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Information-Preserving Transforms: Two Graph Metrics for Simulated Spiking Neural Networks

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Abstract

We are interested in self-organization and adaptation in intelligent systems that are robustly coupled with the real world. Such systems have a variety of sensory inputs that provide access to the richness, complexity, and noise of real-world signals. Specifically, the systems we design and implement are *ab initio* simulated spiking neural networks (SSNNs) with cellular resolution and complex network topologies that evolve according to spike-timing dependent plasticity (STDP). We desire to understand how external signals (like speech, vision, etc.) are encoded in the *dynamics* of such SSNNs. In particular, we are interested in identifying and confirming the extent to which various population-level measurements (or transforms) are information-preserving. Such transforms could be used as an unambiguous way of identifying the nature of the input signals, when given only access to the SSNN dynamics. Our primary objective in this paper is to empirically examine the extent to which a couple of graph metrics provide an information-preserving transform between the input signals and the output signals. In particular, we focus on the standard deviation of the time-varying distributions for local *influence* (weighted out-degree) and local *impressionability* (weighted in-degree), which provide insight into information encoding at the population-level in the dynamics of SSNNs. We report the encouraging results of an experiment carried out in the Language Acquisition and Robotics Group.

Keywords: Ab Initio Cellular Models; Complex Networks; Graph Metrics; Information-Preserving; Multi-Scale Modeling; Neurorobotics; Nonlinear Dynamics; Real-World Coupling; Simulated Spiking Neural Networks; Spike-timing Dependent Plasticity; STDP Learning; Topological Adaptation

1. Introduction

In the Language Acquisition and Robotics Group housed within the Beckman Institute for Advanced Science and Technology, we are designing computational models that enable a humanoid robot (see Fig.1) to learn natural language as a child does-- by interacting with people and the real-world. We embrace the perspective that such learning is based on the existence of a robust multi-sensory associative memory that serves as the cognitive architecture for an embodied agent with access to rich, real-world sensory streams [1]. Traditionally, we developed abstract statistical models of associative memory [2,3,18]. Though they exhibited encouraging results, they certainly

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did not attain the qualitative or quantitative success of the current best natural example we have: the neocortex. Thus, given the state-of-the-art in large-scale simulation tools and experimental neuroscience, we thought it was the right time to begin investigating, from the beginning, an answer to the question ``How is the neocortex so successful at information-processing, especially considering that neuron-neuron communication is phenomenally unreliable?"

In the past, numerous people have considered this question in various forms (like Von Neumann in his work on synthesizing reliable systems from unreliable components [4]), as well as contemporary computational neuroscientists. However, we are specifically interested in identifying *information-bearing* signals (as opposed to *regulatory* signals) in the statistical sense at the population-level [5,6]. We assert that such a signal could be used to ``characterize" a given population, allow the creation of a reduced-order model with respect to information, and serve as the basis for an associative memory. In this paper we examine two candidate information-bearing signals, which could be used for constructing such a reduced-order model.

Section 2 discusses the details of our SSNN design, providing context and motivation for our decisions, as well as particularly outlining the equations and parameter values used to achieve the desired behavior; Section 3 describes the experiment; Section 4 provides the results of the experiment, while Section 5 outlines future work in the short-term and long-term.

Fig. 1 Bert, the iCub humanoid robot: a state-of-the-art platform for research in embodied cognition [7].

2. Simulated Spiking Neural Network Design

Of all the natural and man-made systems that exhibit any level of associativity, the human neocortex is currently the most successful. Thus, examining the way the neocortex accomplishes such a task could provide deep insight into how we, as engineers, could create machines and models with similar capabilities. The neocortex is extremely complex and has structures that carry out various processing functions across a range of spatial and temporal scales. Of course, there is interaction and interdependence between and among the phenomena that occur at these different scales. Therefore, it raises the question-- on which scale should one focus?

Research completed in the past two decades has shown that a spiking neural network (SNN) has an extremely wide range of computational abilities. In particular, it has been displayed that to the extent that a given population carries out a specialized function it is just a reflection of the particular types of signals that have been fed to the population [8]. In other words, a population can be viewed as a *general-purpose* computational-unit that can be adapted to carry out a variety of functions, presumably including multi-sensory integration and associativity. Thus, it is reasonable to think that constructing a realistic, canonical, unspecialized SSNN is a wise first step. To create such a SSNN, one needs to identify a variety of important features that should be included. For our purposes in this paper, we have