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Chapter 18

Advances and perspectives in cognitive architectures

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Abstract

The paper presents four fundamental questions concerning cognitive architecture, with answers provided by the four authors. What exactly does the word "cognitive" mean? What is the difference between a cognitive system and a non-cognitive intelligent system? Is language a necessary feature of cognitive systems? What are the frontiers of research regarding cognitive architectures?

1. Introduction

Cognition is an open concept with no clear boundaries. The word “cognitive” has become a hype, and big companies like Microsoft, IBM, Google and others are now providing some sort of “cognitive” software, but it is not really clear what this means. Cognition is studied in various fields with different perspectives, including psychology, philosophy, neuroscience, linguistics, biology, social sciences, artificial intelligence and computer science, so, from a scientific perspective, to study cognition, one should start defining one’s theoretical framework and principles.

Those pursuing research on cognitive architectures and systems have to deal with various perspectives and open questions. A starting point is making a distinction between natural and artificial systems. Study of natural cognitive systems aims at getting a better and deeper understanding of their fundamental aspects. As one of the consequences of the acquired knowledge on this matter, we foresee the possibility of starting to think about synthetic cognitive systems, or those designed by humans with a practical or theoretical purpose, while pursuing the fundamental aspects that define a system as cognitive.

The authors discuss relevant and fundamental questions concerning cognitive systems research, addressing the attribute “cognitive” in “cognitive systems”, differentiating cognitive system and non-cognitive intelligent systems, discussing language as an important feature in a cognitive system, and debating the research frontiers on cognitive systems and cognitive architectures.

2. Questions

2.1 What does the attribute “cognitive” in “cognitive systems” refer to?

Loula: To describe the relation of the attribute “cognitive” with the concept of “cognitive systems”, it would be necessary to first discuss what “cognition” is. Cognition is related with mind processes, but it is a concept with no clear boundaries and with no consensual definition. The following excerpts illustrate this:

> *Question 1:* What is cognition?
> *Answer:* Information processing as symbolic computation – rule-based manipulation of symbols.
> *Question 2:* How does it work?
> Answer: Through any device which can support and manipulate discrete functional elements – the symbols. The system interacts only with the form of the symbols (their physical attributes), not their meaning.
> *Question 3:* How do I know when a cognitive system is functioning adequately?
> *Answer:* When the symbols appropriately represent some aspect of the real world, and the information processing leads to a successful solution of the problem given to the system.

> *Question 1:* What is cognition?

Answer: Enaction: A history of structural couplings that brings forth a world.
Question 2: How does it work?
Answer: Through a network consisting of multiple levels of interconnected, sensorimotor subnetworks.
Question 3: How do I know when a cognitive system is functioning adequately?
Answer: When it becomes part of an ongoing existing world (as the young of every species do) or shapes a new one (as happens in evolutionary history).

Both excerpts come from the book *The embodied mind: cognitive science and human experience*, by Francisco J. Varela, Eleanor Rosch & Evan Thompson (1991, pp. 42-43, 206-207), discussing different views on cognition. The first one comes from Cognitivism (Cognitive Psychology), which views the mind as an information processing unit, and the second definition is from Embodied (Enactive) Cognition, which recognizes the mind as tightly coupled with the body and with the interaction in an environment. Thus, to relate “cognitive” with “cognitive systems”, one should start defining their theoretical framework and principles.

Moreover, since cognition is studied in various fields with different perspectives, including psychology, philosophy, neuroscience, linguistics, biology, social sciences, artificial intelligence and computer science, the field of study should also come forward. The object of study should also be defined, as the variety of cognitive processes and related phenomena is also wide and may encompass topics such as knowledge, reasoning, belief, language, brain, mind, learning, adaptation, autonomy, intelligence, memory, perception, and also creativity, emotion, communication, altruism, causation, information, epistemology, representation, and more.

For the attribute “cognitive” to relate to the concept of “cognitive system”, there is a broad set of theoretical references, fields of studies and possible processes and elements of interest. Additionally, a cognitive system may be a natural system or an artificial system, and to relate the attribute ‘cognitive’ with an artificial (cognitive) system, we also have to discuss the ontological (or the epistemological) status of this relation.

An artificial cognitive system is, first of all, a system, a set of somehow interrelated elements, but it is also an artifact, designed by a human being to somehow perform a cognitive task. Borrowing a discussion on Artificial Life from a paper by H. Pattee (1989), we can inquire whether this artificial system simulates a cognitive process or whether it realizes a cognitive process. Does an artificial cognitive system function as a (literal) implementation of cognitive processes or does it (only) model and simulate such processes? Moreover, we can also ask whether artificial cognitive system are limited to implementing or modeling natural cognitive systems and processes. Could one go beyond, from cognition-as-we-know-it to cognition-as-it-could-be? We will leave these questions open...

Netto/Muñoz: “Cognitive” is related to a general set of features that should be pursued by a system taking this name. “Cognitive” means the ability to express or to possess cognition, which means reasoning in its broadest sense, not only logical reasoning, but any kind of sensorial interpretation leading to appropriate actions.

“Cognitive systems” refers, as the name suggests, to systems with cognitive capacities. We differentiate between natural and artificial systems. The study of natural cognitive systems aims at getting a better and deeper understanding of their fundamental aspects, including for instance how it is structured, how it develops in the natural neuronal substrate, and so on. This knowledge can be viewed from two main perspectives. On the one hand, supported by neuroscientific analysis, and on the other, by pure philosophical reasoning. As one of the consequences of the acquired knowledge on this matter, we foresee the possibility of creating synthetic cognitive systems, or those designed by humans with a practical or theoretical purpose, while pursuing the fundamental aspects that define a system as cognitive.

It seems that in order to be properly addressed as "cognitive", an artificial system should meet certain expectations, which from a general point of view would be to reflect the corresponding natural systems, keeping their main features. Once we are able to identify and to (at least partially) describe the features of a cognitive system, we should also be able to build artificial ones embedded with such cognitive features. Many questions arise from this expectation, and here we try to identify some of them.

First, natural cognitive systems are autonomous and, if we intend that artificial systems share this attribute, we should not interfere on the way cognition arises in this substrate. The question is how to build a substrate with such independence, where cognition (even the most basic one) can arise. Second, natural cognitive systems result in fact from a strong interrelation among its many component subsystems, in a highly distributed form, making it difficult to understand how cognition emerges. An artificial cognitive system should also have these properties, with autonomy.

So, concluding, more than stating a list of cognitive attributes, expected to be found on each system recognized as such, it is important to understand the main fundamental aspects of a natural cognitive system, and to implement them in an artificial one, giving the system all the autonomy it may have. Of course, the tricky point is how to program such a self-evolving system so that it will perform the expected things that we humans would recognize in a cognitive system. We thus see that there are still many open questions.

Gudwin: In principle, I agree both with Loula's and Netto/Muñoz' views. We are currently seeing an explosion in the use of term "cognitive" in computer and systems science. Big companies like Microsoft, IBM, Google and others are now providing some sort of "cognitive" software, and it is not really clear what this means. The word has become a hype, without a clear understanding of its scope and limitations. As Loula already pointed out, the word "cognitive" has been used extensively under the domain of *Cognitive Sciences*, and even there with different meanings, depending on whether the researcher is a cognitivist, a connectionist, a dynamicist, or an embodied and situated enactivist.

The term "cognitive" appears throughout the scientific literature. We can see expressions like "cognitive systems", "cognitive radio", "cognitive computing", "cognitive management", "cognitive robotics", etc., and one particularly interesting question is what the authors have in mind when they employ the term "cognitive" to describe their realizations. There are many technologies which are pointed out as being "cognitive", such as Symbolic Rule Based Reasoning, Neural Networks (Reinforcement Learning, and more recently Deep Learning), Speech Recognition, Natural Language Understanding, and many others.

Browsing the literature brings us a mix of many different meanings for this term. In many cases, the authors employ a completely non-technical, or naïve use of this term: a use without any technical explanation for its meaning, as if it were self-evident or self-explanatory for the reader (e.g. Dorneich et al., 2005; Xu et al., 2014; Foteinos et al., 2013; Vlacheas et al., 2013). In other papers, the authors implicitly define "cognitive" as related to some sort of sensing/actuating capability: used to define systems with sensing abilities and actuating on the environment (e.g. Gaussier, 2001; Hershberg & Efroni, 2001). Finally, we find other authors who use the term "cognitive" with reference to some sort of cognitive modeling: relying on some model of a high-level human cognitive function which is emulated/simulated in the artificial system (e.g. Dodd & Gutierrez, 2005; Riegler, 2002). Different models of high-level human cognitive functions, like perception, attention, decision-making, planning, action-selection, behavior generation, learning, memory, emotions, language use, consciousness, imagination, social cognition, meta-cognition, etc., can then be used to derive some sort of "cognitive" system. In our opinion, the naïve use should be simply disconsidered, and the sensor/actuator use should also be avoided, as it makes clearly a misuse of the term: any control system might have sensing and actuating abilities, without necessarily being "cognitive" because of that. We conclude that the best way of understanding this term is in the high-level human cognitive functions modeling. So we propose the following meaning for the term "cognitive": we define a cognitive system or module, or sub-system, or whatever else, as a system, module, sub-system, etc. which aims at explicitly modeling human cognitive functions in its inner mechanisms and/or algorithms.

But this is just half of the solution, because now we have the burden of understanding what is a human cognitive function. Let us be a little more systematic on this point. This is a very dangerous subject, because we are supposed to apply a terminology which was designed originally to refer to the human mind, but we intend to make a technical use of the term, so we must be prudent here. Our idea is to start with a terminology referring to a specific phenomena which is the human mind, find a model for explaining the meaning of these terms, perform an abstraction (or a metaphor) to simulate/emulate a mental process as a computational process, and implement this computational process in an artificial system. In this manner, a human cognitive function will translate into a computational "cognitive" process, instantiated in an artificial "cognitive" system. But then, there is a problem related to the scope of what is meant to be "cognitive". In Cognitive Science (mainly in psychology), an older view used to split the mental phenomena in three different categories: perception, cognition and action. Following this older vision, both Perception and Action should be excluded from what might be accounted as "cognitive". This was the rule during the cognitivist period in Cognitive Science. As soon as the enactivists started to stress the importance of the environment in cognitive phenomena, the word "cognitive" gained a wider scope, and all mental phenomena, including perception and action, started to be incorporated in its meaning. With this, phenomena like vision, categorization, speech recognition and behavior generation started to be assumed "cognitive" as well.

2.2 What would be the difference between a cognitive system and a non-cognitive intelligent system?

Loula: To answer the question of the difference between cognitive and non-cognitive intelligent systems, we will focus on the domain of artificial systems, thus comparing artificial cognitive systems and artificial (non-cognitive) intelligent systems. As cognition was defined as an open concept with no clear borders, the same goes for intelligence, which is even more open. But if we are discussing artificial intelligence systems, this brings forward Artificial Intelligence.

The term Artificial Intelligence was coined in 1956, in the name of the Dartmouth Summer Research Project on Artificial Intelligence Conference. Before that, research in the area was not known as Artificial Intelligence, neither were intelligent systems called by this name. Intelligent systems, by that time, included programs for playing games like checkers, logic theorem provers and mathematical problem solvers. But the field of Artificial Intelligence evolved since then, and there is now a wide set of Intelligent Systems, including data mining and machine learning systems, control systems, robotic systems, and more.

Artificial Intelligence is now a broad area that covers a lot of different research agendas. Both Cognitive Systems and (non-cognitive) Intelligent Systems can be considered parts of Artificial Intelligence research efforts, but with different approaches and ambitions. Research on Artificial (non-cognitive) Intelligent Systems are focused on developing flexible and adaptive systems inspired on intelligent (natural) processes and elements, and also on other biological processes that can reveal promising algorithmic solutions to diverse problems. The aim of building Intelligent Systems is to come up with technological artifacts that solve practical problems, inspired by certain approaches. Such Intelligent Systems include (but are not limited to) neural networks systems, fuzzy systems, evolutionary computation systems, natural computing systems, bioinspired systems and robotics, and more.

Research on Artificial Cognitive Systems, on the other hand, has focused on modeling cognitive processes in an effort to reproduce more closely the relations and elements of cognition. Cognition is not just an inspiration for building systems, the aim is to simulate (or realize) cognition, most often a certain aspect of it, with scientific or technological motivations.

Netto/Muñoz: The well-known cognitive systems are the natural ones, embedded in evolved live organisms. But even in this scenario it is hard to establish the threshold above which systems should be accepted or identified as cognitive. One way of thinking would be to characterize a system by a set of (acknowledged) features that seems to be important or fundamental in cognitive systems, even if with different degrees of presence, and then to assess how present they are in each evaluated being.

In this paper, the focus is on artificial systems. For these, the main difference between cognitive and (non-cognitive) intelligent systems is that cognitive systems are closer to the natural systems than their purely intelligent counterparts. Intelligent artificial systems are normally those built upon principles of logic, in accordance with the fundamentals of classic Artificial Intelligence. We may consider intelligent systems as all those that possess intelligent abilities, independently of whether these are explicitly designed by humans (that know what they mean and how to express them algorithmically) or by any another approach leading to an autonomic development. The most important thing would be to recognize such system as intelligent after observing their behavior (depending on how they behave or solve assigned problems, humans assess them as more or less intelligent).

On the other hand, cognitive systems may also present intelligent abilities, but the way they develop is different: no human interference should be allowed in the design of their behavior, meaning they should not have any designer embedded feature. Furthermore, it is expected that the intelligence should be broader, in the sense that it does not target one specific aspect, but rather should be a general intelligence, able to solve whatever is necessary along the existence of the agent embedded with such cognitive capability. This also leads to the concept of “general learning ability”.

To wrap it up, the most important difference between cognitive and non-cognitive intelligent systems is the way their intelligence is developed (natural or artificial evolution) and how it effectively works supporting the agent in which it is embedded (assisting softly on every issue, and focusing hard on specific ones).

Gudwin: I would like to insist here on the issue of cognitive modeling. It is clear that a cognitive system is a kind of intelligent system. But in my point of view, what distinguishes a cognitive system from any other intelligent system is its origin in some sort of cognitive modeling. And cognitive modeling, as I have already pointed out, refers to modeling some mental ability. In other words, if an intelligent system is developed without the support of any cognitive model, then it should not be called cognitive. This is the case, when we use standard techniques from computational intelligence, like fuzzy systems, neural networks (in a more general sense), or genetic algorithms. I would not classify these as cognitive systems, unless a clear inspiration from a cognitive model is addressed. Two topics which are receiving an increased interest in the literature are the topics of “Cognitive Architectures” and “Artificial General Intelligence”. Both topics are somewhat intermixed. In both cases, the idea is to be able to construct computational architectures inspired on cognitive models (in the case of artificial general intelligence, with an extra goal of achieving human level intelligence). Both approaches use different kinds of methodologies. There are symbolic cognitive architectures like SOAR or ACT-R, neural cognitive architectures like Clarion, Leabra, and also other approaches like LIDA, OpenCog, Sigma, etc., using conceptual graphs, semantic networks, belief networks and other kinds of representational structures. There are cognitive architectures like SAL (Synthesis of ACT-R and Leabra), or maybe also Clarion, which try to hybridize symbolic and neural components in order to create a cognitive architecture which may model more closely the many facets of mental activity. There are specific conferences, nowadays, like the NeSy symposiums, running annually since 2005[1], which are trying to investigate how symbolic and neural approaches can be mixed together. So, to me the demarcation line between a cognitive and a non-cognitive system is quite clear: the existence of a cognitive model supporting the technological development. If there is a cognitive model to support it, it can be called cognitive. If there is not, then it should be non-cognitive.

2.3 How is “language” important while considering a cognitive system; is it a necessary feature, or a bonus?

Loula: Language is a remarkable feature of the human species. It is organized, generative and recursive. It is able to express and describe endless possibilities. Language qualitatively differentiates humans being from other animals. From a cognitive perspective, there are components underlying language that are uniquely human, while there are also other components, upon which language is based, that are shared by other animals, as Hauser, Chomsky & Fitch (2002) assert in their article “The faculty of language: what is it, who has it, and how did it evolve?”. Language acquisition and use rely on various other cognitive competences, specific or not, and empirical studies and theoretical descriptions have been trying to understand and

1 See: http://www.neural-symbolic.org/

explain this. So cognitive competences involved in the acquisition and use of language remains an open issue.

Language is certainly an important element to consider in research of (artificial) cognitive systems, as it remains a great challenge in the field. Current (computational) artificial systems do not handle natural language in the same way as natural systems do. Artificial systems are not able to understand what we say in the same way another person would do. In part, this difficulty exists because this natural phenomena is not satisfactorily understood, undermining an appropriate specification in a machine. However, multiple dimensions of language are not adequately considered by engineers of artificial systems, who tend to focus on the syntactical dimension. Natural language involves syntax, but also semantics and pragmatics, and it includes social, cognitive, biological and semiotic aspects.

Language is an important element but not a necessary one to be considered in further advances. There are a lot of cognitive competences, not dependent on language, that are still challenging researchers in cognitive systems. On the other hand, language can be seen as a complex communication system, and as such, a possible and scientifically adequate approach is to focus initially on simpler communication systems, before moving on to language.

Netto/Muñoz: Language seems to be a very important characteristic of a cognitive system, independently of the level it may be expressed. From simple signals communicating facts among animals, through those embedded with some level of structure and therefore with higher power to organize thoughts, to the most developed levels in human beings, in all cases language principles play an important role. But it should not be necessarily considered as a fundamental requirement for a cognitive system. In other words, we should consider that some natural systems (animals) do have some level of cognitive capacity, even though they don't express language abilities. In these cases the cognitive capacities are very poor or constrained, due to the lack of mechanisms that socially structure and develop cognitive concepts.

This means that the "truly" cognitive systems are those enhanced with some sort of language skills. And from this we infer that language is deeply interrelated with cognition, being one of the most important or distinctive features associated to cognition. We can also say that language builds the soft substrate upon which cognition arises (or at least the most sophisticated forms of cognition).

Language is important in two ways. First because it provides a support for reasoning, which is a fundamental aspect of cognitive systems; thus language constitutes a basis for cognitive operations. Secondly, because language helps with communication, allowing information and knowledge exchange between individuals, providing a common basis to establish references for understanding the world they live in.

Gudwin: I think that language is one of the highest cognitive abilities found in human beings. So, clearly, the abilities of understanding and producing language should be considered as important functionalities of cognitive systems. It is clearly what might become an advantage, from an external point of view (for those observing a cognitive system in action). Language may be seen as the mark of cognitive systems, together with perception (vision and speech recognition). From a functional point of view, perceptual and linguistic abilities are being explored by some software companies as the distinctive marks of cognitive systems. But even if one recognizes them as important, I don't think they are a necessary feature of a cognitive system, they are more like a bonus, together with other cognitive abilities, like learning, emotions, reasoning, memory and others. The whole issue of cognitive systems is to make artificial systems more close to our humanity, step by step, giving them abilities which on the past were exclusive to animals and human beings.

Addressing now specifically linguistic understanding, it is important to distinguish two different categories of research. The field of research of simulation of language evolution is bringing us many advances of which some people might not be fully aware. The problem of recognizing and understanding isolated words is being addressed for already some time, with many kinds of language games and many successful computational implementations. This problem can be considered already solved, from a technological perspective. But a much more complicated problem, the recognition of full sentences, conversations and dialogues, is only now being addressed in a more comprehensive way. Research is just starting regarding this. Even though some results have been reported, these results are still very preliminary. This is a topic which will be addressing attention from now on in cognitive systems, and due to that, the topic of language gains a high prominence in cognitive systems studies.

2.4 How do you see the frontiers of research regarding cognitive systems and cognitive architectures; what are the missing gaps; what are the most critical issues?

Loula: There are still a lot of open issues and possible directions for expanding research frontiers in cognitive systems. Concerning especially artificial cognitive systems, there are particular challenges in building systems that models cognitive processes, and a challenge of great interest are representations.

Representations are a topic of interest in Artificial Intelligence (AI) since its foundation and remains an important issue in current research. The initial conception that intelligent systems are capable of reasoning based on representations, following a formal logic approach to cognition, brought about an ontological question, concerning what such representations would be, an ontological issue, and an epistemological question, on how they could be produced and interpreted. The first problem was answered by determining the appropriate data structures, in a merely technical perspective, and determining how to collect and insert data that would represent the knowledge on which inferences would be applied and new knowledge would be obtained. This led to several criticisms, such as the Symbol Grounding Problem, that essentially challenged how something could actually represent something else for an intelligent system, and not only for the designer that provided the data to the system.

On the other hand, the so called Nouvelle AI proposed a new approach for intelligent systems, committed to situatedness and embodiment of cognition. In these new systems, embodied artificial agents are situated in an environment, establishing sense and act loops, and interacting with other agents. Agents would build their cognitive competences as a consequence of their history of sensory-motor cycles and interactions, based on learning, adaptation and evolution. Nevertheless, there was a refusal to deal with representations in this new approach, maybe considered as a minor or unnecessary trait.

Meanwhile, more recently, there has been a great variety of research on the emergence of communication and language among artificial agents, robotic and simulated ones. As a methodological principle, the cognitive or social process of interest is not previously present in a community of agents, but by means of interactive and adaptive processes it can emerge among the agents. But, even though communication and language are strongly related to representational processes, there has been little or no discussion on this issue in such research reports.

Based on the fact that communication can be seen as the production (by a speaker) and the interpretation (by an interpreter) of representations, it is fundamental to understand the characteristics and conditions for the emergence of diverse modalities of representational processes, associated with communication and their relation to other cognitive traits. As such, we have being developing experiments to study underlying representational process on the emergence of communication in a community of artificial agents as a particularly relevant framework. As an essential part of our approach to study representations in communicative cognitive agents, we have used theoretical principles from Charles Sanders Peirce's semiotics to define the model of representation processes, their variety and constraints on dynamics. We believe, and our results have shown, that this is a fruitful approach for synthesizing and analyzing representation processes in artificial cognitive systems, thus expanding the frontiers of cognitive systems.

Netto/Muñoz: The areas of cognitive systems and cognitive architectures should converge more and more, since they express perhaps just different approaches to handle the same subject. We consider cognitive systems as a more general concept (including natural and artificial ones), so it should be an object of a study aiming to provide a deeper understanding of its core features (what it means to be cognitive). On the other hand, cognitive architectures correspond to an engineering approach to support the conception of synthetic cognitive systems. They therefore refer to components and their systemic interrelation, which as a whole constitute a cognitive system.

One of the missing gaps is that there is still a strong human interference on the cognitive architecture design. Normally architectures are designed with some purpose, and even if on runtime we do not see human interference anymore, it is somehow embedded in the designed system. So, it is very hard to have a full blown cognitive architecture, if one expects to have a self-evolved system.

Another important gap refers to the distance between all these artificial systems and real cognitive ones (a distance that will continue for a long time). On the other hand, one sees a continuous improvement, and there is the possibility of starting to use artificial cognitive agents as truly assistants in some fields. Perhaps this should be the way to promote the evolution of studies, projects and products: finding specific niches where this assistive technology can really bring good results.

Gudwin: The field of cognitive systems is actually at the upfront of research in artificial intelligence. There are many open fronts of research, and many important topics which deserve a deeper exploration. Among them, a prominent one is *learning*. Great progress is being reported in the field of *deep learning* in convolutional neural networks, which are being used within cognitive architectures to represent new models of *perception*, applied in computer vision and speech recognition. The field of memory, and specifically *episodic memory*, is also receiving interesting contributions. Nowadays, episodic memory is one of the important missing cognitive abilities in artificial systems, and it is receiving a lot of attention. Episodic memory is also related to the field of *machine consciousness*, which is also at the center of the debate in specialized meetings on cognitive architectures. All of these are an important background for the studies on *grammatical language*, the ability to understand full sentences, as pointed out earlier. The topic of **social cognition** is also relevant in this sense, as many systems are dealing with the real-time dialogue between humans and systems, together with vision and the recognition of the intention to dialogue from the part of human subjects. Other topics as *meta-cognition* and *computer imagination* are also being addressed, together with the more traditional topics of *planning* and *reasoning*, now being considered together with perception and action in order to compose full cognitive architectures. Finally, the topic of *emotions* is also receiving great attention, either by recognizing and detecting human emotions from text and images, or by trying to synthesize feelings and emotions in artificial creatures, like synthetic characters in computer games and robots.

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