Signaling Games

and

Meaning

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Abstract

Evolution could help language emerge from meaningless communication. In this article, we provide the theory behind the evolution of language out of meaningless communication. The theory does not only deal with plain communiaction, but also with the cost of the messages, mutation and difference between a 1:1–mapping from states to actions and a probability distribution for this mapping. Also, correlation and reputation are treated. Most of these theories we have been able to implement in an application, producing results which correspond with the theory. Some results from this research have lead to new questions, which will be good starting points for future work.

1. Introduction

Philosophers of language have deliberated for centuries about the developement of speech, communication and meaning. Is it something that distinguishes men from beast? Is this perhaps what Darwin's missing link was all about? For certain is now that we are not alone. Animals communicate, and they are doing a pretty good job. But how did they get their own languages? God did not give *them* one in Babel. This article is about how they did get one in the end and how evolution was the instrument for achieving it.
At first, the theory behind signaling games will be treated in the second chapter. After explaining the basic form of signaling games, they will be extended to more complex and sophisticated systems, setting the environment for our hypotheses in the third chapter. At some points in the theory we will relate to the program we implemented, this to clarify how our theory is represented there and with which we have performed experiments with our hypotheses.

2. Theory

2.1 The Basics

A signaling game is a simulation of communication between various individuals of a population. Every individual is in a certain 'state', e.g. it is hungry or it's seeing danger, which makes the individual send a message to another individual. This second individual recieves this message and, as a result of that message, performs a certain action. This could be either good or bad for each individual. All individuals can talk and hear: they all have a 'speaker strategy' and a 'hearer strategy'. A speaker-strategy is a mapping from a certain state to a certain message to send. A hearer strategy is another mapping, meant to determine the action that is to be performed after receiving a certain message. Every communicative act involves a speaker-strategy of one individual and a hearer-strategy of another. To clarify this idea, imagine a monkey sitting with his friend in an open spot in the forest. He sees a leopard approaching between the trees (the monkey is seeing danger, the monkey is in a certain state). The monkey alarms the others (the monkey sends a message as result of the percieved danger) and his friends hear that call. They all decide to run away (they perform an action as a result of receiving the message). As a result of the action they all survive. In the signaling game this would result in a positive utility for these individuals. This utility is a value for determining how good an action in a certain state is. In figure 2.1 a payoff-matrix is drawn to visualize the utility the speaker and hearer receive when the hearer performs a certain action when the speaker is in a certain state. As you can see, both speaker and hearer receive a utility of 1 when the hearer performs action a0 when the speaker is in state t0. If the hearer would perform action a1 when the speaker is in state t0, they both don’t get any points. This is obviously unfavorable for both of them.

	a0	a1
t0	1,1	0,0
t1	0,0	1,1

figure 2.1: A straightforward payoff-matrix

This payoff-matrix has two speaker- and hearer-strategies that receive maximum payoff. It is quite clear to see that these strategies are the ones illustrated in figure 2.2

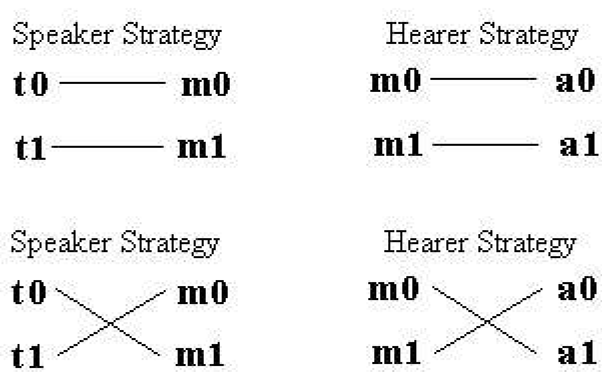


figure 2.2: The two best strategy-pairs resulting in maximum payoff

These signaling games form the tool to predict which strategies will survive in evolution. In other words, the ones that are evolutionary stable. In these evolutionary stable populations the messages have indeed become meaningful. In game theory such situations are spwcial kinds of Nash-equillibria[1]. The reason why they are special, is that in those equilibria real communication is happening. the interpetation of the messages could be "I am in state t0" as well as "Do action a0!!". Here, neither sender nor receiver can do better by unilateral deviation. With this in mind we can now indeed conclude that the two Nash-equillibria resulting from figure 1.1 are the two illustrated in figure 2.2.

2.2 Message Cost

Looking at nature we have to conclude that utility-payoff is not the only thing that determines the optimal strategies for an individual; There is also something called 'cost'. Sometimes it is necessary for the speaker to send an expensive message (one with high cost) to get a certain action performed by the hearer. The total utility for the speaker is now the subtraction of the cost of the message sent, from the value in the payoff-matrix for the action performed by the hearer. This means that sending an expensive message may, at first hand, not appear optimal, but will lead to a total payoff that is higher than the one you can get when you send the cheaper message. The situation described in figure 1.1 has been adapted and extended with a cost-matrix illustrated in figure 2.3.

Payoff-Matrix

	a0	a1
t0	5,10	0,0
t1	5,0	0,10

Cost Matrix

	m0	m1
t0	-2,0	0,0
t1	-6,0	0,0

figure 2.3: Payoff extended with costs.

The optimal strategy for these matrices is drawn in figure 2.4. Even though message m1 is cheaper than m0 it is not sent by anyone in state t0. If everyone would send m1 (which is cheaper), then the hearer cannot distinguish state t0 from t1. This way the hearer would not always get maximum payoff. If the hearer can distinguish state t0 from t1 (by receiving different messages) he can always get maximum payoff, which neutralizes the cost of the messages. This example illustrates the 'handicap-principle', more formally described by Van Rooy (2003).

Speaker Strategy	Hearer Strategy
t0 ——— m0	**m0 ——— A0**
t1 ——— m1	**m1 ——— A1**

figure 2.4: the optimal strategy for the matrices of figure 1.3

[1] A situation where the sender always sends message m0 and the reciever always performs action a0, regardless ot the state & message, is also a Nash-equilibrium. This is, however, a very unfavourable one and will, thus, be eliminated during evolution.

The results from figure 2.1 t/m 2.4 can be computed with a number of formulas. First, we state that we have three collections:

> T, the collection of possible states, with a probability P_T
> M, the collection of possible messages to be sent and
> A, the collection of possible actions to be performed (as a result of a message).

Furthermore, there exist two tables:

> Q, the communication-payoff table: $\mathrm{T} \times \mathrm{A} \rightarrow \mathbb{R}^2$
> C, the cost matrix of the message: $\mathrm{T} \times \mathrm{M} \rightarrow \mathbb{R}^2$

Then one creates a collection of individuals:

> I, with all elements from <T x M , T x A> with a probability P_I

The elements from the tuples in this collection will be denoted as Ss_i for the speaking-stategy for individual i, and Sh_i for the hearing-strategy for the individual i.
There are two probability distributions:

> P_T for T; the probability that an individual is in a certain state;
> P_I for I; the probability that two individuals communicate.

The probability that individual i communicates with individual j is independent of their strategies, so this reduces to $P_I(j)$ as follows:

$$P(h = j|s = i) = P(hearer=j\ |speaker=i\ ) = P_I(j)$$

So every individual has equal probability to communicate with individual i, there is no correlation. This is also known as random pairing.
The expected utility UP individual i gets from speaking (sending messages) is now:

$$\mathrm{UP}(i)=\sum_{j\in I} P(h=j|s=i)\sum_{t\in T} P_T(t)(Q(\mathrm{t},\mathrm{Sh}_j(\mathrm{Ss}_i(t)))[0]+C(\mathrm{t},\mathrm{Ss}_i(t))[0])$$

where [0] is the first element of the cost- or payoff-matrix, because it is the speak-strategy we're dealing with here. For the hear-strategies, the second element in the cost- or payoff-matrix would be used(that would be [1] then, as you can see below). The expected utility UH individual i gets from listening (performing actions as a result of a message recieved) is:

$$\mathrm{UH}(i)=\sum_{j\in I} P(h=i|s=j)\sum_{t\in T} P_T(t)(Q(\mathrm{t},\mathrm{Sh}_i(\mathrm{Ssj}(t)))[1]+C(\mathrm{t},\mathrm{Sh}_i(t))[1])$$

Without cost, the cost-matrix C is filled with zeros, thus the C(t,Ss_i(t))[0]) and C(t,Ss(t))[1]) is zero and can be omitted.
The total expected utility U for individual i is then the average of UP(i) and UH(i):

$$U(i)=\frac{UP(i)+UH(i)}{2}$$

and thus the expected utility of the population $E(U)$ becomes

$$E(U) = \sum_{i \in I} P_i(i)\, U(i)$$

With most instantiations of the payoff- and costmatrices, an equillibrium will be achieved at some point. From that point on, the population is evolutionary stable. This equillibrium does not necessarily have to be the optimal equillibrium; it is possible that the entire population is stuck in a local utility-optimum which is less optimal than the global utility-optimum. This stable population does not need to have meaningful communication, because of the sub-optimality of that local optimum. It depends of the instantiation of the payoff-matrices, cost-matrices and initial distribution of the different strategies whether a global optimum can and will be achieved. Only then can we speak of meaningful communication.

2.3 Mutation

Another important element of nature is the possibility of an individual changing his strategies during evolution. We all know this as *Mutation*. Mutation makes it possible that an apparently stable population is wiped out by a newly mutated individual using another strategy-pair that is more optimal in regard of the payoff-matrix. Mutation occurs in our model by altering the probabilities of a strategy. This altering of probabilities can be done in many ways, but that will be no subject here. Enough mutation makes sure the evolution of strategies doesn't get stuck in a local maximum, but lets the evolution go on to the global maximum.

2.4 Probablistic Strategies

Until now, the mapping from state to message and from message to action has been a discrete mapping. A more natural assumption would be a probabilistic strategy. There always is a chance that an animal (or human) would send a different message than the same animal (or human) in the same situation, thus there should be a probability distribution for the messages chosen from a certain state and for the actions chosen as a result of recieving a message. This distribution can be represented as in figure 2.5: here message m0 has a smaller chance of being sent in state t0 than message m1.

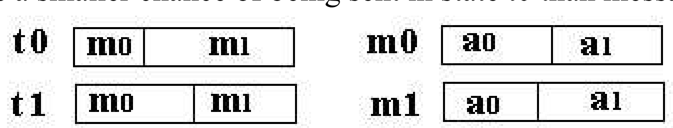


Figure 2.5: probabilistic distributions for messages and actions.

This way a more complex system of signaling could evolve; and with mutation there are an infinite number of different strategies possible. This has an impact on the utility-function too, of course. First, the collection of individuals I becomes a collection with probablistic mapping function:

I, with all elements from $\langle T \rightarrow P_M, T \rightarrow P_A \rangle$

and the utility functions for speaking and hearing become:

$$\mathrm{UP}(i)=\sum_{j\in I} P(h=j|s=i)\sum_{t\in T} P_T(t)\sum_{m\in M} Ss_i(t)(m)\left(\sum_{a\in A}\mathrm{Sh}_j(m)(a)Q(\mathrm{t,a})[0]+C(\mathrm{t,\ m})[0]\right)$$

and

$$\mathrm{UH}(i)=\sum_{j\in I} P(h=i|s=j)\sum_{t\in T} P_T(t)\sum_{m\in M} Ss_j(t)(m)\left(\sum_{a\in A}\mathrm{Sh}_i(m)(a)Q(\mathrm{t,a})[1]+C(\mathrm{t,\ m})[1]\right)$$

The formula for total utility has remained the same.

With these probabilistic mappings, it becomes possible to model ambiguity (one message to multiple actions), synonymy (multiple messages to the same action) and homomorphism (multiple messages for the same state). These three possibilities are drawn in figure 2.6, for clarity both drawn in the probability-distribution manner like fig. 2.5. and in the type-based manner (fig. 2.4).
As one might observe, there is an infinite number of different strategies. The way of dealing with this infinity is to take *N* samples at random from the infinite collection. For the first draw, the probability-distribution of the collection of individuals must be specified (e.g. random, uniform or only one individual). After evolving, we recalculate these chances again and adjust our assumption of the probability-distribution according to these new chances. The next generation will be *N* new random samples from the *N* old individuals, but now the chances for selecting individuals vary due to the adjusted probability-distribution.

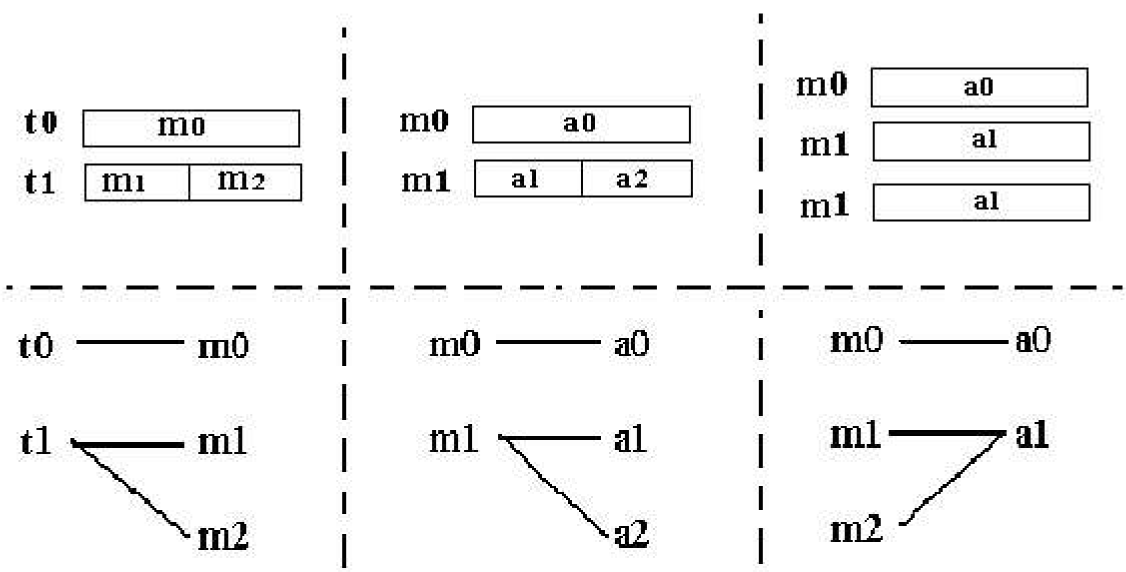


Figure 2.6: from left to right: homomorphism, ambiguity and synonomy.

The adjusted probability distribution (the distribution from the next generation) will be calculated as:

$$P'_I(i)=P_I(i)\cdot\frac{U(i)}{E(U)}$$

$P_I'(i)$ is the probability of choosing individual i for the next generation. From the new P_I' the new generation (N new samples) will randomly be chosen.

2.5 Correlation

In a very small world, all individuals will communicate with each other. But in a larger world, several populations could exist due to the fact that not every individual communicates to every other individual. Now the utility of an individual depends only on the individuals it communicates with. If these are ones which do not differ very much (in strategy) from that individual, several populations could exist in the same world, although only one would do well in a small world. The small differences in strategy would model the small differences of populations which would live close to each other (e.g. Germans are a lot more like Dutch people than Chinese). The difference in signaling strategies can thus be seen as a measure for virtual distance. The chance of communicating with a certain individual depends on the proportionality of equality of the two individuals. This is illustrated in figure 2.7. As you can see, the distribution of communication is a Gaussian distribution. The reason why we have chosen for a Gaussian distribution was because it resembles reality most. Individuals have more chance to communicate with some individual in their vicinity than one far away.

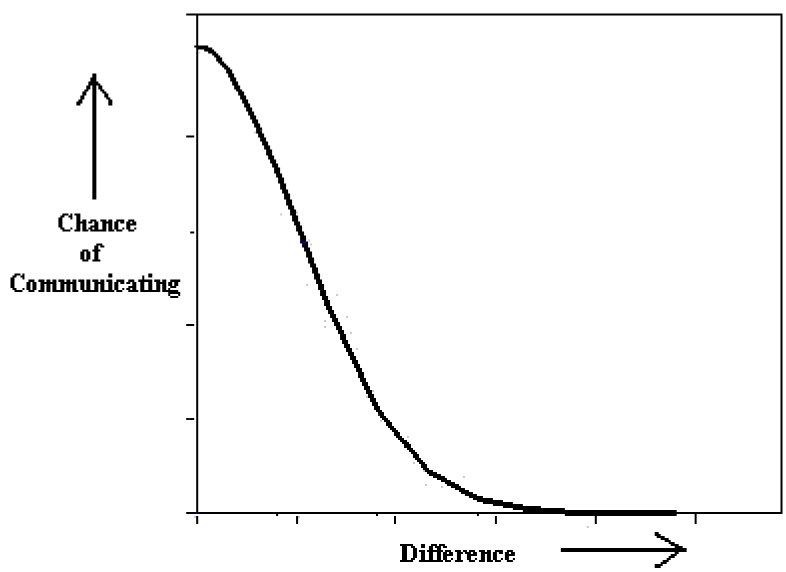


Figure 2.7: Gaussian distribution of communication

For correlation to be part of our model, the formula of the chance that individual i talks to individual j has to be altered. For this, a correlation factor c is needed too:

$$c \in \mathbb{R}$$

Then the new formula becomes:

$$P(h=j|s=i)=\frac{e^{-c\cdot d(i,j)^2}}{\sum_{k\in I} e^{-c\cdot d(i,k)^2}}$$

with *d(i,j)* as the distance between individuals:

$$d(i,j)=\sqrt{d(Ss_i, Ss_j, S, M)^2+d(Sh_i, Sh_j, M, A)^2}$$

As can be seen, the distance is based on the difference in strategies. These differences in strategies from set A to set B are calculated with

$$d(Si, Sj, A, B)=\sqrt{\sum_{a\in A} d(Si(a), Sj(a), B)^2}$$

which uses the difference in probability distributions for the set B:

$$d(Pi, Pj, B)=\int_{b\in B} \frac{|Pi(b)-Pj(b)|}{2} db$$

2.6 Reputation

Another extension of the signaling game is that each individual has a certain 'reputation'. Our way of dealing with this is to give every individual multiple hear- and speak-strategies. They determine which one they use by the reputation of the individual with whom they are communicating. For these multiple hear- ad speakstrategies, multiple payoff matrices are needed for each individual. For reputation we still have the sets *S, M* and *A*, and we need an extra set *R*: a collection of reputations. Also, we need to adjust the communication-payoff table *C* and the cost table *M*. These two now become:

$$Q : R^2 \times T \times A \rightarrow \mathbb{R}^2$$
$$C : R^2 \times T \times M \rightarrow \mathbb{R}^2$$

This means that there is a payoff-table for each reputation-couple. The collection of individuals is created in another way now too:

$$I = \langle R \times S \rightarrow P_m, R \times M \rightarrow P_a, R \rangle$$

Every individual now has its reputation *R*. The payoff-matrices used, as well as the speak- and hearstrategy, depend on the reputation of the individual it is communicating with.

3. Hypotheses

Having stated all this theory makes it possible now to formulate, in this paragraph, the hypotheses that arose during reading several articles and discussing our objectives with our supervisor, dr. R. van Rooy.

We decided not to state every straightforward example graphically over and over again and we will briefly formulate our hypotheses here. In the next chapter they will be dealt with one by one thoroughly.

- In the example mentioned first (figure 2.1) we expect two strategies to survive: either the 'straight' ones or the 'crossed' ones.
- When combining cost with handicap (figure 2.3), will the surviving population still contain individuals that use the more expensive message? We think it would, if the payoff resulting from that expensive message cancels the cost out or when the payoff is higher than the cost.
- Is it possible to simulate a population which consists mostly of individuals with an optimal, evolutionary stable strategy and for a small part of parasitic individuals? This should be possible; these parasitic individuals have a suboptimal combination of a speak- end hearstrategy and we expect those parasites only to survive by the grace of communicating with the ones with the stable strategy.
- Is it possible to simulate a population consisting entirely of individuals who try to make life as hard as possible for the others? Very likely, yes. This would happen if the payoff matrix is instantiated in such a way that speaker and hearer never get payoff at the same time – only one of the two gets payoff in a situation. There will probably no possible combination of strategies which leads to an evolutionary stable situation. We expect that every rising group will eventually be taken over by another.
- Will ambiguity, synonymy and homomorphism(fig. 2.6) emerge? With the probability-distributions of states, essages and actions, it will.
- What will correlation (Gaussian distribution of communication, fig. 2.7) result in? Correlarion will result in multiple (including suboptimal) surviving strategies and probably also "clusters" of strategies.
- Does reputation have any impact on the signalgame? If we state that it's not possible for an individual to change his reputation during evolution, and since many strategies will be based on the principle of mutual benefit from the existence of the other kind, symbiosis will be likely to emerge.
- During all the experiments carried out trying to prove the hypotheses above, one question will remain of great importance: 'Will meaningful communication emerge through evolution from meaningless communication?' Our prediction: Yes. Meaningful communication has arisen when an evolutionary stable population has evolved; the meanings of the messages sent will remain unchanged in the future. Thus, these messages have a meaning.

4. Experiments

We have done several experiments, based on the theories of the first chapter. To do these experiments, the signalling game simulator[2] that has been written for this project, was used.

4.1 A Simple Example

[2] The program can be found at: http://signalgame.blehq.org

To test our implementation of the theory, we ran our program with the most simple payoff table, as mentioned in paragraph 2.1.

	a_0	a_1
s_0	1,1	0,0
s_1	0,0	1,1

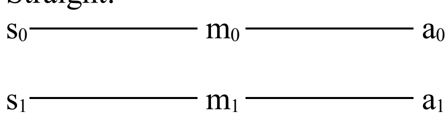
Payoff table for a simple strategy

In this example, there were no message costs, in order to keep it simple.

Results

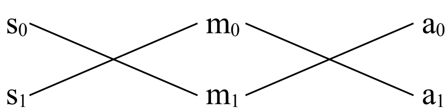
At first a uniform distribution over the probabilities of the different states and the initial uniform distribution over all instances were used. When the above payoff matrix was used no strategy performed better than the others, so the distribution did not change and no optimal unique hearer/speaker strategy emerged. This was because all the strategies were present and that all were of the same size. Because all strategies communicated with each other equally, they had the exact same utility.
When either the probabilities of the states or the initial probabilities of the strategies were non-uniformly distributed, the strategies converged to a single optimal strategy. A factor of mutation was also sufficient to get a single answer.
The winning strategies were one of the two strategies (2.1.1,2.1.2). This was expected since they are both optimal when communicating with themselves and the others.

Straight:



Strategy 4.1.1

Crossed:



Strategy 4.1.2

After multiple runs, the two strategies each occurred about 50% of the time. The one that actually emerged were random, and solely based on which of the strategies gained the upper hand first.

4.2 A simple example (with costs)

In this example, a message cost matrix was introduced into the previous simple example. Now messages could be made more rewarding, and in this way it was possible that that speaking strategies could be favored over others.

	a_0	a_1

s_0	1,1	0,0
s_1	0,0	1,1

payoff table for this example

	m_0	m_1
s_0	1,1	0,0
s_1	0,0	1,1

message cost table for this example[3]

Results

The program was run several times, with and without an equal initial distribution of states and strategies, and with and without different kinds of mutation. There was only one strategy that emerged every time as a stable population: the stable strategy was the same as strategy 4.1.1 of the former experiment.

s_0 —————— m_0 —————— a_0

s_1 —————— m_1 —————— a_1

Strategy 4.1.1

This was expected, since strategy 4.1.2 no longer had the same utility as 4.1.1: it's more rewarding to do message m_0 in state s_0 then it is to do m_1.

4.3: Correlation

Our next experiment was created with correlation in mind. A form of correlation is that populations will have the inclination to communicate more often with themselves and strategies that are similar, than they want to communicate with others. To show the effect of correlation, we did the following experiment:

	a_0	a_1
s_0	0,10	0,0
s_1	0,0	0,10

payoff table

	m_0	m_1
s_0	0,0	0.01,0
s_1	0,0	0.01,0

message cost table

These tables define a signaling game where the listeners are, again, encouraged to do action a_0 in state s_0 and a_1 in s_1. In addition, the speakers get a small bonus if they utter

[3] Note that the message cost table is not really giving costs to the messages, but gives bonuses. Costs are depicted as negative bonuses.

message m_1 in either state. Also, the state chance distribution was not completely uniform: instead, there was a 60 % chance that state s_0 would occur, and a 40 % chance that s_1 would. One would assume that the "cheaper" message m_0 would be assigned to the state that occurred more often, in order to maximize utility. This effect is known as "Horn's Division of Pragmatic Labour".

Results

The example was run with and without correlation, in order to study its effect.
Without correlation, no good signaling strategy emerged. Since the speakers did not get any points for uttering the correct message in the correct state, they were doing no better than strategies that would just utter a random message. And since the payoff for using the cheap message for a state that occurred more often was very small, it was not worth it. Now, with everyone chattering meaningless, it was optimal for the populations just to ignore the speakers, and instead always do m_1. So in the end, all surviving strategies had a different speaking strategy, and a hearing strategy from m_0 to s_1 and from m_1 to s_1.

Now, we tried the same thing with a bit of correlation. In a relatively fast pace, the amount of strategies that would ignore the incoming messages quickly decreased, and a "straight" strategy (as in 4.1.1) emerged. Why is that? Well, since the strategies now spent more time communicating to strategies that resembled themselves, it was more rewarding to be able to understand their own kind. In this way, the strategies communicated more sensibly and "ignoring" strategies were sub-optimal. This effect was also achieved with very small amounts of correlation, although it would take more time to develop a stable speaking strategy. Also, during the various runs a "crossed strategy" (4.1.2) would never survive. This means that the Horn Rule was indeed applicable to this experiment.

4.4 Handicap Example

This example has been taken from a natural situation that occurs often. The general idea is that in a certain population of animals, the males with a better 'quality' try to show that they are better than other males. These better males and their offspring have more chance to survive, because they are, for example, better at finding food. They want to make this clear to the females. The females, who otherwise cannot make a distinction between good and bad males, are better off with a good male because of the better offspring.

To make their quality clear to the females, the males can send different messages. They can choose between cheap and expensive messages: the 'cost' of these messages are that it will cost the males time, or a lot of effort. In this way it will be bad for them in the short run to use this message. The idea is that a good male can easier utter a inexpensive message, while a bad male cannot. Now if the females understand this, a system can emerge where only the good males will use the expensive messages, while the females will only mate with the males that use the expensive message. In this way, only the good males will mate. Although this is not good for the males, who would rather just use the cheap message, it is optimal for the species as a whole, because of the better offspring.

A natural example where this mechanism is clearly present is the deer. In this case, the message is not vocal, but is instead shown by the pair of antlers. The large antlers hinder them in their movement, and cost time and food to grow, and are thus expensive. So a large pair of antlers is an expensive message, while a small one is a cheap message.

We will now try to model this example using payoff and message cost tables.

	female does mate a_0	female does not mate a_1
good male s_0	5,10	0,0
bad male s_1	5,0	0,10

payoff table for this example

In this example, s_0 and s_1 are situations where the male sends a message to the female he wishes to mate with. In situation s_0, this is a good male, and in s_1 the male is bad. The actions show whether the male succeeded: namely, whether the female mates or not. From the table can be derived that the payoff for the males is 5 if they succeed, and 0 when they fail. The females get a high payoff if they mate with the good male, or succeed in avoiding the bad male.

	High cost message m_0	Low cost message m_1
good male s_0	-2½,0	0,0
bad male s_1	-5,0	0,0

message cost table for this example[4]

Both kind of males have to pay for sending an expensive message, but it is easier for the good male, which results in a lower penalty for him. It costs nothing to send the cheap message, nor does it cost anything for the female to hear -or see- the message.

The expected outcome would be the strategy 4.4.1 below. This strategy means that all good males will send the high cost messages and that the females always respond to this message by mating with them. The same for the bad males, they will always send the low cost message and the females will ignore them.

s_0 ———— m_0 ———— a_0

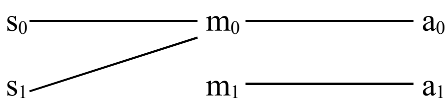
s_1 ———— m_1 ———— a_1

Strategy 4.4.1: a healthy population

[4] The algorithm can't handle the negative values in the cost matrix so to all values should be added 5 to compensate this.

Results

After doing the tests with the above setting, the mentioned outcome surfaced indeed. However there was another group of species that stabilized itself together with the others, namely strategy 4.4.2:



Strategy 4.4.2: braggers

In this strategy all females had the same hearing strategy as those in strategy 4.4.1, so they could mate perfectly well with all good males from the large group of 4.4.1. The strategy of the males differed: the bad males did try to send the high cost message to the females, which worked out because the females were willing to believe that all information was correct. Thus, the males were actually lying to the females. This group of “braggers” had to be small though, and it was dependent on the larger group with strategy 4.4.1. If the group of “braggers” became too big, the females could rely too little on the messages of the males, and the population of “braggers” would become less again. In this way, equilibrium emerged between strategy 4.4.1 and strategy 4.4.2.
Without mutation, the exact size of the groups in this equilibrium depended on the initial distribution of the strategies. With mutation though, the size of the groups would converge to the same equilibrium: with a uniform state distribution (which means, the number of good and bad males is equal), the entire population would always consist of:
Strategy 4.4.1: 84 %
Strategy 4.4.2: 16 %

4.5 The Vervet Monkey Example

This example was also modeled after an interesting example taken from nature. The vervet monkey is a certain kind of monkey, found in Kenya. It has an impressive signaling system to warn their kin about predators that walk in their territory. They are known to have several different calls for different threats, and they also have a few different ways of handling these threats, and thus different interpretations for different calls. This is exactly what we are mainly trying to model with our program, so it is an important example to consider.

For simplicity’s sake, we will only consider 2 states: “danger” and “no danger”. More states will only complicate things, and it will not add meaning anything to this particular example.

So, again, two matrixes were constructed to model this problem.

	run away a_0	stay a_1
danger s_0	1,4	-5,-5
no danger s_1	-2,-2	1,4

payoff table

As can be seen in the table, both hearer and listener were encouraged to use the alarm call for states of danger, and to stay silent when no threat was present. The speaker also got a minor bonus if they could warn the others, because the other monkeys could reward him with, for instance, with a pat on the back.
Note that staying silent while danger is present is very bad, for it would mean that the listening monkey would be eaten.

	use alarm call a_0	stay silent a_1
danger s_0	-3,0	0,0
no danger s_1	-3,0	0,0

message cost table

This table is pretty straightforward: hearing a message is free, as is staying silent. The uttering of the alarm call is pretty expensive though, since that monkey would be attracting the attention of the predator on himself.

In nature, it is not common that a predator would be present, thus we also had to adjust the a priori chance a certain state would occur. We chose for a chance of 10 % for the danger state, and 90 % for the safe state.
This non – uniform state chance, in conjunction with one expensive message is similar to the example given in paragraph 4.3. Thus we would expect that Horn's Division of Pragmatic Labour would again apply, and the "stay silent" message would be used for the most common state, e.g. state s_1.
All in all, we expected that a sound signaling strategy would emerge, namely the "straight" strategy (4.1.1).

Results

This was not the case. No single strategy would emerge, but instead the results were quite chaotic. The signaling system would sometimes emerge, but it would immediately be overrun by "parasites". These parasitic strategies would have a hearing system that was identical to the "straight" one, but instead of using correct messages, they would choose to always use the message that was the cheapest. In this way, they would not have to use the expensive message, while they could still benefit from the group that used a "straight" system: hence, the name "parasites". The utility of the parasites was higher, and the result was that, at a certain moment, there were too many parasites. Other strategies would emerge that did not listen at all, thus all sensible communication would be lost once again. No stable population would survive.

So, what went wrong? To answer this question, we can look at the natural example where this example was taken from: the vervet monkey. The creatures live in small colonies that are cut off from each other. They will mostly communicate with their own group, which largely exists of relatives. Thus, there is a certain amount of correlation present that forces the monkeys to understand the language that they speak themselves.

Thus we ran the simulation again, but now with a high correlation rate of 100. Now, the parasites would be ignored by the sound signaling system, and now the straight signaling system could survive.

If we tried a lower correlation rate of 10 instead, another interesting phenomenon took place: the parasites and the signaling system would form an equilibrium that would stay stable or shift very slowly. So while the parasitic influence was not strong enough to take over the "straight" system, neither was it too weak to not be present at all.

5. Conclusions

Before starting to draw conclusions from the experimental results described in chapter two the following two gradations have to be stated. The application created and used by us was mostly based on existing theories as described in chapter one. For a small part however, assumptions concerning modeling had to be made. This might appear unscientific, but in consultation with R. van Rooy we made decisions that seemed liable to us.

Above all:

- Meaningful communication can emerge in a population where individuals originally communicate senselessly. This is achieved through evolution based on rewards given to successful messages sent and actions taken.

Furthermore:

- Carrying out the first example (figure 1.1) always resulted in an evolutionary stable population, consisting of either the 'straight' ones or the 'crossed' ones. The surviving one of these two depends of the instantiation of the population at the start.
- Combining cost with handicap (figure 1.3) can produce a surviving population which consisted of individuals who use the more expensive message. This depends on the payoff matrix, however. The benefits of using the expensive message should be equal or larger than the cost of this message. Only then could it be fruitful to use the expensive message.
- We have been successful in simulating an environment where a small parasetic group of individuals could coexist with the large, most successfull group. The

eventual percentage of parasites is proportional to the chosen values in the payoff-matrix & cost matrix. We will digress on this in chapter six, Future Work.

- A population consisting entirely of parasites has been possible to simulate, yet the only conclusion drawn from this is that there will never be a stable population. Every rising population will eventually be taken over by another.
- Synonymy and homomorphism (fig. 1.6) can be created with the probability-distributions for states, messages and actions. We have not been able to model ambiguity. This is, as we believe, due to the fact that two states never are completely equal; there is always a small difference, how minimal it might be, between two states.
- Correlation (Gaussian distribution of communication, fig. 1.7) results in multiple (including suboptimal) surviving strategies.

6. Future Work

As we have encountered during the search for good payoff- and costmatrixes to model different aspects of nature, small differdences in the payoff- and costmatrixes can result in a completely different population. It can be an interesting piece of research to predict mathematically what the outcome may be, instead of using common sense. A mathematical model might be created, and threshold-values can be found. With threshold-values we mean the value in the payoff- or costmatrix from where the population which emerges is significantlty diferent.

Due to lack of time, though we have been able to model reputation, we're not sure yet what to expect from certain payoff matrices, so the results from the application could not be checked. This is an excellent field of research, since reputation is a very important aspect in nature. Everywhere where there are groups of animals, there exists some sort of reputation system, with (usually) one animal as the big boss of the group. The prescence of reputation in the model could have a significant effect on the evolving meanings.

All we have treated and produced is of course just a prelude to the examination of developement of human language. An important difference between our model and real (human) language is that real (human) language has words and sentences. Words are composed of several diferent sounds, and sentences in their turn of several words. Our model only deals with "messages", which could be seen as a single sound. When these sounds could be combined, more different messages could be sent using the same amount of sounds (Nowak & Krakauer, 1999). This way, words could be created. We have not been able to implement this in our aplication, but it would be a good topic for future research. A problem which might occur however, is the extreme increase in computational complexity. When words can be created using these sounds (messages) the possible amount of strategies with the type-based approach is already infinite. With the probability-based approach it will be even more complex.

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