PhD Dissertation Defense

Title: Elucidating and leveraging dynamics-function relationships in neural circuits through modeling and optimal control

Abstract:

A fundamental research question in neuroscience pertains to understanding how neural networks through their activity encode and decode information. In this research, we build on methods from theoretical domains such as control theory, dynamical systems analysis and reinforcement learning to investigate such questions. Our objective is two-fold: first, to use methods from engineering to identify specific objectives that neural circuits might be optimizing through their spatiotemporal activity patterns, and second, to draw motivation from neuroscience to formulate new engineering principles such as synthesis of dynamical networks for decentralized control applications. We specifically take a top-down, optimization driven approach in our study - we begin from control-theoretic cost functions and derive network architecture and dynamics by solving a proposed optimization problem. In the first part of the thesis, we examine the neural dynamics facilitating sensory encoding in the olfactory/ chemo-sensory circuit through the lens of a *normative* paradigm. We hypothesize specific optimization objectives that enable accurate detection of a sensory stimulus. Further, this scheme provides insight about sensory adaptation when the system encounters the same stimulus several times in a row. This framework yields neural response patterns that bear remarkable similarity with those observed *in vivo* in early olfactory circuits at both single neuron and population level. We next proceed to synthesize biologically plausible excitatory-inhibitory networks that can realize the derived optimal response patterns. We illustrate the generality of our paradigm by positing several testable predictions and validating them using experimental data from two model organisms - *Caenorhabditis elegans* and *Schistocerca americana*. In the second part of the thesis, motivated by our theoretical and experimental observations of brain circuitry, we focus on deriving dynamical networks that synthesizes control signals in a distributed manner. We address a broader class of optimal control problems in this phase, such as where explicit knowledge about environmental dynamics is unavailable and where the network interacts with the environment through nonlinear dynamics. We hypothesize how the algorithms used in finding a solution to these engineering problems might be constructed through episodic adaptation of network dynamics or through interactions between heterogeneous neural populations. We further contribute to providing theoretical characterization of the algorithms proposed and investigating properties imbibed by these network-based approaches. In the dissertation, we will discuss the technical details involved in deriving these solutions, their interpretations in the context of systems theory and systems neuroscience, and motivate open questions and future directions.