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A General Purpose Architecture for Building Spiking Neuron Models of Biological Cognition

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Tutorial Objectives

We have recently created the world's largest biologically realistic brain model that is capable of performing tasks (Eliasmith et al., 2012). This model uses 2.5 million spiking neurons, takes visual input from a 28x28 pixel visual field, and controls a physically modelled arm. By presenting different visual inputs, the model can perform eight different tasks, including memorizing and writing a list of numbers, single-digit addition via counting, and flexible pattern completion in the Raven's Matrices task. This tutorial is meant to introduce the software toolkit and theoretical background that would allow other researchers to build their own models using the same architecture, allowing them to explore other tasks and brain functions. This tool supports a novel cognitive architecture (SPA; the Semantic Pointer Architecture) that directly connects neuroscience with cognitive science.

Our previous tutorials have focused on the underlying theory of the Neural Engineering Framework (NEF; Eliasmith and Anderson, 2003), a general method for implementing high-level cognitive theories using biologically realistic spiking neurons. In this tutorial, our emphasis will be on building large-scale models with our open-source toolkit Nengo (<<http://nengo.ca>>). The tutorial will be the first presentation of our Semantic Pointer Architecture, a Python module for Nengo which takes a high-level description of the desired cognitive system, including (basic) visual processing, motor control, working memory, associative memory, and cognitive control. The software takes this specification and creates a biologically realistic neural model, including various cortical areas, the basal ganglia, and the thalamus.

An example model using the SPA is shown in Figure 1. It is able to follow basic commands such as "WRITE TWO" and "REMEMBER THREE <long pause> WRITE NUMBER". When run in Nengo, this creates a model with 48,000 spiking neurons and produces predictions of spike patterns, firing rates, fMRI time-courses, accuracy, and reaction times. Complete details can be found in the book *How to Build a Brain* (Eliasmith, 2013).

Participants will leave the tutorial having interactively used a method for constructing cognitive models with spiking neurons, and experience using that method in an intuitive software environment.

```
class Rules:
    def read_action(category='ACTION'):
        set(action=vision*2)
    def read_object(category='OBJECT'):
        set(object=vision*2)
    def do_write(vision='DONE',
                phrase='ACTION*WRITE', scale=0.5):
        set(motor=phrase*'-OBJECT')
    def do_write_remembered(vision='DONE',
                            phrase='ACTION*WRITE+OBJECT*NUMBER'):
        set(motor=memory)
    def do_remember(vision='DONE',
                    phrase='ACTION*REMEMBER', scale=0.5):
        set(memory=phrase*'-OBJECT')

class Parser(SPA):
    vision = Vision()
    category = Buffer(feedback=0)
    action = Buffer(feedback=0)
    object = Buffer(feedback=0)
    actionC = Cleanup(mutual_inhibit=0.5)
    objectC = Cleanup(mutual_inhibit=0.5)
    phrase = Buffer(feedback=0)
    motor = Motor()
    memory = Buffer(pstc_feedback=0.1)
    flow = Flow("""
        action->actionC
        object->objectC
        actionC*1.1->action
        objectC*1.1->object
        action*ACTION->phrase
        object*OBJECT->phrase
        vision.WRITE->category.ACTION
        vision.REMEMBER->category.ACTION
        vision.ONE->category.OBJECT
        vision.TWO->category.OBJECT
        vision.THREE->category.OBJECT
        vision.NUMBER->category.OBJECT
        """)
    BG=BasalGanglia(Rules())
    thal=Thalamus(BG)
```

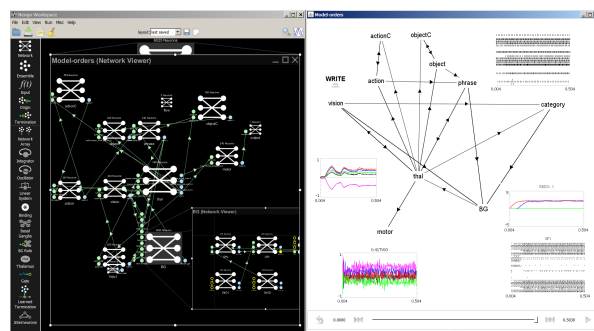


Figure 1: A script (top) to generate a model with 48,000 spiking neurons (bottom left) capable of simple cognitive behaviour (bottom right)

Tutorial Structure

This full-day tutorial starts with a quick overview of the theory behind the Neural Engineering Framework, showing how we can specify models by solving for the synaptic connection weights between groups of neurons that cause particular computations to be approximated. By specifying what each neural group represents and what computations should be computed between neural groups, large-scale neural models can be created. This is paired with many hands-on example of applying these concepts using the Nengo software. Neural groups and connections can be created using a drag-and-drop interface, or using the Python scripting interface. Participants are expected to bring a laptop to follow along with these tutorials (Windows, OS X, and Linux are all supported, and software is provided).

The first half of the tutorial covers the basic principles of the NEF and using Nengo. The second half introduces the concept of *semantic pointers* (vectors that combine the benefits of semantic similarity measures with the compositionality of symbol structures). We show how this method provides a unified approach to many types of cognitive models, including perceptual processing, symbolic reasoning, and motor control models. In particular, we show how these representations can be used to bind and manipulate symbol-like structures.

In this second half of the tutorial, we introduce our semantic pointer architecture and its implementation within Nengo. This provides a scripting language for building cognitive models, allowing researchers to create models of different brain areas and connect them together via the cognitive control of a cortex-basal ganglia-thalamus loop. This system is a general-purpose, biologically constrained, and neurally plausible cognitive architecture implemented using spiking neurons, and is the core foundation of our large-scale brain simulation.

Variants of this tutorial without the SPA cognitive architecture were presented at ICCM 2009, CogSci 2010, Telluride 2011, CogSci 2011, and CogSci 2012.

Tutorial Justification

The Neural Engineering Framework provides a method to bridge the gap between cognitive and neural theories. It has been used to build special-case models of serial-order recall (Choo & Eliasmith, 2010), action selection in the basal ganglia (Stewart, Choo, & Eliasmith, 2010), the Wason card task (Eliasmith, 2005), the Tower of Hanoi task (Stewart & Eliasmith, 2011), and inductive rule generation (Rasmussen & Eliasmith, 2010).

By combining these models with a general method for cognitive control (the cortex-basal ganglia-thalamus loop), we have created the beginnings of a novel biologically realistic cognitive architecture. Our tools allow researchers to quickly create large-scale brain models that combine novel models of particular brain areas with existing models of many other areas. We believe this is a powerful new tool for understanding cognition.

Given that understanding the SPA cognitive architecture requires a basic understanding of the Neural Engineering Framework, we feel that a full-day tutorial is required. The NEF provides an exciting new tool for cognitive science, as it provides a technique for producing direct neural predictions from cognitive theory. It is also general enough that the same framework can be used for category learning, memory research, linguistic processing, vision, and motor control research. Furthermore, components from existing cognitive architectures (such as ACT-R) can be directly interfaced to these neural models.

Audience

Participants are not expected to have any previous experience with neural modeling. All participants are encouraged to bring a laptop for installing Nengo (Linux, OS X, and Windows versions are provided), allowing for hands-on interactions with the models discussed.

Presenters

Chris Eliasmith holds a Canada Research Chair in Theoretical Neuroscience, and is director of the Centre for Theoretical Neuroscience at the University of Waterloo. His recent book, *How to Build a Brain*, and his earlier book, *Neural Engineering*, form the basis for this tutorial.

Terry Stewart is a research associate in the Centre for Theoretical Neuroscience. He developed the SPA module and has used it to create a variety of cognitive models.

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