Embodied and Situated Cognition

Fernando Almeida e Costa[†] **and Luis Mateus Rocha**[‡]

[†]Centre for Computational Neuroscience and Robotics
Evolutionary and Adaptive Systems Group
Cogs/Informatics - School of Science and Technology
University of Sussex, Brighton, BN1 9QH, UK
e-mail: F.AlmeidaCosta@sussex.ac.uk
www: http://informatics.sussex.ac.uk/users/fern21

[‡]School of Informatics and Cognitive Science Program, Indiana University
901 East Tenth Street, Bloomington IN 47408
e-mail: rocha@indiana.edu
www: http://informatics.indiana.edu/rocha

Embodied and Situated Cognition

Fernando Almeida e Costa and Luis Mateus Rocha

Traditionally, Artificial Intelligence (AI) relied strongly on models of representation and direct perception of the world. It was mostly concerned with functional semantics. The control of its robotic artifacts, for instance, was solely based on the high-level symbol-manipulation of agent-independent semantic categories. In this approach, the environment was seen as an ensemble of things out there, independent and detached from the agent who is supposed to mirror them internally as representations .

Artificial Life changed all this. A paradigmatic example is the work of Brooks [2], whose subsumption architecture – later also known as *behavior language* – replaced the traditional high-level control of robots with a functional modularization scheme based on behavior generating modules. Instead of attempting to compute behavior at an abstract level of knowledge representation, this bottom-up approach relies on the self-organization of simpler components to produce a variety of emergent behaviors that depend on the (nonlinear) interaction of a robot with its environment.

The Artificial Life approach to AI entails a Situated/Embodied/Dynamic perspective on cognition. Instead of studying human cognition at the level of abstract concepts, it opted for the study of artificial systems inspired by simpler living organisms, not hitherto considered to be intelligent. Indeed, this approach blurred the conceptual distinction between Life and Cognition, between living and intelligent behavior. The key idea to produce intelligent behavior is that embodiment does not mean merely the control of material components, but a true dynamic coupling between intelligent agent and environment. The dynamically coherent coupling of the agent with its environment is the source of behavior, and not the agent's control system alone. The embodied cognition approach thus moved the modeling of intelligent systems from the study of intricate knowledge-based, representation-rich control systems, to the study of the dynamics of networks of agent and environment components (self-organization).

It can be argued that the components utilized to produce intelligent behavior from such a network are still too high level and do not allow the sort of plasticity that living systems observe. Indeed, it is not always obvious how to physically compartmentalize behavior modules: a bird's wing is both an airfoil and engine at the same time [13]. The sort of behavioral decomposition pursued by Brooks may not have offered yet the kind of entailment or network causality found in living organisms [12] which allows for genuine evolution of new behaviors [3], however, it did mark a very important shift in the practice of AI: the transition from representation-rich, centralized control to a self-organizing practice of autonomous agents. In this alternative view, cognition is no longer modeled as the creation of agent-independent representations of the world, but as the embodied, evolving, interaction of a self-organizing system with its environment. Whichever way embodied agents solve a problem, it is done via the construction of their own classifications – given the set of low-level components they have available – as they interact with their environment, and not by externally imposed representations.

In robotics, Brooks' behavioral decomposition using a design by hand approach was followed by research sharing the same principles of embodiment and situatedness, but taking the path of an automated evolutionary design [8, 5, 6] mostly based on evolutionary computation algorithms. Explicitly, this approach was meant to avoid any human designer bias. Modularity as an *a priori* design principle was abandoned. In this approach the role of human designer was weakened and substituted by an explicit goal of attaining more flexible, indeed unexpected sensory-motor and morphological structures – in the sense of both intrinsic [15] and extrinsic [7,10] morphologies – via evolutionary and developmental natural principles.

Central to this major switch in robotics was the emphasis on time and dynamics. For instance, the study of asynchronous or continuous-time networks became widespread. Indeed, the importance of time-dependent dynamics as an essential component of life and cognition has been a major issue addressed not only by the dynamical systems and embodied approach to Artificial Life and Robotics [1,4] but also in Cognitive Science [14, 11, 9].

All these components of a renewed, Artificial Life-inspired Cognitive Science may be brought under the general designation of *Embodied Situated Cognition* (ESC), which has now become an established approach to Cognitive Science. This interdisciplinary field has produced numerous advances in Psychology, Philosophy of Mind, Social Interaction, Artificial Intelligence, Artificial Life, Robotics, Human-Machine Interaction, Engineering, and Informatics. On November 12^{th} to 15^{th}, 2002, at the Fundação Calouste Gulbenkian in Lisbon, Portugal, we organized the *International Interdisciplinary Seminar on New Robotics, Evolution and Embodied Cognition* (IISREEC) to discuss the achievements, present state of the art, and the future of the ESC approach to Artificial Intelligence and Artificial Life. We invited a well established interdisciplinary group of researchers and organized this discussion around three inter-dependent themes: New Robotics, Complex Evolutionary Systems, and Embodied Cognition[1]. We were particularly interested in tackling four sensitive topics in Embodied Cognition:

1. While ESC draws much inspiration from Nature to engineer its robots and artificial agents – specifically from scientific fields such as Neuroscience, Evolutionary and Developmental Biology – it has produced very little work of consequence to the natural sciences. Are the natural characteristics of artificial, embodied agents simply superficial metaphors, or can they be made rich enough – or indeed simple enough – to model real biological systems?
2. When ESC shifted the focus of intelligent behavior from representation-rich to self-organizing agents, and indeed from abstract intelligent behavior to simpler, physical living behavior, some posited that concepts such as information, representation, and symbols were superfluous to understand cognition, and that the language of dynamical systems theory would be sufficient. Since this original contention has not been resolved, we encouraged participants to re-open the issue using the experience accumulated by practitioners in the field since its more theoretical inception. Can embodied artificial agents scale up to model the more symbolic and informational aspects of human cognition? Are information, representation, and semiotics necessary concepts to study Life and Cognition?

[1] Details of the workshop are available on its web site: http://informatics.indiana.edu/rocha/embrob

3. Given that the field is relatively recent, how does it stand regarding general principles or heuristics that its researchers share and rely upon? How far are we from a consistent corpus of such principles?
4. Are there novel paths and critical problems opening in ESC for the foreseeable future?

In order to facilitate the discussion of these four topics we included researchers working in Biology, Complex Systems, and Social Interaction, with the set of participants traditionally linked to ESC. Furthermore, by encouraging participants to discuss all the issues side by side, the productive conference that ensued, rather than overly abstract, was grounded in specific biological, social, and artificial systems. This is well demonstrated in the transcripts of the discussions which are available at http://informatics.indiana.edu/rocha/embrob.

In this volume, we present articles from most of the participants in the workshop. They offer us a robust view of the state of the art in ESC, and raise questions that will dictate its research agenda for the foreseeable future.

In "*The Development of Embodied Cognition: Six Lessons from Babies*", Linda Smith and Michael Gasser show empirical evidence from developmental psychology for the embodied cognition approach. They argue that embodied intelligence is not achieved simply by endowing intelligent agents with a body, or some physical implementation. Rather, embodied intelligence in humans develops as children grow in and interact with their environment via a sensory-rich body which is particularly fitted to recognize the statistical regularities of this interaction. Furthermore, the development process is very good at building on previous experience – particularly social experience. Finally, since symbols and language are an intricate part of the regularities in the social environment of human children, the embodied developmental process leads to intelligence unmatched in the known natural and artificial world. Thus, the work of Smith and Gasser, suggests that if artificial life and new robotics are to produce artificial systems capable of advancing our knowledge of natural cognition, it needs to focus more on the process of embodied development as a means to achieve a richer artificial intelligence. Furthermore, Smith and Gasser also propose that language and symbols, rather than being discarded from the embodied cognition framework, should be seen as an important component of the development process.

In "*Learning From and About Others: Towards Using Imitation to Bootstrap the Social Understanding of Others by Robots*", Cynthia Breazeal, Daphna Buchsbaum, Jesse Gray, David Gatenby, and Bruce Blumberg exemplify the type of robotics/artificial life research that follows the embodied cognition view of child development pursued by Smith and Gasser. With the goal of building socially intelligent robots, Breazeal et al explore interactive imitation as an important component of the development of intelligence in embodied agents. The objective of their research is first to build robots that can interact socially with humans, but secondly to test models of neonatal facial imitation in infants. Indeed, they present a computational model of facial imitation that is developmental rather than innate, which, being based on ontogenetic interaction, they argue, is better suited for a theory of mind. This way, Breazeal et al show how the ESC approach to robots is used to both advance robotics and test models of human nature and behavior.

In "*Brain-Based Devices for the Study of Nervous Systems and the Development of Intelligent Machines*", Jeffrey Krichmar and Gerald Edelman exemplify the utility of ESC robotics approaches for testing theories of brain function. With their demonstration of how an adaptive device can learn to categorize on the basis of sensory information, they illustrate how novel embodied robotics designs, more than using metaphors from Nature, can be used as a laboratory for research in Biology. Indeed, unlike animal models, brain-based, robotic devices permit analysis of activity at all levels of the nervous system as the device behaves in its environment.

In "*Evolutionary Robotics: A new scientific tool for studying cognition*" Inman Harvey, Ezequiel Di Paolo, Elio Tuci, Rachel Wood, and Matt Quinn, present and exemplify Evolutionary Robotics as a scientific tool for studying minimal models of cognition. Harvey et al present Evolutionary Robotics as a methodology for providing existence proofs, e.g. under the form of sufficient conditions for the natural phenomenon under study, challenging or refuting existing views and unwritten assumptions. The Evolutionary Robotics methodology is furthermore presented as a useful meta-methodological tool for the Natural Sciences. This minimal model approach is explicitly contrasted with the approach taken by computational neurosciences.

In "*New Robotics: Design Principles for Intelligent Systems*", Rolf Pfeifer, Fumiya Iida, and Josh Bongard, present a first step towards the definition of a coherent set of heuristics or design principles for ESC, explicitly addressed to an interdisciplinary audience. They focus in the principles of "ecological balance" and "sensory-motor coordination". Although Pfeifer et al do not elaborate on dynamical systems, they also approach the representation debate indirectly since their definition of New Robotics entails a trade-off between morphologies and control. Because they prefer to emphasize the non-trivial role played by agent morphologies, materials and environment in the cognitive process, the need for control or of a representational level in the system is purposively minimized.

In "*From Wheels to Wings with Evolutionary Spiking Circuits*", Dario Floreano, Jean-Christophe Zufferey, and Jean-Daniel Nicoud, present an overview of their indoor flying project. The project envisages the evolutionary development of a vision-based micro-robot whose controller is composed of adaptive spiking neurons. Floreano et al point out that robotics research in ESC has been dominated by far by terrestrial robots, focusing much more on theoretical and algorithmic issues rather than on energetic autonomy. Bio-inspired flying robotics, draws our attention to the complexity and variety of morphological, bio-mechanical, sensory and neural structures, found by evolution to cope with the requirements for flight – thus opening a novel research area. From a sensory-motor point of view, navigating in the air is a very complex, dynamical task, demanding efficient and adaptive neural circuits. Spiking neural networks were chosen to capture these complexities. The evolutionary approach to design pursued by the authors is chosen to reduce human design choices, a principle also defended by Harvey et al in their article. Affinities of principle – regarding the emphasis on the balance between morphologies and control – are also shared with the article by Pfeifer et al.

In "*Flexible Couplings: Diffusing neuromodulators and adaptive robotics*", Andy Philippides, Phil Husbands, Tom Smith, and Michael O'Shea present two new variants of the GasNet model, which are shown to improve evolvability. This occurs, the authors claim, as a result of the flexible loose coupling of yet distinct – chemical, electrical – processes. The paper draws on evidence from neurosciences and is described as a first step in the study of the coupling issue. It may also be a step in the direction of a deeper, two-way interchange between robotics and neuroscience.

In “*Agency in natural and artificial systems*”, Alvaro Moreno and Arantza Etxeberria elaborate on whether it is possible to artificially build an organization similar to the natural. They base their treatment of the differences between natural and artificial systems on the notion of agency, the conditions for which they analyze. They observe that the deep interrelation between forms of organization and materiality in natural systems does not occur in robots, given the latter’s different embodiment. Thus, they conclude, the particular embodiments of artificial systems impose qualitative differences in the resulting morphologies, from what is achieved by natural systems. This conclusion highlights the difficulty of using artificial systems to study natural phenomena.

In “*Transient phenomena in learning and evolution: genetic assimilation and genetic redistribution*”, Janet Wiles, James Watson, Bradley Tonkes, and Terrence Deacon use evolutionary computation to explore the process by which functional dependence of genes can be transferred from one initial set to many sets, as changes in the environment mask and unmask selective pressures (genetic redistribution). Their simulations build on models of genetic assimilation, such as the Baldwin effect, by which phenotypic-level behavior, such as learning, influences genetic specification. Wiles et al further discuss the relevance of genetic assimilation and genetic redistribution to the evolution of language and other cognitive adaptations.

In “*Material Representations: From the Genetic Code to the Evolution of Cellular Automata*”, Luis Mateus Rocha and Wim Hordijk” present a definition of the concept of representation that relies on a study of the origin of structures that can be used to store memory in evolving systems. This study is based on what is known about genetic memory in Biology, and from novel computer experiments in the evolution of Cellular Automata to solve nontrivial tasks in complex systems theory. Their goal is to show how knowledge of real Biology and Artificial Life experiments can be used to shed new light on the representation debate in ESC, and indeed function as a constructive bridge between the dynamicist and representationalist camps.

In "*Friends Reunited? Evolutionary Robotics and Representational Explanation*", Michael Wheeler draws on a major assumption: that the contentious debates of the early and mid nineties, between representational and non -representational explanations have faded away. At the time, New Robotics took a firm stand for the non-representational camp, but according to the author, a rapprochement between the two camps is now under way. Wheeler digs out two challenges – which he dubs "non-trivial causal spread" and "continuous reciprocal causation" – posed by New Robotics to representationalism. He argues that a transformation of the notion of representation took place in Artificial Life inspired robotics, which "is not at odds with the situated approach to real-time intelligent action" and then discusses whether the two challenges can be faced from that perspective. The evolutionary robotics part of the discussion mostly draws evidence from the evolution of GasNets and evolvable hardware. A conclusion is presented that while a system involving non-trivial causal spread can still be representational in character, the evolution of systems like GasNets and evolvable hardware often display high degrees of continuous reciprocal causation resistant to representational analysis.

In "*Beyond the flesh: some lessons from a Mole Cricket*", Andy Clark deals with the treatment of symbols in Embodied Cognition. In particular, on how should a dynamical systems approach to cognition conceptualize their role. Clark presents symbols as another powerful technological prop in extended cognitive loops that involve embodied agents and different types of technological and cultural scaffolds. Such internal and external props, via cascades of encodings, allow us to map complicated problems into simpler surrogate situations. Thus he proposes that we study the mind as an embodied system that reaches far beyond the flesh.

Acknowledgments.

The IISREEC seminar in Lisbon had its origin in an invitation addressed to us by Professor Fernando Gil who was organizing a series of scientific meetings on the state-of-the-art of various disciplines. We are profoundly indebted to him for his prescience of the present and future importance of the matters covered by the meeting.

We also wish to thank Marta Lança. (secretariat), all the participants, chairpersons and invited discussants at the meeting, and all the external reviewers for this special issue, who provided most valuable feedback in our edition process. We are also very grateful to the Journal *Artificial Life* and particularly its editor Mark Bedau for accepting our proposal for this special issue, and for providing guidance and support throughout the edition process.

Last but not least, we are very grateful for the support granted by the *GlaxoSmithKline* and *Calouste Gulbenkian* Foundations for the organization of the workshop, and, above all, the great support of the *Fundação para a Ciência e Tecnologia* and its President, Fernando Ramôa Ribeiro. Due to fortuitous circumstances Prof. Ramôa Ribeiro was not able to present his closing communication to the seminar, as scheduled. Thus, we include an appendix after this introductory article with the transcription of that communication to the seminar.

Finally, with affection and respect, we would like to dedicate this issue to Esther Thelen who is one of the most influential progenitors of ESC.

Fernando Almeida e Costa
Luis Mateus Rocha

References

[1] Beer, R. D. (1995). "A dynamical systems perspective on agent-environment interaction." In *Artificial Intelligence*, 72, 173-215.

[2] Brooks, R.A. (1991). "Intelligence without reason." In: *Proceedings of the 12th International Conference on Artificial Intelligence*, San Mateo 2992. . Morgan Kaufmann.

[3] Cariani, P. (1992). "Emergence and Artificial Life." In: *Artificial Life II*. C. Langton et al. (eds.). SFI Series in the SciencesComplexity. Addison-Wesley, pp. 775-797.

[4] Cariani, P. (1995), "As if time really mattered: temporal strategies for neural coding of sensory information" *Communication and Cognition - Artificial Intelligence* (CC-AI) **12**(1-2), 161-229. Reprinted in: K Pribram, ed. *Origins: Brain and Self-Organization*, Hillsdale, NJ: Lawrence Erlbaum, 1994; 208-252.

[5] Cliff D., Harvey I. and Husbands P. (1993). “Explorations in evolutionary robotics”. *Adaptive Behavior,* 2:73-110

[6] Floreano D. and Mondada F. (1994). “Automatic creation of an autonomous agent: genetic evolution of a neural-network driven robot”. In D. Cliff, P. Husbands, J. Meyer and S.W. Wilson (Eds.), *From Animals to Animats 3*: *Proceedings of the Third Conference on Simulation of Adaptive Behavior*. Cambridge, MA: MIT Press/Bradford Books

[7] Funes P. and Pollack J. (1998). “Evolutionary Body Building: Adaptive physical designs for robots”. *Artificial Life* 4: 337-357

[8] Husbands P. and Harvey I. (1992). “Evolution versus Design: Controlling Autonomous Robots In Integrating Perception, Planning and Action”: *Proceedings of 3rd Annual Conference on Artificial Intelligence, Simulation and Planning*, IEEE Press, 139-146.

[9] Pattee, H. H. 1995, “Evolving self-reference: matter, symbols, and semantic closure”. *Communication and Cognition – Artificial Intelligence* (CC-AI) **12**(1-2), 9-27.

[10] Pfeifer, R. (2000). “On the role of morphology and materials in adaptive behavior”. *From animals to Animats. Proceedings of the 6th Int. Conference on the Simulation of Adaptive Behavior*. Cambridge, Mass.: MIT Press

[11] Port, R. and Gelder, T. (1995) *Mind as Motion*. Cambridge, Mass.: MIT Press

[12] Prem, E. (1995). “Grounding and the entailment structure in robots and Artificial Life.” In: *Advances in Artificial Life*. F.Moran, A. Moreno, J.J. Merelo, and P. Chacon (eds.). Springer-Verlag, pp. 39-52.

[13] Rosen, R. (1993). “Bionics revisited.” In: *The Machine as a Metaphor and Tool*. H. Haken, A. Karlqvist, and U. Svedin (eds.). Springer-Verlag, pp. 87-100.

[14] Thelen, E. e Smith, L. (1998) *A Dynamic Systems Approach to the Development of Cognition and Action.* The MIT Press, Cambridge, Massachusetts.

[15] Thompson, A. (1997). “Artificial Evolution in the Physical World”. In Gomi, Takashi (ed.) (1997) *Evolutionary Robotics: from intelligent robots to artificial life (ER’97)*, AAI Books

Appendix to the Introduction

Communication from the President of the Fundação para a Ciência e Tecnologia (Portuguese Foundation for Science and Technology)

As President of the Foundation for Science and Technology I am particularly pleased with the organisation in Lisbon of the Seminar on Robotics and would like to thank the organizers for this opportunity to greet its participants, particularly the speakers that have contributed most to its success.

My particular scientific area is chemical engineering and is therefore far from the themes that brought you here. Therefore you cannot expect this address to be one scientific communication to fit the seminar. But I look at your subject as an interested outsider and it is not difficult for me to understand the importance of the presentations and discussions that you held.

Robotics has been for several years an area which, in Portugal, has been funded rather above the average. Recently, this research has particularly benefited from the POSI, which is a structural financing program especially dedicated to the information society and managed by the Foundation for Science and Technology. And, in agreement with the expert international evaluation that the research centres go through every three years, I dare say that some groups in the area have reached an excellent level, which is otherwise shown by their publications and achievements.

We have seen that robots become more and more sophisticated and even play football, which is certainly a rather unexpected goal for the development of science... FCT will even be supporting the Robo Cup 2004, which is something like a football world–cup for robots. However, these players still don’t shout or swear at each other, and don’t kick each other knees. And it is in this context that your seminar becomes important in terms of studying and discussing the new robotics, in which there is a continuing convergence between robotics and the life sciences.

It is interesting to go through the titles of some of the presentations. They mention “sociable robots”, “artificial intelligence”, “machine psychology”, “embodiment”, “evolution”, etc. They all show this final aim of robotics which is to be able to build life or something similar to life. However you have also realized the difficulty of this task and the importance of your efforts. It is therefore an amazing trend and I am sure that your field of science and technologies will in the next few years continue to deliver extraordinary results.

Biologists and doctors will be among the first to find the importance of your developments and certainly among the first to use your achievements.

We, at the Foundation of Science and Technology, will continue to watch and support the scientific advances in the area, and I wish that this shall be a contribution to ensure that the Portuguese scientists will be able to maintain their status in the context of the international community.

Fernando Ramôa Ribeiro