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On the Emergence of Communication: An Argument from Robotics

Wyłanianie się komunikacji: argument z robotyki

INTRODUCTION

The studies on language origins and development and, more generally, on the origins of (human) communication, have recently gained a new momentum. The emergence and development of communication systems (including language) is a multidimensional process and as such calls for an interdisciplinary approach[1]. Generally, the description of the process:

– requires biological explanations (in particular: how biological evolution shapes our organisms and brains),

– calls for analyses of linguistic resources (several researchers claim that we may find "fossils" of earlier forms of communication, e.g. protolanguage, in contemporary languages[2]),

– involves the examination of data from neuroscience (as Wray claims, neurodegenerative diseases help us uncover such fossils of protolanguage[3]),

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[1] M.H. Christiansen, S. Kirby, *Language evolution: Consensus and controversies*, "TRENDS in Cognitive Sciences" 2003, Vol. 7(7), DOI: https://doi.org/10.1016/S1364-6613(03)00136-0.

[2] Cf. R. Jackendoff, *Possible stages in the evolution of the language capacity*, "Trends in Cognitive Sciences" 1999, Vol. 3(7).

[3] A. Wray, *Protolanguage as a holistic system for social interaction*, "Language and Communication" 1998, Vol. 18(1), DOI: https://doi.org/10.1016/S0271-5309(97)00033-5.

– takes into account the results of experimental semiotics (experimental studies on human dialogue, in particular on invention of signs and negotiations of meanings).

Despite the fact that a number of disciplines contribute to the field, the available empirical data (such as, say, the evidence from the emergence of creole languages or sign language in Nicaragua[4]) are still too fragmentary for definitive conclusions to be drawn about the origins of language as a means of communication[5]. Particularly promising here is the research carried out in laboratories on the emergence of communication systems[6].

In this context, a new approach to language emergence and evolution has developed; it deals with either artificial systems created "from scratch" or those which invent their own communication systems based on natural human language. Some of the traditionally considered issues are addressed through the development of groups ('hordes') of robotic agents interacting with their environment and engaging in robot-robot or robot-human interactions. Being the product of the robots' evolution and based on the robots' own signaling system, such interactions lead to the rise of the robots' communication abilities. The development of this new, experimental, approach to the emergence of language and communication in communities of artificial agents is a perfect exemplification of Hurford's[7] *dictum* that computational simulation is a tool for modelling the evolution of language.

In this paper, I would like to suggest a minimal cognitive endowment necessary for the emergence of a communication system. In particular, I would like to formulate initial conditions necessary for the emergence and development[8] of minimal communicative capacity regardless of whether the system succeeds to "attain a linguistic level" or not. Specifically, the paper proposes a set of 'linguistic

[4] Cf. S. Pinker, *The Language Instinct: How the Mind Creates Language*, London 1994.

[5] Cf. T.C. Scott-Philips, S. Kirby, *Language evolution in laboratory*, "Trends in Cognitive Sciences" 2010, Vol. 14, DOI: https://doi.org/10.1016/j.tics.2010.06.006.

[6] Cf. L. Steels, *Experiments on the emergence of human communication*, "Trends in Cognitive Sciences" 2006, Vol. 10(8), DOI: https://doi.org/10.1016/j.tics.2006.06.002, p. 348; B. Galantucci, *An experimental study of the emergence of human communication systems*, "Cognitive Science" 2005, Vol. 29(5), DOI: https://doi.org/10.1207/s15516709cog0000_34 (study on the emergence from scratch of communication systems between human agents).

[7] J.R. Hurford, *Biological evolution of the Saussurean sign as a component of the language acquisition device*, "Lingua" 1989, Vol. 77, DOI: https://doi.org/10.1016/0024-3841(89)90015-6.

[8] The first stage of the HERA project assumes research on development of communication within single "generation" of robots. Consequently, we are interested in modelling of development of individual cognitive skills and development of communication skills. The approach may be treated as 'robotic' counterpart of ontogenetic development (as Zlatev, puts it: "robotogenesis"). Cf. J. Zlatev, *The Epigenesis of Meaning in Human Beings, and Possibly in Robots*, "Minds and Machines" 2001, Vol. 11, DOI: https://doi.org/10.1023/A:1011218919464.

games' which allow robots to train acquired capacities as well as develop new ones. As I will argue, the solutions proposed in this paper allow for achieving a "protolanguage level" in agents, leaving language-related aspects (like a grammar) for future research. The approach makes it possible to manipulate basic factors involved in the evolution of communication, including variation in initial cognitive abilities, sensitivity to environmental factors, size of a "social" group, etc. This should enable us to observe the influence of the initial endowment and subsequent training on communicative abilities of agents.

The term "language" is ambiguous. It is understood in the context of the paper twofold: as a set of cognitive mechanisms responsible for and allowing to learn signals, combine them into sentences and use them to express elements of a knowledge base. I use also the term *language faculty* in reference to such a capacity[9]. The view reflects interests of a cognitive scientist. In the second sense, "language" is understood as a result of mentioned above cognitive mechanisms applied in a particular social environment. The result takes the form of spoken (written) utterances[10].

This article is a result of the author's participation in the preparatory work on the project entitled "The social behaviour of a horde of autonomous robots with communicative competence in robot-robot and human-robot cooperative situations" (henceforth: 'HERA project'). Unless explicitly stated otherwise, the paper presents the author's own contribution to the sub-project: "Aspects of the symbolic communication in a horde of robots".

ON MODELLING OF LANGUAGE AND COMMUNICATION

Approaches to modelling of language and communication in AI research significantly changed since the early years. The change is important, as it reflects changes in thinking about language as a phenomenon within AI community.

Researchers treated language as a distinct "module" and modelled it in the form of a set of mechanisms such as a parser/generator ('programmer'), semantic module ('semantics'), dictionary module etc. The modules were in principle independent of more general cognitive abilities. The designers of natural language systems provided both lexicon and grammar in a fixed form; the early systems were usually unable to learn (or invent) new elements of a dictionary nor learn new

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9 Cf. T. Fitch, *Empirical approaches to the study of language evolution*, "Psychonomic Bulletin and Review Journal" 2017; R. Jackendoff, *Foundations of Language: Brain, Meaning, Grammar, Evolution*, New York 2002.

10 Zlatev (*The Semiotic Hierarchy: Life, consciousness, signs and language*, "Cognitive Semiotics" 2009, Vol. 4, p. 185) enumerates different possible senses of the term.

grammatical rules. A natural language using agent was an „individual"; a community was neither essential nor necessary for a successful use of the language. Finally, language "just was" – it neither emerged nor changed during the "existence" of an agent[11].

Most of these assumptions have been abandoned in contemporary AI approaches to language, particularly in robotic simulations of language emergence and development. The reason for this has been a growing awareness that language, its emergence, evolution and functioning cannot be explained merely in terms of individual cognition. Language has to be explained in the context of a community of language-using agents embedded in their environment. In particular, the final conviction mentioned above has been abandoned. Language communication is now treated as a process emerging from certain basic cognitive capacities and developing according to the principle of epigenesis. The principle is understood as stating that a new structure or activity arises on the basis of existing structures or activities and on the basis of interaction with environment and other agents[12].

In order to address the basic question of *what the initial conditions for the emergence of communication and particularly for language are*[13], the following three broad areas have been identified:

– at the level of an individual, there are basic cognitive abilities (either innate/ pre-programmed or acquired in the course of cognitive activity); the number and kind of these abilities are the main topic of the paper,

– social conditions in which interaction takes place – it is assumed that language may emerge and develop only in communities, where interaction and cooperation between members of the community is forced by some tasks; in addition, the emergence of certain aspects of communication may depend on features of a community. As Swarup and Gasser notice, the size of a social group influences features of a communication system: 'if the community is not large enough, a grammatical language does not emerge'[14]. Apart from size of a social group, the differences in physical and cognitive endowment of members of the group influence a communication system,

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11 A paradigmatic example of such a system was SHRDLU. Cf. T. Winograd, *Procedures as a Representation for Data in a Computer Program for Understanding Natural Language*, MIT AI Technical Report 235, 1972.

12 J. Zlatev, *The Epigenesis of Meaning in Human Beings*...

13 Cf. S. Swarup, L. Gasser, *The role of anticipation in the emergence of language*, [in:] *Anticipatory Behavior in Adaptive Learning Systems: From Brains to Individual and Social Behavior*, eds. M. Butz, O. Sigaud, G. Baldasarre, G. Pezzulo, LNAI 4520, 2007, DOI: https://doi.org/10.1007/978-3-540-74262-3_3.

14 *Ibidem*, p. 38.

– changing environment (containing also other agents) as a scene of robotic actions – language, as we conceive it, is a complex adaptive system[15]; elements of the system (lexicon, conceptualization, links between them) adapt to both: changes in the environment (e.g. new objects encountered) as well as to other language-using creatures (other robots). Consequently, robots should adjust their communication system to changes in an environment. New objects, new features of objects, new situations – all these should be reflected in communication of robots. Such adjustments should involve not only changes in a set of signals, but they should also involve changes in constructions – concatenations of symbols. A relationship between a communication system and an environment is a bidirectional one. On the one hand, changes in "the world" should be reflected in e.g. a set of signals (e.g. when a new feature of a situation is discovered), on the other hand, communication may result in changes in robots' surroundings (e.g. when a robot asks the other robot to remove an obstacle).

Finally, changes in an environment may be treated as a motivation for communication and for development of a communication system.

What this all this means is that no communication system (including language) can be explained merely in terms of individual mental abilities – the three areas or factors just enumerated are crucial for language emergence. Robotic systems allow to study influence of the three factors simultaneously, by placing a horde of robots equipped with basic cognitive abilities in a dynamic environment.

Kirby and Christiansen[16] identified three adaptive systems necessary for emergence of communication and language, including individual learning, biological evolution and cultural transmission. Their proposal partially overlaps with the assumptions of the project, as individual learning may be treated as an instance of cognitive capacities and cultural transmission as a process taking place in the social domain.

THE HERA PROJECT – INITIAL ASSUMPTIONS

The general assumptions of the HERA project, presented below, are motivated by at least two broad areas of research: they are partially inspired by results of multidisciplinary research on emergence and evolution of natural language (evolutionary biology, anthropology, evolutionary linguistics) and partially on results

[15] L. Steels, *Semiotic dynamics for embodied agents*, "IEEE Intelligent Systems" 2006, Vol. 21(3), DOI: https://doi.org/10.1109/MIS.2006.58.

[16] See: S. Kirby, *Natural language from artificial life*, "Artificial Life" 2002, Vol. 8, DOI: https://doi.org/10.1162/106454602320184248, pp. 186–189; M.H. Christiansen, S. Kirby, *op. cit.*, p. 302.

of several approaches to model the emergence and evolution of communication using robotic systems.

The HERA project is planned as an experimental study starting with a 'horde' of 20–25 robots; initially, they should be prepared to perform certain tasks requiring – among others – interaction with their environment and cooperation between them. The robots will have perceptual and motor abilities, dependent on their "bodies". In contrast to early AI projects, it is not purely computational approach, but 'embodied' or 'grounded' one. In other words, changes in robots' knowledge bases, cognitive capacities or motor skills depend crucially on their interactions with their environment – on perception and action. The perceptual apparatus will consist of vision and auditory modules. Consequently, we limit possible sources of information about the surroundings in comparison to human cognitive agents. As a result, the only aspect initially fixed is the primary (and target) communication channel: it is – by analogy to human natural language communication – a vocal-auditory channel. The approach assumes that communication takes place through auditory-vocal modalities. If we treat community of robots as a model of human community, the assumption may be considered a controversial one[17]. According to some researchers, the development of human communication as well as a route to "full" language led through gestures[18]. Such a limitation to a 'spoken' system helps solve the practical problem of detecting meaningful behaviours in mutual interactions of agents. In particular, such an assumption allows for reduction of a number of possible answers to one of the most crucial questions: 'how organisms recognise that certain behaviours are indeed communicative in nature'[19].

In contrast to several contemporary experiments with robots, we do not plan to provide a ready-to-use system of signals. We expect robots to create their own signalling system based on their motor abilities. The signalling system should be dynamic, i.e. it should adapt to the current situation of a robot in its environment[20]. This expectation is reasonable in light of the results obtained by so-called *experimental semiotics*.

Finally, it is assumed that such a set of signals and ways of combining these signals may differ significantly from words and grammar of human language.

Robots are also expected to develop their own conceptualizations of their environment. The conceptual structure will depend on physical equipment (perceptual

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17 Cf. R. Jackendoff, *Possible stages in the evolution*..., p. 272.

18 M. Tomasello, *The Origins of Human Communication*, Cambridge 2008; M. Corballis, *From Hand to Mouth: The Origins of Language*, Princeton 2003.

19 T.C. Scott-Philips, S. Kirby, *op. cit.*, p. 411.

20 Cf. L. Steels, *Experiments on the emergence*..., p. 32 on recent results.

apparatus) of robots as well as on their activity in the environment. Robots are supposed to conceptualize these aspects of their surroundings, which are detected by their perceptual apparatus and which can be influenced and changed by robots' actions. In the case of differences in perceptual apparatus (e.g. differences in sensitivity of detectors of sound) we expect differences in conceptualizations as well. According to the course of development – presented in the following sections – interactions between robots include: observation and imitation of other robots' behaviour, reaction to original or imitated behaviour (in the form of a positive or negative feedback), exchanging signals. Such interactions between robots should lead, according to recent experiments in robots[21], to co-tuning of the conceptualizations[22]. Initially, for reasons mentioned below, it is assumed that 'objects' encountered and conceptualized by robots are situations.

The mappings between signals and relevant concepts representing environment are supposed to be negotiated in interactions, during so-called *language games* (see below). It is not a novel assumption. One may observe the phenomenon in the case of human language[23]. There are also several successful attempts to model such negotiations using robotic agents (in particular *Talking Heads* experiments[24]).

To sum up, the main idea of the project is that robots should be endowed with basic cognitive capacities. These capacities include: distinguishing between physical signals, learning and reproducing such signals, imitating behaviour of other robots, establishing associations as well as generalizing (in a limited form). Basic capacities are supposed to form a basis for emergence of more complex communication activities, namely: ability to describe, to confront descriptions, to extend them. Robots should be provided with vocal-auditory communication channels, be allowed to act in the world and to interact with other robots.

Interactions between robots become important during the second stage of the project. These actions and interactions seem to be crucial, as it is assumed that communicative skills are deeply rooted in action[25]. The project aims to show that

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21 *Idem*, *Language games for autonomous robots*, "IEEE Intelligent Systems" 2001, Vol. 16(5), pp. 16–22.

22 Cf. R. Jackendoff, *Foundations of Language*...

23 S. McRoy, G. Hirst, *Misunderstanding and the negotiation of meaning*, "AAAI Technical Report FS-93-05" 1993; R. Selten, M. Warglien, *The emergence of simple languages in an experimental coordination game*, "Proceedings of the National Academy of Sciences USA" 2007, Vol. 104, DOI: https://doi.org/10.1073/pnas.0702077104.

24 L. Steels, *The Talking Head Experiment. Origins of Words and Meanings*, Berlin 2015.

25 Cf. Ch. Sinha, C. Rodrigez, *Language and the signifying object. From convention to imagination*, [in:] *The Shared Mind. Perspectives on Intersubjectivity*, eds. J. Zlatev, T. Racine, Ch. Sinha, E. Itkonen, New York 2008.

under these conditions a communication system would emerge. The long-term aim is to check if language-like system would emerge as one of the stages (perhaps the final one) of the development of communicative skills[26].

COGNITIVE PRE-ADAPTATIONS AND TRAINING

This section presents the cognitive capacities which seem to play an important role in the emergence of communication. Some of the capacities should be implemented directly in robots in their basic form, to be developed later on during robot-robot interactions.

The tasks listed below should be understood in two ways: as (1) training activities necessary to achieve a certain level of proficiency and (2) a test of a level of proficiency. The higher-level stages depend on lower ones in the sense that each new stage is (partially) based on abilities from previous stage(s)[27].

1. Stage I: development of individual basic abilities

At this stage robots develop individual, 'cognitive' skills. Robots are equipped with certain mechanisms allowing for development of basic abilities. For example, artificial neural networks seem to be the right equipment for distinguishing and memorizing tasks. Such networks may be trained by being given input in the form of e.g. sounds. They are gradually adjusting their pronunciation to presented stimuli[28]. The abilities discussed in the present section depend mostly on individual pre-adaptations of a robot. A robot needs another robot or a human being – as a source of stimuli, however no interaction with other human or robotic agents is necessary at the stage. In that sense, I treat a robot as an individual agent.

1. Robots are able to distinguish (and learn) a basic set of signals (given samples of vocal activity of other robots and/or human beings); they are also supposed to memorize them. This ability allows for adjusting perceptual (in particular auditory) apparatus of a robot for future communicative tasks. Memorization is a prerequisite for building a base of potential signals; it allows also future re-use of memorized

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26 M. Arbib, *The Mirror System Hypothesis on the linkage of action and languages*, [in:] *From Action to Language via the Mirror Neuron System*, ed. M. Arbib, Cambridge 2006, DOI: https://doi.org/10.1017/CBO9780511541599.002; R. Jackendoff, *Possible stages in the evolution…*; J. Zlatev, *From proto-mimesis to language: Evidence from primatology and social neuroscience*, "Journal of Physiology" 2008, Vol. 102(1–3), DOI: https://doi.org/10.1016/j.jphysparis.2008.03.016.

27 Cf. J. Zlatev, *The Epigenesis of Meaning in Human Beings…*, pp. 155–195.

28 P. Vershure, *Taking connectionism seriously*, [in:] *Proceedings of the 14th Annual Conference of the Cognitive Science Society*, Hillsdale 1992.

signals. Christiansen and Kirby[29] point to the ability for hierarchical learning as well as memory for sound sequences as one of basic cognitive pre-adaptations. Memorized signals may be used in future for the creation of new signals.

2.Once a robot is able to discriminate between sounds produced by other agents, it should also be able to imitate the verbal behaviour of other robots, in that case to re-produce the same or a very similar signal. This ability is required if a set of signals is to be shared within a community. I would like to stress, that at this stage we expect just repetition of meaningless signals ('empty' as Steels puts it). The imitation at the stage may take a form of so-called *proto-mimesis*[30], i.e. it involves a mapping between perception of the other robot and perception of agent's own "body").

De Boer[31] designed a system of artificial agents who were able to engage in sound imitation games. During the game, one of the agents produces a sound from its repertoire. The exact form of the sound depends on the physical capabilities of a robot as well as on its past experience. The second agent tries to reproduce the sound and waits for the feedback from the first agent. The first robot tries, in turn, to recognize the sound heard. Although the main goal of De Boer's system was to simulate the emergence of vowels, it is also a good example of an implemented ability to imitate meaningless verbal behaviour.

3. Robots are able to establish associations; in particular, to associate signals with particular situations. There are several experiments with robotic agents, where they were supposed to map signals and their internal states. Yanco and Stein[32] created robots who were able to learn a lexicon, i.e. establish connections between different signals and elements of a set of meanings. What distinguishes the approach presented here from Yanco and Stein's experiment is the source of signals and meanings: in the HERA case meanings are not given by the experimenter but are created in the course of interactions. The mechanism of association, however, may be similar.

The final ability at this stage is a kind of „generalization", an ability to use signals in reference to situations which differ in some respects. We expect robots to be able to ignore some aspects of situations and use the same signal despite mentioned differences. Let us assume that a robot is using a specific

29 M.H. Christiansen, S. Kirby, *op. cit.*, p. 302.

30 Cf. J. Zlatev, *From proto-mimesis to language...*

31 B. De Boer, *Self-Organization in Vowel Systems through Imitation*, [in:] *Proceedings of the Fourth European Conference on Artificial Life*, eds. P. Husbands, I. Harvey, Cambridge 1997.

32 H. Yanco, L. Stein, *An Adaptive Communication Protocol for Cooperating Mobile Robots*, [in:] *From Animals to Animats 2. Proceedings of the Second International Conference on Simulation of Adaptive Behavior*, eds. J.-A. Meyer, H.L. Roitblat, S. Wilson, Cambridge 1993.

signal in the presence of a house with a red roof. Generalization would mean that robot is able to use the same signal in the presence of a house with a green roof. Obviously, such a "generalization" may be instantiated during interactions with other agents.

To sum up the effects of the first stage of training, robots – as individual agents – acquire basic cognitive abilities. Such abilities are necessary for the development that leads to language-like communication. It should be stressed that robots do not have a ready-to-use (i.e. pre-programmed) set of signals; nor do they have pre-established conceptualizations of their environment. In contradistinction to several other studies[33], we expect robots to develop their own system of communication which finally should evolve into a form of a language-like system. At the stage robots are supposed also to develop ability to link signals with elements of internal knowledge base, i.e. a conceptualization. The linking at the stage takes an idiosyncratic form – the connections created by a robot may be accidental; they reflect individual experiences of a robot. No adjustment of associations is assumed at this stage. Co-tuning of connections requires interactions with other agents/robots.

One of the goals of the project is to observe how differences in the basic capacities influence agent's communicative competences. The idea is to manipulate trainings of individual agents and observe how such differentiation results in further communicative behaviour. Let us imagine a situation in which two robots have been trained to discriminate sounds. Each of robots has been trained on different number of signals – the first on 10 000 signals, the second on 30 000 signals[34]. The difference in training may influence robot's ability to communicate (the first robot may be unable to distinguish some signals produced by the second robot). The results of such manipulations should shed a light on cognitive underpinnings of communication and language.

There is one more capacity which should probably be mentioned at this juncture. As some researchers[35] notice, human beings are capable of symbolic activity and this activity precedes emergence of language. Although the symbolic abilities seem to be basic and natural ones and some researchers assume that the capacity for

[33] E.g. N. Iwahashi, *Robots That Learn Language: A Developmental Approach to Situated Human-Robot Conversations*, www.intechopen.com/books/human_robot_interaction/robots_that_learn_language__a_developmental_approach_to_situated_human-robot_conversations [access: 10.11.2017].

[34] Cf. discussion on NETtalk network: T. Sejnowski, C. Rosenberg, *Parallel networks that learn to pronounce English text*, "Complex Systems" 1987, Vol. 1, p. 153.

[35] T. Deacon, *The Symbolic Species: The Co-evolution of Language and the Brain*, New York 1997; M. Donald, *Origins of the Modern Mind: Three Stages in the Evolution of Culture and Cognition*, Cambridge 1991.

symbolization is innate[36], I have the impression that the ability may be decomposed into simpler ones. One candidate for a mechanism underlying symbolic abilities has already been mentioned, namely, the ability to "generalize"; another one will be mentioned in the description of the next stage, when signals are used in the absence of a referent. I do not feel confident, however, to suggest categorically the path leading to symbolization. Perhaps a plausible answer to the question about symbolization will come from future empirical studies on implemented robots.

2. Stage II: bilateral interaction and 'language games'

The second stage of learning and training involves interactions between two agents-robots. The key activity at this stage takes the form of so-called 'language games', i.e. *routinized turn-taking interaction*[37] where one robot produces a signal (sound) and another one receives it and tries to react to it. There is a shared cooperative goal as well as a real-world context and a possibility of non-verbal communication (e.g. gestures).

Robots play the 'Do-as-I-do' game, i.e. one of them produces a sound associated with a situation (as conceptualized by the robot) and simultaneously can perform an action. The 'Do-as-I-do game' involves both vocal and gestural activities of robotic agents (e.g. pointing and producing a sound). The second robot is supposed to imitate the behaviour. The first agent provides a feedback on performance of the second (accepts it or rejects). As already mentioned in the previous section, the ability to imitate others' behaviour seems to be one of the crucial elements in the context of emergence of communication. The imitation at the stage makes use of the more basic ability to imitate trained earlier. However, at this stage imitation is a part of a game (joint activity) between two individual agents. As such it may be treated as a step towards "true mimesis" as it is under robot's control, and it corresponds to other robot's action (similarity), but it is not intended to "*stand for* some action, object or event for an addressee"[38]. Consequently, it may be treated as an instatiation of dyadic mimesis. The main motivation for practicing the ability is Donald's claim[39] that the prime mover behind the development of language and communication is mimesis.

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[36] S. Swarup, L. Gasser, *op. cit.*, p. 39.

[37] L. Steels, *Introducing Fluid Construction Grammar*, [in:] *Design Patterns in Fluid Construction Grammar*, ed. L. Steels, Amsterdam 2011, DOI: https://doi.org/10.1075/cal.11.03ste, p. 343.

[38] J. Zlatev, *From proto-mimesis to language*...

[39] M. Donald, *op. cit.*; *idem*, *A Mind so Rare: The evolution of Human Consciousness*, Norton 2001.

Robots play 'negotiation games', i.e. they adjust signals used in reference to a situation. Until this stage is reached, our robots have at their disposal individual sets of signals and differing conceptualizations. Although the robots are able to associate signals with situations, such associations may have an idiosyncratic character. Taking this into account, it seems that the step involving 'negotiations' is a crucial one in the context of communication. The general schema of 'negotiation games' involves an agent producing a signal in certain context. The context is available perceptually to the second agent as well and the second robot should produce its own signal associated with the situation. Additionally, as reference to situations may result in attending to different aspects of situations, robots make use of the 'gaze following' ability: they should be equipped in a mechanism detecting visual field of other agents. The ability should restrict the scope of possible interpretations. The game continues until robots adjust their signals.

Steels[40] discusses the results of so-called 'naming games', where two artificial agents try to communicate about an object using their own signals. A speaking robot produces an utterance referring to the selected object. The second agent tries to identify the object. In the case of a success the game continues with a new object. In the case of failure, the first robot indicates the intended object. Each turn may result in adjustment of sets of signals of the two robots. As Steels points out, the game requires two mechanisms: alignment and innovation. His experiments show[41] that finally one signal dominates ("winner-takes-all").

By observing human communicative behaviour, we can easily notice human ability to create new signals (words). Such new signals may be used in reference to newly encountered situations (or objects, actions). Novelty is necessary if we place robots in a changing environment – to cope with new situations and new tasks robots have to have a tool for expanding their 'lexicon' as well. In consequence, robots should be equipped with a mechanism for transforming existing signals into new ones. The very basic ability to distinguish and memorize signals seems to underlie innovation. Although the mechanism seems to be sufficient when robots communicate about a limited domain, it may turn out to be insufficient when conceptualization of the domain expands. Jackendoff[42] notices: "If the symbols were holistic gestalts, like primate calls, even a thousand symbols would be impossible to keep distinct in perception and memory". As a result, modification of existing signals may be insufficient and the use of "open, unlimited class of symbols" must be followed by "development of a phonological combinatorial system to enlarge

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40 L. Steels, *Semiotic dynamics for embodied agents*, p. 33.

41 L. Steels, F. Kaplan, *Situated grounded word semantics*, [in:] *Proceedings of the Sixteenth International Joint Conference on Artificial Intelligence*, Vol. 2, 1999, pp. 862–867.

42 R. Jackendoff, *Possible stages in the evolution of the language capacity*, p. 274.

open, unlimited class of symbols"[43]. The problem is one of the future challenges of the HERA project.

Robots use signals in the absence of referents (they play 'find-it-game'). The first robot produces a signal referring to an aspect of an environment which is not in the visual field of the second robot. The second robot's task is to look for possible referent of the signal. Once again, the game ends in the case of positive feedback from the first robot and continues in the case of negative feedback. In the latter case the second robot tries to find a referent again.

The game is based on one of the crucial features of human language, namely 'displacement': human beings are able to discuss objects, actions and situations which are not available for their perceptual systems. The ability to refer to absent (i.e. not available directly) elements of an environment may be seen as a step towards the *non-situation-specificity* of the signals[44] and towards usage of symbols.

The second stage helps achieve the following goals:

– to develop 'micro-communities' of interacting agents (first, robots establish relationships: they share some aspects of a communication system and they have some common experiences),

– to develop the sense of self of an acting agent controlling its own body – as opposed to other agents,

– to develop proto-mimetic ability and even dyadic mimesis in robots[45]; the former requires the ability to distinguish external and own actions; dyadic mimesis is – in addition – under (conscious) control and corresponds to some action (an object or an event). As Zlatev stresses, an act of imitation should be differentiated from action performed by the subject; applying the distinction to the project – a robot should be able to distinguish its own action from the action imitated.

3. Stage III: on the way to (proto)language

Whereas the previous two stages were analogous to 'one-word period' in linguistic development the third stage involves three language games. Although all of them involve the combination and use of two or more signals, I do not expect the emergence of grammar at this stage[46]. I wish to describe the stage as the one leading to protolanguage.

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[43] *Ibidem*.

[44] Cf. *ibidem*, p. 273.

[45] Cf. J. Zlatev, *From proto-mimesis to language*...

[46] As Jackendoff (*Possible stages in the evolution of the language capacity*, p. 275) remarks in his comment on Bickerton, "one can go beyond single-word utterances without achieving modern syntax".

Protolanguage may be characterized as a predecessor of language which lacks syntactic and word-formation rules[47]. This means that creatures capable of protolanguage may use concatenations of words (signals), but these concatenations have no systematic character. Putting aside the nature of protolanguage, the third stage allows robots to use strings of signals in reference to situations:

Robots play the 'guess-what-it-is' game, i.e. they describe (using two or more signals) situations to other robots and expect another robot to identify the situation. Such identification may be displayed by pointing or direction of a visual apparatus (a camera) or in the form of re-description.

Robots confront different descriptions of a situation (the 'find-differences' game). The game allows to practice various signalling of the same situation. Different descriptions may be results of different conceptualizations (analyses) of the same referent. The game should lead to co-tuning of differing conceptualizations.

Robots engage in "proto-conversation", playing the 'who-knows-more' game. The first robot in the game produces a signal referring to a situation. Another robot adds a new signal, the first one adds third etc. In other words, they add one-by-one new "words" – elements of description of a situation.

The essential novelty at this level is the use of two or more signals in reference to one situation/object/action. Such complex description should be correlated with the conceptual development and with an ability to analyse situations in greater detail. If, for example, one of the robots makes a statement: 'a ball, a man, kicking', we may expect another robot to point to, say, a picture of a football match or expect the other robot to produce a signal 'football'. In this case the game should be judged to be successful. I want to stress that to produce a string of signals ('words') such as 'a ball, a man, kicking', the robot has to be able to distinguish between *both* the two entities *and* the action involved in the situation described. Such an analysis is possible due to the implementation of a version of *situation semantics*[48] and situational calculus[49].

I expect two types of transitions to take place at this stage:

– at the conceptual level: from situation as uniform to situation as a composite,

– at the linguistic level: from holophrases to complex expressions.

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[47] Cf. D. Bickerton, *Language and Species*, Chicago 1990; *idem, Language evolution: A brief guide for linguists*, "Lingua" 2007, Vol. 117(3), DOI: https://doi.org/10.1016/j.lingua.2005.02.006.

[48] J. Barwise, J. Perry, *Situations and Attitudes*, Cambridge 1983.

[49] R. Reiter, *The frame problem in the situation calculus: A simple solution (sometimes) and a completeness result for goal regression*, [in:] *Artificial Intelligence and Mathematical Theory of Computation: Papers in Honour of John McCarthy*, ed. V. Lifshitz, San Diego 1991.

The three subsections present hypothetical cognitive abilities necessary for the emergence of language. Some of these abilities have been implemented and tested in existing models; some of them are the author's original proposal and are supposed to be tested in a horde of robots. All of them are results of a conceptual analysis of communication as a complex phenomenon. The task was to find simpler mechanisms underlying such complex phenomenon. These mechanisms should be simple enough for them to be implemented in robots. Contemporary solutions developed within AI – in particular cognitive architectures – provide tools for implementing abilities characterised in section 1 – Stage I: Development of individual basic abilities[50].

4. The course of communicative development

Robots are supposed to acquire and practice the abilities and actions described above step by step, incrementally, in the course of their development. As mentioned above, the higher developmental stages require the completion of the lower stages. Results of the research done on the emergence of communication in natural and artificial systems seem to suggest the possible stages of development of communication. It should not be surprising therefore that I expect a communication system (including protolanguage and language) to evolve incrementally with the concomitant cognitive (and social) development of agents. I expect to be able to observe the stages in the evolution of communicative capacities of robotic agents. As the implementation of the capacities is a subject of the ongoing research in this field, I can only suggest possible stages in the development. Jackendoff's[51] proposal seem to be close to the expected results of the implementation. In particular, I expect the robots' communicative development to proceed in the following steps:

– the use of signals in a non-specific-situation fashion: a robot will be able to use a signal in reference to different situations (stage I, as a result of varying associations and as a result of generalization),

– an open, unlimited class of signals: the robot should be able to extend its lexicon as a result of the robot-robot interactions and through the functioning in an environment (stage II, the invention of new signals may be a necessary part of

[50] Anderson's ACT-R (http://act-r.psy.cmu.edu, see also: J. Anderson, *How Can the Human Mind Occur in the Physical Universe?*, New York 2007, DOI: https://doi.org/10.1093/acprof:oso/9780195324259.001.0001), as a hybrid, i.e. connectionist and symbolic cognitive architecture, seems to be perfect tool for the task. As I mentioned earlier, artificial neural networks – connectionist architectures may be useful as well.

[51] R. Jackendoff, *Possible stages in the evolution of the language capacity*, p. 273.

'naming-games'); Jackendoff observes that this step requires a special basic cognitive endowment: capacious memory and fast retrieval mechanisms,

– the development of a kind of combinatorial system; robots may use two or more signal concatenations in two ways, either by referring to a situation as a whole ('football match') or as reflecting the complexity of the situation ('play field player') (stage III),

– the emergence of protolanguage (the result of completing stage III).

HOW A COMMUNICATION SYSTEM SPREADS IN A HORDE OF ROBOTS

The three stages in the development of robotic agents, presented above, involve individual development as well as bilateral interactions. One more question remains to be answered: How do the mutual adjustments between a pair of robots spread in the whole group of robots? The question concerns the mode of emergence of a communication system (and communication itself) in a community of agents, i.e. in a distributed system of acting robots. It is also the question about sharing lexical and conceptual knowledge in the community of agents. The problem has – in fact – two dimensions. The first one – horizontal – concerns spreading the communication system within a community of robots (or a generation of robots). The second one – vertical – appears when a 'younger', less experienced robot joins the community[52].

Two solutions have been suggested in the literature on robotic systems. The first, called *iterated transmission learning* is stemming from the work of Boyd and Richerson[53] and is adopted by Kirby and co-workers[54]. Iterated learning is defined here as "a process in which an individual acquires a behaviour by observing a similar behaviour in another individual who acquired it in the same way"[55]. To implement this approach, we need robots with the ability to imitate behaviour of other agents as well as some hierarchy in the group (community). This is the hierarchy of robots who are 'teachers' and robots who are 'pupils'. The latter

52 I am grateful to the anonymous reviewer for drawing my attention to this aspect of Kirby's and Steels' solutions.

53 R. Boyd, P.J. Richerson, *The Origin and Evolution of Cultures*, Oxford 2005. Cf. also: L. Steels, *Experiments on the emergence of human…*, p. 349.

54 S. Kirby, T. Griffiths, K. Smith, *Iterated learning and the evolution of language*, "Current Opinion in Neurobiology" 2014, Vol. 28, DOI: https://doi.org/10.1016/j.conb.2014.07.014.

55 Kirby excludes explicit teaching from the scope of iterated learning mechanism. See: S. Kirby, H. Cornish, K. Smith, *Cumulative cultural evolution in the laboratory: An experimental approach to the origins of structure in human language*, "PNAS" 2008, Vol. 105(31), DOI: https://doi.org/10.1073/pnas.0707835105, p. 10681.

observe and imitate behaviour of the former. Then the 'pupils' can transmit the knowledge to their pupils. Such a hierarchy may be a result of – as mentioned above – a succession of generations of robots. The disadvantage of the approach is that transmission of knowledge (language) seems to be 'one-way', i.e. a 'pupil' cannot influence language of his/her/its teacher. The term 'transmission' is deliberately used here: a pupil observes and reproduces observed behaviour in a more-less passive way. Changes in a communication system happen primarily as a result of disturbances in transmission.

An alternative (or rather a complementary) solution, which allows for two-way interactions and co-tuning of behaviour to be performed, called *dynamic semiotics*, has been suggested by Steels[56]. The idea is partially motivated by the results of Galantucci's[57] experiments, mentioned above. Dynamic semiotics is defined as "the processes whereby groups of people or artificial agents collectively invent and negotiate shared semiotic systems"[58]. Steels suggests that self-organization within the community, based on positive feedback between an action and success is the key mechanism responsible for spreading the communication system in the community. Dynamic semiotics is particularly important in the context of language games requiring in the stage II, especially during 'negotiation games' and 'find it games'.

Taking into account richness of communication, I wish to claim that both solutions should be implemented in a horde of robots. The communication system is acquired in various ways, including iterated transmission as well as a kind of group dynamics as characterized by Steels.

PERSPECTIVES: AN EXCURSUS ON SYNTAX AND SEMANTICS

I would like to present now expectations and initial propositions concerning further (i.e. beyond the third stage) development of communication.

Firstly, in line with Langacker[59] we assume that grammatical structures emerge in the course of language usage (and conceptual development). Such structures should evolve together with a communication competence of robots, starting with single signals, via two-signal utterances (proto-syntax), to syntactically complex sentences. On this view, grammatical constructions are not static structures, but change along with a robot linguistic experience and conceptual development. Steels[60] suggested a solution meeting the above requirements, namely the Fluid

[56] L. Steels, *Semiotic dynamics for embodied agents*, p. 32.
[57] B. Galantucci, *op. cit.*
[58] L. Steels, *Semiotic dynamics for embodied agents*, p. 32.
[59] R.W. Langacker, *Foundations of Cognitive Grammar*, Stanford 1987.
[60] L. Steels, *Introducing Fluid Construction…*

Construction Grammar (FCG). The grammar uses so-called constructions (patterns of usage) consisting of two poles: syntactic and semantic. Additional advantage of adapting the solution is that FCG supports implementation of links between syntactic and conceptual levels.

The problem of semantics is often understood as the problem of the domain of interpretation of signals. World – as such domain of interpretation of robotic signals – is usually considered as a set of objects, properties, events or actions. As already mentioned, we assume that, initially, the basic unit of semantic interpretation is a situation (instead of 'objects' or 'actions'). Such an approach requires a special kind of semantics. A good candidate for such a model seems to be Barwise and Perry's[61] version of model of *situation semantics*: "[…] and there are parts of the world, clearly recognized (although not precisely individuated) in common sense and human language. These parts of the world are called situations"[62].

Situations are further analysable into objects, properties, acts etc. Such analysability is a consequence of the interactions with other robots as well as the linguistic and conceptual development of a robotic agent. We take the above process as an analogue of the syntactic aspect of the process of language acquisition, where holophrases, treated as unitary elements, may be further analysed.

LANGUAGE EVOLUTION

As Christiansen and Kirby state:

> […] deep understanding of language evolution can only come from the concerted, joint effort of researchers from a huge range of disciplines. We must understand how our brains and minds work; how language is structured and what it is used for; how early language and modern language differ from each other and from other communication systems; in what ways the biology of hominids has changed; how we manage to acquire language during development; and how learning, culture and evolution interact[63].

This paper raises a question of possible basic cognitive principles hidden behind observable communicative behaviour. In other words, it is a partial answer to the question – asked by Christiansen and Kirby – "how our minds work". It also tries to indicate cognitive capacities responsible for learning necessary for acquisition of a communication system. The human language faculty – as characterized in Introduction – includes various cognitive mechanisms. Some of them

[61] J. Barwise, J. Perry, *Situations and…*

[62] J. Barwise, J. Perry, *The Situation Underground*, [in:] *Stanford Working Papers in Semantics*, eds. J. Barwise, I. Sag, Stanford 1980, pp. 1–55.

[63] M.H. Christiansen, S. Kirby, *op. cit.*, p. 2.

have been enumerated and elaborated above. These mechanisms are supposed to support development of a communication system.

Fitch[64] in his overview of approaches to cognitive evolution in the context of evolution of language indicates a number of basic cognitive capacities necessary for development of communication and language. Such a "basic cognitive toolkit" consists of (among others): auditory capacities, speech output and vocal control, ability to distinguish and learn novel signals and ability to learn to interpret them, different forms of memory, ability to categorize, navigate and plan. These basic abilities are basis of 'higher-level' capacities, like: hierarchical grammar or context-dependent interpretation of signals.

The task of AI approach, in particular robotic implementations, is to show that it is possible that such basic cognitive capacities can interact and develop to – finally – produce a complex ability to communicate and use of language. In that sense, the approach presented here cannot provide additional arguments for language evolution in a phylogenetic or a glottogenetic perspectives. Instead, it can show that – from a point of view of a cognitive scientist – certain cognitive mechanisms, considered in an ontogenetic perspective, are plausible or implementable.

CONCLUDING REMARKS

To broaden the understanding of mechanisms underlying emergence and evolution of communication a new methodology has been adopted involving experiments on groups of interacting, autonomous and grounded robots. Such multi-agent systems allow us to test theories about the mechanisms necessary for development of a communication system. A number of different factors have been identified, with special emphasis on basic cognitive abilities, either innate (pre-programmed) or developed in the course of robot-robot interactions. A number of tests, 'language games', have also been suggested to practice further cognitive capacities necessary for the emergence of communication. As the games are based on local interactions (without a global overview of the communication system) we need a mechanism for spreading conventions in a community. Two such mechanisms are suggested in the research on robotic communication: iterated learning and dynamic semiotics.

The initial solutions and suggestions presented in the paper are treated as a starting point on the route to the emergence of 'full' language. Ultimately, the HERA project aims to model development of communication beyond the third stage, i.e. to explain the transition between protolanguage and full language ability as well.

[64] T. Fitch, *op. cit.*, pp. 5–9.

Several questions about the results of the HERA project and potentially emergent communication system arise here. The autonomy of robotic agents may result in a completely incomprehensible system of signals. We, as human observers, may be incapable of distinguishing individual signals as well as specific, robotic conceptualization of the world. Consequently, we may find ourselves in the situation of the Quinean linguist-interpreter who tries to write a translation manual. In such a case, an attempt to communicate with robots would be an interesting challenge. Assuming that the robotic communication system would differ significantly from human natural language, it is legitimate to ask whether it is reasonable to compare outcomes of experiments on 'hordes' of robots with human communities and relevant communicative behaviour.

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STRESZCZENIE

Niektóre „tradycyjne" kwestie związane z wyłanianiem się i rozwojem języka mogą być rozpatrywane w perspektywnie autonomicznych robotów, ich interakcji ze środowiskiem oraz ich zdolności komunikacyjnych opartych na systemie sygnałów, wyłaniającym się w toku ewolucji robotów. Głównym celem artykułu jest przedstawienie podstawowych, minimalnych zdolności niezbędnych do wyłonienia się komunikacji w grupie robotów. Na początku zarysowana została zmiana, jaka zaszła w podejściu do modelowania języka w kognitywistyce i w szczególności w kognitywistycznych badaniach nad sztuczną inteligencją. W dalszej części zaprezentowano przypuszczalne podstawowe mechanizmy poznawcze, w jakie powinien być wyposażony indywidualny robot, mianowicie: zdolność do rozróżniania sygnałów, do kojarzenia ich z konkretnymi sytuacjami oraz do naśladowania zachowań sygnalizacyjnych. Te podstawowe indywidualne zdolności mogą się rozwijać w ramach grupy współdziałających robotów osadzonych w zmieniającym się środowisku. By przećwiczyć te zdolności i je rozwinąć, roboty biorą udział w serii narzuconych przez eksperymentatora zadań („gier językowych"), takich jak: naśladowanie działań, negocjacje odniesienia, używanie sygnałów przy braku referenta tych sygnałów. Badania nad wyłanianiem się komunikacji w społecznościach naturalnych i sztucznych systemów mogą pomóc w identyfikacji etapów rozwoju zdolności komunikacyjnych.

Słowa kluczowe: wyłanianie się komunikacji; modelowanie robotyczne; poznawcze podstawy komunikacji; gry językowe; semantyka sytuacyjna

SUMMARY

Some "traditional" issues in language emergence and development are viewed through the prism of the interaction of autonomous robots with their environment and through their communicative skills based on the signaling system which emerges as a result of the robots' own evolution. The main goal of the paper is to present initial conditions necessary for the emergence of communication in a group of robots. First, the paper discusses, in relation to the general faculty of language, the change that has taken place within cognitive science, particularly within computational modelling and Artificial Intelligence. Then a number of basic, individual cognitive mechanisms (pre-adaptations) are suggested, including the robots' ability to distinguish signals, associate them with particular situations and imitate signaling behavior. These basic individual abilities may develop in the context of a community of interacting agents as well as in the changing communicative environment. In order to practice and develop the cognitive capacities, robotic agents are expected to engage in a number of activities (‚language games'), including the imitation of actions, the negotiation of reference and the use of signals in the absence of referents. Inquiries into the emergence of communication in natural and artificial systems can help isolate the possible stages of the development of the robots' communicative abilities.

Keywords: emergence of communication; robotic modelling; cognitive underpinnings of communication; linguistic games; situation semantics