

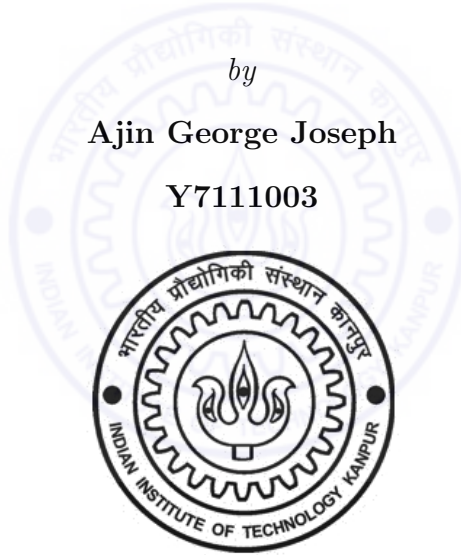
LANGUAGE LEARNING IN ARTIFICIAL
AGENTS: FROM LEXICON TO
COMPOSITIONALITY

A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of
Master of Technology

by

Ajin George Joseph

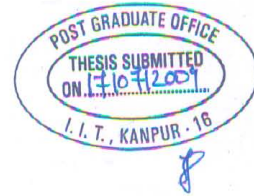
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to the

DEPARTMENT OF COMPUTER SCIENCE AND ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

June 2009



CERTIFICATE

This is to certify that the work contained in the thesis entitled "*Language learning in artificial agents: from lexicon to compositionality*" by *Ajin George Joseph* has been carried out under my supervision.

July 2009

A handwritten signature in black ink, appearing to read "Karnick".

Dr. Harish Karnick

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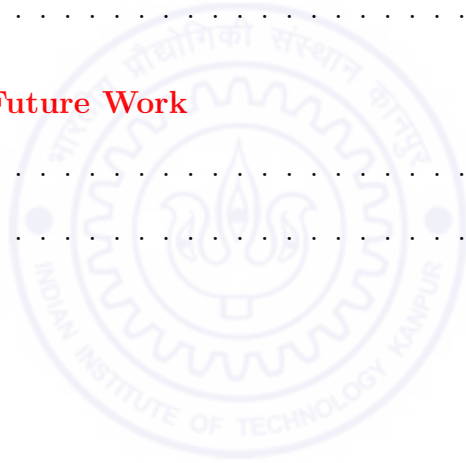
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Abstract

The emergence of language is a breakthrough event in the evolution of humans. It revolutionized the way we think, perceive and interact. The study of language origin and evolution is the study of how language emerges from a situation in which there is no language. The problem of language origin and evolution has puzzled the scientific community for a very long period. In this thesis, using simulation modeling, we have tried to investigate this problem. We have developed a model in which a coordinated communication system emerges among a group of agents having cognitive abilities. We have conducted four experiments each of varying complexity. In all the experiment a coherent language emerges among the population of agents. We observed that the nature of the language that emerges in each experiment is different from the other in terms of synonymy, ambiguity and homonymy. We have extended the model to investigate the evolutionary aspect as well. By adding constraints on the cognitive abilities of the agents new properties such as compositionality emerged in the language.

Chapter 1

Introduction

Human language as a mode of communication is unique to humans and a critical part of what it means to be human. It is, therefore, natural to be curious about how it first came into existence and how it managed to reach its present form. If we go back in time, we can come across ancestors who did not have language. From those non-linguistic ancestors, we have come to possess the ability to use language through a series of generations. How did this transition happen? What made it happen? Were the intermediate languages similar to or different from the language that we use today? These are the main questions concerning language origin and evolution.

In this thesis, we will be investigating the origin of a lexical system in detail. We will be inspecting the lexicalisation of spatial terms in a population of agents. We have developed a model where the agents interact with each other to develop a coordinated communication system. By varying the constraints on the cognitive abilities of the agents, we have developed languages of varying complexities. We have developed languages ranging from simple word-meaning mappings to lan-

languages having simple compositionality. Compositionality is an important feature of structured representational systems, by virtue of which the semantic value of a complex representation is a function of its constituent parts. We will show that the development and evolution of language to greater complexity is driven by the need to optimize communication success.

1.1 Background

The problem of language origin and evolution can be divided into three parts 1) *origin* 2) *emergence* and 3) *evolution*. *Origin* includes studying about how organisms came to use communication and how the tools for processing, creation and acquisition of language developed. *Emergence* deals with the study of the emergence of language assuming individuals already possess the above mentioned language mechanisms. It involves the development of a shared lexicon among a population. A lexicon is a systematic set of mappings between signals and meanings. The signals must be discriminable from one another. Meanings are mental representations which they want to convey to another individual using the medium of language. The signal is just a symbol and its relationship with the meaning is completely arbitrary. The final part *evolution* studies how language evolves over time. It deals with the emergence of properties of the language such as compositionality, syntactic structure, word order and their subsequent evolution.

The study of language origin and evolution is an interdisciplinary field. Evolutionary biology and neurosciences are involved in this study as the human capacity for language has a genetic and neural basis. People from historical linguistics, biology, psychology, psycholinguistics have studied language evolution. It also in-

terests anthropologists as language is culturally transmitted, i.e. transmitted from generation to generation.

Even though this field contains a multitude of theories, the real problem lies in the lack of empirical data. Language emerged from a state of no-language in the past, transitioned through various stages and reached the current state. There is no fossil evidence available about initial states of language. We cannot observe the origin of language. The only scenarios that can be observed are the emergence of pidgin/creole languages, and the language acquisition by children. All of these are a little different from the problem of origin of language. However, the existing data does help in making some predictions about the problem.

Theorizing dominated this field for a long period of time. So much was speculated that it compelled *Societe Linguistique de Paris* to place its famous ban on research and publication on this subject. The most accepted of the theories came from the eminent linguist Noam Chomsky. Chomsky [1] claimed that the innate ability of children to learn a language by listening to a finite set of utterances is possible only if all the languages are variations of a generic *Universal Grammar(UG)* and that humans are equipped with a *language faculty* that contains this *language blueprint*. Chomsky termed this as *Principles and Parameters* approach and the different languages are the results of ascribing different values to the small set of parameters. Chomsky suggested that the language organ may not be the product of natural selection, but a by-product of other evolutionary forces such as an increase in overall brain size and constraints of still unknown laws of structure and growth. The world's best-known evolutionary theorist Stephen Jay Gould [2] also supported this claim. But this claim received strong opposition from Steven Pinker, director of MIT's Center of Cognitive Neuroscience. He compared

language to a complex organ like the eye and claimed that natural selection is the reason behind the development of the language organ [3].

Later new classical scientific approaches and synthetic approaches have been used to investigate the problem of language origin and evolution. Formal methods, chaos theory, non-linear dynamical systems, and evolutionary game theory belong to the former class and computational simulation models to the latter.

Formal language theory [4–6] is a field of computer science and mathematics which provides mathematical models for language origin and evolution of various aspects of language. The study of language origin is mainly the study of the dynamics of the association matrix A . The association matrix links forms to meanings. If the system has m objects and n signals, then the association matrix is a $m \times n$ matrix and the entry a_{ij} represents the strength of the corresponding form-meaning mapping. The value p_{ij} represents the probability of using signal j for object i and it is calculated by $p_{ij} = a_{ij} / \sum_{k=1}^n a_{ik}$ and the element q_{ij} represents the probability of interpreting signal i as object j and calculated by $q_{ij} = a_{ji} / \sum_{k=1}^m a_{ki}$.

The entries of the association matrix keeps changing during language use and the formal model studies the convergence of these matrices and the factors affecting its coherence in a community. They use learning theory and evolutionary dynamics in their models. Learning theory formalizes the procedure of language acquisition. According to learning theory, no learning algorithm can learn an unlimited set of languages. The restricted set of languages learnable by a human brain is called the Universal grammar(UG). Thus UG is the search space of competing grammars and it must be innate. Evolutionary theory studies the cultural transmission of language and the biological evolution of the UG.

M. A. Nowak a leading researcher in this field along with his colleagues tried to predict the evolution of grammar and language using mathematical techniques. He, in his paper ‘The Origin of Language’ [6], concluded that universal grammar might have developed through natural selection. But he freely admitted that he cannot answer why there are so many languages in the world.

The third alternative to theorizing and the mathematical analytic approach is simulation modeling. A simulation is an implementation of a theory in a computer. It involves a population of agents with a certain set of abilities living in an abstract world interacting with each other and with the environment. This simulation modeling is a synthetic approach and it follows a bottom up approach in contrast to the top down approach followed in the more classically analytical approaches. In analytical approaches we analyze the system by dividing the system into different parts each of which is independently studied. Each part is further subdivided until no more divisions are possible. This is the top-down approach. For example in biology, an organism is analyzed by dividing into organs, then organs to different tissues, tissues to cells and so on. But the simulation modeling uses a bottom up approach, which first designs the basic components of the systems, i.e. they design the abilities of the agents, the protocols for their interaction with each other and the interaction with the environment. The computer program will then simulate these interactions and we will be able to observe the emergence of higher-level entities. This type of modeling helps in the study of non-linear systems (systems whose properties cannot be derived from its components easily).

Simulation modeling helps when the system studied is a complex system. A complex system consists of entities interacting with each other and producing global properties which cannot be deduced nor predicted from the behaviour or

properties of the entities involved. The emerging properties are sensitive to the initial conditions and the system can react in unpredictable ways to external disturbances which are not commensurate with the importance or magnitude of the disturbances. Almost all the complex systems are adaptive in nature i.e. they try to fit into the environment they exist. All of these properties are exhibited by language. All the individuals possess linguistic behaviour, and these individuals by interacting with each other produce the global properties of language, thus making language a complex, self-organizing and adaptive system. The linguistic behaviour of individuals (through individual development and biological evolution) and properties of the language evolve in adaptive ways in time. Some complex systems can be hierarchical in nature where a particular entity at one level will be influenced by multiple entities at the lower level. In many such systems, we can see a change in a particular level staying hidden, until a further change at a lower level leads to significant changes at the upper level. The Language system is in fact such a hierarchical system. The neurons inside the brain of individuals interact to produce linguistic behaviour and these individuals using these linguistic abilities interact to produce the global properties of language.

Languages basically exhibit two separate and distinct modes of existence.

1. **E-language:** This is the external observable behaviour in the form of utterance and manifestations of meanings. E-language is completely chaotic and subject to change depending on the circumstances of every day human life.
2. **I-language:** From the buzzing confusion around them in the form of utterances, children develop an order inside by creating coherent systematic grammatical rules and coherent mappings between forms and meanings. These

form the I-language.

Because of these two modes, the computational model has the following components.

- Agents - Agent forms the basic unit of the model. They have the ability to analyze, induce, perceive and invent.
- Meaning space - Meaning space, also called concept space (set) or ontology represented as C is the set we would like to lexicalise. The meanings of the referents in the world are picked from this set. This set may have different kinds of properties - it can be either finite or infinite or they can be structured *i.e.* the concepts have some relationship with each other.
- Signal space - Signal space is the set from which the signals or forms are generated. In experiments dealing with the origin of phonology, a coherent set of phonemes are developed which is represented as Σ . The experiments dealing with origin of languages assume that the community has a coherent phonological system and a coherent set of words are developed. The experiments dealing with origin of syntax, assume that a coherent lexicon exists and develop a coherent syntactical structure in the system.
- Mental Lexicon(ML) - The mental lexicon of the agent stores the signal-meaning mappings. This is the I-language of the agent. This component contains various fields whose values decide the strength of the association. This is represented as ML .
- Lexicon - This forms the vocabulary of the agent. The lexicon written as Γ , is a part of the I-language of the agent. $\Gamma \subset \cup_{i=1}^{\infty} \Sigma^i$. The lexicon keeps on

evolving. We can only enumerate the elements of Γ at a particular point in time. Γ of an agent a at a particular time t can be written as Γ_a^t

- Linguistic interaction strategies - This is the protocol for the interaction between the agents. This involves the utterance by the speaker, the response from the hearer, and the feedback from the speaker regarding the status of the communication and further details if necessary.
- Learning - This forms the core of the simulation. This is part of the cognitive system of the agent. The main aim of this component is the creation and updation of form-meaning associations. The coherence of the feature being investigated, is achieved through the learning algorithm. Most of the learning algorithms contain a positive feedback loop because of which some form-meaning associations will be strengthened while the rest will be weakened during each interaction. The type of learning algorithm involved is influenced to some extent by the linguistic interaction strategies.

1.2 Work of Steels

Steels is the pioneer in the field of simulation modeling of language. His work [7], the Talking Heads experiments, consisted of robots mounted with cameras which act as agents in an abstract world. The world consists of objects which have features like color, height and smell. These features can be used to categorize objects. Agents have sensory channels which can detect the values of these features. The ontology of the agent is represented using a discrimination tree. For each sensory channel there is a tree. The nodes of the trees can be considered meanings

or categories. Initially the lexicon is empty and ontology consists of with single node containing value like (0.0-1.0).

The experiments consists of two phases. In the first phase the agents play *discrimination games*. In a discrimination game, an agent is paired up randomly with another agent. A context of random objects is created and a topic is randomly picked from the context. Both agents will try to uniquely identify the topic from the context using its ontology. If it fails, the ontology is refined by randomly picking a channel and splitting one of the end-nodes. The choice of the node to be split is arbitrary. A forgetting procedure ensures that unused nodes are removed from the trees. The approach used is selectionist. There is a generator of categories and a selectionist procedure maintains or eliminates from the category population. His experiments have shown that this method will result in a coherent(roughly) set of discriminations.

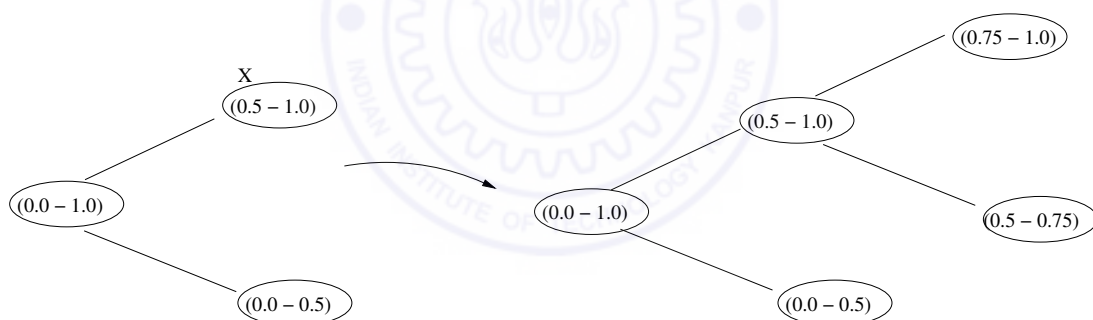


Figure 1.1: Splitting of a leaf node during a discrimination game. Node X was selected for the split

The second phase is the *naming game* which proceeds as follows: Each agent is randomly paired with another agent. The interacting agents agree on a set of randomly picked objects which form the context of the conversation. From this context, the speaker randomly picks an object as the topic of conversation. The

speaker uses extralinguistic means (like pointing) to inform the hearer about the topic. Thus the hearer also identifies the topic. Both agents, using their sensory channels try to categorize the objects in the context. Then the distinct set of categories which uniquely identify the topic from the rest of the objects in the context is identified. This is done separately by both the agents. There may be more than one distinctive categories. The speaker then picks randomly from these distinctive categories and encodes it in an expression in the form of utterance. This is achieved as follows. The speaker tries to find a word for the meaning. If the mappings for the meaning are available in its lexicon it uses the mapping which has the highest confidence. Else it generates a random string using English letters and stores the mapping in its lexicon.

The focus is now changed to the hearer. The hearer tries to decode the expression. The context is available to the hearer. If the word is in his lexicon, the meaning obtained will be used to pick the referent. If the referent is same as the topic, then the game is successful. If not, the game is a failure the hearer updates the lexicon accordingly. The game is played for a large number of rounds and finally a coherent lexicon is seen to develop.

The emergence of a coherent language can be explained through the mechanism of self-organization. Self-organization happens in a non-linear system [8] when there is a positive feedback loop. In this experiment, there is a positive feedback loop between use and success. Words which are more successful dominate in conversations and they propagate through the population. Thus self-organization ensures coherence in the system. The experiment is repeated by varying various parameters like population, interaction strategies etc.

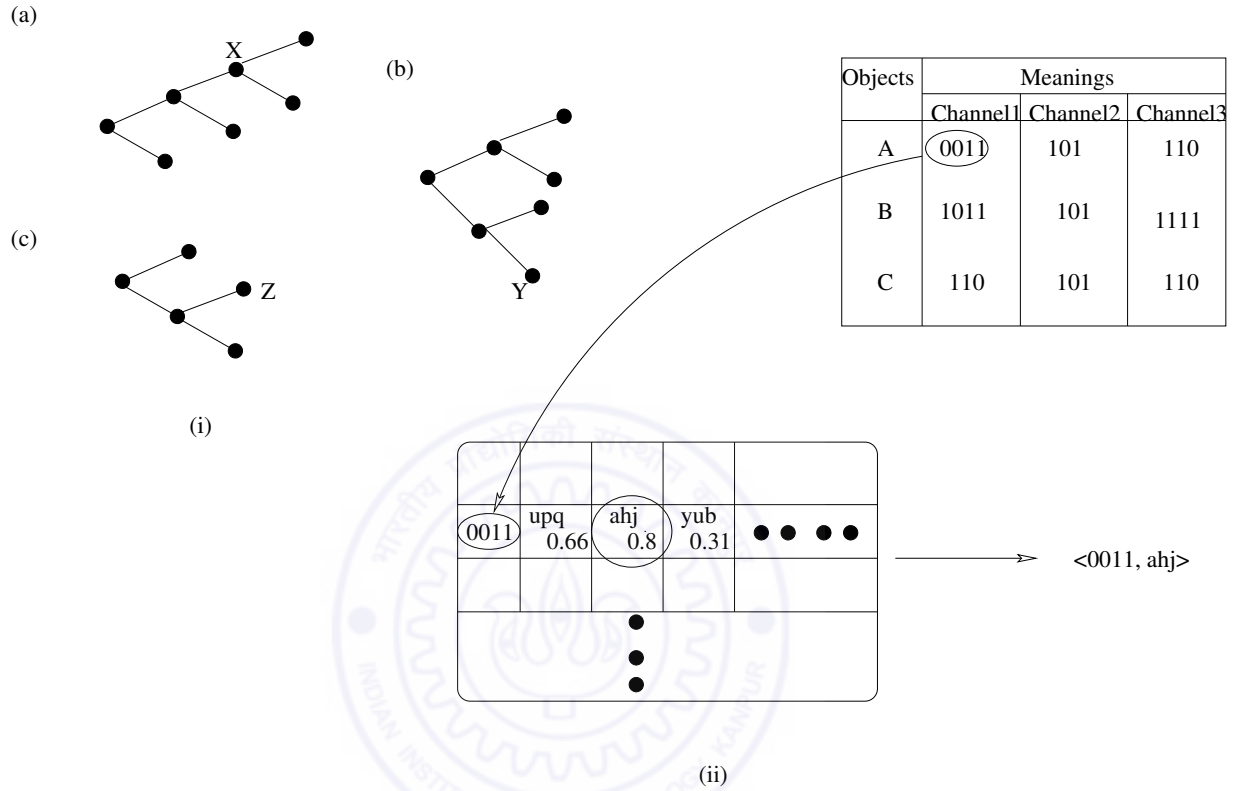


Figure 1.2: (i). Discrimination trees for various sensory channels. For channel 1, the value sensed by the agent lies in node X, similarly for channel 2, the value sensed belongs to node Y and for channel 3, the value sensed for the feature lies in node Z. So meaning for the object will be 0-11(channel 1), 1-00(channel 2), and 2-01(channel 3). Meaning is the sc-path where sc is the channel number and path is the path of the selected node from the root with left path taken marked as 0 and a right one marked as 1. Either of the three identifies the object (ii) Graphical representation of the encoding procedure.

1.3 Work of Smith

Smith in his work [9] was trying to find whether a coherent lexicon can develop if there is no explicit meaning transmission during an interaction. He plays a special kind of game called *selfish game*. In selfish games, no feedback about success of the communication nor about the real meaning of the word goes to the hearer. The learning algorithm of the hearer has to infer the meaning of an utterance based on multiple exposures to the utterance's use in context.

Smith used the Steels setup of Taking Heads experiment. The difference with Steels is in the interaction strategy. As mentioned earlier there is no feedback in the system. The input available to the hearer is the context and the speaker's utterance. The hearer can in no way verify whether the communication was successful or not nor is he informed about the topic if he is not able to interpret the utterance. The only information available to the hearer is the context. So it has to associate the word with all the meanings in the context. You need further social interactions to infer the right meaning. As more and more games are played by an individual with varying contexts, the cross-section of these contexts co-occurring with a word provides the meaning for the word. This is also known as cross-situational learning. This is inspired by Quine's [10] gavagai problem of inducing the meaning of an unfamiliar word from a set, which in principle is infinite. The gavagai problem is defined as follows.

“Suppose a linguist is out with the native speaker of a language. Suddenly a rabbit is seen, and the native speaker utters 'gavagai'. A natural reaction of the linguist will be to induce that gavagai means rabbit. But the speaker might have meant a special kind of rabbit, tree, mammal, climate or anything in the vicinity

which all forms the context'."

This work is motivated by the problem of how children acquire language. For a particular word, children might have been exposed to a number of mappings. They collect all the such mappings developed during different interactions and then pick the common elements.

His experiment was successful in developing a shared lexicon among the population. His work proved that a coherent system can be developed without explicitly transferring meanings nor informing whether communication was successful or not. But coherence is achieved at the cost of time. More rounds had to be played to achieve it.

A relationship is observed between the communicative success and similarity in the meaning structure of the agents. The more coherent the meaning structures are, the more informative the language will be.

1.4 Work of Kirby

Kirby in his work [11] showed that compositional, recursive language can emerge in a population of agents having basic cognitive abilities of learning and perception by taking advantage of coincidental correspondences between part of utterances and parts of meanings. The emergence of compositionality and recursive syntax happens without any selection pressure to communicate well and without any biological evolution. He believed that the language evolution happens at the cultural level rather than at the genetic level. He showed that syntax develops when mapping between two structured sets is passed through the bottleneck of cultural transmission. His experiments also prove the claim made by Neuhaviv [12] that

syntactic structures can emerge from a set of mappings between unstructured signals and structured meanings, and the emerged structure will be similar to the structure exhibited by the meanings.

He developed a framework called the Iterative Learning Model(ILM) [13] for studying the various aspects of language evolution. Each agent was embodied with a finite set of meanings, a learning algorithm, conceptualization module and memory to store the internal representation of the language. The model consisted of two types of agents - adults and children. Adults are proficient in the language and children have an empty lexicon. During each communication episode, a child is coupled with an adult and they play language games. Children are trying to learn the language through their interaction with the adults. Each round consists of a number of such communication episodes. At the end of each round the children become new adults and a new population of agents are brought in to play the role of children and the output of one generation becomes the input to the next generation.

The reason behind the emergence of a recursive grammar is the *poverty of stimulus*. During social transmission, the child is exposed to a subset of the entire mapping space. So the idiosyncratic, vocabulary-based languages cannot survive because they cannot fit into the bottleneck as the form-meaning mappings are arbitrary. So if there exists a structure in the mappings, utterances for non-mapped meanings can be created from the existing lexicon without depending on invention. Structure in the mapping aids in preserving the mapping through generations.

1.5 Work of Vogt

Vogt went a step further than Kirby. His experiments [14] were conducted using Steels Talking Head Simulator. His agents had an evolving concept structure. He used the Iterative Learning Technique of Kirby to study the emergence of syntactic structures. In the beginning all the agents had empty ontologies and grammars. Ontology develops by playing discrimination games and grammars develop using induction techniques.

The model assumes that the community already possess a coherent lexicon. The world has a set of objects like the one in Steels' experiment with a set of attributes like color and shape. Color is a combination of red(r), blue(b) and green(g). All four of these take real values between 0 and 1. These four attributes form the dimensions of the conceptual space of the agent. Meanings are represented as prototypes of the form $c = (c_1, c_2, c_3, c_4)$. The agents sensory channels detect the original values of each of these features and the categorization module returns the point in the ontology which is nearest to this point in the conceptual space. This forms the meaning of the object.

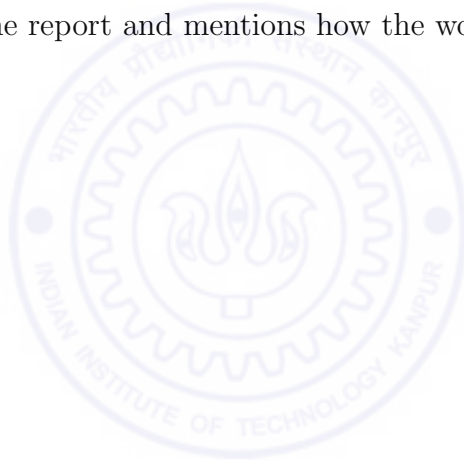
The agents initially play the discrimination game to develop the ontology. The discrimination game is similar to the one played in Smith's experiment i.e. by trying to uniquely identify the topic from the context using the current ontology. If the game fails, the ontology is updated with the feature values of the object. Once the convergence of coherent concept structures happens, the experiment moves to the second phase, which is the language game. The experiment assumes that a coherent lexicon exists. So the concepts are lexicalised, with the most used concepts assigned to shorter words and less used to longer ones. This is in

accordance with Zipfs law [15].

In the second phase, language games are played similar to those of Kirby by using the Iterative Learning Model. After a few iterations compositional structures emerge which reflect the structure of the world to a large extent.

1.6 Organization of the report

The organization of the thesis report is as follows. In Chapter 2, we will be explaining the various experiments conducted. The chapter explains the model to its finer details. In Chapter 3 we will be showing the results of the experiments. Chapter 4 concludes the report and mentions how the work can be extended.



Chapter 2

Experimental setup

In this chapter, we will discuss our model and the finer details about the strategies and learning techniques involved. Although we are investigating the origin and evolution of human languages, use of simulation modeling allows us to deal with only models that are crude simplifications of human languages. Usually the models focus on the features being investigated and abstract away from the natural case. For instance, in our model

- The language developed by the agents is used purely to identify spatial segments and numbers. It is not used to do any task other than to learn from each other.
- The agent-agent interaction protocols are predefined and the mechanisms like joint-attention and corrective feedback are extremely simplified. All the agents are provided with the the same set of cognitive skills and all behave the same way during an interaction.

- A coherent phonological system is assumed to exist in the community. The letters of the English alphabet form the set of phonemes for this model. Strings are generated by randomly picking from this alphabet. All the words are assumed to be of same length. Hence this appears like gibberish to humans.
- Agents exist in an abstract environment much simpler than the real world, represented as a graph where they sit at one node and talk about the neighboring nodes using their language.
- We assume that each agent produces the signals accurately and the produced signals are recognized by the other agent with cent percent precision.
- We also assume that the relationship between the signals and meanings are completely arbitrary.

These simplifications are made to investigate the real problem in hand and thus keeping other details to the bare minimum. The model being developed are influenced by the work done by Madhu and Venkatesh Babu. We will now explain the various entities involved in the model

2.1 The World

The world is where the agents stay and interact. The agents interact with each other and with their environment *i.e.* the world. The world is represented using a spatial weighted, undirected graph whose parameters are configurable. It is called a spatial graph because nodes are spatially located, each node is assigned

a Cartesian coordinate. The weight of an edge is the Euclidean distance between the coordinates of the nodes.

The world has food sources randomly placed at the nodes. The agents consume the food to gain energy. When the agents move between two nodes their energy will be reduced by a factor proportional to the weight of the edge and the age group of the agent whether he is juvenile, young or old. Even the consumption of food requires some energy. The graph (world) is plotted in a Cartesian plane of fixed size with the coordinates of the nodes picked randomly. The neighbors of each node are picked randomly from the set of nodes. The density of the graph, the size of the plane, the food sources and the energy requirements for movements are all configurable parameters.

2.2 Agents

Agents represent the humans in the real world. They form the active organisms of the world. Mentioned below are a few of their properties that are relevant:

- Agents are embodied with basic cognitive abilities for learning, communication and perception.
- Agents have the required set of abilities to perform social activities like joint attention.
- Agents have sensorimotor abilities and they transfer conceptual knowledge between themselves using their linguistic abilities.
- Agents view the world around them through a visual system which is explained in section-[2.2.1](#).

- Agents have strong phonological system. They invent new utterances by using phonemes from this set.
- Agents have a finite life time. They die when their age reaches a limit or when their energy goes below a threshold.
- Agents have the ability to reproduce. New agents are brought to the world through the reproduction mechanism.
- Agents are able to move around the world. The energy consumed for a movement between the nodes depends on whether the agent is juvenile, young or old.

2.2.1 Agent's Visual System

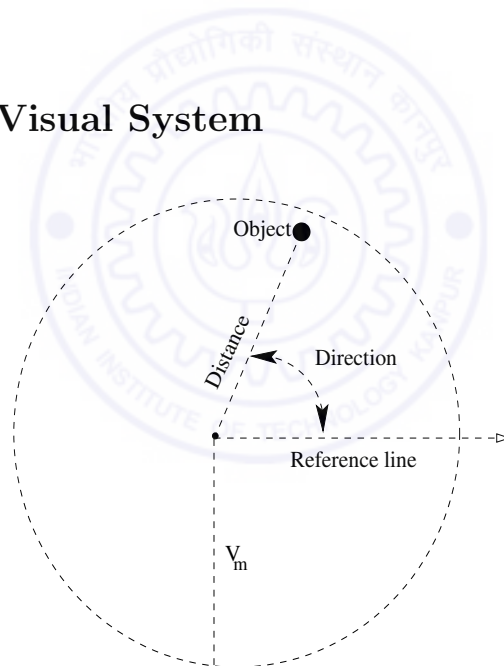


Figure 2.1: Agents visual system showing the concepts of distance, direction and numbering. The circle with radius v_m is the viewable area

An agent sees the world using its visual abilities. Agents have 360^0 vision. The agent's vision is limited to a maximum distance of v_m . An agent has the

ability to calculate direction and distance. The distance metric is assumed to be Euclidean. The direction of an object is the angle of the line joining the object and the agent, with reference to a global reference line. These concepts are shown in figure-2.1. Agents also possess numbering abilities, through which they count and order objects. Since all agents have the same kind of abilities, they all order the same way. All these abilities are innate to the agents. They perceive the world using these abilities.

2.2.2 Conceptualization Module

The conceptualization procedure of an agent is handled by this module. The input to the conceptualization module is provided by the visual system of the agent. The agent conceptualizes the space around him. This forms the agent's internal representation of the space. The most important feature of this module is the *resolution*.

2.2.2.1 Resolution

The agents conceptualize the 360° space around them in the form of equal size segments, which actually partitions the space *i.e.* each segment is disjoint from the other and the union of the segments is the 360° space. The size of each segment is called *resolution* and each segment is called a *sector*. A conceptualization of the space is shown in Figure-2.2. The resolution in that figure is 90° and there are four segments - $[0^\circ, 90^\circ)$, $[90^\circ, 180^\circ)$, $[180^\circ, 270^\circ)$, and $[270^\circ, 360^\circ)$. They are named S_0 , S_1 , S_2 and S_3 respectively. Similarly a 45° agent will have 8 sectors - $[0^\circ, 45^\circ)$, $[45^\circ, 90^\circ)$, $[90^\circ, 135^\circ)$, $[135^\circ, 180^\circ)$, $[180^\circ, 225^\circ)$, $[225^\circ, 270^\circ)$ and $[315^\circ, 360^\circ)$ and

180° agent will have 2 sectors - $[0^\circ, 180^\circ)$ and $[180^\circ, 360^\circ)$. In our experiments, we will be using these 3 kinds of resolutions.

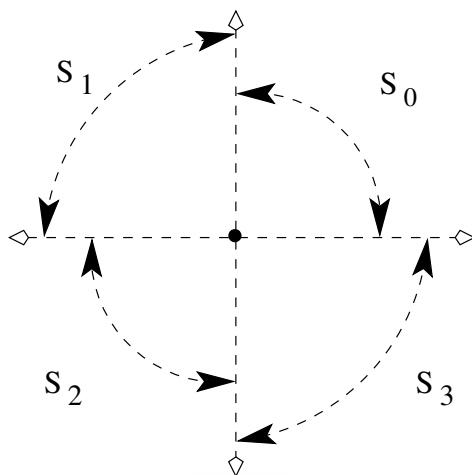


Figure 2.2: Resolution of an agent - Portion of space visible at a particular orientation of the agent

Agents can possess multiple resolutions, for example they can conceptualize the space in 45° , 90° , and 180° . The properties of such agents are discussed later.

2.3 Language game

Languages are maintained and transmitted by acts of speaking. It is also one of the means by which language evolves. This is modeled in our simulation as a language game. A game involves: agents making contact, perceiving the context, making an utterance (speaker), interpretation (by hearer) and response and finally the updation of the mental representation (both lexicon and structure where possible or necessary). The games played here are of the following nature: agents pick a neighboring node of the graph and try to express its location using the medium of language.

2.4 Experiments conducted

This section describes the experiments conducted using this model.

2.4.1 Experiment 1

In this experiment, we study the development of a coherent lexicon among a fixed population of agents.

- Signal space - A coherent phonological system is assumed to exist in the population. The 26 letters of the English alphabet (Σ) form the set of phonemes. The words uttered are all of equal length (assumed to be 5). So the signal space is represented as Σ^5 where Σ is $\{a - z\}$. The words are generated by randomly picking (with replacement) letters from Σ .

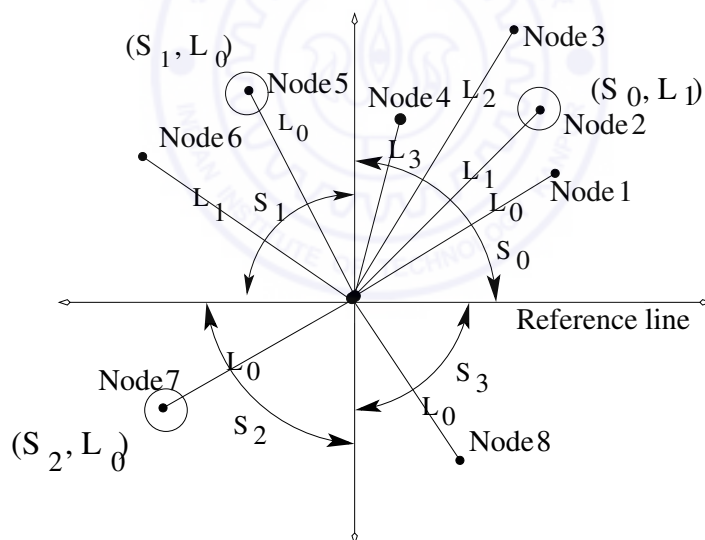


Figure 2.3: The view of a 90° resolution agent. S_0 is the segment $[0^\circ, 90^\circ)$ and S_1 is $[90^\circ, 180^\circ)$, S_2 is $[180^\circ, 270^\circ)$ and S_3 is $[270^\circ, 360^\circ)$. The meanings for the circled nodes are mentioned in the figure

- Meaning space(ontology) - There are two types of concepts - the concept of sector (C_s) and the concept of lines (C_l). The total concept set represented as C is $C_s \cup C_l$. All agents are single resolution agents and they all have the same resolution. So C_s consists of sectors of the resolution. Agents can number the outgoing edges using their numbering abilities . So C_l are line numbers which is an ordered set. So $C_l = \mathbb{N}$, the set of natural numbers. As there is no memory limitation, any number of concepts can be added to this set. A meaning or a category is a prototype of the form $m = (S_i, L_j)$ where S_i is the sector where the neighboring node is located and L_j is the line number of the outgoing edge from the agents node to the neighboring node. So this tuple can identify the node uniquely. So in these experiments we are trying to lexicalise these sectors and line numbers. The combination of sector and line number creates sense and they form a category or meaning and identify a node of the graph(world). Consider the node 2 in the Figure-2.3. The node lies in the second outgoing edge(L_1 where $L_1 = 1$ because counting starts from 0) of the sector S_0 . So the meaning for node 2 is (S_0, L_1) . Similarly the meaning for node 5 and node 7 will be (S_1, L_0) and (S_2, L_0) respectively.
- Mental Lexicon(ML) - The mental lexicon of an agent stores the signal-meaning mappings. The mapping is a many-to-many mapping *i.e.* each word can be associated with multiple meanings and each meaning can have multiple words associated with it. Each mapping has a field called the *mapping reference count(MRC)*. This field specifies how many times the mapping has been successfully referred. It signifies the agents confidence in the mapping.

Initially the agents are placed randomly in the world. All the agents begin with an empty lexicon. Each interaction goes through the following 6 phases:

1. *Making Contact*: An agent located at a particular node is paired up randomly with another agent at the same node. These two agents are the communicative partners for this instance of the language game. One agent becomes the speaker and the other the listener/hearer.
2. *Topic Identification*: Since they are located at the same node, they share the same environment. The neighboring nodes form the context of the conversation. The speaker will randomly pick a neighboring node as the topic of their conversation. The topic is kept hidden from the hearer.
3. *Perception*: The speaker will then try to define the position of the node using its ontology. It develops a category $m = (S_i, L_j)$ as discussed in the previous section.
4. *Encoding*: The speaker then has to express the developed meaning using the medium of language. The meaning developed is a combination of two independent meanings and for each of them signals have to be obtained.

This is achieved using the *cover* procedure. The *cover* procedure takes the meaning as the argument and creates a probability distribution on the set of signals mapped to that meaning in its mental lexicon. The probability σ_w assigned to a particular signal w is given by equation 2.1.

$$\sigma_w = \frac{MRC((m, w))}{\sum_{w_i \in W} MRC((m, w_i))} \quad (2.1)$$

W - the set of words mapped to the given meaning m .

From this set of possible signals, one signal is randomly chosen according to the distribution.

Assume W_s is the word selected for the sector and W_l for the line. The two words are coupled together in the predefined order $\langle W_s, W_l \rangle$, sector word coming first and the line word coming second. This two-word sentence $\langle W_s, W_l \rangle$ is uttered by the speaker.

5. *Decoding*: The listener on hearing the signals, tries to interpret it. The agent interprets the sentence serially. The words in the sentence are interpreted sequentially. A list of meanings which are mapped to the word is extracted and as before a probability distribution is developed on this set where the probability σ_m of a particular meaning m is given by equation 2.2 and a meaning is chosen from this set of possible meanings according to the above distribution. This procedure is called *uncover*.

$$\sigma_m = \frac{MRC((w, m))}{\sum_{m_i \in M} MRC((w, m_i))} \quad (2.2)$$

M - the set of meanings mapped to the given word w

Assume S_i is the interpreted sector and L_j the interpreted line, then composition of these two (S_i, L_j) is the final meaning.

6. *Feedback*: Using the interpreted meaning, the agent locates a node from the neighboring nodes and that node is the referent. The agent expresses the interpretation by moving to that node. The speaker verifies the hearer agent's interpretation by watching the movement of the listener. If the speaker had moved to the topic node, then the language game is a success and the speaker

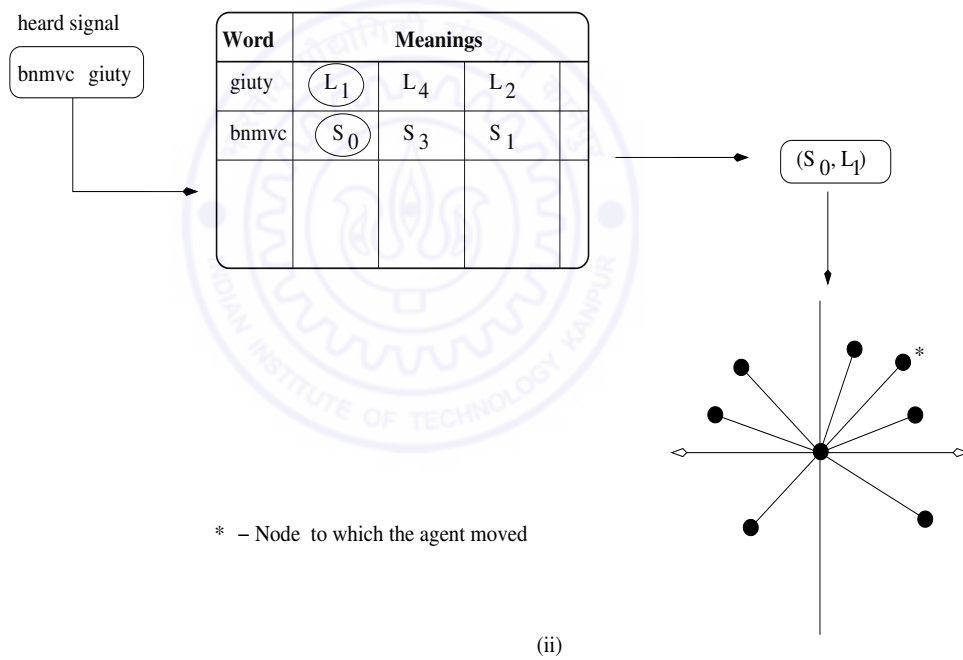
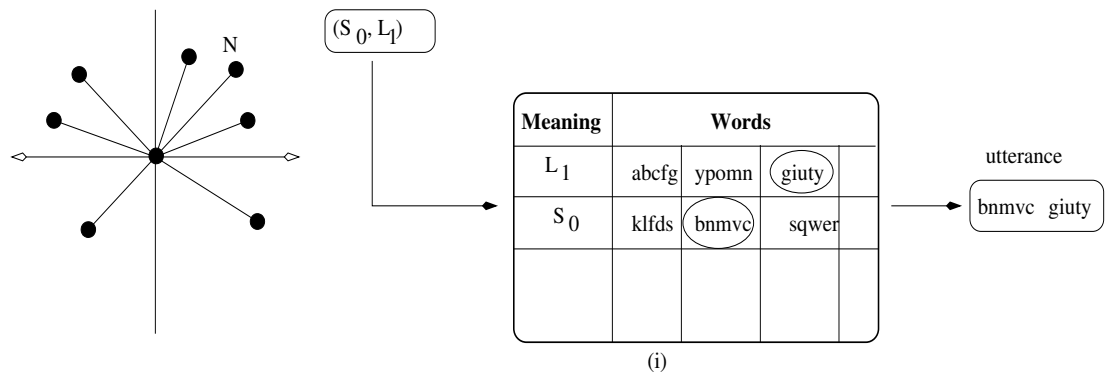


Figure 2.4: Agent-Agent language game interaction (i) The speaker side (ii) The hearer side

acknowledges it. If not then the communication episode is a failure and the speaker informs the listener about the failure of the communication and using the mechanism of joint attention, points to the correct node. Both the agents update their respective lexicon. The nature of the updation depends on the outcome of the game - whether it was successful or not. The updation procedure is discussed later.

2.4.1.1 Learning

The games played in this experiment are observational games. During each communication episode, the context consists of only one entry and it is the location of the node. There is no noise in the system. When there is communication failure there is no confusion regarding the meaning of the utterance. This is because the order of the words is fixed, the first word represents the sector and the second represents the line. If a mapping between the heard word and the conveyed meaning does not exist, a new mapping is created and added to the mental lexicon. If it exists, then the *mapping reference count(MRC)* is updated depending on the outcome of the interaction as follows:

- *Success:*
 - *Speaker:* Increment the *MRC* of the used mappings(both sector and line) by one.
 - *Hearer:* Increment the *MRC* of the used mappings(both sector and line) by one.
- *Failure:*

- *Speaker*: No updation
- *Hearer*: Increment the *MRC* of correct mappings(informed by the speaker during feedback) by one.

2.4.2 Experiment 2

In this experiment, the cognitive abilities of the agents are changed. Now the world contains multi-resolution agents. They possess multiple resolutions. For example an agent can have resolutions of 45^0 , 90^0 and 180^0 . That means, the agent can explain the location of a node in three ways - using a 45^0 sector or a 90^0 sector or a 180^0 sector. The agent's representation of the surroundings is shown in the Figure-2.5.

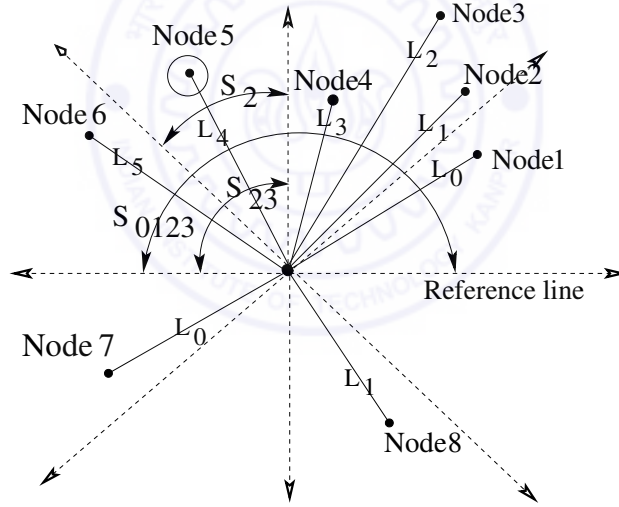


Figure 2.5: Neighborhood perception of a multi-resolution agent. Agent's resolutions are 45^0 , 90^0 and 180^0 . The corresponding locations of the node expressed in the respective resolutions are (S_2, L_0) , (S_{23}, L_0) and (S_{0123}, L_4)

- Signal space - Same as that of the earlier experiment.

- Meaning space - All agents possess multiple resolutions and they all have the same set of resolutions. So the initial sector concept set C_s consists of sectors of each resolution. For example for a $\{45^0, 90^0, 180^0\}$ resolution agent, C_s will have 8 sectors of 45^0 resolution, 4 sectors of 90^0 resolution and 2 of 180^0 resolution. A major difference in this experiment is that the meaning space is structured. In fact the meanings are hierarchical. It is a tree like structure, with each level of the tree containing the sectors of a particular resolution. The figure 2.6 shows the meaning structure of the above mentioned agent. Similarly the line number concept set $C_l = \mathbb{N}$.

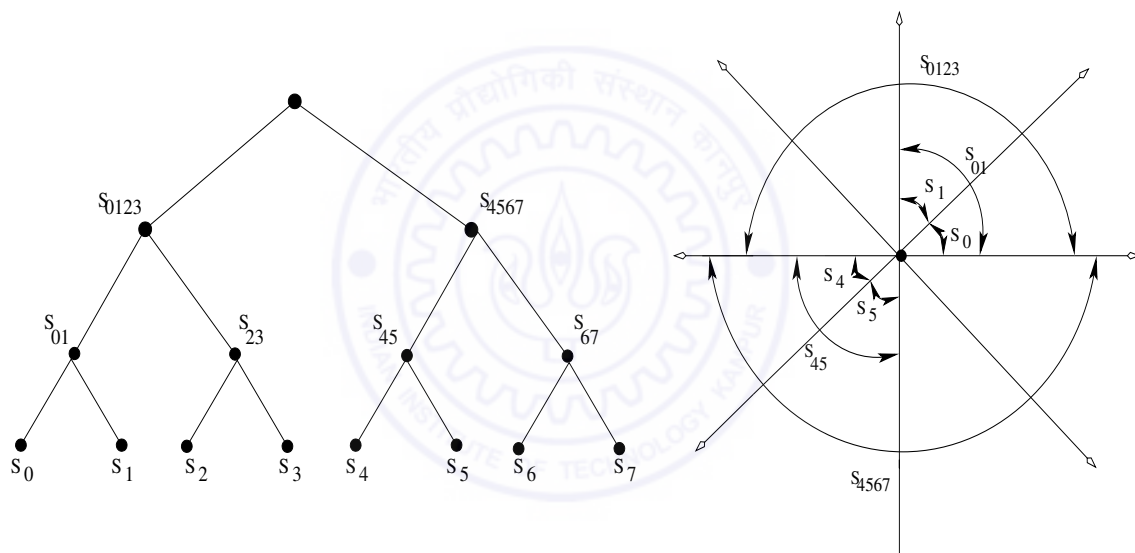


Figure 2.6: Meaning structure of a $\{45^0, 90^0, 180^0\}$ resolution agent. The sector concept set $C_s = \{S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_{01}, S_{02}, S_{03}, S_{0123}, S_{4567}\}$

- Mental Lexicon(ML) - The mental lexicon of an agent stores the signal-meaning mappings. Each signal-meaning mapping in the mental lexicon has got two fields. One is the *mapping usage count*(MUC). It is the number of times the mapping has been used and this value is incremented whenever the

agent uses that mapping. The other is the *mapping success count*(MSC). It is the number of times the usage of the mapping was successful. The success count is incremented only after a successful language game.

The various phases of the interaction are:

1. *Making Contact*: Same as experiment-1
2. *Topic Identification*: Same as experiment-1
3. *Perception*: The speaker will then try to define the position of the node using its ontology. The agents in this experiments have got multiple resolutions. So a resolution is randomly picked(uniform distribution). A meaning (S_p, L_q) is generated using the sector of this resolution which contains the topic node.
4. *Encoding*: For both S_p and L_q words have to generated. Due to the confusion during learning, much ambiguity exists in the language. Oliphant and Batali [16] have developed a strategy which helps in achieving coordinated communication in such situations. The strategy is termed the *obverter* strategy. The *obverter* strategy is about pruning the set of words for the meaning. The idea behind this strategy is for an agent to produce signals that can maximize the probability of a listener interpreting the correct meaning. In this strategy, in order to decide the word for a meaning in hand, the agent reads his own mind and will choose that word which is associated with that meaning. The speaker assumes that his own lexicon approximates that of the listener.

The method can be formally explained as follows:

We want to find a signal w for a meaning m .

$$\begin{aligned}
w_{desired} &= \arg \max_s P(s|m) \\
&= \arg \max_s \frac{P(m|s)P(s)}{P(m)} \\
&= \arg \max_s P(m|s)
\end{aligned}
\tag{2.3}$$

The algorithm for the obverter strategy is mentioned below as Algorithm-1.

input : The meaning m and the list L of words associated with the meaning m in the mental lexicon of the agent

output: The pruned list L_p

```

1  $L_p = \{\}$ ;
2 foreach  $w_i$  in  $L$  do
3    $m_r$  is the agent's interpretation of the word  $w_i$ ;
4    $m_r \leftarrow \text{uncover}(w_i)$ ;
5   if  $m_r == m$  then  $L_p \leftarrow L_p \cup w_i$ ;
6 end

```

Algorithm 1: Obverter strategy

The obverter strategy removes a few words from the list of competing words and returns a pruned set Q . Now the selection mechanism is applied on this set. The selection procedure chooses one word from the list Q . A probability distribution is developed on the set. The probability σ_w associated with a word w is given by

$$\sigma_w = \frac{MSC(< m, w >)}{\sum_{w_i \in Q} MSC(< m, w_i >)}
\tag{2.4}$$

A word is chosen from the pruned list Q according to this probability distri-

bution.

5. *Decoding*: This is done by the listener. The listener on hearing the utterance of the speaker tries to interpret both the words. For each word the listener does the following. In its mental lexicon, the word will have multiple concepts associated with it. A concept is picked using a probability distribution where the probability σ_m of a concept m is given by

$$\sigma_m = \frac{MSC(< w, m >)}{\sum_{m_i \in M} MSC(< w, m_i >)} \quad (2.5)$$

M - the set of words mapped to the given word w .

6. *Feedback*: Same as experiment-1

The learning procedure is slightly modified due to the presence of noise.

2.4.2.1 Learning

A considerable amount of noise has been introduced into the system. The noise is in the form of confusion regarding the real meaning of a word during learning. The interpretation during a communication episode can fail due to two reasons. Either the listener is hearing at least one of the words for the first time or the interpreted meaning is not matching with that of the speaker *i.e* the listener moved to the wrong node. In the former case, a new mapping has to be created. There is a considerable ambiguity here. Since the agent has multiple resolutions, he can define the location of the agent in multiple ways. The agent does not know the real meaning for the utterance. This is similar to the *gavagai* problem mentioned earlier. So the games played are guessing games. The real meaning is hidden from

the listener. In the second case, the hearer has to update its lexicon, based on the corrective feedback received from the speaker.

The updation procedure for the experiment is as follows:

- Speaker:
 - Success: Increment the MSC and MUC of the used meaning by one
 - Failure: Increment the MUC of the used meaning by one

- Hearer:
 - Success: Increment the MSC and MUC of the used meaning by one
 - Failure: The failure has got two cases as mentioned above
 - (a) When at least one of the words of the sentence is unknown to the listener, the interpretation of the sentence fails. From the information given by the speaker during the feedback phase, the listener develops the meanings for the location of the informed node. These entries are the possible candidates for the words. From these sector-line pairs, the pair which corresponds to the lowest resolution is chosen and the words of the sentence are associated with that sector and its corresponding line respectively. This is the induced meaning in this case and MUC and MSC of the induced meaning is incremented. This is demonstrated in the Figure-2.7
 - (b) In this case, the listener had interpreted the sentence wrongly and moved to the wrong node. From this wrong interpretation the listener tries to induce the correct meaning using the feedback information received from the speaker. This is called the meaning-

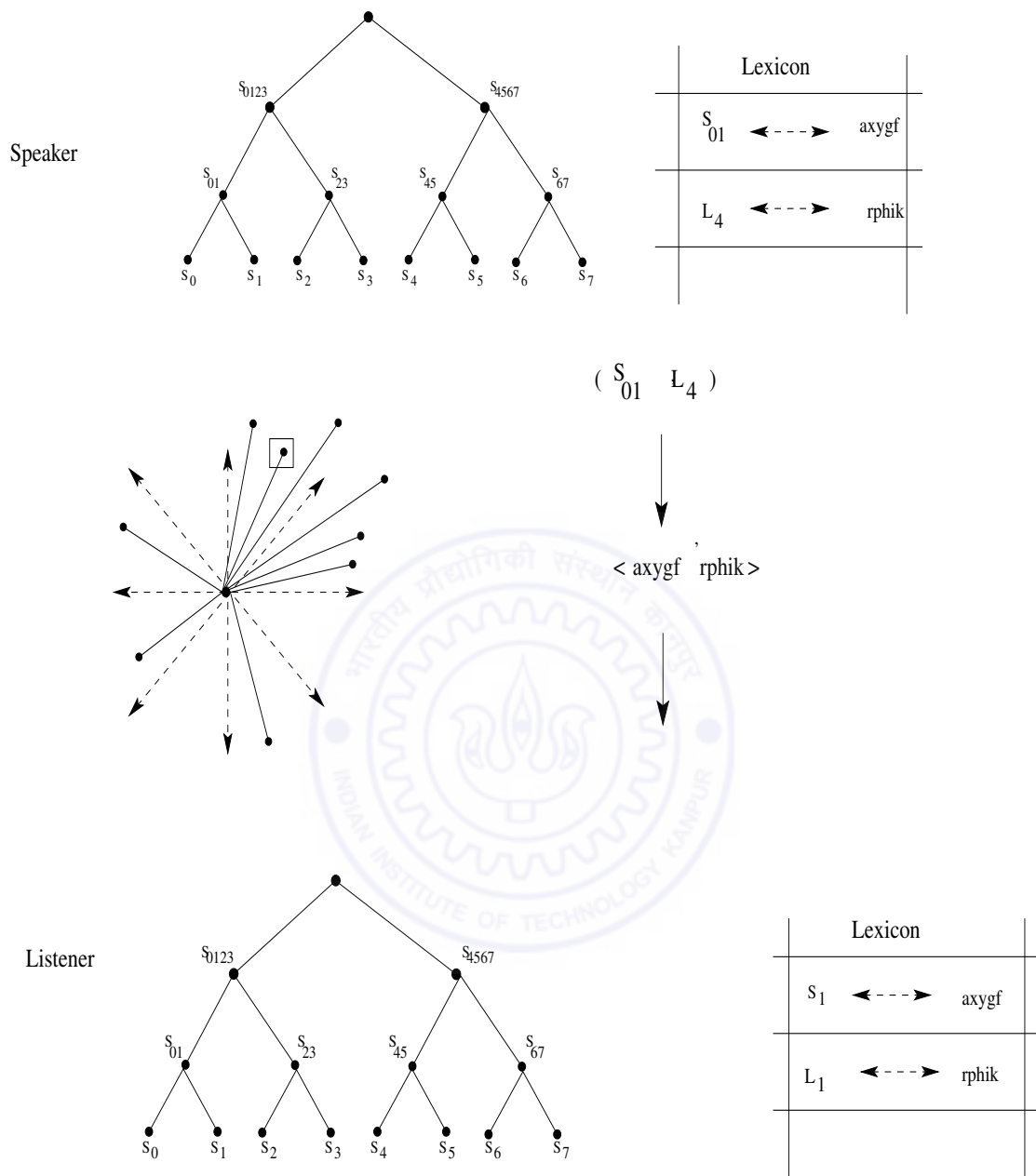


Figure 2.7: The speaker uttered the word $\langle axygf, rphik \rangle$. These words were unknown to the listener. So these words will be associated with the lowest resolution sector *i.e.* the 45° sector containing the node. So the mappings $\langle axygf, S_1 \rangle$ and $\langle rphik, L_1 \rangle$ are added to the listener's mental lexicon.

induction algorithm(Algorithm-3) which is explained in the next section. The *MUC* and *MSC* of the the induced meaning is then incremented by one.

2.4.2.2 Meaning Induction

The aim of the learning algorithm is to induce the mapping used by the speaker during the interaction. The listener learns the mapping of the speaker, and the mapping propagates through the population through his subsequent interactions.

Following functions are used in the procedure:

- *NodeAt(M)*: A function which takes a meaning M as the argument and returns the node at that meaning. For example in Figure-2.5 $NodeAt(S_2, L_0) = Node5$, $NodeAt(S_1, L_0) = Node2$.
- *Parent(S)*: A function which takes a sector S as the argument and the returns the parent sector of S in the meaning structure. For example in Figure-2.6 $Parent(S_0) = S_{01}$.
- *NoOfLines(S)*: A function which takes a sector S as the argument and the returns the number of lines in S . From Figure-2.5, $NoOfLines(S_1) = 3$.

Meaning induction is used by the hearer when he interprets the sentence wrongly. Let the wrong interpretation be $M = (S_u, L_v)$ and the correct node (informed by the speaker) be N . The procedure uses a bottom-up approach. As explained earlier, when a new word (for the hearer) is present in the utterance, the hearer associates the sector word with the lowest resolution sector containing the node and the line word to the line number of the node with respect to that low

resolution sector. Later the sector words start moving up the concept structure to the correct sector if the original sector used by the speaker is from a higher resolution. The line words also move to the correct line numbers.

The principle behind the procedure is as follows. The meaning the speaker is trying to express and the hearer interprets have got two components - sector component and line component. In case of the hearer's interpretation not matching the speaker's, the hearer can find the speaker's hidden meaning from the interpreted (wrongly) meaning by generating all the possible meanings by fixing one component of the interpreted meaning and trying all the valid possibilities of the other component and verifying it with correct node (provided by the speaker during feedback). This is similar to the principle of contrast.

For example let $\langle krtyu, S_1 \rangle$ and $\langle ioytr, L_3 \rangle$ be the speaker's mapping and $\langle krtyu, S_1 \rangle$ and $\langle ioytr, L_5 \rangle$ be the mappings in the listener's lexicon. If the meaning $\langle S_1, L_3 \rangle$ is expressed by the speaker as $\langle krtyu, ioytr \rangle$, the game will fail as the mappings do not match. But the listener can acquire the speaker's mapping by fixing the sector meaning and trying all possible line meanings in that sector *i.e.* by trying all the line numbers L_i of the sector S_1 and checking whether $NodeAt(S_1, L_i)$ equals H . This is the ChooseCase3 Algorithm(Algorithm-4).

Similarly let $\langle krtyu, S_1 \rangle$ and $\langle ioytr, L_5 \rangle$ be the speaker's mapping and $\langle krtyu, S_2 \rangle$ and $\langle ioytr, L_5 \rangle$ be the listener's mapping. Let the utterance made by the speaker be $\langle krtyu, ioytr \rangle$. The game will fail as the mappings are not matching. But the listener can acquire the speaker mapping by fixing the line meaning and trying all sector meanings in its ontology *i.e.* Trying all the sectors S_i of C_s check whether $NodeAt(S_i, L_5)$ equals H . This is the ChooseCase3 Algorithm(Algorithm-5).

The above two cases will succeed only if the component that is fixed matches with the speaker. So initial set of matches of the mappings are achieved through the ChooseCase1 Algorithm(Algorithm-3). The right meaning can be obtained through two means - one by chance *i.e.* when the speaker himself used the lower resolution to explain the node, second through the induction technique. In the latter case, the speaker meaning is obtained from a higher resolution. So the listener has to find the higher resolution sector and line number with respect to that sector and associate the respective words with them. This can only be achieved through a series of interactions. A demonstration of this is explained below.

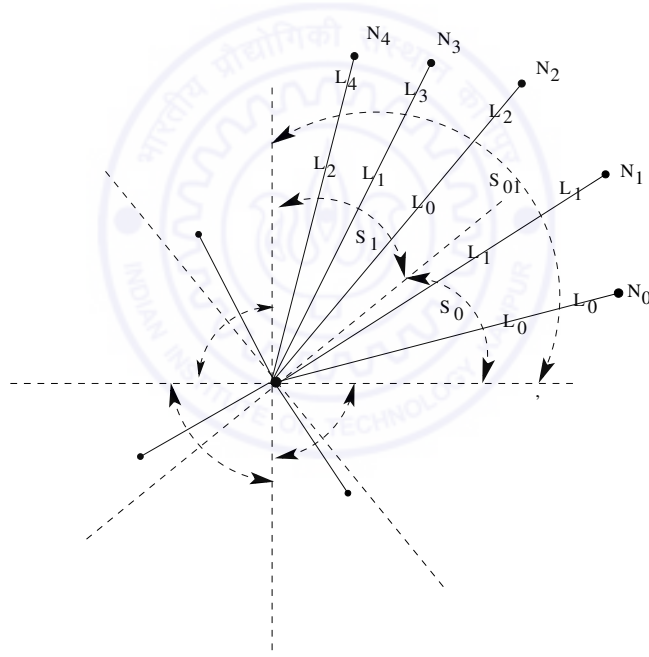


Figure 2.8: Neighborhood of the interacting agents

The neighborhood of the interacting agents is shown in Figure-2.8. In the Figure-2.9 and Figure-2.10, during the interaction (1), the speaker is representing the location of the node N_3 using a 90° sector. Since the word is new to the listener,

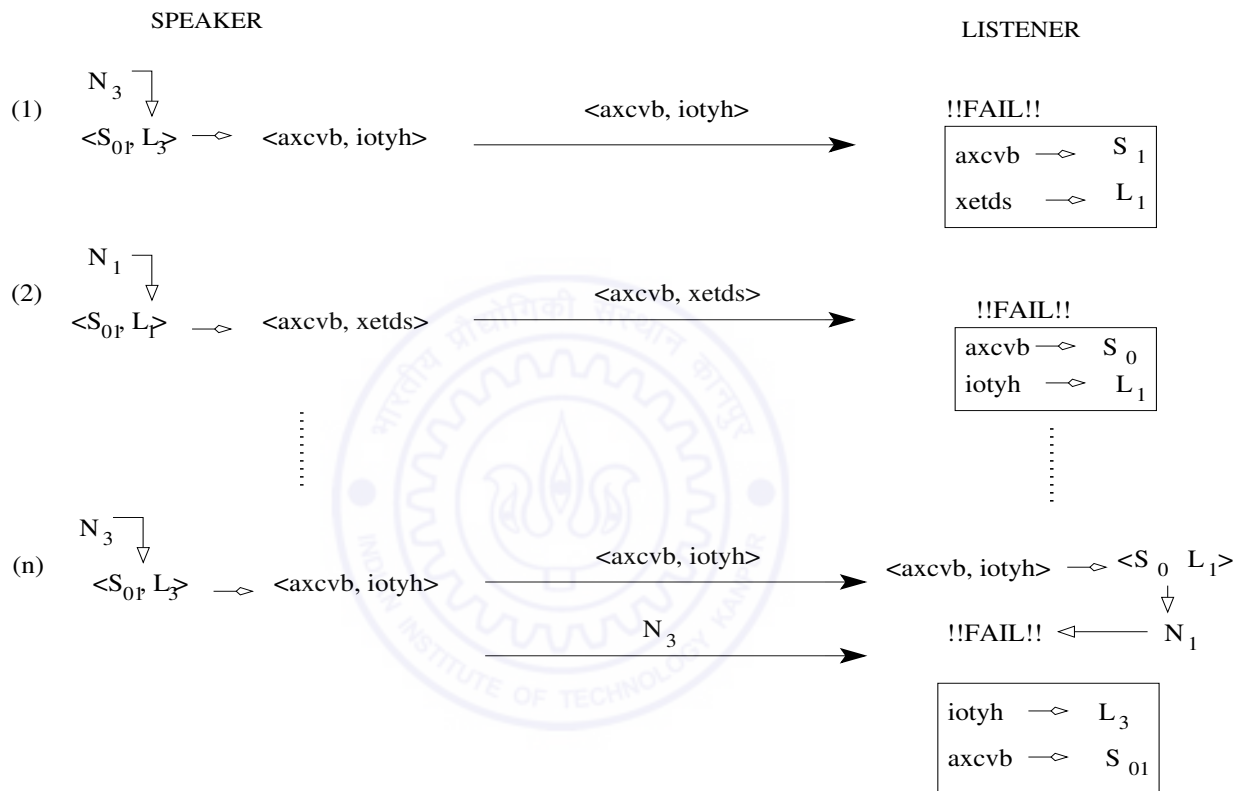


Figure 2.9: Meaning Induction ChooseCase1(a)

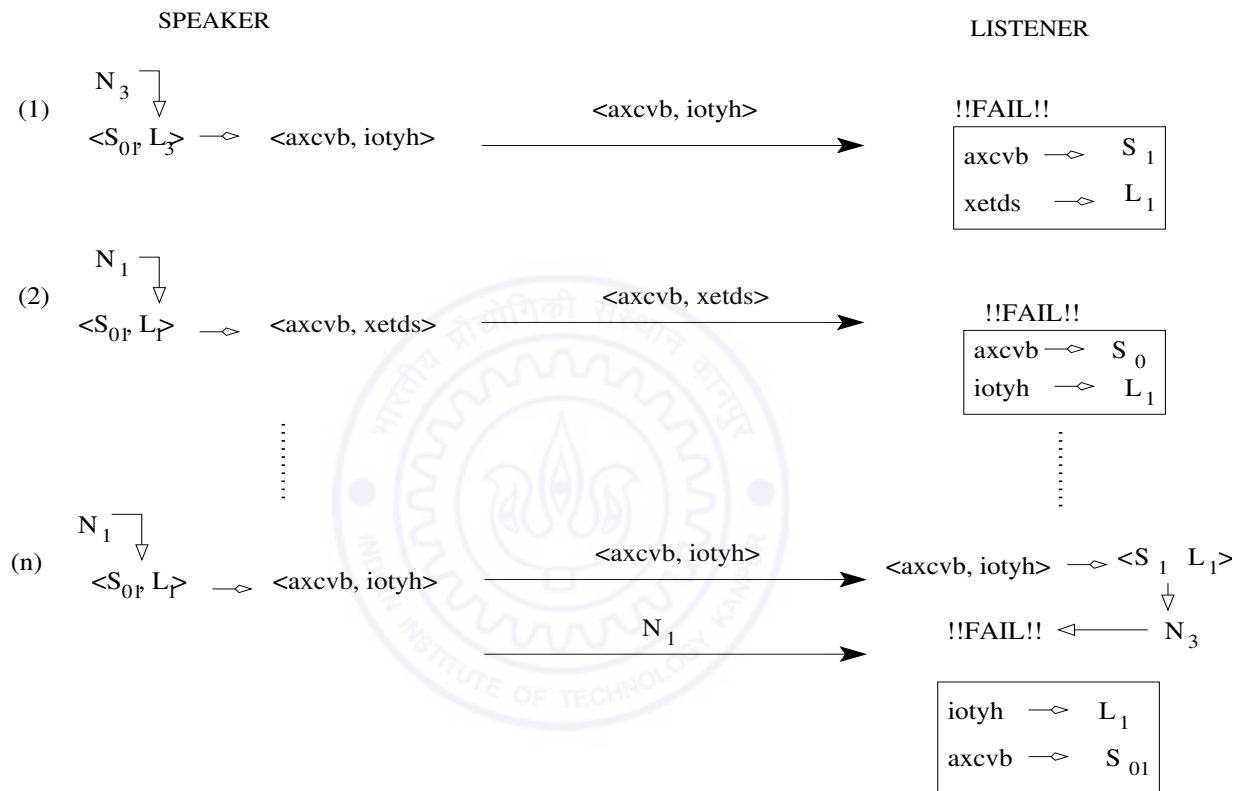


Figure 2.10: Meaning Induction ChooseCase1(b)

it creates mappings for line word and sector word using the 45° sector. During the interaction (2), the same speaker is using the same 90° sector to define the location of node N_1 . Again the game failed as the line word is new to the listener. So the mapping $\langle S_0, axcvb \rangle$ is created by the listener. So two meanings, S_0 and S_1 are associated with the word $axcvb$. Assume that after a finite number of interactions between them, the probabilities of the mappings $\langle S_0, axcvb \rangle$ and $\langle S_1, axcvb \rangle$ are p_0 and p_1 respectively, In the n^{th} interaction (shown in the Figure-2.9 and Figure-2.10), there are two cases:

- (a) $p_0 > p_1$: Assume node N_3 is being picked as the topic and the meaning to be expressed is $\langle S_0, L_3 \rangle$. Hence the speaker will be uttering $\langle axcvb, iotyh \rangle$. Since $p_0 > p_1$, the listener will be interpreting the sentence as $M_n = \langle S_0, L_1 \rangle$ which will derive node N_1 . So the interaction fails, but the topic node N_3 can be derived from M_n as follows

$$NodeAt(\langle Parent(S_0), L_1 + NoOfLines(S_0) \rangle) = N_3. \quad (2.6)$$

From this we can conclude that $axcvb$ represents S_{01} . So the mapping $\langle axcvb, S_{01} \rangle$ and $\langle iotyh, L_3 \rangle$ are added to the mental lexicon. This is shown in Figure-2.9

- (b) $p_1 > p_0$: If node N_1 is being picked as the topic and the meaning to be expressed is $\langle S_0, L_1 \rangle$, then the speaker will be uttering $\langle axcvb, iotyh \rangle$. The hearer will be interpreting it as $M_n = \langle S_1, L_1 \rangle$ which will be derived to N_3 . This game is a failure, but N_1 can be derived from M_n using the

following equation.

$$NodeAt(\langle Parent(S_1), L_1 \rangle) = N_1. \quad (2.7)$$

From this we can conclude that $axcvb$ represents S_{01} . So the mapping $\langle axcvb, S_{01} \rangle$ and $\langle iotyh, L_1 \rangle$ are added to the mental lexicon. This is shown in Figure-2.10

Altogether, the aim of meaning induction procedure is to develop a new meaning $M' = (S_p, L_q)$ from M such that $NodeAt(M') = N$. This can be generalized as

Assume

Utterance of the speaker	—	$\langle W_s, W_l \rangle$
Wrongly interpreted meaning(by the hearer)	—	$M = \langle S_a, L_b \rangle$
$Parent(S_a)$	—	S_p
$LeftChild(S_a)$	—	S_p^l
Correct Node(informed by the speaker)	—	N

If $NodeAt(\langle S_p, L_b \rangle) == N$

then $ML^{(t+1)} = ML^{(t)} \cup \{ \langle S_p, W_s \rangle, \langle L_b, W_l \rangle \}$

ElseIf $NodeAt(\langle S_p, L_b + NoOfLines(S_p^l) \rangle) == N$

then $ML^{(t+1)} = ML^{(t)} \cup \{ \langle S_p, W_s \rangle, \langle L_b + NoOfLines(S_p^l), W_l \rangle \}$

This rule is applied iteratively through high level parents. (See Algorithm-3). If the meaning-induction algorithm could not find any mapping, the meaning with respect to the lowest resolution sector(as used in the unknown word case) will be chosen as the induced meaning.

```

input :  $M_r$ - The wrongly interpreted meaning;
 $N$  - Correct node(informed by the speaker);
output: Derived correct meaning  $M_p$ , which will be returned
1  $M_p$  is initialized with the lower resolution meaning(meaning w.r.t the
   lower resolution sector);
2  $newmeaning \leftarrow \text{ChooseCase1}(M_r)$ ;
3 if  $newmeaning \neq Nil$  then
4 |  $M_p \leftarrow newmeaning$ 
5 else
6 |  $newmeaning \leftarrow \text{ChooseCase2}(M_r)$ ;
7 | if  $newmeaning \neq Nil$  then
8 | |  $M_p \leftarrow newmeaning$ 
9 | else
10 | |  $newmeaning \leftarrow \text{ChooseCase3}(M_r)$ ;
11 | | if  $newmeaning \neq Nil$  then
12 | | |  $M_p \leftarrow newmeaning$ 
13 | | end
14 | end
15 end
16 ;
17 return  $M_p$ 

```

Algorithm 2: Procedure to choose a meaning for a wrongly learnt word

input : $M_r = \langle S_r, L_r \rangle$ - The wrongly interpreted meaning;
 N - Correct node(informed by the speaker);
output: Derived correct meaning M_o , which will be returned

```

1  $M_o \leftarrow Nil$ ;
2  $S_p \leftarrow \text{ParentOf}(S_r)$ ;
3 while  $S_p \neq Nil$  do
4   if  $\text{NodeAt}(\langle S_p, L_r \rangle) == N$  then
5      $M_o \leftarrow \langle S_p, L_r \rangle$ ;
6   else
7      $newline \leftarrow \text{NoOfLines}(\text{LeftChild}(S_p)) + L_r$ ;
8     if  $\text{NodeAt}(\langle S_p, newline \rangle) == N$  then
9        $M_o \leftarrow \langle S_p, newline \rangle$ ;
10    end
11  end
12   $S_p \leftarrow \text{ParentOf}(S_r)$ ;
13 end
14 return  $M_o$ ;

```

Algorithm 3: ChooseCase1

input : $M_r = \langle S_r, L_r \rangle$ - The wrongly interpreted meaning;
 N - Correct node(informed by the speaker);
output: Derived correct meaning M_o , which will be returned

```

1  $M_o \leftarrow Nil$ ;
2 foreach line  $L$  in sector  $S_r$  do
3   if  $\text{NodeAt}(\langle S_r, L \rangle) == N$  then
4      $M_o \leftarrow \langle S_r, L \rangle$ 
5   end
6 end
7 return  $M_o$ ;

```

Algorithm 4: ChooseCase2

<p>input : $M_r = \langle S_r, L_r \rangle$ - The wrongly interpreted meaning; N - Correct node(informed by the speaker); output: Derived correct meaning M_o, which will be returned</p> <pre> 1 C_s - The set containing agent's sectors; 2 $M_o \leftarrow Nil$; 3 foreach sector S in C_s do 4 if NodeAt($\langle S, L_r \rangle$) == N then 5 $M_o \leftarrow \langle S, L_r \rangle$ 6 end 7 end 8 return M_o; </pre>

Algorithm 5: ChooseCase3

2.4.3 Experiment 3

In this experiment, the constraint that all the agents possess the same set of resolutions is removed. The resolution sets of agents may differ from one another. In order to simplify the model the possible resolutions are reduced to the set $\mathcal{U} = \{45^0, 90^0, 180^0\}$. Also, the possible resolution combinations that are available to an agent are reduced to the set $\mathcal{X} = \{\{45^0, 90^0, 180^0\}, \{90^0, 180^0\}, \{180^0\}\}$. The latter constraint is added to maintain the hierarchical structure of the meaning space.

It is interesting to see that because of the limited possibilities in \mathcal{X} , the meaning structures of the agents are overlapping. Figure-2.11 shows this. The encircled subtrees T'_1 and T''_1 are exactly the same as T_2 and T_3 respectively. The sectors of T''_1 are $\{S_{01}, S_{23}, S_{45}, S_{67}, S_{0123}, S_{4567}\}$ and that of T_3 are $\{S_0, S_1, S_2, S_3, S_{01}, S_{23}\}$. They both represent the same set of sectors. These are the common sectors in T_1 and T_2 . The rest of the sectors of T_1 are not present in T_2 and they are the differing sectors. This implies that there is a possibility for the agents to successfully interact

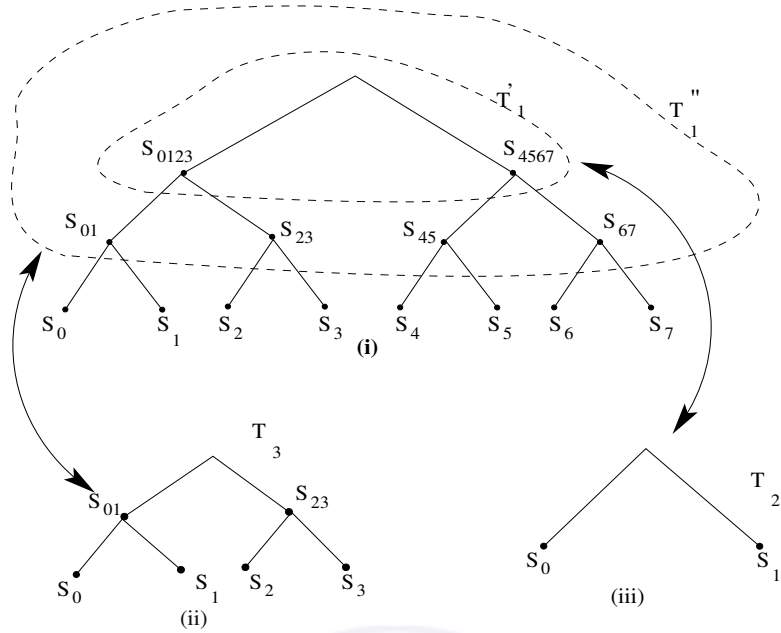


Figure 2.11: (i) Meaning structure of a $\{45^0, 90^0, 180^0\}$ resolution agent.(ii) Meaning structure of a $\{90^0, 180^0\}$ resolution agent.(iii) Meaning structure of a $\{180^0\}$ resolution agent.

if they use their common resolutions.

The learning algorithm and the *decoding* phase are the same as that of *Experiment 2*. The *encoding* phase and the *feedback* phase are being modified. Since the agents have different resolution sets, the strength of their representational abilities are different. An agent with the resolution set $\{90^0, 180^0\}$ cannot understand a 45^0 sector of an agent with resolution set $\{45^0, 90^0, 180^0\}$. The latter agent can represent finer details than the former. This has a negative impact on the convergence of the language when the agents start using the differing concepts. The solution to this is that the agents have to first converge on a coherent set of usable resolutions. This is possible because of the restriction imposed by \mathcal{X} . In the earlier case, the usable set will be $\{45^0, 90^0\}$. To achieve this, a confidence value is associated, as meta-data, with each resolution of an agent. This meta-data called the *resolution*

success count(RSC), counts the number of times the communication was successful when that resolution was used. During the *encoding* phase, the confidence value of the respective resolutions decide the resolution to be used. Once the resolution is decided, the sector of that resolution containing the topic node is used to create the meaning.

The 6 stages of the interaction are as follows:

- (a) *Making Contact*: Same as Experiment-2
- (b) *Topic Identification*: Same as Experiment-2
- (c) *Perception*: The speaker will then try to define the position of the topic node using its ontology. A resolution has to be chosen which has the highest probability of success. For this a probability distribution is developed on the set of resolutions where the probability σ_q of a resolution q is given by:

$$\sigma_q = \frac{RSC(q)}{\sum_{e \in \mathcal{R}} RSC(e)} \text{ where } \mathcal{R} \text{ - resolution set of the agent} \quad (2.8)$$

The meaning is created using the sector S_i of the chosen resolution which contains the topic node. A line number L_j with respect to the sector S_i will be the line component of the meaning. So the category (S_i, L_j) will be the meaning used by the speaker during interaction.

- (d) *Encoding*: Same as Experiment-2.
- (e) *Feedback*: Same as Experiment-2.

2.4.3.1 Learning

The learning algorithm is almost the same as that of experiment-2. The meanings are induced using the same meaning-induction algorithms discussed in section-2.4.2.2. Minor modifications are made in the updation procedure to accommodate the differences in the resolution set of the agents. The overall updation procedure can be summarized as:

- Success:
 - Speaker:
 - * Increment the *MSC* and *MUC* of the used word-meaning mapping by one.
 - * Increment the *RSC* and *RUC* of the used resolution by one.
 - Hearer:
 - * Increment the *MSC* and *MUC* of the used word-meaning mapping by one.
 - * Increment the *RSC* and *RUC* of the used resolution by one.
- Failure:
 - Speaker:
 - * Increment *MUC* of the used word-meaning mapping by one.
 - * Increment *RUC* of the used resolution by one.
 - Hearer:
 - * Increment *MUC* of the used word-meaning mapping by one.

- * Increment RUC of the used resolution by one.
- * Increment RSC and RUC of the induced resolution by one.
- * Increment MSC and MUC of the induced meaning by one.

2.4.4 Experiment 4

In this experiment, the concept set C evolves along with the language. So in this case both ontology C and the lexicon Γ evolves as the game progresses.

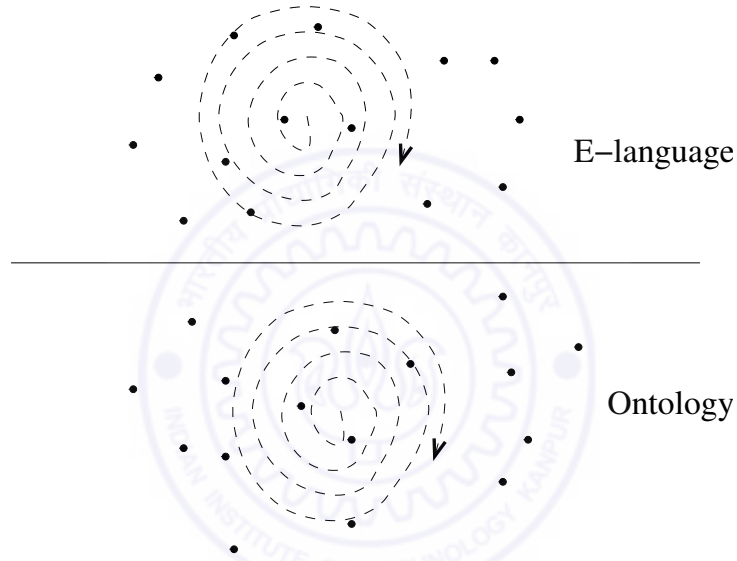


Figure 2.12: Convergence of both ontology and language

Initially $C = C_l = \mathbb{N}$ and the lexicon $\Gamma = \{\}$. Since the agents ontology consists of only C_l , the agent perceives the world using C_l alone *i.e* it just uses numbers to identify nodes(see Figure-2.13). So a single concept can identify objects in the world. So composition of words is not required in this world. This is similar to experiment(1) and the agents have no confusion in inducing the meaning of an unknown word from the feedback received. An extra constraint not present in any of the previous experiments is introduced in this experiment. That is the

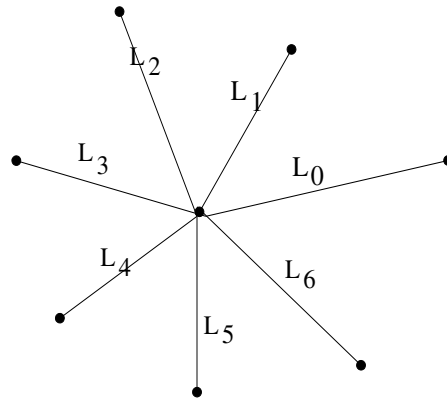


Figure 2.13: Line numbers identifying the nodes

constraint of memory. The agents have limited memory. The concepts are many, but the memory available to store the lexicon is limited in size, less than the number of concepts. The aim of this limitation or bottleneck is to push the agents to bring in new features into their language so that they can overcome this limitation.

2.4.4.1 Memory

The memory of the agent is implemented as a First In First Out (FIFO) buffer. Whenever a word is to be added to the memory, if the memory is not full, the word is added to the tail of the buffer. Otherwise space has to be created to accommodate the new item. This is achieved by removing the head of the buffer and then adding the new item to the tail of the buffer.

2.4.4.2 Evolution of Ontology

The main characteristic of this experiment is the evolving ontology \mathbb{C} of the agents, basically C_s . The utterance of an agent is the result of the interaction between the conceptualization module and the language faculty. A failing language can be either due to the failure of the language faculty (because of the inefficiency of

the learning algorithm or weakness in encoding or decoding phases) or due to the ontology. In this experiment we assume that the latter is the case and change the ontology to C' , which is actually an extension of C . Further games are played with the new ontology C' with the language remaining where it was before the change.

2.4.4.3 Refinement Procedure

The refinement procedure modifies the ontology of the agents. This procedure is invoked at various stages of the simulation. A confidence parameter ζ is attached to the language system of an agent which includes the e-language and components like ontology and language faculty. The parameter ζ is assigned an a priori value. The ζ value of an agent fluctuates as language games are played by the agent. When this value falls below a threshold δ_c (fixed for an experiment), the immediate action from the agent is to refine its concept structure. Further granularity is brought into the ontology.

Initially, the agents only use line numbers as the meanings. So the first refinement will be the conceptualization of space in the form of two sectors - $[0, 180^\circ)$ and $[180^\circ, 360^\circ)$. This transition is shown in the Figure-2.14(1)-(2). So the current ontology of the agent will be $C = \{S_0, S_1\} \cup C_l$, where $S_0 = [0, 180^\circ)$ and $S_1 = [180^\circ, 360^\circ)$. Later in the experiment, the refinement procedure involves splitting each sector of C_s into half. For example, after the second refinement the ontology will be $C = \{S_0, S_1, S_2, S_3, S_{01}, S_{23}\}$, where $S_0 = [0^\circ, 90^\circ)$, $S_1 = [90^\circ, 180^\circ)$, $S_2 = [180^\circ, 270^\circ)$, $S_3 = [270^\circ, 360^\circ)$, $S_{01} = [0^\circ, 180^\circ)$ and $S_{23} = [180^\circ, 360^\circ)$. This transition is shown in Figure-2.14(2)-(3). Similarly after yet another refinement the ontology becomes $C = \{S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_{01}, S_{23}, S_{45}, S_{67}, S_{0123}, S_{4567}\}$, where $S_0 = [0^\circ, 45^\circ)$, $S_1 = [45^\circ, 90^\circ)$, $S_2 = [90^\circ, 135^\circ)$, $S_3 = [135^\circ, 180^\circ)$,

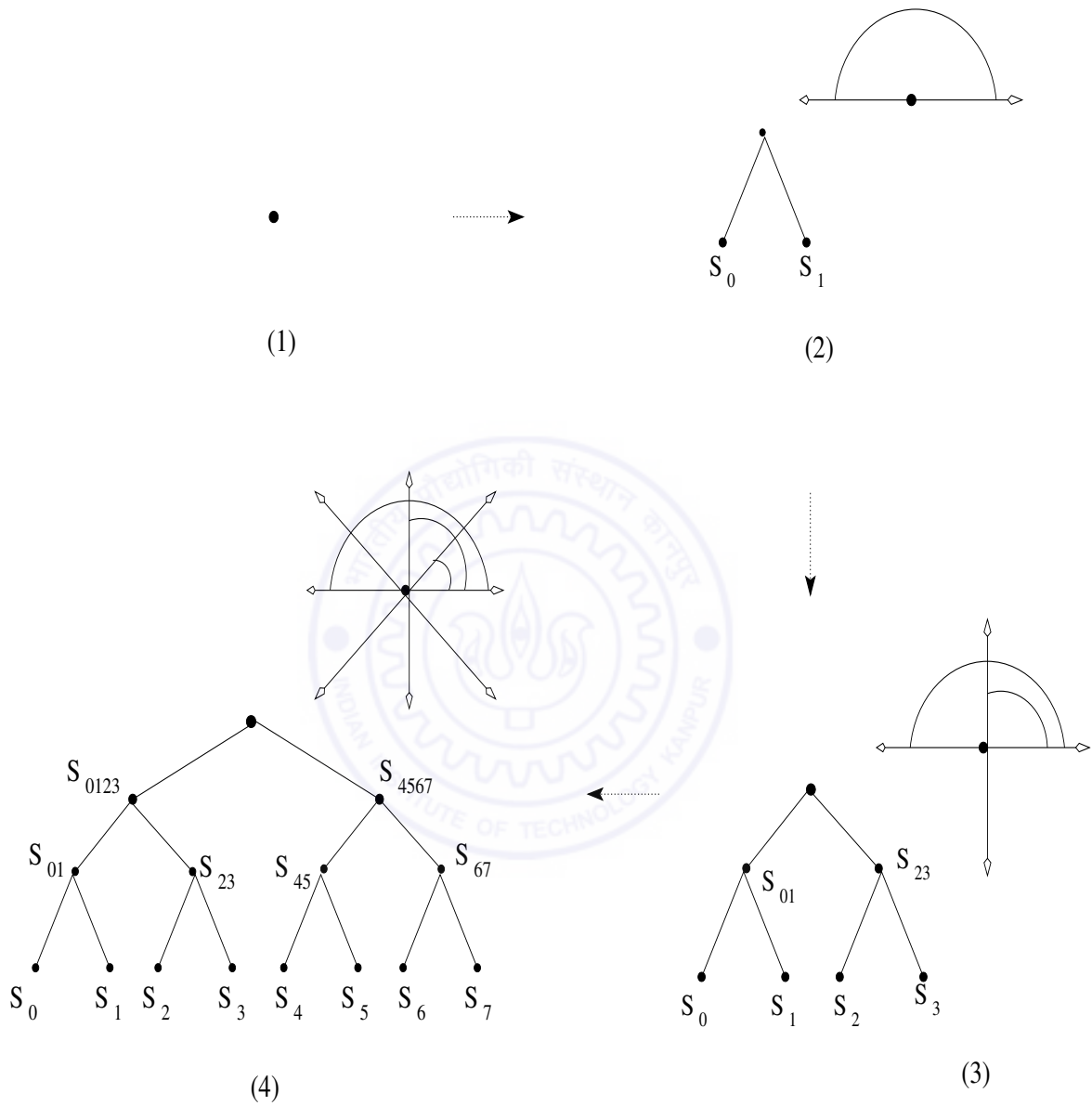


Figure 2.14: Stages of the the evolution of ontology

$S_4 = [180^\circ, 225^\circ)$, $S_5 = [225^\circ, 270^\circ)$, $S_6 = [270^\circ, 315^\circ)$, $S_7 = [315^\circ, 360^\circ)$, $S_{01} = [0^\circ, 90^\circ)$, $S_{23} = [90^\circ, 180^\circ)$, $S_{45} = [180^\circ, 270^\circ)$, $S_{67} = [270^\circ, 360^\circ)$, $S_{0123} = [0^\circ, 180^\circ)$ and $S_{4567} = [180^\circ, 360^\circ)$. This transition is shown in Figure-2.14(3)-(4).

2.4.4.4 Evolution of Language

In this experiment, the evolution of language takes a route which is entirely different from the previous experiments. Initially since a single meaning system was used, the language was unitary. The agents use a single word during interaction. The concept of composition is not present in the community. We can push this system to complete failure by limiting the memory size of the agents to very small values. This pushes the confidence value ζ to values below the threshold δ_c which prompts the refinement of meaning structure. As a result of this, the compositionality property arises in meanings and a meaning used to define the node location is composed of two concepts. This brings in the compositionality property into the language. So language moves from the initial unitary structure to a compositional form, and during this transition a coherent lexicon is developed.

2.4.4.5 The Experiment

- Signal space - Same as experiment-1
- Meaning space - The agents contain an evolving ontology. New sectors will be added to the ontology as needed. A structure exists in the meaning space. Meanings are hierarchical nature. In experiments 2 and 3, the meaning set was fixed. Experiments 2 and 3 play games to lexicalise the fixed ontology. In this experiment, the ontology set (which has to be lexicalised) changes over

time. The evolutionary process was discussed in the earlier section. Because of the limitation in memory, only a few sectors and lines can be lexicalised. So the agents have to first converge on a set of sectors and lines which can be used to represent the location of the nodes. So there is a competition among the elements of the ontology. The successful elements will be used by the agents again and again and its mapping will remain in the memory. To model this, meta-data is associated with each concept (both sector and line) of the ontology. The meta-data contains two fields - *Sector Success Count(SSC)* and *Sector Usage Count(SUC)*. *Sector Usage Count(SUC)* is the total number of times the sector has been used to represent the location of nodes and *Sector Success Count(SSC)* is the total number of times the usage was successful (the interaction was successful).

- Mental Lexicon - Same as experiment-2

Changes are made in *encoding*, *decoding* phases and the *learning* protocol of the agents.

- *Perception*: Agents perceive the topic using its ontology. To provide meaning to the location of a node, the sector containing the node is first selected. The line number is obtained relative to that sector. So the set \mathcal{C}_s decides the meaning to be used for the interaction. In this experiment \mathcal{C}_s is evolving. As the game progresses new elements are added to \mathcal{C}_s . So at a particular moment, there will be multiple sector concepts by which the location of the node can be represented. Here again we use statistical methods and associate a confidence parameter with each sector concept which shows how successful the sector was when previously used. The confidence, η_e of a concept e is

given by the equation 2.9

$$\eta_e = \frac{SSC(e)}{SUC(e)} \quad (2.9)$$

The entry with the largest η_e is chosen as the sector component of the meaning. The line component will be the line number with respect to this chosen sector.

- *Encoding:* Agents can only use words which are in their memory. When the agent has to express a meaning, the words in memory which are mapped to the meaning are picked and as before a probability distribution is created. A word is chosen from this list based on this distribution. If no word exists for the meaning in memory, a new mapping is created as explained in previous experiments.
- *Decoding:* Again the memory bottleneck comes into play. The agent can interpret words which are in memory. If the words used in the language game by the speaker are not present in the listener's memory, the interpretation and the game itself fails and the agent has to update its lexicon in the hope of using it again in future. If the word is in memory the *uncover* procedure of the previous experiments is used.

2.4.4.6 Learning

Learning in this case is much more complex than earlier experiments. The complexity is due to evolving perception. Agents bring in new views when old views are not good enough for survival. There are two kinds of competition here. One is the competition among the concepts about which one stays in the ontology. The

other is the competition among the mappings, *i.e.* the words associated with a particular meaning compete to decide who represents that meaning. The updation procedure can be summarized as:

- Success:
 - Speaker:
 - * Increment the MSC and MUC of the used word-meaning mappings (both sector word and line word) by one.
 - * Increment the SSC and SUC of the used concepts (both sector concept and line concept) by one.
 - Hearer:
 - * Increment the MSC and MUC of the used word-meaning mappings (both sector word and line word) by one.
 - * Increment the SSC and SUC of the used concepts (both sector concept and line concept) by one.
- Failure:
 - Speaker:
 - * Increment the MUC of the used word-meaning mappings (both sector word and line word) by one.
 - * Increment the SUC of the used concepts (both sector concept and line concept) by one.
 - Hearer:

- * Increment the MUC of the used word-meaning mappings (both sector word and line word) by one.
- * Increment the SUC of the used concepts (both sector concept and line concept) by one.
- * Increment the MSC and MUC of the induced word-meaning mappings (both sector word and line word) by one.
- * Increment the SSC and SUC of the induced concepts (both sector concept and line concept) by one.



Chapter 3

Test Results

In this chapter, we present the results of the experiments conducted and the give an interpretation of those results.

3.1 Performance Measures

The simulations are evaluated using two factors- *Communication success ratio* and *Word Coherence ratio*. For the last experiment alone, one additional parameter is considered which is the *Concept coherence ratio*.

- (a) **Communication success ratio:** This value signifies the coherence of the language system. It is the ratio of the number of successful communication interactions to the total number of interactions during the experiment. It gives a rough figure of how successful the whole communicative apparatus was.
- (b) **Word Coherence ratio:** This value signifies the coherence of a particular word-meaning mapping in the emerged language. It is calculated for a par-

ticular word, meaning pair. It is the fraction of the population which has the given word as the most preferred word for the given concept.

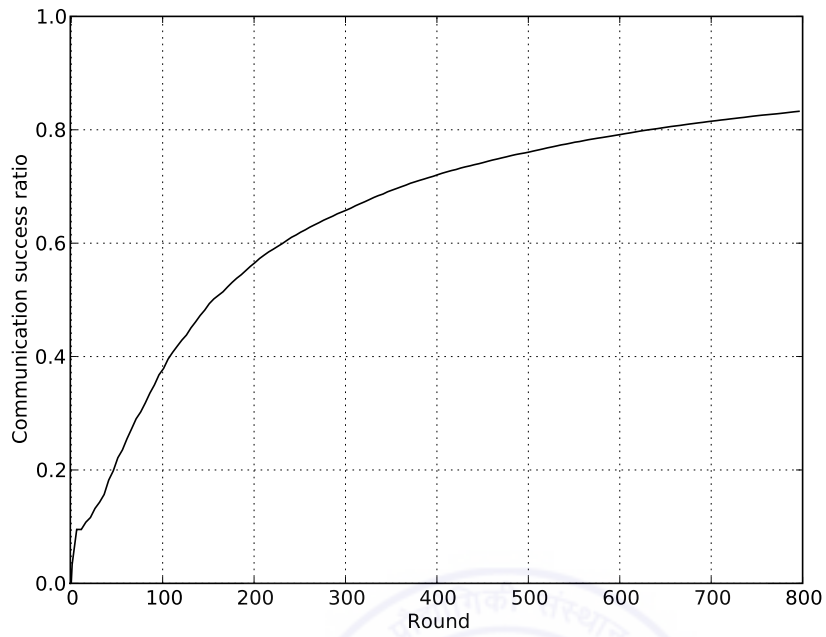
- (c) **Concept Coherence ratio:** This value signifies the coherence of the ontology of the agents. It is used only in experiments where the ontology is dynamic. The value is calculated for a particular concept. It is the fraction of the agents which has the given concept in its ontology.

3.2 Experiment 1

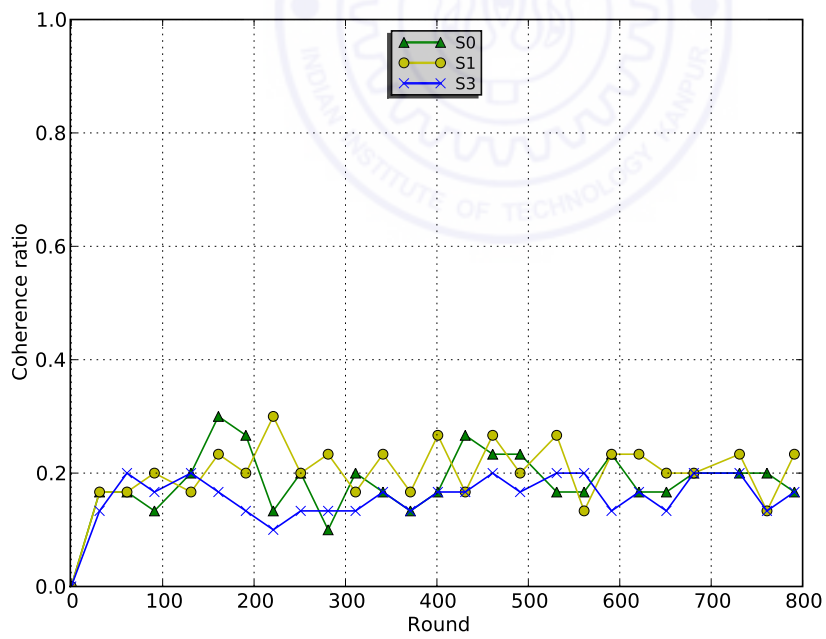
The main components of the experiment are:

- **World:** An undirected graph consisting of 40 nodes plotted on a two-dimensional plane 500x500 in dimension. All the nodes have the same degree, and the degree of each node is set to 22.
- **Agents:** All agents have got only one resolution. The resolution is set to 45° . The agents are considered to be immortal and their energy is set to infinity. The population size is 30.
- **Interactions:** The interaction strategies are the same as explained in chapter-2. In this experiment, each communication episode consists of two interactions. In the first interaction, one of the agents become the speaker and the other becomes the hearer and in the second, the roles are swapped.

The communicative success ratio graph of the experiment is shown in Figure-3.1(a). In the initial stages of the simulation, the games played failed, but later it recovered and is rapidly approaching 1. The curve has positive slope after the



(a) Communicative success ratio



(b) Word coherence ratio

Figure 3.1: Experiment 1

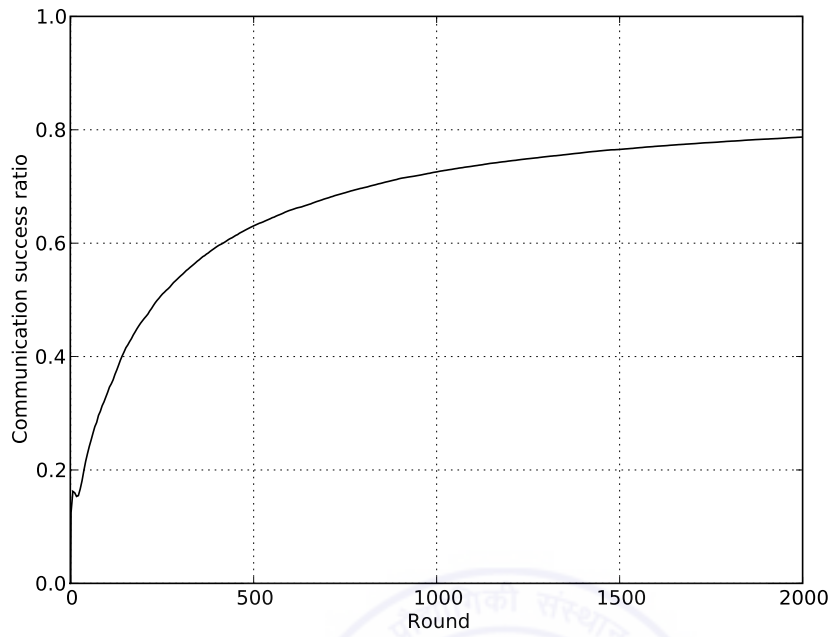
initial stage. Since there is no confusion in understanding the meaning of the utterances, the language converged very rapidly (within 700 rounds). There is absolutely no ambiguity in the emerged language. The word convergence graph figure-3.1(b) gives some interesting results. All the curves in the word coherence graph are lying low. This shows that for each concept there is no common preferred word in the population. But the agents can understand all the words, even though it is not their preferred word. This implies that there are a lot of synonyms in the emerged language. The unlimited memory helps in storing all the mappings.

3.3 Experiment 2

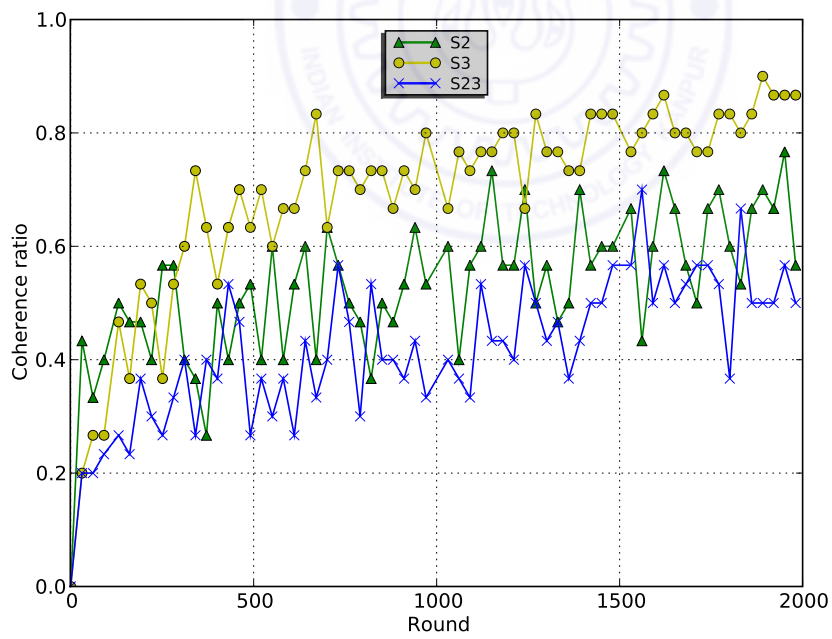
The main components of the experiment are:

- **World:** An undirected graph consisting of 40 nodes plotted on a 2-dimensional plane 500x500 in dimension. All the nodes have the same degree, and the degree of each node is set to 22.
- **Agents:** All the agents are multi-resolution agents. They have the same set of resolutions. The resolution set of the agents was $\{90^\circ, 180^\circ\}$.
- **Interactions:** In this experiment, each communication episode consists of 15 interactions. This helps to resolve the confusion that may arise during a particular interaction of a communication episode within that communication episode itself.

The Communicative success ratio in Figure-3.2(a) shows that the language system is converging. The games played were successful in developing a coordinated communication system. The curve in the figure has got a positive slope and is



(a) Communicative success ratio



(b) Word coherence ratio

Figure 3.2: Experiment 2

approaching 1. The number of rounds it took to converge is much more than Experiment-1. As can be seen in the graph, there is considerable turbulence in the initial stages of the experiment. The duration of this unstable stage is larger than that of the earlier experiment. The reason behind this is an agent's inability to induce the right meaning of the unknown signal because of the presence of multiple meanings. These multiple associations of a particular word have to finally converge to a single association. This requires more number of interactions between agents. The word coherence graph Figure-3.2(b) also shows rising curves. This implies that the majority of the population prefer the same word for a particular concept. This means that the level of synonymy in the evolved language is very less. Another important observation is the emergence of ambiguity in the evolved language. This is due to the confusion in deducing the correct meaning of the heard words.

3.4 Experiment 3

The main components of the experiment are

- **World:** A 40 nodes undirected graph plotted on a two-dimensional plane 500x500 in dimension. All the nodes have the same degree, and the degree is set to 22.
- **Agents:** All the 30 agents are multi-resolution agents. The set of resolutions the agents possess are different. In order to reduce the complexity of the simulation, the set of possible resolution sets were reduced to $\{\{45^\circ, 90^\circ, 180^\circ\}, \{90^\circ, 180^\circ\}, \{180^\circ\}\}$. In this experiment, 15 agents out of

the total 30 have $\{45^\circ, 90^\circ, 180^\circ\}$ as their resolution set. The rest is assigned the resolution set $\{90^\circ, 180^\circ\}$.

- **Interactions:** In this experiment, each communication episode consists of 15 interactions.

As can be seen in the Figure-3.3(a), the language of the population is converging. The rate of convergence is pretty slow in this case as the ontologies of the agents are not similar. The number of rounds taken by the experiment to reach 80% success ratio is more than the previous experiments.

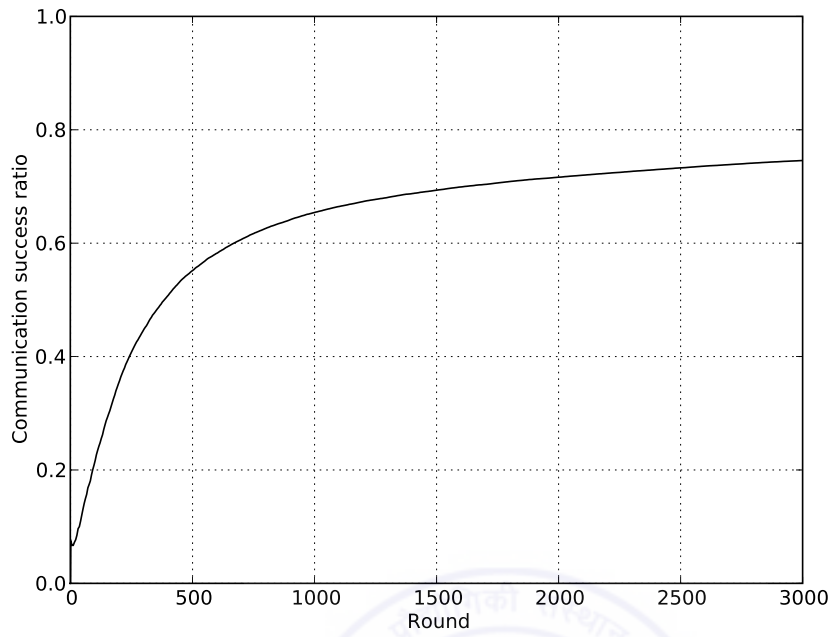
As we know, the aim of all these experiments was to lexicalise the ontology of the agents. The ontology C^A of an agent A with resolution set $\{45^\circ, 90^\circ, 180^\circ\}$ and ontology C^B of agent B with resolution set of $\{90^\circ, 180^\circ\}$ are:

$$C^A = \{S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_{01}, S_{23}, S_{45}, S_{67}, S_{0123}, S_{4567}\} \cup C_l \quad (3.1)$$

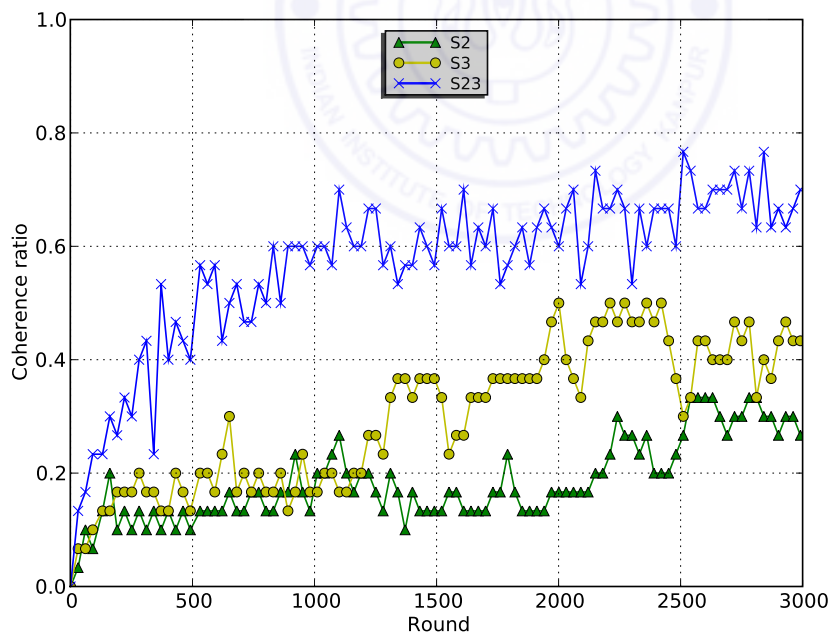
and

$$C^B = \{S_{01}, S_{23}, S_{45}, S_{67}, S_{0123}, S_{4567}\} \cup C_l \quad (3.2)$$

respectively. The two sets, C^A and C^B have common elements which can be used to express the topic. So the language has to converge on these common sectors. The agents are unaware of the differences in their ontologies. The speaker may choose a meaning that may not exist in the listener's ontology which increases the disorder in the language system. But the agents got use histories. The meanings are not chosen at random, they are influenced by the usage history. Some statistical information is stored with each resolution which is actually the usage confidence



(a) Communicative success ratio



(b) Word coherence ratio

Figure 3.3: Experiment 3

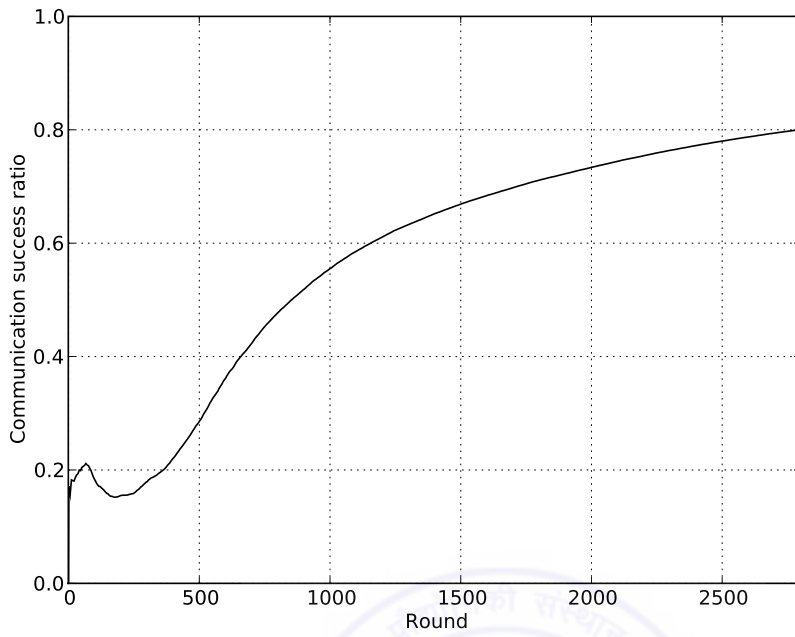
of the resolution, which is used in choosing the meaning. The meaning the agent chooses is from the sectors of the resolution which has the highest confidence. As we see in Figure-3.3(b), sector S_{23} which is common in the population has good higher word convergence while the uncommon sectors S_2 and S_3 which are present in 50% of the agents' ontologies, have a word convergence that is below 0.5. This is because when agents having 45° resolution try to express the meanings S_2 and S_3 , the agents who do not have this resolution, fail to induce the right meaning even though the game may be successful because of the overlap between the sectors of 90° and 45° .

3.5 Experiment 4

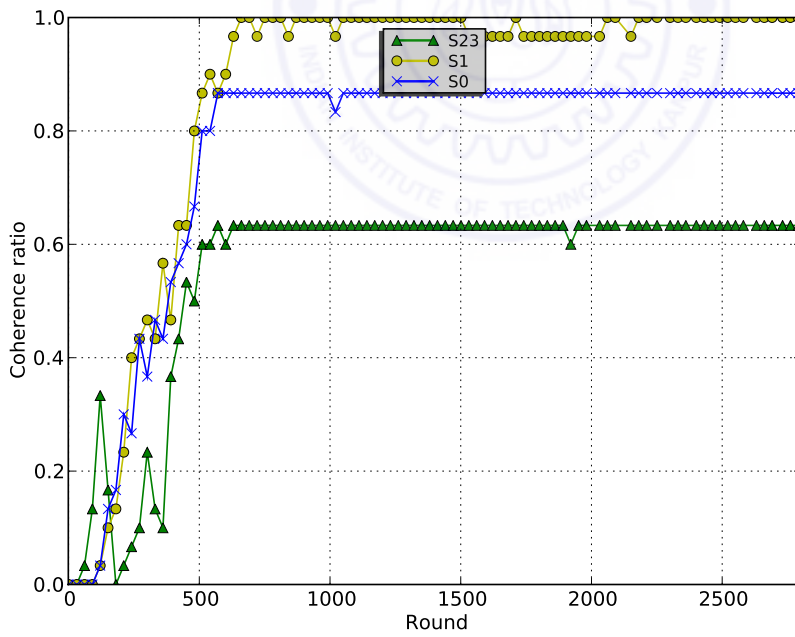
The main components of the experiment are

- **World:** Same as before.
- **Agents:** Initially the agents have no resolution. Their ontology $C = Cl$, consists of just numbers alone. The agents identify the nodes using just the numbers. So initially, the meanings used are not compositional in nature.
- **Interactions:** In this experiment, each communication episode consists of 15 interactions. This helps to resolve the confusion that may arise during a particular interaction of a communication episode within that communication episode itself.

This experiment is the most complex of all the experiments. In this experiment, both language and ontology of the agents evolve. The push for the evolution of the ontology comes from the failure of the language system. The failure of the



(a) Communicative success ratio



(b) Word coherence ratio

Figure 3.4: Experiment 4

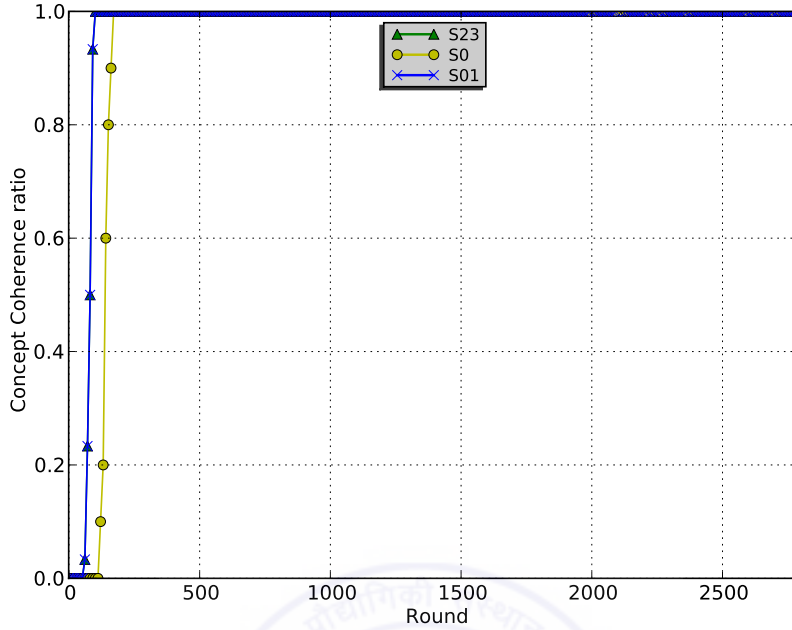


Figure 3.5: Experiment 4: Concept coherence ratio

language is forced by adding an extra constraint on the agents in the form of the *memory bottleneck* i.e. the agent’s memory is limited in size. An agent’s memory is only able to hold a maximum of 31 words at a time. This limits the maximum number of mappings of an agent to the size of the memory. There is a much longer period of instability in this experiment. There is a rise, then a fall and then a rise again after which the curve is moving towards 1.

The communicative success graph for the experiment is shown in Figure-3.4(a). Initially, the ontologies of the agents are $C = C_l$ where $C_l = \mathbb{N}$. So agents only use line numbers to identify the nodes. The minimum density of the graph is set to 22. Since the all the agents interact and since there is no confusion while learning a new word many mappings are required (as seen in experiment-1). But all these mappings cannot be stored in the memory which causes the initial language

games to fail. This results in the deterioration of the agent's confidence in the language. When the confidence falls below a threshold value, the agent modifies its ontology. The threshold for the experiment is set to 0.33. Then the games are played with the modified ontology. The modified ontology is $C = \{S_0, S_1\} \cup C_l$. Now the agents need to use only half of the line numbers required earlier. With this refined ontology, if the lexicalisation process can fit into the memory then the games will succeed. But we see the language games are still failing. This pushes the confidence in the language below the threshold. The refinement process kicks in, thus reducing the required number of lines. This time the memory seems to be enough and the games start succeeding. We can see the graph growing with a positive slope.

As seen in the graph-3.4(b), a majority of the agents have the same preferred word for the concepts. Also shown is the concept coherence graph(Figure-3.5). This graph shows the fraction of the agents which possesses a particular concept. Only 3 concepts, S_0, S_{01} and S_{23} are being plotted. The curves have touched 1, which shows all the agents have acquired all these concepts. This shows that convergence of concepts has also happened.

Chapter 4

Conclusion and Future Work

4.1 Conclusion

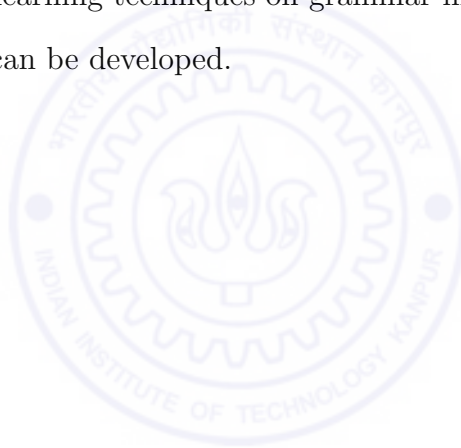
In this thesis, we have developed a model in which agents communicate about their environment using a developing language without explicitly transferring meanings. A coherent language emerged among the population of agents in all the experiments we conducted. The cognitive abilities of the agents include the ability to perceive, invent and induce. The agents interacted with each other through language games and were able to induce the right meaning for an utterance using their cognitive abilities. The agents did not have any dedicated language faculty as such but had abilities to count and order objects and to calculate distance and direction.

Four experiments were conducted in this work. The complexity of the experiment increased as we proceed from experiment-1 to experiment-4. In experiment-1, which is the simplest, the agents were able to induce the right meaning for a lexical item on first encounter itself. The convergence of the language was fast and the

language had a lot of synonyms and absolutely no ambiguity in them. The agents did not require a complex meaning induction mechanism to acquire the language. But from the second experiment onwards, we see a lot of confusion arising regarding the correct meaning of a word. This is due to the complex ontology each of the agents possessed. But the agents were able to induce the right mappings by making use of the structure in the ontology and the history of word usage. Because of the ambiguity in inducing the correct meaning for an unknown word, ambiguity emerges in the language. In experiment 4, we have seen that the agents modify their ontology to fit to the needs of the language. This experiment was completely different from Steels and Vogt. In their games, observation games were played to develop an ontology in the agents and later the agents play language games to lexicalise the ontology. The success of their games depended on the similarity of their meaning structures. In our game (experiment 4), the agents started with a small number of concepts and new concepts emerged among the agents at later stages of the simulation when the existing language was unable to cope. Here both ontology and language (which has to lexicalise the ontology) were evolving in parallel. Even in these complex situations, a coherent system of communication emerges in the population. In the last experiment a different kind of language emerged. In the initial 3 experiments, a proto-language *i.e* a coherent set of word-meaning mappings emerged. But in experiment-4 a compositional language emerged. In the initial stages of the experiment agents tried to develop a proto-language which failed due to the inability of the agents to store all the words. This pushed the agents to develop a new language that had composition.

4.2 Future Work

What we saw in these experiments was the emergence of a protolanguage and the emergence of language properties like compositionality. But the compositionality achieved is partial in nature. The experiment assumed that all the agents will use the same word order *i.e.* sector followed by line. This can be changed and the word order can be made flexible and we can study whether syntax *i.e.* word order also emerges. In the experiments conducted when the listener hears an utterance, it is able to split the utterance into a sector word and a line word. This is because the simulations assumed that the agents knows the pause symbol. This can be removed and by using machine learning techniques on grammar induction a language with syntactical properties can be developed.



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