Social Learning through Evolution of Language

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Abstract. This paper presents an approach to simulating the evolution of language in which communication is viewed as an emerging phenomenon with both genetic and social components. A model is presented in which a population of agents is able to evolve a shared grammatical language from a purely lexical one, with critical elements of the faculty of language developed as a result of the need to navigate in and exchange information about the environment.

1 Introduction

This paper discusses the evolution of language in societies of learning agents exposed to evolutionary pressure, and the impact the emerging social phenomenon of language has on the agents' performance on the task being learned.

There has been a lot of interest in adaptive and learning agents and multi-agent systems recently, with learning of co-ordination, timeliness of learning, combining evolutionary adaptation with individual learning and the learning of communication among the issues at the focus of attention [1]. Language has a dual role in societies of learning agents, as its concepts are a means of communicating knowledge, yet they also represent a repository of knowledge distributed among its speakers, but almost never present as a whole in the memory of anyone of them. Language is a powerful tool where cooperation is needed. In an evolutionary set-up where individuals of a species compete for survival, a speech act disclosing the location of valuable resources can be seen as altruistic, as it helps the listener at the speaker’s expense. Altruism directed to relatives has been observed in nature [2] and proven to be evolutionary viable in computer simulations [3]. Here language will be seen as a form of kinship-driven altruism.

This paper builds on our earlier suggestion that some of the origins of human language can be found in the need to share information about the environment, which could result in a proto-language, the grammatical structure of which copies the structure of the landscape [4]. In a research review published shortly after, Hauser, Chomsky and Fitch [5] consider navigation as one possible computational problem, the solution to which required the evolution of recursion, which they assume to be the only uniquely human component of the faculty of language. Their paper also suggests a possible link between the abilities needed for
optimal foraging and computationally efficient processing of language. In a more general way, the suggestion that “language could have developed as a means of transferring information about the spatial aspects of the environment (how to get somewhere, how to find food)” appears as early as 1978, in a footnote in O’Keefe and Nadel’s book [6]. We shall describe one possible mechanism through which language grounded in the environment could emerge, and study the impact that language has on the generic learning task of any living creature, namely, to increase success in survival and reproduction.

2 Simulations of the Evolution of Language

In recent years, there has been much research carried out in attempting to model the evolution of language through computer simulation. This research falls broadly into two classes, simulations in which language emerges in a single generation and simulations concerned with evolving a language over several generations.

In the former class, one of the most prominent researchers is Steels [7]. In his simulations, a population manages to arrive at a single, shared lexical language through participating in a series of ‘language games’. In a language game, two agents both discuss an object visible to them. If they can agree on a word (or set of words) to describe that object, then they both increase the weight they associate with that word/meaning pair. After many language games involving different agents, a shared global lexicon emerges. Batali also presents an interesting simulation in which a language emerges [8]. In this case, a compositional language occurs through a series of language games. The mechanisms for playing the games and the memory that the agents possess is significantly different in the two simulations, but in both cases a globally understood language emerges from a series of local interactions.

Amongst those studying languages which are created over several generations, Kirby’s simulations [9] are amongst the most compelling, though Zuidema & Hogeweg [10] and Oliphant & Batali [11] also present interesting results. In Kirby’s simulations, a single agent attempts to express (resorting to invention if necessary) a subset of meanings sampled from a set of meanings expressed in predicate calculus while another agent attempts to learn to speak based on the linguistic output paired with the expressed meaning of the first agent. The agent which listened is then required to speak in the same way as the first agent, while its output is learned by yet another agent. After thousands of cycles of this expression/induction behaviour, a grammar with the minimum number of necessary rules is seen to emerge and persist from generation to generation. Kirby attributes this to the ‘linguistic bottleneck’ that prevents the observation of all meanings by a single agent. Only compositional grammars can successfully pass through this bottleneck, as idiosyncratic phrases present in a grammar may fail to be expressed at some cycle and be lost from the language. This explanation for the emergence of grammar differs considerably from the views expressed by many linguists, most notably Chomsky, who suggest that humans have become adapted to language, rather than language adapting to humans.
Chomsky suggested that a learning bias facilitating the acquisition of language is present in humans in the form of a highly specialised Language Acquisition Device (LAD) [12, 13]. Learning a language by children exposed to it then would only require setting the specific parameters of the LAD in order to acquire an appropriate model (grammar) [14].

Our approach differs from all of those simulations mentioned above in several important aspects. Primarily, we see language as a tool to achieve some purpose. This means that we can consider issues such as when language will come to be used by a population, whereas other researchers have simply assumed that language is beneficial and sidestepped these issues. We also differ in our approach by assuming that the meaning of an utterance must be inferred from its context. The majority of previous research has explicitly given agents the signal and the meaning that it represents. We propose to remove this, instead having agents deduce the meaning of a signal based on the context within which it is used. Finally, we have agents subject to natural selection based on properties not directly linked to their linguistic ability. In other research, either agents have been selected directly for their ability to speak (making the results striking yet inevitable) or no selection of agents has been used (either the population is static or all agents are removed with equal probability).

3 Altruism and Neo-Darwinism

Our research is based within the domain of simulating learned communication systems. Here of particular interest is the issue of why any individual should develop or choose to use such a system to speak. More specifically, we present a framework in which the urge to use language is seen as an inherited feature selected by evolution, while language itself is a social phenomenon that is passed on through interaction rather than genetically inherited. Clearly, an entity that is able to use such a communication system to understand the meanings of others’ speech is at an advantage, as it can gain information through the work of others rather than its own toil. However, it is less apparent why an individual should choose to speak, when this will clearly give others an advantage that this one has had to work hard to gain.

In Darwinian terms, by helping others with no obvious benefit to itself, the individual has acted altruistically, decreasing its own fitness relative to that of others, and therefore we would expect such behaviour to be selected against by nature. However, the existence of human language clearly shows that in at least one case natural selection has acted opposite to this expectation. Researchers studying learned languages have not studied this question, but several researchers [15, 16] have looked at similar problems in the domain of innate communication systems and we look to this work for possible approaches. They have found that, in their most abstract models, communication does indeed seem to be selected against if an agent can choose not to speak without penalty. However, there are possible modifications to these systems that seem to encourage communication to occur. A spatial distribution is one such modification that can be applied, with agents interacting more with those spatially adjacent to them.
This promotes reciprocal altruism, in which both entities benefit by cooperating rather than competing.

Another possible explanation is to look at the issue of altruism from a Neo-Darwinian perspective. Hamilton [17] shows us that if we view the basic element of evolution not as the individual, but as the gene, we find that natural selection may actually favour selfless acts in the form of kinship-driven altruism. This form of altruism involves helping relatives proportionally to their degree of kinship to the altruistic entity. For instance, should such an entity die saving the lives of three of its children, there will probably be more copies of its genes remaining alive than if it had preserved its own life. Through this mechanism, a hypothetical gene promoting altruism would be able to spread itself. We begin our current work assuming that altruism has been promoted and fixed in the environment as has been shown in our previous work [3].

4 Evolution of Language in Multi-Agent Systems

We have chosen to simulate the evolution of language within a multi-agent system (MAS) setting. This allows us to simulate with ease many of the potentially relevant phenomena, such as the density and spatial distribution of agents (language speakers) and resources, along with the degree of agents' mobility. The MAS framework also permits to study the behaviour and social (both verbal and non-verbal) acts of each and every individual, if necessary.

Simulations of the evolution of language using the multi-agent paradigm can be of interest to the designer of any general-purpose agent-based applications. In a dynamic environment that changes considerably during an agent's lifetime, the faculty of learning could be essential to its success. Machine learning techniques could be used for this purpose [1]. Learning biases that specify the range of possible hypotheses are indispensable in machine learning, and their choice is crucial to the success of any of its algorithms. In an evolutionary MAS setting, sexual reproduction and mutation can be used to explore a range of possible learning biases, from which natural selection would choose the best. Evolution in the MAS can follow the Darwinian principle that individual experience cannot change one's genes. One would expect Darwinian evolution to advance in small steps, and select only very general concepts, as they would have to remain useful for many generations. One could also implement Lamarckian evolution: use a MAS in which the parents' experience can be reflected in the learning bias inherited by their offspring. Lamarckian evolution is faster, but brings the risks of inheriting too specific concepts based on the parents' personal experience.

This work explores yet another, third, way of evolving a learning bias that is open to populations of agents able to communicate. Language uses concepts that are specific enough to be useful in the description of a variety of aspects of the agent's environment (including other agents), yet general enough to correspond to shared experience. In this way, the concepts of a language serve as a bias used to describe the world that is inherited through social interaction rather than genes. However, to preserve the additional advantage that the use of language
brings about in the case of a changing environment, the MAS designer should allow the language to evolve.

5 The York Multi-Agent Environment

The York Multi-Agent Environment [18] is a general-purpose Java-based platform for the simulation of learning and natural selection in a community of agents. The system draws a parallel with the world of nature. It provides tools for the specification of a two-dimensional environment with a range of features, such as different types of terrain, landmarks, food and water resources. The environment consists of a number of squares, each of which can hold up to four agents. The user can edit to a large extent the specification of each of a number of species of agents—what they eat, what types of sensors they possess. A snapshot of an ongoing experiment is shown in figure 1.

The agents have a default, hard-coded behaviour, which can be used as a baseline reference in the evaluation of learning. The behaviour is based on the notion of “drives”, which represent the intensity of each of the agents’ basic needs. There are three such drives used in the current implementation: hunger, thirst and sex drive. At each step, after a payment of energy is made to remain alive, the drives are evaluated and an appropriate action is taken. If at the beginning of a time step an agent finds itself to be hungry, it will attempt to find food. Likewise, if it is thirsty it will endeavour to find water. Should an agent require both food and water it will deal with the more pressing need. Utilising a resource will reduce the appropriate drive back to its minimum level.

If two agents sharing a location have adequately low levels of hunger and thirst, they can have offspring if their sex drive is sufficiently high and they can afford the cost of reproduction, which is subtracted as a payment from their energy levels. The offspring created has initial energy levels equal to the parents’ cost of mating.

6 Evolving Songlines

Our approach was initially inspired by Chatwin’s description of songlines [19], a form of oral tradition among Australian aboriginal tribes. Songlines reflect a belief that “Ancestral Beings roamed once the face of the earth, creating the features of the landscape... along the tracks that mark their journeys [20].” Songs and dances often function as title deeds to land, recording myths about the creation of particular sites. In the grouping of songs into series, “the most pervasive is the geographical organisation of songlines, where each ‘small song’ equates with a different site along an ancestral journey, and the series as a whole constitutes a sung map [20].” In our simplified interpretation, a songline describes a fixed migration route of a group of individuals as a list of landmarks, the evocative names (and descriptions) of which help unassisted recognition.

Disclosing the songline to outsiders is often strictly prohibited. One could see this as an attempt to protect the tribal knowledge about the location of scarce resources. Nevertheless, there are situations in which members of different tribes
may decide to exchange parts of their songlines. From our point of view, sharing
the knowledge of a songline within the tribe can be seen as a form of kinship-
driven altruism, and inter-tribal exchange of songlines as reciprocal altruism.
The main characteristics of our approach are as follows:

- Use a MAS to simulate the evolution of language;
- Assume that altruistic behaviour between relatives (i.e., kinship-driven altruism) exists in the population, e.g., has been promoted by natural selection as demonstrated in our previous work [9]. In fact all agents behave as if clones sharing a single genotype;
- Set the agents to perform an altruistic act of sharing information about the location of resources in the environment. These resources are exhaustible, but when depleted will renew themselves after a period of time.

Information about resource location is shared in the form of paths, consisting of sequences of landmarks that are to be seen along the way to the target destina-
tion. Though the act of communication incurs no direct energy cost for the speaker, sharing information about resource location is clearly an altruistic act for two reasons. Firstly, it is likely to increase the fitness of the receiver, who will subsequently know the location of more resources and, secondly, the speaker is likely to have more difficulty in surviving, as it has to share the exhaustible resources with the receiver.

Landmarks are identified by unique names, which are shared by the whole population. The names are not derived from the landmark properties. There are two ways in which an agent may acquire a new path; it may find one through exploration, or it be given one linguistically by another agent. In both cases, rules are stored internally as a grammar rule of the form:

\[ \text{goto}\{\text{Target Resource}\} \rightarrow \text{goto}\{\text{Pos}(X)\} , L_1, L_2, \ldots, L_n \]

where \( L_i \) are landmark names, and \( \text{Pos}(X) \) is the current position of the listener defined by the snapshot of its surroundings, stored as a matrix of the visible landmarks with the vision range limited. Rules of the above form can be interpreted either as procedural rules guiding the agent from location \( X \) to resource of the given type or, alternatively, as grammar rules of a regular language.

It should be noted that the description of path chosen is a relatively impoverished one. So, for instance, no absolute or relative co-ordinates of landmarks are used, neither is the direction to follow or distance between consecutive landmarks described. The assumption made is that each landmark would be visible from the previous (or random exploration would be needed to find it).

In addition to the rules of the form presented above, it is vital that an agent can travel to the beginning point of a path: without a rule that states how to arrive at \( \text{Pos}(X) \), the rule is of little practical use. To this end, agents collect and store information about the landmarks they pass while wandering around the environment in a short-term memory, which is distinct from its knowledge of grammar rules. When a position of some importance is reached, this sequence of landmarks is used to add a new grammar rule to the agent’s knowledge stating...
the path between the locations in question. For example, an agent may begin at position $Pos(A)$ and randomly pass landmarks $L_1, L_2$ and $L_3$ before arriving at a significant position, $Pos(B)$. The following rule will then be added to the agent’s knowledge base:

\[
goto(Pos(B)) \rightarrow \goto(Pos(A)), L_1, L_2, L_3
\]

This rule states that to travel to $Pos(B)$ is equivalent to travelling to $Pos(A)$ and then passing the given landmarks in order. Additionally the inverse of the rule is also added allowing the agent to return from $Pos(A)$ to $Pos(B)$. A rule will also be added to explain why this point is of interest, namely which resource it contains:

\[
goto(food) \rightarrow \goto(Pos(B))
\]

To access the information stored in the grammar in order to reach resources, the agent will need to generate a sequence of landmarks from the grammar, which will form a path that the agent can follow. This is done by using the grammar to generate a list consisting of only landmark names. The starting rule for this process is one of the rules with the left-hand side of $goto(TargetResource)$. These rules are kept in a queue with the first rule taken when one is needed and then returned to the rear. Enqueuing the rules in this way ensures agents do not become dependent on a small number of resources, but explore the environment more fully. In order that the parsing does not recurse indefinitely, an additional rule is needed stating that going to the current location of the agent can be rewritten as an empty sequence of landmarks. The parsing takes place using an A* search, with the metric based on the length of the path; this guarantees agents take the shortest route of which they are aware. As a route between the agent’s current position and the resource it wishes to find may consist of following several sections of path (e.g. an agent may have to go from point A to point B to point C), the grammar is compositional: an agent will need to compose the rules to get from A to B with the rule to get from B to C in order to get from A to C. Furthermore, an agent may initially use one route to get from A to C, but on acquiring a shorter route between B and C, will change the route it takes between A and C appropriately.

When a pair of agents meet at a point, they may exchange routes to resources. As stated earlier, this is viewed as an altruistic act that has been previously promoted by evolution. Generating a route for exchange is carried out using exactly the same process that an agent would implement if generating the route for its own use. This route is subsequently passed to the other agent, who stores it as a rule of a similar form to those shown above. Whether the route generated leads to food or water is decided before the interaction occurs based on the needs of the agents concerned. This ensures that the agent receiving the route knows whether to follow the route when it is hungry or when it is thirsty.

7 Results and Evaluation

Intuitively, one would expect to find a relationship between the range of sight that the agents possess and the frequency of landmarks in the environment, on
one hand, and the usefulness of the path representation chosen, on the other. For instance, communication might be expected to provide the greatest benefit when the resources are spaced so they are frequently out of sight, and if one landmark is not so far from another than meaningful descriptions of paths become impossible.

If, in a given environment, linguistic descriptions prove useful, i.e., storing and exchanging them promotes the survival of the agents involved, one would expect to observe the following two phenomena:

- Agents possess sets of rules describing paths, which ultimately lead to a useful resource;
- This set of rules can be seen as a proto-language, the grammatical structure of which copies the structure of the landscape.

Evaluation of the benefits of language was conducted using the environment shown in figure 1. Agents had a range of sight set to two squares in all directions (including diagonally). This prevented agents from observing a food resource when close to a water resource, but ensured plentiful landmarks by which to navigate. To compensate for the wide spacing between resources, agents had their exploration algorithm biased to give them a tendency to travel in a straight line with a probability of deviating left or right at each step. The environment was initially loaded with many more (uniformly distributed) agents than the resources were able to sustain in the long term. This overloading of the environment ensured that meetings between pairs of agents was frequent early in the simulation, since without these meetings language would not have been used and thus be of no consequence to the simulation. The criteria used to measure any benefit that language provides to the community of speakers was to record population size and total energy (and water) of the population, and to compare this to a control population in which there was no exchange of information, but otherwise behaved identically: our hypothesis was that language evolution is a form of multi-agent learning which allows a population to improve performance as measured by its exploitation of resources.

The results of our experiment (as shown in figures 2, 3 and 4) clearly show a significant improvement in performance by the population of agents capable of using language. In this experiment, the maximum lifetime of an agent was set to be 300 cycles: if an agent had not died of hunger or thirst after this time, it died as a result of old age. At the end of the simulation run shown, the agents remaining in the population must be at least the fourth generation. Though both populations initially decline greatly in number (as was predicted due to the overloading of the environment), the population able to use language fairs better over the course of several generations than the other population, which in many cases dies out entirely by the third generation.

It is not difficult to see some of the potential benefits of language a priori due to the way in which an agent is able to survive. In the system without language, the only method of survival is for an agent to locate both resources by randomly discovering them while wandering in the environment, and then following the memorised paths. The probability of an agent surviving in a later generation is very similar to the probability of an agent surviving in the initial
population, as it faces the same challenges of locating resources that the earlier
generation had. In the population where language was not suppressed, agents in
the initial population had to locate the resources through exploration in much
the same way as those in a population without language (though some agents
unable to find the resources may be directed to them by more successful agents).
However in later generations an agent is able to learn of the location of resources
from its parents through language, and hence the survival rate of agents born
into later generations of the speaking population is far greater due to the fact
less exploration is needed. It was possible however, that sharing knowledge about
resources could lead to a population with similar, very low levels of energy below
the minimum needed for reproduction: while language could help more agents to
survive, this population could be less viable in the long term due to an inability
to reproduce.

A separate form of evaluation is possible in which we examine the language
as interesting in its own right, instead of viewing it as merely the way in which
information is exchanged. By observing the internal language (set of rules) of
each agent, one can measure the similarity between the languages used by each
pair of agents as the ratio of shared rules and (hierarchically) cluster all agents
accordingly. If agents are split into a set of mutually exclusive clusters, all agents
within the same cluster can be seen as speakers of the same, shared language. In
this case, language is seen as a social artefact that only exists in the community
of its speakers.

In a second environment in which food and water were more plentiful and
more evenly spread than in the previous experiment, simulations were run to
examine the type of language which emerged. Reproduction was not used in
these experiments, as the aim was to observe how the language spoken by agents
changed over time, and the addition of new agents to the population could alter
the way agents clustered. Our aim was not to study the advantage language gave
in some task, hence only agents capable of language were studied without using
non-speaking agents and no record of population dynamics was kept. Cluster
diagrams resulting from a single run of this experiment are shown in figures
6–7. The diagrams show that the agents spontaneously arrange themselves into
various distinct subsets, which manage to persist over time. Most of the agents
which are closely related in the initial graph are still close in the latter graph,
in most cases still clustering most tightly with the same agent, though some
agents such as 50 and 21 do migrate to different groups. The difference between
cluster diagrams for an environment with more resources which are more easily
found, and that for an environment with lower numbers of resources is very
apparent. When several food and water sources are available, the community
splits into well-defined subsets each of which is linguistically distinct from the
others. In contrast, when few resources are available, less well-defined groups
are formed, with little distance between them. This is due to the fact that when
many resources are available, agents find it possible to exist in a sub-region of
the environment having little contact with the larger community.
Fig. 1. The York Multi-Agent Environment. Agents are shown in white, water resources in light grey, food resources in black and landmarks in dark grey.

Fig. 2. Population size of communicating and non-communicating groups of agents.

Fig. 3. Food levels of communicating and non-communicating groups of agents.

Fig. 4. Water levels of communicating and non-communicating groups of agents.

Fig. 5. Clustering by agent (after 40 cycles) for an environment with single food and water resources. Agents are referred to by their unique identifying numbers on the x-axis. Y-axis shows the number of different rules between clusters.

Fig. 6. Clustering by agent (after 80 cycles) for an environment with multiple resources.

Fig. 7. Clustering by agent (after 100 cycles) for an environment with multiple resources.
In the sparser environment however, agents are forced into having similar grammars, as all rules gained will mention a small amount of significant places common to all individuals.

Linking the properties of language to the environment in which it emerged has a precedent. Pagel [21] presents a detailed account of the variation of diversity of human languages in relation to environmental properties, such as latitude and number of habitats. He also demonstrates the correlation between linguistic diversity and genetic diversity (number of species) in a given ecosystem. One observation of particular interest is the reference to Birdsall's discovery that the density of Australian aboriginal languages is higher in wetter areas [22]. This is variously explained as a result of the higher potential of the environment to sustain more groups that are self-sufficient or due to migration towards richer areas.

8 Conclusions and Future Work

We have outlined in this paper one possible system whereby a useful simple compositional language is able to emerge from a purely lexical one. Furthermore, we have shown that the existence of such a language can improve the performance of agents able to use it. Our presented experiments have hinted at the possibility of language becoming severed into different mutually unintelligible communities under some conditions, a direction worth exploring further in the future.

Though currently, there is no explicit ranking of rules based on their usefulness in finding resources, a system does emerge whereby some rules are used more frequently and in preference to others. This occurs in situations where an agent has several rules for travelling between a single pair of points. In this situation, the route with the shorter length (i.e. the least number of landmarks) will always be chosen in preference to the other due to the metric used in the parsing process. Future improvements to the system would involve making such ranking explicit. Rules could then be pruned when found to be of little or no continuing use. This would prevent the apparent linguistic difference between agents speaking the same dialect increasing with time, even though they possess very similar knowledge. For similar reasons, it is important that duplicated information be removed from the grammar. This produces an unnecessary degree of separation between agents when they are clustered, and severely slows the speed of simulation. These changes would not lead to change in the behaviour of the system, however the grammar could also be acted on by some process of induction, with the aim of both reducing its size and producing new knowledge not previously held.

At present, we have assumed that landmarks can be distinguished between by globally recognised words. In our ongoing work, we intend to remove this condition and investigate a situation in which the same name is used for all landmarks of the same type, and these names are evolved through a process of negotiation as in Luc Steels' work [7] at the same time as the routes between resources are discovered.
References
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