Chapter 2
Artificial Organisms with Human Language

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Abstract If artificial organisms are constructed with the goal to better understand the behaviour of real organisms, artificial organisms that resemble human beings should possess a communication system with the same properties of human language. This chapter tries to identify nine such properties and for each of them to describe what has been done and what has to be done. Human language: (1) is made up of signals which are arbitrarily connected to their meanings, (2) has syntax and, more generally, its signals are made up of smaller signals, (3) is culturally transmitted and culturally evolved, (4) is used to communicate with oneself and not only with others, (5) is particularly sophisticated for communicating information about the external environment, (6) uses displaced signals, (7) is intentional and requires recognition of intentions in others, (8) is the product of a complex nervous system, (9) influences human cognition. Communication presupposes a shared worldview which depends on the brain, body, and adaptive pattern of the organisms that want to communicate, and this represents a critical challenge also for communication between robots and us.

1 Understanding the Behavior of Real Organisms by Constructing Artificial Organisms

Traditional theories of behavior are expressed by using the words of the common language and this poses a problem because the words of the common language tend to have unclear and ambiguous meanings, and it is difficult to derive detailed and noncontroversial empirical predictions from verbally formulated theories. The availability of computers makes it possible to explore another way of formulating theories of behavior and, more generally, scientific theories. A theory becomes the blueprint for constructing an artefact, which can be a computer simulation or a physical device controlled by a computer (robot). To the extent that the artefact behaves like some real organism, one can conclude that the theory incorporated in the artefact is a good theory of the behavior of the organism. There are at least two advantages to expressing theories of behavior as artefacts. First, theories necessarily have to be formulated in an operational and unambiguous way because otherwise the artefact

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cannot be constructed. Second, theories will generate a very large number of detailed and noncontroversial empirical predictions because the behaviors exhibited by the artefact are the empirical predictions derived from the theory incorporated in the artefact.

Artificial organisms that behave like real organisms can be constructed with two different goals in mind. They can be constructed with the purely scientific goal to better understand the behavior of real organisms, or they can be constructed as devices that have practical applications. The two goals can be mutually beneficial. Artificial organisms that are constructed for purely scientific reasons can suggest new and better applications, while the need to design artificial devices that have useful applications may suggest new scientific questions and possible answers to these questions. However, the two goals should be kept distinct. Artificial organisms with purely scientific goals may have no practical applications or their practical applications may only be discovered in the future, while devices with practical applications may not be like real organisms and may even violate the principles that govern the behavior of real organisms. In any case, the criteria for judging the goodness of an artefact are different in the two cases. An artefact with purely scientific goals has to generate behaviors that reproduce as closely as possible the behavior of real organisms, while an artefact with practical applications has only to be useful and, possibly, to possess economic value.

There are many decisions to be made if one wants to construct artificial systems that behave like organisms. One can ignore that the behavior of real organisms is controlled by a physical system, the nervous system, and endow artificial organisms with a purely symbolic system of rules that determine their behavior (artificial intelligence; cf. the approaches illustrated in Part III of this book), or one can endow the artificial organisms with a control system which reproduces in its essential characteristics the physical structure and way of functioning of the nervous system (neural networks, connectionism; cf. the approaches illustrated in Part II of this book). One can ignore the fact that organisms have a body which interacts with the physical environment, receiving sensory input from the environment and responding with movements that change the environment (classical connectionism), or one can construct artificial organisms that have a body and interact with a physical environment (embodied and situated agents, econets, robots). One can ignore that behavior is adaptive and is the result of a long evolutionary history and train the organisms only using learning algorithms, or one can work with populations of artificial organisms that both evolve in a succession of generations and develop and learn during their life (evolutionary robotics, artificial life).

Another choice is whether artificial organisms are simulated in a computer and interact with an environment which also is simulated, or they are real physical devices that interact with the real physical environment. In both cases there are advantages and disadvantages. Constructing purely simulated artificial organisms is less costly and makes it possible to ignore the present limitations of physical devices, but simulations do not fully exploit what the actual physical interactions of the artificial device with the physical environment can tell us concerning the behavior of real organisms.

In this chapter we will discuss the open challenges of constructing artificial organisms that possess a communication system that resembles human language and we will make the following methodological choices, although we will not justify these choices here. Artificial organisms have a body, interact with a physical environment, possess a control system which resembles the nervous system, and can both evolve at the population level and learn at the individual level. The organisms can be either simulated in a computer or realized as actual physical devices. We are interested in artificial organisms as scientific tools rather than as technologies with practical applications, but at the end of the chapter we will discuss an important implication of "basic" research for "applied" research aimed at constructing robots that interact with humans.

2 Artificial Organisms with Human Language

An important class of behaviors exhibited by many animals are communicative behaviors. Communication consists in the production of behaviors that have the function of causing sensory input for other individuals (signals) and in the ability to respond appropriately to the signals produced by other individuals. Human beings have communicative behaviors that resemble the communicative behaviors of other animals, but they also have a system of signals, language, with properties rather different from the communicative signals of other animals. As always when one compares human beings with other animals, there is no neat dividing line between humans and other animals and one can find simpler manifestations of typical human traits in this or that nonhuman animal. Furthermore, human language first arose in primates that only possessed animal communication systems and an important research question is how the transition took place. But human language clearly has a number of properties and functions that distinguishes it from animal communication and, even if this or that feature of human language can be found, at least in embryonic form, in animal systems, the simultaneous presence of all the features appears to be unique to human language (Hauser 1996).

Much current work aimed at constructing artificial systems that are embodied, interact with an environment, and are controlled by neural networks is dedicated to endow these systems with communicative abilities but this work has been mostly restricted to simple animal-like signals. Linguistic signals are more complicated than animal-like signals and endowing an artificial organism with a human-like language largely remains a task for the future. This is part of a more general problem of constructing artificial organisms that resemble human beings. There is much talk today of humanoid robots, but current humanoid robots only have the external appearance of a human being in that they walk on two legs, have two arms and two hands, and a human-like face. When it comes to behavior, current humanoid robots possess few behaviors that can be called specifically human. The development of artificial organisms that have human-like language requires that these organisms possess many other abilities and properties that characterize human beings beyond language. This is why constructing artificial organisms with a human-like language is a very difficult task.

If we want to construct artificial organisms that possess human language, at least in embryonic form, it is important to ask which properties and functions characterize human language and distinguish human language from animal communication systems. What we will do in this chapter is review these properties and functions from the point of view of constructing artificial organisms that can be said to have human language.

The fundamental properties of human language have been discussed many times in the literature since Hockett (1960). The following is a possible and to some extent arbitrary list.

Human language:

1. Is made up of signals which are arbitrarily connected to their meanings.
2. Has syntax and, more generally, its signals are made up of smaller signals.
3. Is culturally transmitted and culturally evolved.
4. Is used to communicate with oneself and not only with others.
5. Is particularly sophisticated for communicating information about the external environment.
6. Uses displaced signals.
7. Is intentional and requires recognition of intentions in others.
8. Is the product of a complex nervous system.
9. Influences human cognition.

The remaining part of the chapter will be devoted to discussing these properties in more detail and to defining the challenges that they pose to research aimed at constructing artificial organisms that possess human language.

3 Nine Properties of Human Language

3.1 Linguistic Signals are Arbitrarily Linked to Their Meanings

Sensory input for an organism which is caused by the behavior of another organism is a signal if it is associated with a meaning in the nervous system of both organisms. What characterizes human language is that the link between a signal and its meaning is arbitrary. Human language is arbitrary at the level of its basic signals, i.e., words (or, better, morphemes), and a word is arbitrarily linked to its meaning in two senses. First, if one hears the word for the first time, it is impossible to guess what the meaning of the word is. Second, variations in the physical realization of the word, for example, its loudness, do not generally tell the receiver anything about variations in the meaning of the signal.

To discuss the arbitrariness of the word-meaning relation it may be useful to imagine a simple neural network model of language like the following (Mirolli and Parisi 2005b). The neural network controlling the behavior of the artificial organism is made up of two modules, a nonlinguistic module and a linguistic module.

The nonlinguistic module has input units encoding objects and actions perceived by the organism and output units encoding the organism's non-linguistic actions, such as reaching and grasping an object. The linguistic module has input units encoding linguistic signals (heard words) and output units encoding the phono-articulatory movements of the organism that result in the production of linguistic signals (spoken words). Both modules include one or more intermediate layers of internal units between the input units and the output units, and activation flows from the input units through the internal units to the output units. Basically, both modules function because some input arrives to the module's input units and the module responds with some output. If the two modules were separated, the nonlinguistic module would be able to generate nonlinguistic behaviors in response to non-linguistic sensory inputs such as seeing an object and responding by reaching and grasping the object, while the linguistic module could imitate heard linguistic sounds by generating phono-articulatory movements that reproduce the sound, or respond to a heard sound with an associated sound. But the sounds would have no meaning. The sounds have meaning because the two modules are connected together by bidirectional links going from the internal units of the nonlinguistic module to the internal units of the linguistic module, and vice versa. These inter-module connections give meaning to the sounds heard or pronounced by the linguistic module. If some non-linguistic input enters the non-linguistic module, for example, the organism sees an object, activation goes to the module's internal units and then to the internal units of the linguistic module, through the connections linking the nonlinguistic to the linguistic module, and the organism responds with a pronounced sound. This is naming. If some linguistic input enters the linguistic module, that is, the organism hears a word, for example, a verbal command, activation spreads to the module's internal units and then to the internal units of the nonlinguistic module, and the organism responds by executing the action which has been verbally commanded. This is language understanding.

Notice that this neural architecture may also be used to capture the linking of signals to their meanings in animal-like, nonarbitrary, communicative systems, and more generally, the linking of different sensory modalities in multi-channel sensory-motor mapping. Given the sort of modular neural architecture we have described, if a neural network receives different sensory inputs at the same time and there is some systematic co-variation (statistical correlation) between co-occurring inputs, the network will be able to extract the regularities implicit in this co-variation and will be able to exploit these regularities in a number of ways. For example, if two sensory inputs tend to co-occur together and in one occasion one of the two inputs occurs without the other, the neural network will be able to generate the internal activation normally evoked by the missing input by using the internal activation evoked by the other input. If an organism visually perceives the spatial contact between its hand and an object and at the same time receives a tactile input from the object, the organism's neural network will be able to self-generate the tactile perception (internal activation pattern in the tactile module) on the basis of the visual input only, that is, in the absence of tactile input. Or vice versa, the organism might be able to self-generate the visual perception of spatial contact between its hand and the object (internal activation in the visual module) in the absence of actual visual input. The same applies to the non-arbitrary linking of signals and their meanings in non-linguistic communication systems. In both cases the non-arbitrary character of the inter-module linking transpires because new inputs automatically generate the internal activation evoked by the associated input, and physical variations in one input are systematically associated with variations in the internal activation evoked by the other input. Language is different because, as we have said, the linking between internal activations in the two modules is arbitrary. No meaning (activation pattern of the internal units of the non-linguistic module) can be generated in response to linguistic signals (words) that are heard for the first time, and variations in the physical realization of the linguistic signal are not associated to corresponding variations of the meaning of the signal. This arbitrariness may explain many properties of language and may have many important consequences for its function.

The challenge here is to construct artificial organisms that are controlled by a neural network which has the ability to arbitrarily map signals into meanings, and vice versa. What is critical is to design or, better, to evolve a neural network architecture which is capable of this type of arbitrary mapping.

3.2 Language is Compositional

Animal signals tend to be simple in the sense that they are not made of smaller signals that have meaning. Although some animal signals may be analyzed as combinations of recurring parts, the parts do not have separate meanings. Linguistic signals are complex. They are made up of smaller signals that have their own separate meaning, and it is the particular way in which the smaller signals are combined in a larger signal that determines the meaning of the overall signal. This combinatorial or compositional character of human signals manifests itself at a hierarchy of levels: phonemes (that do not have separate meaning) are composed into morphemes, morphemes into words, words into phrases, phrases into sentences, sentences into discourses and dialogues.

Suppose you want to be able to communicate the following facts:

- The book is on the table.
- The pen is on the table.
- The book is under the table.
- The pen is under the table.
- The book is on the chair.
- The pen is on the chair.
- The book is under the chair.
- The pen is under the chair.

If your communication system is made of simple signals, you would need eight different signals, one for each of the eight different facts to be communicated. If, on the other hand, you have human language, six simple signals would be sufficient ("book," "pen," "on," "under," "table," "chair") because you would be able to communicate the eight facts by combining together three simple signals (words) to form one complex signal (sentence). Compositionality in communication is very powerful. By adding one more signal to your set of six simple signals, e.g., "glass," you would be able to communicate four new facts (the glass is on the table, the glass is under the table, the glass is on the chair, the glass is under the chair). With longer and longer complex signals, adding a limited number of further simple signals would allow you to generate an increasing and very large number of complex signals. Furthermore, compositional languages allow you to both produce and understand new signals, that is, new combinations of existing signals.

One critical challenge for the development of artificial organism with human-like language is to be able to construct organisms that start with an animal-like communication system with only simple, noncompositional, signals and gradually develop a human-like communication system with complex, compositional signals. Once a communication system with complex signals exists, it has to be learned by the new members of a community of artificial organisms (children; cf. Sect. 3.3). As we have suggested in Sect. 3.1, language is learned by noticing the systematic co-variation of specific signals with specific aspects of one's experience and incorporating these co-variations in one's nervous system. If a newborn organism is exposed to complex signals, the organism's neural network has to be able to notice the co-variation of specific sub-parts of a complex signal with specific sub-components of its current experience and to incorporate these partial co-variations in its connection weights, not the co-variation of the entire complex signal with the entire experience.

As already noted, human language is compositional at all levels, from phonemes to morphemes to words, phrases, and sentences. But the critical aspect of human language's compositionality that we should be able to incorporate in our artificial organisms is syntax, which is the combining of words into phrases and phrases into sentences. In a sentence, the meanings of the words are combined together to generate the meaning of the sentence. Since there may be many different ways to combine together the meanings of a set of words into the meaning of a sentence (e.g., John loves Mary vs. Mary loves John), sentences must provide some cues for combining together the meanings of the words in the way which is intended by the speaker. These cues are called grammar. Grammatical cues can consist of the order in which the words follow each other in the sentence or in special signals which may be attached to words (bound morphemes) or free-standing (function words). (We return to compositionality in Sect. 3.2 below.) One possible hypothesis to be tested with evolving artificial organisms is that human language has gone through three successive stages (Parisi 1983). In Stage 1, linguistic signals were already linked arbitrarily to their meanings, but this proto-language only included simple, noncompositional signals (words). In Stage 2, language became compositional but it lacked grammar, that is, there were no explicit cues for putting together the meanings of simple signals that made up a complex signal (sentence) to obtain the meaning of the complex signal. It was the nonlinguistic context that helped the hearer to arrive at the correct meaning of the complex signal, that is, the meaning intended by the speaker. Finally in Stage 3, that is, the stage of all known human languages, grammar emerged as a set of explicit cues that direct the hearer to the correct combination of the meanings of the component signals to obtain the meaning of the sentence. As we have already noted, compositional languages are more effective than noncompositional languages because they allow speakers/hearers to produce/understand a large set of complex signals by storing in their brains only a much smaller set of simple signals (the lexicon) and because they allow speakers/hearers to communicate about new facts and new experiences. Compositional languages with grammar are more effective than compositional languages without grammar because they make the meaning of complex signal more unambiguous and less dependent on context. Furthermore, compositional languages, both with and without grammar, may be more effective than noncompositional languages because they force the speaker/hearer to analyze and articulate complex situations and experiences in their component parts (cf. Sect. 3.9). The challenge here is to evolve a population of artificial organisms which because of the increasing adaptive value of the different communication systems moves from Stage 1 to Stage 2 and then to Stage 3.

Although human language is compositional (or generative), one must not exaggerate this property of human language. It has been calculated (Wray 2002) that almost 70% of actually produced complex signals (phrases and sentences) are idiomatic, where an idiomatic signal is a linguistic expression composed of many words but whose meaning cannot be "generated" from the meanings of the component words and the "rules" of grammar (e.g., "to hit the bucket"). This implies that the neural network underlying human language cannot just be a neural network made up of two distinct components, a lexical component and a grammatical component, however the two components are translated in neural network terms. Idiomatic expressions have at the same time properties of lexical items and properties of complex signals that are composed of simpler signals and, furthermore, idiomatic expressions can have different degrees and types of idiomaticity. Therefore lexicon and syntax cannot be two separate components or modules but there should be a continuity and a gradedness between lexicon and syntax. Another thing to consider is that various degrees of idiomaticity characterize the morphological structure of the words of many human languages in which words are composed of smaller signals possessing meaning (morphemes). Hence, it would be nice if the neural network solution adopted for capturing idiomaticity at the syntactic level (words that make up a phrase or a sentence) could be extended to capture idiomaticity at the lexical level (morphemes that make up a word).

3.3 Language is Culturally Transmitted and Evolved

While most animal communication systems are genetically transmitted and are the result of a long process of biological evolution, human languages are culturally transmitted, that is, learned from others, although the ability to learn a human language and perhaps some universal properties shared by all human languages may be biologically evolved and genetically inherited. Human infants acquire language by interacting with other people who already possess the language. Historical languages, such as English or Italian, arise through a process of selective cultural transmission of linguistic signals and the constant addition of new signals. Groups of humans who learn their linguistic behaviors from each other possess the same language, and this language tends to differ from the language of other groups. If for some reason one group splits into two separate groups with few reciprocal contacts and interactions, after a certain number of generations the changes that take place in the language of each group because of the selective transmission of linguistic signals and the constant addition of new variants of signals will result in the emergence of two distinct languages, with little capacity of the members of one group to speak and understand the language of the other group.

Reproducing these properties of human language in artificial organisms will require that we work with populations of artificial organisms that are born, develop and learn, possibly reproduce, and die. Using these populations of organisms we should be able to simulate both biological and cultural transmission and evolution. An organism inherits a genotype from its parents which encodes some basic characteristics of the organism, including the organism's propensity to learn from others, that is, to learn to align the way in which it reacts to sensory input to that of the other organisms with which it interacts. Learning from others can be reproduced in artificial organisms if the organisms possess a neural network that receives as sensory input the encoding of some effect of the behavior of another individual and responds to this input with an action that produces another sensory input. The network compares the two inputs and changes its connection weights so that the discrepancy between the two inputs is progressively reduced. But, as we have said, language does not remain identical from one generation to the next. Some signals happen to be more likely to be transmitted than others (cf. the various types of cultural biases discussed by Boyd and Richerson 1985) and new signals are constantly added to the pool of signals because of random noise at transmission, the invention of new signals, and the introduction of signals from the language of other groups.

As we have already said, learning a language presupposes that the learner has genetically inherited from its parents not only a general propensity to learn from others (which applies to learning from others many other behaviors beyond language; cf. Herbert Simon's notion of docility: Simon 1990), but also a specific predisposition to learn a communicative system with arbitrary signals (cf. Sect. 3.1), compositionality, and grammar (cf. Sect. 3.2). The challenge here is to be able to evolve genotypes that incorporate both a general tendency to learn from others and the specific propensities which make it possible to learn a human-like language and underlie language universals.

3.4 Language is Used to Talk to Oneself and Not Only to Others

Animals use their signals to communicate with other animals, mostly conspecifics and in some cases members of other species. Human language is used to communicate with conspecifics but it is also used to communicate with oneself. One individual produces a signal but the signal is not produced to communicate information to other individuals or to influence other individuals but is produced to communicate information to oneself and to influence one's own behavior (private speech). In many cases the signal, i.e., the linguistic sound, is not even externally emitted but is only internally generated so that other individuals cannot perceive it (inner speech). This is a crucial property which distinguishes human language from animal communication systems and it is a property that may have played an important role not only relatively recently when language had already reached its present form (cf. Stage 3 in Sect. 3.2 above) but since the earliest stages of the emergence of language from animal communication systems (Mirolli and Parisi 2005a, 2006).

An important objective of research using artificial organisms is to construct artificial organisms that produce signals for themselves (Steels 2003). Humans produce signals both for other individuals and for themselves, and they appear to use mostly the same signals both for others and for themselves (but according to Vygotsky, language for oneself is somewhat different from language for others; Vygotsky 1962). However, it is an open question whether there might exist real organisms—or whether it would be possible to construct artificial organisms—that have a communication system which is only used to communicate with oneself, and not also for communicating with other individuals (cf. Wittgenstein's private language argument). But, of course, the most interesting research question is what the function(s) of producing signals for oneself might be (Mirolli and Parisi 2009). A simple function might be a memory function. Information which arrives to the input units of an agent's neural network might be better stored for future use if the information is mapped into a linguistic signal and it is the linguistic signal that is retained in the neural network's memory rather than the raw information itself. Linguistic signals may occupy less space in memory than the raw information to which they refer or, if the preservation of information in memory requires recycling of the information, the recycling can be easier and more efficient if it is signals that are recycled, that is, repeated to oneself, instead of the raw information itself. Storing information in the form of linguistic signals may take place in two different situations. The first situation is social. One individual perceives some raw information as input and it produces a signal that describes the information as output. The signal is received by another individual, which stores the linguistic signal and, when it needs the information, maps back the signal into the information (Mirolli and Parisi 2005a). The second situation is purely individual. The individual is all alone, it perceives some information in the environment that it would be useful to keep in memory, and the individual produces a signal and stores in its memory the signal rather than the information itself. Other adaptive uses of producing signals for oneself are not difficult to identify. Talking with oneself might help to analyze and articulate one's experiences (cf. Sect. 3.9), which might lead to a better understanding of these experiences, including the understanding of cause/effect relations, and to better generalizations. Or talking to oneself might allow one to linguistically describe one's predictions on the effects of one's actions before actually executing the actions so that it becomes easier to evaluate these effects and decide whether to execute an action or omit to do so.

If one is able to linguistically describe both one's own (possible) actions and their predicted effects, this may lead to the generation of chains of linguistically labeled predictions extending into the future, which would result in better control and more adaptive behavior. Finally, talking to oneself may underlie the generation of linguistically described facts from other linguistically described facts (deduction), with a purely internal increase in known facts. These advantages become even greater because the same language is used both to communicate with other individuals and to communicate to oneself. With language, an individual is helped by other individuals and helps other individuals to remember information, to analyze situations and experiences, to predict, decide and plan, and to deduce linguistically described facts from other linguistic facts, and all these benefits transfer to using language for oneself. In fact, the use of language for talking to oneself explains much of what we call mental life (thinking, remembering, reasoning, predicting, planning, deciding) and the social nature of mental life in humans. Therefore, constructing a robot that can communicate with itself is a critical step toward a mental robotics (Parisi 2007).

3.5 Language is Used for Communicating About the External Environment

Animal signals mostly communicate information about the sender of the signal, its current location, its sexual or individual identity, its current emotional state, its intentions and attitudes (Hauser 1996). There are exceptions such as the pheromone signals of the ants, food calls, alarm calls, the dances of the bees, but these signals communicate very restricted information about the external environment. In contrast, human language is very sophisticated for communicating information about the external environment and, more specifically, spatial information: where things are, how they can be reached, what their spatial relations are, etc. One can even advance the hypothesis that the advantages of possessing a communication system so useful for communicating information about the external environment have been an important pressure for the biological/cultural emergence of human language. In any case, language has a rich repertoire of signals for identifying objects and landmarks in the environment and for describing spatial relationships between objects and landmarks. These signals appear to be critical for artificial organisms that have to displace themselves in the environment and that have to communicate to each other where things are in the environment and how they can be reached.

Spatial information is only one type of information about the external environment which is communicated by using language. Counting and measuring things is another. Counting requires that the organism is able to repeat an action (any action) with respect to each element of a set of elements and to produce a fixed succession of signals (one, two, three…) in correspondence to each of these actions. The last signal which is produced is the number of elements in the set. Measuring is creating an arbitrary unit (meter, gram, liter, etc.) and counting the number of times the unit applies to some entity. If our artificial organisms must be able to know their environment, both individually and socially, with the sophistication which characterizes human beings, their communicative behaviors should include these more specialized uses of language.

Of course, human language is more sophisticated than animal communication systems for communicating not only about space and the external environment but also for communicating about many other things such as time, abstract entities, social behaviors and social rules, although it does not appear to be very sophisticated for communicating about emotions and the inner life compared to nonverbal communicative behavior. The construction of artificial organisms possessing a human-like language will require to reproduce all these characteristics of human language.

3.6 Language Uses Displaced Signals

Imagine an organism that discovers where some entity, say, a prey, is located in the environment and it wants to communicate this information to other individuals so that the other individuals can also find the prey. One way of doing this is to remain near the prey and to emit a signal, say a loud sound, which can be received by the other individuals. The other individuals respond to the received signal by approaching the source of the signal, that is, the sender, and, therefore, the prey itself. This solution has many limitations. One limitation is that the sender has to produce the signal while remaining near to the prey. The signal is useless if the sender moves away and then it produces the signal. Another limitation is that the other individuals must be close enough so that they can receive the signal, that is, hear the sound. A third limitation is that hearing the signal may cause the prey to fly away.

A different solution is to produce a signal which co-varies with the location in which the prey has been discovered, where the location of the prey is identified with respect to some landmark. Imagine that the prey can be found either near the river or near the hill. The discoverer of the prey produces one signal when it finds the prey near the river and a different signal when it finds the prey near the hill. The other individuals respond to the first signal by going to the river and to the second signal by going to the hill. This system of communicating information about the location of the prey has none of the limitations of the preceding system. The sender of the signal can produce the signal whatever its current location in space. It can produce the signal in any place and at any time. The receivers of the signal must be near the sender of the signal when the signal is emitted in order to be able to hear the signal, but this may happen separately for each individual receiver of the signal. Furthermore, one receiver of the signal can communicate the signal to another individual, and so on in a chain, with no need for all the individuals to be together at any given time and place. Finally, since the discoverer of the prey can produce the signal after it has moved away from the prey, the signal can be produced with no risk that the prey hears the signal and flies away.

Signals whose meaning or function is independent of the current location of the sender of the signal and of the time in which they are produced are called "displaced" signals (Hockett 1960). Emitting a loud sound when one discovers the prey is to produce a non-displaced signal. Emitting a signal that co-varies with the location in which the prey has been discovered is to produce a displaced signal. Animal signals tend to be non-displaced. Linguistic signals are displaced signals. One exception are so called deictic signals such as "this," "that," "I," "you," "here," "there," which can only be responded to appropriately if both the speaker and the receiver of the signal are located in a particular location in space when the signal is emitted and received.

One interesting contrast between displaced vs. deictic signals concerns pointing. Pointing, with a gaze or with a finger, is one way of communicating where things are. Notwithstanding its limitations as a deictic signal, pointing has advantages in comparison with the use of explicit linguistic signals since one can point to entities that may have no linguistic label associated with them and perhaps processing the pointing requires less cognitive/neural resources than processing linguistic labels. Therefore, one interesting research direction is to create artificial organisms that are able to point. Although it is deictic and therefore can only be used for communicating the location of objects which are present in the space currently accessible to the senses of both the sender and the receiver of the pointing signal, pointing is not generally found in animals. This seems to indicate that pointing is a complex cognitive/communicative ability and this complexity extends to deictic linguistic signals such as "this," "that," "here," "there," "to the left of," etc.

Human language can communicate information not only about other places but also about past and future states of the sender ("I was angry,"/"I will be angry") or of the environment ("the book was on the table," "the book will be on the table"). The challenge is to endow artificial agents with both the capacity to use spatially and temporally displaced signals and the capacity to use deictic signals, including pointing.

3.7 Language is Intentional and Requires Recognizing the Intentions of Others

Intentional communication, and intentional behavior more generally, appears to be linked to the tendency/ability to predict the consequences of one's own actions. A purely reactive organism is an organism that receives some input from the external environment or from inside its own body and responds by producing some movement that changes either the physical relation of the agent's body to the external environment (e.g., the agent displaces itself in the environment) or the external environment itself (the agent manipulates the environment). The neural network that underlies the behavior of a purely reactive agent can have a purely feed-forward architecture in which activation simply spreads from sensory input to motor output. But consider a network architecture which includes a set of units encoding a prediction of the next sensory input. Given the current input which is encoded as some specific pattern of activation in the network's sensory units, the network generates a pattern of activation in one particular subset of internal units (prediction units) that matches the pattern of activation that will be observed in the sensory units at some later time. This pattern of activation is a prediction.

There are two kinds of predictions. An organism can generate a prediction of the next sensory input when the next sensory input is independent of the agent's own behavior. Examples are predicting the next spatial position of a moving object or predicting the weather. Or the organism can generate a prediction of the next sensory input when this input depends both on the current input and on the physical action with which the agent responds to the current input. For example, the organism predicts the sound that it will hear when it will open its hand holding a glass and the glass will reach the ground. These are the predictions that interest us here. To be able to predict the consequences of its actions, the organism must be able to encode its motor response (open the hand) to the current sensory input (seeing and feeling the glass in one's hand) as a pattern of activation in the motor output units but must generate a prediction of what the sensory consequences will be (the sound that will be heard when the glass will reach the ground) before the motor response is physically executed.

Consider the behavior of producing communicative signals. Imagine an organism which is ready to respond to some input with the production of a signal and consider two possibilities. In one case the organism is a purely reactive organism. The organism's neural network receives some input from the external environment (or from inside the organism's body) and it responds to this input by producing a signal which is received by another organism. Communicative signals that are produced in such a reactive way appear those of nonhuman animals and the expressive (non-linguistic) signals produced by humans. But consider an organism which is not purely reactive. The organism's neural network responds to the input by encoding one particular movement in its phono-articulatory output units but is able to delay the physical production of the signal until it has generated a prediction concerning the consequences that the signal will produce in the receiver of the signal. If this prediction feeds back into the organism's neural network because the prediction units send connections to the rest of the neural network, the organism can decide whether to physically producing the planned signal or to refrain from doing so. In these circumstances we might begin to say that the sender has an intentional communicative behavior.

The role of intentionality in linguistic behavior should not be restricted to the communicating agent, but one must also consider that human beings tend to consider other human beings as agents possessing intentionality. Speaking is producing communicative signals intentionally, but understanding implies the ability to recognize the intentions of others (speakers). More generally, human language involves the capacity for joint attention, the capacity to maintain and update a common ground, and the capacity to infer communicative and social intentions behind overt behavior. In fact, if we want to construct artificial organisms with human-like language, we will have to consider the fundamental cooperative infrastructure that seems to be necessary to produce and understand human language (Tomasello 2008).

3.8 Language is the Product of a Complex Nervous System

Human beings have a more complex nervous system and a more complex communication system than other animals, especially insects, and it is probable that the two things are related. Human language has only been possible given the complex nervous system possessed by humans and, at the same time, it is possible that the development of a complex communication system such as language has been one of the evolutionary pressures for the emergence of a complex nervous system.

While constructing artificial organisms with a simple, insect-like, communication systems may not require that any special attention be devoted to the architecture of the neural network controlling the organisms' behavior, artificial organisms with a human-like communication system should be endowed with a more complex and explicitly designed (evolved) neural architecture. We will describe a speculative neural network architecture but of course it is critical to match the architecture with what is known about the architecture which underlies language in real brains.

Children from birth to 1 year do not have language. During their first year they develop from a sensory-motor point of view, acquiring various perceptual and manipulatory abilities such as looking at things and reaching and manipulating objects, and at the same time they acquire various acoustic/phono-articulatory abilities, such as repeating their own sounds, babbling, and, at least from 6 months on, incorporating in the sounds they produce some of the properties of the sounds of the particular language spoken in their environment. For artificial organisms, this implies that the connection weights linking input to output within the organism's neural network are gradually modified so that inputs gradually result in the appropriate outputs. However, the two developments appear to be separated. It is as if the nervous system of the child before 1 year of age consisted of two separated sub-networks, a nonlinguistic sub-network with mostly visual or tactile input and movement output (movements of the eyes, face, arms, hands, legs) and another sub-network which will become the linguistic module we have discussed in the section on linguistic arbitrariness but which at this time is just a sub-network with sound input and phono-articulatory output.

At around 1 year, the two sub-networks become functionally (and perhaps even anatomically) linked. The child begins to acquire language. The weights of the connections linking the units of one sub-network to the units of the other sub-network progressively change their value so that an input in one sub-network causes an appropriate output in the other sub-network, and vice versa. As we have discussed in the section on linguistic arbitrariness, language comprehension consists of being able to generate the appropriate output in the nonlinguistic sub-network given some particular input in the linguistic sub-network, while language production consists in being able to generate the appropriate output with the linguistic sub-network given some particular input in the nonlinguistic sub-network.

Given the reciprocal connections between the nonlinguistic sub-network (module) and the linguistic sub-network (module), other functions involving language are possible. For example, the organism can receive some input in its nonlinguistic module, this input elicits an activation pattern in the internal units of the nonlinguistic module, this activation pattern elicits in turn an activation pattern in the internal units of the linguistic network (via the connections from the nonlinguistic to the linguistic module), and this activation pattern returns to the sensory-motor network (via the connections from the linguistic to the nonlinguistic module). As we have discussed in the section on using language to talk to oneself, this implies that how the world is perceived and reacted to by artificial organisms possessing a human-like language is influenced by how the organisms linguistically label and describe the world. The organisms live in a "linguistically commented" world. Acting and thinking (talking to oneself) become intermingled.

Another dimension of architectural and functional complexity of the neural network of an artificial organisms endowed with a human-like communication system derives from the multi-level compositionality of human language. As already described, linguistic signals are made up of a hierarchy of linguistic units: phonemes, morphemes, words, phrases, and sentences. How is this reflected in the structure and way of functioning of the organisms' neural network?

Let us consider the linguistic module, that is, the sub-network which takes heard sounds as input and produces sounds via phono-articulatory movements as output. One can hypothesize that this module is made up of a succession of internal layers, one for each level of linguistic units. There is a layer for phonemes, just above the acoustic input units, followed by a layer for morphemes, then by a layer for words, a layer for phrases, and finally a layer for sentences, although what we call "layer" may not correspond to a set of network units but, especially for the higher levels in the compositional hierarchy, to a set of dynamic processes. Each internal layer has an associated layer of memory units (Elman 1990) in which the activation pattern appearing in the corresponding internal units is copied at each cycle. The memory units send their connections to the units of the internal layer in such a way that the entire circuit functions as a cumulative memory. For instance, given the word "cats," first the sound /k/ is heard, it elicits an activation pattern in the phonemic layer, and this activation pattern is stored in the associated memory units of the phonemic layer. Then the sound /a/ is heard, this sound elicits an activation pattern in the phonemic units but this activation pattern also contains information from the preceding sound /k/ because of the connections arriving from the associated memory units where the activation pattern elicited by the sound /k/ has been stored. The same happens for the third sound of the word cat, that is, the sound /t/. At this point the morpheme "cat" has been recognized, which means that the information which has accumulated at the level of the phonemic units evokes an activation pattern in the next layer of internal units, the morphemic layer. This pattern is stored in the memory units associated with the morphemic layer. When the sound /s/ of the word "cats" is also processed, this sound is recognized as a new morpheme, its activation pattern is stored together with the activation pattern of the morpheme "cat," and the two morphemes generate the word "cats" at the next higher level, the word or lexical layer of internal units.

How is a linguistic unit recognized? Aside from phonemes, which have no meaning, linguistic units, from morphemes to sentences, are recognized because of the connections linking the linguistic module to the nonlinguistic module. A linguistic unit is recognized because an activation pattern in the linguistic module elicits an activation pattern in the nonlinguistic module. The sequence of phonemes /k/ /a/ /t/ is recognized as the morpheme "cat" because the activation pattern elicited by the sequence of phonemes in the linguistic module elicits one specific activation pattern in the nonlinguistic module (the meaning of "cat"). Notice that morphemes and words are different from phrases and sentences, though. Morphemes and words find their meanings already there in the nonlinguistic module. Phrases and sentences obtain their meanings through a process of syntactic construction (Steels and Wellens 2006), although the widespread idiomaticity of human language discussed in Sect. 3.2 indicates the two processes cannot be neatly separated.

3.9 Language Influences Human Cognition

A final crucial difference between human language and animal communication systems is that animal communication systems do not appear to have any influence on how animals behave when they are not communicating, whereas language seems to lead to a global restructuring of behavior and cognition in humans. The communication systems of nonhuman animals appear to be juxtaposed to their cognitive abilities and not to have any particular influence on these abilities. The influence of language on human cognition is so deep and widespread that one can reasonably propose the hypothesis that language has emerged in humans not only because it is a very articulated and flexible social communication system but also because it results in a much more articulated and powerful way of knowing and dealing with reality in the individual (Mirolli and Parisi 2005a, 2006). The implication is that constructing artificial organisms with human-like systems of communication will shape the entire behaviour of the artificial organisms, not only the manner in which they communicate.

The influence of language on human behaviour and cognition can be linked to the fact that language is used by humans to talk to oneself and not only to communicate with others (see Sect. 3.4 above), and to the role that language plays in the mental life of humans, i.e., in their rememberings, thoughts, predictions, plans, etc. As we have already said, humans live in a "commented" world, that is, in a world which they constantly label and describe by using language. They respond to this "commented" world, not to the world "as it is." However, the influence of language on human cognition may go beyond that. Language may influence cognition in humans even when humans are not speaking either to others or to themselves (thinking). The distinction can be captured by referring to the network architecture with the two interconnected modules, the non-linguistic module and the linguistic module. When an input is received by the nonlinguistic module and the input causes an activation pattern in the internal units of the nonlinguistic module, two different things can happen. First, the activation pattern in the nonlinguistic module elicits an activation pattern in the internal units of the linguistic module which in turn influences the activation pattern in the nonlinguistic module in a sort of feedback loop. The organism is talking to itself and language can have an influence on the organism's cognition. But it can also be that language has left a permanent trace in the nonlinguistic module itself, so that when an input arrives to the input units of the nonlinguistic module, the way in which this input is internally elaborated, that is, the activation pattern it elicits in the nonlinguistic module's internal units, is influenced by language with no need to activate the linguistic module.

How language can influence cognition in artificial organisms and what are the consequences of having language for the behaviour of these organisms are very interesting research topics (Mirolli and Parisi 2009). Here are some examples of directions that can be explored.

Categories in neural networks can be thought of as "clouds" of points in the abstract hyperspace that corresponds to a given layer of internal units. This hyperspace has as many dimensions as are the units in the layer. One point in the hyperspace corresponds to one activation pattern that can appear in the layer's units. Each point belonging to the "cloud" is the activation pattern which appears in the layer of internal units when the agent experiences one specific instance of the category. Adopting an action-based view of cognition (Ferdinando and Parisi 2004), different experiences are put together to form a single category if the agent has to respond with the same action to all instances of the category. For example different edible mushrooms are instances of the same category ("good mushrooms") because they have to be responded to with the same action of approaching and eating them. Different poisonous mushrooms are also instances of the same category ("bad mushrooms") which is different from the category of good mushrooms because they have to be responded to with another type of action: avoiding them. Learning consists in adjusting the network's connection weights so that these weights generate good "clouds", that is, "clouds" that are as small as possible and as distant as possible from other "clouds," i.e., from other categories that must be responded to with different actions. One role that language can have in cognition is that it can help the organism to have better "clouds", i.e., "clouds" that are smaller and more distant from each other than the "clouds" of organisms that do not have language. And better "clouds" lead to better behavior (Mirolli and Parisi 2005b, 2006).

Another influence that language can have on cognition is that language can allow the organism to articulate its perception of reality in ways which are suggested by language, for example isolating perceived objects that correspond to single words, separating different aspects of objects as these different aspects are separately articulated in a phrase or sentence, e.g., noun + adjective or noun (agent) + verb (action) + noun (object of action).

A more general influence that language can have on cognition is language's role in enlarging the agent's temporal perspective on reality. Nonlinguistic agents can have both memory and prediction abilities that allow them to know and take into consideration in their behavior both the past and the future. However, it is clear that to preserve the past in the form of linguistic expressions that refer to past experiences and to articulate and make explicit one's predictions about the future by putting these predictions in words, may greatly enlarge an agent's temporal perspective on reality, thereby augmenting the effectiveness of its behavior.

4 Between Them or with Us?

If we want to construct artificial organisms that possess human language there is a fundamental question that we need to answer: Do we want to construct artificial organisms that are able to communicate between them, or are we (also) interested in constructing artificial organisms that can communicate with us? Some research addresses the first problem: How communication can emerge in groups of artificial organisms allowing them to exchange information which is used in both individual and collective tasks. However, there is also much research which is devoted to the second problem: Can we construct artificial organisms (robots) that can communicate with us? This second problem has obvious practical consequences and applications but, as we will try to show, it is also interesting from a theoretical point of view.

The critical issue is if, and to what extent, two organisms that communicate with each other must have the same "worldview" or, more generally, must be similar in important respects. The fact that there is some interspecific communication in animals seem to imply that to communicate two organisms need not to belong to the same species and need not to be identical (aside from interindividual differences). Even human beings can communicate with pet animals. However, interspecific communication appears to be quite limited in its possibilities. To allow free communication, or communication approaching the complexity of intraspecific communication, the two organisms that communicate must be similar and share the same general view of reality. Current artificial organisms and human beings are very different and they cannot be said to share the same worldview. We will not try to define what is a worldview but we will assume that the worldview of any particular organism, real or artificial, depends on the organism's sensory and motor organs, on the morphology of the organism's body, on what is inside its body (the nervous system and other internal systems), and on the environment in which the organism lives. Current artificial organisms and human beings tend to be very different in all these respects. Hence, if a shared worldview is a precondition for communication we cannot expect to be able to develop artificial organisms that can communicate with us any time soon. They may be able to communicate between them but not with us.

Let us consider sensory organs. Humans have a variety of sensory organs and sensory modalities. We respond to visual, acoustic, tactile, proprioceptive, taste, and olfactory sensory input. This variety of sensory modalities influences our view of the world and therefore what we can communicate about. Consider an artificial organism with sensory modalities different from the sensory modalities of human beings, for example, the organism imagined by the British philosopher Peter Strawson (Strawson 1959), which has only the acoustic sensory modality and lives in a world of only sounds. Could we communicate with such an imagined organism?

Or consider an artificial organism with no sense of touch. If the artificial organism has to reach an object with its hand, the organism finds it easier to learn to reach the object if when the hand makes contact with the object the organism's neural network has sensory units encoding a sensation of touch (Schlesinger and Parisi 2001). But the role of touch may be even more important from a "worldview" point of view.

Consider how we distinguish our own body from other objects that are present in our environment. When some portion of our body, e.g., our hand, makes contact with an object, our sensory organs encode a sensation of touch. When our hand makes contact with our body we feel both a sensation of touch in our hand and a sensation of touch (of being touched) in the part of the body which has been touched by the hand. If a robot has no sense of touch the robot may be unable to distinguish between the objects that are present in the environment and that particular object which is its own body. Could we communicate with an artificial organism which does not distinguish its body from the other objects that populate its environment?

The distinction between one's own body and the rest of the physical world can also be based on another sensory modality, the proprioceptive modality, which is associated with the movements of the body. A visually perceived moving object is recognized as part of my body, e.g., as my hand, if the visual input from the object co-varies with the proprioceptive input from my body (my arm), whereas if there is no such co-variation, the object belongs to the environment which lies outside my body. Hence, proprioceptive sensory input, like the sense of touch, may be necessary to give a special status to my body among the different objects that make up my world.

This leads us beyond the organism's sensory organs and poses the problem of the organism's motor organs. To share the same worldview and to communicate with one another two organisms must not only have the same sensory organs but also the same motor organs. What appears to be crucial in shaping the worldview possessed by human beings is that they have two very articulated hands with which they manipulate in very complex ways the physical world. Robotics is very important from the point of view of the science of mind because it makes completely clear the crucial role played by an organism's body and its motor organs and capacities in determining what we have called the worldview of the organism. Both philosophy and psychology have traditionally shared a passive view of cognition and of knowledge of the world as based on sensory input from the environment rather than on the motor actions with which we manipulate the environment. This passive view is wrong, and robotics makes this entirely clear. For example, using simulations with a robotic arm it is possible to demonstrate that the robot's internal categories are not based on representing in similar ways, inside the neural network that controls the robot's arm, physically similar sensory inputs but on representing in similar ways sensory inputs which may be physically different but have to be responded to with the same action (Ferdinando and Parisi 2004).

The role of the sameness of the motor apparatus of two organisms in allowing the two organisms to have a shared worldview and to be able to communicate with each other can be demonstrated for a variety of different aspects of their worldview. For example, an organism's worldview may include the fact that physical objects have a property called length and different objects may be of different lengths. But measuring the length of an object may require moving another object of fixed length (e.g., a meter) along the object to be measured and counting how many times this has to be done to cover the entire object (cf. Sect. 3.5). How could an artificial organism without human-like hands be able to measure the length of things and communicate with us about the length of things?

Considering more cognitive abilities, the brain of two organisms must be sufficiently similar to be able to display similar cognitive abilities. One important cognitive ability that underlies the worldview of human beings is the ability to predict the next sensory input on the basis of the current sensory input and a planned but still nonexecuted motor response to the current sensory input (cf. Sect. 3.7). It might be that only artificial organisms that have this type of predictive ability can share our worldview and therefore be able to communicate with us. For example the ability to predict the consequences of one's own actions can underlie a sense of agency. In a recent psychological experiment, when human subjects pressed one button they heard a high sound, while when they pressed another button they heard a low sound. After a certain number of trials, the subjects said that they were the authors of the sound when the high sound followed their pressing of the first button and the low sound their pressing of the second button, but not when a low sound followed their pressing of the first button and a high sound followed their pressing of the second button. And they did not feel to be the authors of the sounds if the appropriate sounds followed their pressing of the two buttons but with a longer delay than they were used to. This experiment seems to imply that a sense of agency derives from the capacity of an organism to link actions to the their sensory consequences (with the appropriate time interval) and that organisms which do not possess this capacity may lack a sense of agency.

Other examples are not difficult to find. How can an artificial organism communicate with us about dreams or pains or thoughts if the robot does not have dreams, does not feel pain, or is not able to communicate with itself (think)? Today one often hears of robots displaying or recognizing emotions but this is very superficial talk since current robots cannot actually feel emotions and therefore they can only talk about unfelt emotions. To feel anything a robot's body must reproduce not only the external morphology of an organism's body but also the internal organs and systems of an organism's body and the physical interactions between the robot's control system and these internal organs and systems (cf. the notion of internal robotics; Parisi 2004). Even to really understand what their users do and what they feel might be impossible for robots if the robots' control system does not include the equivalent of the mirror neurons that exist in the brain of primates (Gallese et al. 2004).

We have proposed some examples trying to show that if they have to share the same worldview two organisms must possess the same sensory organs, the same motor organs and, in some appropriate sense, the same brain and other internal systems. But if two organisms do not share the same worldview they can communicate with each other only in very limited ways. Only an artificial organism with the sensory, motor, and neural apparatus of human beings can have what psychologists call "object permanence," what philosophers call "particulars," "a sense of agency," "a sense of others," etc., whereas an artificial organism with a different sensory, motor, and neural apparatus would have a view of the world which does not include these features. And if they don't share these cognitive features as part of their worldview, it may be impossible for artificial organisms to communicate with humans except in very limited ways.

Communication between technological artefacts (e.g., computers) and their users has been addressed in the past within a symbol manipulation or artificial intelligence perspective which ignores the body, the movements of the body, and the structure and way of functioning of the physical system which controls the organism's behaviour, i.e., the brain. But traditional automatic language understanding and automatic language production systems cannot possibly go beyond very limited performance levels. To understand what is human language and to allow human beings to interact with artefacts by using language it is necessary a robotic approach, that is, it is necessary to construct artificial systems that have a body, a brain, and interact physically with the environment. Linguistic signals, like all communication signals, obtain their meaning from the interactions of the organism with the environment. Since these interactions depend on the organism's sensory, motor, and neural apparatus, and on the morphology and dynamics of the organism's physical body, organisms with different bodies and with different sensory, motor, and neural apparatuses will have signals with different meanings, and won't be able to communicate with one another beyond seriously restricted limits. This conclusion appears to be theoretically, and not only practically, interesting because it makes it clear that to construct artificial organisms with a human-like language it will be necessary to construct artificial organisms with a human-like body, brain and, more generally, adaptive pattern.

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