Intership proposal:
Generative models of chemotaxis and phototaxis

Grégoire Sergeant-Perthuis*, David Colliaux† and Elias Tsigaridas‡

Microorganisms have the ability to move towards locations of high concentrations in nutrients for bacteria such as E. coli and high illumination for microalgae such as Chlamydomonas. These behaviors, chemotaxis, and phototaxis, rely on fine biochemical dynamics and may be considered as simple models of purposeful behavior. Modeling those is thus crucial for unveiling minimal agency and can be useful for the design of microscopic robotic systems. The biochemical cascades implementing taxis may be modeled in detail, as was done for chemotaxis in [8], or we can rely on a phenomenological model of the associated behavior, see for example [5] for phototaxis. Each involves distinct modeling paradigms, such as chemical Bayesian machines on one side [1] and *Active Inference* descriptions on the other [9, 10].

In particular, D. Colliaux introduced in [1] a Bayesian interpretation of the molecular cascades that underlie chemotaxis and phototaxis. It shows that any Bayesian inference on discrete variables can be implemented through a generic biochemical cascade and that any generic biochemical cascade can be interpreted as Bayesian inference. A simple cascade was designed to implement phototaxis. On the other hand, Active Inference also known as the *Free Energy Principle* [3] proposes an algorithm for modeling agents with 'adaptive behaviors' which is widely used in applications and celebrated for it [2]. In this setting, agents are presumed to possess an internal model of their environment, which they use to maintain beliefs that evolve over time based on observations providing insight into the state of their environment; such assumption is sometimes coined the *Bayesian Brain Hypothesis*. Active Inference is not the only framework that allows for modeling 'adaptive behaviors'. For instance, stochastic optimal control models agents with either complete (*Markov Decision Process*) or incomplete (*Partially Observable Markov Decision Process*) information about their environment, with the objective of maximizing cumulative rewards over time. Similarly, reinforcement learning pursues this objective, particularly when the reward function itself is stochastic. It could be argued that Active Inference represents a Bayesian approach to stochastic optimal control [4]. A. Tschantz et al. [9] proposed a generative model of active inference for chemotaxis. Theoretical predictions on the behavior of agents governed by active inference remain

*LCQB, Sorbonne Université
†Sony CSL
‡Ouragan, Inria Paris

an open problem; it is a problem on which G. Sergeant-Perthuis worked in the context of exploratory behaviors [6, 7, 10].

The internship will encompass both computational and theoretical aspects. On the computational side, the objective is to identify metrics that enable the comparison of each model's capacity to generate adaptive behaviors. Through these comparisons, we aim to extract key modeling components that can be applied to address the more complex and less understood nature of accurate generative models of phototaxis. On the theoretical side, this project will serve as a platform to develop tools to assess the adequacy of each model in simulating adaptive behaviors *a priori*, and to explore the boundaries within which these models can accurately replicate complex behaviors.

The internship will be jointly supervised by Grégoire Sergeant-Perthuis and Elias Tsigaridas at Sorbonne Université, and by David Colliaux at Sony CSL. Both laboratories are located in the 5th arrondissement of Paris. The duration of the internship is 6 months, and the remuneration will be in line with the standard rates for internships.

References

[1] David Colliaux, Pierre Bessière, and Jacques Droulez. Cell signaling as a probabilistic computer. *International Journal of Approximate Reasoning*, 83:385–399, 2017.

[2] Lancelot Da Costa, Thomas Parr, Noor Sajid, Sebastijan Veselic, Victorita Neacsu, and Karl Friston. Active inference on discrete state-spaces: A synthesis. *Journal of Mathematical Psychology*, 99:102447, 2020.

[3] Karl J. Friston. The free-energy principle: a unified brain theory? *Nature Reviews Neuroscience*, 11:127–138, 2010.

[4] Karl John Friston, Spyridon Samothrakis, and Read Montague. Active inference and agency: optimal control without cost functions. *Biological Cybernetics*, 106:523 – 541, 2012.

[5] Andrea Giometto, Florian Altermatt, Amos Maritan, Roman Stocker, and Andrea Rinaldo. Generalized receptor law governs phototaxis in the phytoplankton euglena gracilis. *Proceedings of the National Academy of Sciences*, 112(22):7045–7050, 2015.

[6] D. Rudrauf, G. Sergeant-Perthuis, O. Belli, Y. Tisserand, and G. Di Marzo Serugendo. Modeling the subjective perspective of consciousness and its role in the control of behaviours. *Journal of Theoretical Biology*, 534:110957, 2022.

[7] Grégoire Sergeant-Perthuis, Nils Ruet, David Rudrauf, Dimitri Ognibene, and Yvain Tisserand. Influence of the geometry of the feature space on curiosity based exploration. In *NeurIPS 2023 workshop: Information-Theoretic Principles in Cognitive Systems*, 2023.

[8] Antai Tao, Rongjing Zhang, and Junhua Yuan. Direct mapping from intracellular chemotaxis signaling to single-cell swimming behavior. *Biophysical Journal*, 119(12):2461–2468, 2020.

[9] Alexander Tschantz, Anil K Seth, and Christopher L Buckley. Learning action-oriented models through active inference. *PLoS computational biology*, 16(4):e1007805, 2020.

[10] Jules Tsukahara and Gregoire Sergeant-Perthuis. A short presentation of active inference. March 2024. Unpublished, link to draft.