Meerkat Manor: An Exploration of Animat-Based Evolution and Communication

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Abstract

In this paper we explore animat-based communication. Our animats represent meerkats, and we create several different environments that utilize signaling to varying degrees. Specifically, we explore the evolution of communication, the benefits and difficulties of evolving an understanding of communication, having continuous-valued communication versus discretized, having dishonest communication, various mating techniques and brain representations, and evolving to communicate when there is a delayed reward.

Contents

1 Introduction

The field of Artificial Life has attracted much research during the last decade, yielding insights not only within artificial intelligence, but within fields including biology, linguistics, and behavioral psychology. An *animat* is a primitive, sensor-based, artificial agent with limited functionality. Studying animats allows one to model simple creatures within a virtual environment, and to observe the behaviors, capabilities, and patterns that may emerge over time.

Animats may be represented by either software simulation or by constructing animal-like, physical robots [1]. For each of our experiments, we represented animats via software simulation.

In Section 2, we describe elements that are good for environments with communication.
In Section 3, we describe features that are common throughout our various experiments.
We conducted the following 4 experiments, each of which has its own section:

- Experiment 1 (Section 4) focused on building a foundation for communication
- Experiment 2 (Section 5) focused on evolution of communication
- Experiment 3 (Section 6) focused on mate selection and dishonest communication
- Experiment 4 (Section 7) focused on understanding when to communicate

2 Framework Background

We were careful in creating the environments for our experiments. We took into consideration lessons from MacLennon [3] and Steels [5].

MacLennon [3] outlined three "minimum requirements" for an environment to be conducive to communication:

1. Some agents must be able to perceive things that others cannot. Otherwise, it would be pointless to communicate.
2. The sender must be able to alter something that the receiver can perceive.
3. The environment must be as simple as possible, providing few distractions for the phenomena to emerge.

Steels [5] detailed three important environmental characteristics:

1. Basically, no individual agent should be completely omniscient. Users should represent a distributed system, and nobody should be able to control everyone else.
2. Nobody should be a mind reader or be able to directly change one's internal states.
3. The size of the population should be dynamic, along with the meaning of the language.

We tried to abide by these guidelines, except for the last point. Most of the communication-related papers that we researched had populations of a static size. Having a dynamically-sized population could allow populations to diminish to 0 or increase indefinitely. We wanted to avoid these problems.

3 Framework

Each experiment is conducted within an environment. We interchangeably use the words *environment* and *playground.* Each environment is a toroidal n x n grid that contains various objects. The environment has $2\frac{1}{2}$ dimensions, for our square grid environment allows objects to simultaneously occupy the same cell and pass over one another.

3.1 Objects

The types of objects and number of objects vary per experiment. The following is a list of the possible types of objects, along with the colors by which they are represented:

- animats
  - male meerkat (red)
  - female meerkat (orange)
- inanimates
  - food pellet (light green)
  - food cluster (gradients of green)

All objects have a size of 1 square unit.

3.1.1 Animats

Each meerkat animat has the following features:

- (a) sensors
- (b) actions
- (c) brain
- (d) energy

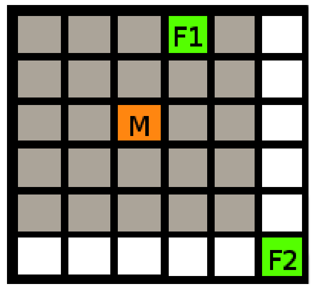
In some experiments, energy is not used, and in others, animats have hard-coded brains. The details are mentioned in each experiment's section. Further explanation of each feature follows:

(a) sensors: Every meerkat has sensor(s) that detect objects within its surroundings. Depending on the experiment, sensors differ in (1) what they detect and (2) the range in which they can detect. A sensor might detect one of the following:

- food
- meerkats
- communication signals from other animats

We define *sensing radius* to represent how many units in each cardinal direction that a meerkat may sense. For example, Figure 1 shows an example of a female meerkat with a sensing radius of 2. The female meerkat is represented by the orange cell. Food is represented by the green cells. The female meerkat can sense anything that lies within one of the grey cells. Thus, she can detect food F1 but not food F2.

Figure 1: Example of a female meerkat with a sensing radius of 2



(b) actions:

At each time step, a meerkat will perform an action. The types of possible actions vary from experiment to experiment, and they are detailed within each experiment's section.

We note that throughout all of our experiments, when meerkats eat or mate, they do so automatically –granted that the criteria were met to do so. In other words, meerkats do not have separate motor neurons that are used for mating or eating.

In some experiments, meerkats have brains. In others, they do not. If a meerkat does not have a brain, it acts in a pre-defined, deterministic manner based on its sensors. If a meerkat does have a brain, it uses the brain to determine how to act at each time step.

(c) brain:

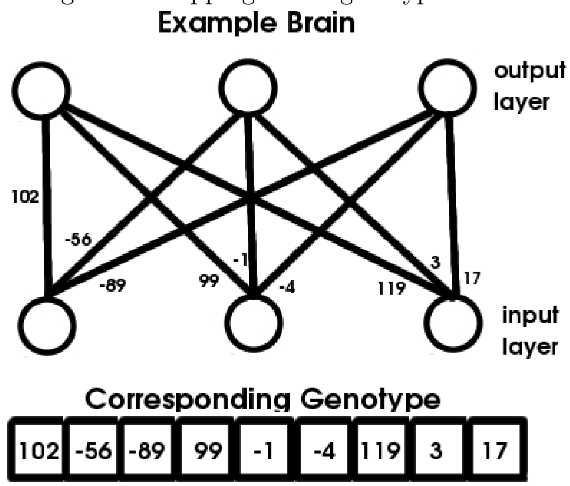
An animat's brain is usually represented by either an artificial neural net (ANN) or a finite-state machine (FSM). Other representations include production systems, simple look-up tables, associative memory, recurrent neural nets, and dynamical neural nets [2][4]. For our experiments, we represented each meerkat's brain with a feed-forward ANN. We varied the brain representations per experiment, and the details are specified later. Note that anytime a brain has an input neuron for each cardinal direction (i.e., N, S, E, W), only one of the neurons will fire (have a value of 1) – the others will have a value of 0. The neuron that fires will be the one that corresponds with the location of the closest sensed object. For example, say a meerkat senses that the closest object is 5 units north and 3 units west. The north direction has the greater distance and will thus fire.

Within a given experiment, all meerkats of the same sex will have the same brain structure. However, each meerkat's brain will have its own individual weights, which will be specified by the meerkat's *genotype*.

The *genotype* is a vector of bytes ranging from -128 to 127. Each one of these bytes is called a *gene* and corresponds to exactly one weight of the ANN brain. Figure 2 illustrates this mapping between genotype and brain. In addition, our genotypes are *diploid*, whereby one's genotype includes not only one's own genes (as Figure 2 shows), but it includes genes for the opposite sex. This affects the produced offspring, for a new offspring may then have both female and male genes that come from both its father and mother.

One's genotype is determined by a genetic algorithm (GA), and the specifics depend on an experiment's method of mating – mentioned in subsection 3.2.

Figure 2: Mapping of the genotype to brain



Regardless of the exact brain structure, each brain has:

- input neurons, denoted by x
- output neurons, denoted by o
- connection between the input layer and output layer

w_{kj} represents a connection between a input neuron x_j to output neuron o_k

Each output neuron o_k has a value defined as:

$$o_k = \sum_{j=1}^{p} w_{kj}x_j, \text{ where } p \text{ represents the number of input neurons}$$

The output neuron that has the highest value corresponds to the action that the meerkat will perform.

(d) energy: Each meerkat in Experiments 1 and 4 has a level of energy. The meerkats in Experiments 2 and 3 do not.

Energy-possessing meerkats are initialized with 200 units of energy. Meekats gain energy by occupying cells that contain food, and they lose energy by moving, which occurs at each time step. The exact specifics of how much energy is gained or lost are noted within each experiment's section. We define the term *food gain* to represent the amount of energy that meerkats gain for eating, which varies per experiment.

3.1.2 Inanimats

Experiments 1 has food pellets. Experiment 4 has food clusters. Experiments 2 and 3 do not have food.

(a) food pellet:

A food pellet is light-green in color and has 50 units of energy, and a meerkat may eat a fractional amount of this.

Food pellets are randomly placed within the playground at the beginning of each experiment. For every food pellet that is consumed, a new food pellet is randomly placed.

If multiple food pellets occupy the same cell, the represented color becomes proportionately darker.

The number of food pellets within an environment varies per experiment and will be mentioned accordingly.

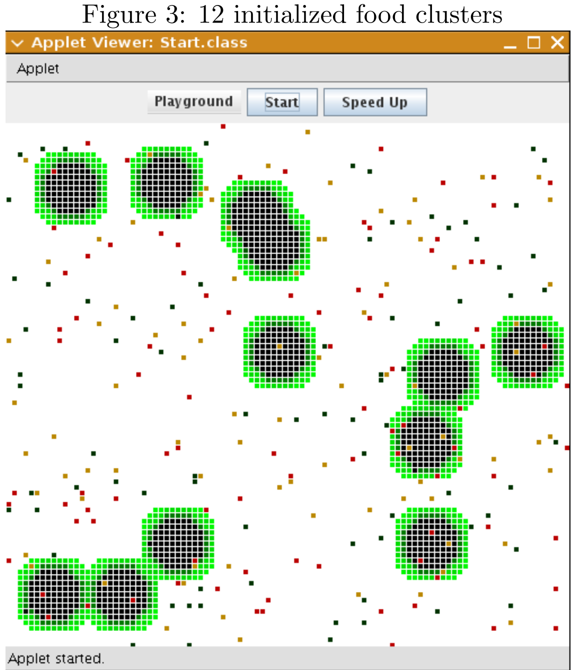
(b) food cluster:

A food cluster is a group of food pellets, and the density of the cluster follows a Gaussian-based distribution: the center of the cluster has the most number of food pellets, and the edges of the cluster have few food pellets. Specifically, any cell that is x units from the center has the following food density, with respect to the total amount of the energy within the cluster:

$$\frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \quad (1)$$

Figure 3 illustrates the appearance of food clusters. Remember, food is represented by shades of green, males are represented by red, and females are represented by orange.

Figure 3: 12 initialized food clusters



3.2 Mating

We define two ways of mating:

- **natural mating:** reproduction occurs when two meerkats of the opposite sex occupy the exact same cell. In some experiments, the female or male must also meet other criteria in order for reproduction to actually occur. Regardless of the requirements, after mating occurs, the father is relocated to a random location and the offspring are birth in random locations.
- **synthetic mating:** reproduction occurs at the end of a *generation* – a set number of time steps. In which case, the N most fit meerkats are selected to breed and their offspring are entered into the next generation. Note, N and the definition of "most fit" are specified for each experiment.

Given two meerkats of the opposite sex who are selected to reproduce, our genetic algorithm applies a crossover function on their genotypes. Each offspring will start to inherit genes from either its father or mother (the decision of which parent is randomly picked). As the genes are iteratively copied into the offspring from the chosen parent, there is a $\frac{1}{n}$ chance (where n represents the length of the genotype) of switching the parent from which the genes are being copied. We apply *mutations* with a chance of .01 for each gene. When a gene is mutated, it is assigned a new, random byte.

3.3 Definition Recap

Each experiment has different values for the following parameters. Yet, the behaviors and results from each experiment were not dependent on the parameters having the exact values that were specified. Rather, we only vary the values across experiments in order to suit each experiment's task.

Table 1: Glossary

term	**definition**
sensing radius	the farthest distance in any cardinal direction at which a meerkat can sense an object
num food pellets	the number of food pellets within a playground
initial energy	the number of energy points a meerkat is born with (200 for all of our experiments)
moving cost	the number of energy points a meerkat loses every time he moves
signal cost	the number of energy points a meerkat loses every time he sends a signal
signal honesty	the percentage of the time that a signal conveys accurate information
food gain	the number of energy points a meerkat gains by eating food
mating style	the method of mating (either synthetic or natural – see Section 3.2)

4 Experiment 1: Building a Foundation for Communication

4.1 Motivation

We were interested in seeing if meerkats could evolve their abilities to navigate towards the objects closest to them, whether it be food or a meerkat of the opposite sex. We also wanted to see if meerkats could evolve a method of deciding when to pursue each object. Our goal was for meerkats to pursue food when they were low on food, and for them to pursue mates after they had eaten. We hoped that the results from this experiment could serve as a baseline against which we could compare later experiments that allowed our animats to communicate. Thus, this experiment can be viewed as an attempt to build a foundation for communication.

4.2 Environment

The environment was comprised of:

1. animats:
    - 100 male meerkats (mobile)
    - 100 female meerkats (mobile)
2. inanimate objects:
    - 200 food pellets

Each meerkat had:

- sensors:
  - food sensor
  - mate sensor (only used if in *horny-mode,* which is defined below)
- actions:
  - move north
  - move south
  - move west
  - move east
  - rest

Table 2: Experiment 1: Environment Details

parameter	**value**
female sensing radius	10
male sensing radius	3
num initial food pellets	200
male moving cost	3
female moving cost	3
food gain	50
mating style	natural

4.3 Approach

The males were given such a small (3 units) sensing radius so that it would be hard for them to find food. Thus, if this experiment succeeded, we would hopefully see improved performance if we were to grant the meerkats the ability to communicate food signals.

4.3.1 Mating

Remember, for *all experiments,* mating occured automatically in the sense that no additional motor neurons were used for mating. The meerkats mated via the *natural* method, which required a female and male to co-occupy a cell. In addition, females only mated with a male if his level of energy was higher than the average value of energy amongst the males within her sensing range. Females' ability to sense males' energy levels is comparable to that in nature when females observe the richness of plumage of nearby males. Females were programmed to only mate with above-average males in an attempt to produce offspring who were best at finding food and females.

We provided each male and female with a *horny level.* When one's horny level reached a certain threshold, the meerkat was in *horny-mode* and pursued mates. Meerkats acted as follows:

```
at each time step {
  if meerkats are horny, then sense and pursue mates
  otherwise (if meerkats are not horny), then sense and pursue food
```

```
  increase horny level
}
```

The actual code can be found in Appendix Part B.

4.3.2 Brain

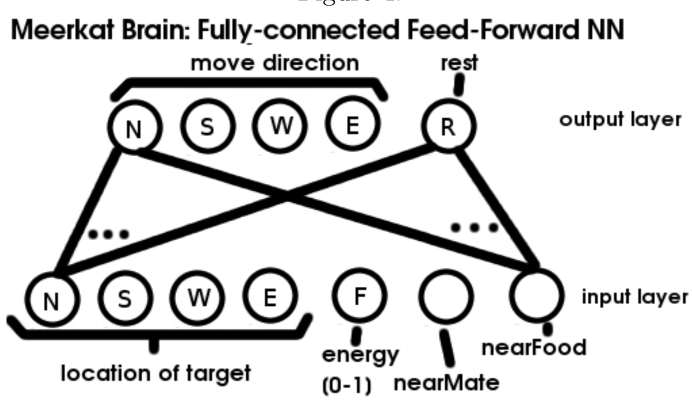
The brain is pictured in Figure 4 and has 7 input neurons:

- 4 boolean-valued neurons for the cardinal direction of the closest sensed object
- energy: real-valued number from 0 to 1; represents the meerkat's amount of energy
- nearMate: boolean-valued; fires if the closest object is a meeerkat of opposite sex
- nearFood: boolean-valued; fires if closest object is food

The brain has 5 output neurons, each of which corresponds with a possible action that the meerkat may perform:

- 4 direction-based neurons. If one of these fires, the meerkat moves in that direction
- rest: meerkat does not move and does not lose any energy

Figure 4:



4.4 Results

The results show that our experiment failed: the meerkats were unable to evolve to navigate towards the object closest to them. The meerkats were unable to pursue mates and food based on their energy levels and horny levels.

From Time 1 to 5,000, the number of meerkats who would rest steadily decreased. By Time 5,000, only 12 of 200 meerkats would ever rest. The meerkats evolved, and resting did not provide an advantage to meerkats. Thus, those who would rest were replaced with non-resting offspring.

From Time 1 to 10,000, meerkats did not improve their ability to correctly move in the direction of the closest sensed object. For example, by Time 10,000, meerkats moved in the correct direction no more

Table 3: Time 10,000

Frequency of Meerkats' Responses to Input					
input layer	move N	move S	move W	move E	rest
$< 1, 0, 0, 0, .5, 1, 0 >$	38	46	41	69	6
$< 0, 1, 0, 0, .5, 1, 0 >$	46	55	38	58	3
$< 0, 0, 1, 0, .5, 1, 0 >$	39	60	37	55	9
$< 0, 0, 0, 1, .5, 1, 0 >$	40	56	61	41	2

frequently than they moved in any of the wrong directions – as seen in Table 3, which ideally would look like a diagonal matrix within the 4 center columns.

By Time 15,000 meerkats evolved to increase the frequency of breeding and reaching food (see Figure 5). Yet, the meerkats did not evolve to navigate in the correct direction of the closest target. Rather, the majority of females moved east, regardless of what their sensors sensed. Likewise, the majority of males moved south, regardless of their sensors. This is seen in Tables 4 and 5. Although this behavior was not desired, it provided the meerkats with a reliable means of finding food and mates. Subsequent reruns of the experiment demonstrated consistent results: males and females evolved to move in orthogonal directions from one another by Time 15,000.

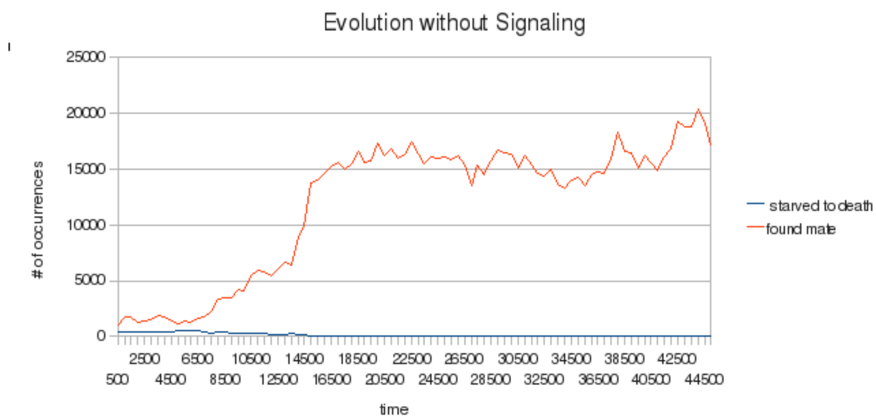
Table 4: Time 15,000

Frequency of Male Meerkat Responses					
input layer	move N	move S	move W	move E	rest
$< 1, 0, 0, 0, .5, 1, 0 >$	9	68	11	8	4
$< 0, 1, 0, 0, .5, 1, 0 >$	20	56	5	18	1
$< 0, 0, 1, 0, .5, 1, 0 >$	5	72	6	13	4
$< 0, 0, 0, 1, .5, 1, 0 >$	2	61	29	5	3

Table 5: Time 15,000

Frequency of Female Meerkat Responses					
input layer	move N	move S	move W	move E	rest
$< 1, 0, 0, 0, .5, 1, 0 >$	12	27	4	55	2
$< 0, 1, 0, 0, .5, 1, 0 >$	18	10	3	67	2
$< 0, 0, 1, 0, .5, 1, 0 >$	4	16	11	64	5
$< 0, 0, 0, 1, .5, 1, 0 >$	8	6	12	71	3

Figure 5: Evolution throughout 50,000 time steps



By Time 50,000 the aforementioned behavior was even more prevalent, as seen in Tables 6 and 7. The meerkats failed to evolve further.

Table 6: Time 50,000

Frequency of Male Meerkat Responses					
input layer	move N	move S	move W	move E	rest
$< 1, 0, 0, 0, .5, 1, 0 >$	2	91	3	3	1
$< 0, 1, 0, 0, .5, 1, 0 >$	5	89	5	1	0
$< 0, 0, 1, 0, .5, 1, 0 >$	3	92	0	4	1
$< 0, 0, 0, 1, .5, 1, 0 >$	7	84	2	4	3

Table 7: Time 50,000

Frequency of Female Meerkat Responses					
input layer	move N	move S	move W	move E	rest
$< 1, 0, 0, 0, .5, 1, 0 >$	3	12	2	82	1
$< 0, 1, 0, 0, .5, 1, 0 >$	4	1	3	90	2
$< 0, 0, 1, 0, .5, 1, 0 >$	8	5	1	86	0
$< 0, 0, 0, 1, .5, 1, 0 >$	3	3	2	91	1

4.5 Discussion

We believe the experiment failed due to the following 4 reasons, which we then discuss in more detail:

1. both females and males were mobile
2. requirements for mating were too high
3. insufficient motivation for evolving in the intended way
4. representation of the brain

First, when both males and females are moving, it makes it harder for males to reach females. Naturally, a non-moving target would be easier for males to reach than a moving one.

Second, even if a male meerkat has evolved to perfectly navigate towards the closest female, mating is not guaranteed. Remember, if a female is not in horny-mode, she will not sense males in her sensing range. Instead, she will attempt to move towards the closest food pellet. So even if both a male and female have perfect navigation skills, they will not necessarily produce offspring merely because one of them is not in horny-mode. In this situation, a male may continue to chase a female who is pursuing food until he dies from a depleted amount of energy.

Third, there was not strong enough motivation for meerkats to evolve the ability to navigate towards food and mates, or to decide which one to pursue in the presence of both. Meerkats needed to find food in order to live, as they were pressured due to the cost of moving at each time step. Yet, food was plentiful enough such that meerkats who ran in a straight line could survive. If fact, even when we decreased the number of food pellets in the playground, the results were the same: running in a straight line was the only technique that evolved. Similarly, there was not enough pressure for the meerkats to evolve to navigate towards a mate. When meerkats were in horny-mode, pursuing the closest mate was not always advantageous – as detailed in the previous point. Thus, meerkats would merely pursue mates by running in a straight line, as they did with pursuing food. If we relaxed the requirement of having females only mate with above-average males, meerkats would mate more frequently. Yet, relaxing this requirement would also allow meerkats who were poor at navigating to reproduce.

Fourth, the input layer of the brain did not make a distinction between what the closest object was at any given time. We suspect that results would have been better if we had separate input neurons for food pellets and nearby meerkats. Also, if we had provided our meerkats with additional neurons that helped with deciding with object to pursue, results might have improved.

Remember, our goal was to later introduce signaling as a means to improve meerkats' performance, and the signaling would be beneficial since the males had a small sensing radius of size 3. To experiment, we increased our sensing radius to size 20. Doing this allowed us to observe the expected results had signaling been implemented. Increasing the sensor size yielded us with the same failing results. Thus, we concluded that this experiment failed to serve as a foundation for communication. Our next experiment attempted to overcome the four weaknesses we addressed.

5 Experiment 2: Evolution of Communication

5.1 Motivation

In Experiment 2, we studied the evolution of communication and attempted to overcome the four weaknesses that we outlined for Experiment 1. The changes are later described in detail. Notably, meerkats only had one task in this experiment: mate finding. Experiment 2 is based on Werner and Dyer's past work [6], and we were interested in having meerkats find mates via communicating with one another.

Females will communicate to males. Males will merely listen to the signals and move according to their own *dialect.* We define a meerkat's *dialect* as one's set of meanings for the four possible signals. For example, at any given time, a female meerkat can produce signal 1, signal 2, signal 3, or signal 4. Maybe the female represents "move north" by signal 1, "move south" by signal 2, and so on. Her representation of the four signals is her dialect. We initialized the environment with meerkats who had randomly assigned dialects. Therefore, a male's dialect might interpret signal 1 to mean "move east," even though the female sender might have a different meaning for it. We were interested in seeing if meerkats would evolve to have the same dialect.

Specifically, our goal was for the meerkats to increase their ability to find mates, and we wanted to observe how the meerkats' dialects evolve over time.

5.2 Environment

The environment was comprised of:

1. animats:
   - 100 male meerkats (mobile)
   - 100 female meerkats (stationary)
2. inanimate objects:
   - none

Table 8: Experiment 2: Environment Details

parameter	**value**
female signal honesty	100% honest
female signal cost	0
female sensing radius	10
male sensing radius	n/a (males only receive signals from females)
num initial food pellets	0
male moving cost	0
female moving cost	n/a
food gain	n/a
mating style	natural

5.3 Approach

Females were stationary, and at each time step they performed one of the following actions for every male that was within her sensing range:

- send signal 1
- send signal 2
- send signal 3
- send signal 4

A female determined which signal to send based on the cardinal direction that the signal-receiving male should have moved. Subsection 5.3.1 explains more details on how females determined which signal to send.

Each male listened to the received signal that came from the closest female, and he acted according to his interpretation of the signal. Subsection 5.3.2 explains more details on how males determined how to move.

At each time step, a male performed one of the following actions:

- move north

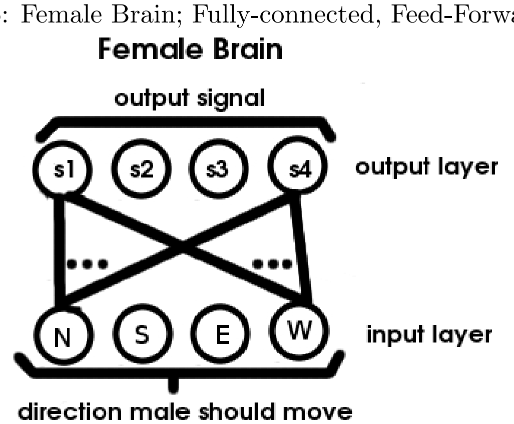
- move south
- move east
- move west

5.3.1 Female's Brain

The female brain is pictured in Figure 6. The input layer represents the direction in which she wants the signal-receiving male to move. The output neuron that has the highest value represents the signal that she will send.

The relationship between the input layer and output layer can be viewed as a function $f(x) = y$, where x represents the input neuron that will fire, and y represents the output neuron that will fire. There is no guarantee that $f(x)$ is *onto* or *one-to-one*. If it is not *onto*, a female will send less than 4 different types of signals. This is not ideal, for this case would imply that a female has no way to represent some of the directions that she wishes males to move. If it is not *one-to-one*, a female will send the same signal to represent two or more distinct directions in which she wishes males to move. Therefore, it is ideal for each female brain to be *onto* and *one-to-one*.

Figure 6: Female Brain; Fully-connected, Feed-Forward ANN



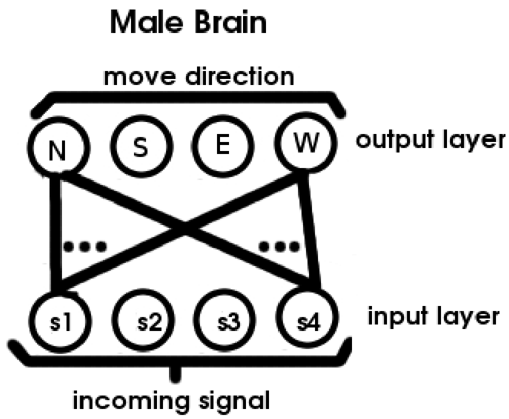
5.3.2 Male's Brain

The male brain is pictured in Figure 7. The input layer represents the received signal from the closest female. The output layer represents the direction in which the male will move.

Like the female's brain, the male's brain can be thought of as a function $g(n) = m$, where n represents the input signal and m represents the direction he will move. Likewise, $g(n)$ will ideally be *onto* and *one-to-one*. Given our notation, n is actually $f(x)$. Thus, $g(f(x)) = m$. It should be clear that the actual mappings of input x to output y, and input n to output m are not important. Rather, the only important parts are that both $f(x)$ and $g(n)$ are *onto* and *one-to-one*, and that a given output m is the same as the initial input x.

In other words, it does not matter which signal a female sends, as long as she has a unique signal for each of the four directions. Likewise, it does not matter which direction that a male moves based on the input signal, as long as (1) he moves in a unique direction for each possible signal, and that (2) the direction in which he moves is the same as how the female intended. For example, if a female senses a male who is south of her, she will send to the male a signal that represents "move north." The male will interpret the signal, and the goal is for him to move north.

Figure 7: Male Brain; Fully-connected, Feed-Forward ANN

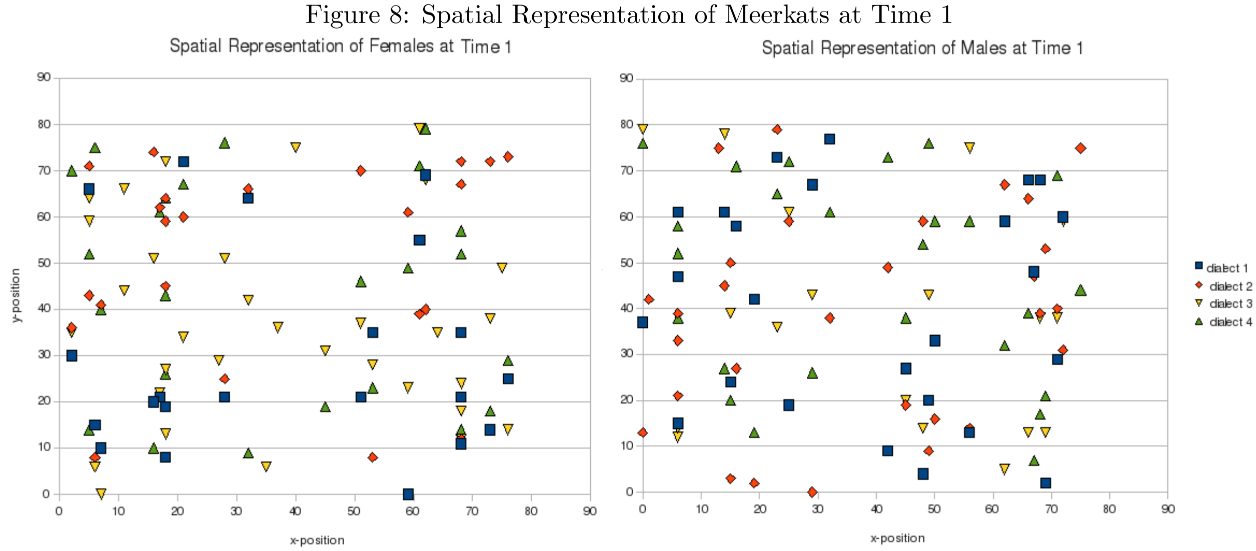


5.4 Results

At Time 1, the meerkats were initialized with randomly assigned dialects. Because of this, females were usually unable to successfully direct males to them. Figure 8 (left side) shows all of the females frozen at Time 1, along with how they would emit the signal to mean "move north." (The female's input layer would equal $< 1, 0, 0, 0 >$.) Notice how there is roughly an equal number of distinct dialects amongst the females; each of the four signals is emitted roughly the same number of times. Likewise, the males had roughly an equal number of distinct dialects for the interpretation of the received signal $< 1, 0, 0, 0 >$ (see Figure 8, right side).

Because of the wide diversity in the dialects between females and males, the males appeared to move in a random-walk fashion. From Time 1 to 1,000, it was not noticeable that males were pursuing females.

Figure 8: Spatial Representation of Meerkats at Time 1



Unlike [6], the males in our experiment did not go through a development stage in which they would all move in one particular direction. The main reason for this difference is because each of our males' four possible actions involved moving in a particular direction. Yet, in [6], only one of the four possible actions involved moving. (The other three actions were standing still, turning right, and turning left.) Moving clearly offers an increased likelihood of mating with a female, so it makes sense for [6] to encounter a stage whereby males interpret every female signal to mean "move forward." Yet, in our experiment, each of the four possible actions provided an equally advantageous opportunity for mating. Thus, it would not make sense for the males in our experiment to interpret every female signal to mean any one particular action.

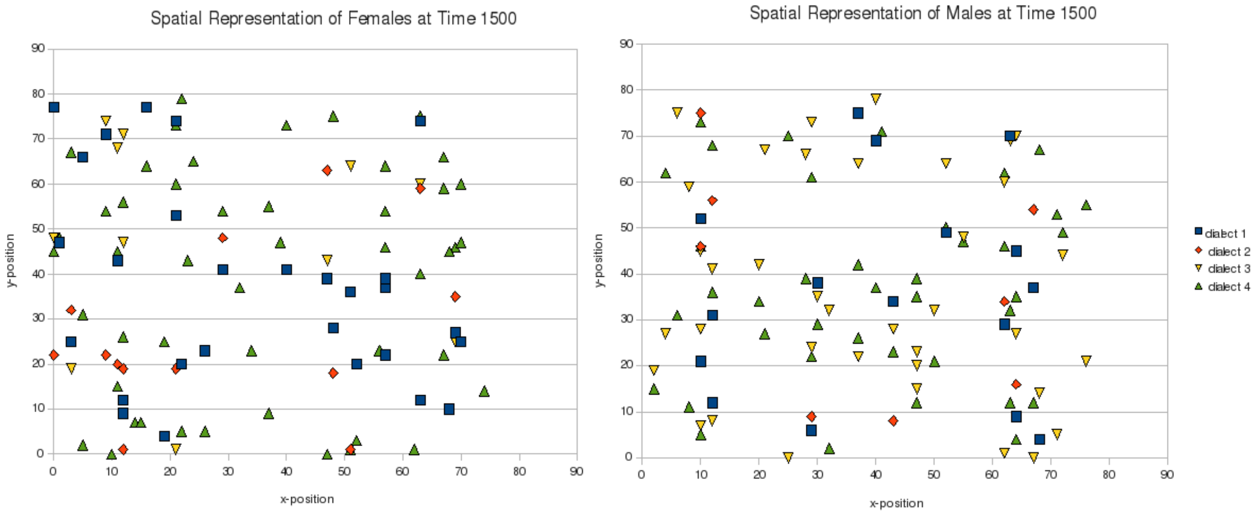
Yet, at Time 1,500, the meerkats behaved similar to this "all move-in-one-direction" behavior: males moved west more often than they moved in any other direction, as seen in Table 9. Table 9 shows the success rate of communications. At the current time step of 1,500, we looked at each of the 100 females. For each of these 100 females, we looked at how each of the 100 males would respond to a signal sent from the female. For example, the first row represents that males were south of the females, and that the males should move north. Each female sent her "move north" signal to each of the 100 males, and we tallied the movements of the males in each column. Within the first row, we see that males correctly moved north only 1,354 out of the 10,000 times. Ideally, our table would resemble a diagonal matrix. By Time 1,500, this was not the case. Specifically, males moved west 15,922 out of 40,000 times. The only time when males generally did not move west was when they should have moved south (they correctly moved south 4,756 out of 10,000 times).

The spatial mapping of "move north" (female input layer of $< 1, 0, 0, 0 >$) is shown in Figure 9. The females primarily had two dialects for "move north," represented by blue and green. Likewise, the males also generally responded to the signals in two distinct ways, coincidentally represented by the same colors.

Table 9: Time 1,500

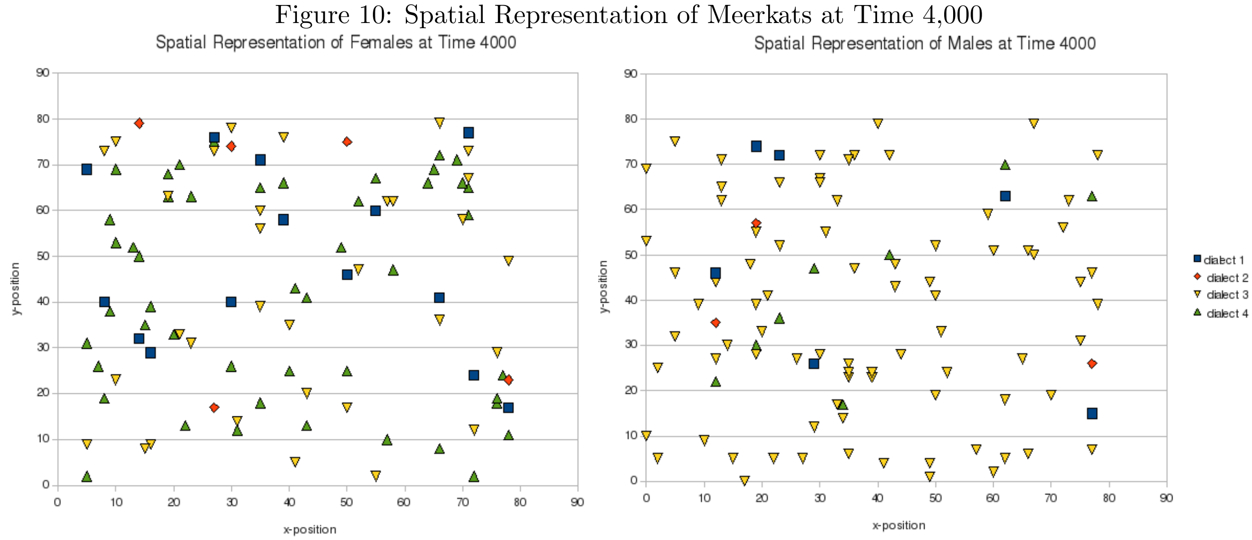
Transitions from Female to Male				
female's intended message	male moves N	male moves S	male moves E	male moves W
move north	1354	1896	2272	4478
move south	1032	4756	1550	2662
move east	1479	1459	2978	4084
move west	1351	1868	2083	4698

Figure 9: Spatial Representation of Meerkats at Time 1,500



From Time 1,500 to 6,000, the meerkats evolved their dialects such that "move west" was no longer the dominate action. Interestingly, by Time 4,000, the meerkats were able to successfully communicate three of the four actions. Females could not successfully communicate "move north." Figure 10 shows that females had three main dialects for representing "move north," and Table 10 illustrates that males only moved north 12 out of 400 times.

Figure 10: Spatial Representation of Meerkats at Time 4,000



The meerkats experienced a winner-take-all scenario. Females and males who could not successfully communicate were quickly replaced by new offspring. Even if meerkats could successfully communicate, they too were eventually replaced if they had a dialect that was not the most common. Therefore, less popular

Table 10: Time 4,000

Males' Reactions to Received Signals				
received signal	male moves N	male moves S	male moves E	male moves W
$< 1, 0, 0, 0 >$	6	3	83	8
$< 0, 1, 0, 0 >$	1	96	1	2
$< 0, 0, 1, 0 >$	5	44	2	49
$< 0, 0, 0, 1 >$	5	0	3	92

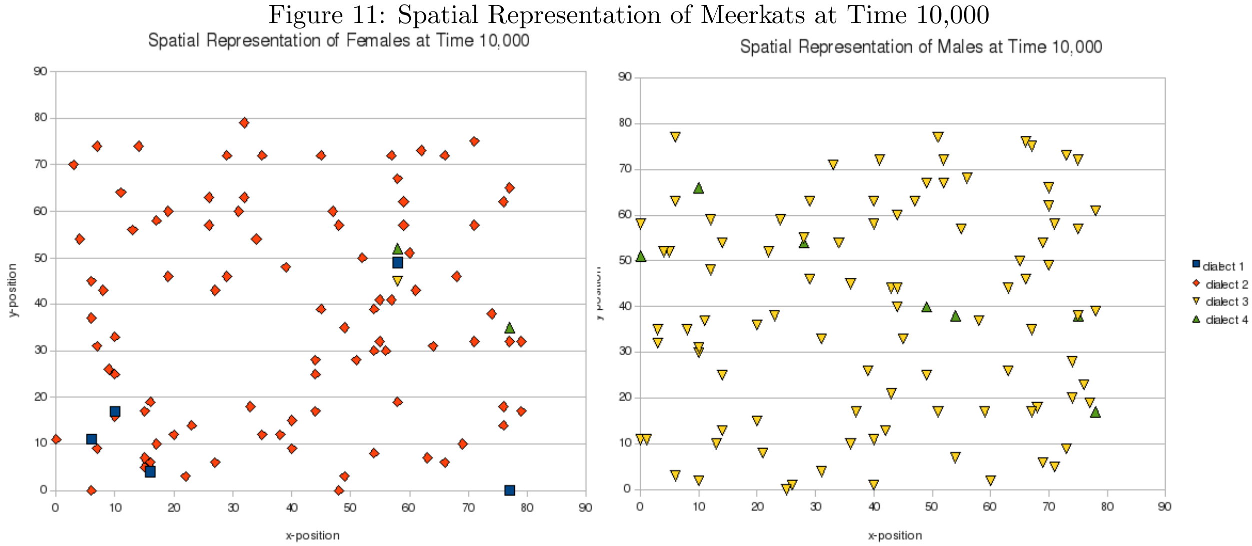
dialects were eliminated. The reason is that meerkats who would successfully mate produced offspring with similar dialects, and this continued to occur with increased frequency until one dialect dominated the environment.

By Time 10,000, the prevalence of one dialect started to exist, as shown in Table 11 and Figure 11. Notice that the diagonal in Table 11 has the highest values, which demonstrates that the females were able to successfully communicate to the males most of the time. Yet, there were still a few meerkats who did not speak the dominate dialect, but this is primarily due to our experiment's GA mutation rate of .01.

Table 11: Time 10,000

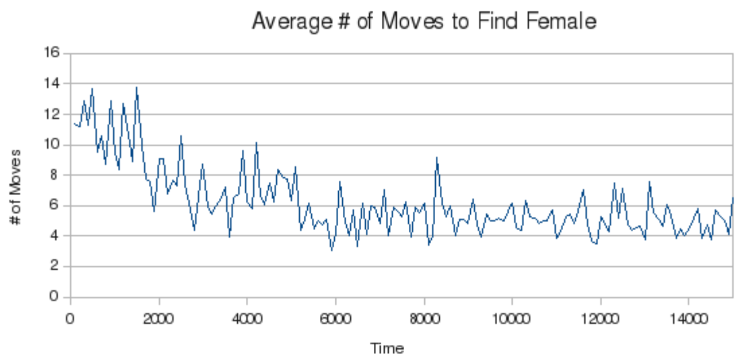
Transitions from Female to Male				
female's intended message	male moves N	male moves S	male moves E	male moves W
move north	8204	468	745	583
move south	292	9219	5	484
move east	281	670	8379	670
move west	763	386	381	8470

Figure 11: Spatial Representation of Meerkats at Time 10,000



By Time 15,000, the meerkats reached their peak performance, and we were yielded with negligible improvements from that of Time 10,000. In Figure 12, we see the average number of moves that males took in order to find females. The results show that our experiment was a success, for our males were able to successfully navigate towards females. Also, we were able to observe that although there were fluctuations in dialects during the beginning of the experiment, eventually one dialect prevailed amongst our meerkats.

Figure 12: Average Number of Moves to Find Female



5.5 Adding More Movement Actions

With the success of our last experiment, we wondered if we could achieve even better results by allowing our male meerkats the ability to move not only in 4 directions, but in 8 adjacent directions:

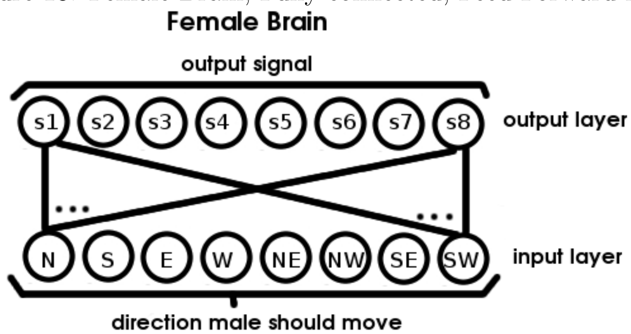
1. north
2. south
3. east
4. west
5. north-east
6. north-west
7. south-east
8. south-west

All other environmental variables remained identical to that described earlier for when meerkats had only 4 options of movement.

5.5.1 Brains

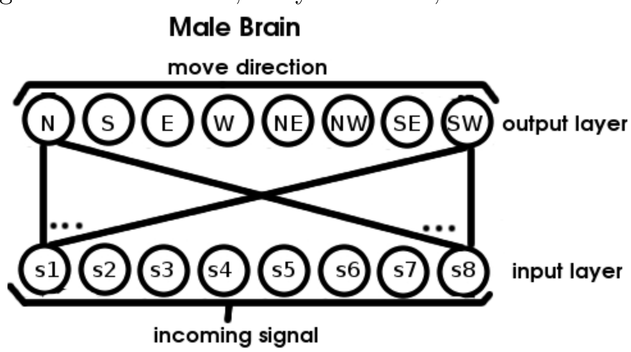
In order for females to direct males to move in 8 directions, females were given the ability to emit 8 different types of signals, as seen in Figure 13.

Figure 13: Female Brain; Fully-connected, Feed-Forward ANN



Males received female signals, and at each time step they chose to move in one of 8 directions, as seen in Figure 14.

Figure 14: Male Brain; Fully-connected, Feed-Forward ANN



5.5.2 Results/Discussion

We anticipated that the results would be similar to previous approach that allowed our meerkats to only move in 4 directions and emit 4 distinct signals. Specifically, we predicted that meerkats would evolve such that (1) only one dialect would prevail, and that (2) male meerkats would increasingly improve their ability to find females. Yet, we expected that our meerkats would take longer to evolve these 2 features than they did when our system only had 4 movement actions and 4 signals. Our reasoning for this expectation was that the brains for the new approach were comprised of 64 connections instead of only 16 like the previous experiment. So, we anticipated that it would take a longer time for meerkats to evolve to have good genotypes. However, we expected that eventually the meerkats would be able to outperform the previous 4-signal approach in that they would be able to find females in fewer number of steps. We believed this because the 4 newly-added movements (NE, NW, SE, SW) allow meerkats to move in a way that previously required 2 movements.

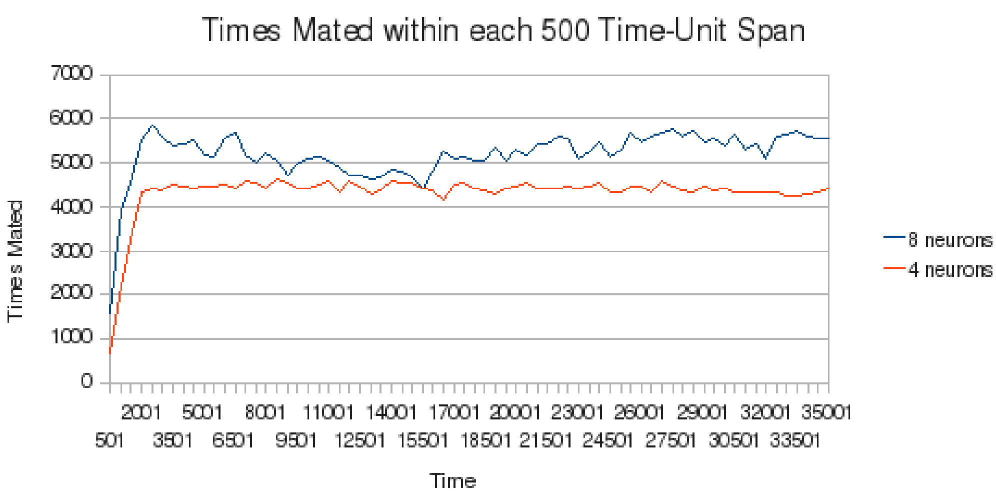
Table 12 shows a transition table that counts the frequency of males' output response per every possible input from the females. Ideally, the table would resemble a diagonal matrix. Notice that the first four rows include many misses, especially for "move south." The reason for this is that the males were rarely required to only move north, east, south, or west. For example, a female rarely sent signals to mean "move north," as this would require the male to be perfectly aligned with the female on the x-axis of the playground. Instead, females sent signals to mean "move northeast" or "move northwest" much more frequently than "move north."

Figure 15 shows that we were wrong in predicting that the 8-signal approach would evolve much slower than the 4-signal approach; the 8-signal approach immediately performed better than the previous 4-signal approach. The reason is that even when the meerkat has not yet evolved to perfectly move diagonally (i.e., NE, NW, SE, or SW) when he should, moving diagonally always covers more ground than moving non-diagonally. The previous 4-signal approach requires meerkats to move twice (over then up/down) in order to do what the 8-signal approach can do in one step.

Table 12: Time 20,000

Transitions from Female to Male								
female's intended message	N	S	E	W	NE	NW	SE	SW
move N	2444	18	265	375	630	1743	696	229
move S	7	234	0	0	75	59	6024	1
move E	0	80	6000	0	0	0	0	320
move W	2	252	157	5850	0	5	78	56
move NE	294	122	1282	0	4200	35	7	460
move NW	244	0	0	0	378	4279	1314	185
move SE	12	234	0	0	36	76	6030	12
move SW	158	1188	81	75	0	395	79	4424

Figure 15: Comparison of the new 8-signal approach vs the old 4-signal approach



6 Experiment 3: Developing Mate Selection

6.1 Motivation

We were interested in seeing if male meerkats could evolve their mate selection – the decision of whom to pursue. Each female had a *prettiness* attribute, and females communicated (to males) signals that represented their level of prettiness. Males were motivated to pursue prettier females because males were proportionately rewarded, depending on the female's degree of prettiness.

Unlike Experiment 2, we did not allow for evolution of communication. Rather, the females' communication signals were pre-defined. Our goal was for male meerkats to evolve to improve their abilities to find females, and for the males to evolve to pursue the prettier females. The degree of prettiness was directly proportionate to the amount of reward a male received when reaching the female.

We experimented with having continuous-valued signals instead of discretized-signals.

Next, we allowed females to be "picky," whereby males were probabilistically rewarded for finding females. Our goal was for males to evolve such that they would not pursue the prettiest girls, for the prettiest girls were the least likely to reward males.

Next, we allowed females to send dishonest mating calls. Each female probabilistically lied about her degree of prettiness. More details follow within subsection 6.7. We were interested in seeing if males could evolve their mate selection such that they factor in the chance of females' being dishonest.

6.2 Environment

The environment was comprised of:

1. animats:
   - 200 male meerkats (mobile)
   - 200 female meerkats (stationary)
2. inanimate objects:
   - none

Table 13: Experiment 3: Environment Details

parameter	**value**
female signal honesty	100% honest
female signal cost	0
female sensing radius	10
male sensing radius	n/a (males only receive signals from females)
num initial food pellets	0
male moving cost	0
female moving cost	n/a
food gain	n/a
mating style	synthetic

6.3 Approach

Females were stationary, and at each time step they performed one of the following actions to each male that was sensed:

- send signal 1 (means move north)
- send signal 2 (means move south)
- send signal 3 (means move east)

- send signal 4 (means move west)

Each signal had 1 of the following 3 volumes:

- soft
- medium
- loud

A female determined which of the 4 signals to send based on the cardinal direction that the signal-receiving male should have moved. Females were randomly assigned a degree of prettiness $p \in \{1, 5, 10\}$ which determined the volume of her signal (soft, medium, loud, respectively). Thus, prettier females always sent louder signals. By "louder signals," we mean that males both (1) could receive louder signals from farther distances than quiter signals; and (2) if a male received both a loud and soft signal, each of which originated from the same distance, the male would register the louder one as having a characteristic of being "louder."

Note, we use the term *quality-1, quality-5, quality-10* to represent females who had prettiness value of 1, 5, and 10, respectively. When a male found a female, he was rewarded with 1, 5, and 10 points for finding females with prettiness of 1, 5, and 10, respectively. More details follow in subsection 6.3.3.

At each time step, each male determined a signal to which to listen and act. Subsection 6.3.2 explains more details.

Males could perform any of the following actions:

- move north
- move south
- move east
- move west

6.3.1 Female's Brain

Females did not have a brain. Females deterministically sent signals, as described above.

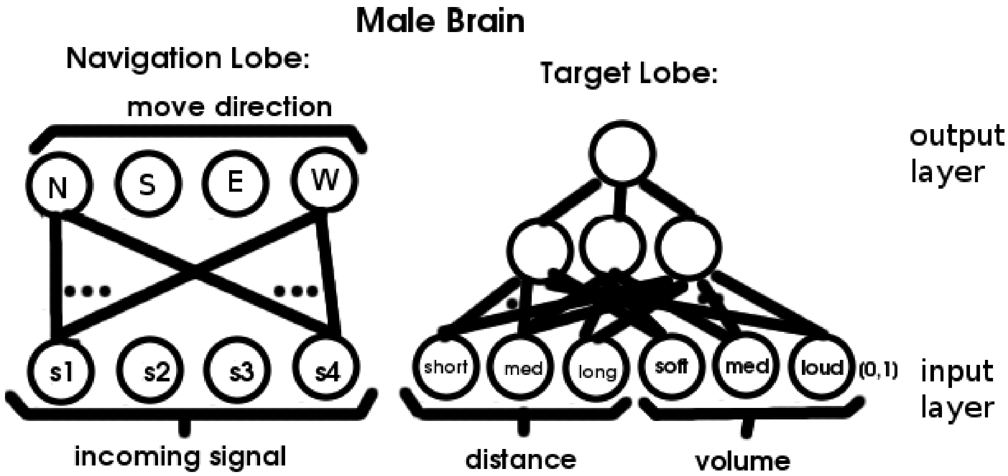
6.3.2 Male's Brain

We created 2 disjoint lobes within the male brain:

1. *target lobe:* determines which signal to listen to
2. *navigation lobe:* determines how to navigate based on the signal

The male brain in pictured in Figure 16.

Figure 16: Male Brain for Mate Finding



Each signal that a male received was input into his target lobe. Specifically, the target lobe was only concerned with the distance and volume attributes of each signal. The signal with the highest output value was the one to which he listened, and it was inputted into the navigation lobe. The navigation lobe determined how a male moved, based entirely on the signal type (i.e., signal 1, signal 3, etc.)

6.3.3 Mating

Every 500 time steps constituted a *generation.* Our experiments lasted for at least 100 generations. At the end of each generation, the 12 most fit males were selected for mating, where fitness was measured by (1) quantity of females found and (2) quality of females found. Specifically, at the end of each generation, we created two rankings of meerkats: $R1$, which ranked males by the number of times they found a female; $R2$, which ranked males by the average prettiness value of the females they found.

Then, we developed a new weighted ranking $R3$ which was based on $R1$ and $R2$. For our experiments, we preferred quality more than quantity. Thus, $R3$ ranked males by their $fitness\ score$, as follows:

$$fitness\ score\ of\ male\ m = .2 * R1[m] + .8 * R2[m] \tag{2}$$

where $RX[m]$ represents male m's index within rank list X

6.4 Results

Our results show that Experiment 3 was a success: males were able to improve both their mate-finding abilities and mate-selection abilities.

During Generation 1, males only found a total of 1,383 females, and the average prettiness value of these females was 5.88 (as seen in Figures 17 and 18, respectively). By this time, males had no significant ability to find females.

Figure 17: Males' Improving Mate-Finding Abilities

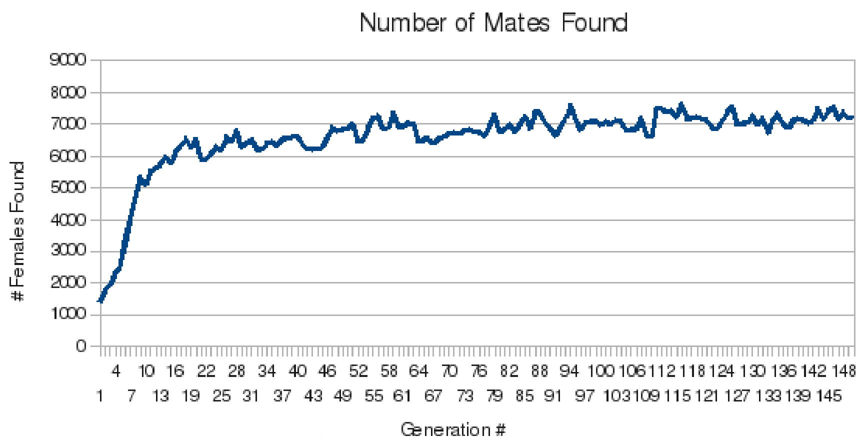
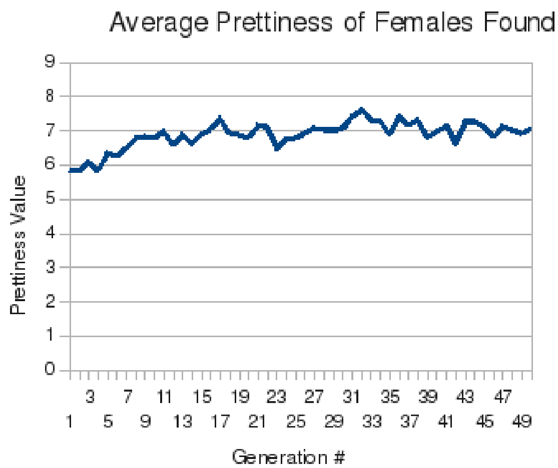


Figure 18: Males' Improving Mate-Selection Abilities



By Generation 5, males began to develop their mate-finding and mate-selection abilities, as seen by Table 14. Table 14 shows the output of the males' target lobes for various female inputs. Specifically, the value in the right-most column is the summation of all males' target lobe output neuron for the given scenario represented per row. Remember, males listened to the signal that had the highest target lobe output neuron. When males received signals from quality-1 females, they correctly pursued the females who were closest to them. The same is true for when males received signals from quality-5 and quality-10 females, as shown in the upper half of Table 14. However, males had not yet evolved to pursue the prettiest females. For example, the lower half of Table 14 shows that when males received signals from females at any set distance, males *generally* pursued the quality-5 females. We use the the term "generally" because the right-most value is summation of all males, as previously stated.

By Generation 20, males had reached a near-peak performance with their mate-finding and mate-selection abilities. Males found 6,513 females who averaged a prettiness value of 7.17 (as shown in Figures 17 and 18, respectively). Later generations yielded only slight performance differences. The average prettiness value of pursued females did not increase closer to a value of 10 because of 2 reasons:

1. females with pretty value of 10 were not prevalent enough for males to always receive a signal from one
2. our fitness function included some preference towards quantity of mates, rather than only quality

Males correctly pursued the closest females, as shown in the upper half of Table 15. The lower half of the table shows that when males received signals from females from a "close" distance, males, on average, correctly pursued quality-10 females. However, when females were at a "medium" or "far" distance, males generally pursued quality-5 females.

By Generation 50, males had evolved to correctly pursue the prettiest females. The upper half of Table 16 shows that males correctly pursued the closest females with any set prettiness value. The lower half of Table 16 shows that males correctly pursued females in the order of quality-10, quality-5, then quality-1.

Table 14: Males start to develop mate-selection abilities

Male Target Lobe by Generation 5						
distance			volume			males' output
close	med	far	soft	med	loud	accumulated output
1	0	0	1	0	0	-2104.1342298182085
0	1	0	1	0	0	-3225.1272683861175
0	0	1	1	0	0	-4043.9751662666545
1	0	0	0	1	0	-1893.4454769639735
0	1	0	0	1	0	-3067.468284395284
0	0	1	0	1	0	-3863.04156679772
1	0	0	0	0	1	-2209.174837299399
0	1	0	0	0	1	-2980.6047268536013
0	0	1	0	0	1	-3916.6188599791913
1	0	0	1	0	0	-2104.1342298182085
1	0	0	0	1	0	-1893.4454769639735
1	0	0	0	0	1	-2209.174837299399
0	1	0	1	0	0	-3225.1272683861175
0	1	0	0	1	0	-3067.468284395284
0	1	0	0	0	1	-2980.6047268536013
0	0	1	1	0	0	-4043.9751662666545
0	0	1	0	1	0	-3863.04156679772
0	0	1	0	0	1	-3916.6188599791913

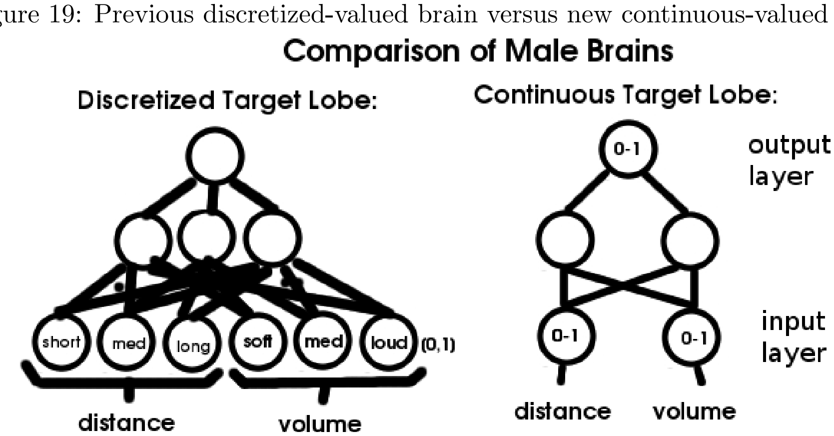
6.5 Continuous-Valued Signals

Our target lobe originally had 3 loudness neurons, which we believe was appropriate since there were exactly 3 distinct degrees of prettiness. Yet, we were curious if we could obtain comparable results if our females sent signals with continuous-valued volume. So, instead of only allowing females to send signals of 3 different types of loudness, a signal could have any real-valued loudness level l, where $l \in [0, 1]$. The changes are shown in Figure 19.

Table 15: Males further develop mate-selection abilities

Male Target Lobe by Generation 20						
distance			volume			males' output
close	med	far	soft	med	loud	accumulated output
1	0	0	1	0	0	-10775.230103473732
0	1	0	1	0	0	-13274.786629709137
0	0	1	1	0	0	-17863.544339342086
1	0	0	0	1	0	-12196.527851478775
0	1	0	0	1	0	-13217.395352672784
0	0	1	0	1	0	-16904.41196261861
1	0	0	0	0	1	-10531.807708347369
0	1	0	0	0	1	-14994.613898404297
0	0	1	0	0	1	-19556.15651916176
1	0	0	1	0	0	-10775.230103473732
1	0	0	0	1	0	-12196.527851478775
1	0	0	0	0	1	-10531.807708347369
0	1	0	1	0	0	-13274.786629709137
0	1	0	0	1	0	-13217.395352672784
0	1	0	0	0	1	-14994.613898404297
0	0	1	1	0	0	-17863.544339342086
0	0	1	0	1	0	-16904.41196261861
0	0	1	0	0	1	-19556.15651916176

Figure 19: Previous discretized-valued brain versus new continuous-valued brain



We expected that the results would be comparable to, but slightly worse than, the results yielded from the original discretized-valued approach. We anticipated worse results because the target lobe of the discretized-valued approach had exactly 3 input neurons, allowing each neuron to perfectly coincide with one of the degrees of prettiness. The continuous-valued approach, however, has a more compact target lobe representation, and the aforementioned pairing of neurons to prettiness is not possible.

Table 16: Males fully developed mate-selection abilities

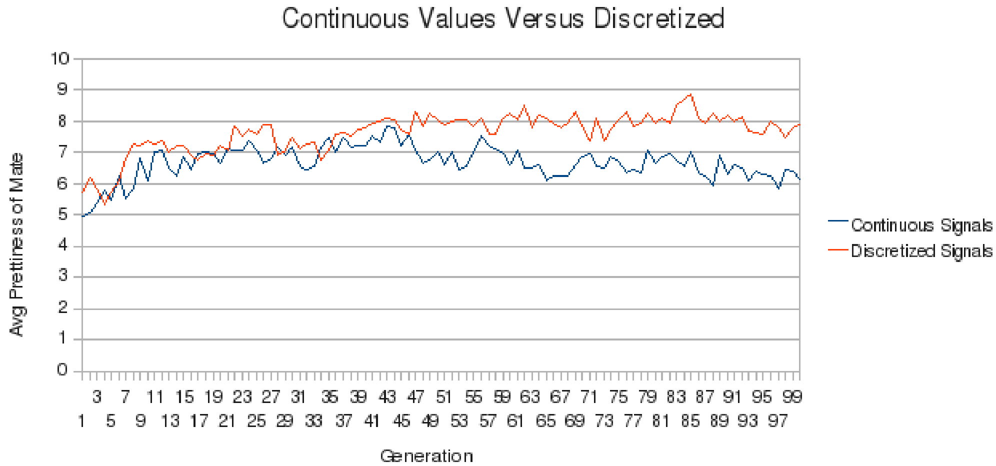
Male Target Lobe by Generation 50						
distance			volume			males' output
close	med	far	soft	med	loud	accumulated output
1	0	0	1	0	0	6417.0167366193
0	1	0	1	0	0	-3353.1693917814173
0	0	1	1	0	0	-3588.3487287563134
1	0	0	0	1	0	7768.954562184334
0	1	0	0	1	0	-3012.249284675235
0	0	1	0	1	0	-3210.584238600022
1	0	0	0	0	1	12901.427259846365
0	1	0	0	0	1	1562.958093355352
0	0	1	0	0	1	475.99574822771046
1	0	0	1	0	0	6417.0167366193
1	0	0	0	1	0	7768.954562184334
1	0	0	0	0	1	12901.427259846365
0	1	0	1	0	0	-3353.1693917814173
0	1	0	0	1	0	-3012.249284675235
0	1	0	0	0	1	1562.958093355352
0	0	1	1	0	0	-3588.3487287563134
0	0	1	0	1	0	-3210.584238600022
0	0	1	0	0	1	475.99574822771046

6.5.1 Results

Figure 20 illustrates that our expected results occurred. The continuous-valued approach started with males typically finding quality-5 females, whereas the discretized-valued approach starts at 5.76. Only during Generations 5, 18, 29, and 35 did the continuous-valued approach yield superior mate-selection results. Until Generation 46, the two approaches yielded relatively comparable results. However, starting at Generation 47 the results of the continuous-valued approach worsened, and the discretized-valued approach proved to offer better results.

We expect that if our system had more degrees of prettiness, and that the discretized-valued target brain still had 3 neurons for loudness, then the continuous-valued approach would offer superior results. We expect this because the discretized version would only have 3 distinct neurons to represent 10 degrees of prettiness. However, the continuous version would not have to make this generalization, for it has a wider range of representation.

Figure 20: Continuous-Valued Approach vs Discretized-Valued Approach



6.6 Adding Pickiness

To make our experiment more natural, we changed our system so that females probabilistically rewarded males who found them. Previously, anytime a male and female co-occupied a cell, the male was said to have "found her," and he gained points that were equivalent to the prettiness of the female. However, in this section, males no longer had a 100% chance of being rewarded with points for finding females. Rather, we define the probability $P(p)$ as the likelihood that a male will be rewarded for finding a female with prettiness value p:

$$P(p) = U(0,1) \leq 1 - (\frac{p}{argmax(p)+\epsilon})^2, \text{ where } p = \text{prettiness value and } \epsilon = .1$$

Our goal was for males to evolve so that they no longer preferred quality-10 females the most, for the prettiest girls were the least likely to reward males. Table 17 illustrates females' expected probability of rewarding, which was based on females' degrees of prettiness.

Table 17: Females are now selective

Mating with Females		
prettiness	probability of mating	expected prettiness points reward
1	.9901	.9901
5	.7549	3.775
10	.0197	.1970

6.6.1 Results/Analysis:

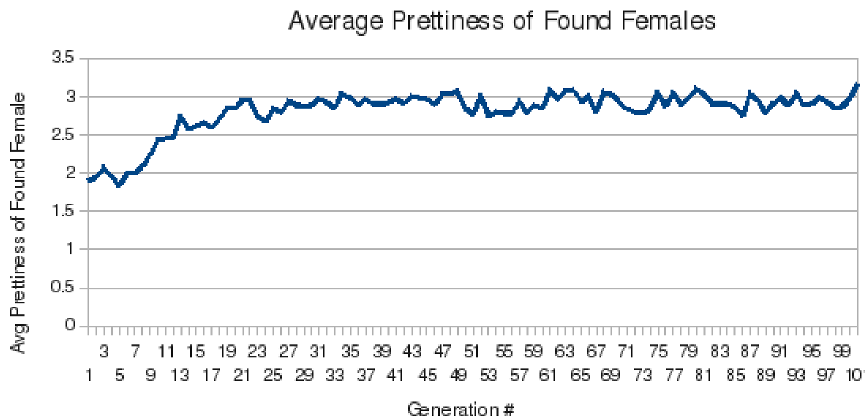
Based on the expected gain – shown in Table 17 – it is most advantageous for males to pursue quality-5 females. Pursuing quality-1 females offers the second highest reward.

Figure 21 shows the males succeeded in evolving their decision of whom to pursue. By Generation 1, males found females who had an average prettiness value of 1.86. Remember, this contrasts with the starting prettiness of 5.88 seen in Figure 18 because the prettiest females in this experiment were the pickiest, so males were often not rewarded for finding the quality-10 girls.

As the generations progressed, males evolved to pursue quality-5 girls more frequently. By Generation 20, the males had evolved to find females who had an average prettiness value of 2.95. Subsequent generations yielded only slight improvements. The males performed the best in Generation 64, whereby the found females averaged a prettiness of 3.09. Males never reached a prettiness value of 5.0 because (1) quality-5 females were not always nearby every male; (2) our fitness function gave some weight towards the quantity (rather than quality) of found females.

Table 18 shows the males' target lobes performance. The upper half of the table shows that for any group of females with a set degree of prettiness, males correctly pursued the closest females. The lower half of the table shows that for any group of females who were at the same distance from the males, males generally pursued quality-5 females. This is the behavior that we hoped for, and it shows that males adapted to females' pickiness. Moreover, males pursued quality-1 females more frequently than they did quality-10 females, which further agrees with what we mentioned as ideal results.

Figure 21: Males Do Not Pursue Prettiest Females



6.7 Adding Dishonesty

In the previous section, males evolved to reflect females' pickiness. In this section, the females not only probabilistically rewarded males who found them, but females also probabilistically sent dishonest signals to falsely represent themselves as being prettier than they actually were. Our goal was for males to evolve to not pursue females who are more likely to lie about their prettiness.

6.7.1 Approach

Remember, throughout all of Experiment 3, males evolved to infer prettiness by the volume of females' signals. In this section, females probabilistically increased their volume in attempt to appear prettier than they actually were.

Each female was randomly assigned an *age*, where $0 < age \leq 100$. Females' signals had an associated pitch, which was one of the following:

- high
- medium

Table 18: Males Correctly Pursue Females

Male Brains by Generation 100						
distance			volume			males' output
close	med	far	soft	med	loud	accumulated output
1	0	0	1	0	0	-1390.0477101067297
0	1	0	1	0	0	-1633.1393710655957
0	0	1	1	0	0	-2120.894160239169
1	0	0	0	1	0	-87.93522497138405
0	1	0	0	1	0	-835.5398477119826
0	0	1	0	1	0	-1058.023589914364
1	0	0	0	0	1	-1871.350704625181
0	1	0	0	0	1	-2183.788113161976
0	0	1	0	0	1	-2585.835452836359
1	0	0	1	0	0	-1390.0477101067297
1	0	0	0	1	0	-87.93522497138405
1	0	0	0	0	1	-1871.350704625181
0	1	0	1	0	0	-1633.1393710655957
0	1	0	0	1	0	-835.5398477119826
0	1	0	0	0	1	-2183.788113161976
0	0	1	1	0	0	-2120.894160239169
0	0	1	0	1	0	-1058.023589914364
0	0	1	0	0	1	-2585.835452836359

- low

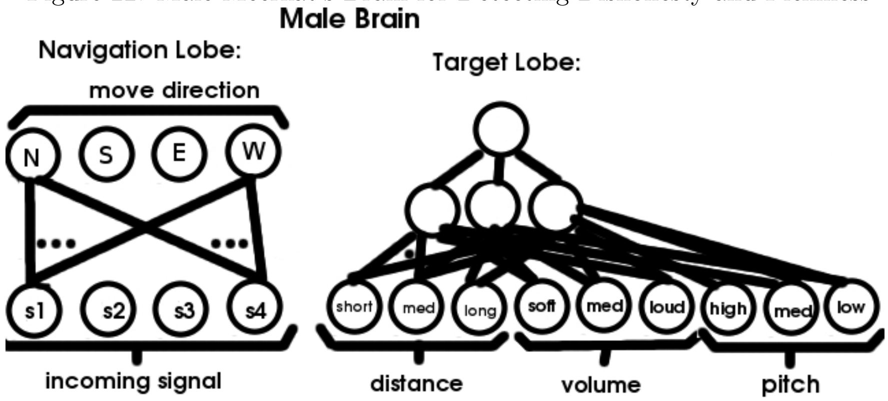
Age and pitch were directly correlated; the older a female, the lower her pitch was. Females probabilistically sent dishonest signals based on their age. Specifically, the probability that a female's signal was truthful $P(x)$, given that the female's age is x, follows:

$$P(x) = U(0,1) \leq (1 - x/100)^2, \text{ where } x = \text{age}$$

Thus, the higher-pitched female signals were generally more truthful than lower-pitched female signals.

We changed males' target lobes to concern the pitch of females' signals, and our goal was males to evolve to associate signal pitch with truthfulness. Males' new target lobe is seen in Figure 22.

Figure 22: Male Meerkat's Brain for Detecting Dishonesty and Pickiness



6.7.2 Results

Males were able to successfully evolve to (1) associate the pitch of a signal with the female's honesty; (2) not pursue the females who were most likely to lie; and (3) not pursue the prettiest girls, for they were the ones least likely to reward males.

Figure 23: Male Meerkat's Detect Dishonesty and Pickiness

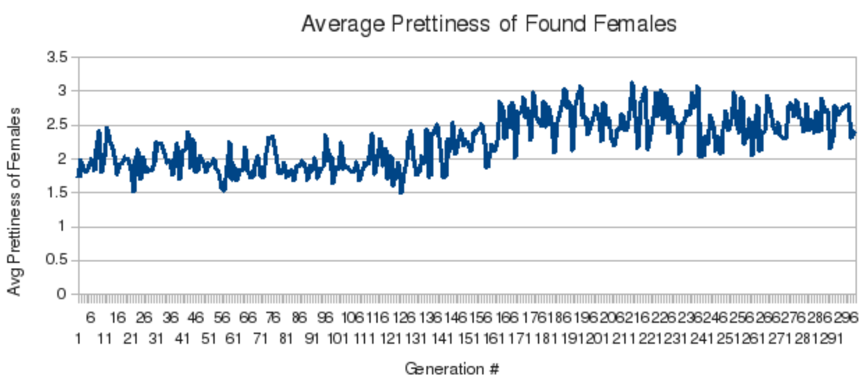


Figure 23 shows that males initially found females who averaged a prettiness value of 1.72. By Generation 12, males appeared to have improved, for they found females who averaged prettiness of 2.44. Yet, this was only a temporary success, for the males had not yet fully evolved.

By Generation 22, males had worsened in their pursuing females, for they found females who averaged prettiness of 1.51. The reason for this is that males had not yet evolved to correctly associate the pitch of females' signals with females' being dishonest. This is apparent by Table 19, which shows males' responses to various female signal inputs. Specifically, it is shown that regardless of the females' prettiness (represented by the loudness of her signals), males generally preferred pursuing the most deceitful females – the ones who had low-pitched signals.

By Generation 97, males improved, as depicted by the local maximum within Figure 23. The following observations are notable from Table 20:

Table 19: Results of Generation 22

Male Brains by Generation 22									
distance			volume			pitch			output
close	med	far	soft	med	loud	high	med	low	acc. output
1	0	0	1	0	0	1	0	0	-4902.110513756734
1	0	0	1	0	0	0	1	0	-4354.960868789533
1	0	0	1	0	0	0	0	1	-3553.2866347208596
1	0	0	0	1	0	1	0	0	-5067.79828837037
1	0	0	0	1	0	0	1	0	-4335.738752588638
1	0	0	0	1	0	0	0	1	-3810.0493599753167
1	0	0	0	0	1	1	0	0	-4810.868432207199
1	0	0	0	0	1	0	1	0	-4410.22358123278
1	0	0	0	0	1	0	0	1	-3452.2099161881215

Table 20: Results of Generation 97

Male Brains by Generation 97									
distance			volume			pitch			output
close	med	far	soft	med	loud	high	med	low	acc. output
1	0	0	1	0	0	1	0	0	-2930.194512202544
1	0	0	1	0	0	0	1	0	-652.0195415796555
1	0	0	1	0	0	0	0	1	-5575.446610659392
1	0	0	0	1	0	1	0	0	-2505.6981813177354
1	0	0	0	1	0	0	1	0	-3517.5761620965095
1	0	0	0	1	0	0	0	1	-5750.572221725689
1	0	0	0	0	1	1	0	0	-1098.0628585487714
1	0	0	0	0	1	0	1	0	-4773.963904826603
1	0	0	0	0	1	0	0	1	-4975.383291216731

- males correctly pursued females who had more truthful (high-pitched) signals in only 2 out of the 3 cases (when pursuing quality-5 and quality-10 females, as seen in rows 4-9).
- when females sent high-pitched signals, males incorrectly pursued quality-10 females more often than they pursued quality-5 or quality-1 females (seen by rows 1, 4, and 7).
- when females sent med-pitched signals, males correctly pursued quality-1 and quality-5 females more often than they pursued quality-10 (seen by rows 2, 5, and 8).
- when females sent low-pitched signals, males incorrectly pursued quality-10 females more often than they pursued quality-5 or quality-1 females (seen by rows 3, 6, and 9).

By Generation 216, males had reached their peak performance. The following observations are notable from Table 21:

- when considering any group of females who emit signals with the set loudness, males correctly listened to the more truthful (high-pitched) signals (males listened to high-pitched signals most frequently, followed by med-pitched then low-pitched signals – regardless of pursuing quality-1, quality-5, or quality-10 females).

Table 21: Results of Generation 216

Male Brains by Generation 216									
distance			volume			pitch			output
close	med	far	soft	med	loud	high	med	low	acc. output
1	0	0	1	0	0	1	0	0	16243.283692770063
1	0	0	1	0	0	0	1	0	15167.271028406778
1	0	0	1	0	0	0	0	1	13510.238757273357
1	0	0	0	1	0	1	0	0	16575.471651680213
1	0	0	0	1	0	0	1	0	15529.657464030339
1	0	0	0	1	0	0	0	1	14595.889066139738
1	0	0	0	0	1	1	0	0	15158.461988543066
1	0	0	0	0	1	0	1	0	15029.491820616116
1	0	0	0	0	1	0	0	1	11300.6500119265

- when females sent high-pitched signals, males correctly pursued quality-5 females most often, followed by quality-1 then quality-10 females (seen by rows 1, 4, and 7).
- when females sent med-pitched signals, males correctly pursued quality-5 females most often, followed by quality-1 then quality-10 females (seen by rows 2, 5, and 8).
- when females sent low-pitched signals, males correctly pursued quality-5 females most often, followed by quality-1 then quality-10 females (seen by rows 3, 6, and 9).

After Generation 216, males' performance continued to fluctuate, as seen in Figure 23. This is because females' rewarding males and females' honesty were both probabilistic. So, even when males evolved to correctly anticipate (1) which females were most likely to reward males and (2) when females' were lying, some females behaved in atypical ways, causing males to continuously evolve and change. Nevertheless, because of the relatively stable, good performance, we consider this experiment a success.

7 Experiment 4: When To Communicate

7.1 Motivation

Experiments 1, 2, and 3 had no associated cost for sending signals. In Experiment 4, we were motivated to see how meerkats would behave when signalling had an associated cost. Specifically, we were curious if meerkats would evolve to send signals to others, even when there was initially no clear motivation to do so – the reward for signaling would have a delayed, conditional payoff. Our goal was for meerkats to evolve to only send signals to others in the cases where they were likely to receive a reward for doing so.

7.2 Environment

The environment was comprised of:

1. animats:
   - 100 asexual meerkats (mobile)
2. inanimate objects:
   - food clusters

Table 22: Experiment 4: Environment Details

parameter	**value**
meerkat signal honesty	100% honest
meerkat signal cost	variable (1, 2, or 3, depending on distance)
meerkat sensing radius	15
num initial food clusters	12
meerkat moving cost	1
food gain	2
mating style	synthetic

7.3 Approach

At each time step, a meerkat performed one of the following actions:

- send cardinal-direction signal to meerkat(s)
- move north
- move south
- move east
- move west

If a meerkat was on a food cluster, he had the option of sending signals to others in attempt to navigate them towards the food cluster. If a meerkat was not on a food cluster, he followed his received signals in attempt to navigate towards a food cluster. This is described by the following pseudo-code, from the perspective of a meerkat:

```
if i am on a food cluster {
  determine if i should send a signal to anyone (and to whom)
}

if i am not on a food cluster {
  if i received food signal(s) from others {
    follow the signal that most others are telling me
  }
  if i received no food signals {
    move randomly
  }
}
```

The actual code can be found in Appendix Part C.

When a meerkat reached a food cluster, he signalled to other meerkats the direction of his found food cluster. This can be viewed as one communicating, "Hey, food is over here." The cost a meerkat encountered for sending a signal was based on the distance the signal had to travel, as seen in Table 23.

If a meerkat m reached a food cluster (and thus listened to the signals), meerkats who sent signals to meerkat m were rewarded x, where $x = 2 * \Sigma\ cost\ of\ signal\ to\ meerkat\ m$

Table 23: Experiment 4: Signal Costs

distance to signal-receiving meerkat	signal cost
1-5 units	1
6-10 units	2
11-15 units	3

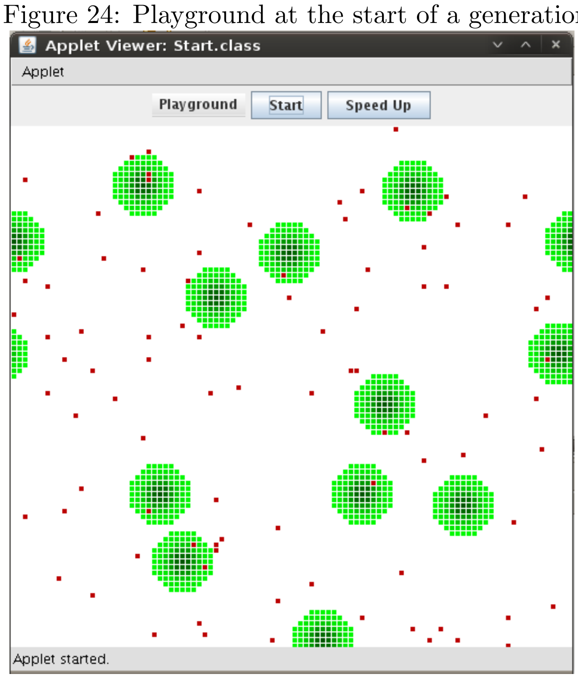
Thus, a meerkat was well-rewarded when meerkats to whom they sent signals reached his food cluster. However, meerkats should not have (1) sent signals to every meerkat or (2) sent signals continuously, for there were 2 main risks:

1. depleting one's own energy by sending too many signals (continuously sending signals would kill a meerkat quickly)
2. a signal-sending meerkat was not rewarded if a signal-receiving meerkat reached a food cluster on which the sender did not reside

Therefore, it was ideal for meerkats to evolve to only send signals when there was a strong likelihood that the signal-receiving meerkat would listen to the signal.

The playground is pictured in Figure 24. Note that the total surface area of the 12 food clusters was small enough such that during the start of each generation, approximately 15 of the 100 randomly placed meerkats were placed on non-food-cluster area. Remember though, as soon as a meerkat reached a food cluster, he then became a signal-sender who communicated to the other meerkats the location of his found food cluster.

Figure 24: Playground at the start of a generation



7.3.1 Brain

The brain is used for deciding if the meerkat will send a signal to a meerkat m, and the brain is pictured in Figure 25.

The brain had 10 input neurons:

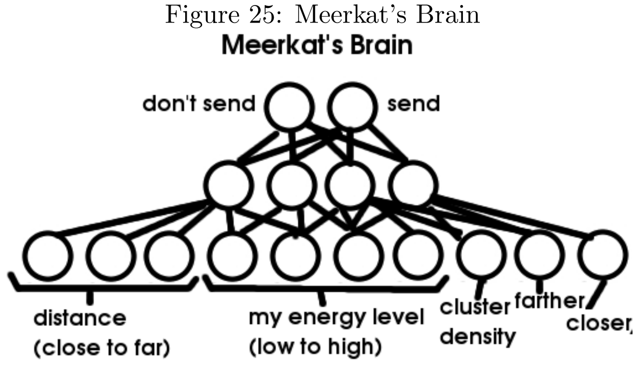
- 3 boolean-valued neurons for the distance to the meerkat to whom we are considering sending a signal
  - meerkat is 1-5 units away
  - meerkat is 6-10 units away
  - meerkat is 11-15 units way
- 4 boolean-valued neurons that concern his own energy level
  - energy is between 1 and 50
  - energy is between 51 and 100
  - energy is between 101 and 150
  - energy is greater than 151
- 1 real-valued neuron that represents the density of how many meerkats are at the current food cluster
- 1 boolean-valued neuron that represents the signal-receiving meerkat has moved farther away since last time step
- 1 boolean-valued neuron that represents the signal-receiving meerkat has moved closer to us since last time step

The brain had 2 real-valued output neurons:

- **don't send** - represents the meerkat should not send a signal to meerkat m
- **send** - represents the meerkat should send a signal to meerkat m

The meerkat performed the action of the output neuron with the higher value.

Figure 25: Meerkat's Brain



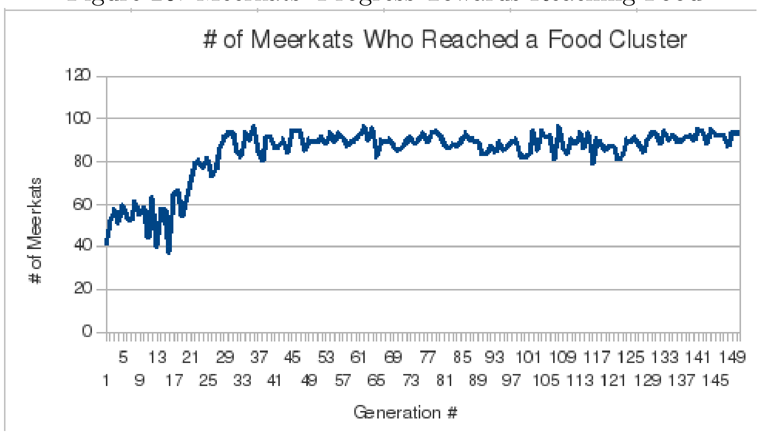
7.3.2 Mating

A generation lasted 200 time units. At the end of each generation, the 15 meerkats who had the highest energy were picked to breed with one another. The experiment lasted for 150 generations.

7.4 Results

Our experiment was a success; meerkats were able to evolve to send signals when there was a strong likelihood of receiving an eventual reward.

Figure 26: Meerkats' Progress Towards Reaching Food



During Generation 1, meerkats sent signals too frequently: 11 of the initial 15 signal-sending meerkats died due to having no energy left. Furthermore, only 41 out of the 100 meerkats resided on a food cluster by the end of Generation 1, as seen in Figure 26. Described in Table 24 are the brains of the 41 meerkats who remained at the end of Generation 1. The primary notable feature of the 41 remaining meerkats is that anytime a signal-receiving meerkat m was sensed – regardless of $m's$ situation – the meerkats would continuously send signals to m. The reasons why these 41 remaining meerkats did not die with depleted energy is because (1) they reached the food cluster shortly before the generation ended; and (2) there were only 7 remaining meerkats to whom to send signals, not all of whom were within the remaining meerkats' sensing range.

By Generation 23, meerkats improved their performance: only 4 of the initial 15 signal-sending meerkats died due to having no energy left. 78 of the 100 meerkats resided on a food cluster by the end of Generation 23, as seen in Figure 26 and described in Table 25. In Table 25, one can observe that the meerkats evolved to not signal as frequently as in Generation 1, which caused the improved survival rate. Also, the lower half of the table has more occurrences of "send" than does the upper half of the table. This shows that the meerkats sent signals slightly more frequently to those who were moving towards their food cluster instead of to those who were moving away from their food cluster.

By Generation 36, meerkats had steadily improved their performance. 92 of the 100 meerkats reached food and resided on a food cluster by the end of Generation 36, as seen in Figure 26 and described in Table 26. Table 26 shows that meerkats evolved in a such a way that only one feature primarily determined to whom a meerkat would send a signal: the direction that the signal-receiving meerkat was moving. If the signal-receiving meerkat was moving *away* from the signaler/food cluster, then the signal-sending meerkat would typically not waste his energy to communicate to him – as seen in the upper half of table. Yet, if the signal-receiving meerkat was moving *towards* the signaler/food cluster, then the signal-sending meerkat would typically take the risk of communicating to him – as seen in the lower half of the table. Oddly, when a meerkat had an amount of energy between 51 and 100, he typically sent a signal, regardless of the direction that the signal-receiving meerkat was moving. This provided the meerkats with no recognizable advantage.

Table 24: Results of Generation 1

Meerkats' Responses to Input											
distance			my energy				cluster	meerkat direction		output signal	
close	med	far	< 50	51-100	101-150	> 150	density	away	towards	don't send	send
1	0	0	1	0	0	0	0.5	1	0	6	35
1	0	0	0	1	0	0	0.5	1	0	4	37
1	0	0	0	0	1	0	0.5	1	0	3	38
1	0	0	0	0	0	1	0.5	1	0	7	34
0	1	0	1	0	0	0	0.5	1	0	5	36
0	1	0	0	1	0	0	0.5	1	0	5	36
0	1	0	0	0	1	0	0.5	1	0	3	38
0	1	0	0	0	0	1	0.5	1	0	8	33
0	0	1	1	0	0	0	0.5	1	0	7	34
0	0	1	0	1	0	0	0.5	1	0	6	35
0	0	1	0	0	1	0	0.5	1	0	4	37
0	0	1	0	0	0	1	0.5	1	0	8	33
1	0	0	1	0	0	0	0.5	0	1	2	39
1	0	0	0	1	0	0	0.5	0	1	2	39
1	0	0	0	0	1	0	0.5	0	1	1	40
1	0	0	0	0	0	1	0.5	0	1	3	38
0	1	0	1	0	0	0	0.5	0	1	3	38
0	1	0	0	1	0	0	0.5	0	1	1	40
0	1	0	0	0	1	0	0.5	0	1	3	38
0	1	0	0	0	0	1	0.5	0	1	4	37
0	0	1	1	0	0	0	0.5	0	1	6	35
0	0	1	0	1	0	0	0.5	0	1	3	38
0	0	1	0	0	1	0	0.5	0	1	4	37
0	0	1	0	0	0	1	0.5	0	1	5	36

By Generation 150, meerkats had fully evolved and demonstrated the ability to send signals strictly when there is a strong likelihood of receiving a benefit. 95 of 100 meerkats resided on food clusters by the end of Generation 150. Table 27 shows that meerkats primarily only sent signals to those who were moving towards one's food cluster, as was the case by Generation 36. In addition, by Generation 150, meerkats had evolved to send signals more frequently when they possessed higher amounts of energy. For example, the "don't send" column of the table decreases monotonically within every group of 4 rows. This shows that for any set distance, meerkats would communicate more often when they had sufficient energy to take the risk.

Also, within the lower half of Table 27, we see that meerkats more often communicated to meerkats who were farther away. The reasoning for this is that it costs more to send signals to far away meerkats than it does to send signals to close-by meerkats; thus, the reward is also greater. Anytime a signal-receiving meerkat is heading towards a signal-sending meerkat, it is worth the risk of communicating, especially when one is far away, for the reward is potentially higher. Our meerkats successfully evolved to exhibit this behavior.

8 Conclusions

We explored animat-based communication by conducting 4 experiments.

In Experiment 1, we attempted to build a foundation for communication. We encountered difficulties and

Table 25: Results of Generation 23

Meerkats' Responses to Input											
distance			my energy				cluster	meerkat direction		output signal	
close	med	far	< 50	51-100	101-150	> 150	density	away	towards	don't send	send
1	0	0	1	0	0	0	0.5	1	0	40	38
1	0	0	0	1	0	0	0.5	1	0	6	72
1	0	0	0	0	1	0	0.5	1	0	39	39
1	0	0	0	0	0	1	0.5	1	0	42	36
0	1	0	1	0	0	0	0.5	1	0	48	30
0	1	0	0	1	0	0	0.5	1	0	9	69
0	1	0	0	0	1	0	0.5	1	0	38	40
0	1	0	0	0	0	1	0.5	1	0	42	36
0	0	1	1	0	0	0	0.5	1	0	53	25
0	0	1	0	1	0	0	0.5	1	0	24	54
0	0	1	0	0	1	0	0.5	1	0	52	26
0	0	1	0	0	0	1	0.5	1	0	59	19
1	0	0	1	0	0	0	0.5	0	1	32	46
1	0	0	0	1	0	0	0.5	0	1	1	77
1	0	0	0	0	1	0	0.5	0	1	9	69
1	0	0	0	0	0	1	0.5	0	1	33	45
0	1	0	1	0	0	0	0.5	0	1	34	44
0	1	0	0	1	0	0	0.5	0	1	0	78
0	1	0	0	0	1	0	0.5	0	1	10	68
0	1	0	0	0	0	1	0.5	0	1	27	51
0	0	1	1	0	0	0	0.5	0	1	50	28
0	0	1	0	1	0	0	0.5	0	1	20	58
0	0	1	0	0	1	0	0.5	0	1	25	53
0	0	1	0	0	0	1	0.5	0	1	51	27

consequently learned the importance of providing animats with clear-cut, strong motivations for exhibiting the intended behavior. We learned that natural mating, despite being more realistic than synthetic mating, might provide challenges for agents to find one another – especially if all animats are mobile. Last, we learned not to overwhelm our agents with trying to evolve to perform too many tasks at the same time; rather, it is best to keep the environment and brain representations as simple as needed.

In Experiment 2, we explored evolving communication. We learned that it is possible for agents to unanimously evolve a dialect to speak with one another, whereby all agents agree on the same convention of which signals mean which actions. This evolution can occur even when animats are all initialized with completely random, different dialects. We also learned that allowing an animat to have more actions does not necessarily complicate the system or take longer for the animats to evolve.

In Experiment 3, we explored mate selection. We learned that animats can evolve to understand which mates offer the highest reward, and that they can appropriately pursue those "prettier" mates. Next, we learned that continuous-based signals can offer advantages over discretized signals, and that the brain representation plays a large role in which approach would be better. We learned that even when we grant female animats the ability to be picky in who they reward, male animats are able to appropriately evolve so as to pursue the ones who are most likely to offer a high reward. Essentially, the male animats are able to maximize their expected gain. Last, we learned that even when female animats have the ability to probabilistically

Table 26: Results of Generation 36

Meerkats' Responses to Input											
distance			my energy				cluster	meerkat direction		output signal	
close	med	far	< 50	51-100	101-150	> 150	density	away	towards	don't send	send
1	0	0	1	0	0	0	0.5	1	0	87	5
1	0	0	0	1	0	0	0.5	1	0	82	10
1	0	0	0	0	1	0	0.5	1	0	87	5
1	0	0	0	0	0	1	0.5	1	0	87	5
0	1	0	1	0	0	0	0.5	1	0	87	5
0	1	0	0	1	0	0	0.5	1	0	23	69
0	1	0	0	0	1	0	0.5	1	0	85	7
0	1	0	0	0	0	1	0.5	1	0	86	6
0	0	1	1	0	0	0	0.5	1	0	88	4
0	0	1	0	1	0	0	0.5	1	0	67	25
0	0	1	0	0	1	0	0.5	1	0	87	5
0	0	1	0	0	0	1	0.5	1	0	87	5
1	0	0	1	0	0	0	0.5	0	1	76	16
1	0	0	0	1	0	0	0.5	0	1	0	92
1	0	0	0	0	1	0	0.5	0	1	6	86
1	0	0	0	0	0	1	0.5	0	1	20	72
0	1	0	1	0	0	0	0.5	0	1	23	69
0	1	0	0	1	0	0	0.5	0	1	0	92
0	1	0	0	0	1	0	0.5	0	1	1	91
0	1	0	0	0	0	1	0.5	0	1	2	90
0	0	1	1	0	0	0	0.5	0	1	28	64
0	0	1	0	1	0	0	0.5	0	1	1	91
0	0	1	0	0	1	0	0.5	0	1	2	90
0	0	1	0	0	0	1	0.5	0	1	8	84

send dishonest mating calls, male animats are still able to evolve in a way to pursue females who are most likely to reward them – even while factoring in the likelihood of females' being dishonest in their mating calls.

In Experiment 4, we explored signaling when there is an associated cost. We learned that animats are able to evolve to send navigation signals to others, even when the reward for doing so is not even guaranteed, and is delayed at best. We learned that animats could evolve to communicate in a way that maximizes their expected gain.

In addition, we were exposed to and learned many other elements that went into conducting these experiments, including: the features that comprise a sound, non-fragile environment; the advantages and disadvantages of natural mating versus synthetic mating; how to make an appropriate fitness function; how to clearly quantify animats' performance; how to realistically represent the brain architectures. Most importantly, we gained an overall understanding of the work and progress that has taken place within the field of animat-based communication. We were highly pleased with our findings, and we found it to be an enjoyable project.

Table 27: Results of Generation 150

Meerkats' Responses to Input											
distance			my energy				cluster	meerkat direction		output signal	
close	med	far	< 50	51-100	101-150	> 150	density	away	towards	don't send	send
1	0	0	1	0	0	0	0.5	1	0	94	1
1	0	0	0	1	0	0	0.5	1	0	87	8
1	0	0	0	0	1	0	0.5	1	0	87	8
1	0	0	0	0	0	1	0.5	1	0	80	15
0	1	0	1	0	0	0	0.5	1	0	95	0
0	1	0	0	1	0	0	0.5	1	0	86	9
0	1	0	0	0	1	0	0.5	1	0	82	3
0	1	0	0	0	0	1	0.5	1	0	80	15
0	0	1	1	0	0	0	0.5	1	0	95	0
0	0	1	0	1	0	0	0.5	1	0	88	7
0	0	1	0	0	1	0	0.5	1	0	88	7
0	0	1	0	0	0	1	0.5	1	0	81	14
1	0	0	1	0	0	0	0.5	0	1	6	89
1	0	0	0	1	0	0	0.5	0	1	1	94
1	0	0	0	0	1	0	0.5	0	1	0	95
1	0	0	0	0	0	1	0.5	0	1	0	95
0	1	0	1	0	0	0	0.5	0	1	20	75
0	1	0	0	1	0	0	0.5	0	1	12	83
0	1	0	0	0	1	0	0.5	0	1	10	85
0	1	0	0	0	0	1	0.5	0	1	0	95
0	0	1	1	0	0	0	0.5	0	1	27	68
0	0	1	0	1	0	0	0.5	0	1	22	73
0	0	1	0	0	1	0	0.5	0	1	12	83
0	0	1	0	0	0	1	0.5	0	1	0	95

9 Acknowledgements

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A Appendix

The repository for this work can be found at `http://cs.ucla.edu/~ctanner/masters_project/`

If you have any questions, please do not hesitate to e-mail at christanner@ucla.edu

B Experiment 1: Meerkats' Thinking Process

```
public void think() {

  // check if meerkat is not in horny-mode
  if (super.sexualDrive < this.originalSexualDriveThreshold) {
    this.senses = senseNearbyFood();
    super.sexualDrive++;

  } else { // meerkat is in horny-mode
    this.senses = senseNearbyMates();
  }

  this.brain.setSenses(this.senses);
  this.brain.think(); // determines how to act
  this.brain.act(); // acts
}
```

C Experiment 4: Meerkats' Thinking Process

```
public void think() {

  // check if meerkat is on a food cluster
  if (this.isOnFoodCluster == true) {
    this.senses = senseNearbyMeerkats();
    this.brain.setSenses(this.senses);
    this.brain.thinkOfSendingSignals(); // determines if we should send any signals
    this.brain.act(); // sends signals

  } else {
    this.brain.setSenses(this.incomingSignals);
    this.brain.move(); // determines how to move
  }
```