Internship project, master level, 2023

Title: Emergence, control and open-ended evolution in cellular automata

Supervision: Bert Chan, Gautier Hamon and Mayalen Etcheverry, in collaboration with Eleni Nisioti, Clément Moulin-Frier and Pierre-Yves Oudeyer

Team: Flowers team, Inria Bordeaux (location of the internship) and Google Brain Tokyo

Level: Master 2 internship

Duration: 6 months, around February July 2023 (with flexibility).

Keywords: emergence in complex systems, sensorimotor control, open-ended evolution, origins of life, cellular automata, machine learning (deep neural networks, optimization algorithms), automatic discovery, scientific programming with Python.

How to apply: contact mayalen.etcheverry@inria.fr bert.chan@inria.fr gautier.hamon@inria.fr pierre-yves.oudeyer@inria.fr and clement.moulin-frier@inria.fr with a CV and letter of motivation, and adding the tag [application] in the object of emails.

Context

Many systems that we encounter in Nature are self-organized and dynamic, and their study often reveals the emergence of highly-structured morphologies capable of complex behaviors evolved for survival in their environment. In the artificial world, cellular automata (CAs) are among the examples of widely-studied self-organizing systems. For instance, the artificial life (ALife) community has studied the emergence of spatially localized patterns (SLPs) in CAs, giving hints to the theories of the origins of life [1]. SLPs have a local extension and can exist independently of other patterns, resembling artificial "creatures" that can survive for an extended period of time and interact with their environment. In parallel, in the embodied AI community, we generally assume an agent with a given body (morphology) and a given set of possible actions (sensorimotor capabilities), and aim to study the mechanisms of learning to control the agent behaviors (i.e. the agent's "brain").

In this project, we ask the following questions: how to reunite those two perspectives and jointly study the emergence of body morphologies and behavioral sensorimotor capabilities? Can we bootstrap processes of open-ended evolution in such complex systems?

Project

In this project, we will consider Lenia [2,3] as an environment of study. Lenia is a system of continuous cellular automata which can generate a wide range of complex patterns and dynamics, where some of the emerging structures seem to look and behave like real-world microscopic organisms. It was developed by Bert Chan who will co-supervise this internship.

While the notions of agents, environment, and possible agent-environment interactions are typically predefined in reinforcement learning and robotic settings; in self-organizing systems such as Lenia the notion of agent and actions (sensorimotor capabilities) is more difficult to interpret. Yet, when looking at the emergent creatures (see example video here and here), they already seem to have some sort of proto-sensorimotor control in their emergent behaviors.

Moreover, our research team has recently proposed a new method for discovering creatures displaying sensorimotor capabilities in cellular automata [9]. For this aim, we have introduced environmental elements in Lenia to search for self-organizing creatures capable of reacting to the perturbations induced by the environment. The method is based on curriculum learning, Intrinsically Motivated Goal Exploration Processes (IMGEP) and on gradient descent. Using a newly-introduced differentiable version of Lenia, the method is able to discover the rules leading to the emergence of robust creatures with sensorimotor capabilities. The creatures obtained, using only local update rules, are able to regenerate and preserve their integrity and structure while dealing with the obstacles or other creatures in their way. They also show great generalization to unseen environments.

The objective of the internship is to extend the range of morphological, behavioral and functional complexity in the Lenia environment (starting from our recent works in [9 and [14]), and to further explore the emergence of functional morphologies and behaviors. Several directions of research can be explored during the internship:

- **Studying emergent open-ended evolution in Lenia.** An important challenge in Artificial Life and Artificial Intelligence is to design systems displaying *open-ended intrinsic evolution* (i.e unbounded growth of complexity through intrinsic evolutionary processes) [12]. Such a process is called *intrinsic* since no final objective (i.e fixed fitness function) is set by the experimenter, as in natural evolution where there is no final goal [13]. We have recently made preliminary steps in this direction by designing a CA where multiple creatures, each with their own evolvable learning rules, can co-exist and interact in a shared environment. Our first results are very promising (see last video in [14]) and we now want to scale them to larger simulations on GPU clusters to study open-ended dynamics in these systems.

- **Introducing mechanisms of resource consumptions by the creatures.** This will provide a more functional notion of reward for the optimization of the creatures where, instead of explicitly optimizing for moving creatures as in [9], moving behavior would emerge as a solution to collect limited resource in the environment (see [11] for an evolutionary perspective). In a second step, competition for limited resources can possibly bootstrap the emergence of species co-adaptation towards increasingly skilled creatures (a phenomenon known as “autocurricula” in the machine learning literature [10]). We have recently introduced mechanisms for mass-conservation in Lenia [14], which we think is a key step in achieving the above.
- **Exploring mechanisms of reproduction among creatures.** In recent experiments, we have observed such phenomena (a third creature being formed from the collusion of two others, resulting in three surviving creatures -- see [9]). Although we didn't optimize for reproduction in this prior work, the same method based on curriculum-driven IMGEP with gradient descent could be used to explicitly optimize for robust reproduction with variation, which potentially opens the road toward open-ended evolution in Lenia (in particular if coupled with the previous point).
- **Studying conditions for the emergence of learning and memory mechanisms in sensorimotor creatures.** This comes as a natural extension of our recent work on emergent sensorimotor behavior in [9]. We could extend the environment such that obtaining maximal reward requires creatures to encode and maintain information for some amount of time (see [11] for an evolutionary perspective). Here again, we can use the same tools (curriculum-driven IMGEP with gradient descent) to study how learning and memory can emerge from the self-organising dynamics of the creatures.

Requirements: We are looking for motivated MSc students (Master II). Programming skills and prior experience with Python and deep learning frameworks (Pytorch, Tensorflow) are expected.

References

[1] Randall D Beer. Autopoiesis and cognition in the game of life. Artificial Life (2004).

[2] Bert Wang-Chak Chan. Lenia-biology of artificial life . Complex Systems (2019).

[3] Bert Wang-Chak Chan. Lenia and expanded universe . Artificial Life (2020). https://www.mitpressjournals.org/doi/abs/10.1162/isal_a_00297

[4] William Gilpin. Cellular automata as convolutional neural networks . Physical review (2018).

[5] Alexander Mordvintsev, Ettore Randazzo, Eyvind Niklasson, and Michael Levin. Growing neural cellular automata . Distill (2020). https://distill.pub/2020/growing-ca .

[6] Deepak Pathak, Christopher Lu, Trevor Darrell, Phillip Isola, and Alexei A Efros. Learning to control self-assembling morphologies: a study of generalization via modularity . NeurIPS (2019).

[7] Chris Reinke, Mayalen Etcheverry and Pierre-Yves Oudeyer. Intrinsically Motivated Discovery of Diverse Patterns in Self-Organizing Systems. ICLR (2020). Blogpost: https://developmentalsystems.org/intrinsically_motivated_discovery_of_diverse_patterns

[8] Mayalen Etcheverry, Clément Moulin-Frier and Pierre-Yves Oudeyer. Hierarchically Organized Latent Modules for Exploratory Search in Morphogenetic Systems . NeurIPS (2020).

[9] Gautier Hamon, Mayalen Etcheverry, Bert Chan, Clément Moulin-Frier, Pierre-Yves Oudeyer (2021). Learning Sensorimotor Agency in Cellular Automata. Blog post available at https://developmentalsystems.org/sensorimotor-lenia/

[10] Leibo, J. Z., Hughes, E., Lanctot, M., & Graepel, T. (2019). Autocurricula and the emergence of innovation from social interaction: A manifesto for multi-agent intelligence research. ArXiv Preprint ArXiv:1903.00742.

[11] Cisek, P. Resynthesizing behavior through phylogenetic refinement. Atten Percept Psychophys 81, 2265–2287 (2019). https://doi.org/10.3758/s13414-019-01760-1

[12] Stanley, K.O.: Why Open-Endedness Matters. Artificial Life 25(3), 232–235 (2019). https://doi.org/10.1162/artl_a_00294

[13] Lehman, J., Stanley, K.O.: Novelty Search and the Problem with Objectives. In: Riolo, R., Vladislavleva, E., Moore, J.H. (eds.) Genetic Programming Theory and Practice IX, pp. 37–56. Genetic and Evolutionary Computation, Springer, New York, NY (2011). https://doi.org/10.1007/978-1-4614-1770-5_3

[14] Flow-Lenia: https://sites.google.com/view/flowlenia/ (a paper will be available soon)