Internship project, master level, 2021

Title: Emergence and control of sensorimotor capabilities in cellular automata

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

Team: Flowers team, Inria Bordeaux

Duration: 6 months, around February - July 2021.

Keywords: emergence in complex systems, sensorimotor control, cellular automaton, machine learning (deep neural networks, optimization algorithms), automatic discovery, scientific programming with Python.

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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 question: how to reunite those two perspectives and jointly study the emergence of body morphologies and behavioral sensorimotor capabilities?

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 *agent*, *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.

The main objective of this internship is to formalize the notion of agent and emergent sensorimotor capabilities in self-organizing systems such as Lenia cellular automata. Several directions of research can be explored during the internship:

- CAs can be expressed as convolutional neural networks (CNN) [4] and the differentiability of CNN can be leveraged for optimizing the CA rules and converging

toward key behaviors such as generation of the patterns [5]. Yet, this approach requires the prior characterization of an objective loss/reward. A possible direction for the internship is to propose several formalizations of such reward, not only pattern-matching loss as in [5] but also considering the notion of functionality and interaction with the environment as in [6].

- For this, it will be useful to introduce the notion of "environment" in Lenia (eg: drawing walls or adding resources of food) and then to characterize the interactions of the emergent creatures with the environment (eg: does the creature's trajectory learns to avoid the walls or to converge toward food locations).
- Ultimately, we would like to combine this project with recent work in the team investigating the usage of intrinsically motivated goal exploration algorithms (IMGEPs) for the exploration of self-organizing systems [7,8]. We believe that combining sensorimotor control and intrinsically-motivated discovery is a very promising direction for the automated discovery of interesting behaviors in artificial complex systems.

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).