuli as found in trail-following ants [Wyatt2003]. Phonotaxis occurs in crickets [Webb1994] where the mate aligns to the sound's source. Klinotaxis occurs in fly maggots moving toward a light source by comparing the intensity of the light from each side of their bodies, resulting in a wavy course. Tropotaxis is exhibited by wood lice [Lorenz1981] and results in their heading directly toward a light source through the use of their compound eyes.

Fixed-action patterns are time-extended response patterns triggered by a stimulus but persisting for longer than the stimulus itself [Lorenz1981]. Unlike reflexive behaviour, the intensity and duration of the response is not governed by the strength and duration of the stimulus. Similarly, fixed-action patterns may be motivated, and they may result from a much broader range of stimuli than those that govern a simple reflex. Examples include egg-retrieving behaviour of the grey-lying goose, the song of crickets, locust flight patterns, and crayfish escape behaviour [Arkin1999].

Besides these behaviours, motivated behaviours are governed not only by environmental stimuli but also by the internal state of the animal, being influenced by such things as appetite.

In table 2.1, some popular action selection mechanisms are summarised. The table contains five columns, namely author, discipline(s) in which the **ASM** has been used, the architecture, how the Stimuli are combined, in which context they are used, and the number of creatures that the **ASM** is applied. The aim of this table is to characterise several architectures where action selection plays an important role. The disciplines of these architectures range from natural system to artificial systems. The combination of stimuli is important because they affect how the action is selected. The context and number of creatures is used to compare it to the work proposed here. As it can be seen most of this action selection mechanisms were developed for just one creature (robot) in mind, and the context was not in 3D graphics, as proposed here. The exception is Reynolds' flocking mechanism and Tu's system. However, it has to be noted that Tu's system is a simulation that did not run in real time.

Action Selection Mechanisms				
ASM	Disciplines	Architecture	Combination of Stimuli	Context and no.
Brooks	robotic	distributed network of finite state machines	sub-summed	Physical Robots 1 - ?
Blumberg	ethology	Hierarchical Behaviour System using Releasing mechanisms with learning	Summed	3D Graphics 1
Tyrrell	ethology	Loose hierarchy of behaviours	can be any function	Grid 1
Humphrys	Reinforcement learning Brooksian ethology	W-learning Minimising "worst unhappiness"	synthesised and subsumed	Grid 1
Bryson	ethology	Reactive Hierarchy	synthesised	Grid 1
Montes	Basal Ganglia neurology	Neurological model of mammalian basal ganglia	leaky integration	Robot 1
Martinez	robotics ethology	Reactive behaviours blended used in conjunction to accomplish a navigating task	context depending blending	Robot 1
Reynolds	animal behaviour computer graphics	Flocking behaviour with collision avoidance, velocity matching and flock centring	vectorial summation	3D (Rough) tens
Barnes	robotics	Reactive Behavioural Synthesis	Synthesised	Physical Robot 1
Tu	ethology computer graphics physics based modelling	Physics based modelling of Artificial Fish, hierarchical action selection	winner-takes-all	3D Graphics (photo-realistic) tens
Arkin	ethology guided	perceptual processes attached to motor schemas	Vector summation	Physical Robot 1
Maes	ANN and robotics	Non-hierarchical distributed network	summed	robot 1 ?
Negrete	neurophysiology	Non-hierarchical distributed network of neuro-humoral neurons	summed	2D 1

Table 2.1: Reactive Action Selection Mechanisms

2.1 Ethology -Theories of ASM

2.1.1 Drives

The concept of *drive* is not new, but it can be associated with Hull [Hull1943] . Drives (or motivations)[1], are thought to exist because it is possible to see indirect evidence of them (physiologically or neurologically). For example in [Canamero1997] homoeostasis is used to control internal variables like motivations (drives). In mammals, for example when our dog has been deprived of food, we notice a motivation in the animal as we perceive that our pet is eager to be fed and appears to be hungry. This concept of hunger is an example of what Hull calls a *drive*. An example involving hunger is the next personal anecdote. Our family was travelling a long distance in a car in Mexico. When we finally found somewhere to eat, we found the food delicious, and my granddad said: *el mejor ingrediente es el hambre* “the best ingredient is hunger”. What he meant is that, besides motivating us to eat, hunger changed the perception of the experience; we enjoyed the food even more, because we were very hungry. A sample of drives implementation can be found in [Tyrrell1993].

Ethologists have proposed several hierarchal structures like [Baerends1976] [Tinbergen1969] [Lorenz1981] [McFarland1999] [Dawkins1976]. Next we will discuss some of them.

2.1.2 Baerends

Baerends [Baerends1976] presented a hierarchical decomposition of activities organised in sub-systems. In his work Baerends discussed the behaviour of two animals he had studied, the digger wasp and the herring gull, and then he proposed mechanisms to account for the aspects of their behaviour. The mechanisms are hierarchical with a mutual inhibition between separate systems as in figure 2.1. (mutual inhibition has been implemented in

[1]We are modeling animals, not humans, and thus the author took the liberty to treat motivations and drives as the same thing.

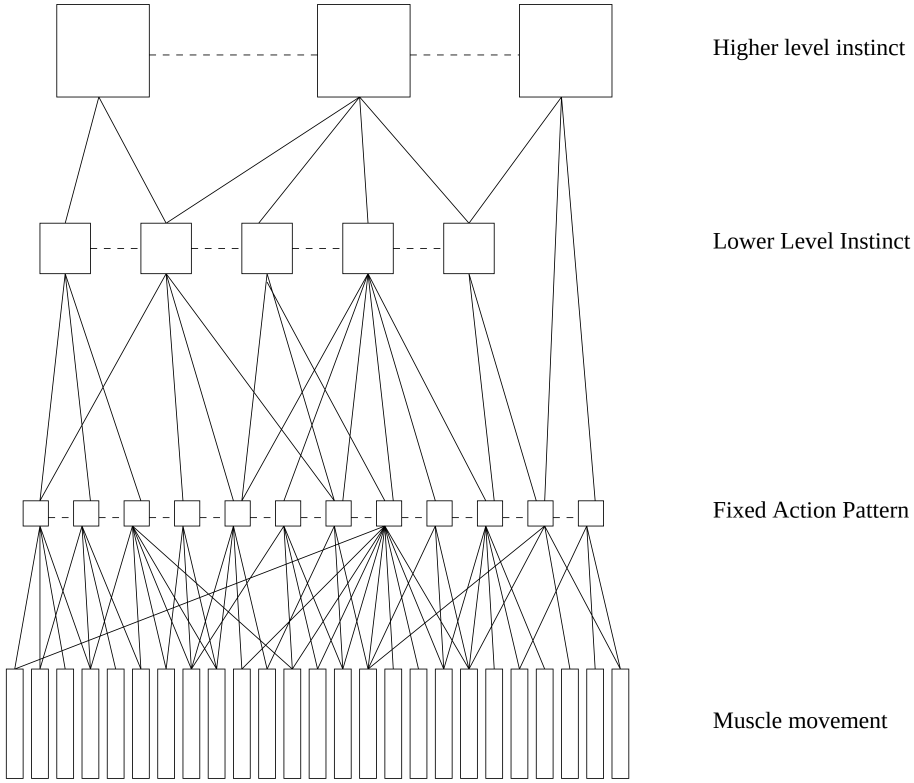


Figure 2.1: The hierarchical scheme of Baerends, showing the interrelationships of the centres. Disjoint lines represent inhibitory relationships between mechanisms of the same order. After [Lorenz1981]

Computational **ASM** as in [Blumberg1996]

2.1.3 Tinbergen

Tinbergen in [Tinbergen1969] argues that instinctive behaviour (Fixed Action Patterns) is dependent on external and internal causal factors. The work presented herewith is compatible with his statement as external stimuli (sensors) as well as internal (emotions and drives) combine to select a so called consummatory act. He also uses hierarchies as seen figure 2.2. Hierarchical centres of the major reproductive instinct of the stickle back male are shown in figure 2.3. Motivational impulses are represented by straight arrows which 'load' the centres (shown as circles). These impulses may come from the external environment as

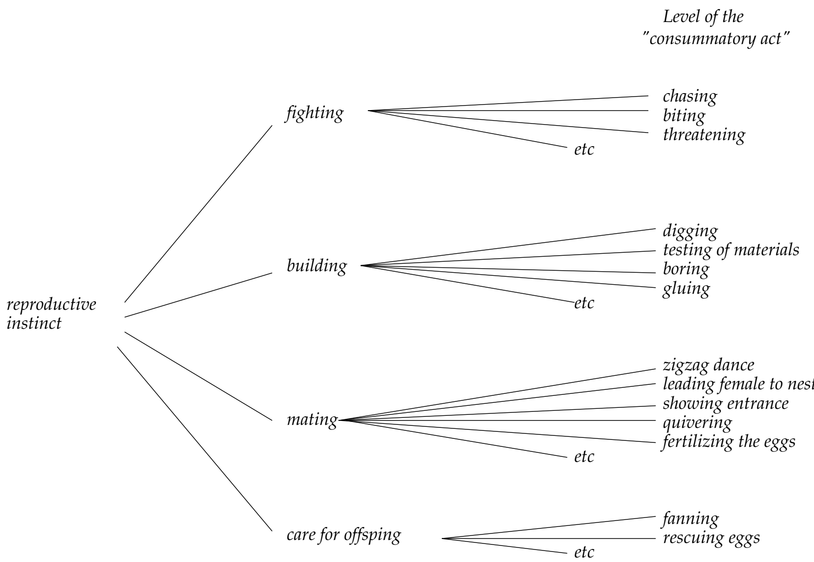


Figure 2.2: The principle of hierarchical organisation illustrated by the reproductive instinct of the male three-spined stickleback. After Tinbergen 1969

well as from superiordinated centres. The shaded rectangles indicate inhibiting influences, which prevent a continuous discharge of motor impulses. These blocks are removed by innate releasing mechanisms. When this has occurred the animal will show specific appetitive behaviour until more specific releasing stimuli activate the next subordinated instinct and the still more specific behaviour. The concave, two-headed arrows between centres of the same level indicate inhibiting relationships and the existence of DISPLACEMENT ACTIVITIES. Below the level of the consummatory acts a number of centres come into action simultaneously.

2.1.4 Lorenz

Lorenz suggested that motor patterns that are used for different purposes can be labelled as "tool activities" (*Werkzeugbewegungen*) because, like simple tools, they can serve more than one function. They are also known as "multipurpose movements". In this sense they are related to the overlapping relationships of Baerend's centres. More than other

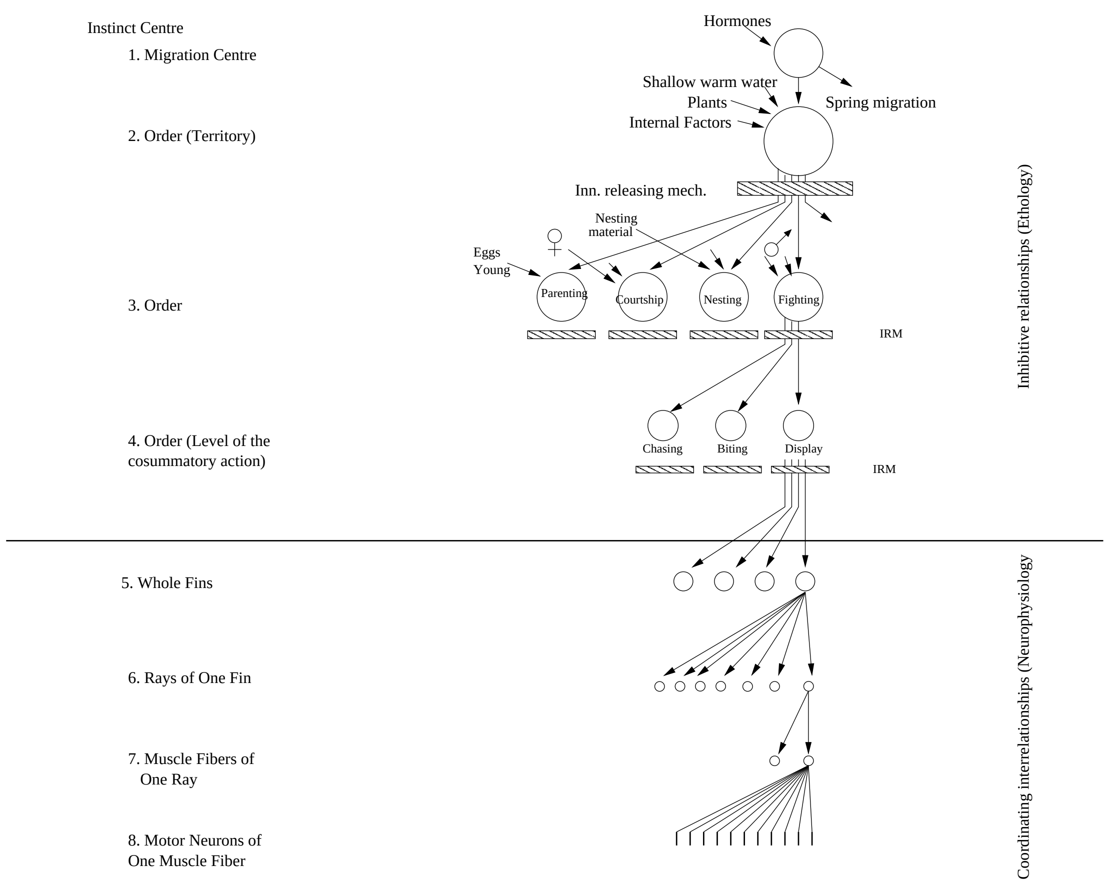


Figure 2.3: Tinbergen's hierarchical centres of the major reproductive instinct of the stickle back male. After Lorenz 1981

instinctive motor patterns, multipurpose movements show a rapid lowering of thresholds whenever they are not used for a time. Similarly, the excitability is sometimes increased, further it actually creates an excitation of its own which activates the whole organism and causes the animal to search for releasing stimuli. This can be related to bully individuals that just want an excuse to fight (release their fighting behaviour).

Action Readiness is another interesting aspect in Animal Behaviour. An example of the need to discharge a behaviour can be found in the the movie *Amores Perros* -Pancho (the dog) was so excited that, after killing a dog, he still wanted a fight. The owner of the dog wanted him to discharge his action readiness with another dog from a neighbour, a fellow foe. This need to release his action readiness was Pancho's ultimate doom. He was killed by Cofi, the neighbour's dog wandering in the street.

Lorenz claims that one can be in no doubt that higher organisms are subject to threshold fluctuations which concern not one, but many or all of an animal's responses to external stimulation; a human can be sleepy when overtired (i.e. *low general arousal*), or generally aroused after having drunk too much coffee, or tea in Britain. Lorenz developed a model which can be likened with emotion, the Psycho hydraulic model, shown in figure 2.4. Similar to an emotion and action readiness the tank slowly fills up with water, and when the tank is full the water is released. The valve is not immediately closed.

Lorenz states that

> *A long-enduring state of quiescence of a fixed motor pattern not only needs to a lowering of the thresholds of releasing stimuli but also induces a state of general restlessness in the organism as a whole.*

This can be modelled with emotions by arousing the animal, another option could be to increase a drive, for example curiosity. We chose to use emotions in our architecture.

Our architecture is hard-wired in the same sense that ethologist such as Lorenz and Tinbergen explained that some motor patterns are fixed (that is *phylogenetically programmed*)

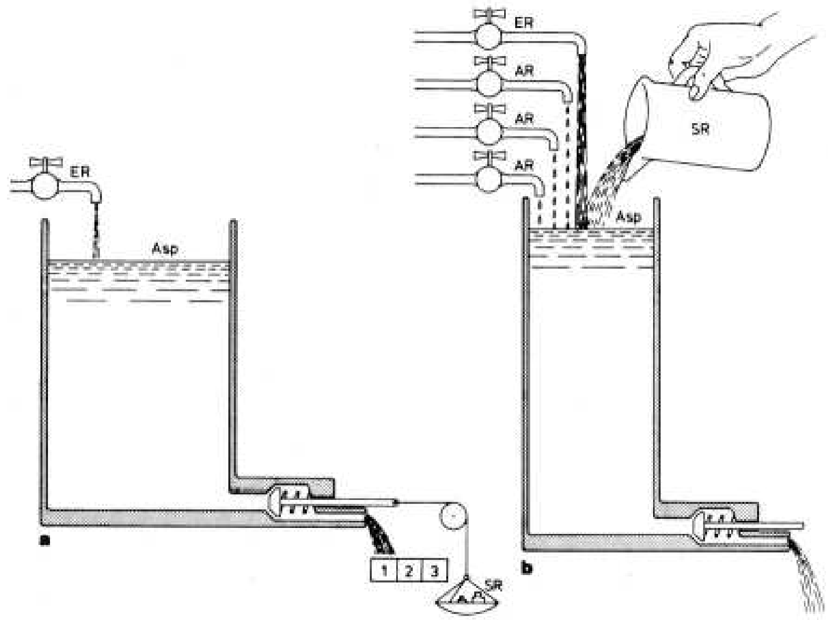


Figure 2.4: Lorenz's Psycho hydraulic thought model. Taken from Lorenz 1981

and they are released through Innate Releasing Mechanisms **IRM** –in German, *angeborener Auslömechanismus* (**AAM**). ,

Several mechanisms exist for spatial orientation, but two in particular are of special interest that are described in [Lorenz1981]. *Kinesis* which can be summarised as a reactive rule of slowing down when meeting favourable conditions and speeding up where encountering unfavourable conditions. This can be related to the escape behaviour in grazing animals. Most organisms do not however move in an absolutely straight line; the protozoans mentioned above usually swim along the line of a screw –regularly and wrongly described as a spiral. When orienting to favourable localities, the effect of kinesis can be improved by increasing the angle of the random deviations from the straight line. By these means, the organism is kept in the desirable environment longer and is made to exploit an increased part of its area . This process, termed *klinokinesis* is found in grazing mammals, as wells as in swimming protozoa and higher crustacea.

Lorenz saw the necessity of a superior command locus at the stage of evolution when an organism has developed more than one system of behaviour patterns of which only one can function at any given time. Such a juncture becomes imperative in order to prevent incompatible motor patterns from "meshing gears" by being discharged simultaneously. For example a dog that is lying down cannot activate the motor pattern to run. Such a mechanism was implemented successfully in [Blumberg1996]. A comparatively simple physiological organisation achieving this purpose is what biocyberneticists call maximum selecting system [Lorenz1981]. It is presented in figure 2.5. The mechanisms built in act as a filter between the several sources of specific excitation and the motor pathways through which Action Specific Potential (**ASP**) is discharged. By causing a "backward-directed subtraction", it effectuates a simple mutual inhibition among the action patterns involved. The principle of "lateral backward inhibition" makes certain that the behaviour pattern processing with the highest ASP value, at a given moment, has free access to its consummatory action unobstructed by any competing motivation.

2.2 Computational ASM

Reactive Action Selection has been ever present in Robotics, for example Grey Walter's [Walter1950] tortoises show some behaviour which resemble those in animals, Braitenberg labelled some of his vehicles' behaviours [Braitenberg1984] "love" and "fear".

2.2.1 Tyrrell

Tyrrell produced a system [Tyrrell1993] in which he tested a broad range of action selection mechanisms. The system can be categorised in two separate subsystems one which is what he called the simulated environment which is an either graphical 2D representation developed for a Sun, using the now deprecated SunTools, or a text representation. In there different objects and threat can be placed in a gridded world. A creature is placed

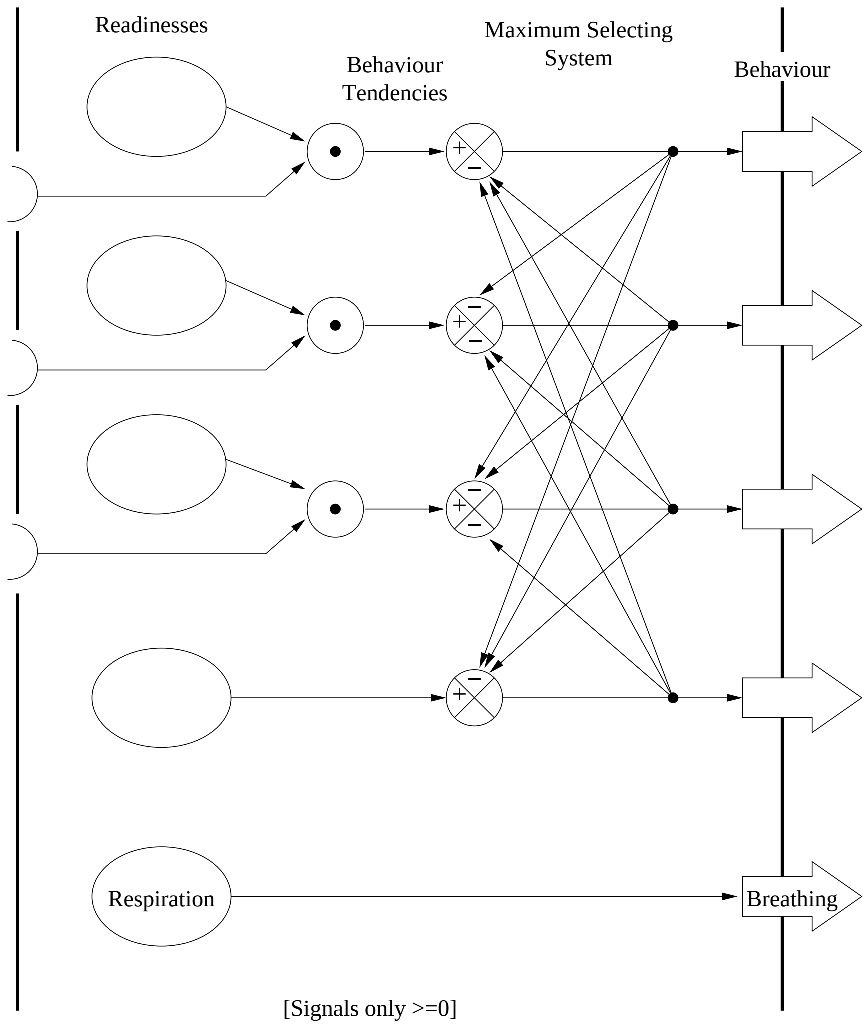


Figure 2.5: Lorenz inhibition amongst competing behaviours. After Lorenz 1981

in the world, and it can move in eight directions **N, NW, NE, W, E, S, SW, SE**. The creature is imbued with internal and external sensors. These sensors in fact regulate the behaviour of the artificial animal. He tested different action selection mechanisms, that is how the creature performed in the simulated environment whilst 'taking decisions' using a certain action selection mechanism. He tested Brooks' subsumption mechanism, Pattie Maes' spread activation network, Hull's drives, Rosenblatt and Payton' free flowing network and later his modified version of Rosenblatt and Payton's architecture. This last mechanism was the one that performed best. That is that has the better survival rate of the creatures. This work is a very laudable effort as it not only tested different Action Selection Mechanims, but it also provided a testbed for them. Another interesting feature is that it is easily configurable through files and directories. Tyrrell's simulated environment has been used by other researchers to test other action selection mechanisms, one of example of such use is that of [Bryson2000]. A more recent system that is similar to Tyrrell's is that of [Blumberg1996].

2.2.2 Brooks

Brooks seminal work on robotics, the so called subsumption architecture [Brooks1986] is defined to be multi-layered as seen in figure 2.6. Each layer (or behaviour) is designed to achieve an action. The behaviour on each level is implemented via a network of finite state machimes (**FSMs**) that swap control information through interconnected wires. Each FSM has the capability to store simple Lisp structures and derive outputs from its inputs in a reactive manner. What this gives is a deterministic result. Brooks switched the prevailing architectural paradigm from linear (or vertical) to parallel (or horizontal) and his work has inspired many others, for example [Mataric1990] [Connell1990] who experimented with Stimulus Reaction robots capable of wandering, obstacle avoidance and wall following

Similar reactive architectures for behavioural robots are Arkin's schemas [Arkin1999]

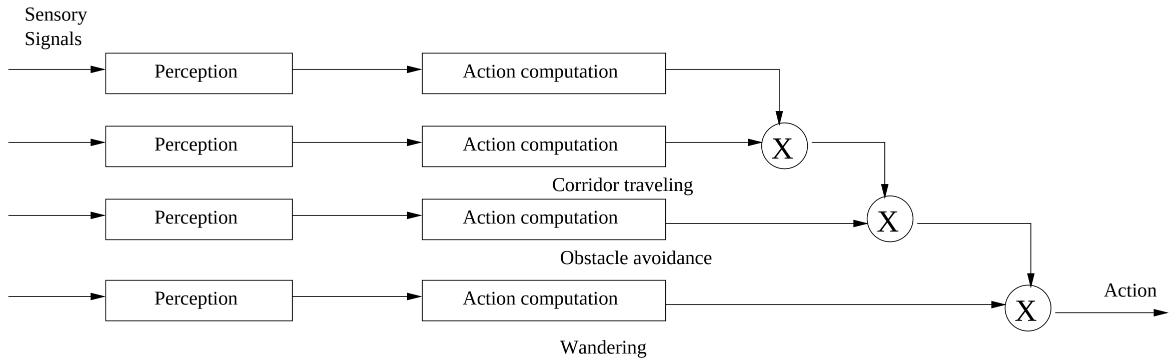


Figure 2.6: Brooks Subsumption Architecture

and Salford's Behavioural Synthesis Architecture **BSA** [Barnes1996].

2.2.3 Arkin's schemas

Arkin [Arkin1999] says

> *Schemas were defined as a means by which understanding is able to categorise sensory perception in the process of realising knowledge or experience. Neurophysiological schema theory emerged early in the twentieth century. The first application was an effort to explain postural control mechanisms in humans. Schema theory has influenced psychology as well, serving as a bridging abstraction between brain and mind.*

In this sense schemas are on the level on Tyrrell's extended Rosenblatt and Platt free flow hierarchical structure for action selection. Also similar to schemas is the BSA [Barnes1996], an architecture developed for mobile robots.

According to Arkin, schemas can be used as a higher-level abstraction that is in turn decomposed into a collection of neural networks. In figure 2.7 it can be seen that behavioural modelling can be modelled with schemas and/or neural networks. This is possible because they are at different levels of abstraction. In this sense the nodes in the Action selection mechanism proposed by Tyrrell is similar to Arkin's schemas.

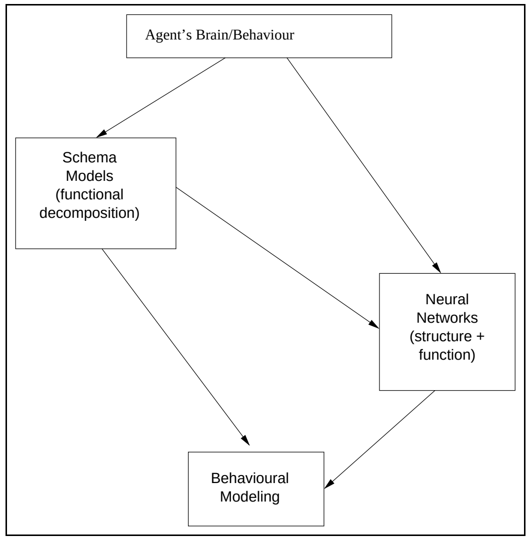


Figure 2.7: Abstract behavioural models. After Arkin 1999

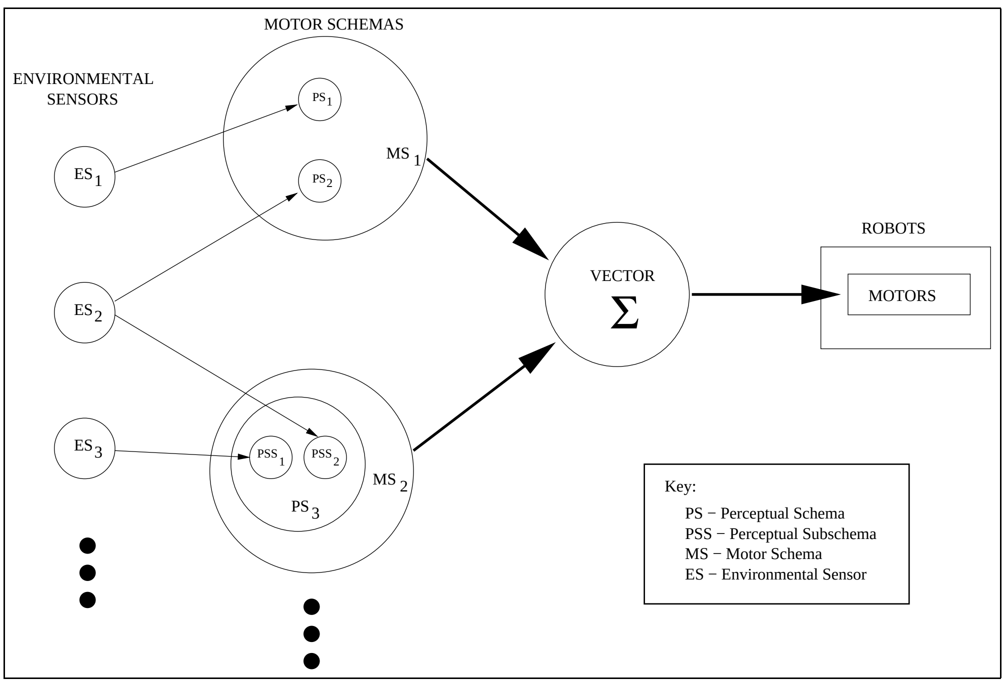


Figure 2.8: Perception-action schema relationships. After Arkin 1999

2.2.4 Finite State Acceptor Diagrams

Finite State Acceptors have been useful to solve problems involving the description of aggregations and sequences of behaviours. They make explicit the behaviours that are active at any given time and the transitions between them. Finite state acceptors have a formal description . For example from [Arkin1999]:

> *Finite state acceptor M can be specified by a quadruple $(Q, \delta, q0, F)$ with Q representing the set of allowable behavioural states; δ being a transition function mapping the input and the current state to another, or even the same, state; $q0$ denoting the starting behavioural configuration; and F representing a set of accepting states, a subset of Q, indicating completion of the sensorimotor task. δ can be represented in a tabular form where the arcs represent state transition in the FSA and are invoked by the arriving stimuli.*

For an example see figure 2.9 and table 2.2.

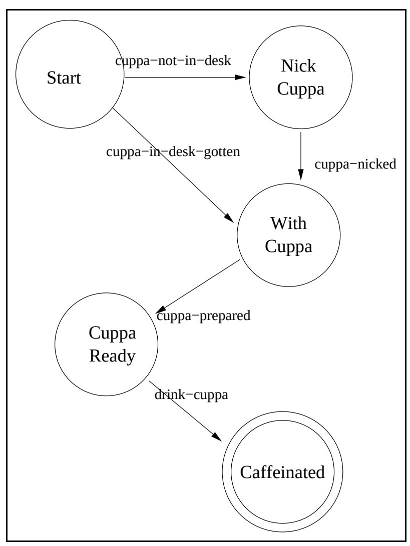


Figure 2.9: Finite State Acceptor diagram

2.2.5 Neurologically inspired models

Recent experiments e.f., [Montes-Gonzalez *et al.*2000] have shown that the basal ganglia plays an important role in action selection in animals. These experiments have shown that appropriate and clean switching can be achieved by an embodied basal ganglia between

δ	q	$input$	$\delta(q, input)$
	start	cuppa-not-in-desk	Nick-Cuppa
	start	cuppa-found-desk	With-Cuppa
	Nick-Cuppa	cuppa-nicked	With-Cuppa
	With-Cuppa	cuppa-prepared	Cuppa-Ready
	Cuppa-Read	drink-cuppa	Caffeinated

Table 2.2: FSA representing drinking a cuppa

wall-following, search, 'food'-pickup, corner-finding, and 'food'-deposit behaviours. The robot can be seen to select the appropriate actions for different circumstances and to generate integrated sequences of behaviour.

At each time-step both extrinsic and intrinsic variables are provided to the input components of the basal ganglia which compute a salience value for each behaviour as a weighted function of all the variables relevant to that behaviour. The intrinsic circuitry of the basal ganglia model then resolves the competition between behaviours and dis-inhibits the winning action subsystems. The general architecture is shown in figure 2.10. The model also includes motivations, namely *fear* and *hunger*, which affect collecting behaviours (*wall-seek* and *corner-seek*).

2.2.6 Tu

Tu developed a computational system or artificial fish based on animal behaviour, biomechanics, locomotion and perception, see figure 2.11. In her framework [Tu and Terzopoulos1994], the higher control mechanisms correspond to the fish's behaviour system, where the action selection process - the competition over the control of the motor controllers -happens at two levels: the intention level and the action level.

At the intention level, different desires compete over what should be done (which desire is to become the current intention), given the animal's external and internal conditions. Once the intention generator selects an intention, it attempts to satisfy the intention by

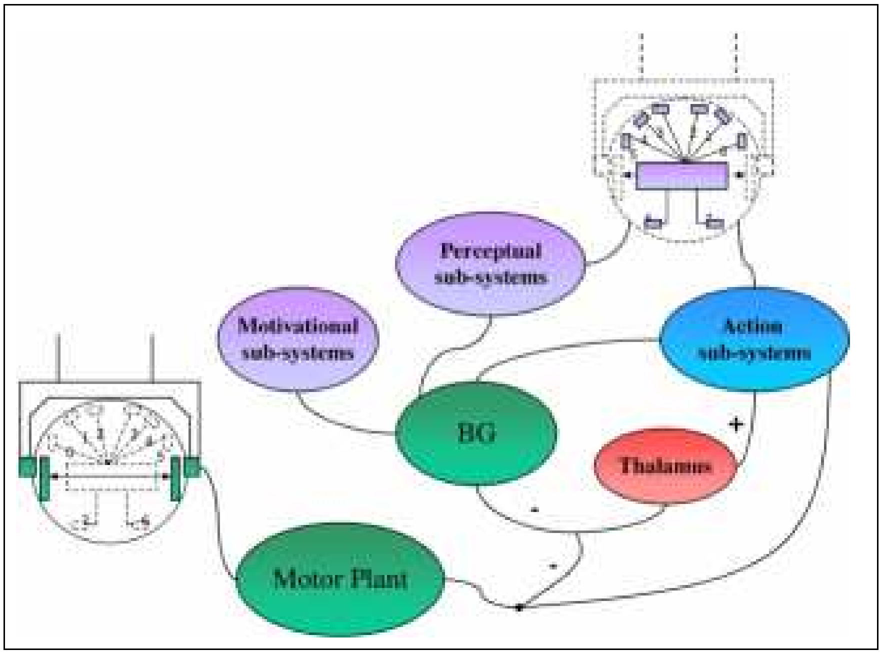


Figure 2.10: Overview of Architecture. From Montes-Gonzalez 2001

passing control to a behaviour routine along the data from an attention mechanism. The artificial fish included nine behaviour routines listed below, plus five subroutines (listed within brackets below):

1. Avoid-static-obstacle
2. Avoiding-fish
3. Chasing-target
4. Eating-food
5. mating (looping, circling, ascending, nuzzling)
6. leaving
7. wandering
8. escaping

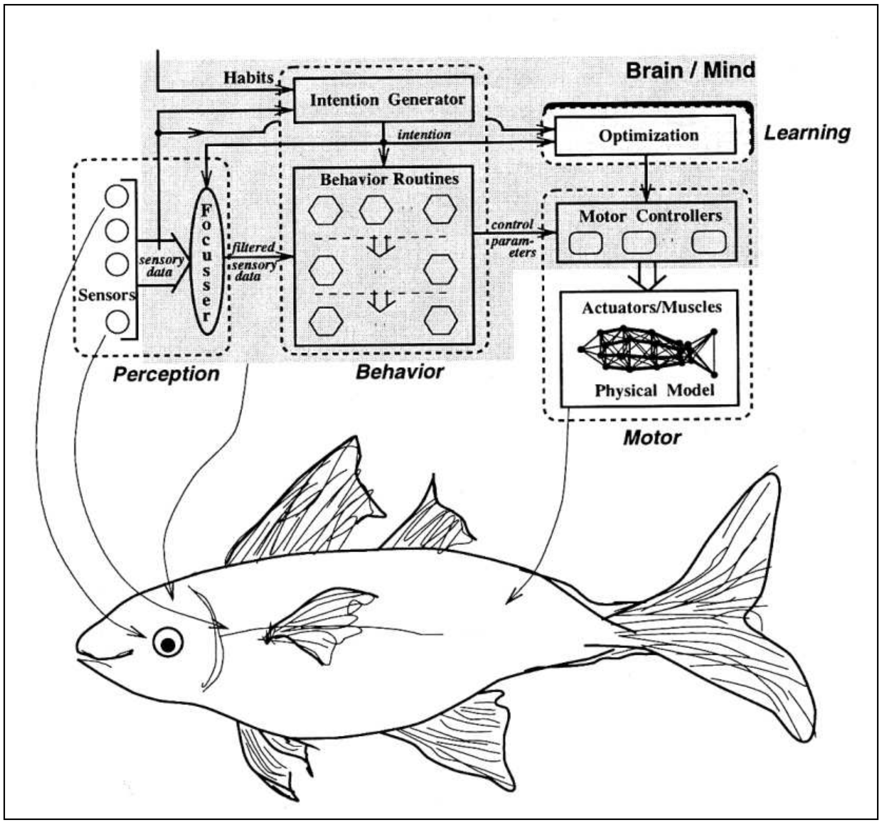


Figure 2.11: System overview of the artificial fish. From [Tu1999]

9. schooling

The activated behaviour routine uses the focused perceptual data to select appropriate Motion Controllers (**MC**s) and provide them with the proper motor control parameters. More than one Motion Controller may be chosen if they are not mutually exclusive. For instance, swim-MC and ascend-MC can be selected simultaneously.

2.3 Solutions to problems when using Reactive Behaviours

2.3.1 Local minima

One of the problems with reactive models is that like any local decision-making approach, they can get stuck in local minima. One such case is found in navigation when stuck in a corner, see figure 2.12. In that case the robot's reactive behaviour of moving towards a beacon orients itself to move south-east, but the robot is doomed to be stuck in a local minimum, in a corner. So it is common for reactive systems to have a meta (upper) layer to get out of this local minimum. Examples of this can be found using Fuzzy logic [Barnes *et al.*1997] [Martínez-Barberá2001] Planning [Ranganathan and Koenig2003] emotion [Delgado-Mata *et al.*2003] [Canamero1997] [Velásquez1997] reactive planning, like in [Ranganathan and Koenig2003], temporal reasoning [Downie2001]. Further, in reactive planning it has been found a need to add en even upper layer like emotion [Bryson2002]

A common local minima problem in artificial creatures that used reactive systems is that of dithering. For example, if a virtual deer is exactly amidst a food source and a water source and if the thirst and the hunger drives present similar high values, then when the animal reaches a food source and eats something, the thirst drive will be unbearable and the deer would move to drink some water, and when it reaches the water source it would drink a little water and the the hunger drive would direct the animal to the food source and so forth, see figure 2.13. To solve this problem is to allow the animal some sort of persistence, an example has been implemented in Blumberg [Blumberg1996]. Another solution, as proposed in this work is to allow an emotion solve conflicting behaviours.

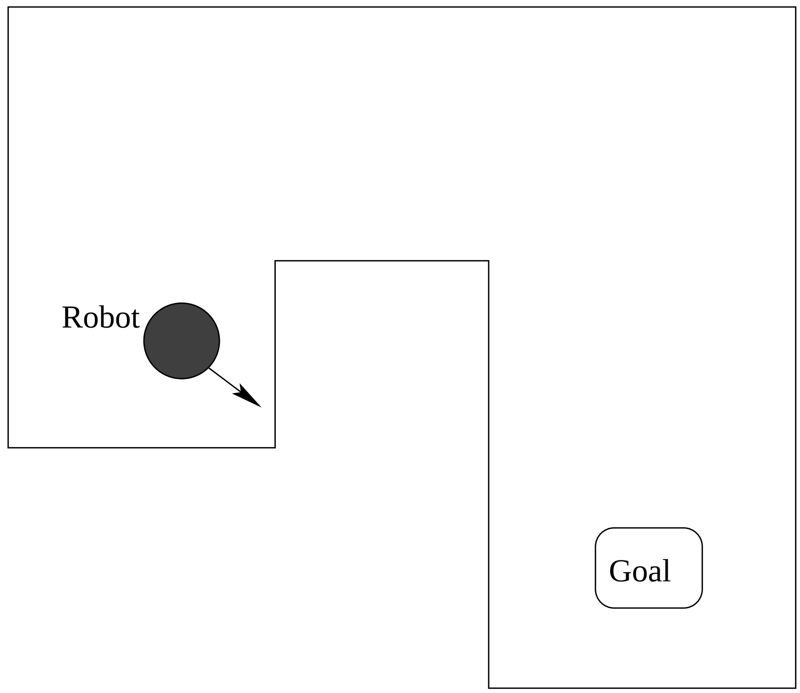


Figure 2.12: Robot stuck in a local minimum

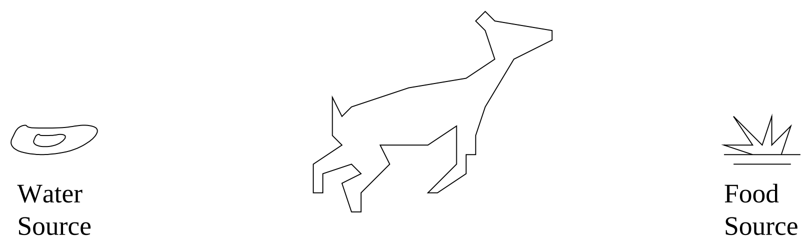


Figure 2.13: Deer dithering between a food source and water source

Planning

It is common for architectures to base the reactive layer on one of the good-old-fashioned-AI theories. For example [Ranganathan and Koenig2003] is a three layered architecture using Arkin's schemas [Arkin1989] for its reactive layer. For its deliberative layer, it uses a searching algorithm, D* lite [Koenig and Likhachev2002], and in the sequencing layer it uses a planner. Thus their robot architecture operates in three different navigation modes. In mode 1, reactive navigation controls the robot and attempts to move it to the goal. In mode 2, reactive navigation controls the robot and attempts to move it to the way-point provided by the planner. In mode 3, the planner directly controls the robot and attempts to move it to the goal. Changes between mode 1 and 2 depend on two variables PERSISTENCE and ANGLE deviation, and this is similar to behaviour exhaustion in Lorenz [Lorenz1981]. To change a behaviour that clearly is not contributing to the achievement of a desired goal. This is also similar to lowering utilities in the behaviour patterns in the BAMUVA architecture, which will be described later. Changes from mode 2 to 3 take place when a number of unsuccessful attempts exceed what was defined in the PERSISTENCE variable. This can be seen as a frustration (misery) emotion. A similar system (but two layered) is presented in [Chao *et al.*2000] where a reactive and planning layer are combined to perform a high level task such as construction. The simulations are however carried out in a 2D environment.

Fuzzy Logic

In [Martínez-Barberá2001] the reactive layer is used for behaviours like collision avoidance and the deliberative layer has been used to develop a map of the terrain and later navigate it using the A* algorithm. A Blackboard [Hayes-Roth1985] is used, which can been seen as a shared data structure amongst agents -similar to those in Minsky's society of Mind [Minsky1985]. Fuzzy logic is used in different levels: agent behaviour definition, result behaviour fusion, sensor filtering, and actuators control. Although impressive since this work has been made for a real mobile robot, it has the restriction of not further modifying the world after the map has been assembled ("learnt ?"). Therefore, this approach is not viable in a changing virtual environment.

Reinforcement Learning

Reinforcement learning has also been used for Action Selection. Humphrys [Humphrys1997] proposes a method to minimise an overall "unhappiness" function to select the behaviour.

This work is very similar to that of Tyrrell [Tyrrell1993], in which different action selection mechanisms are tested. Humphrys used this tests to see how reinforcement learning can "learn" to select the most appropriate behaviour. Though this seems a good idea, avoiding hard-coding of behaviours even in this gridded-word (like those described in [Tyrrell1993] [Canamero1997] [Bryson2000]), the author reached the conclusion that more complexity is required to be added to the simulated world. And like the gridded world of Tyrrell, Cañamero and Bryson, it differs from our proposed architecture in that it includes only a single creature, whilst in our work the interaction is with more than a dozen creatures.

Reinforcement learning has also been used in navigation to improve the performance of reactive systems. [Chao *et al.*2000] has integrated a Brooksian type of reactive mechanism with the additional quality that the mapping between sensorial stimuli and actions is learnt using reinforcement learning rules.

2.3.2 Action Selection for agents in a 3D Space

Action Selection Mechanisms for agents in a 3D Space have differences to those in a gridded world. For example, the sensors need to be different. That is, whilst in a gridded world the space is discrete; in a 3D world the space is (most likely) continuous. One of the advantages of working in a 3D space is that an ASM could be 'exported' to a robot deployed in the real world.

Temporal Reasoning -C4 Synthetic Characters Group

In MIT's Synthetic Characters Group interesting behaviour enhancements are used [Downie2001]. This are adverb parameters, specifically blending motions using adverb parameters. For example: walk *rapidly* or walk *slowly* . This was inspired on the seminal work presented by Rose [Rose *et al.*1998]. Also temporal reasoning is used to avoid conflicting behaviours and time is used as a critical asset. Their architecture an action tuple was proposed. An

Action Tuple is inside the core of the behaviour system where it is the primitive action type. These, action tuples, explicitly represent hypotheses about the world. Each action-tuple is a statement concerning the probabilistic outcome of a given action in a given context, together with the likely value of doing this. This is shown in figure 2.14. In contrast to work based on ethology like the one proposed here, the structure of action-tuples is flat rather than hierarchical. The action-tuple structure can capture the primitive temporal

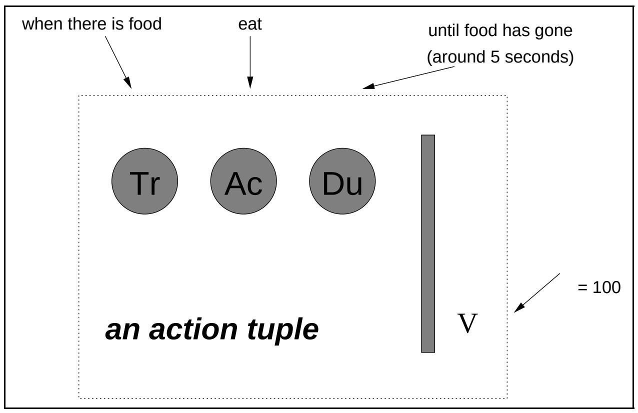


Figure 2.14: c4's The action tuple. After [Downie2001]

relations of the interval algebra [Allen and Ferguson1994] (*equal, before, touching, overlapping, during, simultaneous-starting, simultaneous-ending* and 6 inverses). This is used to engineer constraints in the triggering and ending conditions. It is also used to resolve conflicts with a myriad of sequential and overlapping actions and to enforce relationships between action-tuple activations.

Perlin

Systems discussed so far are working at an abstract level rather than affecting more directly the movements of actors in 3D space. Here a system to generate believable 3D motions is discussed. Perlin's architecture [Perlin1996] solves an interesting problem when trying to change between poses (or behaviours) in 3D space. For example (using his term) if actor has his hands behind the back and he want to clap, using a standard motion interpolation the hands would go through the body, which is not acceptable. Hence a Finite State Machine (**FSM**) is used to force the use of intermediate poses for example hands at the sides when entering or leaving the troublesome action.

Perlin's architecture also blends degrees of freedom from different behaviours. But while he specifically considers the problems of 3D spaces, it needs to be stressed the fact that he is interested in actors, not in autonomous agents. Actions are formed by movement of nineteen universal joints, each joint having three axes of rotation. Two limit parameters are used to specify the range of rotation allowable around each axis. A third, a time parameter, which is an expression of sine, cosine, and noise, controls the speed of movement.

Each action has a natural frequency associated with the weight and inertia of the various body parts. The phases of all actions are synchronised by running them all off the same master clock.

At any given moment, every potential action has a weight assigned to it. For each joint, the contributions from all the actions to that joint's position are combined via a convex sum.

Transitioning from one action to another is accomplished by building dependencies between the weights of actions. Dependencies are controlled by state variables and continuous variables. The state variables consists of discrete boolean values; i.e., either a character wants to perform a particular action, for example, walking, or she does not. The continuous variables consist of continuous values which vary between zero and one. These values are derived by integrating the effect over time of the discrete states. These continuous parameters provide the weights for the convex sum which drives the character.

Another contribution to accomplish believable behaviours is the addition of noise to subtle motions, like breathing. This is important also to inform the user that the avatar or character is active or “alive”.

Blumberg Computational Model

Blumberg's PhD dissertation [Blumberg1996] is a significant effort, since it uses knowledge from a number of different fields. Blumberg's Silas uses an action-selection mechanism motivated by ethology. The intuition behind utilising such models is that biological systems already exhibit complex behaviour. He states that if structurally similar computational processes are used, this might produce equally complex behaviour in artificial systems.

Blumberg used different ethological means to solve some of the problems that can arise when using a Behaviour-Based Approach to Action Selection. He used a loose hierarchy, similar to that found in Tyrrell [Tyrrell1993]. This provides the advantages of a hierarchical system, similar to that proposed by ethologists. But at the same time this approach offers the flexibility of not having a congestion of all the sensorial data in the top-most node of the hierarchy. To solve dithering he used Lorenz [Lorenz1981] mutual inhibition. As shown earlier in figure 2.5. This is a really interesting work, but it was developed with just one animal in mind, Silas, a dog.

The Magic Mirror paradigm used in his work, which combined real video with synthetic characters and projected the composited video onto a screen, served as inspiration for other work such as Paolo Petta's interactive exhibit [Petta1999].

He identified five key problems in developing creatures with behaviour and character.

- Relevance: Do the right things. A problem of Action Selection.
- Persistence: Show the right amount of persistence.
- Adaptation: learn new strategies to achieve goals.
- Motivational State: Convey intentionality and motivational state in way that can be understood.

- External Control: allow an external entity to provide real time control at multiple levels of abstraction.

This work is very relevant to ours with the difference that we are not interested in providing the creatures with a learning capability, and that we are interested in the interactions of multiple emotionally equipped virtual agents, rather than single agents. Additionally, Blumberg was interested in developing a system to produce expressiveness not in creating an internal emotional state. In other words, he was not interested in creating an embodied emotional agent.

2.3.3 Creatures

Creatures is an artificial life program that allows a player to stimulate the Intelligence and growth of a creature hatched from an abandoned egg. The object of the game is to teach your Norn (the species you hatch from the egg) to survive on its own in the world of Albia. In order to do this, a Norn must know how to interact with his or her environment, and have knowledge of what is good or bad to its health and well being.

Basically Creatures is about Life, from birth to death, reproduction, and genetic engineering and experimentation. Though this is a complex game in many aspects, the interface and approach to it are not.

Creatures is a commercial product that has been claimed as the first *game* that uses artificial DNA, and an endocrine system that models chemical receptors and transmitters, inspired by Artificial Life. Steve Grand, who wrote creatures wanted to *put the life back into technology* [Grand1997] -not via quasi-intelligent, monolithic expert systems, but fully-rounded, thinking, caring, even reproducing organisms that are more than the sum of their parts. Creatures is just a toy, but he hopes it counts as a small step towards that goal.

Underlying the brain there is a simple emotional system of drives and needs which motivates the creature to act and regulates its learning. This mechanism is deeply interconnected with the other bodily systems such as digestion, linking brain inextricably with body. This is similar to Damasio's [Damasio1996] treatment of relation between brain/mind and body as a whole.

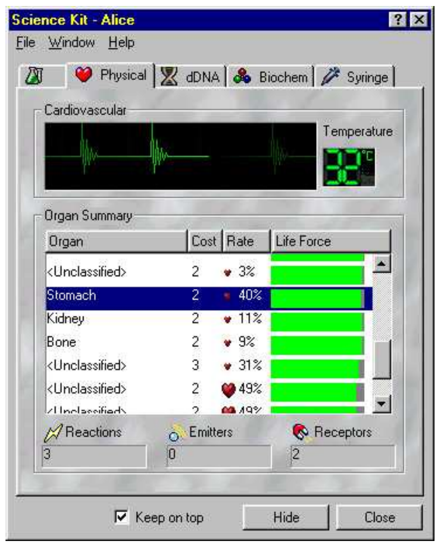
One of the winning points of this game is that the user becomes emotionally attached to the Norns that they hatched. She becomes preoccupied with the well- being of their artificial creatures. Creatures has different tools one can use to check on a Norn, like the Health kit, which checks his heart rate and levels of hunger, exhaustion, and boredom. The Science kit shows the biochemical, internal, hormonal states, and other characteristics of your Norn.

This program is interesting because the user, even at a young ag,e becomes interested in the behaviour of artificial creatures. Also it shows that using concepts from other disciplines like neurons, genes and systems like the digestive an interesting product was successfully marketed.

2.4 Summary

In this chapter different approaches to the problem of "what to do next" were discussed. Theories of Action Selection that have been put forward by ethologists were described; these theories are hierarchical in contrast to other flat theories like that of Hull's. Computational Action Selection Mechanism have been developed and they were discussed in this chapter, related to this work are the ones developed by Tyrrell and Blumberg. Later some shortcomings of reactive behaviours were discussed. Also solutions to those shortcoming were presented, as background to the later discussion on the use of emotion to mediate between competing behaviours. The lessons learnt from action in this chapter are presented.

(a) Norm in Albia World



(b) Science kit in Creatures game

Figure 2.15: Norn in creatures game

1. Ethology concepts had been used and implemented successfully in Action Selection Mechanisms.

2. It has been found that reactive systems present problems like dithering (local minima) and thus a meta-layer is normally added to solve conflicts. Examples include planning, Fuzzy Logic and, related to what is presented here, Emotion.

3. Solutions to reactive behaviours problems include: For 2D spaces (and normally

gridded worlds) and similar to the work presented here 3D spaces like Blumberg, Perlin, Tu and Downie.

4. In 3D spaces researchers are more interested in behaviour believability (Rose, Perlin) and other more interested in a more abstract level (adding autonomous behaviour) like Blumberg and Tu. Downie blends agent concepts and ideas from Perlin and Rose.

Chapter 3

Emotion

> Amar es combatir, es abrir puertas, dejar de ser fantasma con un numero a cadena perpetua condenado por un amo sin rostro.
>
> To love is to battle, to open doors to cease to be a ghost with a number forever in chains, forever condemned by a faceless master.
>
> Libertad bajo palabra.
>
> – *Octavio Paz*
>
> How much better is to weep at joy than to joy at weeping.
>
> Much Ado Nothing.
>
> –*Shakespeare*
>
> Fear. The oldest tool of power. If you are distracted by fear of those around you, it keeps you from seeing the actions of those above.
>
> X-Files 2:3. –*Fox Mulder*

In this work the 'feeling' of a bodily state is deemed important to action selection as will be discussed later; this work will also present the communication of emotions to affect action selection, which is rather important for survival behaviours like escape.

The presentation of this chapter is divided in three parts. The first presents a review of relevant emotion theories. The second presents a review of emotion architectures and their relation to the emotion theories and to each other. The third part presents a summary.

3.1 Emotion Theories

Emotions have been studied for a long time. Plato once said that passions and desires and fears make it impossible for us to think [1] and that passions are the wild beasts trying to escape from the human body [2].

One of the earliest books to have been written on the subject of animal and human emotion is Darwin's seminal work *The Expression of Emotions in Man and Animals* [Darwin1872] where he found that some animals (including humans) exhibit emotions through facial-expression and posture. Other early work in emotion include research from James [James1884] and Cannon [Cannon1929].

As said previously traditionally there have been some problems with typical action selection mechanisms, such as dithering. Emotion can be used to solve that kind of problem and has also been used in various applications to make characters more believable. This work also aims to communicate emotion in creatures to affect their group behaviour. Thus, relevant literature will be reviewed. In this chapter emotion is discussed in relation to a single agent and in the next chapter emotion communication will be discussed.

Similar work to William James [James1884] is still carried out by researchers, and his idea of feedback is still widely accepted, though not in its original form. He said

> *... that the bodily manifestations must first be interposed between, and that the more rational statement is that we feel sorry because we cry, angry because we strike, afraid because we tremble, and not that we cry, strike, or tremble,*

[1]Plato *Phaedo* cited in [LeDoux1998].
[2]idem.

> *because we are sorry, angry, or fearful, as the case may be. Without the bodily states following on the perception, the latter would be purely cognitive in form, pale, colourless, destitute of emotional warmth. We might then see the bear, and judge it best to run, receive the insult and deem it right to strike, but we could not actually feel afraid or angry.*

On the other hand Cannon's research [Cannon1929] led him to propose the concept of an "emergency reaction", (similar to the notion of drive), a specific physiological response of the body that accompanies any state in which physical energy must be exerted. According to Cannon's hypothesis, the flow of blood is redistributed to the body areas that will be active during an emergency situation so that energy supplies, which are carried around in the blood will reach the critical muscles and organs. The bodily responses that make up the emergency reaction were believed by Cannon to be mediated by the sympathetic nervous system, a division of the autonomic nervous system (**ANS**). These days one would agree, except that evidence suggests that this is regulated by the endocrine system.

Emotion has been studied by researchers from different fields and each one with an approach particular to the field that they belong to. Researchers from neurology had been studying the structures of the brain that are involved in the process of eliciting emotions. On the other hand as Ortony suggests [Ortony *et al.*1988]

> *psychology appraisal theory has been widely investigated; in appraisal theory humans make an internal representation of the external environment and the state of the "self" and appraisal or construal is formed.*

There are also theories that combine neurological and cognitive accounts, the best example is Izard's four systems of emotion activation model [Izard1993] and Smith's model which describes the links between appraisal and the physiological experience of distinct emotions [Smith and Kirby2001].

3.1.1 Neuroscience (non-cognitive) accounts

Damasio (a psychologist) has shown, through the experiments of his patients, that without emotion (as in patients with injuries in the frontal lobe) decision making is flawed. Relating to the discussion in chapter 2 on why emotion can be used to improve action selection. Le Doux, a neuroscientist, has found that in the pathway of emotion in the brain the amygdala plays an important role. In this work we have chosen to model the different brain systems involved in action selection and in emotional experience, the internals will be discussed in chapter 5

Damasio

Damasio's influential work [Damasio1996] was based on neuropsychology; his patient, Elliot developed a brain tumour that damaged his prefrontal cortex.

> *Although Elliot began behaving irrationally, testing Elliot revealed that his intelligence, attention and memory remained unaffected by his illness. Instead Elliot had lost the ability to experience emotion; and the lack of emotional guidance rendered decision-making a dangerous game of roulette.*

. Hence Damasio claims that patients with frontal lobe damage take decisions that did not take into account his best interest. From the patient's decisions, it can be assumed that there is no evidence of concern about their future, no sign of forethought.

Further, Damasio states that the machinery for his decision making was so flawed that he could no longer be an effective social being. In spite of being confronted with the disastrous results of his decisions, he did not learn from his mistakes. From this evidence it has been speculated [Picard1997] that reduction in emotion may constitute an important source of irrational behaviour.

Damasio also put forward the concept of ‘somatic markers’ (or *gut feelings*) where he claims that the body experience associated with the ’feeling’ of an emotion is important to mark an emotion, and maybe be used as a tool in decision making. Thus, if an unpleasant feeling is perceived when choosing an option, maybe the next time we are presented with an unpleasant outcome, a ’feeling’ will help us avoid a bad choice. Emotions act as a bias in decision-making. Although the concept of ‘somatic markers’ was developed with humans as their subject, it can also be applied to other animals. For example in the case of fear, when an animal freezes, a decision is biased so greatly that it can be said that the actual decision was made as a result of the emotion being elicited.

Since we humans are closely related to monkeys in terms of evolution, it is fair to assume that monkeys with prefrontal damage can no longer follow the complex social conventions characteristic of the organisation of a monkey troop. From this last point, it can be assumed that emotion plays an important role in social animals, in general and in chapter 4 literature on group behaviour and communication will be reviewed.

According to Damasio, to name one, the limbic system is the ‘centre’ of emotions, and it is composed of several structures [Damasio1996]: the cingulate gyrus, in the cerebral cortex, and the amygdala and the basal fore-brain, two collections of nuclei. LeDoux [LeDoux2000] has found that in particular the amygdala plays a fundamental role in emotional experience.

Emotion and the ’feeling’ of its happening share vital circuitry used to regulate bodily functions. I remember a puppy we owned that, when beign groomed, wagged the tail and then wet himself. In this sense Damasio [Damasio1996] states that the process of emotion and feeling are part and parcel of the neural machinery for biological regulation, whose core is constituted by homoeostatic controls, drives and instincts. Further the lower levels in the neural edifice of reason are the same ones that regulate the processing of emotions and feelings, along with the body functions necessary for an organism’s survival .

Emotions can be categorised as Primary emotions (‘innate’, Jamesian): these depend on limbic circuitry, the amygdala and the anterior cingulate being the prime players. For Damasio, the most universal emotions are Happiness, Sadness, Anger, Fear, and Disgust, and correspond to profiles of body state response which are largely pre-organised in the James’ sense. For different authors, primary emotions are different: table 3.1 summarises the primary emotions according to various emotion researchers. From this list we focus on fear in this work, though other emotions are included in the architecture as discussed later.

To ’feel’ emotion something must trigger it and if the subject in question does not have a pathology that affects him, the environment plays an important role. In this Damasio argues that:

> *the environment makes its mark on the organism in a variety of ways. One is by stimulating neural activity in the eye (inside which is the retina), the ear, and the myriad nerve terminals in the skin, taste buds, and nasal mucosa. Nerve terminals send signals to circumscribed entry points in the brain, the so-called early sensory cortices of vision, hearing, somatic sensors, taste, and olfaction.*

During the adaptation of different species through evolution it has been found to be adaptively advantageous, to have neural circuits that can trigger fast emotions so that an emotion is felt and can be used to avoid destruction (for example, fight or flight behaviours) by predators or adverse environmental conditions.

In figure 3.1 it can be seen that with an appropriate stimulus the amygdala (A) is activated and a number of responses ensue: internal responses (marked IR); muscular responses; visceral responses (autonomic signals); and responses to neurotransmitter nuclei and hypothalamus (H). The hypothalamus gives rise to endocrine (like those used in this work in aprocrine glands) and other chemical responses which use a bloodstream route.

Theorist	Fundamental emotions	Basis for selection	Reference
Arnold, M.B.	anger aversion courage dejection desire despair fear hate hope love sadness	relation to action tendencies	Arnold (1960)
Ekman, P.	anger disgust fear joy sadness surprise	universal facial expressions	Ekman Friesen & Ellsworth (1982)
Frijda, N.	desire joy pride surprise distress anger aversion contempt fear shame	forms of action readiness	Frijda (1987, and personal communication)
Gray, J.	rage/terror anxiety joy	hardwired	Gray (1982)
James, W.	fear grief love rage	bodily involvement	James (1884)
McDougall, W.	anger disgust elation fear subjection tender-emotion wonder	relation to instincts	McDougall (1926)
Mowrer, O.H.	pain pleasure	unlearned emotional states	Mowrer (1960)
Oatley, K, and Johnston-Laird, P.N.	anger disgust fear happiness sadness	do not require propositional content	Oatley & Johnston-Laird (1987)
Panksepp, J.	expectancy fear rage panic	hardwired	Panksepp (1982)
Plutchik, R.	acceptance anger anticipation disgust joy fear sadness surprise	relation to adaptive biological processes	Plutchik (1980)
Tomkins, S.S.	anger interest contempt disgust distress fear joy shame surprise	density of neural firing	Tomkins (1984)
Watson, J.B.	fear love rage	hardwired	Watson (1930)
Weiner, B.	happiness sadness	attribution-independent	Weiner & Graham (1984)

Table 3.1: A selection of lists of “fundamental” or “basic” emotions from [Ortony *et al.*1988]

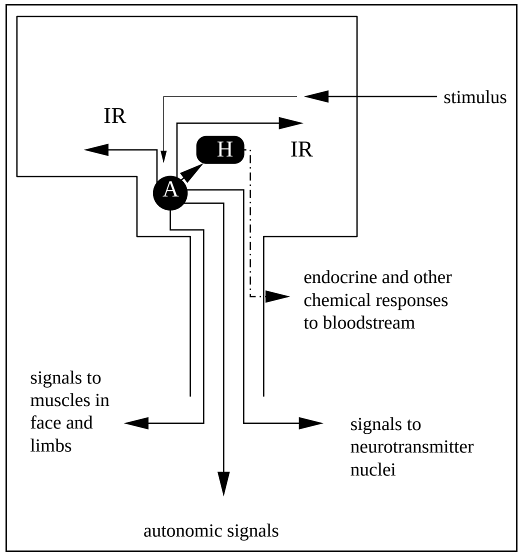


Figure 3.1: Primary Emotions. The black perimeter stands for the brain and brain stem. After [Damasio1996]

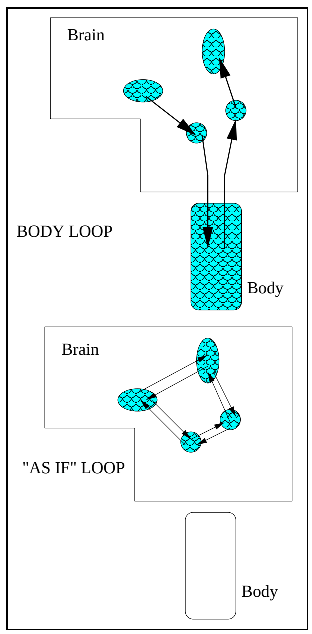


Figure 3.2: Diagram of the "body loop" and the "as if" loop. After [Damasio1996]

Antonio Damasio believes that in many situations emotions and feeling are operated from mind/body to body and back to mind/brain. This contrast with Descartes's separation of mind and body. In Damasio's work (with which we agree), the concept of mind and body as a whole is used through-out; thus we argue that the agent needs to be embodied to 'feel' the emotion and behave in an advantageous manner as in flight or fight. In this sense the agent needs to be embodied or at least 'think' that he is embodied. Damasio suggests that there are devices that help us feel “as if” we were having an emotional state, see figure 3.2 , as if the body were being activated and modified.

It is known that chemical substances can change emotions and moods; alcohol, narcotics, and a host of pharmacological agents can modify how we feel.

LeDoux

LeDoux (and others) has shown beyond the shadow of a doubt that the amygdala plays a role in emotion. The amygdala system is part of the limbic system, which is the centre of emotions, it consists of two almond-shaped structures in the brain's limbic region.

The amygdala has projections to many cortical areas. In addition to projecting back to cortical sensory areas from which it receives inputs, the amygdala also projects to some sensory areas from which it does not receive inputs. This may be very important in directing attention to emotionally relevant stimuli by keeping the short term object buffer focused on the stimuli to which the amygdala is assigning significance. [LeDoux1998]

Emotions in animals, in particular fear, can be studied because there are very good tools available for their study, like fear conditioning. In a typical fear conditioning experiment, the subject, such as a rat, is placed in a small container. A sound then comes on, and is followed by a brief mild shock to the rat's feet. After repeating several times such pairings of -sound and shock- the rat begins to be afraid when it hears the sound. We argue that the emotional stimuli can be either conditioned as in this example or hard-wired (in the pathways of neural circuitry through evolution for survival purposes) such as when one hears a sudden sound from behind one's back, or when a small chick sees a flying object resembling a predator. See figure 3.4 for the pathway to produce an emotional response as proposed by LeDoux.

As said before, it has been found in animals, in particular rats, that the basal ganglia plays an important role in action selection. Le Doux argues that the basal ganglia [LeDoux1998] may be important in instrumental emotional behaviour, which he calls "emotional actions", and in this work the basal ganglia has a pathway to the amygdala, and the amygdala affects action selection and can be labelled as an "emotional action".

In this work the idea that an emotion is 'felt' for a while and not just lasting a short time is important, because an animal must keep running even if it can no longer directly perceive the predator following him. In the same vein, LeDoux states that the arousal systems activated by the amygdala are important in sustaining a feeling of fear. See figure 3.3 for some of the responses to an emotion been triggered in the amygdala.

LeDoux claims much of what the brain does in relation to emotion, occurs outside of conscious awareness. LeDoux states that

> *although this may seem obvious, the study of emotion has been so focused on the problem of emotional consciousness that the basic underlying emotional mechanisms have often been given short shrift.*

Although thoughts can easily trigger emotions (by activating the amygdala), we are not very effective at wilfully turning off emotions (by deactivating the amygdala). Telling yourself that you should not be anxious or depressed does not help much. Cognitive accounts will be discussed next.

3.1.2 Cognitive accounts

The concept of appraisal was put forward by Magda Arnold in an influential book published in 1960 [Arnold1960]. She defined appraisal as the mental assessment of the potential harm or benefit of a situation and argued that emotion is the "felt tendency" toward anything

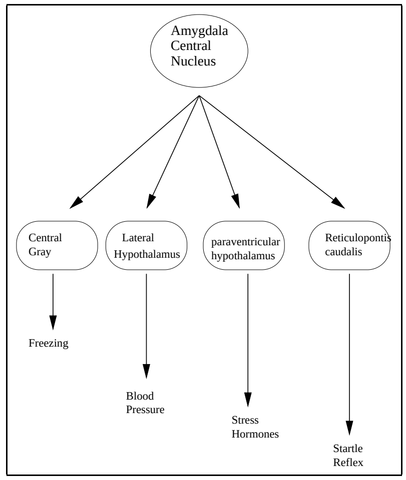


Figure 3.3: Fear Response. After [LeDoux1998]

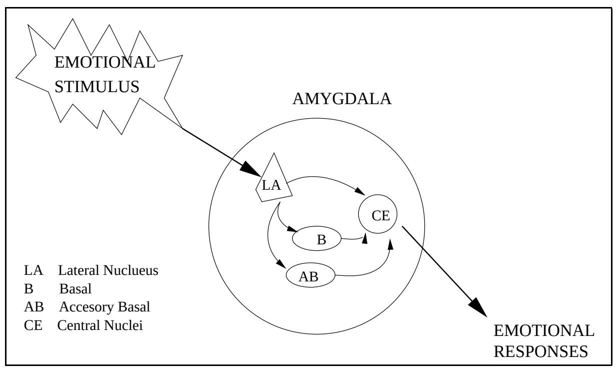


Figure 3.4: Pathway in amygdala. After [LeDoux1998]

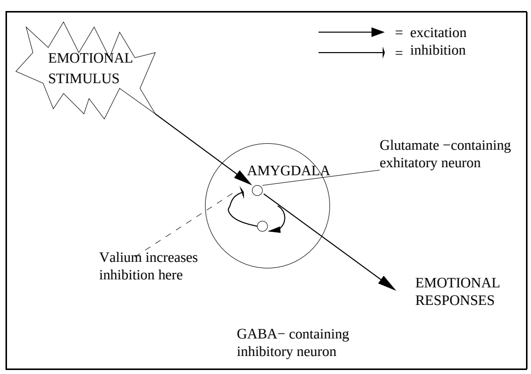


Figure 3.5: Excitatory and inhibitory impulses in amygdala. After [LeDoux1998]

appraised as good or away from anything appraised as bad. Although the appraisal process itself occurs unconsciously, its effects are registered in consciousness as an emotional feeling. Later Lazarus argued [Lazarus1991]that emotions can be initiated automatically (unconsciously) or consciously, but he emphasised the role of higher thought processes and consciousness, especially in coping with emotional reactions once they exist. Summarising his position, he noted that cognition is both a necessary and sufficient condition of emotion, so it can be assumed that he claimed that other animals do not have emotions, a position with which we do not agree given the evidence presented in this work. Appraisals provide an explanation of why the same event can give rise to different emotions in different individuals, or even in one individual at different times. Conversely, appraisals offer an explanation for understanding what differentiates emotions from one another.

By far the most common used Model for modelling emotion in agents implemented in cognitive architectures of emotions in Artificial Intelligence is that of Ortony, Collins and Clore [Ortony *et al.*1988], hereafter (OCC Model) which is described below.

The OCC Emotion Model

According to the OCC model, there are four main kinds of evidence about emotions: language, self reports, behaviour and physiology. The latter two kinds concern the consequences or concomitants involving emotional states, but not their origins, which they think are based upon the cognitive construal of events, although other research has found that not only cognitive appraisals can elicit emotions [Izard1993] [LeDoux1998] [Smith and Kirby2001], but that they can also be triggered unconsciously.

Instead of attempting to describe every possible emotion, the model of Ortony, Collins and Clore (OCC) works at a level of emotional clusters, called emotion types, where the emotions within each cluster share similar causes. For example the distress type described all emotions caused by displeasing events. Distress includes individual emotions, such as sad, distraught, and lovesick that differ in less significant dimensions such as intensity and the reason the event was found to be unpleasant. The OCC taxonomy of emotions is illustrated in figure 3.6.

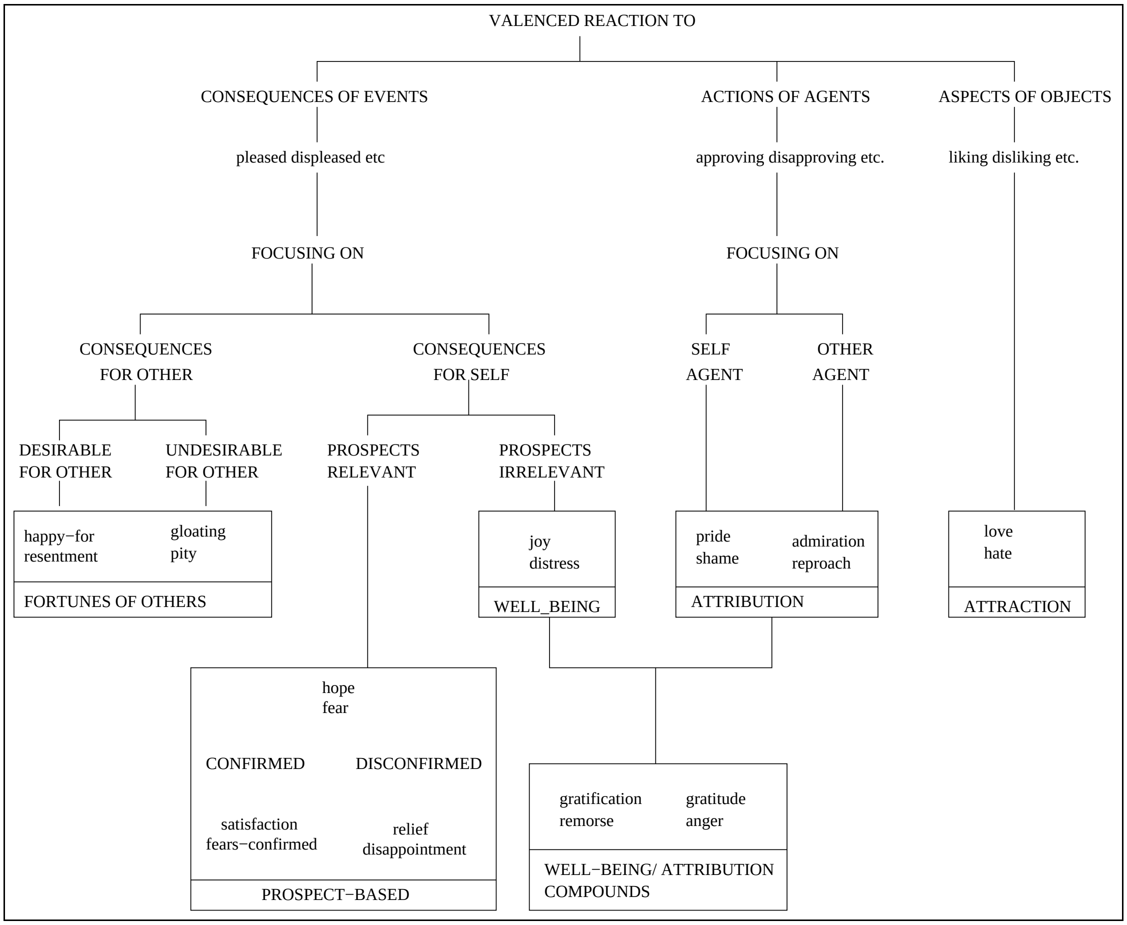


Figure 3.6: Global structure of emotion types from [Ortony *et al.*1988]

Although this model was not made for animal emotions they claim that it is tempting to suppose that animals experience fear. However, attributions are typically based on observations of behaviours (aggressive behaviour or avoidance behaviour), though there are several examples of animals that appear to experience emotions like joy, anger, sadness, grief and even shame [Masson and McCarthy1996].

In the OCC model any non-emotional state that is experienced can, in principle, give rise to a valenced reaction; for example, hunger (a non-emotional state) can trigger the valenced reaction of distress.

In general, any valenced reaction to an object or event can give rise to emotions, thus, psychological states themselves (including emotional ones) are candidates for emotion inducing objects and events, thus leading the possibility of chains of additional, new emotions.

The OCC model proposes that emotions are the results of three types of subjective appraisals:

1. The appraisal of the pleasingness of events with respect to the agent's goals.
2. The appraisal of the approval of the actions of the agent or another agent with respect to a set of standards for behaviour.
3. The appraisal of the liking of objects with respect to the attitudes of the agent.

The model also proposes a compound set of emotions caused by combinations of other emotions. Altogether, these give rise to a number of emotions, like joy, distress, hope, fear, pride, shame, admiration, reproach anger gratitude, gratification and remorse. One may disagree with some aspects of the OCC, which is basically a taxonomy; for example, it is particularly odd that anger is a compound emotion, when most authors regard it as a primary emotion. There are animals that show an angry behaviour, it is debatable that they appraise anger as a consequence for oneself!

Frijda

Frijda's theory of emotion [Frijda and Moffat1994] elicitation is also a cognitive appraisal theory, like other appraisal theories [Ortony *et al.*1988][Roseman *et al.*1990]. It includes a matching mechanism whereby features of a situation are mapped onto a set of output emotions. Figure 3.7 shows Frijda's Model of Emotion Eliciting.

Together with other emotion theorists [Oatley1992] [Sloman and Croucher1981] Frijda emphasises the cognitive nature of emotionality and claims that a machine operating under similar conditions, with needs to be satisfied, difficulties at every corner, and only limited power and knowledge, would also have to be emotional in order to survive.

In Frijda's theory of emotion evaluation processes, appraisals mediate between the occurrence of significant events and changes of internal *action tendencies* that are accompanied by characteristic expressive behaviour. An action tendency is defined as readiness for different actions having the same intent or goal state i.e., *states of readiness to achieve or maintain a given kind of relationship with the environment.*

One of the primary issues in Frijda's model is that an action readiness changer is propsed, see figure 3.7. This effectively is a meta layer to the action readiness proposed by ethologists like Lorenz. Thus, one can say that emotion could serve as a meta-layer to affect actions.

Ekman

The so-called basic emotions approach distills those emotions that have distinctive facial expressions, like those seen in figure 3.8, associated with them and seem to be universal: fear, anger, sadness, happiness, disgust, and surprise. More precisely, Ekman prefers to talk about (basic) emotion families.

A product of Ekman research was that a feedback loop with the body was proved. So expanding the chest may not be a bad idea when one is feeling down. Thus, in a similar way to what has been described in the previous section, the body plays an important role in the 'emotional experience'. In his study [Ekman1993] Ekman asked the subjects to move certain facial muscles. Without realising it, they were asked to exhibit facial expressions characteristic of different emotions. Then they were asked to answer some questions about their mood. It turned out that they were influenced by their facial expressions. As in this study, in the work presented here the body plays an important role in emotional 'feeling'.

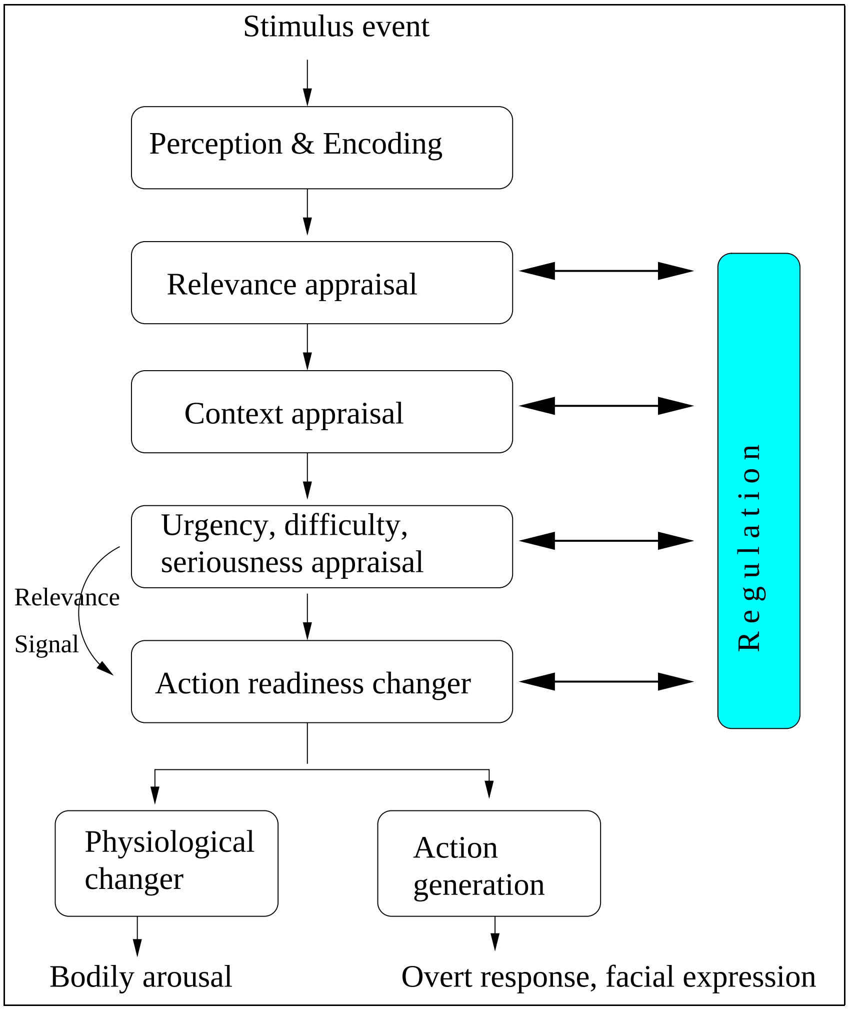


Figure 3.7: The Emotion Process from [Frijda and Moffat1994]

Figure 3.8: Fear Facial Expression

Other models of emotion

Sloman's approach to emotion [Sloman2001] proposes that the cognitive mechanism cannot be investigated in isolation but must be embedded within the overall architecture that includes mechanisms concerned with perception as well as the generation and management of motives and affective states, in a resource-bounded agent. Sloman does not draw a sharp line between cognitive and emotional processing. Sloman's work views emotions as "dispositional tendencies", tightly coupled with motivation and the organism's goals. Emotions may or may not be conscious. Contrary to [Panksepp1994b], hunger is not treated as a basic emotion, but it is treated as a drive and not handled in the Amygdala, but in the hypothalamus. As pointed out in [Scherer1994], the verbal labelling of emotions is not identical across different cultures, but he argues that anger and fear are defined as emotions and linked to the flight and fight behaviour which are important across species. As said before, in the architecture developed in this work fear plays a predominant role.

3.1.3 Hybrid Models of Emotion

Izard proposed that there are four types of elicitors of emotion in humans [Izard1993]. His model is shown in figure 3.9. This model is relevant because it is an incremental architecture drawing from evolution; according to him the neural processes are the first to have been in place to elicit emotions. Since we are developing our architecture starting from a low-level architecture to elicit emotions, it seems appropriate to anchor our architecture in a biologically plausible architecture that is compatible with emotions in humans as well as in other animals. This model conforms to this requirement. Izard argues:

> *From an evolutionary-developmental perspective, the systems may be viewed as a loosely organised hierarchical arrangement, with neural systems, the simplest*

> *and most rapid, at the base and cognitive systems, the most complex and versatile, at the top. The emotion activating systems operate under a number of constraints, including genetically influenced individual differences.*

The four types of emotion elicitors in Izard's model are:

Neural. Effects of neurotransmitter and other neurochemical processes. These processes run independently, in the background, and are influenced by hormones, sleep, diet, depression medication, etc.

Sensorimotor. Effect on posture, facial expression, muscular tension, and other central efferent activity. These effects primarily intensify a given emotional state, but in some cases appear to be capable of generating new affective states.

Motivational. Effect on sensory provocations such as anger provoked by pain, of drives such as hunger, and emotions evoking each other.

Cognitive. Effect on cortical reasoning.

In Izard and Tomkins [Tomkins1962] an emotion is distinguished from a drive state. They have argued that drives, such as hunger, thirst, sex, and the need to eliminate, are cyclical in nature. Or that they depend on time and no other stimuli is needed to elicit a drive, nonetheless with an emotion an appropriate stimulus is needed as seen in the previous section.

Smith

Smith theory of emotions is one of the few that proposes a link between appraisals and autonomic activity. Further, [Smith and Kirby2001] suggests that:

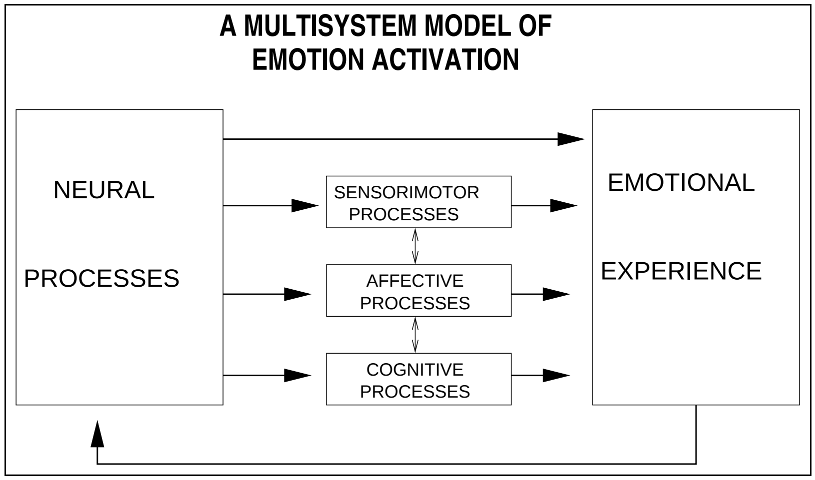


Figure 3.9: A multi-system model of emotion activation from [Izard1993]

> *consistent with the view that autonomic activity in emotion physically prepares the person to contend with the adaptational implications of the appraised situation, two major components of autonomic activity, cardiovascular and electrodermal (skin conductance) activity have both been associated with task engagement. Also electro-dermal activity, which has been associated with attentional processes, such as orienting response appears to be closely associated with the attentional aspects of task engagement.*

Similar to Frijda [Frijda1986], Smith claims that an important self-regulatory function imputed to emotion is that of attention regulation as stated in [Smith and Kirby2001]. A number of authors conceptualise the emotion system as a *well-being monitor*' or *alarm system*. An important function of the emotional response is to redirect the person's focal attention to adaptationally relevant events in the social environment.

3.2 Emotion-Based Architectures

The latest scientific findings indicate that emotions play an essential role in rational decision making, perception, learning, and a variety of other cognitive functions. We all know by experience that too much emotion can impair decision making, though Picard [Picard1997] claims that *too little emotion can impair decision making* as well. She says that if we want computers to be genuinely intelligent, to adapt to us, and to interact naturally with us, then they will need the ability to recognise and express emotions, to have emotions and to have what has come to be called *emotional intelligence*. Some popular books had been available on the subject, one such book is that of [Goleman1996].

Modern theories of emotion are thus richly detailed in information-processing terms, and lend themselves to computational modelling. Several models have been implemented based on emotion theories, particularly appraisal theories like Frijda's [Frijda1986] and the OCC model [Ortony *et al.*1988]. ACRES [Swagerman1987] is a model that was implemented based on the former, and Elliot's Affective Reasoner [Elliot1992] is based on the latter.

The architectures described in this section incorporate models of different aspects of emotions, motivations, and personality. There are different approaches to modelling emotion; and as described in the previous section they can be identified as non-cognitive -accounts; cognitive accounts; and a hybrid approach which combine elements of both. Next some of the most representative architectures will be discussed.

3.2.1 Cañamero

Cañamero's work is representative of the non-cognitive approach, which is a position similar to the one we took in the work presented here. She [Canamero1997] states that

> *contrary to cognitive approaches, we do not tackle these directly, but go below the agent level and use physiological parameters to model them. Motivations drive behaviour selection and organisation based on the notions of arousal and satiation.*

In Cañamero's agents, emotions exert further control by the simulation of hormones that may affect the creature's perceptive, attentional, and motivational mechanisms. They also modify the intensity and execution of the selected behaviour. In her system an emotion *is an agent that amplifies (or modifies) the motivational state of a creature and its perceived bodily state.* It is characterised by: *an incentive stimulus; an intensity proportional to its level of activation; a list of hormones it releases when activated; a list of physiological symptoms; and a list of physiological variables it can affect.* She uses Marvin Minski's [Minsky1985] society of mind approach where: *any part or process of the mind that by itself is simple enough to understand -even though the interactions among groups of such agents may produce phenomena that are much harder to understand.* In her system, agents are used in several tasks like sensing the environment and processing sensory data. Other agents are associated with a particular direction or region in space; there are also effector agents, behaviour agents and manager agents. This approach can be characterised as an agent oriented approach, analogous to an object oriented approach, in the sense that a group of agents collectively form the brain.

Similar to Cañamero's approach, Kravits [Kravitz1988] used artificial hormones to bias behaviour selection in a model inspired in a real lobster, controlling in this way the gross behaviour of the animal: however, hormones did not alter individual behaviours or lower level motor actions, or consummatory acts for ethologists [Tinbergen1969].

Cañamero argues that:

> *motivations are inferred internal states postulated to explain the variability of behavioural responses that cannot be exclusively accounted for by observable stimuli. These states or drives constitute urges to action based on bodily needs related to self-sufficiency and survival.*

It should be noticed that this work was done in grid-based world and so the sensors used are different from the ones proposed in this work. Later, she developed an interesting architecture to elicit emotions in a robot made out of Lego blocks [Canamero and Freslund2000]; in this work she used some of Tomkin's model of emotion, similar to Izard's. The interesting point is that in that model and the proposed architecture, emotions are elicited depending on different pattern stimuli. For example if the robot is patted for a small amount of time, this will elicit a different emotion than if it is patted a bit longer. This was in young children. They definitely respond differently if patted gently and briefly in the buttock than if being smacked with force.

3.2.2 Velásquez

Velásquez developed Cathexis [Velásquez1998], a very complete emotional architecture that integrates emotions, drives, and behaviours, and focuses on modelling some of the aspects of emotions as fundamental components within the process of decision-making. The emotion eliciting part of the architecture is based on Izard's four systems model for emotion eliciting [Izard1993], described above: Neural, Sensorimotor, motivational and cognitive. He used appraisal theory [Roseman *et al.*1990] in his earlier model [Velásquez1997], but later he revised the cognitive elicitors to be learnt through emotional experiences, instead of having them pre-wired.

His system also includes a drive system which represent urges that force the agent into action. Here he states [Velásquez1998] that a hunger drive will aid in controlling the behaviour that directly affects the level of food intake by the agent. His architecture is based upon work from ethology [Tinbergen1969] and is similar to certain action-selection architectures [Tyrrell1993] [Blumberg1994]. The behaviour system is distributed and composed of a network of behaviours, such as "fight", "kiss" or "smile". Each of these behaviours competes for the control of the agent. The decision of which behaviour should be active is based on the value of each of the behaviours, which is recalculated on every cycle. Each behaviour contains two major components: the expressive or Motor Component and the Experiential Component. He shows how the mechanisms of primary emotions can be used as building blocks for the acquisition of emotional memories that serve as biasing mechanisms during the process of making decisions and selecting actions.

3.2.3 Cognitive architectures

ACRES is an (emotional) database-interface [Swagerman1987]. The user can ask ACRES for data, can turn debugging on and off, can ask ACRES to say what its last "experienced" emotion was, and can end the session by "killing" it. (The "kill" command has to be entered twice to stop the program, and after the first entry ACRES invariably "begs" to continue.) ACRES has a hierarchy of concerns which are, in decreasing order of importance: to stay alive, to have prompt input from the User (not too much waiting while he goes off for a cup of tea), to have accurate input (with few spelling errors), to have varied input (so that the program is fully used), to do what the User wants, and least important of all is to turn tracing/debugging on and off.

The output of the program is either the expected response to a query, or spontaneously generated "emotional expression", which is in upper case to distinguish it. The emotional expressions are to indicate the system's emotional state to the user, but also to change the user's behaviour to please the system more. They are thus also planned (or at least goal-oriented) acts to get some desired behaviour from the user. If the user does not comply with the system's wishes, then he will be gradually excluded from the system, losing his privileges. First he will find that the system no longer allows him to change the database; then it will not allow him even to read it anymore.

ACRES does not have an equivalent to autonomic arousal or other physiological mechanism in humans, such as blood chemistry and neurotransmitter concentrations in the brain. This has been shown to be a problem [Moffat *et al.*1993] because the agent can be angry and the next minute happy, which is not very believable.

Similar systems are Elliot's Affective Reasoner [Elliot1992], though the Affective Reasoner is based on the OCC model and has a more complex graphical interface. A contrasting system is Cañamero's which used a non-cognitive approach in which homoeostatic variables influence behaviour, already discussed above.

CogAff: Sloman

Sloman classifies emotions as primary, secondary and tertiary. His model [Sloman2001] sees emotion as an embedded component of his ultimate goal, a model of a complete mind.

According to him, primary emotions relate to evolutionarily very old reactive architectures shared with many other animals, even insects. All they require is a reactive architecture with a global "alarm" system.

Sloman argues that secondary emotions (like apprehension, relief, excited anticipation) are possible only in organisms which also have deliberative mechanisms, which developed much later and are probably far less widespread.

Sloman states that tertiary emotions (e.g. infatuation, humiliation, guilt, debilitating grief) *require a third architectural layer, which evolved even later and is probably very much rarer*, and he suspects that they do not exist in new-born humans. He has called this a "meta-management" layer, which provides mechanisms for monitoring, evaluating, and controlling "internal" processes.

Paolo Petta

Paolo Petta's architecture [Petta1999] was carried out in the context of the development of an immersive interactive virtual environment in which a single user and a synthetic actor engage in an improvisational interaction between peers. His architecture for emotions uses Frijda's [Frijda1986] appraisal theory; in his system emotions are processes that continuously evaluate the environment (including the whole external environment and the subject itself) according to dimensions of relevance to the subject: Each individual will make its own appraisals and thus an emotion will be triggered or not. This work is similar to what is proposed here in the sense that different agents can elicit different emotions depending on their configuration, though it should be noticed that in this work emotions are not triggered through appraisals but through simulated neural circuitry.

In his system, Petta and coworkers used the "magic mirror" metaphor introduced in MIT's ALIVE project [Darrell *et al.*1994]: a human user stands in front of a large screen onto which her own image is composited into a display which includes animated graphics. It is interesting the way in which the virtual creature shows action expression by means of animated textures which encode the activation of action tendencies in dimensions of psychological perception, such as warmth of the colour tone, feel of the material or "excitableness" of the texture pattern.

Magy Seif El-Nasr

Magy El-Nasr's architecture [El-Nasr *et al.*2000] includes a computational model of emotions using a fuzzy-logic representation to map events and observations to emotional states. The model also includes inductive learning algorithms to learn patterns of events, associations among objects, and expectations. Related to this work is that proposed in [Delgado-Mata *et al.*2002], which was later changed to use structures resembling neural circuitry for emotion elicitation instead of using fuzzy logic to simulate the Amygdala, where the emotions act as in [LeDoux1998].

3.3 Summary

In this section ideas about emotion theories and architectures have been put forward. It has been shown that two different accounts on emotion can be characterised: a low level account, with ideas put forward by neuroscientists like LeDoux. They found that Amygdala is at the centre of the emotional experience, whereas a high level account, put forward by Frijda, Ortony et al, is the other known account. In the former, it has also been stated that the body plays a vital role in emotional experience. In the latter, we considered a number of appraisal theories. In these theories it is claimed that a cognitive appraisal process must take place before a 'feeling' occurs. Examples are Frijda's model and the OCC model; this latter can be described as a taxonomy and is very popular with computer scientists. Also architectures which use emotions have been discussed, such as that of Velásquez and Cañamero. Research has also been carried out in detecting emotion (specially in humans) like Picard [Picard1997]. In this chapter we have discussed the individual emotional experience. In chapter 4 a section on emotional communication is discussed.

In this work, emotions are pre-wired, that is primary (Jamesian). We have chosen to model the pathways in the emotional experiences. Thus, as stated in this chapter, the Amygdala plays a predominant role. Also important is the fact that emotion can be used to avoid problems in action selection, for example dithering. Relevant is the idea of Frijda of changing action readiness, because animals have shown changes in its action readiness depending on internal state. We argued that emotions can happen in animals as well as in humans. We also state that cognition is not a requirement to 'feel' an emotion.

Chapter 4

Group Behaviour (Communication)

> I really wanted to be able to communicate –everybody that was around, bring them together as one body.
>
> –*Carlos Santana*
>
> "Well, why don't you join up with them ? I've told you before we have to be on the side of whoever's winning."
>
> "I've aleady done it"
>
> "Then why are you here ?"
>
> Pedro Páramo.
>
> *Juan Rulfo*

In this chapter we will consider communication (signalling) between conspecifics and group behaviour. In the first section we will discuss how signalling is performed in real animals, later we will discuss robots that are closely inspired by their real counterparts, such as the cricket robot, which is inspired in invertebrate neuroscience, and finally we will look at group animation and how by using a few rules striking behaviour, see figure 4.1, can be achieved in group animation, as in the approach proposed by Reynolds in [Reynolds1987].

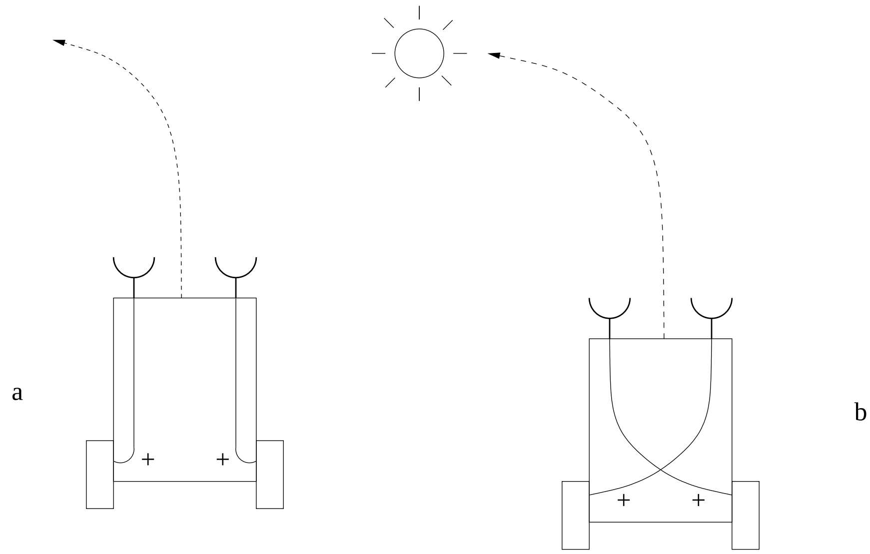


Figure 4.1: Vehicles a and b in the vicinity of a source (circle with rays emanating from it). Vehicle b orients toward the source (aggression), a away from it (fear). After Braitenberg 1984

	Type of signal			
Feature of channel	Chemical	Auditory	Visual	Tactile
Range	Long	Long	Medium	Short
Rate of change of signal	Slow	Fast	Fast	Fast
Ability to go past obstacles	Good	Good	Poor	Poor
Locatability	Variable	Medium	High	High
Energetic cost	Low	High	Low	Low

Table 4.1: Advantages of different sensory channels of communication. In McFarland 1999

McFarland suggests that "*The effectiveness of animal signals is influenced by the physical environment, the nature of the receiver and the influence of other signallers*", he also states that "*different sensory modalities are best suited to different habitats*", as can be seen in table 4.1. Much depends, therefore, upon the physical nature of the habitat.

4.1 Animal Communication

The importance of communication between conspecifics becomes clear specially when groups become larger. Tinbergen claims [Tinbergen1965]

> *Many animals aggregate in groups larger than families. Such groups may be composed of several families, such as a flock of geese or swans, or they consist of individuals which are no longer united by family ties. The benefits which individuals derive from grouping together can be of various kinds. Among these, the defence against predators is the most obvious one [as in this work -author's comment]. Members of a flock of higher animals warn each other in case of danger, and the flock as a whole therefore is as alert as the most observant of its individuals. Moreover, many animals join each other in communal attack. These activities are mainly found in the higher animals, but lower down in the scale we find numerous other functions of flocking.*

Different animal communicate using different type of signals, and Tinbergen [Tinbergen1965] says that group behaviour

> *This can be effected by signals, acting upon various sense of organs of the reactors. In birds, these signals are usually visual, or auditory or both. The wing specular of ducks and geese, which are brightly coloured and differ from one species to another, have been shown to serve this function*

4.1.1 Phonotaxis

Robots have been used to learn about and test several systems of invertebrate animals, this is important because both fields have been enriched by their collaboration. For example Barbara Webb has developed a robot which is very impressive and relevant to the topic of this chapter; communication between robotic crickets simulating the auditory and neural systems of a cricket [Webb1994] and an improved version [Webb *et al.*2003] (although the cricket sender is here simulated by sound transmitted via a loud-speaker). The interesting behaviour is performed by the receiver which moves toward the sound source. This behaviour is called phonotaxis. Thus, it is relevant to our work in that communication between conspecifics has been simulated using invertebrate neuroscience. That is, artificial neural networks have been developed to perform the cricket's phonotaxis behaviour. This behaviour could be tagged as a "love call", nonetheless it does not constitute emotional communication as the work proposed herein, whose architecture will be discussed later. The reader is referred to Barbara Webb's excellent overview article on invertebrate neuroscience in robotics [Webb2002].

4.1.2 Honeybee dances

It has been shown that social insects use communication between members of their colonies. Bees signal information like direction and orientation of food source, that a human observer can also read and interpret [von Frisch1967]. Esch et al [Esch *et al.*2001] realised an experiment in which they found that retinal image flow in bees is used to compute the distance to the food source. They point out:

> *When foragers collect food in a short, narrow tunnel, they dance as if the food source were much farther away. Dancers gauge distance by retinal image flow on their way to their destination. Their visually driven odometer misreads distance because the close tunnel walls increase optic flow. We examined how hive mates interpret these dances. Here we show that recruited bees search outside in the direction of the tunnel where the foragers come from. Thus dances must convey information about the direction of the food source and the total amount of image motion 'en route' to the food source , but they do not convey information about absolute distances...*

The communication between the returning bee and the would-be foragers is carried out by what is known as "The waggle dance", see figure 4.2. The worker bee performs an

Figure 4.2: Waggle dance. After Gould 1988

elaborate dance on the vertical surface of a comb. The dance generally takes the form of a figure of the number eight (except when the distance is not relevant). The duration of the dance is relative to the bee's perceived distance to the food source and the angle of start is the angle of the food source in relation to the sun. See figure 4.3

What is important to observe is that, like other animals, bees communicate vital information to other members of their species, in this case, direction and perceived distance to the food source. In the system proposed in this work we have chosen to communicate using chemicals, because, as it can be see from table 4.1 chemicals do not need to be close to the signal's source and there is no need to have a line of sight between the sender and the receiver to successfully communicate the intended message.

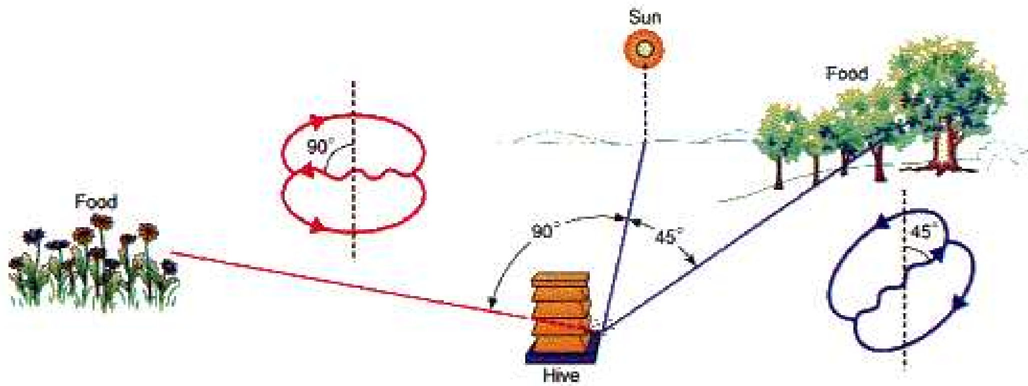


Figure 4.3: Waggle dance and relation to food source. Modified from Kimball 1983 [Kimball1983]

4.1.3 Pheromones

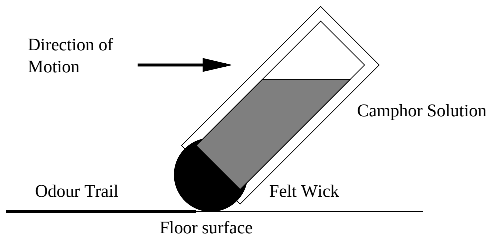
Pheromones have been regarded as very important in animal signalling, but it has not been until recently that textbooks have appeared [Wyatt2003]. Pheromones are widely used in animals to achieve different goals: signaling conspecifics of danger, creating bonding between a mother and child; signalling oestrus in females and for other roles in mating.

In invertebrates, pheromones are widely used: example is a colony of ants, adapting its foraging efforts to the nearest, most promising food source [Bonabeau *et al.*1999]. Recruitment of other foragers is accomplished by pheromone trails: a successful ant returns to the nest leaving behind a "smell" on the ground. This smell biases the movements of other foragers. When the latter also find a food source at the end of the pheromone trail they reinforce the trail by depositing new pheromone markerss. This same process is used in artificial systems like complex telephone networks, whence a pheromone-like trail is left by a successful connection [Bonabeau *et al.*1999].

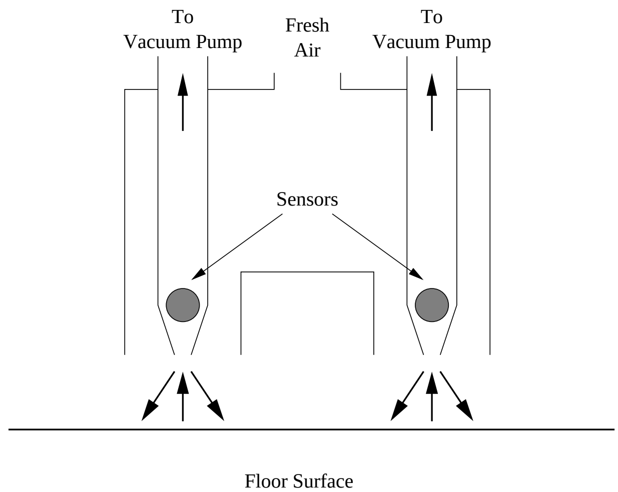
Artificial pheromones have also been used in robotics: a research team in Australia did emulated ant behaviour in robotic systems capable of both laying down and detecting chemical trails (artificial pheromones), see figure 4.1.3. [Arkin1999] provides an interesting overview:

> *These systems exhibit chemotaxis: detecting and orienting themselves along a chemical trail. Camphor, a volatile chemical used in mothballs, serves as the chemical scent. The application method is straightforward: the robot drags a felt-tipped pen containing camphor across the floor as it moves, depositing a trail one centimetre wide. Sensing is more complex. The detection device contains two sensor heads separated by 50 mm. An inlet draws in air from immediately below the sensor across a gravimetric detector crystal. An air down-flow surrounding the inlet insures that the inlet air is arriving from directly below the sensor. The detector crystal is treated with a coating that absorbs camphor, and as mass is added, the crystal's resonant frequency changes in proportion to the amount of camphor absorbed. When this chemo-tactic system has been attached to a tracked mobile robot provided with an algorithm that strives to keep the odour trail between the two sensor inlets, the robot has been able to follow the chemo-tactic trail successfully for up to one-half hour after the application of the camphor trail.*

An interesting application of pheromones in robotics, is described in [Payton *et al.*2001], where a swarm of robots communicate using artificial pheromones with each robot acting as a pheromone in a free expansion gas. This is similar to the work proposed here is that pheromones are locally transmitted without specifying a recipient, pheromones decay over time, reducing obsolete information. A criticism of the approach taken is that they use the concept of the pheromones-like messages being relayed directly from robot to robot. In the system proposed here pheromone messages are not relayed directly, but via the internal emotional mechanism described in chapter 5.



(a) Camphor applicator



(b) Dual head sensing device

Figure 4.4: Chemotaxis hardware: (a) the camphor applicator. (b) The dual head sensing device. After Arkin 1999

Another application of real pheromones [Wyatt2003] is in pest control: several techniques for pest control have benefited from the use of pheromones like 'lure and kill', mating disruption, to stop fertilisation of eggs by preventing adult males and females from finding each other and monitoring, where traps are used to quantify the population of a pest. Other uses of pheromones include conspecific scent marking to prevent colonisation.

In the work presented here pheromones are used to communicate the internal emotional state (such as fear) between artificial animals of the same species or conspecifics. The internals of this work will be defined in chapter 5.

4.2 Artificial Sensors

For communication between animals, the receiving animal must have some form of sensor. For example, olfactory, auditory, visual, tactile and/or for taste. To accomplish this in a Virtual Environment or within a robot, artificial sensors must be developed.

Sensors have been developed for several computer graphics creatures: one example is in the creatures in Hamsterdam [Blumberg1994]. Typically these have one or more "sniff" sensors with which to perform direct sensing. The sniff sensors were intended to be an idealised "nose", which given a list of kinds of creatures for which to sniff, will find the closest instance of each kind of creature on a given time tick. In this respect the artificial nose proposed in this work is quite different from that developed by Blumberg in that the one developed here is based on biological and artificial noses and the communication is carried out via the environment. Even Blumberg acknowledge the limitations of his "nose sensors".

> *The greatest problem with direct sensing is that it can provide the creature with super-natural sensing and this in turn can lead to super-natural behaviour. The fundamental problem is that direct sensing is "cheating".*

Odour sensors or artificial noses have been the inspiration behind the artificial nose proposed in this work. Gardner [Gardner and Bartlett1999] points out:

> *It is clear that the types of sensors which can be used in an electronic nose to to be ones which are responsive to molecules in the gas phase. Many different types if gas sensor are available and many of these have been used in electronic noses at one time or another.*

According to Grardner, odour molecules are typically volatile organic molecules with relative molar mases in the range 30 to 300 Dalton. Furthermore, the structure of the molecules is important in determining the odour. Unlike physical artificial noses we need to take in and process the molecules in real-time; in industrial applications the result can be acceptable even if it is computed for several seconds.

4.3 Group Animation

Since the system described in this work was developed in a virtual environment it is important to discuss group animation. As pointed out in [Parent2002], when animating groups of objects, three general classes of techniques are usually considered, depending on the number of elements being controlled and the sophistication of the control strategy. These general types of techniques are particle systems, flocking, and (autonomous) behavioural animation.

A *particle system* is a large collection of objects (particles) which, taken together, represent a fuzzy object [Reeves1983]. Particle systems are based on physics, and particles themselves are supposed not to have intelligence, therefore this kind of technique is usually employed to animate groups of objects that represent non-living objects.

Flocking systems typically have a medium number of objects, each one of them controlled by a relatively simple set of rules that operate locally. The objects exhibit some limited intelligence and are governed by some relatively simple physics. This type of technique is usually employed to animate objects that represent living objects with simple behaviour.

Particle systems and flocking systems produce the so-called *emergent behaviour*, that is, a global effect generated by local rules. For example, one can speak of a flock of birds having a certain motion, even though there is not any control specific to the flock as an entity.

Autonomous behaviour is usually employed to animate one or a few objects which are supposed to be "intelligent". Therefore this kind of technique is usually employed to animate groups of objects that represent living objects. Generally each object is controlled by a sophisticated set of rules.

As we are trying to simulate the behaviour of medium-size animal flocks, we have decided to base the group animation algorithm on flocking techniques. However, we also want every animal to show a sophisticated behaviour based, among other things, on its emotional state. Therefore, our system is hybrid, in that it shows a global flocking behaviour but at the same time each object is controlled by a complicated autonomous behaviour.

4.3.1 Boids

The collective behaviour of flocks, herds and schools has been studied in artificial life [Langton1995] and complex systems [Flake1999] areas. This kind of behaviour seems complex, however, as Reynolds suggested [Reynolds1987], it can be modelled by applying a few simple rules to every individual. In his model of so-called boids, every individual (boid) tries to fulfil three conditions: cohesion or flock centring (attempt to stay close to nearby flock-mates), alignment or velocity matching (attempt to match velocity with nearby flock-mates), and separation or collision avoidance (avoid collisions with nearby flock-mates). Boids has been successfully used to animate the behaviour of flocks in several famous films.

Recently Reynolds has created an improvement to take user input into account and has added a finite state machine controlling transitions between behaviours (walk and fly), the application is called pigeons in the park [Reynolds2000]. This is relevant to our work in the sense that a change of behaviour in a group of animals is addressed, but in contrast with the system proposed herein, individual creatures do not have an internal state. The trigger for flying is made by the computation of collision detection between an ellipsoid and the pigeons, also the behaviour is contagious in the sense that a pigeon will fly if a threshold is passed of a number of pigeons taking off near the pigeon in question.

4.3.2 Computer Games

Interesting examples of group behaviour can be found in video games, especially, when the essence of the game is group behaviour; and two of the best exponents in this exciting field are *Herdy Gerdy* see figure 4.5(a) which was published by Core, and *Pikmin* see figure see figure 4.5(b) developed by the excellent game designer Shigeru Miyamoto of Nintendo.

The aim of Herdy Gerdy is to safely shepherd a number of creatures to a pen. To accomplish this, an interesting group behaviour algorithm was developed to affect the behaviour of the creatures depending on a vector composed by the orientation and velocity of the player (Herdy). The movement of the creatures is accomplished through a flocking type group behaviour.

On the other hand, in Pikmin the player (the character Olimar) controls a set of creatures (called Pikmin) to accomplish tasks. This game is of particular interest because the player can interact with a large group of pikmin (up to one hundred). The group behaviour animation is carried out by an algorithm which resembles Reynold's **boids**. This game can be catalogued as Strategy but it is quite interactive in that the player has to interact with the pikmin constantly to accomplish his or her goals.

4.4 Other group behaviour

Other non-graphical systems have been developed using algorithms that resemble animal flocking, one outstanding case is the robot sheep dog [Vaughan *et al.*2000], in which a mobile robot gathers and manoeuvres a flock of ducks. To accomplish this, an algorithm takes vision data from a camera placed on top of a circular arena 7 meters in diameter. The algorithm takes the vision system data (that is the positions of the robot flock R, flock F and a goal G) as input and it returns a vector with the desired trajectory. $f(R, F, G) \rightarrow \vec{r}$. To test this system a simple model of flocking was developed. It differs from the algorithm

(a) Herdy Gerdy screen shot

(b) Pikmin screen shot

Figure 4.5: The images from the video games that use group behaviour

developed in our in that emotion was not included. The rules are:

1. The ducklets are attracted to each other, aggregating the flock. Similar to Reynold's cohesion.

2. The ducklets are repelled from each other, preventing collisions and maintaining inter-ducklet spacing. Similar to separation or collision avoidance in Reynold's algorithm.

3. The ducklets are repelled from the arena wall, preventing collisions. A specialisation of Reynold's separation rule.

4. The ducklets are repelled from the robot. Yet another specialisation of Reynold's separation rule.

This approach is relevant to the work described herein as it combines a physical creature, a robot, with real animals. In that project they observed the animals' behaviour from an ethological perspective. However, the flocking algorithm that they use is rather simple and they acknowledge that in the sense that the flock is considered to be a single unit (a blob). A flock of mobile robots has also been demonstrated in [Mataric1996], thus similar to graphical creatures, flocking has also been tested in mobile robots.

4.5 Communicating emotion

As said before, olfaction can be used to signal amongst conspecifics. One of those signals can be emotion. Emotion communication in animals, including humans is of course multi-modal, using for example facial expression, posture and olfaction, that is through pheromones. It is said that love at first sight is actually possible; on this account researchers have found that pheromones can play an important role in mate selection for females [Grammer1993]. Also bonding between a mother and her child is important for adaptive behaviour and specifically as a means of survival; three week old infants can produce facial expression of happiness to their caregivers. It is not clear what triggers the elation of this facial expression, maybe through adaptation we humans have been imprinted with the knowledge that it is good to do so, insofact the caregiver will not throw us out the window when we (as infants) have been crying all night!

In another context, it is said that dogs smell fear. It is risky to do such an affirmation. Fear is an emotion, subjective to the individual, and thus cannot be communicated as such, but according to David McFarland (author's personal communication), mammals emit pheromones through apocrine glands as an emotional response, and as a means to communicate that state to conspecifics, and they could adapt their behaviour accordingly. Research has found that odours produce a range of emotional responses in animals, including humans [Ehrlichman and Bastone1977] [Izard1993]. This is adaptively advantageous because olfaction is part of the brain (that humans share with other animals through evolution), which can generate fast emotional-responses, that is without the need for cognitive processes. In this respect [Kitchell *et al.*1995] points out that:

> *The use of pheromones to alert conspecifics or members of a social group to the presence of an intruder or a potential attacker is common in many animal species. For example, in the presence of an intruder, several species of social hymenoptera secrete pheromones which cause defensive behaviour among conspecifics. This alarm pheromone is thought to have two effects: (1) it alerts conspecifics to the threat of danger, and (2) it acts as a chemical repellent to the intruder. In this manner, the "fear scent" produced by the honeybee worker does not provoke aggression by a predator, but instead functions in hive protection. Another example of the role that olfactory cues play in communicating alarm among animals in found in carnivorous mammals of the family of Mustelidae. Mustelids are distinctive among mammals in their defensive use of anal scent glands to produce olfactory warning signals. All mustelids are characterised as having well developed anal scent glands. In particular weasels, wolverines, and skunks have been documented to release repellent odour from these glands where alarmed.*

Emotion can be communicated by smell. Research [Grammer1993] has shown that a panel of women can discriminate between armpit swabs take from people watching "happy" and "sad" films. The emotions of others, for example fear, contentment, sexuality, may therefore be experienced and communicated by smell.

Neurons from the lateral olfactory tract project to different systems in the brain: the amygdala, septal nuclei, pre-pyriform cortex, the entorhinal cortex and the subiculum. Many of these structures form part of the limbic system, and ancient region in the brain concerned with motivation, emotion and certain kinds of memory.

In the work presented here, communication of emotion through artificial pheromones has been chosen because as discussed in this chapter, because they are a cheap and efficient way of signalling amongst conspecifics. The internals of the architecture will be discussed in the next chapter.

4.6 Summary

In this chapter we have presented communication (signalling) performed by real animals, also some examples of communication between robots have been presented, and the chapter has described how group behaviour has been used in computer graphics and video games. In the work presented here chemical signals (pheromones) were chosen to communicate emotional states such as fear, because their properties are suitable in changing environments. Other options for detecting emotion would be by reading body poses, but the computational power required to achieve this is too high given that target of the work presented here is to the test the architecture in a virtual environment that runs in real time, that is 24 frames per second. On the other hand chemical signals do not need as much processing power to be detected, exuded and simulated.

Chapter 5

Architecture

> It is impossible to understand Art and the glory of its history without avowing religious spirituality and the mythical roots that lead us to the very reason of being of the artistic phenomenon. Without the one or the other there would be no Egyptian pyramids nor those of ancient Mexico. Would the Greek temples and Gothic cathedrals have existed? Would the amazing marvels of the Renaissance and the Baroque have come about?
>
> – *Luis Barragan. Pritzker Architecture Prize Laureate*
>
> Come, every frustum longs to be a cone,
> And every vector dreams of matrices.
> Hark to the gentle gradient of the breeze:
> It whispers of a more ergodic zone.
> Cyberiad.
>
> – *Stanislaw Lem*

In this chapter we describe an architecture for self-animated emotionally influenced flocking creatures which builds on the ideas from ethology, emotion and signalling that were presented in the previous chapters. This architecture has been implemented as an

XML file-configured application for developing and testing creatures performing group behaviour inside a Virtual Environment. This design, briefly described in chapter 1, was created iteratively, which in some way resembles natural evolution, keeping and improving what works and getting rid of what it does not. This chapter is organised around several iterations as they occurred during the development of the mentioned architecture. This is carried-out in an iterative process, analogous to the way nature systems evolve, namely what works is kept and what it does not is removed. The first 6 sections correspond to 6 iterations, that is one section per iteration. The evolution of the architecture is shown in figure 5.26

5.1 Iteration 1: BAMUVA

In the first iteration a full implementation of the Behavioural Synthesis Architecture **BSA** was developed -The Behaviour Based Architecture for Multiple Virtual Agents- henceforth **BAMUVA**, which explored the feasibility of using the **BSA** in Virtual Environments [Delgado-Mata and Aylett2000]. **BAMUVA** is formed by a creature's 'brain' which contains behaviour switches, they contain behaviour packets and preconditions. Behaviour Packets are formed out of one or more behaviour patterns **bp**. An example of a behaviour switch (going towards a beacon) is presented in figure 5.1.

The basic component in the architecture is the behaviour pattern, **bp**, where

$$\mathbf{bp} = \begin{bmatrix} r \\ u \end{bmatrix} \tag{5.1}$$

and

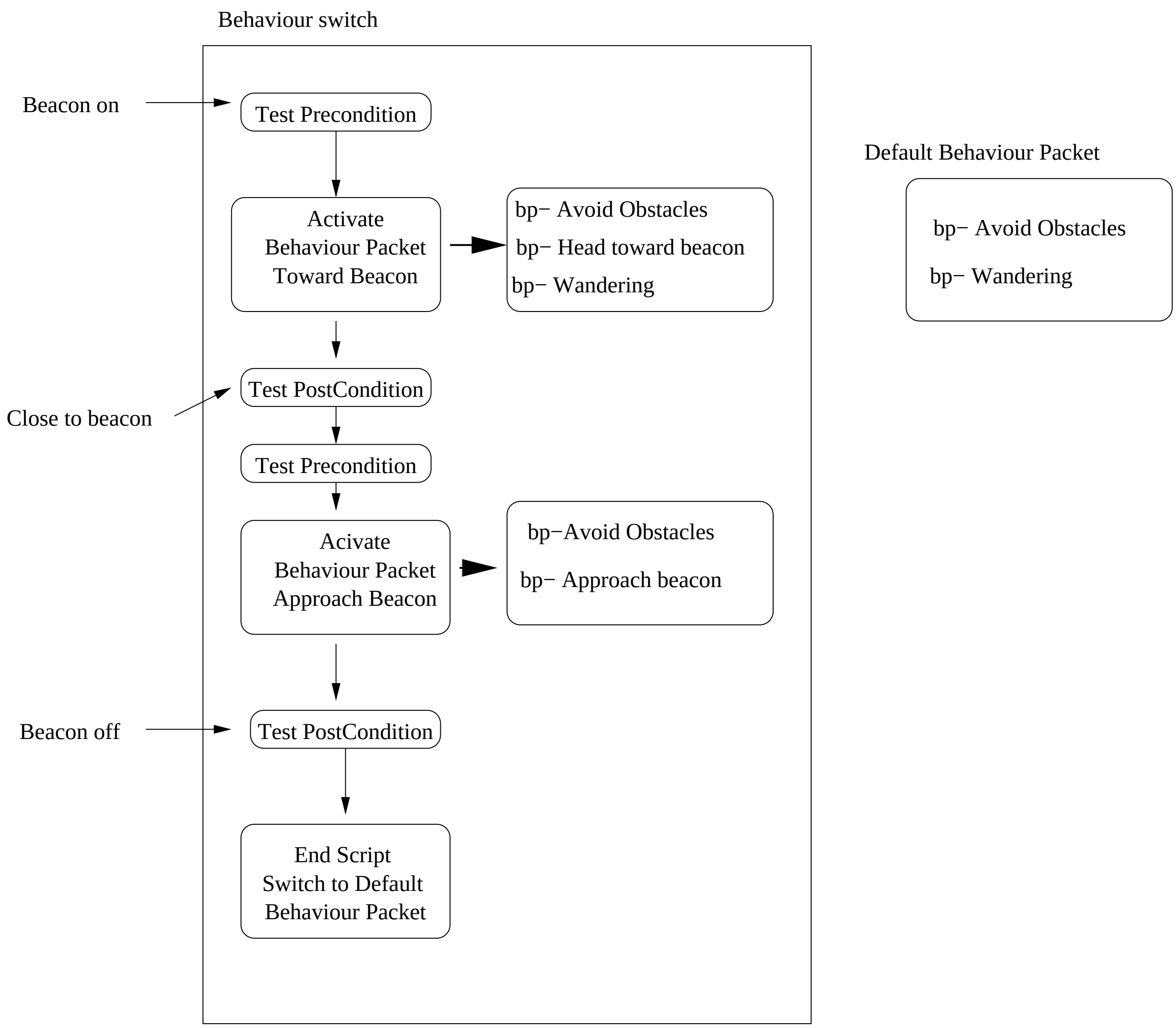


Figure 5.1: Implemented behaviour switch using BAMUVA

$$r = f_r(s) \tag{5.2}$$

$$u = f_u(s) \tag{5.3}$$

r is the desired motion response and is a function, f_r, of a given sensory stimulus, s.

Associated with every response is a measure of its utility or importance, u. This quantity is a function , f_u, of the same sensory stimulus. Hence a **bp** defines not only what the motion response should be for a given sensor input, but it also provides a measure as how the relative importance of this response varies with respect to the same sensor input. The values of r and u constitute a vector known as *utilitor*. Figure 5.2 shows an example of a simple **bp** that might exist at a given level. Consider the situation where the sensory stimulus relates to a creature's forward facing distance to an obstacle measuring sensor and the associated motion response relates to the forward velocity for the creature. From figure 5.2 it can be seen that as the robot get nearer to the object, its forward translate velocity will be reduced to zero. At the same time the associated utility for the motion response increases. Thus as the creature get nearer to an object in its path, the more important it becomes to the creature to slow down. At any point in time, t, multiple conflicting motion responses are typically generated. For example, a creature may be moving towards a goal location when an obstacle unexpectedly appears in its path and at the same time senses that it *feels* hungry. In such situation what should it do? In BAMUVA, conflicting motion responses are resolved by a behaviour synthesis mechanism to produce a resultant motion response. Competing utilitors are resolved by a process of linear superposition which generates a resultant utilitor, UX_t where:

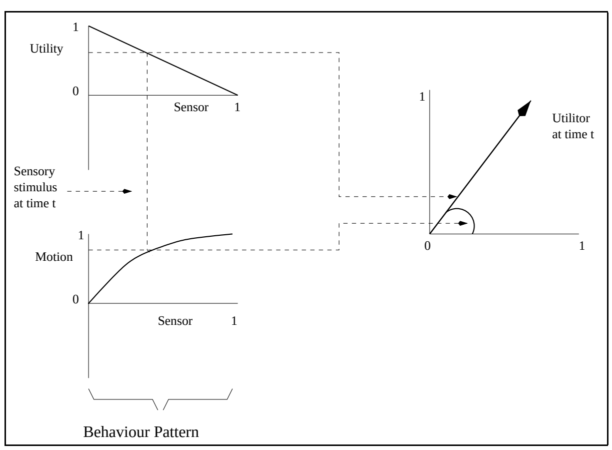


Figure 5.2: Behaviour pattern example

$$\mathbf{UX_t} = \sum_{n=1}^{m} u(t,n) \cdot e^{j \cdot r(t,n)} \tag{5.4}$$

and m equals the total number of related utilitors generated from the different behaviour levels concerned with motion. Given a resultant utilitor, a resultant utility, uX_t, and a resultant motion response, rX_t are simply obtained from

$$\mathbf{yX_t} = \frac{|U\ X_t|}{m} \tag{5.5}$$

$$\mathbf{yX_t} = arg(U\ X_t) \tag{5.6}$$

X identifies the relevant degree of freedom, e.g. forward movement, and the result motion response, rX_t, is then executed by the creature. From equation 4, it can be seen that generating a resultant utilitor from different behaviours within the architecture constitutes a process of additive synthesis, see figure 5.3

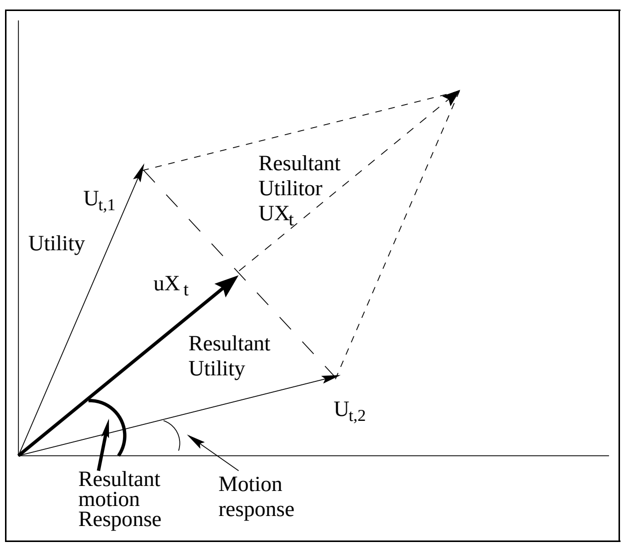


Figure 5.3: Generating a resultant utility and motion response from two constituent utilitors

Bp´ s are collected into behaviour packets: a collection of patterns, which linked together can accomplish a goal. For example through a set of patterns like object-avoidance, navigate-towards-beacon and wander, the creature can accomplish the task of reaching a beacon in a cluttered environment

The next abstraction is the behaviour script, which is a list of packets each of which is triggered by a sensory pre-condition. A behaviour script, by permitting behaviour packets to be activated and deactivated, supports goal searching, allowing a behaviourally driven creature to accomplish tasks with complex sequential structure.

The architecture is an Object Oriented extension to the Behaviour Synthesis Architecture, which was developed at the University of Salford [Barnes1996], to accomplish a task through cooperating robots. This work used ethological knowledge similar to the one described in Animal Behaviour literature [McFarland1999]. While each robot had a repertoire of simple behaviour patterns, complexity emerged through interactions between behaviour patterns and between robots.

To make believable creatures, animation of their movement is important and a previous attempt was made to develop using Division [Aylett *et al.*1999] but it lacked animation and the behaviour did not look believable. So an animation engine was envisaged.

5.2 Iteration 2: Animation Engine (Maverik)

5.2.1 Computer Graphics

Transformations in a 3D space are usually represented using homogeneous coordinates, so 3D transformations can be represented by 4 x 4 matrices.

Translation in 3D is given by the following matrix:

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & T_x \\ 0 & 1 & 0 & T_y \\ 0 & 0 & 1 & T_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.7}$$

Scaling is defined by.

$$\mathbf{S} = \begin{bmatrix} S_x & 0 & 0 & 0 \\ 0 & S_y & 0 & 0 \\ 0 & 0 & S_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.8}$$

For rotation 3 matrices are provides one for each axis. The x-axis rotation matrix is

$$\mathbf{R_x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.9}$$

The y-axis rotation matrix is

$$\mathbf{R_y} = \begin{bmatrix} \cos\theta & 0 & \sin\theta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.10}$$

The z-axis rotation matrix is

$$\mathbf{R_z} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 & 0 \\ \sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.11}$$

The aim of these matrices is to allow any number of rotation, scaling, and translations to be multiplied together.

The resulting matrix can be applied to each vertex that define a geometry. An example is provided next on how matrix transformations are used to generate a pose.

Animation

As the aim set when starting this work was to develop believable artificial animals, it was found that animations were needed. In [Aylett *et al.*1999] the characters (Teletubbies) were not animated and thus seemed like ghostly figures floating around.

The animation that was required needed to be computed each frame (around 30 times per second) but be sufficiently realistic so that it should seem believable. Another aim in developing the system was to produce a multi-platform running system; one of the target platforms was the SGI IRIX with a fully immersive environment so the difference of the

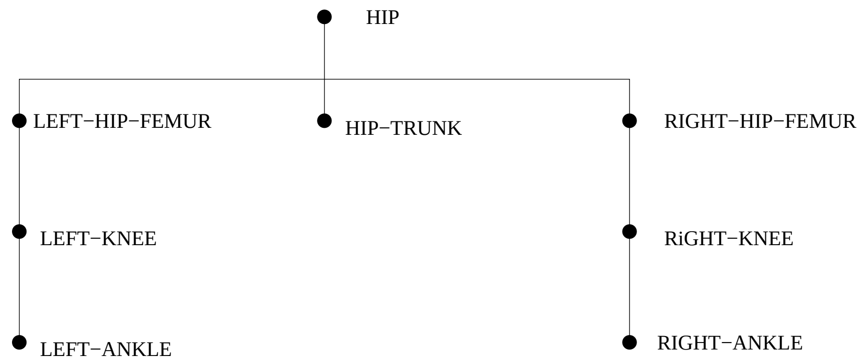


Figure 5.4: Tree of joints for animating a two-legged creature (like chicken)

perceived sense of presence with users could be tested. The previously developed version of the Virtual Environment that used **BSA** was developed using Division, but at the time the license was quite restrictive and the company itself was ceasing to exist so a less restrictive licensed API for **VE** was searched. Maverik was considered as a viable alternative.

In Maverik (or other APIs for IRIX) an animation has to be created step-by-step because there is no import utility which will read animations developed in packages like 3D Studio Max Character Studio. Further the animation packages that exist are mostly concerned with human animation and not with other species of animals.

So to this end, an animation engine was developed and it is described next. A forward kinematics animation was developed, see figure 5.4. In this figure a hierarchy of joints is shown, with the top-most being the hip. And the children are shown downwards in the figure. For example the left-knee joint is a child of the left-hip-femur joint.

A file to describe the relation of the joints was developed and it is shown next. In this file the hierarchy is described and also linked to each joint there is a limb (part), a geometry which is defined by means of a file.

Next an excerpt of the file **chick.geom** is shown.

```
; File Created by Carlos Delgado
; 23 June 2000
```

```
;  type     number joints number parts
geom-info         8             8
;
;  root joint
root-joint - 0.0 0.0 0.0
;        father joint  x y z  relative to previous father joint
; left leg joints
joint    0  0.24  -0.72 0.0
joint    1  0.0   -0.40 0.0
joint    2  0.0   -0.40 0.0
;right leg joints
joint    0  -0.24  -0.72 0.0
joint    4  0.0    -0.40 0.0
joint    5  0.0    -0.40 0.0
joint    0  0.0    -0.52 0.0
; Part Joint   x     y    z   Relative to Joint    Filename      Name
; Body
part      0   0.0   0.0  0.0             ./objects/chick_hack.ac     HACK
;left leg parts
part      1   0.0  -0.20 0.0             ./objects/chick_thigh.ac    LEFT_THIGH
part      2   0.0  -0.20 0.0             ./objects/chick_shin.ac     LEFT_SHIN
part      3   0.0  -0.04 0.10            ./objects/chick_foot.ac     LEFT_FOOT
;left leg parts
part      4   0.0  -0.20 0.0             ./objects/chick_thigh.ac    RIGHT_THIGH
part      5   0.0  -0.20 0.0             ./objects/chick_shin.ac     RIGHT_SHIN
part      6   0.0  -0.04 0.10            ./objects/chick_foot.ac     RIGHT_FOOT
```

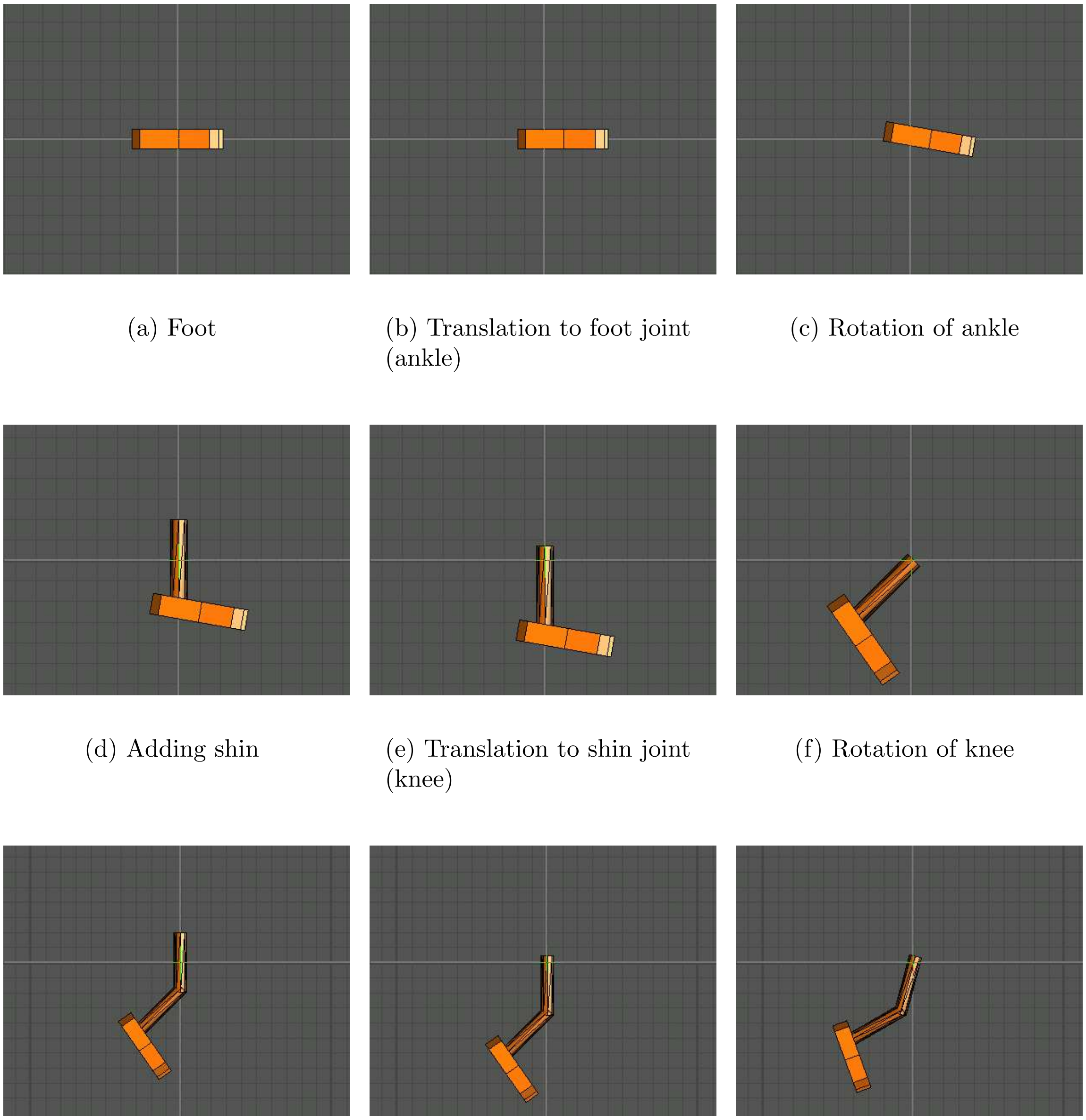
Next an expo of the file **chick.frame** is shown. In this file the key-frames are stored.

```
;left leg
frame     21      1         -20.0
frame     21      2          45.0
frame     21      3          10.0
```

The result shown in figures 5.5(a) to 5.5(i) is done with the following pseudo-code. As it can be seen it is a recursive algorithm. It should be noticed that the parameter is a constant reference and thus the stack is not filled with a lot of data, just the references to the matrices.

```
update limb (matrix parameter m)
BEGIN
  rotMatrix = rotation of joint;
  offsetGeom = offSet of the Geometry in relation to the Joint.
  offsetJoin = offset of the Joint in relation to parent.
  transMatrix = offsetJoint* m * rotMatrix * offsetGeom;
  for each limb  update ( - offsetGeom);
  _mRes.set ((float *)   _transMatrix._m);
  set limb's position  to  _transMatrix
...
END
```

Different views of the assembled leg are shown in figure 5.6. The complete model of the chick is shown in figure 5.7. As said before an BAMUVA was the library used for



(a) Foot

(b) Translation to foot joint (ankle)

(c) Rotation of ankle

(d) Adding shin

(e) Translation to shin joint (knee)

(f) Rotation of knee

(g) Adding thigh

(h) Translation to thigh joint (hip)

(i) Rotation of thigh-hip joint

Figure 5.5: Example procedure to assemble a pose

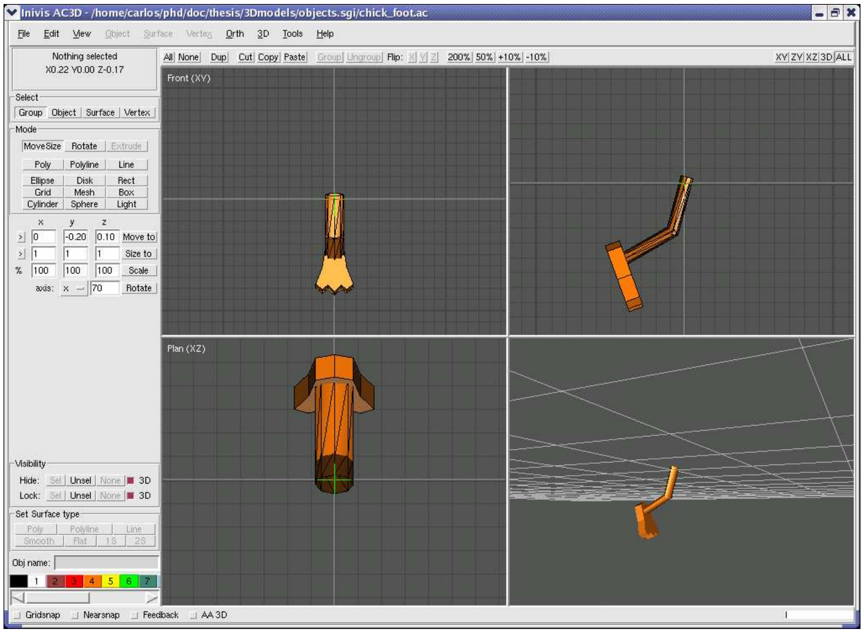


Figure 5.6: Different views from a pose being assembled

implementing reactive behaviours. The behaviours depend on the entry of the sensors and so a library of sensors was developed, a distance sensor can be seen in figure 5.7. Because the target is to run the application in real time (24-30 frames per second), a low polygon count is prefered. It can be seen in figure 5.8 that the wire frame of the different objects contain low number of polygons.

This software served as a tool to implement agents in a Virtual Environment for the MSc VE module Agents and Avatars. It was desirable to test the system with an immersive display device to evaluate whether the users feel a sense of presence within the virtual environment and how far their perception of presence is affected by incorporating autonomous creatures. An attempt was made to run the virtual environment on a CAVE without success in pite of efforts made with the developers .We concluded that Maverik was not suited to run on the CAVE, so other options were investigated.

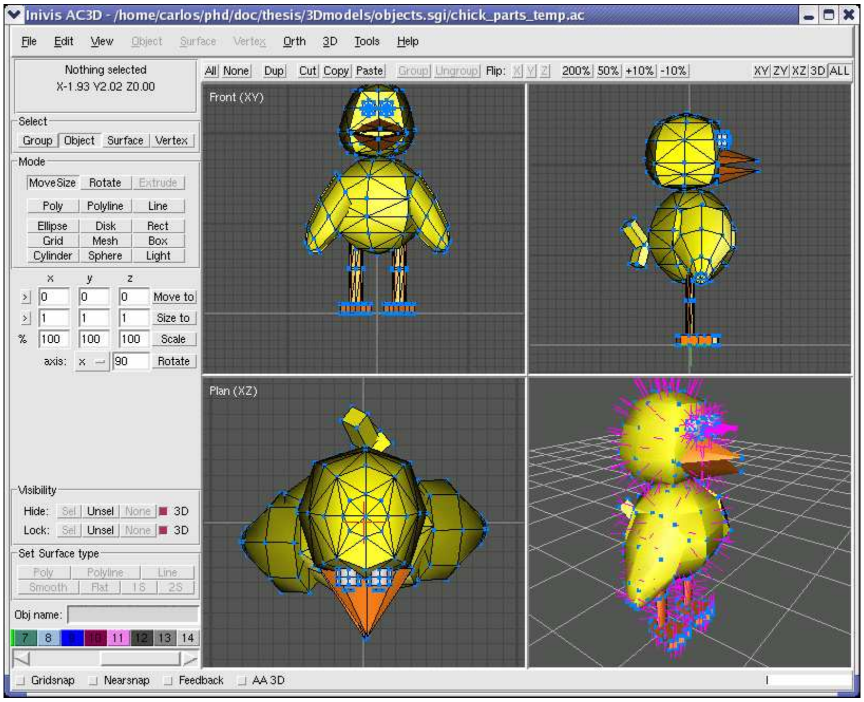


Figure 5.7: Modelling a Chick

Figure 5.8: Virtual Chick model

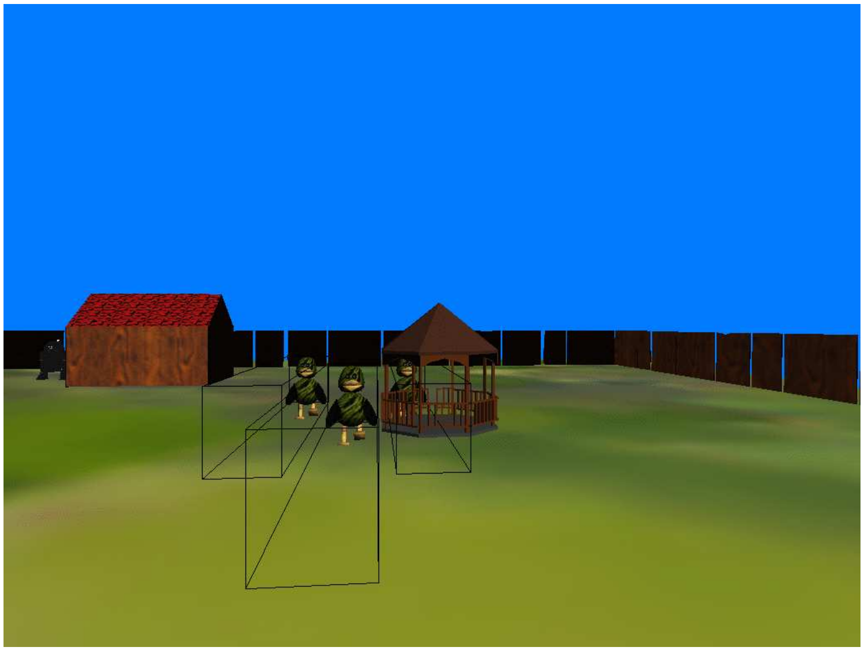


Figure 5.9: Sensor for autonomous virtual agents

Figure 5.10: The wire frame of the Virtual Environment

5.3 Iteration 3: Performer and the CAVE

The natural option was to use CAVElib, a widely used API to develop applications of immersive environments, as it handles all the low-level interaction with the systems to render the images in the four screens. Also runs as aseamless superset of SGI's OpenGL Performer.

The Virtual Environment uses SGI's OpenGL Performer, which contains a scene graph. In our architecture, three types of files are used to define the contents of the VE.

- A configuration file which defines the objects to be included in the world.
- A file defining the geometries of the objects.
- A file defining the repertoire of animations.

There can be three types of objects in the World: static objects, moving objects and creatures (which are a specialisation of moving objects, inheriting their animation capabilities). There is a geometry file associated with each of these objects. That file can be imported into the scene-graph, see figure 5.11. Each time-step, the objects' transformation matrices are updated. Then, the scene-graph is traversed in order to generate a new frame.

As its name implies, moving objects can be animated. That is, their geometries are updated to generate movements and rotations producing an 'illusion of life'. The animation in the moving objects is controlled by joints (as in [Blumberg1996]). The animation of the animal's movement was motion-captured from [Muybridge1957]. The resulting data was stored in a animation file, specifying the rotation of each joint in relation to its parent (another joint). There is a geometry related to each joint which is updated using matrix computation.

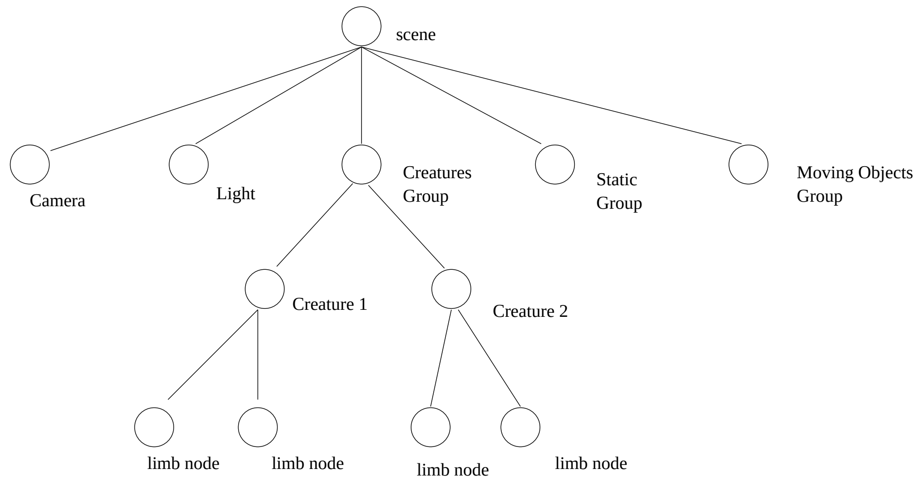


Figure 5.11: Scene-graph used to generate a virtual environment

5.3.1 Interpolation

To compute intermediate key-frames an interpolation algorithm was added as seen in formula 5.12.

$$y^{'} = y_1 + \frac{(x - x^{'})(y_2 - y_1)}{x_2 - x_1} \tag{5.12}$$

where x_1 and y_1 are the starting values and x_2 and y_2 the final values and $y^{'}$ is the interpolated calculated value, that depends on $x^{'}$.

5.3.2 Physics

To increase realism simple physics has been added to architecture in the form a ground sensor.

$$\mathbf{x(t) = X_0 + V_0 t + \frac{1}{2} g t^2} \tag{5.13}$$

where $\mathbf{x}, \mathbf{X_0}, \mathbf{V_0 and g}$ are vectors. This formula is used to compute the position of an object or an animal, it is used when the animal (or object) falls-down; the position is affected by gravity g.

5.3.3 Geometry Repository

One of the aims of the work described herein is to have multiple creatures and to achieve this, optimal use of memory was found to be critical. This was assisted by the use of a scene graph as explained above. To reduce the space needed by the multiple geometries, a geometry repository was developed. It was developed using a Singleton Pattern [Gamma *et al.*1996], so that there was just one instance of it. In this Geometry Repository, geometries are stored by name using a STL Map data structure (similar to a hash table). When loading a geometry for a new object, if it is not already stored in the repository, it is loaded (imported from its native format for example Open Inventor) and stored in the repository, and a reference is made to the map. This is shown in figures 5.13(a) and 5.13(b). When a geometry is already in the repository then a link is created between the node and the geometry in the repository. See figures 5.14(a) and 5.14(b).

The geometries used to produce virtual animals vary from very low-polygon count (rough boxes) to very high quality, photo-realistic like movies like Final Fantasy.

As said before as we are aiming to develop a realtime system, so that a compromise on the number of polygons (triangles has to be achieved). The model of the sheep has a medium-low-polygon count. Table 5.1 shows the number of polygons and the memory the geometry occupies in Performer data structures. This can be calculated as:

$$grm = ms + np * ps * nl + ss * l + gs + n * ps \tag{5.14}$$

where:

- grm is the memory occupied in the geometry repository.
- ms is the memory occcupied by the map data structure.

Limb	Num. Triangles	Num. Bytes
Hip	1	561
Body	384	17693
Front left thigh	192	9105
Front left Shin	192	5840
Front right thigh	192	9105
Front right Shin	192	5840
Rear left leg	384	14795
Rear right leg	384	14795
Head (and neck)	1328	46637
Total	3249	118120

Table 5.1: Space needed for a sheep creature 3D model

- np is the number of pointers for each node (normally 2)
- ps is the memory occupied by a pointer.
- nl is the number of limbs
- ss is the size of the string.
- gs is the number of bytes occupied by the geometry.
- n is the number of items.

Formula 5.14 was used to compute the values shown in column 3 of table 5.2. The values shown in that table were also used to produce figure 5.12. As it can be seen there is a huge difference in memory growth especially when the number of creatures is greater than 10.

After testing the environment, it was found that the action selection mechanism (BA-MUVA) had limitations to produce believable behaviours. The first limitation was its lack of structural flexibility . Whereas in hierarchical systems, as those described in chapter 2, some behaviours can be accommodated in the hierarchy as tools. This is, common behaviours can be reused with the appropriate connections in the hierarchy. Another limitation was that the architecture produces a response in terms of a limited number of

Num. of Sheep	Normal	Geometry Repository
1	118120	118937
2	236240	119013
5	590600	119241
10	1181200	119621
15	1771800	120001
20	2362400	120381
25	2953000	120761
50	5906000	122661

Table 5.2: Comparison between normal memory handling and use of a geometry repository

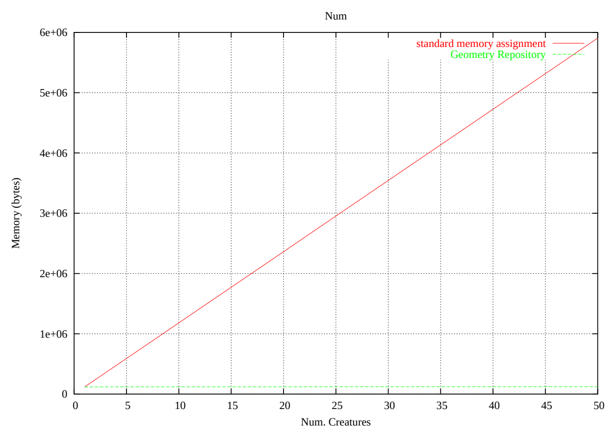
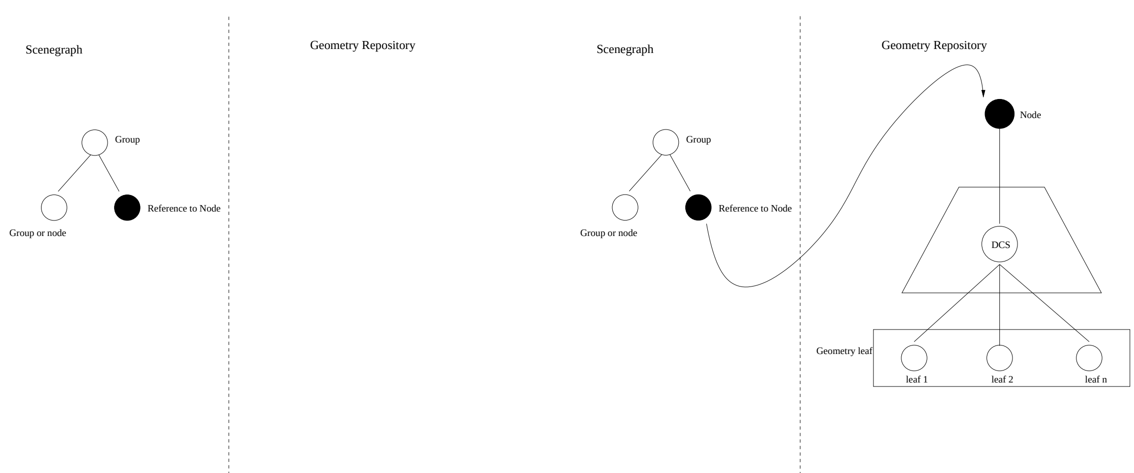
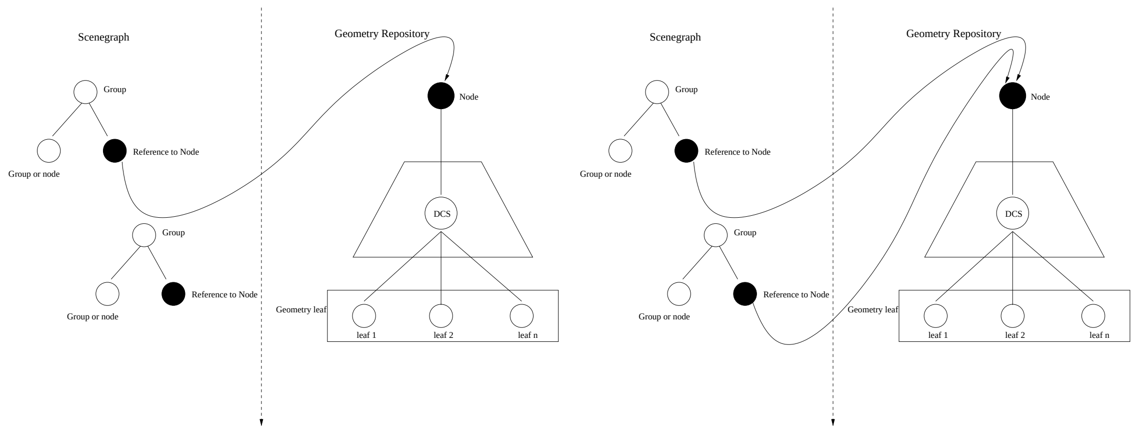


Figure 5.12: Comparison between standard memory assignment and use of a geometry repository



(a) Data structures before (b) Data structures after

Figure 5.13: Loading a geometry when it does not exist in the repository



(a) Data structures before (b) Data structures after

Figure 5.14: Linking to a geometry when it does exist in the repository

degrees of freedom. Typically two, rotation and translation. The relation between the sensors and the output was normally hard-coded. If we were to use the architecture in an animated figure it would increase the complexity nearly ten-fold.

Other options were looked and since the aim was to produce beleivable animals affected by emotion, as said before, we looked at ethology, emotion theories, and group behaviour for inspiration.

5.4 Iteration 4: NEMBEVA

In this iteration, the creatures' brains were designed using ethology, theories of emotion and neurology [1] as main sources of inspiration. The basic task of an animal brain has often been split into three sub-tasks as shown in figure 5.15a. Our model (see figure 5.15b) adds a fourth sub-task, emotions. The four sub-tasks in our system are therefore: perception

[1] Although systems inside an animal brain can serve multiple purposes, many researches have found a main purpose for some systems. The author took the liberty to assign a particular system to handle a single purpose; for example, the emotion systems are defined inside the Amygdala.

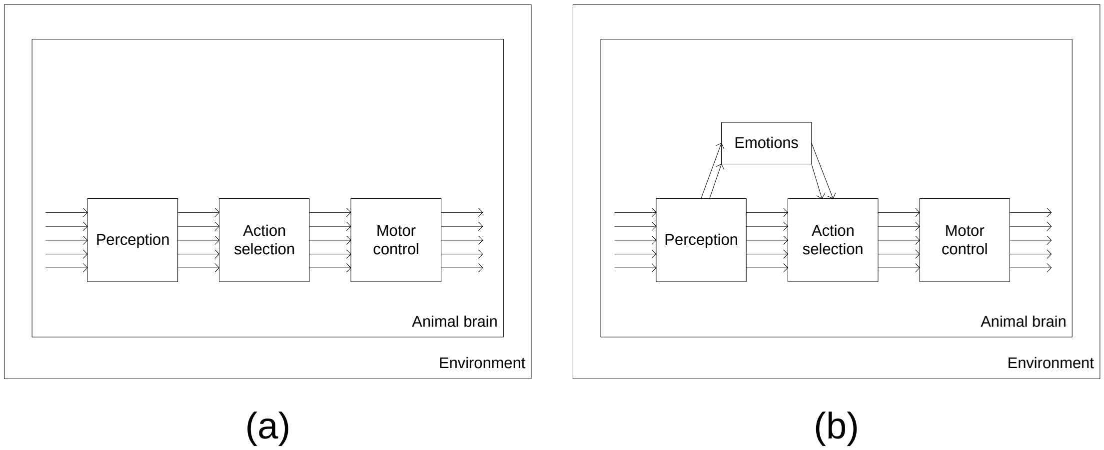


Figure 5.15: Two decompositions of the functions of an animal's brain

(sensing of the environment and interpretation of the sensory signals to provide a high-level description of the environment), emotions (which affect the behaviour of the animals, exemplified by the conspecifics flight-flocking), action selection (using the perceptual and emotional inputs to decide which of the animal's repertoire of actions is most suitable at that moment) and motor control (transforming the chosen action into a pattern of "physical" actions to produce the animation of the animal).

Figure 5.16 shows a more detailed diagram of the designed architecture, and the next sections describe its components.

Our action selection mechanism is based on Tyrrell's model [Tyrrell1993]. This model is a development of Rosenblatt & Payton's original idea [Rosenblatt and Payton1989] (basically a connectionist, hierarchical, feed-forward network), to which temporal and uncertainty penalties were added, and for which a more specific rule for combination of preferences was produced. Note that among other stimuli, our action selection mechanism takes the emotional states (outputs of the emotional devices) of the virtual animal.

The functional architecture of the 'brain' developed for the virtual creatures draws on concepts from neurology, as seen in figure 5.16. A module *hypothalamus* is used to store the drives, one called *sensorial cortex* stores sensor data, one called *amygdala* contains

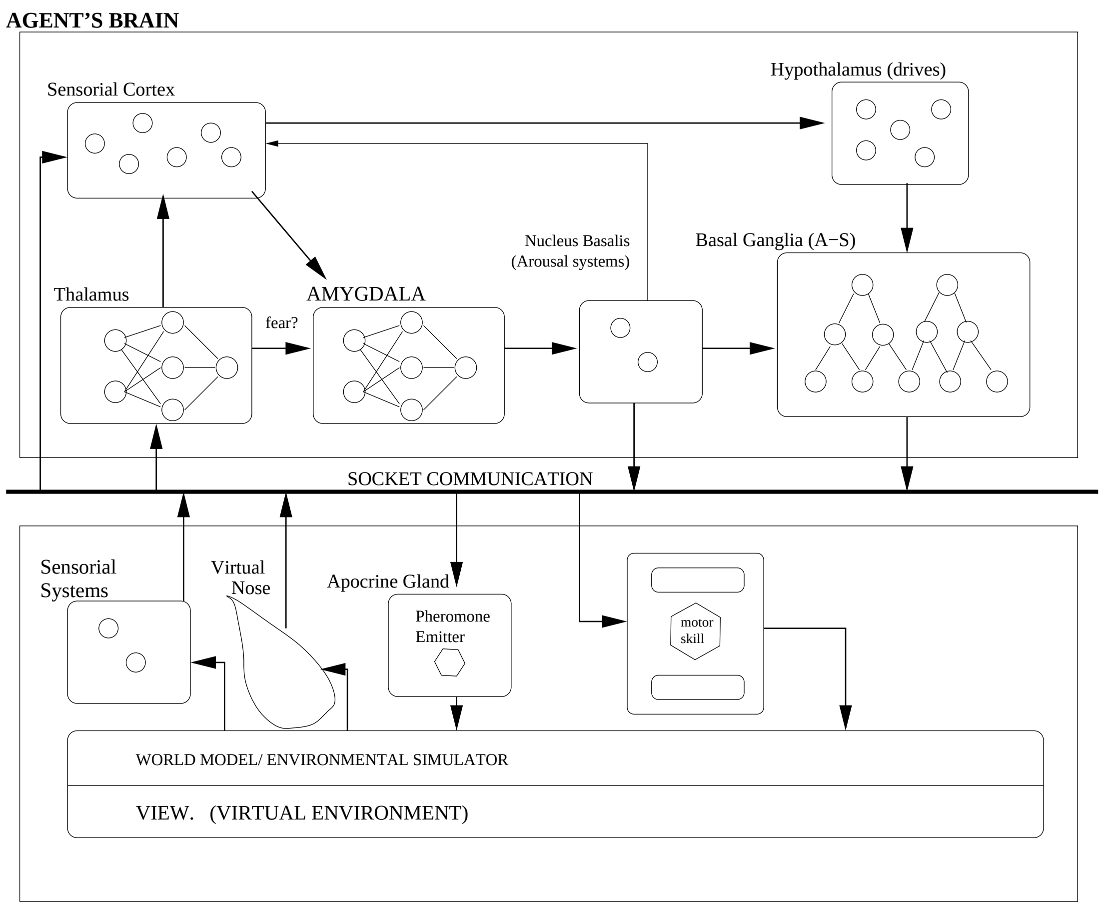


Figure 5.16: Detailed architecture

the emotional systems like Fear, Joy and Anger, and one called *Basal Ganglia* contains the hierarchical mechanism for selecting actions, similar to those found and described by ethologists as mentioned above. Each of the listed modules is defined in XML giving the name of each of the system/variables, the inputs associated to them, a weight, and a function (acting as a filter) which in turn generated a feed-forward hierarchy like the one described in [Tyrrell1993].

Recent research has found that the Basal Ganglia plays an important role in mammals action selection [Montes-Gonzalez2001]) so that in this model, see figure 5.16, the Basal Ganglia is a tree composed of nodes. Each receives one or more inputs from other components in the brain represented by the input tag in the XML file next to the description of possible inputs.

H Hypothalamus, the drives like H_Hunger.

C Sensorial Cortex, the sensor's data like C_Flight_Zone.

B Basal Ganglia, input from upper nodes for example B_TLN_Graze.

A Amygdala, for the virtual animal's emotions for example A_FearSystem.

Associated with each input is a weight representing its significance to the node. Each node has a function allowing it to combine the values of its inputs in a synthesis process producing the output value. Below we show a portion of one of the XML files used to create the relations between the Basal Ganglia (Action Selection) with the other components in the animal's brain (see figure 5.17 for a complete network of the brain's connections created with the Pajek Network Analysis tool [Batagelj and Mrvar1998]).

```
<contents>
<node>
```

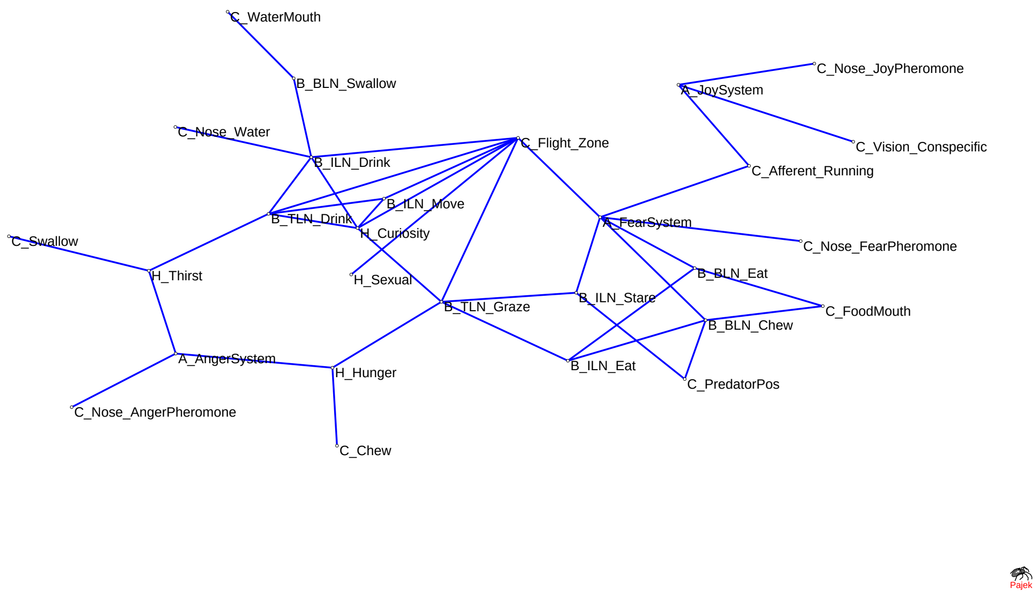


Figure 5.17: Net representing connections in the virtual animal's brain

```
<node_name name="B_TLN_Graze"/>

<input weight="0.2" from="H_Hunger"/>

<input weight="0.5" from="H_Curiosity"/>

<input weight="0.7" from="C_Flight_Zone"/>

<function name="tansig"/>

</node>

<node_name name="B_ILN_Move"/>

<input weight="0.2" from="B_TLN_Graze"/>

<function name="tansig"/>

</node>

<node>

<node_name name="B_ILN_Eat"/>

<input weight="0.2" from="B_TLN_Graze"/>

<function name="tansig"/>
```

```
</node>
<node>
<node_name name="B_BLN_Chew"/>
<input weight="0.2" from="B_ILN_Eat"/>
<input weight="0.4" from="A_FearSystem"/>
<input weight="0.5" from="C_PredatorPos"/>
<input weight="0.7" from="C_FoodMouth"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_BLN_Eat"/>
<input weight="0.2" from="B_ILN_Eat"/>
<input weight="-0.4" from="A_FearSystem"/>
<input weight="-0.2" from="C_FoodMouth"/>
<function name="tansig"/>
</node>
</contents>
```

5.4.1 Body

The Body contains the sensors (Receptors) and the gland used to signal the pheromones to conspecifics. The receptors are organised in a hierarchy. Different kind of receptors exist in the architecture, these are:

- **Propioceptors** are used to test internal variable like hunger.
- **Exteroreceptors** are used to perceive external events.

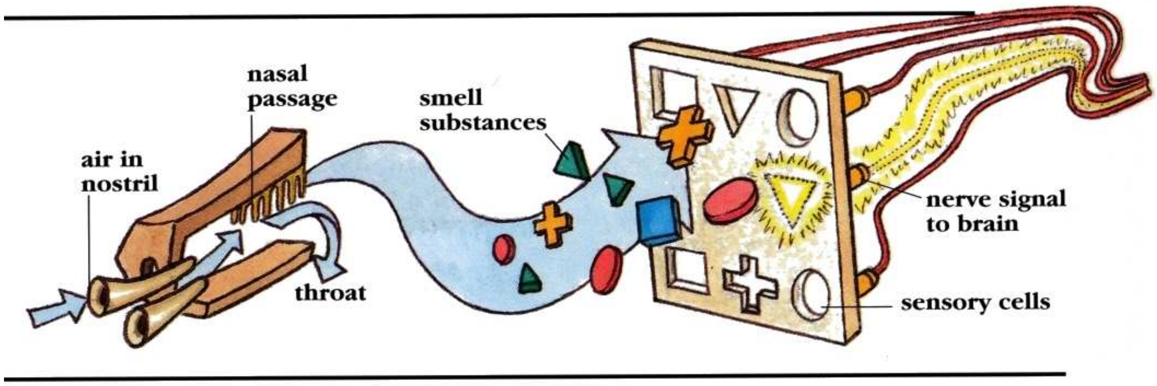


Figure 5.18: Olfaction. From Kelly 1994 [Kelly *et al.*1994]

- **Chemoreceptors** are a kind o exteroreceptor, which are used to sense chemicals; for example, some kinds of molecules like pheromones.

Nose

The nose is a vital component of this architecture and is composed of several olfactory receptors, these receptors are chemoreceptors (read above) which correspond to each type of pheromone[2] (at the moment fear, anger and joy), water and food. Each update cycle in the body calls an update in the nose which tests (using Boltzmann formula) the probability of the the pheromones particles to be smelled by the creature, and if it exceeds a threshold in the receptor then the value is stored in the receptor and it is added to the sensor data which is passed to the brain. The Nose is configured via an XML file, see appendix F.

Flight-Zone

Some animals, in particular mammals, have a so-called flight-zone; that is, a space such that when a perceived predator or intruder enters it the animal becomes edgy, and more often than not will fly from the perceived danger. We have chosen to model this sensor,

[2]Even there are other emotion systems implemented in the architecture, fear was used in the experiments discussed in the following chapter.

Figure 5.19: Flight zone in sheep

and in doing so we tried to follow an ethological approach [Lorenz1981] [McFarland1999]. Figure 5.19 shows an example with real animals, sheep.

The flight zone sensor is implemented using standard collision detection between two spheres. Thus, if the distance between the spheres' two centres 5.15 is:

$$d = \sqrt{(x_c - x_p)^2 + (y_c - y_p)^2 + (z_c - z_p)^2} \tag{5.15}$$

and

$$d < r_c + r_p \tag{5.16}$$

where d is the distance as defined in 5.15, the creatures position is defined by point $C(x_c, y_c, z_c)$ and predator's position is defined by point $P(x_p, y_p, z_p)$.

Then collision occurs if 5.16 is true; that is, if the the distance d is smaller than the

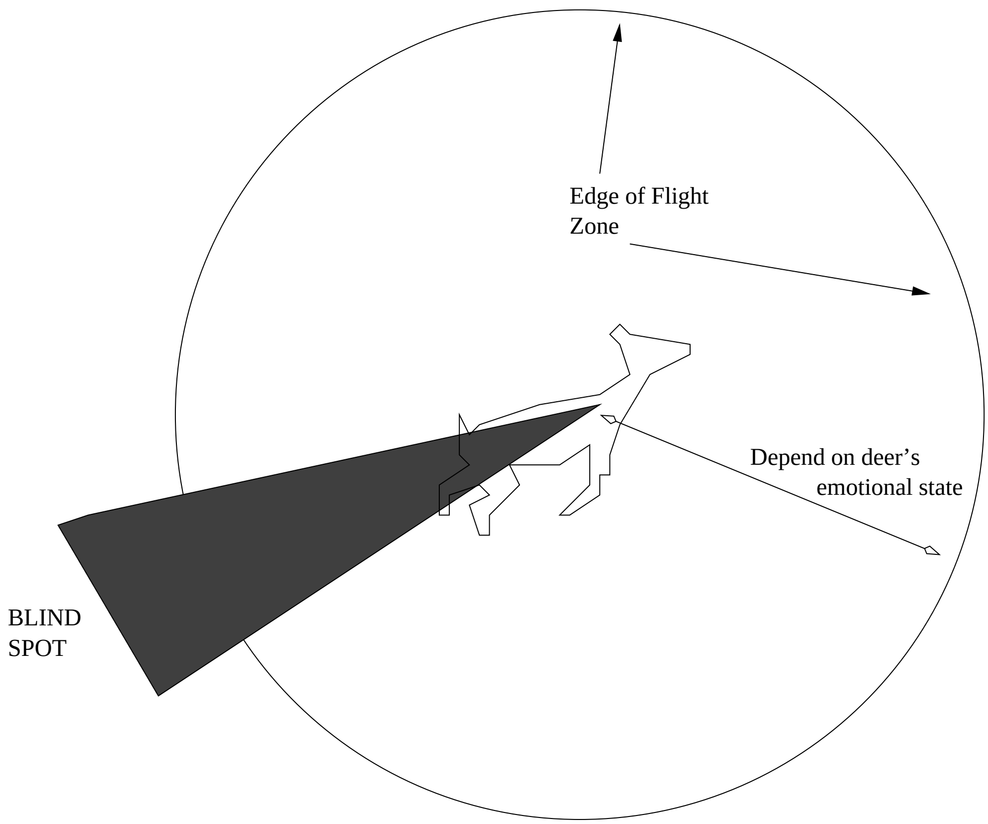


Figure 5.20: Mammal flight zone

sum of the creature sphere's radius r_c and that of the predator r_p.

$$x^2 + y^2 = r^2 \tag{5.17}$$

$$y = mx \tag{5.18}$$

$$x^2 = \frac{r^2}{1 + m^2} \tag{5.19}$$

$m_b s$ is the negation of the m of the creature (i.e. $-m$), because the flight zone is in the opposite direction to that in which the creature is facing as seen in figure 5.20

$$m_1 = m - \frac{m_{bs}}{2} \tag{5.20}$$

$$m_2 = m + \frac{m_{bs}}{2} \tag{5.21}$$

From formula 5.19

x_c and y_c give creature position

x_p and y_p give predator position

then

$$x_1 = \sqrt{\frac{r^2}{1 + {m_1}^2}} + x_c \tag{5.22}$$

$$y_1 = m_1 x + y_c \tag{5.23}$$

and

$$x_2 = \sqrt{\frac{r^2}{1+{m_2}^2}} + x_c \tag{5.24}$$

$$y_2 = m_2 x + y_c \tag{5.25}$$

To test if the predator is in the blind spot, matrix calculations are used. If the determinant of 5.26 is positive (that is, it is on the left) [Preparata and Shamos1985] and if the determinant of 5.27 is negative (the predator is on the right), it means that the predator is in the blind spot.

$$\begin{vmatrix} x_c & y_c & 1 \\ x_1 & y_1 & 1 \\ x_p & y_p & 1 \end{vmatrix} \tag{5.26}$$

$$\begin{vmatrix} x_c & y_c & 1 \\ x_2 & y_2 & 1 \\ x_p & y_p & 1 \end{vmatrix} \tag{5.27}$$

Finally if a collision has happened, and the predator is not inside the blind-spot, the flight zone intensity is inversely proportional to the distance of the perceived predator from the creature; that is, the closer the predator, the stronger the intensity of the sensor's signal.

5.4.2 Hypothalamus - Drives

Drives use a sigmoid function to compute the growth of the drive in question. For example, for Hunger, figure 6.8 shows the growth rate.

The drives are computed with the formula 5.29. This function is used because it is found in growth in biological systems and also has the property of being limited between the values 0 and 1. In this system, the values are stored in the XML file used to define the Hypothalamus, that is the set of drives, see appendix D. The formula to compute a drive intensity is:

$$x = k + gt + w\sum_{i=1}^{n} factor_i \tag{5.28}$$

$$HI = \frac{1}{1 + \exp^{-x}} \tag{5.29}$$

where :

- k is a constant to offset the shape of the sigmoid function.
- g affect the shape of the graph.
- t is time elapsed.
- w is the weight to the factors that affect hunger in special food.
- HI is a drive, for example Hunger.

5.4.3 Sensorial Cortex -Sensorial Data

The sensor data perceived by the body is sent via UDP sockets to the brain, specifically to the Sensorial Cortex.

5.4.4 Amygdala -Emotion

To compute emotion, a sigmoidal function is used as described in equation 5.30. Sigmoidal functions are often used by reseachers to describe growth in natural systems. Tests have been carried out to detect emotions in humans using conductance in the skin [Picard1997]. The function used to describe the intensity of the emotion in those tests, is sigmoidal.

$$y = \frac{1}{1 + \exp^{-g(x - x_o)}}$$

where:

- g is the growth rate used to control the steepness of the sigmoidal function.
- x_o is used to offset the graph to the right or left.
- x is the input
- y is the output from the sigmoidal function.

To compute the intensity of the emotion:

$$E_i(t) = y\left(f(E_i(t-1)) + \sum_j^m A_j)\right) \tag{5.30}$$

where:

- E_i is the intensity of emotion i.
- y is the sigmoidal function as defined in equation 5.30.
- $f(E_i(t-1))$ is a function of emotion decay of Emotion E_i at time $t-1$.
- $\sum_j^m A_j$ is the sum of m affecting variables A_j to the emotional system (they can be either excitatory (positive) or inhibitory (negative).

5.4.5 Basal Ganglia -Action Selection

To select an Action, a hierarchy was formed with an XML file similar to the one shown in appendix E. This hierarchy is similar to the hierachies described by ethologists. It is important to note that there are at three types of nodes: Top, Intermediate node and Bottom layer node. The bottom layer node is what Tinbergen describes as the consummatory act. To avoid sensorial congestion, each type of node can receive sensor data as well as data from an upper node. This is a similar approach to that of Tyrrell [Tyrrell1993]. As said before, concepts from Pattern Design are used throughout the architecture. One special case is when sending the sensorial data to the nodes in the hierarchy. This is carried out with using the Observer/Subscriber pattern shown in appendix H. In this pattern, when a value in the subject changes, it sends a messages to all of the Observers to retrieve the updated data. A comparison of this with the approach in Tyrell shows that in Tyrrell the complexity is O(n^2) as compared to the updating complexity of sensorial data here of O(n).

A sigmoidal equation in the basal ganglia is used for constraining the values between 0 and 1. As exposed before, a sigmoidal function was chosen, because it is useful to define growth in natural systems. For example, Lorenz's Action Readiness growth, see chapter 2, could be defined in terms of a sigmoidal function; work from ethology was a source of inspiration whilst carrying out this work.

$$y = \frac{1}{1 + \exp^{-g(x - x_o)}} \tag{5.31}$$

where:

- g is the growth rate used to control the steepness of the sigmoidal function.

- x_o is used to offset the graph to the right or left.
- x is the input
- y is the output from the sigmoidal function.

To compute the intensity in the top node:

$$BT_i(t) = y\left(\sum_j^m I_j\right) \tag{5.32}$$

where:

- BT_i is the intensity of the Top Node i.
- y is a filter applied as a constrain to the values; it can be a sigmoidal function as defined in equation 5.31.
- $\sum_j^m I_j$ is the sum of m input variables I_j to the top node (they can be either excitatory (positive) or inhibitory (negative). These variables are normally Sensorial Cortex data, or data from an emotional system, like fear.

For the intermediate layer:

$$BI_i(t) = y\left(\sum_j^m I_j\right) \tag{5.33}$$

where:

- BI_i is the intensity of the Intermediate Node i.
- y is a filter applied in to constrain the values; it can be a sigmoidal function as defined in equation 5.31.
- $\sum_j^m I_j$ is the sum of m affecting variables I_j to the Intermdiate Node (they can be either excitatory (positive) or inhibitory (negative). This affecting variables are

normally Sensorial Cortex data, data from an emotional System, like fear, or data from a Top Layer Node. In order to be a intermediate layer node it needs to be linked to at least one Top Layer, by means of an input variable.

For the bottom layer:

$$BB_i(t) = y\left(\sum_j^m I_j\right) \tag{5.34}$$

where:

- BB_i is the intensity of the Intermediate Node i.
- y is a filter applied in to constrain the values; it can be a sigmoidal function as defined in equation 5.31.
- $\sum_j^m I_j$ is the sum of m affecting variables I_j to the Intermdiate Node (they can be either excitatory (positive) or inhibitory (negative). This affecting variables are normally Sensorial Cortex data, data from an emotional System, like fear, or data from a Intermediate Layer Node. In order to be a Bottom Layer Node it needs to be linked to at least one Intermediate Layer, by means of an input variable.

An Action is Selected in the Bottom Layer. This Selected Action is thus sent to the Animation Engine which is in the body, via socket UDP.

5.4.6 Communicating Emotions

Because the virtual animals described herein exist in a VE and not in the real world, in principle the transmission of emotion between agents could just be carried out by 'cheating', that is by allowing agents to read each other's emotional state directly. We choose not to do this however, as this produces undesired side-effects like giving the creature super-natural powers. Some recent video games, like Metal Gear Solid, are based on the premises that the enemy can perceive only what she was meant to perceive. That is, if she is behind a wall then she could not perceive the user's avatar, and its artificial intelligence routine would make her behave in a beleivable manner, namely not attack the user's avatar.

The nose has been linked with emotional responses and intelligence. Recent experiments [Grammer1993] have shown that mammals, including humans, emit pheromones through apocrine glands as an emotional response, and as a means to communicate that state to conspecifics, who can adapt their behaviour accordingly; research has found that odours produce a range of emotion responses in animals, including humans [Izard1993], which is adaptively advantageous because olfaction is part of the old smell-brain which can generate fast emotional-responses, that is without the need of cognitive processes. In this respect [Kitchell *et al.*1995] points out: "The use of pheromones to alert conspecifics or members of a social group to the presence of an intruder or a potential attacker is common in many animal species. For example, in the presence of an intruder, several species of social hymenoptera secrete pheromones which cause defensive behaviour among conspecifics. This alarm pheromone is thought to have two effects: (1) it alerts conspecifics to the threat of danger, and (2) it acts as a chemical repellent to the intruder.

Animals have a particular keen sense of smell; [Mery1970] writes: "One of the odours released by perspiration -either human or animals- is butyric acid, one gram of which contains seven thousand million billion molecules, an ungraspable number! Imagine that this acid is spread at precise moment throughout all the rooms in a ten-story building. A man would only smell it if he were to take a breath of air at the window, and then only at that precise moment. But if the same gram of odour were spread over a city like Hamburg, a dog could perceive it from anywhere up to an altitude of 300 feet!"

Every living entity, be it nutritious, poisonous, sexual partner, predator or prey, has a distinctive molecular signature that can be carried in the wind." Neary [Neary2001]points out that sheep, particularly range sheep, will usually move more readily into the wind than with the wind, allowing them to utilise their sense of smell.

In real animals, chemoreceptors (exteroceptors and interoceptors) are used to identify chemical substances and detect their concentration. Smell exists even among very primitive forms of life. In our architecture we intend to model the exteroceptors which detect the presence of chemicals in the external environment.

In this work, to illustrate the use of emotion and drives to influence behaviours, sheep had been selected as the exemplar creature; to feel secure [Reinhardt and Reinhardt2002] claims that

> *A sheep need to be with other sheep in order to be in a state of well-being and normative physiology. Sheep will always try to maintain uninterrupted visual contact with at least one other sheep, and they will flock together at any sign of danger*

This suggests that a specific sensor for other nearby sheep can be used to elicit a distress emotion in case of the absence of other conspecifics.

To support the communication of emotions, an environmental simulator has been developed, its tasks include changing the temperature and other environmental variables depending on the time of day and on the season, which depends on statistical historical data. An alarmed animal sends virtual pheromones to the environmental simulator and they are simulated using the free expansion gas formula in which the volume depends on the temperature and altitude (both simulated environmental variables). To compute the distribution of the pheromones a set of particles has been simulated using Boltzmann distribution formula 5.35, which is shown and described next.

$$n\left(y\right) = n_o e^{\frac{mgy}{k_b}T} \tag{5.35}$$

Where m is the pheromone's mass; g is the gravity; y is the altitude; k_b is the Boltzmann number; T is the temperature; n_o is N/V; N is number of molecules exuded by the apocrine gland, which is related to the intensity of the emotional signal; and V is the Volume.

The virtual animal includes a virtual nose used to detect pheromones, if any, that are near the creature. To smell a pheromone the threshold set in the current experiment is $200 \cdot 10^{-16}$ because [Marshall *et al.*1981] has shown that animals have 1000 to 10000 more sensitivity than humans and Wyatt [Wyatt2003] claims that the threshold in humans to detect certain "emotional response odours", like those exuded from the armpits, is 200 per trillion parts, that is $200 \cdot 10^{-12}$.

In the architecture animals signal through pheromones that they are in fear. The diagram 5.21 represent mammals signalling through pheromones. The diagrams represent four animals that communicate an emotion for example fear through pheromones exuded through glands [Wyatt2003]. The different shaded colours represent the animals' position at three different times, with the darkest the oldest t_1 and the white the last time-step of the simulation. Pheromones are represented through the concentric circumferences, taken at 9 different time steps.

As seen in figure 5.22, an abstraction of the body was developed to perform the bodily functions of perception and activation of glands in one place.

In figures 5.23(a) – 5.23(i)the pheromones represented by the sphere are visualised in the virtual environment.

5.5 Iteration 5: Klinokinesis

Grazing mammals, like sheep, actually spend most of their time grazing: an experiment has shown [Ruckstuhl1998] that 80% of the animals day-time activity involved grazing or lying ruminating. Thus grazing was seen as an important element of the repertoire of

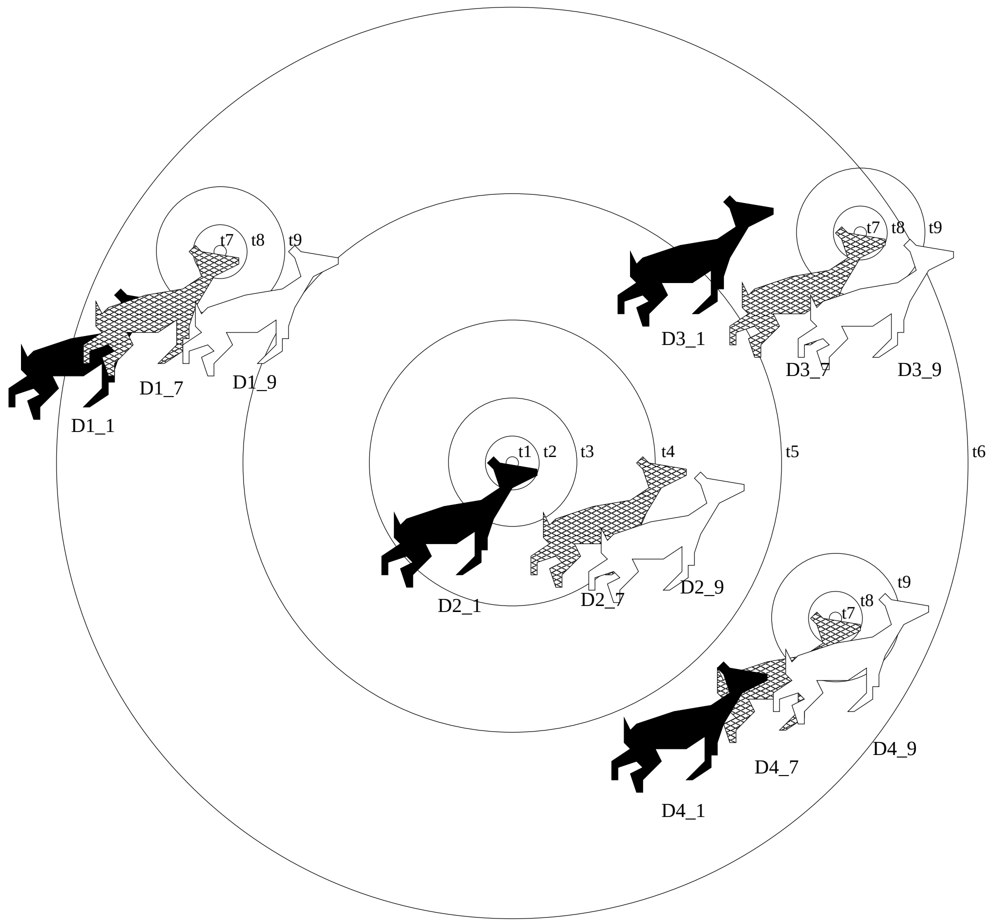


Figure 5.21: Emotional signalling through pheromones

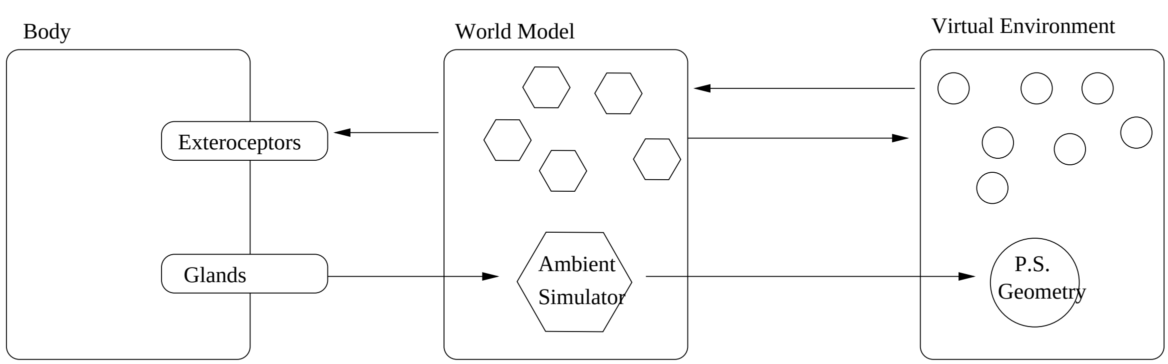


Figure 5.22: Overview of the animals signalling in a Virtual Environment

(a) Pheromones at Time step 1

(b) Pheromones at Time step 2

(c) Pheromones at Time step 3

(d) Pheromones at Time step 4

(e) Pheromones at Time step 5

(f) Pheromones at Time step 6

(g) Pheromones at Time step 7

(h) Pheromones at Time step 8

(i) Pheromones at Time step 9

Figure 5.23: Pheromones liberated in the virtual environment

δ	q	*input*	$\delta(q, input)$
	start	go-default	stand-still
	stand-still	P (0.3)	walking
	stand-still	P (0.3)	starting-to-eat
	stand-still	P (0.2)	rotating-left
	stand-still	P (0.2)	rotating-right
	stand-still	in-fear	end
	stand-still	do-nothing	stand-still
	walking	P (0.3)	stand-still
	walking	P (0.7)	walking
	rotating-left	P (0.9)	stand-still
	rotating-left	P (0.1)	rotating-left
	rotating-right	P (0.9)	stand-still
	rotating-right	P (0.1)	rotating-right
	starting-to-eat	head-down	eating
	eating	P (0.6)	eating
	eating	P (0.4)	finishing-to-eat
	finishing-to-eat	head-up	stand-still

Table 5.3: FSA representing grazing behaviour

the virtual animal's behaviour. To model this, and drawing from ethology, *klinokinesis*, described in chapter 2, is simulated through a Finite State Acceptor [Arkin1999] and has been augmented with transitions based on probability, as shown in table 5.3. Here δ represents the table with all the transitions, q represents the state, *input* represents the input to start a transition, and $\delta(q, input)$ is the resulting state from state q with input *input*. P(n) represents the probability of performing the transition defined in the corresponding table's row.

5.6 Iteration 6: Flocking

To perform group behaviour in the system, we looked at work done in the fiel of computer graphics. The natural option was to base or group behaviour algortihm on *boids* [Reynolds1987], although we have extended it with an additional rule (escape), and, most importantly, the flocking behaviour itself is parameterised by the emotional devices output, that is, by the values of the emotions the boids feel. The escape rule is used to influence the behaviour of each boid in such a way that it escapes from potential danger (essentially predators) in its vicinity. Therefore, in our model each virtual animal moves itself along a vector, which is the resultant of four component vectors, one for each of the behavioural rules, which are:

Cohesion - attempt to stay close to nearby flockmates.

Alignment - attempt to match velocity with nearby flockmates.

Separation - avoid collisions with nearby flockmates.

Escape - escape from potential danger (predators for example).

The calculation of the resultant vector, $Velocity$, for a virtual animal A is as follows:

$$V_A = \underbrace{(Cf \cdot Cef \cdot Cv)}_{Cohesion} + \underbrace{(Af \cdot Aef \cdot Av)}_{Alignment} + \underbrace{(Sf \cdot Sef \cdot Sv)}_{Separation} + \underbrace{(Ef \cdot Eef \cdot Ev)}_{Escape} \quad (5.36)$$

$$Velocity_A = limit(V_A, (MVef \cdot MaxVelocity)) \quad (5.37)$$

where Cv, Av, Sv and Ev are the component vectors corresponding to the cohesion, alignment, separation and escape rules respectively. Cf, Af, Sf and Ef are factors representing the importance of the component vectors Cv, Av, Sv and Ev respectively. These factors allow each component vector to be weighted independently. Cef, Aef, Sef and Eef are factors representing the importance of the component vectors Cv, Av, Sv and Ev respectively, given the current emotional state of the virtual animal. That is, each of these factors is a function that takes the current values of the animal's emotions and generates a weight for its related component vector. $MaxVelocity$ is the maximum velocity

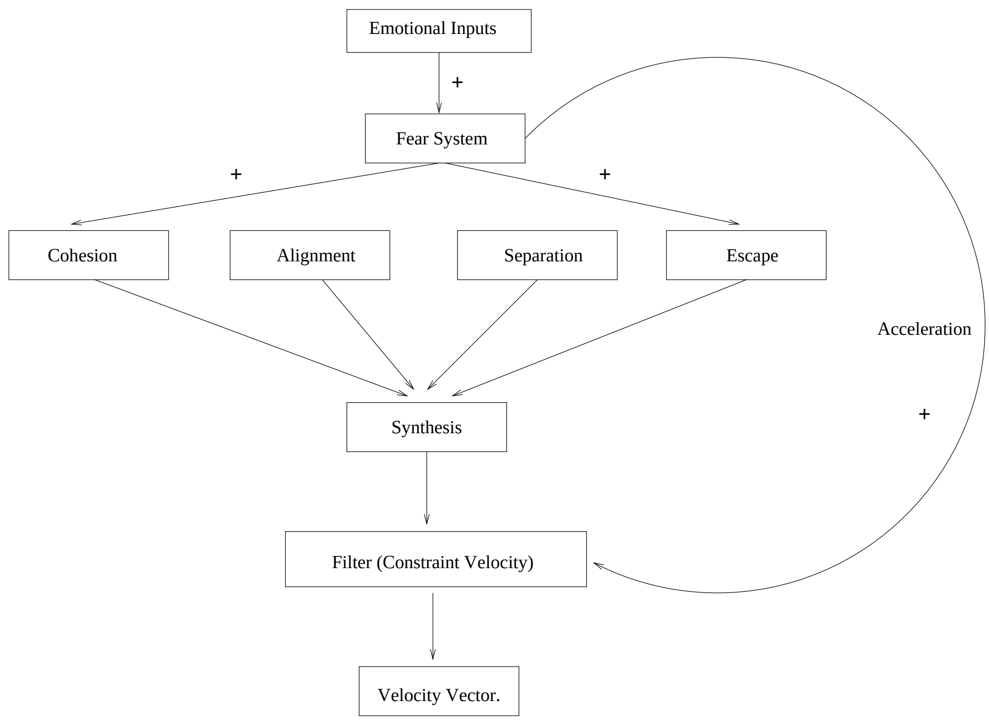


Figure 5.24: How *fear* parameterises the flocking algorithm

allowed to the animal. $MVef$ is a factor whose value is calculated as a function of the current values of the animal's emotions. It allows an increase and decrease in the animal's $MaxVelocity$ depending on its emotional state. *limit* is a function whose value is equal to its first parameter if this is not greater than its second one; otherwise the function value is equal to its second parameter.

The emotional factors (Cef, Aef, Sef, Eef, and $MVef$) reflect ethologic heuristic rules. Figure 5.24 shows an example of how emotions parameterise the flocking behaviour. In particular, it shows how *fear* affects the component vectors of the animals' behaviour. The greater the fear an animal feels, the greater the weight of both its cohesion vector (the animal tries to stay closer to nearby flockmates) and its escape vector (the animal try to stay farther from the potential danger). The resultant vector obtained by adding the four basic vectors is then scaled so as to not exceed the maximum speed. This maximum velocity is parameterised by the fear as well. The greater the fear an animal feels, the

library	Num. Lines of Code
NEMBEVA	4794
math	2000
network	2298
thread	890
XML Parser	967
Total	10949

Table 5.4: Lines of code for a animal's brain

greater the speed it is able to reach.

5.7 Agents in a Virtual Environment

The resulting architecture described in the iterations of the previous sections has been tested in a virtual environment [Delgado-Mata *et al.*2002]. The architecture described is three layered. Namely the creatures' brain, the world model (which include the animals' bodies) and the virtual environment. As seen in figure 5.16 the agent's brain is composed of processes that run independently (on a Linux workstation) and each of the agents' brains receives the sensor data via network sockets; similarly they send the selected action to the world model which contains agents' bodies and the environmental simulation. The changes made to the model are reflected on each frame in the virtual environment which was developed using IRIS OpenGL Performer. This mechanism allows modularity and extensibility to add/modify the behaviour of the artificial animals. Figure 5.25 shows the system running a virtual environment with artificial deer.

The implementation is of nearly 28000 lines of C++ code. The brain consists of 10949 lines of code developed in GNU C++. Table 5.4 shows the number of lines for each of the libraries composing the brain. The virtual environment consists of 16762 lines of C++ code. Table 5.5 shows the number of lines for each of the libraries composing the VE.

library	Num. Lines of Code
body	1553
virtual	7731
list	1610
network	2252
FSA	680
math	2046
thread	890
Total	16762

Table 5.5: Lines of code for the virtual environment

Tests have been carried out in the system and they have shown that the users are significantly more engaged when artificial animals (shown in next chapter) like deer populate the virtual environment and perform what they assess as “intelligent” behaviour than when there are no animals at all or where the deer are just standing in static poses. However, we also hypothesised that emotion plays an important role in regulating flocking behaviour amongst herding mammals.

On the one hand, it is evolutionarily advantageous for animals in a herd to flock close to each other to have more chance of surviving the threat posed by predators. On the other hand, as said before, grazing mammals spend most of the time grazing so it would be expected that scattering widely into grassy areas would be beneficial. Somehow a compromise must be reached between collective and individual behaviour. As already described, emotion and communication amongst conspecifics is used to enhance the action selection mechanisms. So a test was designed to test the hypothesis, in which a rigid flocking would serve as a baseline for organised group behaviour and a purely individual behaviour of animals would be tested as the other end of the scale, and in between would lie flocking and emotional flocking.

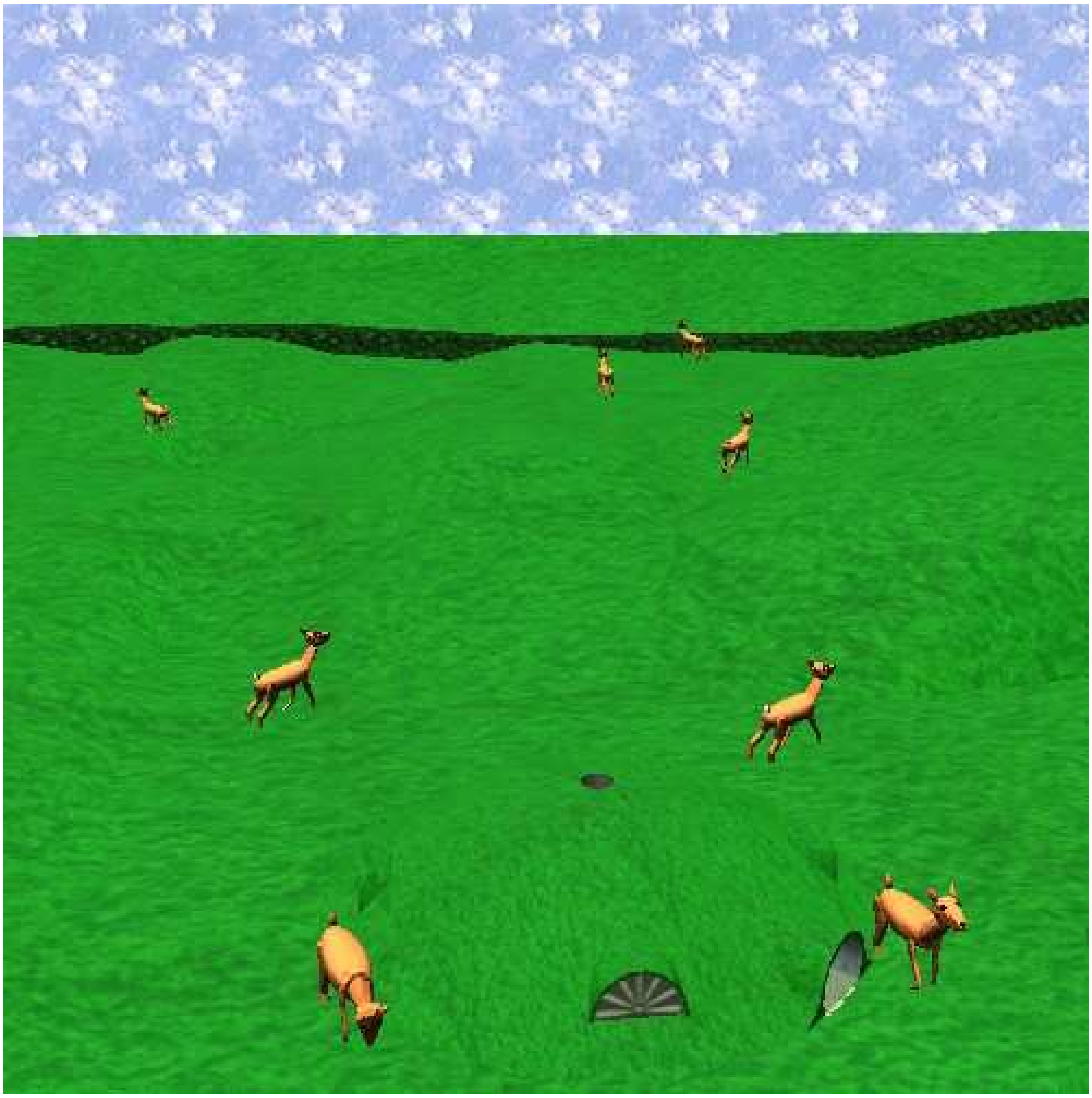


Figure 5.25: Artificial deer grazing in a Virtual Environment

5.8 Summary

In this chapter the architecture of the thesis was presented. The architecture followed an iterative process, analogous to the way nature systems evolve, namely what works is kept and what it does not is removed. It started from the first iteration where a reactive architecture was developed, this provided a text output only interface. The second iteration involved a Virtual Environment developed in Maverik, with the related change in the reactive architecture to be able to be used in the VE instead of with text. The VE in Maverik was found to be not appropriate for use in the CAVE and thus in third iteration a change to Performer was made, in which it was possible to seamlessly integrate the libraries necessary to run applications in the CAVE. In the fourth iteration, an architecture was developed inspired in ethology and emotion theory, to solve shortcomings of in the animals' behaviours when adding several animations. Refinements of the architecture are iterations 5 (Klinokinesis) and iteration 6 (Emotion-communicated flocking). The evolution of the architecture is shown in figure 5.26.

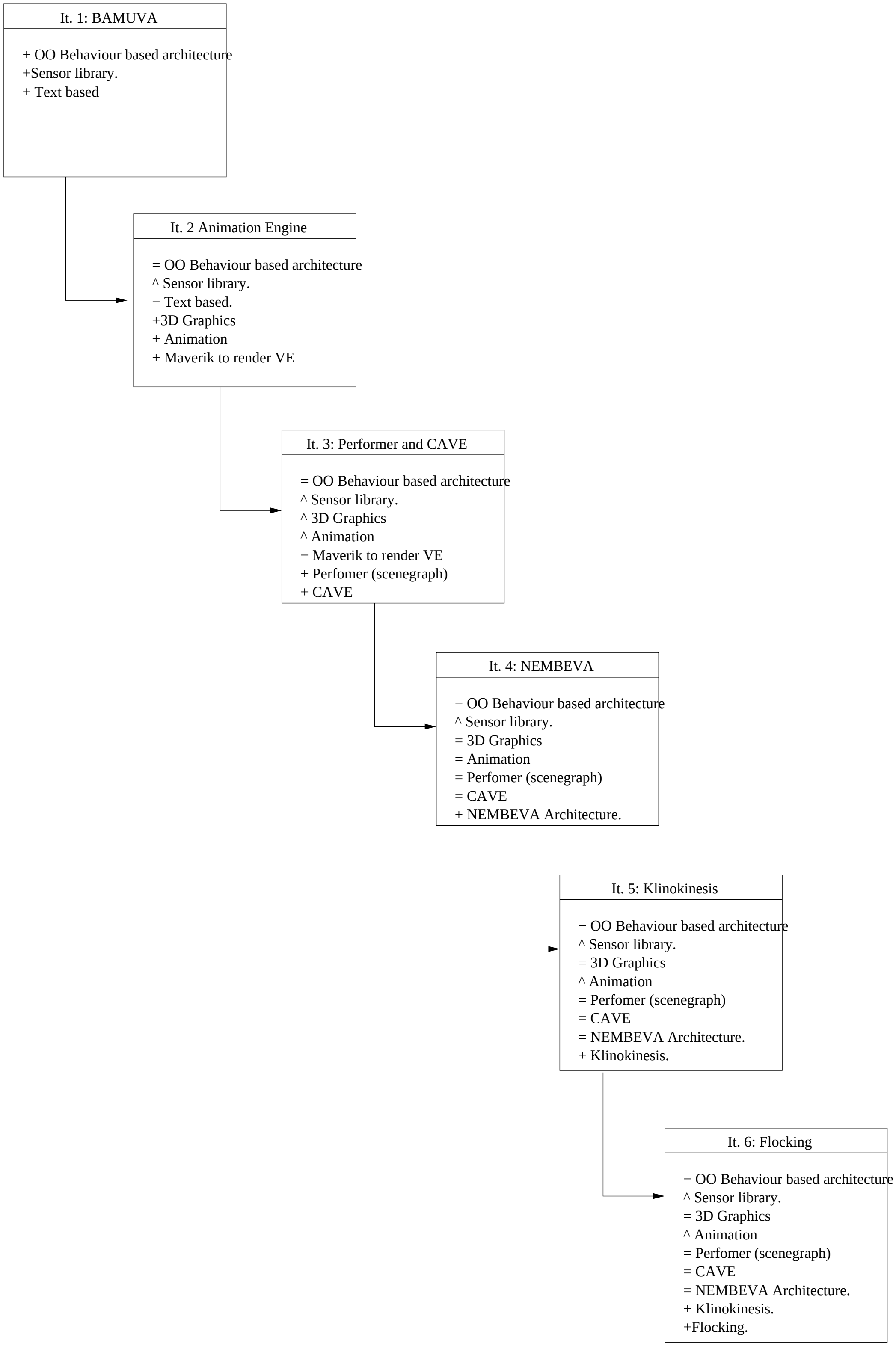


Figure 5.26: Iterations of the architecture. Key for the figure: + added from previous iteration, - removed from previous iteration, = same as previous iteration, and ˆ improved from previous iteration.

Chapter 6

Experiments and Results

Forget the medals, the greatest victory is to be acclaimed for your style.

– *Johan Cruyff*

This chapter will start with the description of a tool that was developed to receive real data from the application, which was used to produce plots. These plots include the experiments designed to produce different read-outs of the systems. For example the realtion of the fear emotional system with the flight zone sensor.

One of the aims of creating this architecture was to improve the believability of virtual environments, in particular the behaviour of artificial mammals. To this end, in order to test the architecture, experiments with real users were design to "measure" the increased believability that this architecture provides. After these experiments were carried out, a test was designed to characterise the group behaviour of different scenarios.

6.1 Tool

A tool was developed to produce plots using GnuPlot to analyse data. This tools has been used to good effect to fine-tune weights and in some cases to fine tune function calibration

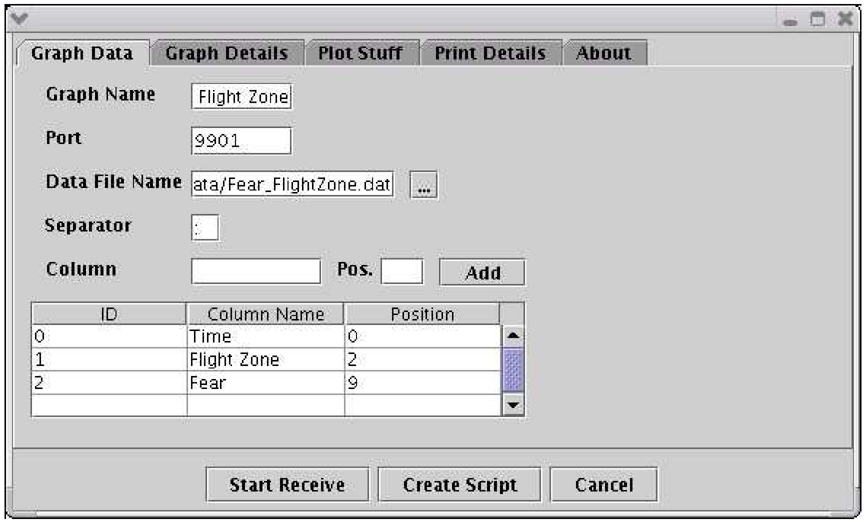


Figure 6.1: Snapshot of Plotting tool

between an input and an output. One such case is a the relation between the Flight Zone Sensor with the Fear emotional system. This tool was developed in Java 6.1. It has the following properties:

1. Contains a GUI to configure the plots
2. It listens to a port selected in the GUI.
3. Produces two files. One file is for the data set and the other to produce a script with commands to generate the plot in GNU plot.

A sample plot produced with the tool is shown in figure 6.2

6.1.1 Emotion

As stated previously, this tool has been used to fine-tune some of the output, such as that of the fear emotional system. Fear is triggered by different stimuli, for example the flight zone sensor. See appendix B for a sample XML file used to create the Amygdala, that is the different emotional systems.

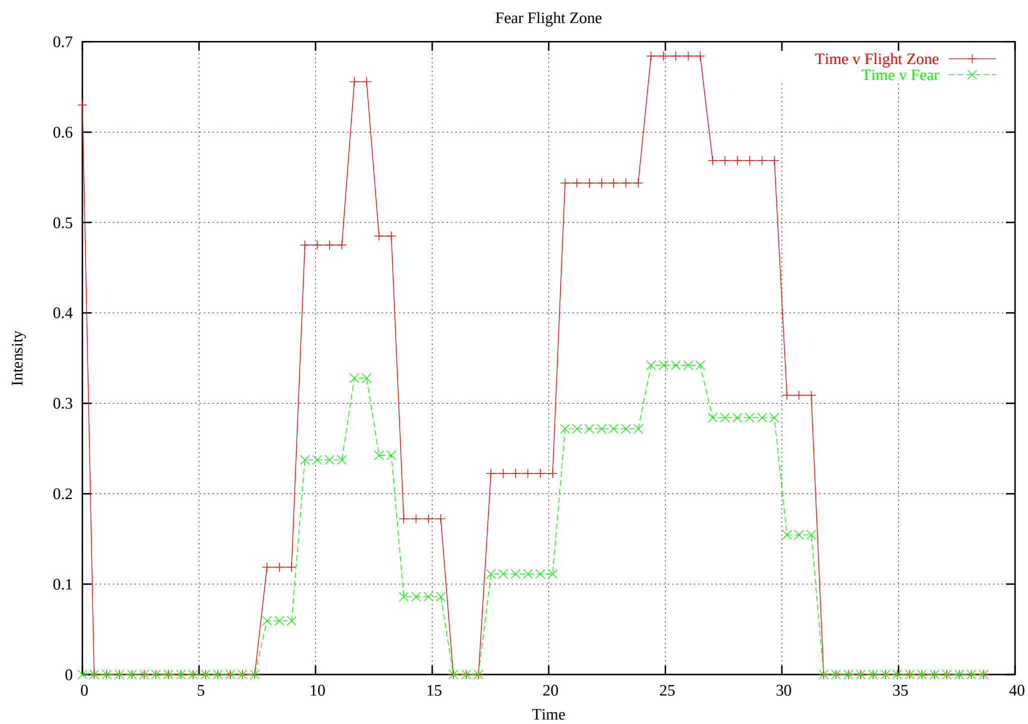


Figure 6.2: Naïve relation between Fear and Flight Zone

Several iterations will be shown to exemplify the fine-tuning of an emotional system.

The first attempt, shown in figure 6.2, presents a linear relationship between Fear and Flight-Zone. This is a naïve attempt, that although intuitive, does not resemble how an emotion intensity grows; see [Picard1997] for graphs of experiments on emotion in humans.

The second, shown in figure 6.3 replaces the linear relationship between the input and the output, with a sigmoid function. However in this naïve attempt, the emotion output is constrained in a very short range. The reader is referred to chapter 5 for the formulae on sigmoidal functions. This attempt still has shortcomings, as it can be appreciated the range of values is very small and worse they are constrained in the values near the maximum of 1. This would make the elicitation of an emotion particularly haphazard.

A third, shown in figure 6.4, aimed to improve the previous function, move the lower values close to zero. It can be appreciated that the Fear output is still constained in a small range. The values need scaling.

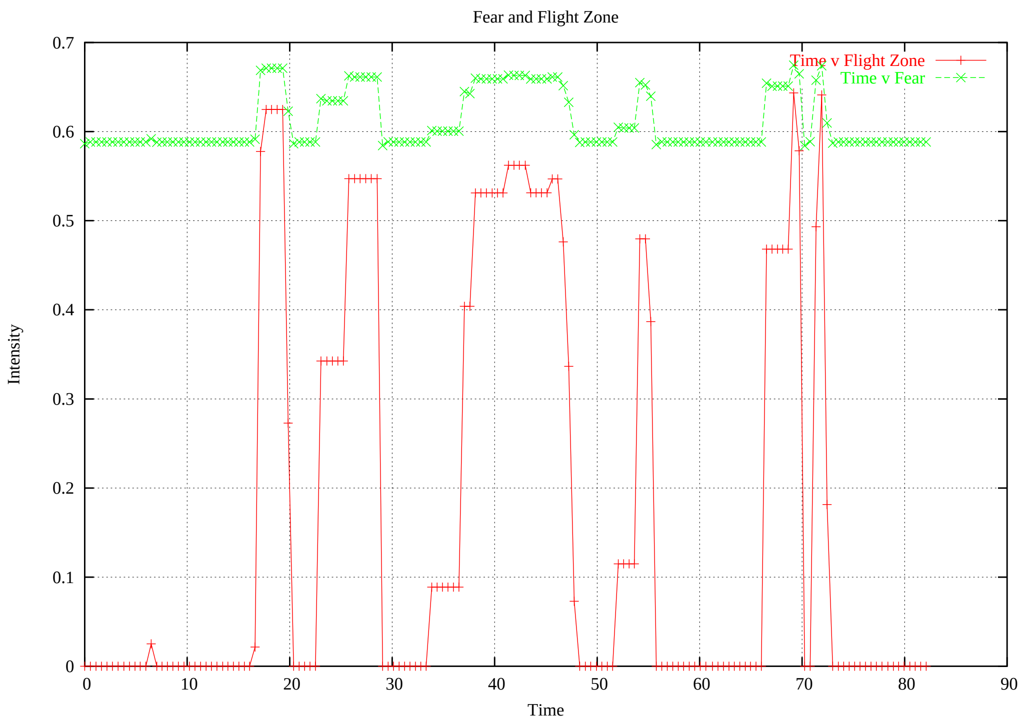


Figure 6.3: Relation Fear and Flight Zone using a sigmoid function

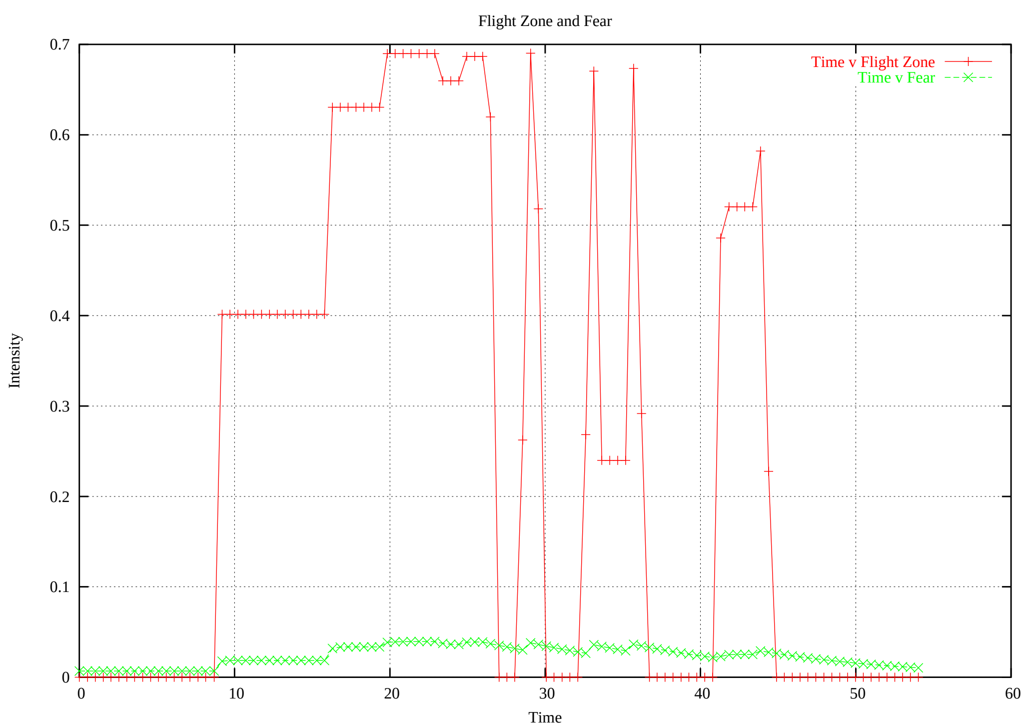


Figure 6.4: Relation Fear and Flight Zone using a sigmoidal function needs scaling

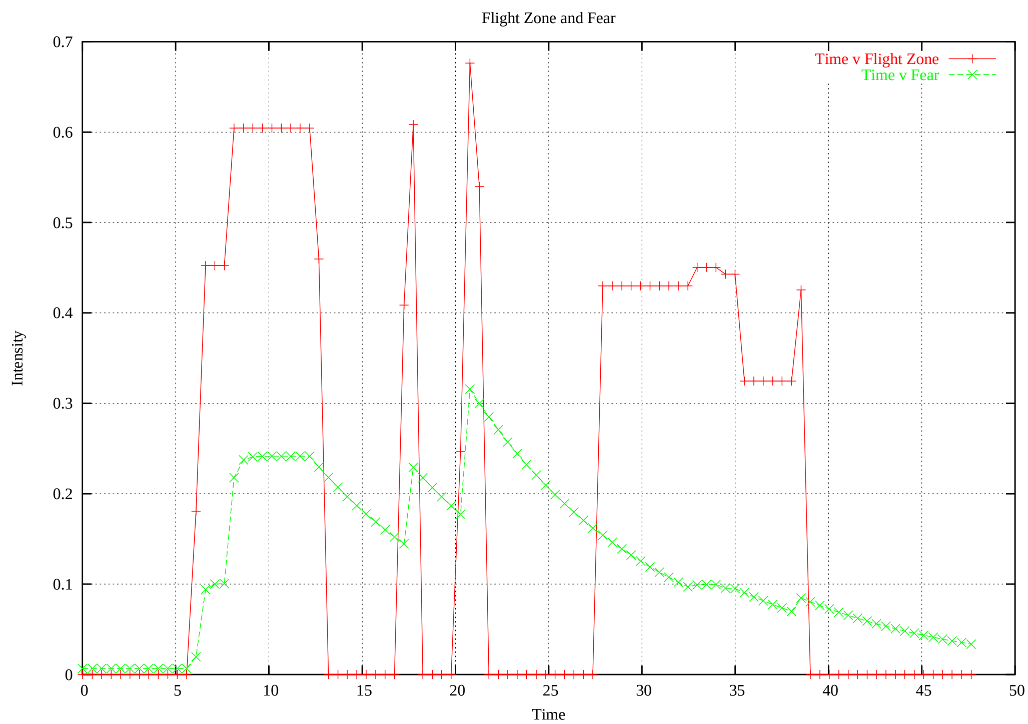


Figure 6.5: Relation Fear and Flight Zone using a sigmoidal function, scaling almost, the decreasing should be less linear, to conform to Lorenz' Action Readiness

A fourth attempt, shown in figure 6.5, the values are scaled to a more suitable range of values but the decrease of the emotional intensity seems linear, which is not the case in the feeling of an emotion. This is discussed in chapter 3, and shown in figure 2.4.

The last attempt, shown in figure 6.6 shows an emotion being elicited in a similar manner as in real-life.

The design is compatible with Lorenz's Psychohidraulic model, that is, an emotion builds up momentum, but once it is elicited the emotion decreases gradually.

As seen in this section, the tool was useful in visualising the shortcomings of the model. It was thus possible to improve them to make the 'feeling' similar to the emotional experience in real animals.

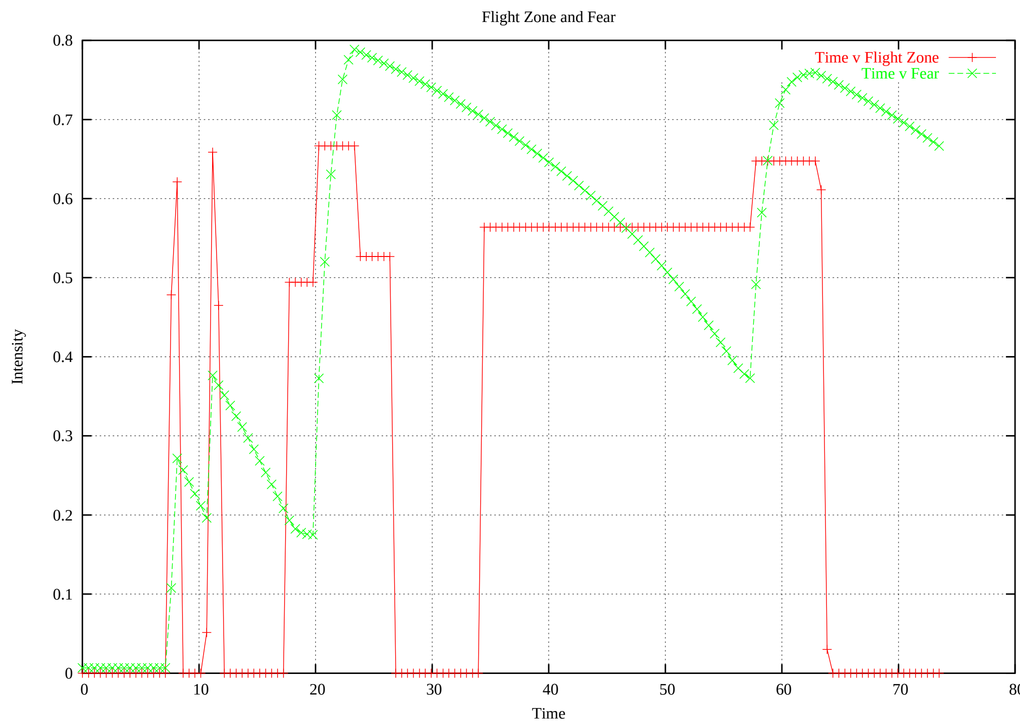


Figure 6.6: Relation Fear and Flight Zone using a sigmoidal function, scale conforms to Lorenz action Psycho hydraulic though model, as described before, see figure 2.4 Decreasing not linear.

6.1.2 Hypothalamus - Drives

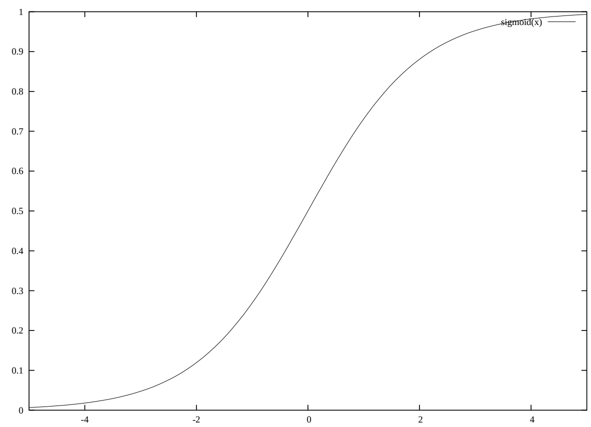
Experiments were also made with drives. The drives are constrained to values between 0 and 1. This allows the values to be computed and compared in similar terms. To achieve this, a sigmoidal function is used that has interesting properties. One of them is that is often used to describe growth in natural systems. Basically a drive is a variable that if not satiated grows over time. Other possibily to represent growth in internal variables, like hunger, is found in [Tyrrell1993]; he used simple algebra. The sigmoidal function is shown in figures 6.7(a) and 6.7(b). Figure 6.7(a) shows a complete sigmoid function, that is, constrain the negative and positive values to values in a range between 0 and 1. Figure 6.7(b) shows that the positive values have been constrained.

An example of a drive as defined in this work is hunger. If the animal does not eat, then the hunger drive will increase constantly until the animal dies! This can be appreciated in figure 6.8.

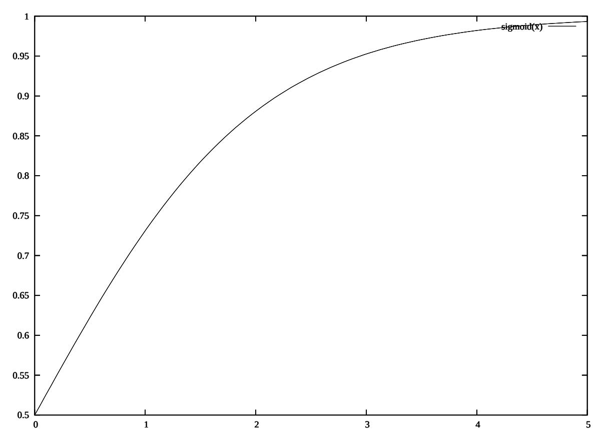
Another example is that of the relation between the hunger drive and the emotional 'feeling' of anger. This makes sense adaptively, as an angry animal will fight fiercely against competitors for often scarce food. Figure 6.9 shows the growth of anger in relation to that of hunger and thirst; it should be noticed that although these values were taken from the real system, the case is hypothetical as the affected animal would have been long dead because of hunger thirst and/or rage!.

6.2 Experiments with users

Two preliminary experiments were devised to establish the contribution of behaviours to the perceived realism of the animals within the environments and the contribution to the overall experience. This section reports two separate experiments. In experiment 1, the contribution of virtual animals to a static virtual environment are assessed. The animals



(a) Complete sigmoid function



(b) Sigmoid positive function

Figure 6.7: Sigmoid function

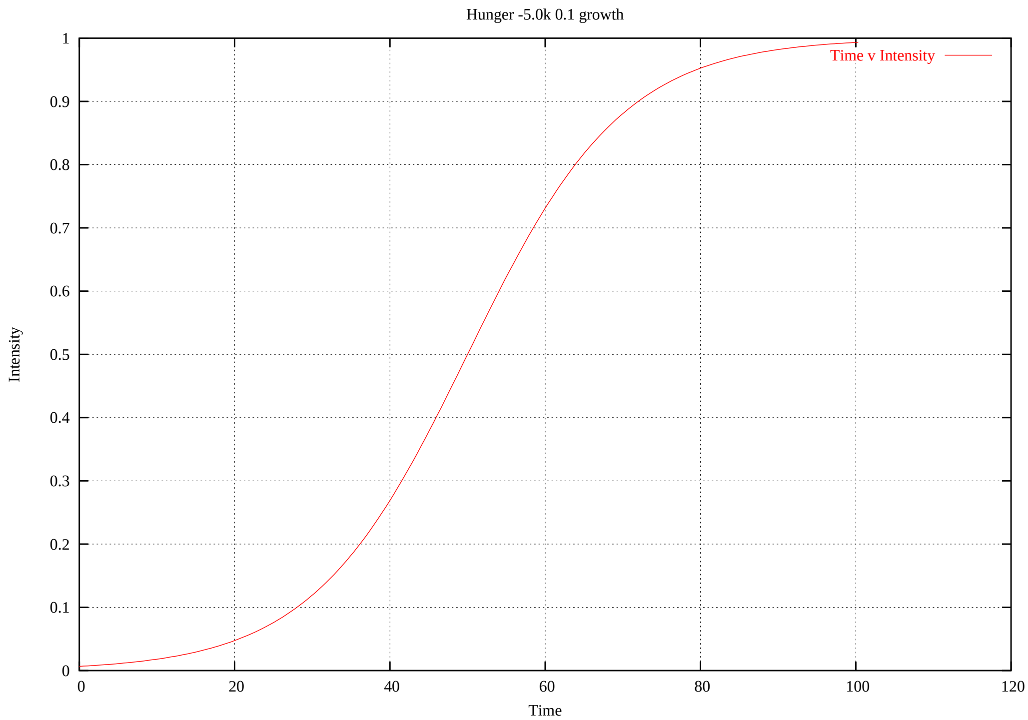


Figure 6.8: Hunger growth

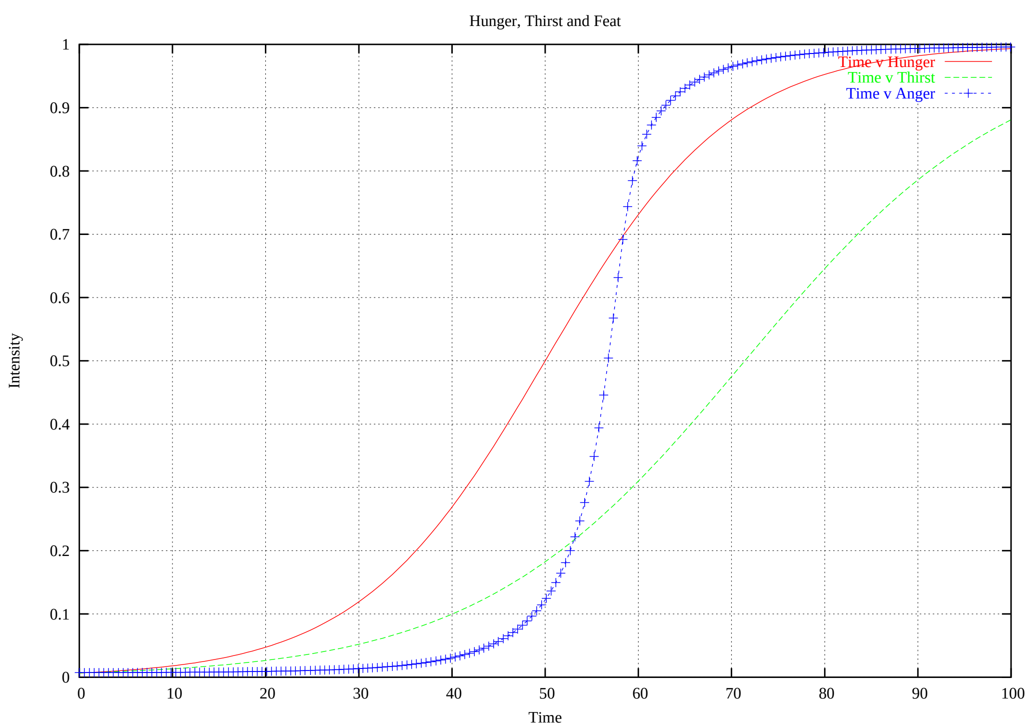


Figure 6.9: Anger in relation to hunger and thirst

are given different levels of behaviour and participants are asked to rate the effect of the behaviours on the perceived realism of the animals themselves, and on the richness of the environment. In experiment 2, video sequences of virtual animals imbued with combinations of different behaviours were viewed by participants who rated the level of realism of the behaviours and the effect on the virtual environment.

6.2.1 Experiment 1.

The first experiment investigated whether the addition of virtual animals to a static environment displayed using immersive technologies, might improve the experience. A range of behaviours were assigned to the virtual animals. The impact of the various behaviours were compared and reported in the following sections. This experiment was developed on two computers, one running Linux for the brains and the other a 16 MIPS R10000 Processors SGI Origin Computer for rendering Palenque on the CAVE (see figure 6.10). See chapter 5 for a description of the architecture, in figure 6.11 a snapshot of grazing deer is shown.

Method

15 participants (9 males and 6 females) from the Centre for Virtual Environments at Salford University took part in the initial study. All participants had at least 1 year post graduate experience of working in an immersive virtual environment. Participants with less experience were deemed ineligible to take part in the study, in order to minimise the confounding influence of the novelty factor associated with the technology. Participants entered a 4 sided CAVE, in which the Palenque environment was projected. While the individuals were free to move about to some extent within the CAVE itself, the experimenter guided each participant through the virtual environment on a predetermined path, which was standardised across all participants. The environment was populated with a herd of

Figure 6.10: Users in the CAVE observing grazing deer

Figure 6.11: Grazing deer to enhance a virtual environment

deer, whose behaviour varied according to one of three experimental conditions. In condition A, each deer adopted a static pose (e.g., grazing or standing). In condition B, deer were animated with motion captured data from live animals. Movement in condition B was restricted to walking only. The animals behaviour was defined by a reactive engine, which ensured obstacles were avoided [Delgado-Mata and Aylett2000]. In condition C, deer were imbued with a variety of different behaviours (walk, graze, rotate, stand, and associated transitions) [Delgado-Mata *et al.*2003]. Behaviours were assigned at random according to a predefined set of heuristics. Participants experienced all three conditions. The order of presentation was randomised according to a latin square design. Participants experienced each condition for between 4 and 5 minutes. Upon completion of each condition participants were asked to assign a subjective rating to 10 different aspects of the environment according to a 7 point Likert scale (See appendix I).

Statistical Analysis

For each aspect of the environment ordinal Likert scores were compared across conditions using Friedmans test. Where significant differences were observed, a Wilcoxon signed ranks test was used to examine individual differences. All tests were 2-tailed.

Results

Figure 6.12 displays the median ratings for each condition. In all but one case, deer exhibiting moving behaviours were perceived to significantly enrich the environment. The greatest difference occured in relation to the extent to which animals appeared alive in the environment, with animals in the static condition being rated significantly less than in either the walking condition ($Z = 3.429, P = 0.001$) or the more sophisticated behaviour condition ($Z = 3.322, P = 0.001$). The smallest significant difference was observed in terms of the graphical representation of the animal, with static animals being rated slightly less than the richest behaviour condition ($Z = 2.486, P = 0.013$). Differences in the graphical representation of static and walking animals missed statistical significance at the $\alpha = 0.05$ level ($Z = 1.997, P = 0.058$). No significant differences were observed in the extent to which different behavioural patterns engaged participants in the environment.

No significant differences were observed in participants ratings of walking compared to more varied movement. However, participants ratings tended to improve with more varied behaviours. The proportion of participants who assigned a rating of 6 or more to the realism of the environment (Q3) in condition B was 46.6%. This increased to 73.4% in condition C ($\chi^2 = 4.773, df = 1, P = 0.029$).

Discussion

The results indicate a significant improvement in participants responses when movement is added to the deer. Participants felt the deer appeared more real and that they contributed more to the environment. However, the difference between basic and more sophisticated behaviours is much more slight. To some extent this was to be expected, as B and C both represent a change in state from A, whereas C could be construed as merely a modification of B. However, it is interesting to note other potential contributory factors for this effect, and the connotations of such a result for application developers in this area. One reason

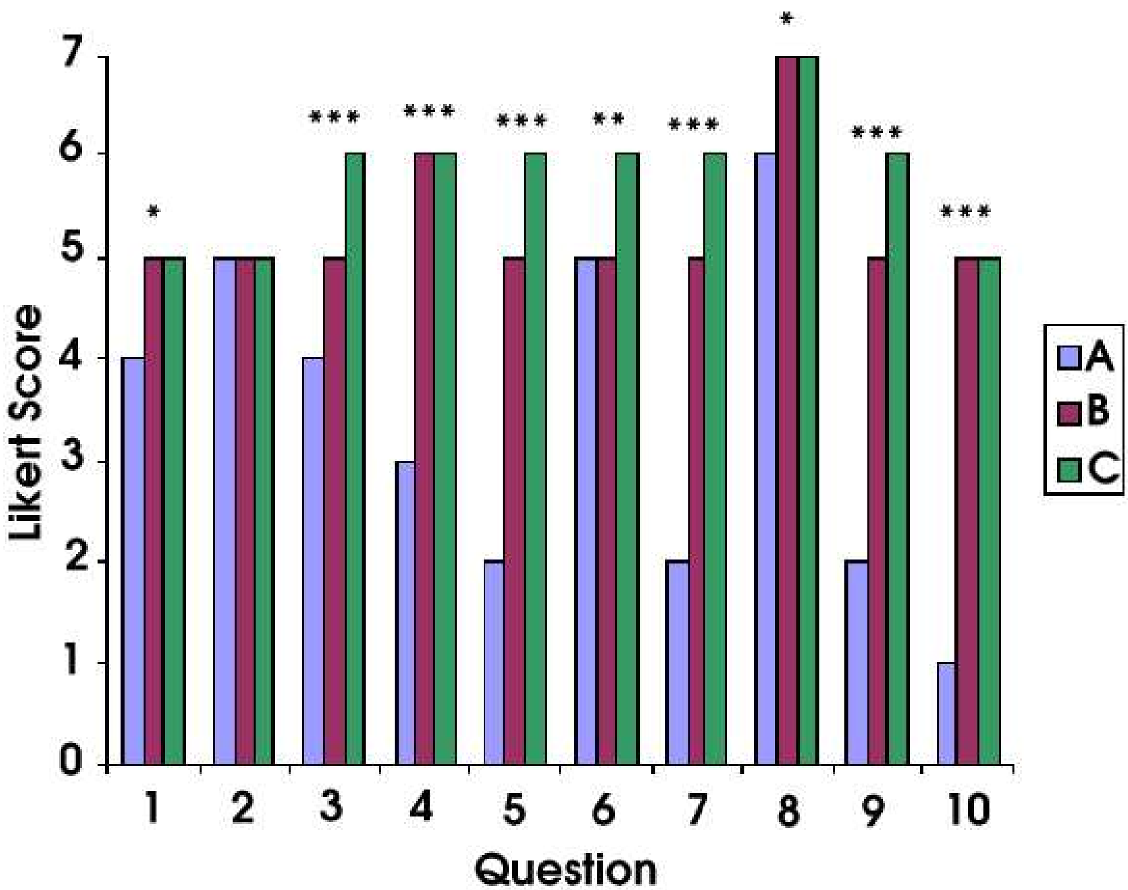


Figure 6.12: Median responses to experiment 1 questions (see appendix I) across all conditions ($*P < 0.05, **P < 0.01, ***P < 0.001$)

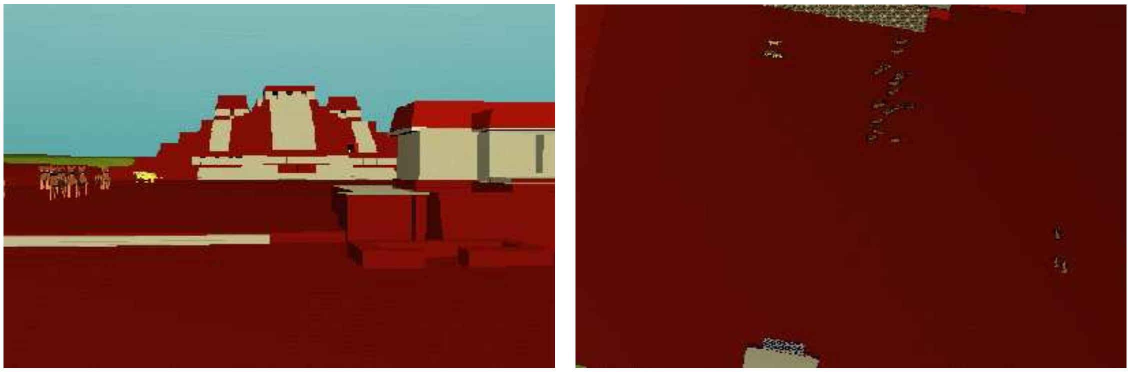
that the reported differences between behaviours did not achieve significance may have been due to the granularity of the rating scale employed in the experiment. Participants tended to rate the addition of movement in the virtual environmnet highly. Using a 7 point Likert scale meant that there was proportionally little room to express any further improvements. However, it must be noted that participants may simply not associate the refinements in behaviour with an improved representation to a significant enough degree. This raises the question of whether the provision of behaviours adheres to a law of diminishing returns. It is clear that application developers expend a proportionally large amount of effort refining behaviours, which may make significantly less of a perceived contribution than merely adding movement in the first place. In this experiment the behaviour of the deer was refined in condition C, rather than adding ostensibly new behaviours. This may also have contributed to the poor significance rating between the two moving conditions.

6.2.2 Experiment 2.

In the second experiment video sequences of virtual animals displaying particular combinations of different behaviors were shown to participants. These video sequences were recorded from the Calakmul virtual environment (see Figure 6.13) on the VRML and Java developed system (see Implementation).

Method

20 participants (15 male and 5 female) from Instituto de Estudios Superiores de Monterrey, Mexico took part in the experiment. Participants were asked to rate their experience with computers, virtual environments and animal behaviour. Experience with computers ranged from moderate, to very experienced, with a majority rating their experience as reasonable or better. Experience with virtual environments ranged uniformly from none to experienced. Experience with animal behaviour ranged from none, to experienced, with a



(a) Walking view (b) Aerial view

Figure 6.13: Views of a Mayan city of Calakmul with virtual animals.

majority having little or no experience. Participants were shown 5 sequences of video (each 5 minutes in length). Each sequence comprised an aerial view of a herd of deer moving around in an enclosed environment (see figure 4b), part of Calakmul, and a number of threats to the Deer (the threats in this experiment were represented by Jaguars). Each sequence corresponded to 1 of the 5 conditions listed below. As in the previous experiment each participant viewed all conditions and rated their reactions to various aspects of the experience on completion of each condition (see Appendix A).

A . Deer do not perceive the jaguars nor its flockmates.

B . Escape. Deer do not perceive their flockmates, but they do perceive the jaguars.

C . Flocking. Deer do not perceive the jaguars, but they do perceive their flockmates.

D . Flocking + escape. Deer perceive both the jaguars and their flockmates.

E . Emotions. Deer perceive both the jaguars and their flockmates, and their response is driven by emotions.

The 7 point Likert scale employed in experiment 1, was extended to a 10 point Likert scale in an effort to improve sensitivity. In addition, questions were focused on those aspects of the environment where most significant differences were likely to be perceived, as informed by experiment 1.

Statistical Analysis

Wilcoxons signed ranks tests were applied a-priori between conditions A and C, B and C, B and D, C and D and D and E. Bonferroni adjustment for multiple comparisons was applied accordingly.

Results

Conditions A (no behaviours) and C (flocking only) differed significantly on 3 out of 7 questions. Figure 6.14 compares participants ratings for conditions A and C. Participants rated the deers tendancy to perceive the environment greater in condition C than A ($Z = 2.84, P = 0.025$). Additionally participants also rated the deers tendancy to react to the envrionment greater in condition C than A ($Z = 2.828, P = 0.025$). The greatest difference between the conditions was observed in relation to the perceived reaction of the deer to one another. The median rating for condition A was 0, and 9 for condition C ($Z = 3.846, P = 0.001$).

Conditions B (escape only) and C (flocking only) differed significantly on 3 out of 7 questions. Figure 6.15 compares participants ratings for conditions B and C. Participants perceived a significantly more realistic behaviour pattern in condition B than C ($Z = 2.506, P = 0.02$). However, participants felt that the deer perceived one another to a greater extent in condition C than in condition B ($Z = 3.733, P = 0.001$). The greatest difference between the conditions was observed in relation to the emotional reaction of the deer. The median rating for condition C was 0, and 7 for condition B ($Z = 3.844, P = 0.001$).

Conditions B (escape only) and D(escape + flocking) differed significantly on 6 out of 7 questions. Figure 6.16 compares participants ratings for conditions B and D. Participants

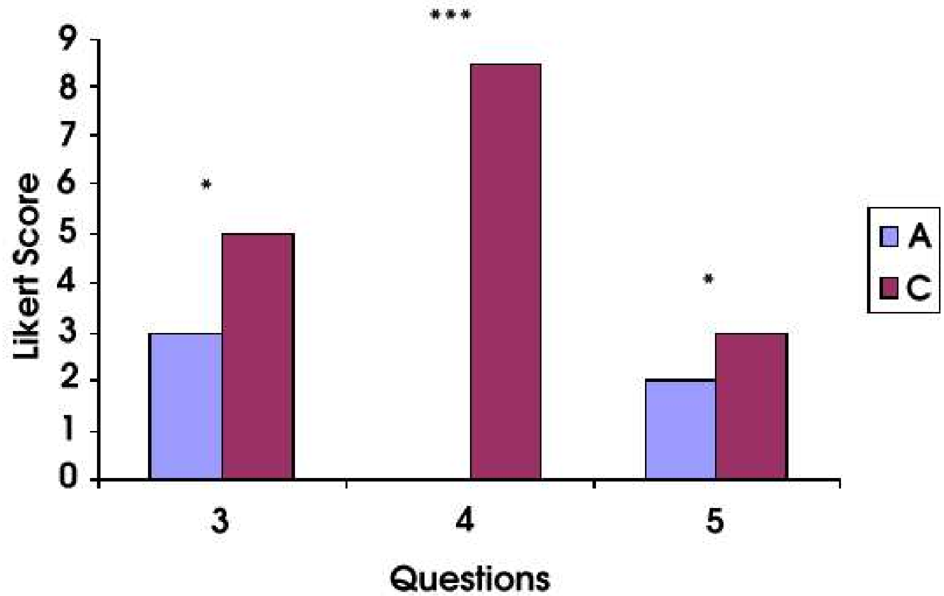


Figure 6.14: Significant differences in subjective ratings between the no behaviour and flocking only conditions ($*P < 0.05, **P < 0.01, ***P < 0.001$)

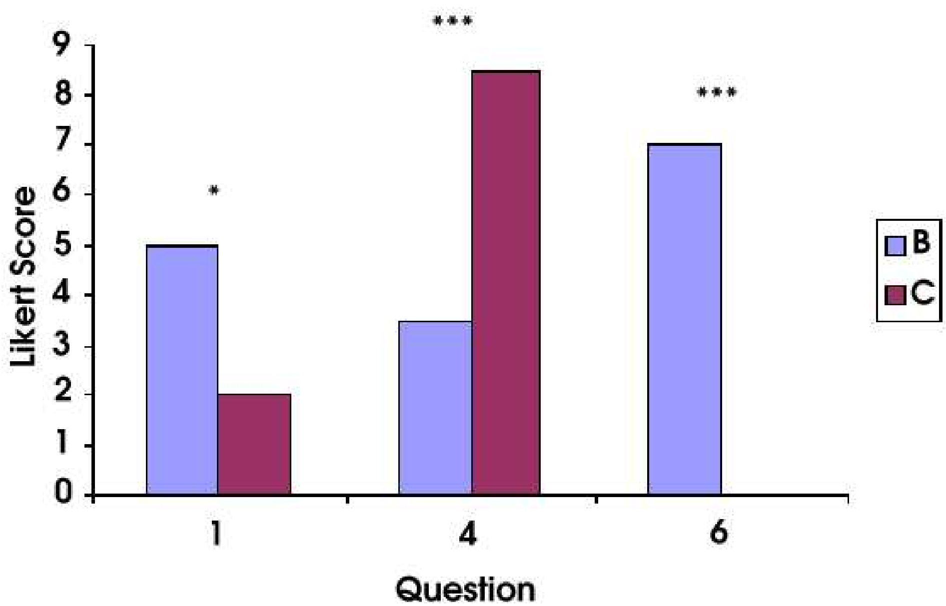


Figure 6.15: Significant differences in subjective ratings between the flocking only and escape only conditions ($*P < 0.05, **P < 0.01, ***P < 0.001$)

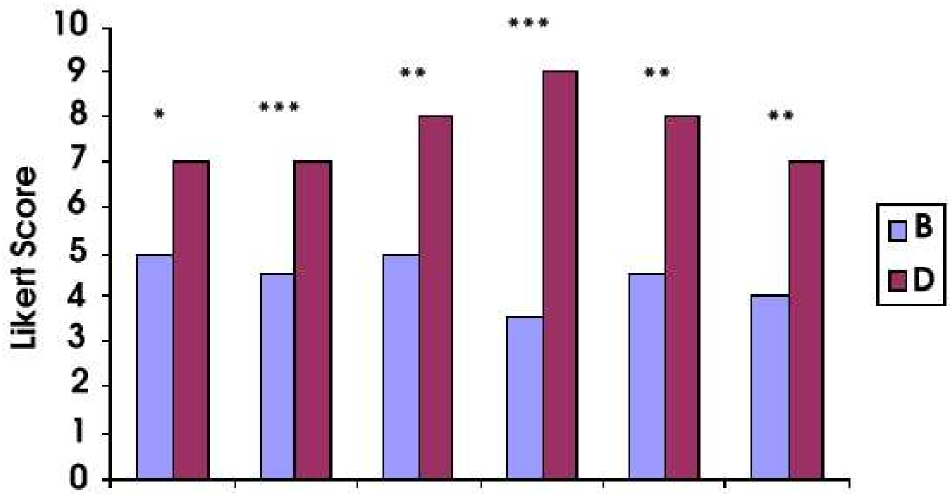


Figure 6.16: Significant differences in subjective ratings between the escape only and the flocking + escape conditions ($*P < 0.05, **P < 0.01, ***P < 0.001$)

rated condition D greater than condition B in all the significantly reported results. The greatest difference between conditions was observed in relation to the reaction of the deer to one another. The median rating for condition B was 4, and 9 for condition D ($Z = 3.628, P = 0.001$). The smallest difference between conditions was observed in relation to the realism of the behaviour of the deer. The median rating for condition B was 5, and 7 for condition D ($Z = 3.12, P = 0.02$)

Conditions C (flocking only) and D (escape + flocking) differed significantly on 6 out of 7 the questions. Figure 6.17 compares participants ratings for conditions C and D. Participants rated condition D greater than condition C in all significantly reported responses. The greatest difference in responses was observed in relation to the degree to which the deer displayed an emotional response. The median rating for condition C was 0, and 7 for condition D ($Z = 3.637, P = 0.001$). The smallest difference in responses was observed in relation to the degree to which the deer appeared to perceive the environment. The

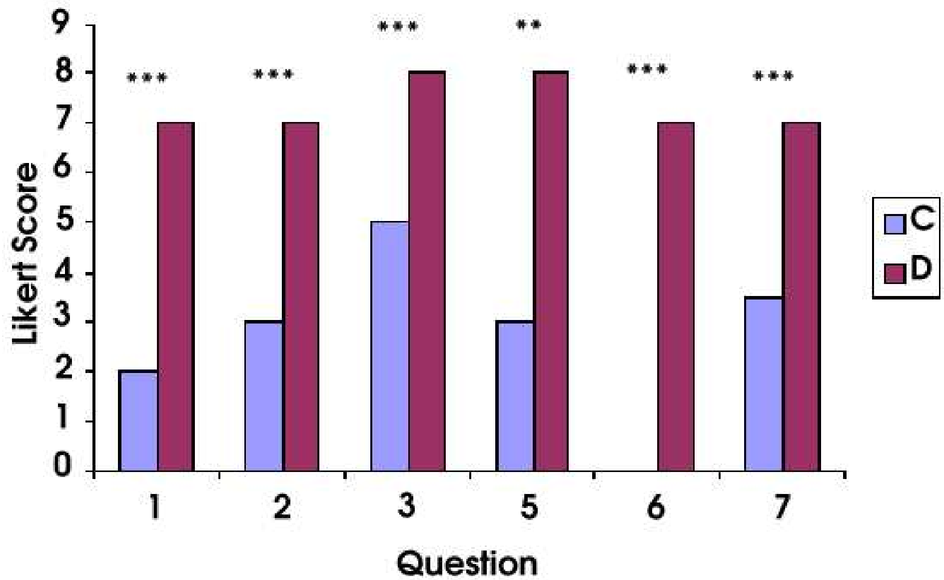


Figure 6.17: Significant differences in subjective ratings between the flocking only and escape + flocking conditions ($*P < 0.05, **P < 0.01, ***P < 0.001$)

median rating for condition C was 5, and 8 for condition D ($Z = 3.53, P = 0.001$).

Conditions D (flocking + escape) and E (escape + flocking + emotion) differed significantly on all the questions. Figure 6.18 compares participants' ratings for conditions D and E. Participants rated condition E greater than condition D in all significantly reported responses. The greatest differences in responses was observed in relation to the degree to which the deer displayed an emotional response. The median rating for condition D was 7, and 10 for condition E ($Z = 3.546, P = 0.001$). The smallest difference in responses was observed in relation to the degree to which the deer appeared to perceive the environment. The median rating for condition D was 9, and 10 for condition E($Z = 2.97, P = 0.015$).

Discusssion

Experiment 2 imbued the deer with a variety of behaviours. Participants reported a significant improvement in the manner in which the deer reacted to one another and to the

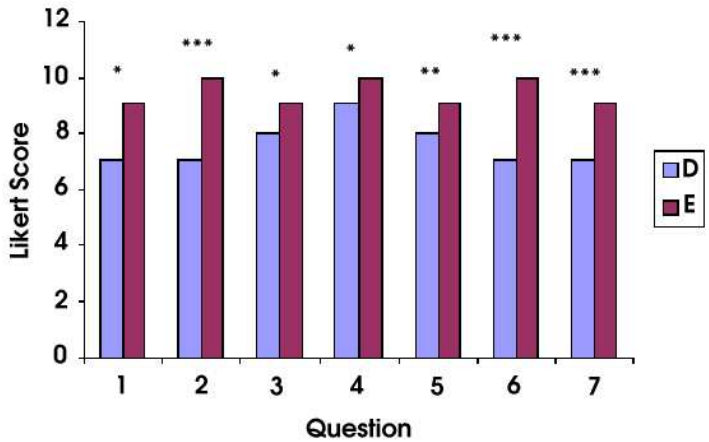


Figure 6.18: Significant differences in subjective ratings between the escape + flocking and emotion conditions ($*P < 0.05, **P < 0.01, ***P < 0.001$)

environment when flocking-only behaviour was added. However, the participants did not rate a significant improvement in realism, naturalness of behaviour, or contribution to the richness of the environment. This would seem to be comensurate with the findings in experiment 1. Refining the behaviour of the deer did not add significantly to the perception of the realism of the environment. When comparing flocking behaviour to the escape behaviour however, the escape behaviour appeared to add a degree of perceived realism to the deer. This is a significant point, as the escape behaviour is a reaction to something other than other deer in the environment, and it is represented by a marked change in behaviour. Thus it could be argued that the escape behaviour adds another perceived behaviour to the deer, rather than refining an existing one. If deer are imbued with both flocking and escape behaviour, then the behaviour of the deer appears significantly more real and makes more of a general contribution to the realism of the environment. This is an interesting result as the separate behaviours appear to complement one another in this respect, with the combination of behaviours having a more significant effect than when the behaviours are presented on their own. Furthermore, the general effect of the combined behaviours is greater still when the escape behaviour is refined by the emotion component, fear. This result raises the question, why does refining some behaviours appear to improve the perceived realism of the deer, while refining others does not. One reason for the effect may be that while flocking behaviour is more representative of the behaviour of the real animals, in a virtual environment flocking behaviour may seem more synthetic. Whereas, adding an emotional component to the escape behaviour rationalises and refines the behaviour of the deer, giving them a greater sense of autonomy. The analysis of the results of experiment 1 indicated that there may be some adherence to the law of diminishing returns when developing behaviours for virtual animals. However, a comparison of the two experiments seems to indicate that rather than diminishing perceptions of realism by combining and refining behaviours, one can significantly enhance the experience through the appropriate systematic combination of behaviours. In this endeavour it is important to mix behaviours that react directly to elements of the environment (e.g., escape) with behaviours that promote naturalistic behaviour (e.g., flocking). Refinements of reaction behaviours that make them appear more natural and understandable to the observer (e.g., emotion) can also greatly enhance the experience. Clearly these effects have been represented in a limited fashion in this study due to the number of participants tested.

6.3 Characterising behaviour

After the tests described in the previous section we wanted to characterise the complex group behaviour. The tests shown next were designed to achieve that aim. Some plots of the trajectories followed by the animals were produced, as seen in figures 6.19(a)–6.19(f) for 5 animals and in figures 6.22(a)–6.22(f) for 20 animals, similarly plots were produced for 10 and 15 animals. In total 24 positional plots (X, Y) were created, where 600 time steps were obtained and the trajectories are shown. It is intuitively clear that different flocking choices produce different plots.

- **Rigid Flocking.** To produce rigid flocking, the herd of animals was tightly (maximum 10 centimetres distance between members of the herd) packed and the animals were all facing the same direction at all times. This is the baseline condition for optimum coordination.

- **No Flocking No Escape.** In this scenario the animals were not moving as a herd, but each one of them was moving on its own with no knowledge (perception) of other animals or predators. This is the baseline condition for individual behaviour.

- **Escape.** This scenario is similar to the previous one except that the animals perceive the danger presented by the predators and individually move to avoid them.

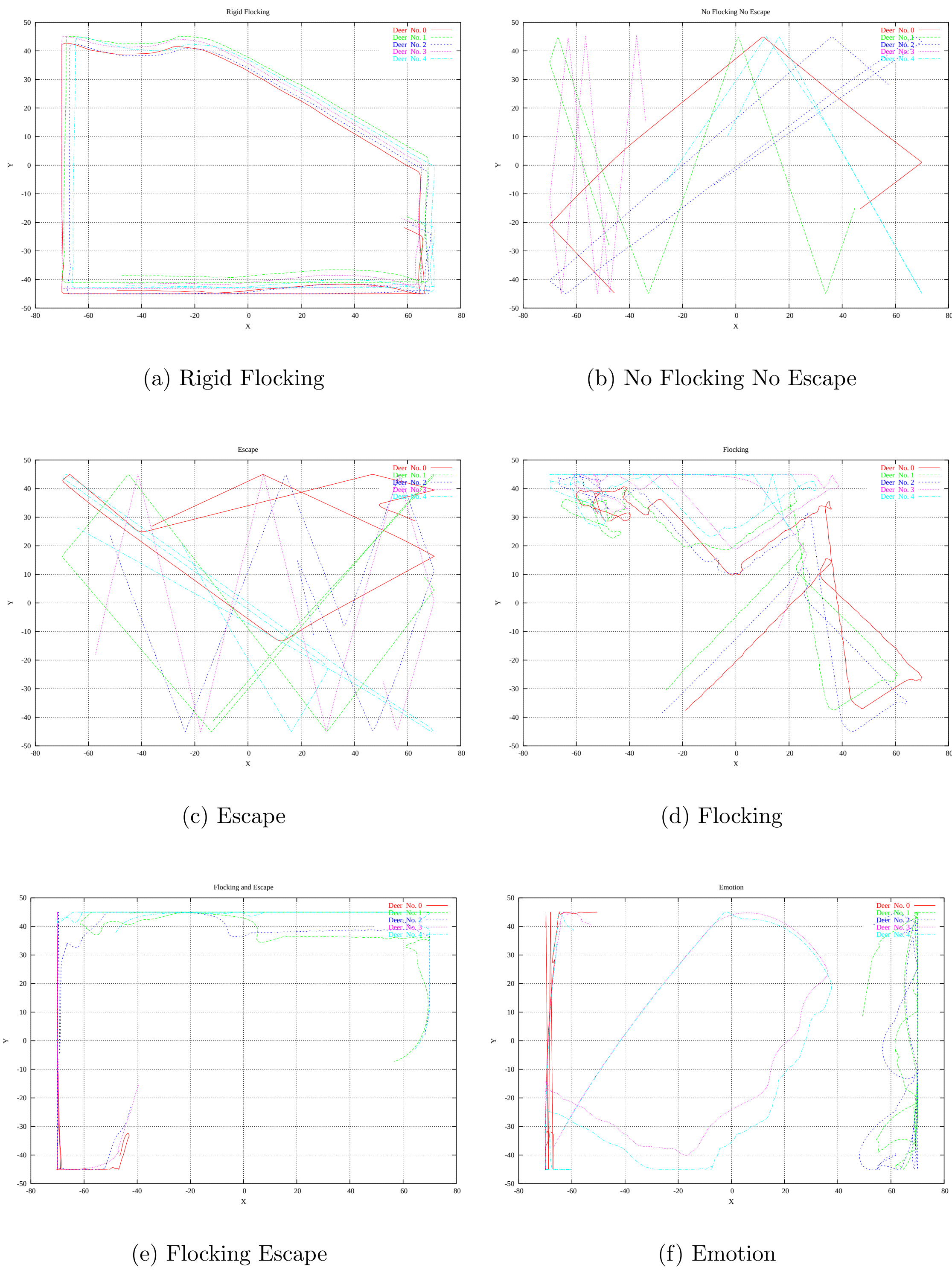
- **Flocking.** In this scenario the animals perceive each other, try to avoid collisions between each other and try to stay close to the herd. As it can be seen the plot produced looks quite complex.

- **Flocking and Escape.** This scenario is similar to flocking with the addition that the animals perceive the danger presented by the predators, and move to avoid them.

- **Emotion.** In this scenario emotion (fear) is elicited in the animals and communicated amongst them. To achieve this artificial pheromones are exuded when fear is 'felt' as they perceive the danger presented by the predators [Delgado-Mata *et al.*2003], this 'feeling' affects the behaviour of the animals as they try to stay close as a herd and their velocity is affected as well.

6.3.1 Complexity measurement

Before we start this section it would be a good idea to notice that as implied by its own name, in emergence something more complex arises from simpler rules, in our case flocking



(a) Rigid Flocking

(b) No Flocking No Escape

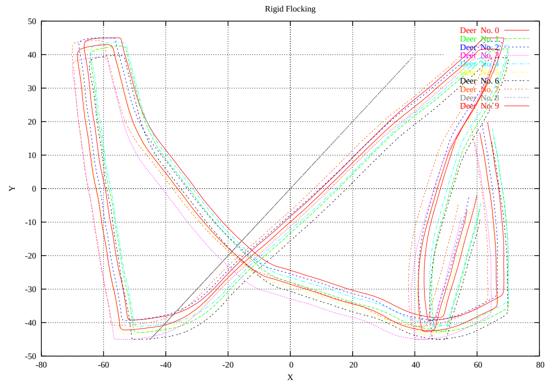
(c) Escape

(d) Flocking

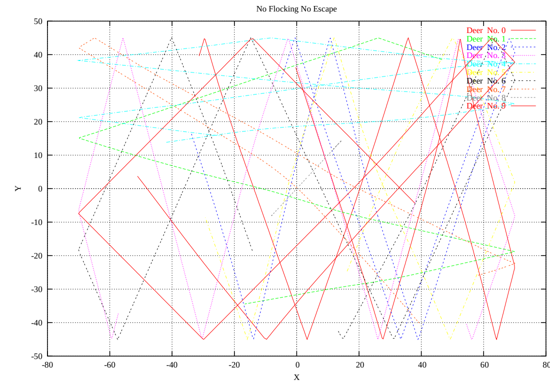
(e) Flocking Escape

(f) Emotion

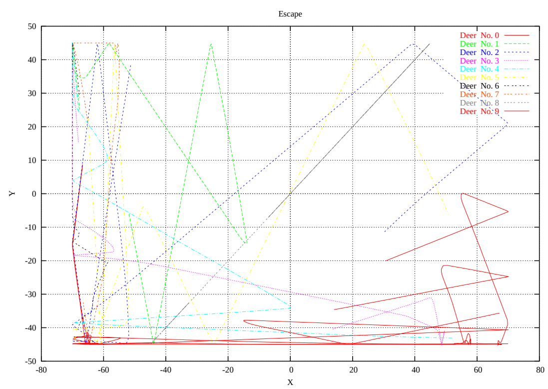
Figure 6.19: Flocking with 5 animals plots



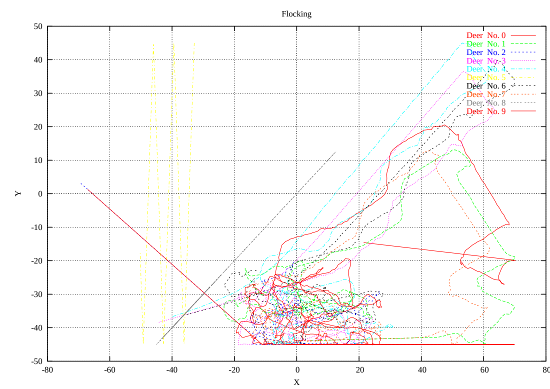
(a) Rigid Flocking



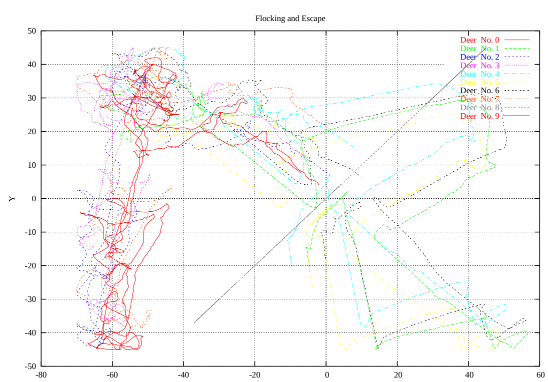
(b) No Flocking No Escape



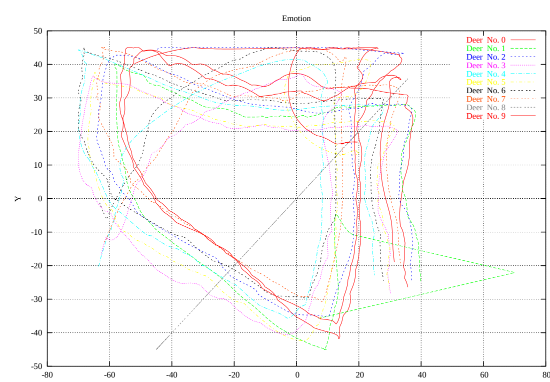
(c) Escape



(d) Flocking

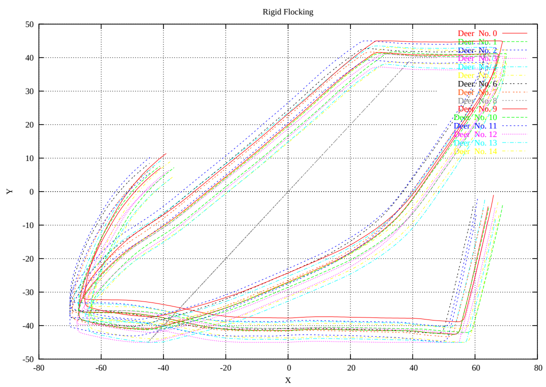


(e) Flocking Escape

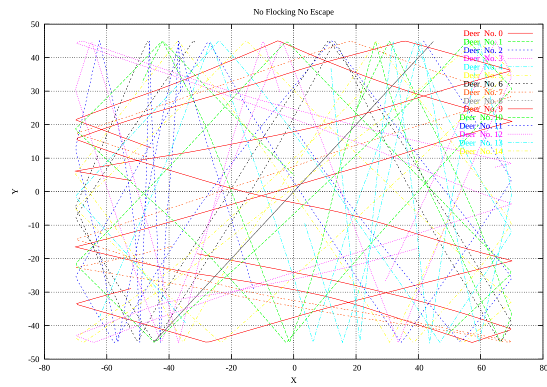


(f) Emotion

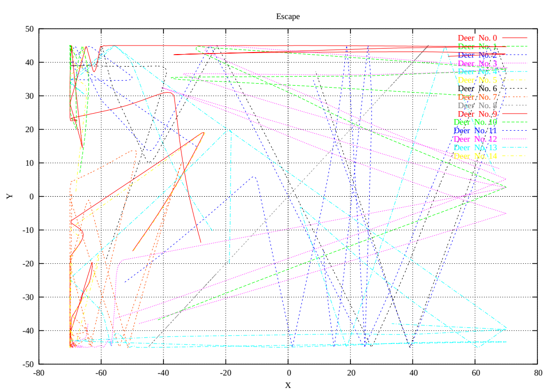
Figure 6.20: Flocking with 10 animals plots



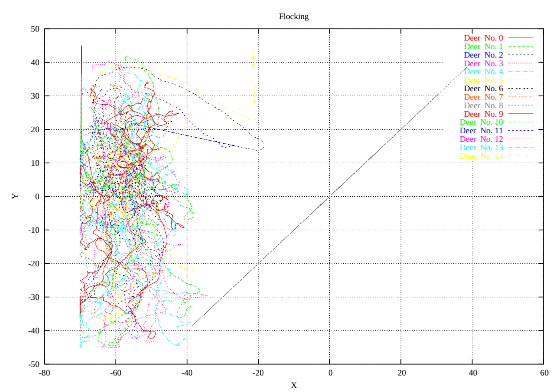
(a) Rigid Flocking



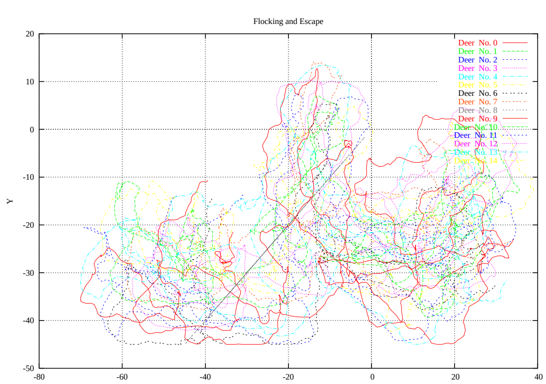
(b) No Flocking No Escape



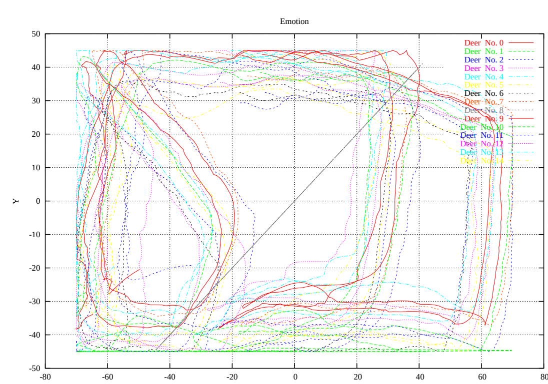
(c) Escape



(d) Flocking

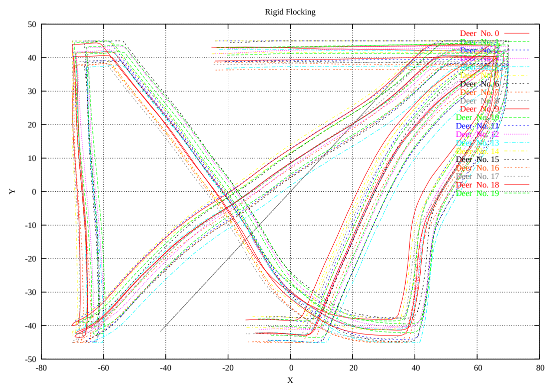


(e) Flocking Escape

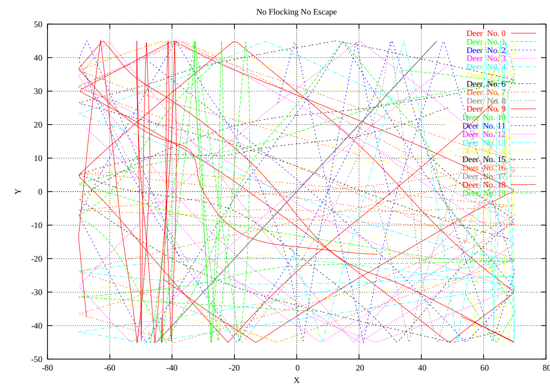


(f) Emotion

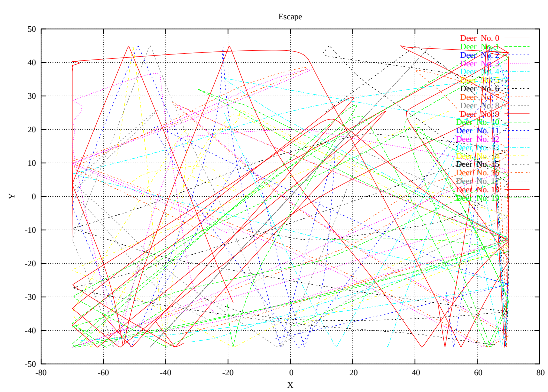
Figure 6.21: Flocking with 15 animals plots



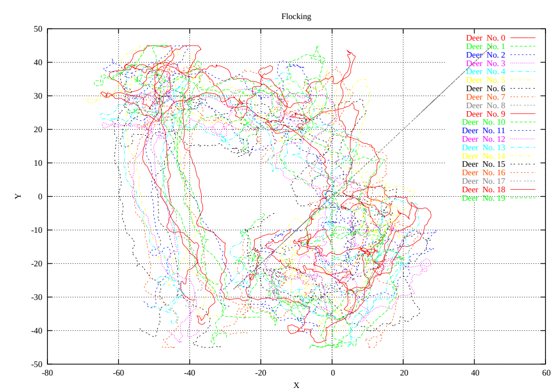
(a) Rigid Flocking



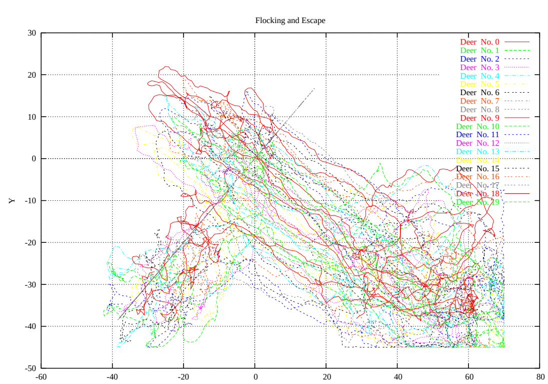
(b) No Flocking No Escape



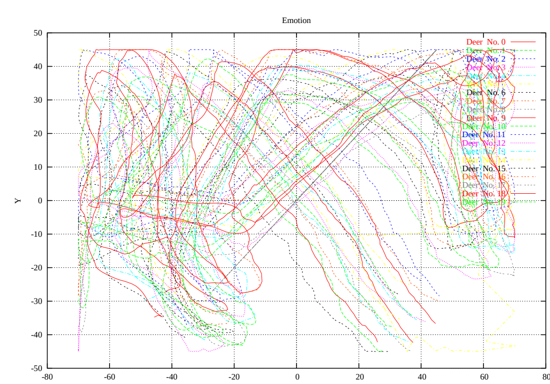
(c) Escape



(d) Flocking



(e) Flocking Escape



(f) Emotion

Figure 6.22: Flocking with 20 animals plots

emerges from the interactions between the agents, and the agents and its environment, so it is difficult to characterise emergence. Taking this into account, a useful approach is that of [Wright *et al.*2001]. There a system to measure emergence and complexity was presented. We have used a similar approach to test the different flocking mechanisms [Delgado-Mata and Aylett2004].

First we will describe the measurement system for flocking used, later the results using the system are presented.

As said before, 600 samples (M) were taken for the animals, so for 20 animals as seen in figure 6.3, and with N degrees of freedom that is 20 (4) (20 animals times position x,y and velocity x,y), which gives a matrix A was composed:

$$A = \begin{pmatrix} {x_1}^1 & {y_1}^1 & \dot{x}_1^1 & \dot{y}_1^1 & \cdots & {x_1}^N & {y_1}^N & \dot{x}_1^N & \dot{y}_1^N \\ & & & & \vdots & & & & \\ {x_M}^1 & {y_M}^1 & \dot{x}_M^1 & \dot{y}_M^1 & \cdots & {x_M}^N & {y_M}^N & \dot{x}_M^N & \dot{y}_M^N \end{pmatrix}$$

To compute the singular values, from linear algebra, the equation 6.1 was used.

$$A = USV^T \tag{6.1}$$

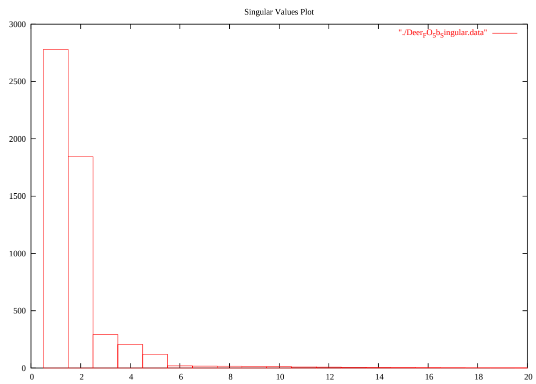
The singular values $\sigma_i = S_i$ are all non-negative and generally are presented in a decreasing sequence $\sigma_1 >= \sigma_2 >= \cdots >= \sigma_N >= 0$; singular values can be used as an approximation of the matrix. Singular values of rigid flocking are shown in figures 6.23(a) (5 animals), 6.24(a) (10 animals) , 6.25(a) (15 animals), and 6.26(a) (20 animals). Singular values of emotion and flocking are shown in figures 6.23(f) (5 animals), 6.24(f) (10 animals), 6.25(f) (15 animals), and 6.26(f) (20 animals). Sixteen more singular values plots are provided for the other conditions. From these plots, it can be seen that each type of flocking has a distinctive shape. Thus, out of the singular values an entropy of the system can be computed from N values. The singular values are normalised, because by definition $\sum_i P_i = 1$ [Bonabeau *et al.*1999], in our case P_i is σ_i. The formula for entropy used is:

$$E_s = -\sum_{i=1}^{N} {\sigma_i}' \log_2 {\sigma_i}' \tag{6.2}$$

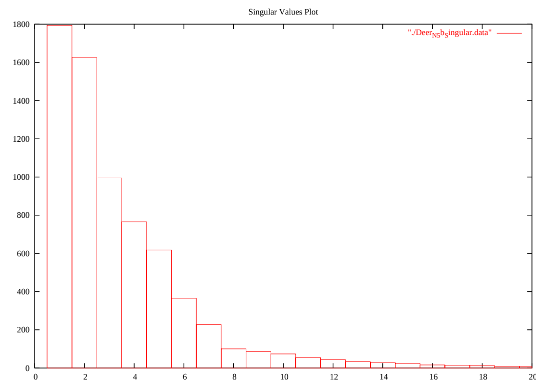
where ${\sigma_i}'$ is the normalised singular value. And since entropy can be seen as a $\log_2$ count of the number of states in a system [Bonabeau *et al.*1999], the effective number of states and thus the complexity is given by the expression:

$$\Omega = 2^{E_s} \tag{6.3}$$

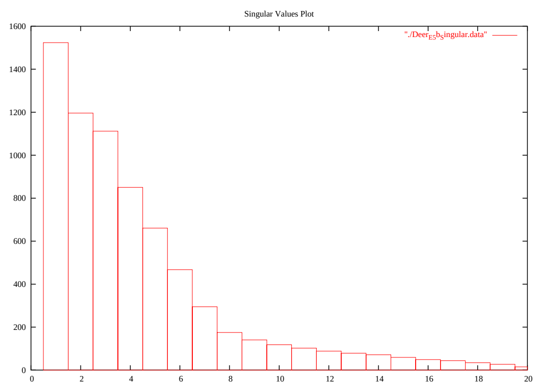
To compute complexity, a tool was developed, firstly to receive data from the virtual environment, secondly to produce plots of different types of flocking (shown in this section), thirdly to compute complexity as defined in formula 6.3 and lastly to produce a plot out of the complexities with different types of flocking and with different number of creatures. In figure 6.27 it can be seen that the plot of the rigid flocking is the one that shows the least complexity, intuitively supported by looking at figure 6.22(a). Flocking, flocking with escape, and no flocking, no escape, and the escape behaviour are more complex than rigid flocking, and they are almost always more complex than flocking with emotion. The exception is the five boid case where flocking with emotion, according to the result obtained and shown in the plot, is more complex than flocking with escape. This can be explained as follows: a further test has shown that in order to show flocking behaviour at least 9 animals should be in a herd. When there are fewer animals than this, when the animals escape from a predator, they separate from the flock and they do not regroup at all during



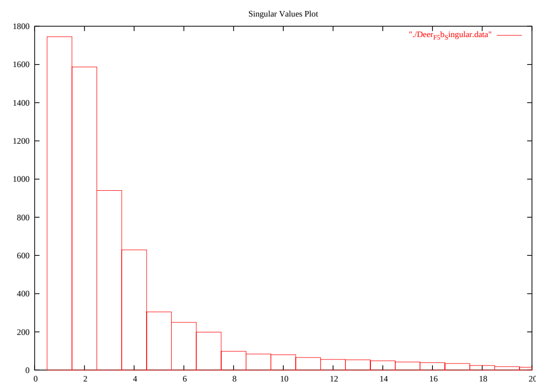
(a) Rigid Flocking



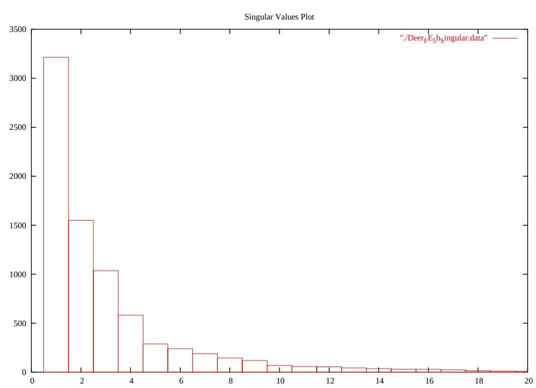
(b) No Flocking No Escape



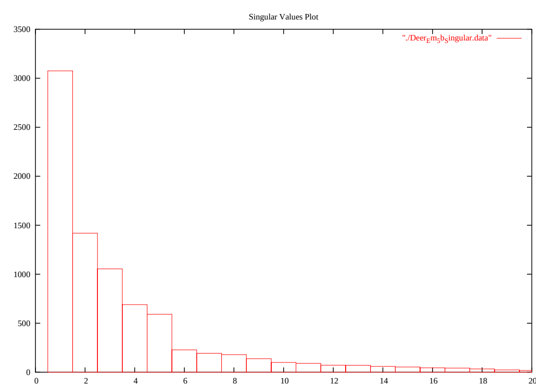
(c) Escape



(d) Flocking

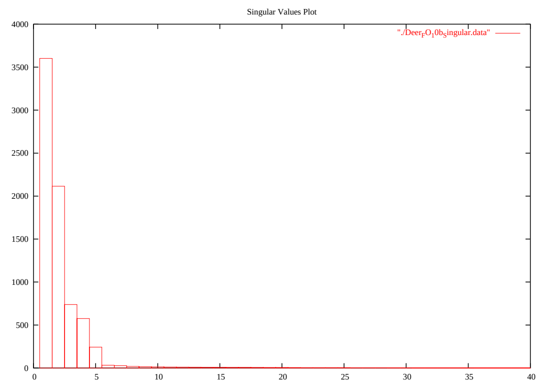


(e) Flocking Escape

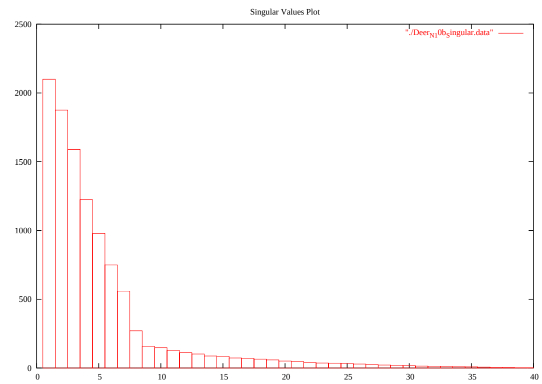


(f) Emotion

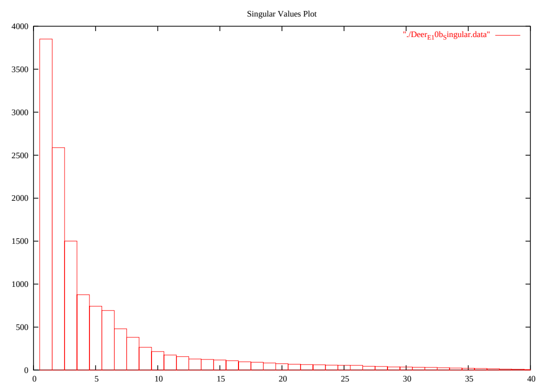
Figure 6.23: Singular Values for data with 5 animals



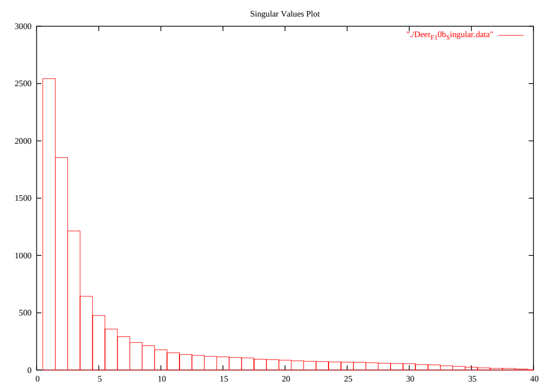
(a) Rigid Flocking



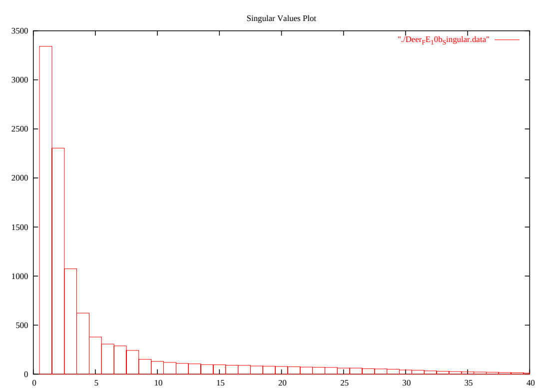
(b) No Flocking No Escape



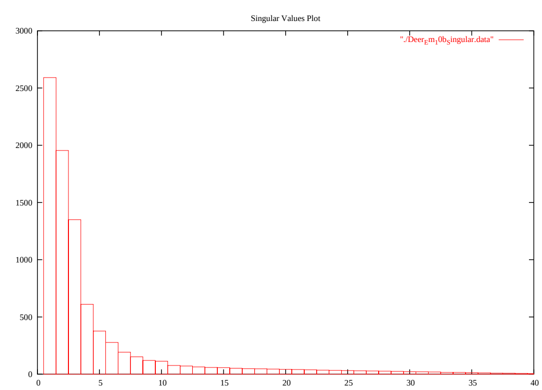
(c) Escape



(d) Flocking

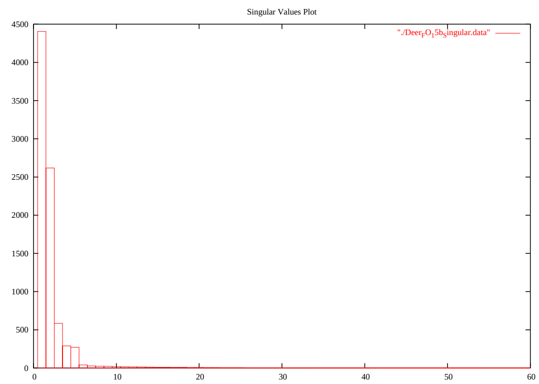


(e) Flocking Escape

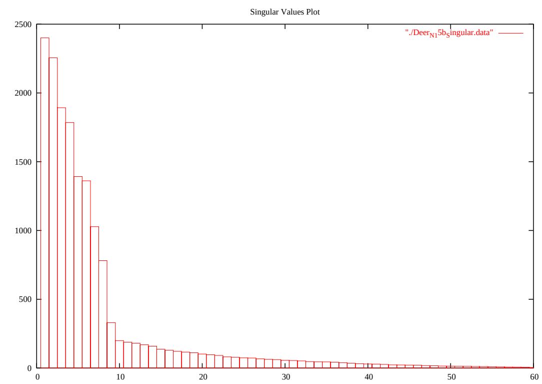


(f) Emotion

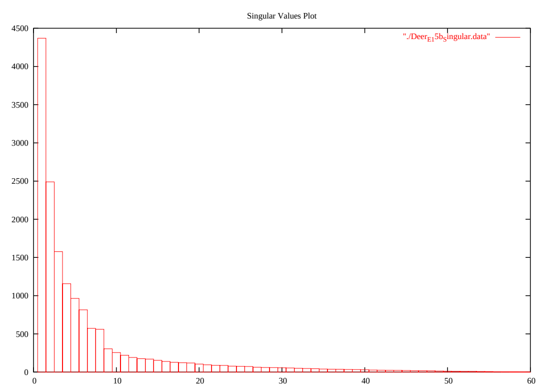
Figure 6.24: Singular Values for data with 10 animals



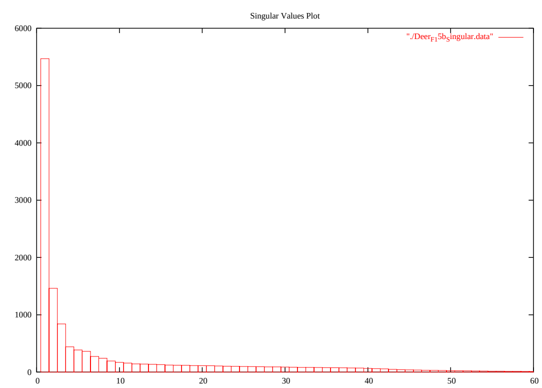
(a) Rigid Flocking



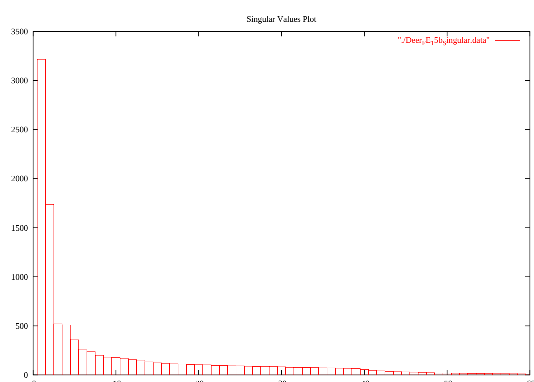
(b) No Flocking No Escape



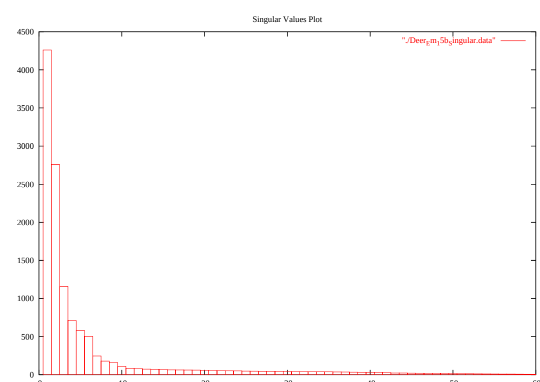
(c) Escape



(d) Flocking

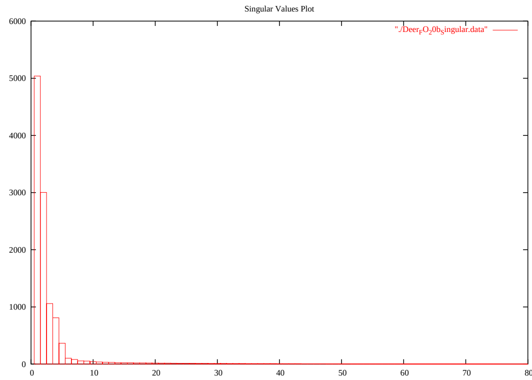


(e) Flocking Escape

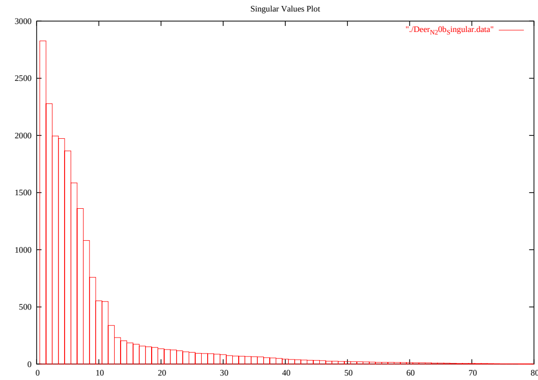


(f) Emotion

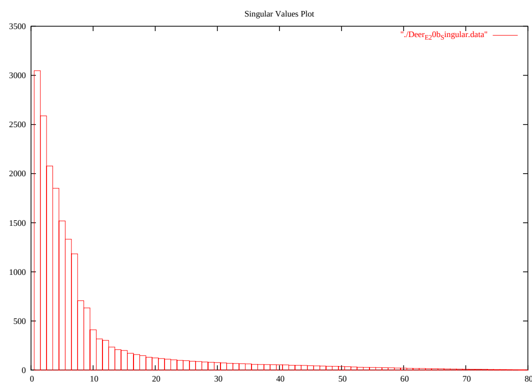
Figure 6.25: Singular Values for data with 15 animals



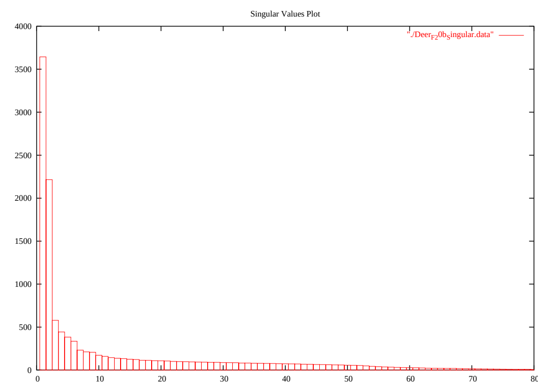
(a) Rigid Flocking



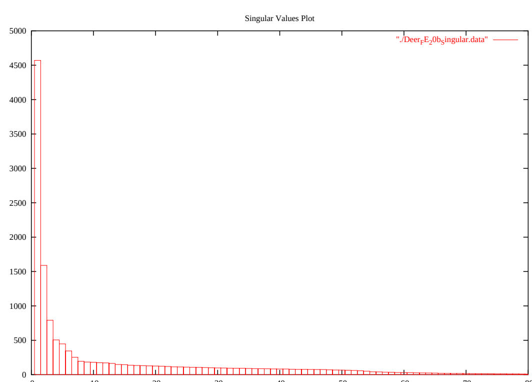
(b) No Flocking No Escape



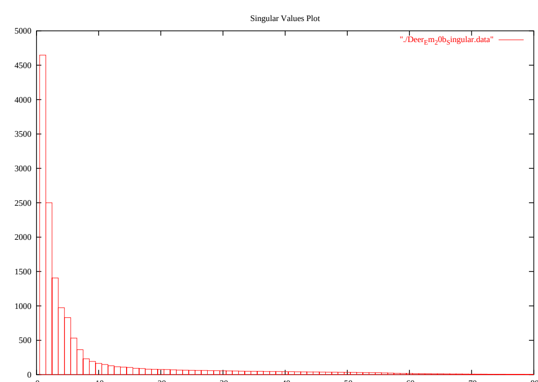
(c) Escape



(d) Flocking



(e) Flocking Escape



(f) Emotion

Figure 6.26: Singular Values for data with 20 animals

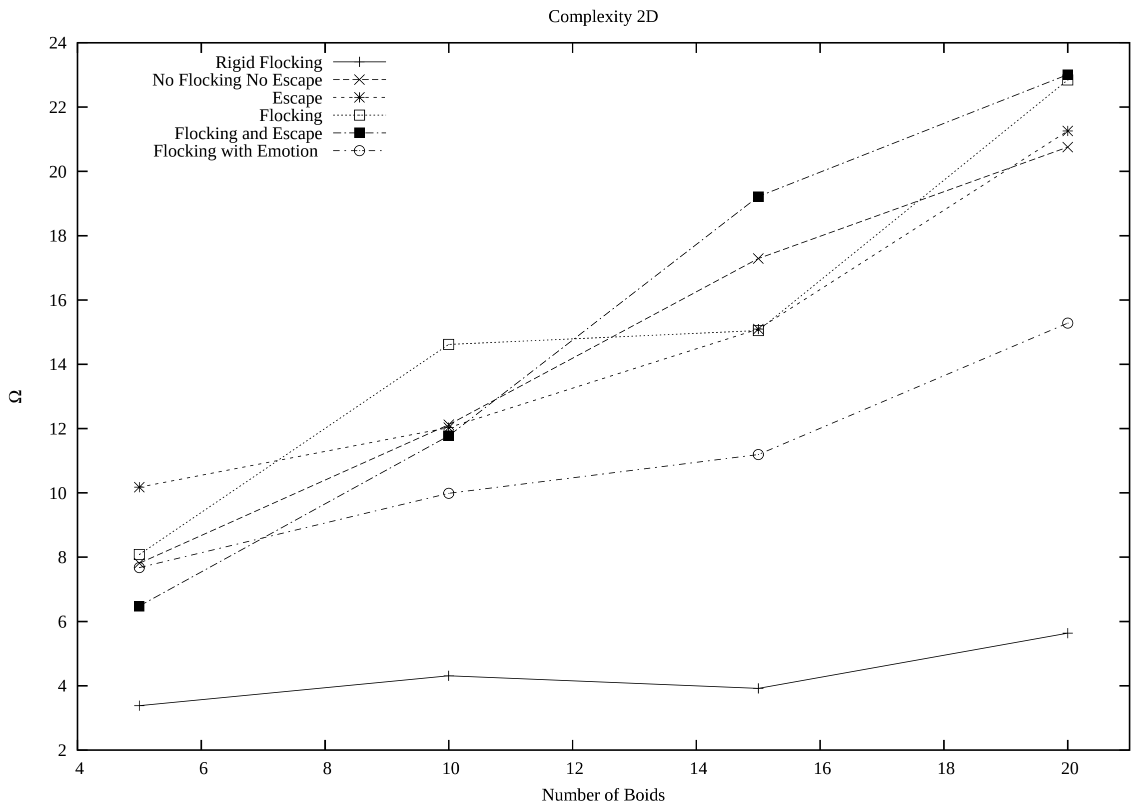


Figure 6.27: Complexity plot

the duration of the test [Delgado-Mata2004]. The results from this section have shown that emotion can be used to mediate between group behaviour (flocking) and individual behaviour (grazing).

6.4 Summary

This chapter presented experiments and results. It started by describing a tool and how it was used to produce plots of data from the working system and later to fine-tune the weights and functions that relate the inputs to the output of system such as the emotional system of fear.

Then, it described experiments that were carried out with real users and this were analised to investigate how the sense of beign present in a virtual environment is affected by the adding of artificial animals behaving in what they (users) perceive as interesting behaviour.

Lastly the chapter presented a mechanism to characterise complex group behaviour, and some plots were produced with this mechanism. We argued that emotion plays an important role in organising complex behaviour. But maintaining some proporties that are advantageous to the individual.

Chapter 7

Conclusions and future work

Espero que la salida sea feliz.

I hope that the exit is joyful.

– *Frida Kahlo*

7.1 Conclusions

We presented an ethologically imbued action-selection mechanism for self-animated artificial animals that communicate emotions amongst each other to influence their behaviour. The mechanism is hierarchical, which is consistent with what ethology researchers have postulated when observing the behaviour of real animals. Finite State Acceptors were added to simulate grazing behaviour. Further results have shown that grazing behaviour when coupled together with emotional group communication [Delgado-Mata *et al.*2003] adds to the sense of presence in virtual environments. The Action Selection Mechanism presented here is an essential component in the overall architecture shown in figure 5.16. A mechanism for measuring the characteristics of flocking was explored and the results are consistent with the hypothesis that emotion plays an important role in action selection, having been tested in a framework of different flocking algorithms. It was shown that complexity per se does not make a better flocking algorithm, but when complexity (flocking) is directed by emotion a more believable behaviour is obtained.

Emotion plays an important role in affecting the behaviour of the creatures. It is a integral part of the architecture and it is not an optional add-on. This is compatible with the notion that emotion is a vital component for decision making as argued in section 3.1.1.

The effect of emotion on the persistence of individual behaviours is already understood, but this work has shown that emotion is also a functional component on social interaction.

This work has shown that it is feasible to bring together the simple rule-based architectures of flocking with the more complex architectures of autonomous agents.

Results suggest that populating a virtual heritage site (or similar virtual environments) with virtual animals can improve the experience, particularly if the animals are engaged in some autonomous activities. The studies presented herein showed that while flocking behaviours are performed in isolation, an ambiguous effect on the observer's impression of the realism of the environment occurs. However, when they are combined with other behaviours which react more directly to the environment, the impact on the user can be more powerful. The studies reported herein imply an interesting relationship between types of behaviours and the strength of the experience.

7.2 Contributions

As discussed in chapter 1 a set of primary contributions and some secondary contributions to knowledge were achieved whilst carrying out the research. They are described next.

7.2.1 Primary contributions

The first of these is a novel emotional communication system via virtual pheromones in an artificial environment. It includes the uncommon development of an artificial nose and environmental simulation. This includes the simulation of particles in a free expansion gas to imitate the pheromones.

The second contribution is the mechanism to mediate between group behaviour (like flocking) and individual behaviours (like grazing) as these two behaviours are vital for grazing mammals. Improvements of the traditional flocking algorithm have been proposed and one example is offered by the Reynolds himself, as discussed in section 4.3.1. Contrasting to what is exposed herein, that model does not provide means of communication amongst individuals and does not provide an imbued emotion mechanism.

Similarly, mechanisms present in nature exist for mediating between an egoistical behaviour (beneficial for the individual) and altruistic (beneficial for the group). It has been found that sometimes it is advantageous to the individual to be altruistic as in the future the helper could receive help too.

7.2.2 Secondary contributions

Whilst carrying out the research described herein, secondary contributions to knowledge have been achieved. They are described next.

- A modular toolkit to develop emotional animals in a very configurable way using XML (eXtensible Markup Language. A text markup language for interchange of structured data) files to define each of the animal's brain parts, like Amygdala, Hypothalamus, Basal Ganglia and Sensorial Cortex.
- The use of the Observer-Subject Pattern [Gamma *et al.*1996] in the Sensorial Cortex data as it reduces the complexity of algorithms. This is discussed in section 5.4.5 .
- The results obtained with real users when they observed the environment, which can be seen in section 6.2.
- The results of an experiment which involved measurement to characterise group behaviour is presented and discussed in chapter 6.3.
- The development of the ethologically inspired flight-zone sensor, described in section 5.4.1. It differs from traditional collision detection between two spheres in that it contains a blind spot.
- An animation engine for animals, examples include four legged mammals, birds, humans and eight legged spiders. This animations are easily configured 5.2.1. Although toolkits exist for animating characters they were developed with humans in mind.
- The animation engine is part of the framework used to develop agents, This framework has been used in the MSc in Virtual Environments module: Agents and Avatars. This has been in place for four years running. It

uses the architecture described in sections 5.1, 5.2 and 5.3.

- The trials carried out to create an immersive environment using Maverik. This trials have shown that it is not ideal solution to develop an immersive VE. No other student has followed the same route since. The discussion on why Maverik was not suitable is found in section 5.2.

7.3 Critical Evaluation

In chapter 3, we argued that an emotional experience is not unique to humans. This contrasts what some authors claim: To feel emotion, one must cognitively assess the situation, and just then an emotion could be elicited. Also that the mind is the only requirement to elicit an emotion. But, as claimed by Damasio, we argued that the body is required component to 'feel' an emotion, and that for this to happen both body and mind are required. In the architecture presented in section 5.4, the body plays an important role in the emotional feeling as the emotion affects the behaviour of the animal. Further, the path-ways are in place to affect other systems like the attention mechanism.

Although socket communication, as explained in section 5.7, is useful to distribute work-load, especially to separate the agent architecture from the virtual environment simulation; a mechanism to automate the process is needed if more than a few animals (20) are simulated.

It would have been ideal to compare the behaviour with real animals. Although the tests presented in section 6.2 are valid, in the sense that they assess if the users find the animals' behaviour believable, it would have been desirable to work close together with ethologists like in Barbara Webb's research group, who herself is an ethologist. At present, one of the main hypothesis: can animal communicate an emotion through pheromones? David McFarland (through personal communication with the author), a retired ethologist, claimed that it is possible.

Signalling is an interesting field in animal behaviour as it affects social interaction. Chemical signalling is an emerging field, and as far was we are aware, a chemical signalling system in a virtual environment had not yet been implemented. We hope that this work changes this situation, and that chemical signalling can be seen as a viable way of communicating emotions (or other messages) within virtual environments. It was argued in chapter 4 that chemical signalling has several advantages over other means of communication. For example visual barriers are not an impediment to receive a message from a sender, even if the receiver is on the other side of the obstacle.

Although it is difficult to test and characterise animals behaviour, a neat test was devised using complexity with singular values, see section 6.3.1. Although, we think that another measure to find the relation between an increase in the sense of presence by the user against the architecture's complexity would be interesting. One such test could be measuring computation cycles against the improved sense of presence. In the results shown in section 6.2, some individuals perceived animals standing in poses as “being alive”. This could be because the users might perceive them as doing something whilst standing in a pose, for example grazing. Although these users were the exception, it raises the question of how much complexity is needed before we start obtaining diminishing returns.

7.4 Future Work

It would be interesting to further this work by modelling a different flocking animal, for example the musk ox, which responds to predators by forming a horns-out circle of adult animals with the young inside. We argue that our extended architecture can support a much wider and more realistic spread of flocking behaviour and therefore represents a contribution to believable virtual animals.

A further development of the architecture might incorporate evolution, using genetic programming. It would then be possible for this architecture to evolve different personalities which could be coded in genes which would define the connections between different parts of the brain. For example different animals could have contrasting personalities like fearful or aggressive depending on the weight and connections of the emotional system in turn affecting the action selection of the creature. Also it would be interesting to differentiate the behaviour of males and females, for example in [Ruckstuhl1998] the result of observing sheep behaviour shows that ewes spend more time grazing than males and rams spend significantly longer lying.

Besides separating emotional traits between sexes, it would be interesting, as suggested in [Panksepp1994a], to separate traits amongst different species. Because different species exhibit different emotional strengths and weaknesses. For example, different emotions are found in predators from those found in herbivores. The former are more likely to benefit from aggressive behaviour, whereas the latter would benefit from fear. This is, as discussed in chapter 3, useful to survive predators' attacks.

Another direction to further this work is with real robots. For example an interesting work would be to incorporate the Sony Dog AIBO with an electronic nose. At present a viable sensor would be very limited, besides the pheromones would need to be compatible with the smell sensor. This could make the design cumbersome.

Another work would be to test the full architecture, described in section 5.4 using different decision-making mechanism. For example winner-takes-all against voting based decision [Avila-Garcia *et al.*2002]. Or winner-takes-all against a synthesis mechanism, for example the **BSA**.

Another improvement is to add a higher level to test the emotional architecture with higher tasks as in emergent narrative. As exposed in section 3.1.3, the emotion model chosen in this work is 4 types of emotion elicitors, and one of them is cognitive elicitor. It would also bee interesting to test the user response when combining creatures with different levels of emotion. This is, to test a work such as the one proposed here [Ibanez *et al.*2004].

Similarly, the addition of learning would further the architecture to simulate more complex behaviours that improve with experience. Particularly, it would be interesting to link emotion signalling with emotional experiences. For example if a particular distressing experience happened in a particular place. The next time that the creature visits that place an emotion (for example fear) would be elicited, even in the absence of the triggering emotion (like a set of particularly nasty predators). This would be evolutionary advantageous as the creature would avoid a particular place (with the predators maybe hiding) which could be particularly dangerous. Architectures including emotional memories have been investigated in individual agents [Velásquez1998].

As said before, a mechanism to distribute the work-load was needed when simulating more than a few animals. Research is under way to develop such mechanism to distribute the work-load amongst a number of CPUs [Pérez *et al.*2004].

7.5 Concluding marks

The thesis shows a novel design to model emotion signalling in virtual animals, to make them more believable. Herein we discussed a mechanism of communication that has not been explored in virtual environments. Communication through chemical signals and artificial noses. The author hopes that this work provides a step towards exploring this fascinating area.

Appendices

Appendix A

Metaconfiguration

This file is a meta configuration file. Where the files used for configuration is defined. It is of particular relevance, whence the particular files for each creature are defined this is important. Each animal can have different capabilities, and as said before, in future work each creature can evolve to have a particular personality trait for example fearful or bold. This depends on how the sensors affect the different emotions like fear and anger.

```
<contents>
# Created by Carlos Delgado 2003
<general_conf name = "Deer_01"
              send_file =  "./data/SendController_01.xml"
              receive_file = "./data/ReceiveController_01.xml"/>
<brain_conf cortex_file = "nembevaData/Cortex.xml"
            hypothalamus_file = "nembevaData/Hypothalamus.xml"
            amygdala_file ="nembevaData/Amygdala.xml"
            basalganglia_file = "nembevaData/BasalGanglia.xml" />
```

```
</contents>
```

Appendix B

Amygdala (Emotional Systems) Definition XML File


```
<contents>
<node>
<system name="A_FearSystem" plot= "No"/>
<input weight="0.4" from="C_Nose_FearPheromone"/>
<input weight="0.6" from="C_Flight_Zone"/>
<input weight="0.3" from="C_Afferent_Running"/>
<input weight="-0.4" from="C_Vision_Conspecific"/>
<function name="sigmoid" threshold="0.4"/>
</node>
<node>
<system name="A_JoySystem" plot= "No" />
<input weight="0.2" from ="C_Nose_JoyPheromone"/>
<input weight="0.5" from="C_Vision_Conspecific"/>
<input weight="0.4" from="C_Afferent_Running"/>
```

```
<input weight="-0.4" from="H_Hunger"/>

<input weight="-0.4" from="H_Thirst"/>

<function name="sigmoid" threshold="0.6"/>

</node>

<node>

<system name="A_AngerSystem"  plot= "Yes" />

<input weight="0.2" from ="C_Nose_AngerPheromone"/>

<input weight="0.4" from="H_Hunger"/>

<input weight="0.4" from="H_Thirst"/>

<function name="sigmoid" threshold="0.999"/>

</node>

</contents>
```

Appendix C

Sensorial Cortex (Sensor Data) Definition XML File


```
<contents>
# is this a comment ?
<sensor name = "C_Flight_Zone" stimuli = "0.0"  weight="0.7" plot = "Y"/>
<sensor name = "C_Nose_FearPheromone" stimuli = "0.0"  weight="0.6" plot = "Y"/>
<sensor name = "C_Nose_JoyPheromone" stimuli = "0.0"  weight="0.8" plot = "Y"/>
<sensor name = "C_Nose_AngerPheromone" stimuli = "0.0"  weight="0.8" plot = "Y"/>
<sensor name = "C_Nose_Water" stimuli = "0.01"  weight="0.3" plot = "N"/>
<sensor name = "C_Chew" stimuli = "0.01"  weight="0.3" plot = "Y"/>
<sensor name = "C_Swallow" stimuli = "0.01"  weight="0.3" plot = "Y" />
<sensor name = "C_Afferent_Running" stimuli = "0.01"  weight="0.3" plot = "N" />
<sensor name = "C_Vision_Conspecific" stimuli = "0.01"  weight="0.3" plot = "N" />
<sensor name = "C_PredatorPos" stimuli = "0.01"  weight="0.3" plot = "N"/>
<sensor name = "C_FoodMouth" stimuli = "0.01"  weight="0.3" plot = "N"/>
<sensor name = "C_WaterMouth" stimuli = "0.01"  weight="0.3" plot = "N" />
```

```
</contents>
```

Appendix D

Hypothalamus (Drives) Definition XML File

```
<contents>

# is this a comment ?

<node>

<drive name = "H_Hunger" stimuli = "0.0"  weight="0.8"  growth="0.1" plot ="Y"/>

<input weight="-0.3" from="C_Chew"/>

<function name="tansig"/>

</node>

<node>

<drive name = "H_Thirst" stimuli = "0.2"  weight="0.3"  growth= "0.07" plot="Y"/>

<input weight="0.4" from="C_Swallow"/>

<function name="tansig"/>

</node>

<node>

<drive name = "H_Curiosity" stimuli = "0.1"  weight="0.2" growth= "0.05" plot="N"/>
```

```
<input weight="0.2" from="C_Flight_Zone"/>

<function name="tansig"/>

</node>

<node>

<drive name = "H_Sexual" stimuli = "0.9"  weight="0.3"   growth= "0.05" plot="N"/>

<input weight="0.2" from="C_Flight_Zone"/>

<function name="tansig"/>

</node>

</contents>
```

Appendix E

Basal Ganglia (Action Selection) Definition XML File


```
<contents>
<node>
<node_name name="B_TLN_Graze"/>
<input weight="0.2" from="H_Hunger"/>
<input weight="0.5" from="H_Curiosity"/>
<input weight="0.7" from="C_Flight_Zone"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_TLN_Drink"/>
<input weight="0.2" from="H_Thirst"/>
<input weight="0.5" from="H_Curiosity"/>
<input weight="-0.5" from="C_Flight_Zone"/>
<input weight="-0.5" from="C_Flight_Zone"/>
```

```
<function name="tansig"/>
</node>
<node>
<node_name name="B_ILN_Move"/>
<input weight="0.2" from="B_TLN_Graze"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_ILN_Eat"/>
<input weight="0.2" from="B_TLN_Graze"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_ILN_Stare"/>
<input weight="0.2" from="B_TLN_Graze"/>
<input weight="0.4" from="A_FearSystem"/>
<input weight="0.5" from="C_PredatorPos"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_BLN_Chew" plot = "Y"/>
<input weight="0.2" from="B_ILN_Eat"/>
<input weight="0.4" from="A_FearSystem"/>
<input weight="0.5" from="C_PredatorPos"/>
<input weight="0.7" from="C_FoodMouth"/>
<function name="tansig"/>
```

```
</node>
<node>
<node_name name="B_BLN_Eat" plot = "Y" />
<input weight="0.2" from="B_ILN_Eat"/>
<input weight="-0.4" from="A_FearSystem"/>
<input weight="-0.2" from="C_FoodMouth"/>
<function name="tansig"/>
</node>

<node>
<node_name name="B_ILN_Move" plot = "Y" />
<input weight="0.5" from="H_Curiosity"/>
<input weight="-0.5" from="C_Flight_Zone"/>
<input weight="0.2" from="B_TLN_Drink"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_ILN_Drink"/>
<input weight="0.5" from="H_Curiosity"/>
<input weight="-0.5" from="C_Flight_Zone"/>
<input weight="0.5" from="C_Nose_Water"/>
<input weight="0.5" from="B_TLN_Drink"/>
<function name="tansig"/>
</node>
<node>
<node_name name="B_BLN_Swallow" plot = "N"/>
```

```
<input weight="0.5" from="C_WaterMouth"/>

<input weight="-0.5" from="B_ILN_Drink"/>

<function name="tansig"/>

</node>

<node>

<node_name name="B_BLN_Drink" plot = "N"/>

<input weight="-0.3" from="C_WaterMouth"/>

<input weight="-0.5" from="B_ILN_Drink"/>

<function name="tansig"/>

</node>

</contents>
```

Appendix F

Nose Definition XML File

```
<contents>

<structure  num_types="5" num_origins="4" />

<row_name   n0="C_Nose_FearPheromone" n1="C_Nose_AngerPheromone" n2="C_Nose_JoyPher

<mat_row    w0="0.9" w1="0.5"  w2="0.7"  w3="0.0"  w4 = "0.0" />

<mat_row    w0="0.4" w1="0.7"  w2="0.1"  w3="0.0"  w4 = "0.0" />

<mat_row    w0="0.0" w1="0.0"  w2="0.0"  w3="0.9"  w4 = "0.0" />

<mat_row    w0="0.9" w1="0.5"  w2="0.7"  w3="0.0"  w4 = "0.9" />

</contents>
```

Appendix G

Networking Definition XML File

G.1 Send XML File

```
<contents>

# is this a comment ?

<item name= "VE" LocalPort = "9051"  ServerPort = "8000" ServerIP = "146.87.133.50"

<plotter name= "Plott" LocalPort = "9151" ServerPort= "9901" ServerIP = "146.87.133

</contents>
```

G.2 Receive XML File

```
<contents>

# is this a comment ?

<conf LocalPort = "7001" />

<subject name = "C_Flight_Zone" />

<subject name = "C_Nose_FearPheromone" />
```

```
<subject name = "C_Nose_JoyPheromone" />
#<subject name = "C_Nose_Water" />
#<subject name = "C_Nose_Food" />
<subject name = "C_Chew" />
<subject name = "C_Swallow" />
<subject name = "C_Nose_AngerPheromone" />
<subject name = "C_Afferent_Running" />
<subject name = "C_Vision_Conspecific" />
<subject name = "C_PredatorPos" />
<subject name = "C_FoodMouth" />
<subject name = "C_WaterMouth" />
</contents>
```

Appendix H

UML Patterns

Design is heavily using concepts from Object Oriented Analysis and Design and Design Patterns [Gamma *et al.*1996]. It has been useful because as described in chapter 5, the use of the pattern Observer-Subject changed reduced the computational cicles to arrive to an action beign selected.

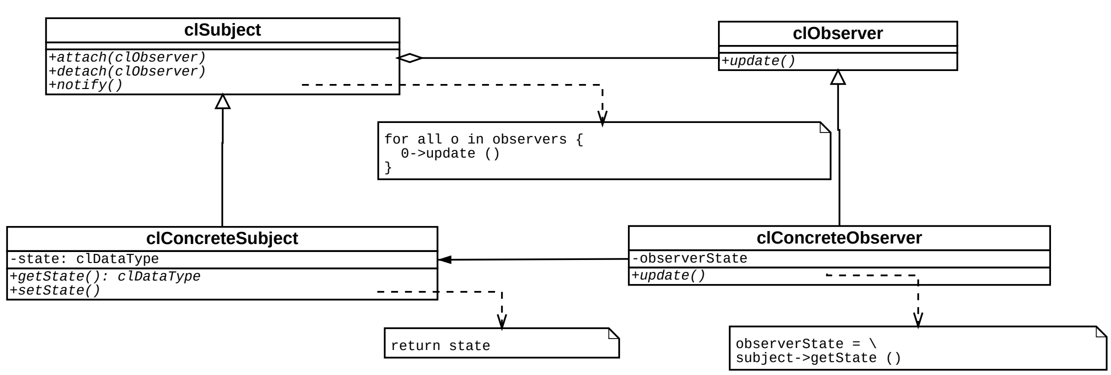


Figure H.1: Observer/Subject Pattern in UML

Appendix I

Questions for experiments

I.1 Questions for Experiment 1

(All questions were rated on a 7 point Likert scale)

1. How realistic was the graphical representation of the animals in the environment?

2. How much did the environment engage you generally?

3. How much did the animals add to the realism of the environment?

4. Did the animals seem alive in the environment?

5. Did the animals appear to be behaving in an intelligent manner?

6. How compelling was your sense of moving around inside the virtual environment?

7. How realistic was the behaviour of the animals?

8. How quickly did you adjust to the virtual environment experience?

9. To what extent did the animals seem to be reacting to their environment?

10. To what extent did the animals appear to be reacting with one another?

I.2 Questions for Experiment 2.

(All questions were rated on a 10 point Likert scale)

1. Please rate how real the behaviour of the deer seemed.

2. Please rate how natural the behaviour of the deer seemed.

3. Please rate to what degree you felt the deer appeared to perceive the environment.

4. Please rate to what degree you felt the deer appeared to perceive one another.

5. Please rate to what degree the deer appeared to react to the environment.

6. To what degree did the deer appear to make an emotional reaction?

7. To what degree did the movement of the deer appear to enrich the environment?

Bibliography

[Allen and Ferguson1994] James F Allen and George Ferguson. Actions and events in interval temporal logic. *Journal of Logic and Computation*, 4(5):531–579, 1994.

[Arkin1989] Ronald C Arkin. Motor schema-based mobile robot navigation. *Journal of Robotics Research*, 8(4):92–112, 1989.

[Arkin1999] Ronald C Arkin. *Behavior-Based Robotics*. MIT Press, Cambridge, Massachusetts, 1999.

[Arnold1960] Magda B Arnold. *Emotion and Personality*. Columbia University Press, New York, 1960.

[Avila-Garcia *et al.*2002] Orlando Avila-Garcia, Lola Canamero, and Rene de Boekhorst. Analyzing the performance of "winner-take-all" and "voting-based" action selection policies within the two-resource problem. In Francisco J. Garijo, José Cristóbal Riquelme Santos, and Miguel Toro, editors, *IBERAMIA*, volume 2527 of *Lecture Notes in Computer Science*. Springer, 2002.

[Aylett *et al.*1999] Ruth S Aylett, Anthony Horrobin, John J O'Hare, A Osman, and Michael Polyak. Virtual teletubbies: reapplying a robot architecture to virtual agents. In *3rd International Conference on Autonomous*

Agents, Seattle Washington, 1999.

[Baerends1976] Gerald P Baerends. The functional organization of behaviour. *Animal Behaviour*, 24:726–738, 1976.

[Barnes *et al.*1997] Dave P Barnes, R A Ghanea-Hercock, R S Aylett, and Alex M Coddington. Many hands make light work? an investigation into behaviourally controlled cooperant autonomous mobile robots. In L Johnson, editor, *Proceedings of the first International Conference on Autonomous Agents*, pages 413–20, Marina del-Rey, Calif., 1997. ACM Press.

[Barnes1996] Dave P Barnes. A behaviour synthesis architecture for cooperant mobile robot. In John O Gray and D G Caldwell, editors, *Advanced Robotics and Intelligent Machines*, pages 295 – 314. IEE Control Engineering Series 51, United Kingdom, 1996.

[Batagelj and Mrvar1998] Vladimir Batagelj and Adrej Mrvar. Pajek –program for large network analysis. *Connections*, 21(2):47–57, 1998.

[Blumberg1994] Bruce Blumberg. Action-selection in hamsterdam: Lessons from ethology. In *Proceedings of the Third International Conference on Simulation of Adaptive Behavior*, Brighton, England, 1994.

[Blumberg1996] Bruce Blumberg. *Old Tricks, New Dogs: Ethology and Interactive Creatures*. PhD thesis, Massachusetts Institute of Technology, MIT, Cambridge, MA, 1996.

[Bonabeau *et al.*1999] Eric Bonabeau, Marco Dorigo, and Guy Theraulaz. *Swarm Intelligence: From Natural to Artificial Systems*. Oxford University Press Inc, USA, 1999.

[Booch *et al.*1999] Grady Booch, James Rumbaugh, and Ivar Jacobson. *The*

Unified Modeling Language: User Guide. Addison Wesley, Indianapolis, Indiana, 1999.

[Braitenberg1984] Valentino Braitenberg. *Vehicles: Experiments in Synthetic Psychology.* Papermac, Oxford, United Kingdom, 1984.

[Brooks1986] Rodney A Brooks. A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation*, 2(1):14–23, 1986.

[Bryson2000] Joanna Bryson. Hierarchy and sequence vs. full parallelism in action selection. In Jean-Arcady Meyer, Alain Berthoz, Dario Floreano, Herbert L Roiblat, and Stewart W Wilson, editors, *From Animals to Animals 6: Proceedings of the 6th International Conference on the Simulation of Adaptive Behaviour*, Cambridge, Mass., 2000. MIT Press.

[Bryson2002] Joanna Bryson. Modularity and spatialized learning: Behavior based re-examining artificial intelligence. In *Proceedings of the Workshop on Adaptive Behavior in Anticipatory Learning Systems (ABiALS'02)*, Edinburgh, Scotland, 2002.

[Canamero and Freslund2000] Dolores Canamero and J Freslund. How does it feel? emotional interaction with a humanoid lego robot. In K Dautenhahn, editor, *Socially Intelligent Agents: The Human in the Loop. Papers from the AAAI 2000 Fall Symposium*, Menlo Park, Calif., 2000. AAAI Press.

[Canamero1997] Dolores Canamero. Modeling motivations and emotions as a basis for intelligent behaviour. In L Johnson, editor, *Proceedings of the first International Conference on Autonomous Agents*, Marina del-Rey, Calif., 1997. ACM Press.

[Cannon1929] Walter B Cannon. *Bodily Changes in pain, hunger, fear and rage.* Appleton and Co., New York and London, 1929.

[Chao *et al.*2000] Gerald Chao, Anand Panangadan, and Michael G Dyer. Learning to integrate reactive and planning behaviors for construction. In Jean-Arcady Meyer, Alain Berthoz, Dario Floreano, Herbert L Roiblat, and Stewart W Wilson, editors, *From Animals to Animals 6: Proceedings of the 6th International Conference on the Simulation of Adaptive Behaviour*, pages 167 – 176, Cambridge, Mass., 2000. MIT Press.

[Connell1990] J H Connell. A colony architecture applied to robot navigation. Technical Report 1151, MIT Media Laboratory, Cambridge MA, 1990.

[Damasio1996] Antonio Damasio. *Descartes' Error:Emotion, Reason and the Human Brain*. Papermac, Oxford, United Kingdom, 1996.

[Darrell *et al.*1994] T Darrell, Pattie Maes, Bruce Blumberg, and A P Pentland. A novel environment for situated vision and behaviour. Technical report, MIT Media Laboratory, Cambridge MA, 1994.

[Darwin1872] Charles Darwin. *The expression of the emotions in man and animals*. John Muray, Great Britain, 1872.

[Dawkins1976] Richard Dawkins. Hierarchical organisation: A candidate principle for ethology. In Bateson & Hinde, editor, *Growing Points in Ethology*. Cambridge University Press, 1976.

[Delgado-Mata and Aylett2000] Carlos Delgado-Mata and Ruth Aylett. From robots to creatures: Extending a robot behaviour based architecture to create virtual creatures. In Rene Mayorga, editor, *Proceedings of ISRA 2000*, Monterrey, Mexico, 2000. IT Monterrey.

[Delgado-Mata and Aylett2004] Carlos Delgado-Mata and Ruth S Aylett. Emotion and action selection: Regulating the collective behaviour of agents in virtual environments. In Nick Jennings, Milind Tambe, Carles Sierra, and

Liz Sonenberg, editors, *International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2004)*, New York, 2004. To appear.

[Delgado-Mata *et al.*2002] Carlos Delgado-Mata, Rocio Ruiz-Rodarte, Ruth S Aylett, M A Perez-Cisneros, and P A Cook. Illusion of life in palenque: Communicating emotions inside a virtual environment for maya cultural heritage. In Helmut Prendinger, editor, *PRICAI: Seventh Pacific Rim International Conference on Artificial Intelligence*, Tokyo, Japan, 2002. PRICAI.

[Delgado-Mata *et al.*2003] Carlos Delgado-Mata, Jesus Ibanez, and Ruth Aylett. Let's run for it: Conspecific emotional flocking triggered via virtual pheromones. In Andreas Butz, Antonio Krüger, and Patrick Oliver, editors, *LNCS Smart Graphics 2003*, pages 131–140, Heidelberg, Germany, 2003. Springer-Verlag.

[Delgado-Mata2004] Carlos Delgado-Mata. Characterising emotion signalling and affected group behaviour in virtual mammals. In Leonid Sheremetov, editor, *Intelligent Virtual Environments and Virtual Agents, in Workshop on Intelligent Computing 2004*, pages 299–307, ITESM CCM, Mexico, 2004.

[Downie2001] Marc Downie. behaviour, animation, music: the music and movement of synthetic characters. Master's thesis, Massachusetts Institute of Technology, MIT, Cambridge, MA, 2001.

[Ehrlichman and Bastone1977] H Ehrlichman and L Bastone. *Olfaction and Emotion*, pages 300–332. Springer Verlag, New York, 1977.

[Ekman1992] Paul Ekman. An argument for basic emotions. In N L Stein and K Oatley, editors, *Basic Emotions*, United Kingdom, 1992.

[Ekman1993] Paul Ekman. Facial expression and motion. *American Psychologist*, 48, 1993.

[El-Nasr *et al.*2000] Magy Seif El-Nasr, John Yen, and Thomas R Iorger. Flame-fuzzy logic adaptive model of emotions. *Autonomous Agents and Multi-Agent Systems*, pages 219–257, September 2000.

[Elliot1992] Clark Davidson Elliot. *The Affective Reasoner: A process model of emotions in a multi-agent system.* PhD thesis, Northwestern University, Evanston, Illinois, 1992.

[Esch *et al.*2001] H E Esch, S Zhang, M V Srinivasan, and J Tautz. Honeybee dances communicate distances measured by optic flow. *Nature*, (411):581–583, 2001.

[Flake1999] G. W. Flake. *The Computational Beauty of Nature : Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation.* MIT Press, 1999.

[Frijda and Moffat1994] N Frijda and David Moffat. Modelling emotion. *Cognitive Studies*, pages 71–86, 1994.

[Frijda1986] Nico H Frijda. *The Emotions.* Cambridge University Press, United Kingdom, 1986.

[Gamma *et al.*1996] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. *Design Patterns.* Addison Wesley Longman, Reading Massachusetts, 1996.

[Gardner and Bartlett1999] Julian W Gardner and Philip N Bartlett. *Electronic Noses: Principles and Practice.* Oxford University Press, Oxford, United Kingdom, 1999.

[Goleman1996] Daniel Goleman. *Emotional Intelligence.* Bloomsbury, United Kingdom, 1996.

[Grammer1993] Karl Grammer. 5-alpha-androst-16en-3alpha-one: a male pheromone ? *Ethology and Sociobiology*, 14(3):201–207, 1993.

[Grand1997] Steve Grand. Creatures: An exercise in creation. *IEEE Intelligent Systems Magazine*, July 1997.

[Hayes-Roth1985] Barbara Hayes-Roth. A blackboard architecture for control. *Artificial Intelligence*, 26(3):251–321, 1985.

[Hoorn *et al.*2003] Johan F Hoorn, Elly A Konjin, and Gerrit C Van der Veer. Virtual reality: Do not augment realism, augment relevance. *Upgrade - Human-Computer Interaction: Overcoming Barriers*, 4(1):18–26, February 2003.

[Hull1943] C Hull. *Principles of Behavior: and Introduction to Behavior Theory*. D. Appleton-Century-Crofts, New York, 1943.

[Humphrys1997] Mark Humphrys. *Action Selection methods using Reinforcement Learning*. PhD thesis, Trinity Hall, University of Cambridge, Cambridge, United Kingdom, 1997.

[Ibanez *et al.*2004] Jesus Ibanez, Carlos Delgado-Mata, Ruth S Aylett, and Rocio Ruiz. Don't you escape! i'll tell you my story. In Raúl Monroy, Gustavo Arroyo-Figueroa, Luis Enrique Sucar, and Humberto Sossa, editors, *MICAI 2004*, number 2972 in LNAI, pages 49–58. Springer-Verlag, 2004.

[Izard1993] Carol E Izard. Four systems for emotion activation: Cognitive and noncognitive processes. *Psychological Review*, 100(1):68–90, 1993.

[Jacobson *et al.*1999] Ivar Jacobson, Grady Booch, and James Rumbaugh. *The Unified Software Development Process*. Addison Wesley, Indianapolis, Indiana, 1999.

[James1884] William James. What is an emotion ? *Mind*, 9:188–205, 1884.

[Kelly *et al.*1994] John Kelly, Philip Whitfield, and Obin. *The Robot Zoo.* Turner Publishing, Inc, Atlanta, USA, 1994.

[Kimball1983] John W Kimball. *Biology.* Addison-Wesley, London, 5th edition edition, 1983.

[Kitchell *et al.*1995] Anne Kitchell, Sharon Lynn, and Shiva Vafai. 10 smell myths: Uncovering the stinkin' truth. Technical report, Department of Biological Sciences, University of South Carolina, 1995.

[Koenig and Likhachev2002] Sven Koenig and Maxim Likhachev. Improved fast replanning for robot navigation in unknown terrain. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, Washington, DC, 2002.

[Kravitz1988] Edward A Kravitz. Hormonal control of behaviour:amones and the biasing of behavioural output in lobsters. *Science*, 241:1775–1781, September 1988.

[Langton1995] C. Langton. *Artificial Life: An Overview.* MIT Press, Cambridge, MA, 1995.

[Lazarus1991] Richard E Lazarus. Cognition and motivation in emotion. *American Psychologist*, 46(4):352–367, 1991.

[LeDoux1995] Joseph LeDoux. Emotion: Clues from the brain. *Annual Review of Psychology*, 46:209–235, 1995.

[LeDoux1998] Joseph LeDoux. *The Emotional Brain.* Simon & Schuster, United Kingdom, 1998.

[LeDoux2000] Joseph LeDoux. Emotion circuits of the brain. *Annual Review of Neuroscience*, 23:155–184, 2000.

[Lorenz1981] Konrad Lorenz. *The Foundations of Ethology.* Springer-Verlag, Heidelberg, 1981.

[Marshall *et al.*1981] D A Marshall, L Blumer, and D G Moulton. Odor detection curves for n-pentanoic acid in dogs and humans. *Chemical Senses*, 6:445–453, 1981.

[Martínez-Barberá2001] Humberto Martínez-Barberá. *A Distributed Architecture for Intelligent Control in Autonomous Mobile Robots:An Applied Approach to the Development of the Quaky-Ant Platform.* PhD thesis, Universidad de Murcia, Murcia, Spain, 2001.

[Masson and McCarthy1996] Jeffrey Masson and Susan McCarthy. *When Elephants Weep: The Emotional Lives of Animals.* Vintage, United Kingdom, 1996.

[Mataric1990] Maja Mataric. A distributed model for mobile robot environment learning and navigation. Technical Report AIM-TR-1228, MIT Media Laboratory, Cambridge MA, 1990.

[Mataric1996] Maja J Mataric. Designing and understanding adaptive group behavior. *Adaptive Behavior*, 4(1):51–80, 1996.

[McFarland1999] David McFarland. *Animal Behaviour.* Addison Wesley Longman, England, 1999.

[Mery1970] Fernand Mery. *The Life, History and Magic of the Dog.* Grosset & Dunlap, New York, USA, 1970.

[Minsky1985] Marvin Minsky. *The Society of Mind.* Simon & Schuster, New York, USA, 1985.

[Moffat *et al.*1993] David Moffat, Nico Frijda, and Hans Phaf. Analysis of a computer model of emotions. In Aaron Sloman, D Hogg, G Humpheys, and

A Ramsay, editors, *Prospects for artificial intelligence*, pages 219–228. IOS Press, Amsterdam, 1993.

[Montes-Gonzalez *et al.*2000] Fernando Montes-Gonzalez, Tony J Prescott, Kevin Gurney, Mark Humphries, and Peter Redgrave. An embodied model of action selection mechanisms in the vertebrate brain. In Jean-Arcady Meyer, Alain Berthoz, Dario Floreano, Herbert L Roiblat, and Stewart W Wilson, editors, *From Animals to Animals 6: Proceedings of the 6th International Conference on the Simulation of Adaptive Behaviour*, Cambridge, Mass., 2000. MIT Press.

[Montes-Gonzalez2001] Fernando M Montes-Gonzalez. *An action Selection Mechanism based on Vertebrate Basal Ganglia*. PhD thesis, Psychology Department, University of Sheffield, Sheffield, United Kingdom, 2001.

[Muybridge1957] Eadweard Muybridge. *Animals in Motion*. Dover Publication, Canada, 1957.

[Neary2001] Mike Neary. Sheep sense. *The Working Border Collie*, 2001.

[Nilsson1998] Nils Nilsson. *Artificial Intelligence: A New Synthesis*. Morgan Kauffman, 1998.

[Oatley1992] K Oatley. *Best Laid Schemes*. Cambridge University Press, United Kingdom, 1992.

[Ortony *et al.*1988] Andrew Ortony, Gerald L Clore, and Allan Collins. *The Cognitive Structure of Emotions*. Cambridge University Press, USA, 1988.

[Panksepp1994a] Jaak Panksepp. *Basic Emotions Ramify Widely in the Brain, Yielding Many Concepts That Cannot Be Distiguished Unambiguously...Yet*, pages 86–88. Oxford University Press, New York, 1994.

[Panksepp1994b] Jaak Panksepp. *The Basics of Basic Emotion*, pages 20–24. Oxford University Press, New York, 1994.

[Parent2002] Rick Parent. *Computer Animation: Algorithms and Techniques*. Morgan Kaufmann, San Fransisco, CA, 2002.

[Payton *et al.*2001] David Payton, Mike Daily, Regina Estkowski, Mike Howard, and Craig Lee. Pheromone robotics. *Autonomous Robots*, 11(3):319–324, November 2001.

[Pérez *et al.*2004] Jose Pérez, Carlos Delgado-Mata, and Ruth S Aylett. Giving embodied agents a grid-boost. In Leonid Sheremetov, editor, *Intelligent Virtual Environments and Virtual Agents, in Workshop on Intelligent Computing 2004*, pages 333–340, ITESM CCM, Mexico, 2004.

[Perlin1996] Ken Perlin. Improv: A system for scripting interactive actors in virtual worlds. In *Siggraph 1996 Conference Proceedings*. Addison Wesley, 1996.

[Petta1999] Paolo Petta. Principled generation of expressive behaviour in an interactive exhibit. In *Third International Conference on Autonomous Agents (Agents '99)*, Seattle, WA, USA, 1999. ACM.

[Pfeifer and Scheier2001] Rolf Pfeifer and Christian Scheier. *Understanding Intelligence*. MIT Press, Cambridge, Massachusetts, 2001.

[Picard1997] Rosalind Picard. *Affective Computing*. MIT Press, Cambridge, MA, USA, 1997.

[Preparata and Shamos1985] Franco P Preparata and Michael Ian Shamos. *Computational Geometry: An Introduction*. Springer-Verlag, New York, 1985.

[Ranganathan and Koenig2003] Ananth Ranganathan and Sven Koenig. A reactive robot architecture with planning on demand. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, Las Vegas, Nevada, 2003.

[Reeves1983] W. Reeves. Particle systems - a technique for modeling a class of fuzzy objects. *ACM Transactions on Graphics*, 2(2):91–108, 1983.

[Reinhardt and Reinhardt2002] Viktor Reinhardt and Annie Reinhardt. Comfortable quarters for laboratory animals. In Viktor Reinhardt and Annie Reinhardt, editors, *Comfortable Quarters for Laboratory Animals*. Animal Welfare Institute, Washington, DC, 2002.

[Reynolds1987] Craig W Reynolds. Flocks, herds, and schools: A distributed behavioral model. *Computer Graphics*, 21(4):25–34, 1987.

[Reynolds2000] Craig W Reynolds. Interaction with groups of autonomous characters. In *Game Developers Conference 2000*. CMP Game Media Group, 2000.

[Rose *et al.*1998] Charles Rose, Michael Cohen, and Bobby Bodenheimer. Verbs and adverbs: Multidimensional motion interpolation. *IEEE Computer Graphics and Applications*, 18(5):32–40, 1998.

[Roseman *et al.*1990] Ira J Roseman, Martin S Spindel, and Paul E Jose. Appraisals of emotion-eliciting events: Testing a theory of discrete emotions. *Journal of Personality and Social Psychology*, 59(5):899–915, 1990.

[Rosenblatt and Payton1989] J.K. Rosenblatt and D.W. Payton. A fine-grained alternative to the subsumption architecture for mobile robot control. In *Proceedings of the IEEE/INNS International Joint Conference on Neural Networks*, volume 2, pages 317–324, Washington DC, June 1989.

[Ruckstuhl1998] Kathreen E Ruckstuhl. Foraging behaviour and sexual segregation in bighorn sheep. *Animal Behaviour*, 56(1):99–106, 1998.

[Russell and Norvig2003] Stuart Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach*. Prentice Hall, second edition, 2003. ISBN 0-13-080302-2.

[Scherer1994] Klaus R Scherer. *Toward a concept of "modal Emotions"*, pages 86–88. Oxford University Press, New York, 1994.

[Sloman and Croucher1981] Aaron Sloman and M Croucher. Why robots will have emotions. In *Proceedings of the 7th International Joint Conference on Artificial Intelligence (IJCAI'81)*, University of British Columbia, Vancouver, Canada, 1981.

[Sloman1993] Aaron Sloman. *Prospects for Artificial Intelligence*, chapter Prospects for AI as the general science of Intelligence, pages 1–10. IOS, Amsterdam, 1993.

[Sloman2001] Aaron Sloman. Beyond shallow models of emotions. *Cognitive Processing*, 2(1):177–198, 2001.

[Smith and Kirby2001] Craig A Smith and Leslie D Kirby. On elicitation, differentiation, and organization of emotion: Structural and procedural considerations. In *Emotional and Intelligent II: The Tangled Knot of Social Cognition, 2001 AAAI Fall Symposium*, North Falmouth, Massachusetts, November 2001.

[Swagerman1987] J Swagerman. *The Artificial Concern REalization System ACRES: A computer model of emotion. University of Amsterdam.* PhD thesis, University of Amsterdam, Amsterdam, Netherlands, 1987.

[Tinbergen1965] Nikolaas Tinbergen. *Social behaviour in animals*. Methuen & co ltd., United Kingdom, second edition, 1965.

[Tinbergen1969] Nikolaas Tinbergen. *The study of instinct*. Oxford University Press, United Kingdom, 1969.

[Tomkins1962] Tomkins. *Affect, imagenery, consciousness: Vol 1. Porsitive affects*. Springer, New York, 1962.

[Tu and Terzopoulos1994] Xiaoyuan Tu and Demetri Terzopoulos. Artificial fishes: Physics, locomotion, perception, behavior. In *In Proceedings of SIGGRAPH'94*, pages 43–50. ACM Computer Graphics, 1994.

[Tu1999] Xioyuan Tu. *Artificial Animals for Computer Animation: Biomechanics, Locomotion, Perception and Behavior*. Number 1635 in LNCS. Springer Verlag, Heidelberg, Germany, 1999.

[Tyrrell1993] Toby Tyrrell. *Computational Mechanisms for Action Selection*. PhD thesis, University of Edinburgh, Edinburgh, Scotland, 1993.

[Vaughan *et al.*2000] Richard T Vaughan, Neil Sumpter, Jane Henderson, Andy Frost, and Stephen Cameron. Experiments in automatic flock control. *Robotics and Autonomous Systems*, 31:109–117, 2000.

[Velásquez1997] Juan Velásquez. Modeling emotions and other motivations in synthetic agents. In *Proceedings of the Fourteenth National Conference on Artificial Intelligence (AAAI-97)*, Providence, RI, 1997. MIT/AAAI Press.

[Velásquez1998] Juan Velásquez. When robots weep: Emotional memories and decision-making. In *Proceedings of the Fifteenth National Conference on Artificial Intelligence (AAAI-98)*, Madison, WI, 1998. MIT/AAAI Press.

[von Frisch1967] Karl von Frisch. *The dance language and orientation of bees*. Belknap Press : Oxford University Press, Cambridge, Mass., 1967.

[Walter1950] William Grey Walter. An imitation of life. *Scientific American*, 185(5):42–54, 1950.

[Webb *et al.*2003] Barbara Webb, Richard Reeve, Andrew Horchler, and Roger Quinn. Testing a model of cricket phonotaxis on an outdoor robot platform. In Ulrich Nehmzow and Chris Melhuish, editors, *Towards Intelligent Mobile Robotics 2003: TIMR'03*. University of West England, 2003.

[Webb1994] Barbara Webb. Robotic experiments in cricket phonotaxis. In *Proceedings of the Third International Conference on Simulation of Adaptive Behavior*, Brighton, England, 1994.

[Webb2002] Barbara Webb. Robots in invertebrate neuroscience. *Nature*, (417):359–363, 2002.

[Wright *et al.*2001] W A Wright, R E Smith, M Danek, and P Greenway. A generalisable measure of self-organisation and emergence. In G. Dorffner, H. Bischof, and K. Hornik, editors, *Artificial Neural Networks - ICANN 2001*, number 2130 in LNCS, pages 857–864. Springer-Verlag, 2001.

[Wyatt2003] Tristam D Wyatt. *Pheromones and Animal Behaviour*. Cambridge University Press, Cambrigde, U.K., 2003.