

ISSN 2186-7437

## NII Shonan Meeting Report

No. 2016-14

# Cognitive Development and Symbol Emergence in Humans and Robots

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October 3–7, 2016



National Institute of Informatics  
2-1-2 Hitotsubashi, Chiyoda-Ku, Tokyo, Japan

# Cognitive Development and Symbol Emergence in Humans and Robots

Organizers:

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## Overview

Recent advances in modern robotics and machine learning, including Bayesian nonparametrics and deep learning, have brought the possibility of creating embodied computational intelligences that behave adaptively in real-world environments once more to the fore. Symbol emergence in robotics is an emerging research field that attempts to solve interdisciplinary problems related to the use of symbols, using a constructive approach [1].

Symbol systems have been an important and problematic topic in both artificial intelligence and cognitive science. Human beings make use of symbol systems to recognize various phenomena in the world and to communicate and collaborate with other entities, including robots and other humans. Newell et al. proposed the physical symbol system hypothesis, and this notion had been fundamental to conventional artificial intelligence and cognitive science [2]. The main misunderstanding in the physical symbol system hypothesis is that they assume that a symbol system exists without any real-world information. Owing to the missing link between the symbol system and the real-world, the physical symbol system is ungrounded, and therefore unable to function appropriately in complex environments. The symbol grounding problem and intelligence without representation arguments challenged the conventional naive understanding about and implementation of a symbol system [4, 3]. In cognitive science, Barsalou shed the light on a perceptual aspect of symbol system and proposed the perceptual symbol system [5].

The fundamental problem is that many researchers have been conflating the kinds of symbols that usually appear in programming languages, and human meaning-oriented symbols. Steels call them *c*-symbols and *m*-symbols, respectively [6], pointing out the ill-posed characteristics of the original symbol grounding problem. To understand the human meaning-oriented symbol system and develop an intelligent robot that can communicate and collaborate with humans, we have to model the dynamics of the symbol system on the basis of embodied cognition and semiotic communication among the agents in a bottom-up and data-driven manner.

In the developmental and cognitive sciences, there are still many unsolved problems in human infant language acquisition and concept formation processes. An integrative model that can explain the process of language acquisition and the use of the obtained language simultaneously is still missing. To understand the process of language acquisition, we require a description of the dynamic process of language-related capabilities, e.g., learning vocabulary, constructing mutual belief, forming multimodal concepts, and learning syntax. A computational model based on machine learning provides a promising model for understanding cognitive phenomena related to language acquisition. Similarly, an embodied computational model for language evolution is important in evolutionary linguistics.

This Shonan meeting focused on the constructive approach towards embodied language acquisition, symbol emergence and cognitive development in autonomous systems, including human and robots. To foster this, we aimed for interdisciplinary discussions with a wide viewpoint from various research fields including not only related computer science and robotics but also cognitive science, developmental psychology, linguistics, and other fields in the humanities. The scope of this meeting included language acquisition, developmental robotics, human-robot interaction, machine learning, cognitive science, artificial intelligence, neural networks, multimodal sensory experience (auditory, speech, gestures), language evolution, and semiotics. The following sessions were assigned to discuss symbol emergence and cognitive development in humanities and robotics.

- Computational models of embodied language acquisition
- Learning methods and system integration for human-robot long-term communication and collaboration
- Human symbol systems and cognitive development
- Models for understanding semiotic and linguistic communication
- Language and cultural evolution in human society

## Participants

The following researchers participated in the Shonan meeting.

- Dr. Dearden , Richard , Schlumberger Gould Research , UK
- Prof. Hagiwara , Yoshinobu , Ritsumeikan University , Japan
- Dr. Hoffmann , Matej , iCub Facility, Italian Institute of Technology , Italy
- Prof. Inamura , Tetsunari , National Institute of Informatics , Japan
- Prof. Iwahashi , Naoto , Okayama Prefectural University , Japan
- Dr. Jamone , Lorenzo , Instituto Superior Tecnico , Portugal
- Prof. Matsuka , Toshihiko , Chiba University , Japan

- Prof. Moriguchi , Yusuke , Kyoto University , Japan
- Prof. Nagai, Takayuki, The University of Electro-Communications, Japan
- Prof. Nakamura , Tomoaki , The University of Electro-Communications , Japan
- Prof. Orita , Naho , Tohoku University , Japan
- Prof. Oztop , Erhan , Ozyegin University Computer Science , Turkey
- Prof. Piater , Justus , Universitat Innsbruck , Austria
- Dr. Rosman , Benjamin , University of the Witwatersrand , South Africa
- Prof. Sandini , Giulio , Istituto Italiano di Tecnologia , Italy
- Prof. Taguchi , Ryo , Nagoya Institute of Technology , Japan
- Prof. Taniguchi , Tadahiro , Ritsumeikan University , Japan
- Prof. Ugur , Emre , Bogazici University , Turkey
- Prof. Vijayakumar , Sethu , The University of Edinburgh , UK
- Prof. Worgotter , Florentin , Univ. of Gottingen , Germany
- Dr. Yamakawa , Hiroshi , Dwanjo , Japan

## Schedule

### Arrival day: 2nd October (Sunday)

- 15:00 Check-in
- 19:00 Welcome Banquet
- 21:00 Free time

### Seminar 1st day: 3rd October (Monday)

- 9:00 Short Introduction of Shonan meeting by organizers (**Tadahiro Taniguchi**)
- 9:30 Startup session (ice breaking & self-introduction)
- 10:30 Coffee break
- 11:00 Opening remarks by organizers (**Emre Ugur**)
- 12:00 Lunch
- 13:30 Group Photo Shooting
- 14:00 Seminar slot A1 (3 blocks = 12 talks in total at most) Each block consists of 4 x 5 minutes talks at most.
- 15:30 Coffee break

- 16:00 Seminar slot A2 (4 blocks = 16 talks in total at most) Each block consists of 4 x 5 minutes talks at most.
- 18:00 Dinner
- 20:00 Free time

### Seminar 2nd day: 4th October (Tuesday)

- 9:00 Announcement from organizers
- 9:10 Seminar slot A3 (invited talk by **Giulio Sandini**) 40 min. talk +30 min. Q&A
- 10:20 Coffee break
- 10:50 Seminar slot A4 (invited talk by **Justus Piater** )
- 12:00 Lunch
- 13:30 Seminar slot A5 (invited talks by **Sethu Vijayakumar** and **Takayuki Nagai**) 40 min. talk +20 min. Q&A
- 15:30 Coffee break
- 16:00 Seminar slot A6 (invited talk by **Florentin Worgotter**) 40 min. talk +30 min. Q&A
- 17:10 Group discussion
- 18:30 Dinner
- 20:00 Free time

### Seminar 3rd day: 5th October (Wednesday)

- 9:00 Seminar slot B1: Short talks
- 10:30 Coffee break
- 11:00 Seminar slot B2 (Planning of the remaining workshop)
- 12:00 Lunch
- 14:00 Excursion: Jomyo-ji temple and Japanese tea ceremony
- 18:30 Main Banquet
- 21:00 Free time

### **Seminar 4th day: 6th October (Thursday)**

- 9:00 Seminar slot B3
- 10:30 Coffee break
- 11:00 Seminar slot B4
- 12:00 Lunch
- 13:30 Seminar slot B5
- 15:30 Coffee break
- 16:00 Seminar slot B6
- 17:30 Discussion
- 18:30 Dinner
- 20:30 Free time

### **Seminar 5th day: 7th October (Friday)**

- 9:00 Closing session & Announcement from participants
- 10:30 Coffee break
- 11:00 Closing remarks & Follow-up plan
- 12:00 Lunch

This was a tentative schedule of the workshop. Based on the nature of Shonan meeting, we managed the schedule very flexible. Roughly speaking, each participant introduced his/her background on the first day, and five representative participants gave talks about the history and current important issues in this fields on the second day. On the third day, we had some talks given by some participants who was late in the morning and had an excursion in the afternoon. The half of the fourth day was spent in group discussion. All participants are grouped into three teams. Each team had a topic raised based on the discussion held in the first three days. In the afternoon of the fourth day, we came together and had a general discussion about the three topics. On the fifth day, i.e., final day's morning, we had a wrap-up discussion about the topics we discussed throughout the meeting. After determining a plan, i.e., writing a collaborative paper, we closed our exciting workshop.

### **Invited talks**

We had five invited long talks on the second day of the seminar. The organizers did not ask them to submit any titles or abstracts. The brief summaries of the talks are as follows.

## **Giulio Sandini**

He talked about developmental robotics and human-robot interaction. The main message of the talk was that humanoids research is an important tool to understand brain functions and human cognition. He introduced the history of building an international iCub community and potential of the robots that interact with people naturally in the context of science.

## **Justus Piater**

He talked about how a robot should obtain its knowledge, e.g., skills for manipulating an object. After emphasizing the importance of learning capability, he introduced the notion of structural bootstrapping. The notion of the structural bootstrapping became one of the main issues in the discussions throughout the Shonan meeting. He also introduced two representative studies that his group conducted, e.g., “skill learning using stacked classifiers” and “skill learning using projective simulation.”

## **Sethu Vijayakumar**

Developing a humanoid that can perform appropriately in the real environment is a crucial challenge in both of engineering and science. He firstly introduced his humanoid robot project with NASA. He talked about the challenges in motion planning, adaptation and learning in humanoid robotics. Relating the topic of the workshop, he also put importance on the adaptive human in the loop behavior and shared autonomy. Finally, he also gave an important comment about translation activity and social impact of robotics and related technologies.

## **Takayuki Nagai**

Takayuki introduced his series of research about a robot’s language acquisition and symbol emergence in robotics. He insisted that multimodal categorization is crucial for a robot to understand its environment, He also demonstrated experiments using a robot named HSR, which was newly developed by TOYOTA. He also showed a motion segmentation method that enables a robot to learn new motions from observation.

## **Florentin Worgotter**

He organized a workshop entitled Robotics in the 21st Century: Thoughts from 100 Smart People. He briefly reported the workshop inviting 100 speakers from related fields. After that, he talked about the relationship between object meaning, affordance, and skill learning.

## **Group Discussion**

In the group discussion held on the third and the fourth days, each participant joined one of three groups and had a discussion about fundamental questions in cognitive development and symbol emergence. The topics themselves were raised and organized through the discussion held during the first three days.

## Group 1: Representations & Symbols

Matej Hoffmann, Lorenzo Jamone, Benjamin Rosman, Richard Dearden, Toshiko Matsuka, Naoto Iwahashi

Group 1 discussed the following questions.

1. Is there a hierarchy of things - from discrete states, over high-level features, categories, concepts, etc.? Where do symbols fit in?
2. Given that the agent creates some symbols: what symbols to create and/or keep?
  - What is the relationship between symbols and concepts?
  - Are symbols substantially different from discretized states?
  - Can symbol be seen as different levels of abstraction in a hierarchical architecture? (high-level features?)
3. Given that the agent has created compact representations with grammatical manipulation like in language, they might help to achieve more intelligent non-linguistic behaviors (e.g. problem solving). How does syntactic manipulation/ grammar help?
4. How does context influence the symbols and/or their interpretation?

## Group 2: High-Level Cognition

Florentin Wrgtter, Tadahiro Taniguchi, Emre Ugur, Justus Piater

Group 2 had a discussion about the definition of a symbol and its origin.

1. Do symbols (concepts) need to emerge at all?
  - With a finite set of concepts, can we describe all relevant aspects of the world?
  - Grounding, relations, etc. still to be learned

## Group 3: Human-in-the-loop system

Sethu Vijayakumar, Giulio Sandini, Erhan Oztop, Tetsunari Inamura, Yoshinobu Hagiwara

Group 3 had a discussion about how to create the better human-robot interaction in real and virtual reality environment, and its relationship with symbol emergence.

1. How to design stable shared autonomous system?
  - Estimation of others state/intention
  - How to represent others model (by robot)
  - Interaction between robots and human through exchange of force/dynamics and exchange of symbolic information to share a kind of state

The discussion reached a conclusion as follows.

- Symbol emergence requires communication in physical world
- Exchange of both of symbolic and physical information /representation is important
- We have to pay attention to distinguish symbol and language
- Do we need to define layer structure of symbol/concept/word/language?

## Closing session

In the closing, i.e., wrap-up, session, the organizer wrapped up the all of the discussion and gave a talk about the tentative agreement about “what is?” problems, e.g., “what is a symbol?” and “what is a concept?” They are quite important problems in the developmental robotics and human-robot interaction because people are using symbols, concepts and a language to communicate and collaborate with people and robots. The conclusion of this meeting is not a perfect solution to this philosophical problem. However, building mutual understandings about key topics in different communities and having a tentative agreement about important issues are crucially important to make progress in the research field. We agreed to write a survey paper about the topic jointly and closed the exciting meeting.

## Main discussions and contributions

Main discussions in the meeting were centered around the questions: “whether symbols emerge?” and if yes “what are the mechanisms?” and “what are the next challenges in symbol emergence” questions.

We discussed that symbol emergence through robot’s own interactive exploration has been shown in simple setups [7], however, methods that can discover powerful concepts (via exploration, development, teaching, etc.) in high-dimensional perception-action spaces are still missing. The symbols emerged in the mentioned simple space without any human intervention, but at the same time, the experiments were designed such that such an emergence was expected from programmer’s point of view. When we scale up to such high-dimensional learning spaces, how a robot can discover unexpected symbols and can make progress without hard constraints on the system are important research questions.

We discussed that full exploration of such high-dimensional perception-action spaces might be challenging and one can resort to observations from human task executions. For this, huge experience cyber shared in virtual reality environments might be exploited. Be it real or virtual reality data; we need powerful methods that enable hierarchical decomposition of temporal sensorimotor data coming from such observations. The challenge is an autonomous generation of predictable and useful concepts that are represented at different levels of abstractions, allow inference in different complexity levels, allow symbolic planning, are

influenced by language, and can be used as the basic units (i.e. internal representations) to connect the external world. Therefore, symbol emergence should be posed as a multi-facet problem that should take into account different sources of information for learning and different points for exploitation. In this respect, the methods that we require should enable simultaneous learning of syntax of object manipulation and syntax in language from speech signals. To scale up to high-dimensional spaces and provide a symbol emergence framework, we might need cognitive architectures that integrate different general mechanisms. The cognitive architectures should take experiences of different types and representations, such as sensorimotor and social, into account. The general mechanisms include such as deep neural networks on the one side of the spectrum and probabilistic programming techniques on the other side. Such a general approach might be useful in interfacing smoothly and generally between different (discrete, continuous, syntactic) representations in a way that naturally incorporates both perception and action.

Last but not least, during the meeting, we heavily discussed the definitions and relations between related notions such as “concept,” “category,” “syntactic element” and “symbol.” These concepts have been used interchangeably in different theories and fields to refer to similar phenomena. Formally defining and consolidating the terminology in the context of symbol emergence in humans and robots has been beyond our 5-days workshop.

Therefore, we have set up an agenda to write a journal paper which discusses symbol emergence problem from different points of view providing a comprehensive literature review and revealing the next big challenges. This journal paper is currently under preparation [8].

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