NCS: A Large-Scale Brain Simulator

University of Nevada, Reno

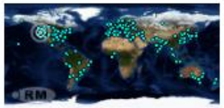
Brain Computation Lab

www.cse.unr.edu/brain

Brain Computation Lab

Navigation

- Research Projects
- People
- Publications
- Sponsors
- Conferences
- Opportunities
- University of Nevada, Reno
- Department of Computer Science and Engineering
- School of Medicine
- Biomedical Engineering Program



Welcome to the Brain Laboratory!

Good Morning!

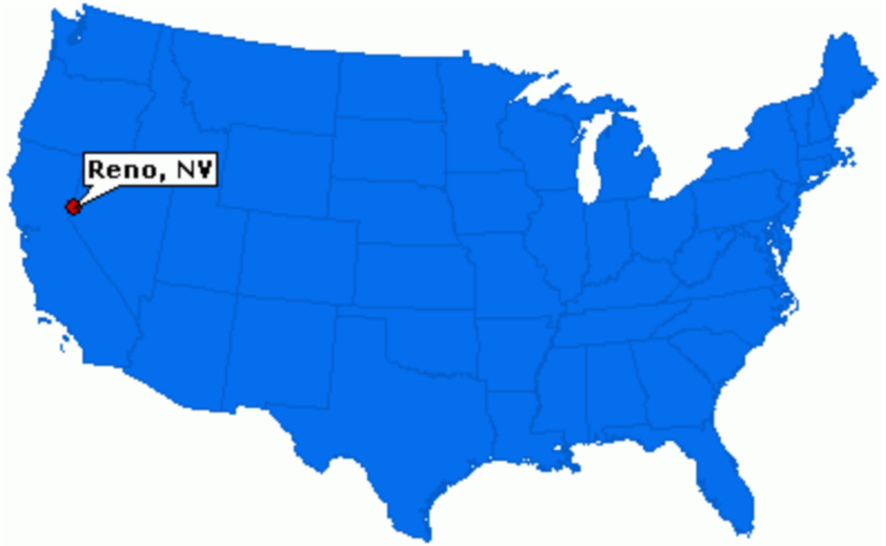
Founded in 2001, the brain lab is a joint research center between the departments of Computer Science & Engineering, Medicine, Physiology & Cell Biology, and the program of Biomedical Engineering. It also has neurobiological collaborations with the Brain Mind Institute at the EPFL (Switzerland), the University of Cergy Pontoise (France), and the University of Bonn (Germany).

Our researchers consists primarily of undergraduate/graduate students and alumni of the University of Nevada, Reno. They are actively developing computational innovations to understand the physiological processes that give rise to neocortical memory, learning, and cognition. Our models and experiments help understand brain pathophysiology and create brain-like artificial intelligence and neural prosthetic devices.

New Publications

- Goal-related navigation of a neuromorphic virtual robot
- Brainlab: a Python toolkit to aid in the design, simulation, and analysis of spiking neural networks with the NeoCortical Simulator
- Design and Implementation of an NCS-NeuroML Translator
- Real-Time Human-Robot Interaction Underlying Neurorobotic Trust and Intent Recognition

Reno, Nevada



University of Nevada, Reno

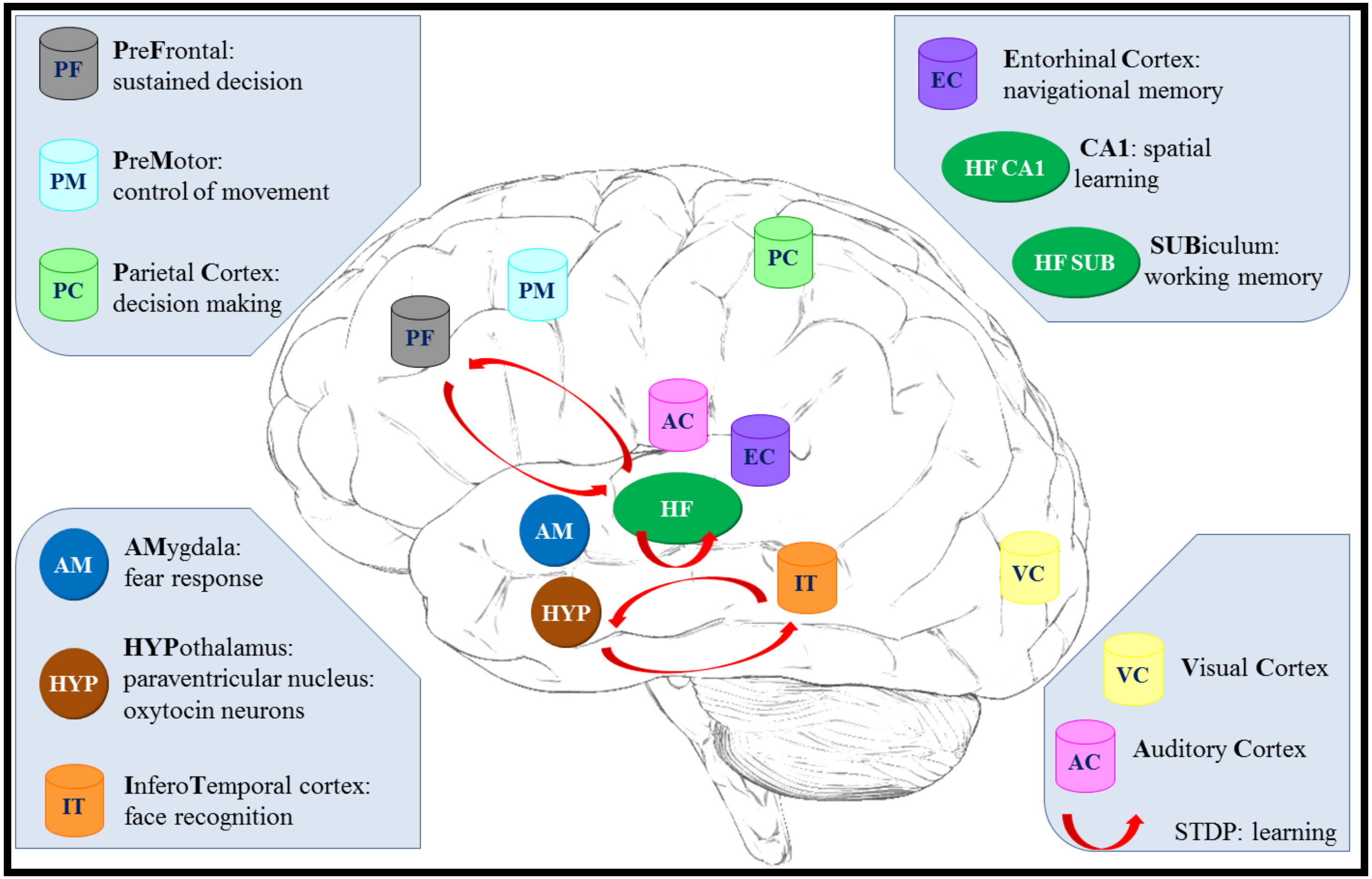
What is NCS?

- The NeoCortical Simulator (NCS) is designed for modeling large-scale neural networks and systems
- One of the first simulators to support neurorobotic applications
- Different types of neuron models available:
    - Leaky integrate-and-fire / Hodgkin-Huxley
    - Izhikevich
- Free and open source
- Developed and maintained by the UNR Brain Computation Laboratory

Why use NCS?

- Biological brain models
- Real-time Simulation
- Different levels of abstraction
- Several neuron models
- GPU computation
- No programming language experience required
- Good for modeling neural systems and networks
- Up to 1M neurons and 100M synapses in quasi real-time

Modeled Brain Regions Using NCS



History of NCS

- **Version 1:1999**
  - Matlab – Goodman, Markram, and McKenna
  - 160-cell, 2-column architecture
    - Each cell was modeled as a single integrative compartment (point neuron) with a spike mechanism,
      - calcium-dependent (AHP) channels, and
      - voltage-sensitive A and M (muscarinic) potassium channels

M.M. Kellog, H.R. Wills, and P.H. Goodman. "A biologically realistic computer model of neocortical associative learning for the study of aging and dementia." J. Investig. Med., 47(2), February 1999.

History of NCS

- **Version 1b: 1999**
  - Direct translation to C from Matlab
  - 24 times faster.
  - tested on mixed excitatory-inhibitory networks of up to 1,000 cells

M.M. Kellog, H.R. Wills, and P.H. Goodman. "A biologically realistic computer model of neocortical associative learning for the study of aging and dementia." J. Investig. Med., 47(2), February 1999.

History of NCS

- **Version 2: 1999**
  - code was then redesigned and rewritten for distributed processing on an existing 20-cpu cluster (Pentium II).
  - Initial trials of this code were performed on cortical networks of 2 to 1,000 cells

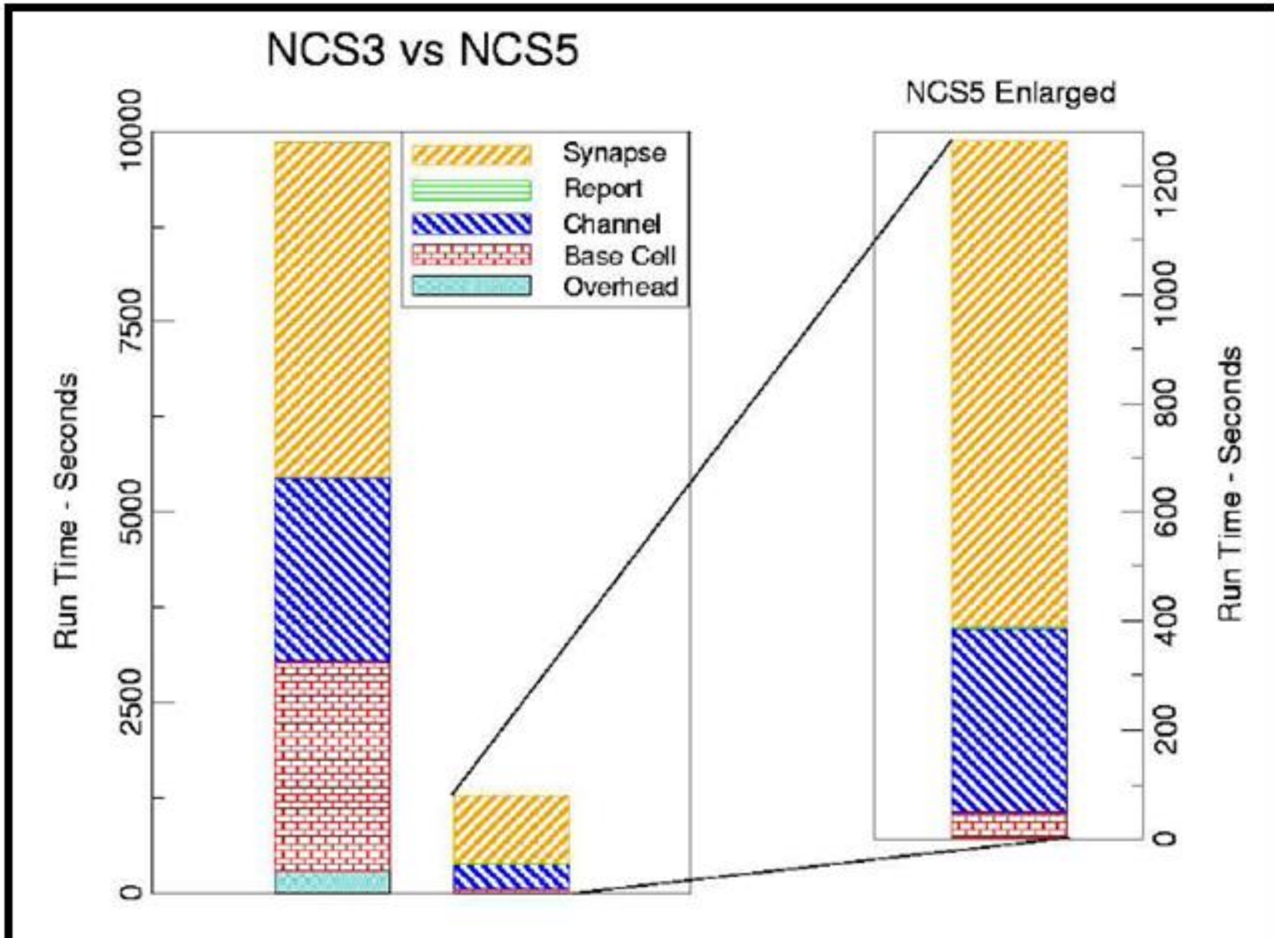
M.M. Kellog, H.R. Wills, and P.H. Goodman. "A biologically realistic computer model of neocortical associative learning for the study of aging and dementia." J. Investig. Med., 47(2), February 1999.

History of NCS

Item	NCS3	NCS5	Ratio
Overhead[a]	294.167	1.897	155.1
Base Cell/Cmp[b]	0.020	3.035	153.6
Channel[b]	0.152	0.398	2.6
Report[c]	0.017	4.113	239.4
Synapse, 0Hebb[b]	0.031	0.383	12.5
Synapse, +-Hebb[b]	0.020	0.368	18.1

a) Seconds.
b) Millions of Objects Processed per Second
c) Millions of Values Reported per Second

History of NCS



James Frye, James G. King, Christine J. Wilson, and Frederick C. Harris, Jr. “QQ: Nanoscale timing and profiling” In Proceedings of PMEO-PDS, Denver, CO, April 3-8 2005.

NCS5 Hardware

2007

2008

Sun v20z Opteron
(60 CPUs)

ONR DURIP 2007:

Sun 4600s and 4500s
16 core boxes with 200GB of RAM
connected by Infiniband
And several 24TB disk arrays

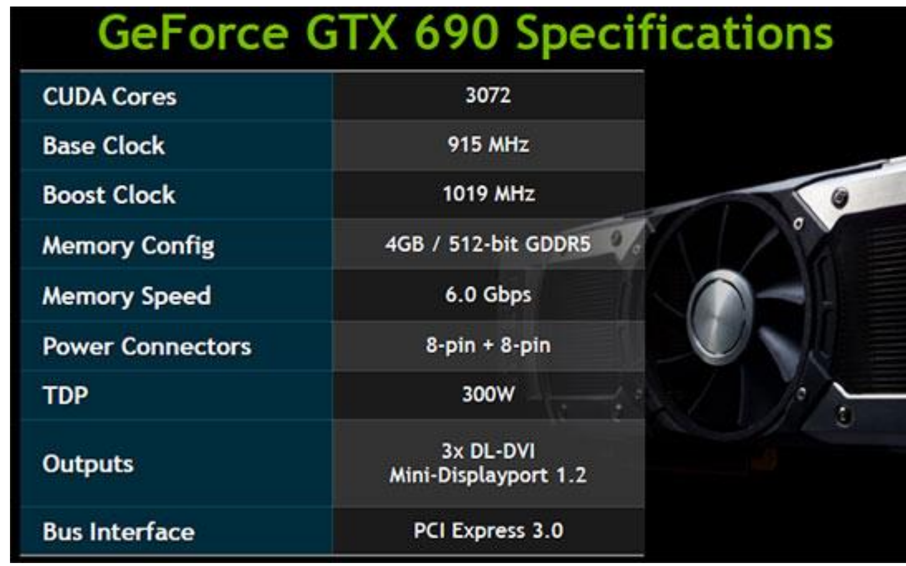
ONR DURIP 2008:

Current NCS version 6 implementation

- GPU/CPU/cluster-based
  - Runs on CPUs and CUDA devices simultaneously
- Plugin interface for multiple model support
  - LIF/HH Neurons
  - Izhikevich Neurons
  - Ability to design your own
- Ability for multi-scale modeling

NCS 6 Software / Hardware

- Linux based operating system
- NVIDIA GPU (GeForce GTX 400 series or higher)



Current Optimization

- C++ 11
- Heavily threaded
  - Latency hiding
  - Increased occupancy
- Modular message passing design
- GPU usage for parallel computation
- Load-balancing across heterogeneous clusters

Performance Data

Izhikevich

Izhikevich 1 second simulation			
Machines	# Neurons (k)	Synapses (M)	Time (s)
1	100	10	0.90
4	400	40	1.00
8	500	50	1.03
8	1000	100	3.16

Izhikevich 10 second simulation			
Machines	# Neurons (k)	Synapses (M)	Time (s)
1	100	10	8.98
4	400	40	9.89
8	500	50	10.13
8	1000	100	23.97

Performance Data
LIF

LIF 1 second simulation			
Machines	# Neurons (k)	Synapses (M)	Time (s)
1	25	6	1.36
4	50	12	1.18
8	50	12	0.99
8	300	75	2.82

LIF 10 second simulation			
Machines	# Neurons (k)	Synapses (M)	Time (s)
1	25	6	13.53
4	50	12	11.63
8	50	12	9.34
8	300	75	28.08

Leaky Integrate-and-Fire Model

Brain

- Define the simulation as a whole
- Preliminary outline of other structures
  - Anatomy
  - Stimuli
  - Reports
- Extrinsic connections
- Include files

Brain

```
BRAIN
        TYPE                Two_cell_MODEL_model
        JOB                 Two_cell_MODEL_model
        FSV                 1000
        DURATION            1
        SEED                -21
        DISTANCE            NO

################################ COLUMN TYPE##################################
    COLUMN_TYPE     TWO_CELL_MODEL_COLUMN

################################ STIM INJECT##################################
    STIMULUS_INJECT     TWO_CELL_MODEL_STIM

##############################################################################

############################### REPORTS ######################################
    REPORT      VOLTAGE_CELL_1
    REPORT      VOLTAGE_CELL_2

END_BRAIN
```

Anatomy

- Columns
- Layers
- Cells
- Compartments
- Channels

Anatomy

```
############################### Define Column Shells #########################
COLUMN_SHELL
    TYPE            TWO_CELL_MODEL_SHELL
    WIDTH           300
    HEIGHT          800
    LOCATION        0             800
END_COLUMN_SHELL

############################### Fill Columns #################################
COLUMN
    TYPE            TWO_CELL_MODEL_COLUMN
    COLUMN_SHELL    TWO_CELL_MODEL_SHELL
    LAYER_TYPE      layer_TWO_CELL_MODEL
END_COLUMN

############################### Define Layer Shells ########################
LAYER_SHELL
    TYPE            layer_TWO_CELL_MODEL_shell
    LOWER           0
    UPPER           49
END_LAYER_SHELL

############################### Fill Layers ##################################
LAYER
        TYPE                    layer_TWO_CELL_MODEL
        LAYER_SHELL             layer_TWO_CELL_MODEL_shell
        CELL_TYPE               TWO_CELL_MODEL_1     1
        CELL_TYPE               TWO_CELL_MODEL_2     1

###############################################################################
# ----- connections
###############################################################################
        CONNECT
                    TWO_CELL_MODEL_1       somaE
                    TWO_CELL_MODEL_2       somaE
                    synEE_TWO_CELL_MODEL   1   0
END_LAYER
```

Channels

- Km
  - Only has one activation particle (m). Inhibits its parent cell from reaching threshold
- Kahp
  - After Hyper Polarization Channels (Kahp) are voltage independent but Calcium dependent
- Ka
  - Helps the cell deal with background noise. It has both an activation (m) and inactivation (h) particle

Channel Km

```
CHANNEL Km
        TYPE                                m
        M_INITIAL                           0.0                 0.0
        REVERSAL_POTENTIAL                  -80                 0
        M_POWER                             1
        E_HALF_MIN_M                        -44
        SLOPE_FACTOR_M                      40          20      8.8
        TAU_SCALE_FACTOR_M                  0.303
        UNITARY_G                           5
        STRENGTH                            0.00015
END_CHANNEL
```

Channel Kahp

```
CHANNEL Kahp
        TYPE                                ahp1
        SEED                                999999
        M_INITIAL                           0.0             0.0
        REVERSAL_POTENTIAL                  -80             0
        M_POWER                             2
        UNITARY_G                           6
        STRENGTH                            0.00015
        CA_SCALE_FACTOR                     0.000125
        CA_EXP_FACTOR                       2
        CA_HALF_MIN                         2.5
        CA_TAU_SCALE_FACTOR                 0.01
END_CHANNEL
```

Channel Ka

```
CHANNEL Ka
        TYPE                                a
        M_INITIAL                           0.0               0.0
        H_INITIAL                           1.0               0.0
        REVERSAL_POTENTIAL                  -80               0
        M_POWER                             1
        H_POWER                             1
        E_HALF_MIN_M                        11
        E_HALF_MIN_H                        -56
        SLOPE_FACTOR_M                      18
        SLOPE_FACTOR_H                      18
        UNITARY_G                           0.12
        STRENGTH                            2.5
        V_TAU_VALUE_M                       0.0002            9999
        V_TAU_VALUE_H                       0.03     0.08     0.13     0.18     0.23
        V_TAU_VOLTAGE_M                     100
        V_TAU_VOLTAGE_H                     -21      -1       10       21
END_CHANNEL
```

Stimulus

- External Stimulation (visual, audio…)
- Type of signals
  - Linear
  - Pulse
  - Noise
  - File-based
- Multiple times
- Different Destinations

Stimulus

```
#######################   STIMULUS INJECTS   ###############################

STIMULUS_INJECT
    TYPE            TWO_CELL_MODEL_STIM
    STIM_TYPE       realstim_TWO_CELL_MODEL
    INJECT          TWO_CELL_MODEL_COLUMN        layer_TWO_CELL_MODEL    TWO_CELL_MODEL_1        somaE   1
END_STIMULUS_INJECT

#############################define STIMULUS ###############################

STIMULUS
        TYPE                    realstim_TWO_CELL_MODEL
        MODE                    CURRENT
        PATTERN                 PULSE
        TIME_INCREMENT          0.1
        FREQ_COLS               100
        CELLS_PER_FREQ          1
        DYN_RANGE               0       75
        TIMING                  EXACT
        SAMESEED                NO
        AMP_START               4
        WIDTH                   .010
        TIME_START              0.500
        TIME_END                0.600
       #FREQ_START              99999
END_STIMULUS
```

Connections

- Extrinsic and intrinsic connections
- Synapse connections
- From the source to the destination
- With or without decaying distance effects
- Recurrent connections

Connections

```
###############################################################################
        CONNECT
                    TWO_CELL_MODEL_1       somaE
                    TWO_CELL_MODEL_2       somaE
                    synEE_TWO_CELL_MODEL   1   0
```

Synapses

- Connections between other cells and their compartments
- Excitatory
- Inhibitory
- Synaptic Waveform
- Learning
  - Short term synaptic dynamics
    - Facilitation
    - Depression
  - Long term synaptic dynamics (Hebbian Learning)
    - STDP rule

Synapses

```
###############SYNAPSES TWO_CELL_MODEL_MODEL###################################

SYNAPSE
    TYPE           synEE_TWO_CELL_MODEL
    SFD_LABEL            NO_SFD
    LEARN_LABEL          NO_STDP
    SYN_PSG        PSGexcit
    MAX_CONDUCT    0.004
    DELAY          0.005  0.010
    SYN_REVERSAL   0     0
    ABSOLUTE_USE   0.25    0.1
END_SYNAPSE

######################## NO SFD ##############################################

SYN_FACIL_DEPRESS
        TYPE                    NO_SFD
        SFD                     NONE
        FACIL_TAU               0.0           0.0
        DEPR_TAU                0.0           0.0
END_SYN_FACIL_DEPRESS

############################### Long-term synaptic Dynamics ###################

SYN_LEARNING
        TYPE                    NO_STDP
        LEARNING                NONE
        LEARNING_SHAPE          EXPONENT
        NEG_HEB_WINDOW          0.1             0.0
        POS_HEB_WINDOW          0.05            0.0
        POS_HEB_PEAK_DELTA_USE  0.02            0.0
        NEG_HEB_PEAK_DELTA_USE  0.01            0.0
        POS_HEB_PEAK_TIME       0.005           0.0
        NEG_HEB_PEAK_TIME       0.005           0.0
END_SYN_LEARNING


############################### synaptic CONDUCTANCE WAVEFORMS ###############

SYN_PSG
        TYPE                    PSGexcit
        PSG_FILE                ./EPSG_Vogels_FSV1k_TAU05.inc
END_SYN_PSG
```

Reports

- Data about cells
- Report files:
  - Voltage
  - Current
  - Firecount
  - Channel
  - Synaptic strengths
- Automatically generated and saved

Reports

```
################## TWO_CELL_MODEL_MODEL REPORTS #########################

REPORT
    TYPE                    VOLTAGE_CELL_1
    CELLS                   TWO_CELL_MODEL_COLUMN layer_TWO_CELL_MODEL TWO_CELL_MODEL_1 somaE
    PROB                    1
    REPORT_ON               VOLTAGE
    FILENAME                TWO_CELL_MODEL_1_VOLTAGE_E.txt
    ASCII
    FREQUENCY               1
    TIME_START              0
    TIME_END                100
END_REPORT

REPORT
    TYPE                    VOLTAGE_CELL_2
    CELLS                   TWO_CELL_MODEL_COLUMN layer_TWO_CELL_MODEL TWO_CELL_MODEL_2 somaE
    PROB                    1
    REPORT_ON               VOLTAGE
    FILENAME                TWO_CELL_MODEL_2_VOLTAGE_E.txt
    ASCII
    FREQUENCY               1
    TIME_START              0
    TIME_END                100
END_REPORT
```

Izhikevich Model

Files

- Neuron file
- Synapse file
- Current file

Neuron File

- Parameters
  - NeuronID
  - a
  - b
  - c
  - d
  - u
  - v
- Regular Spiking

neuron.in

```
0 0.02 0.2 -65 8 -60 -12
```

Synapse File

- Parameters
  - PreNeuron
  - PostNeuron
  - Delay
  - Weight
  - APlus
  - AMinus
  - TauPlus
  - TauMinus

Current File

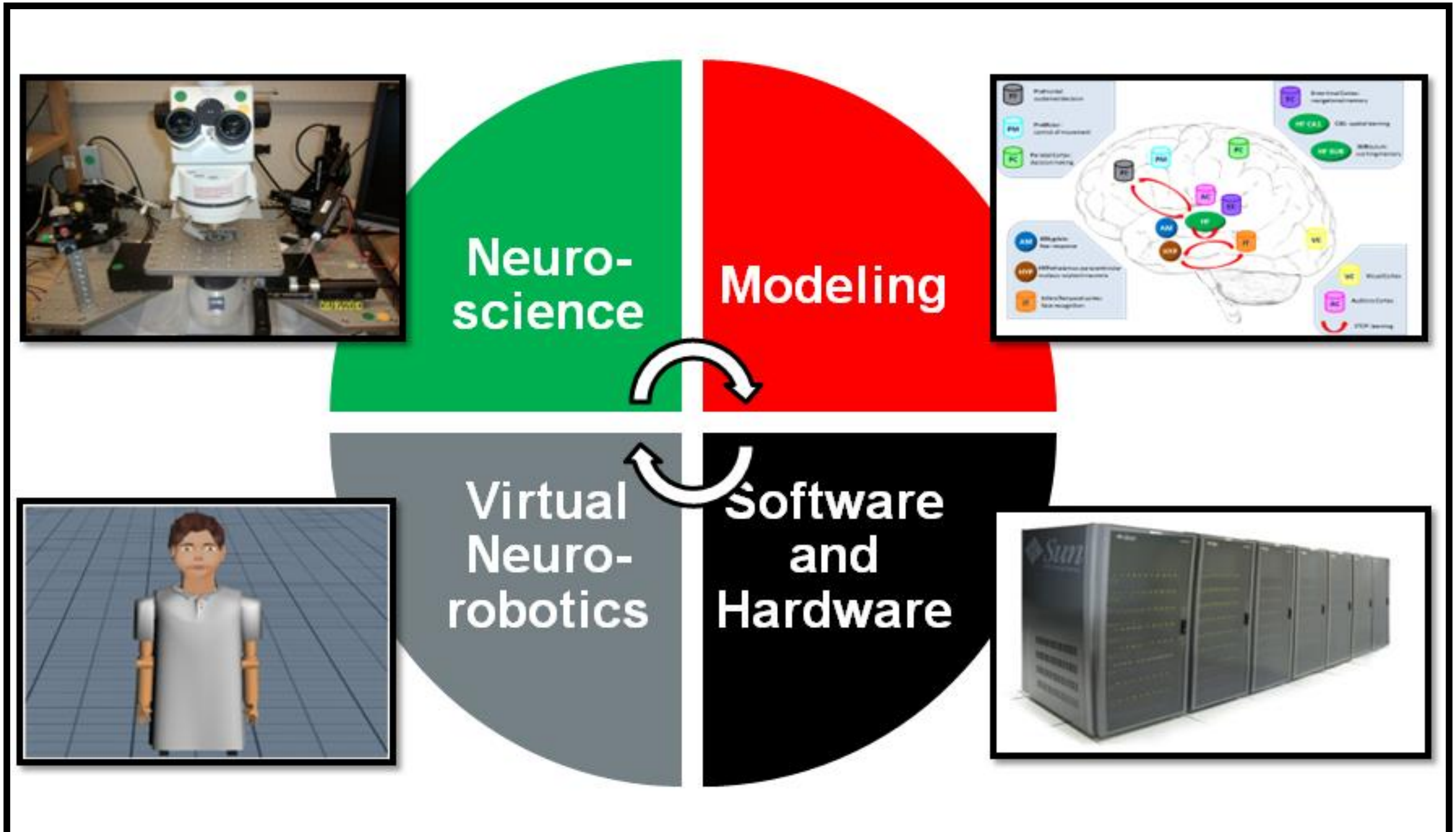
- Parameters
  - Neuron ID
  - Time start
  - Time end
  - Amp
  - Width
  - Frequency
- Regular Spiking

current.in

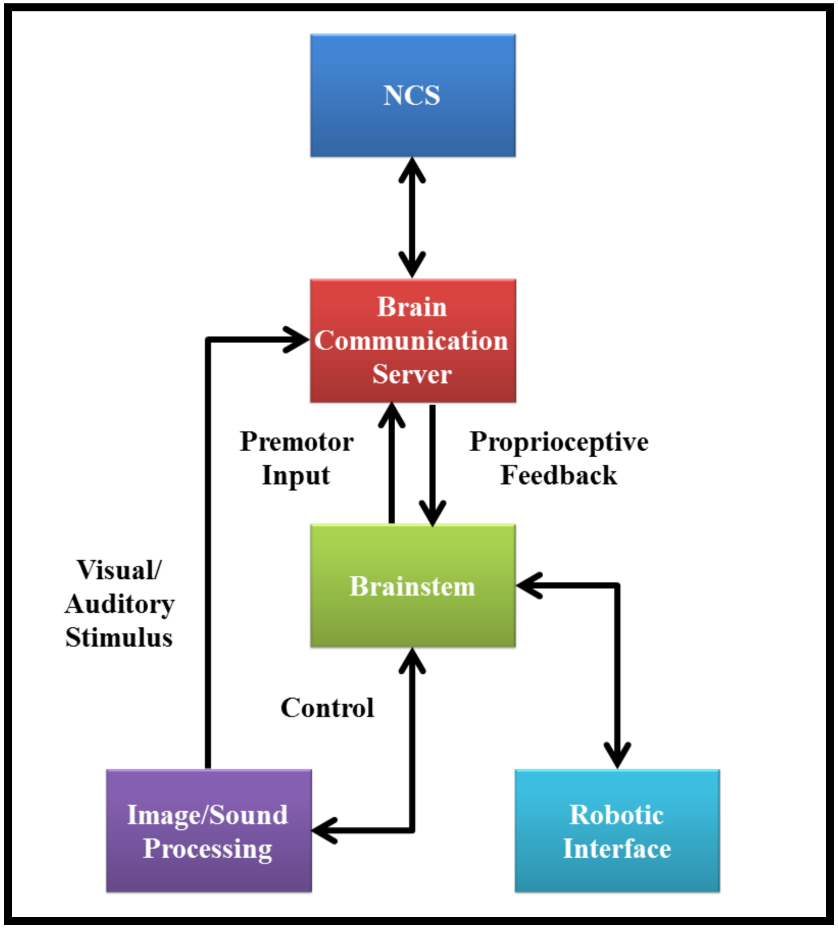
```
0 0.01 1 10 1 1
```

Robotic Applications with NCS

Technical Approach



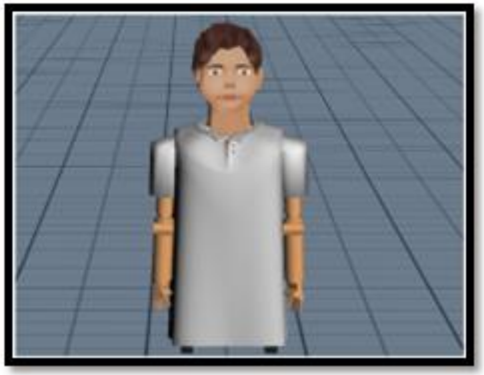
Virtual NeuroRobotic (VNR)

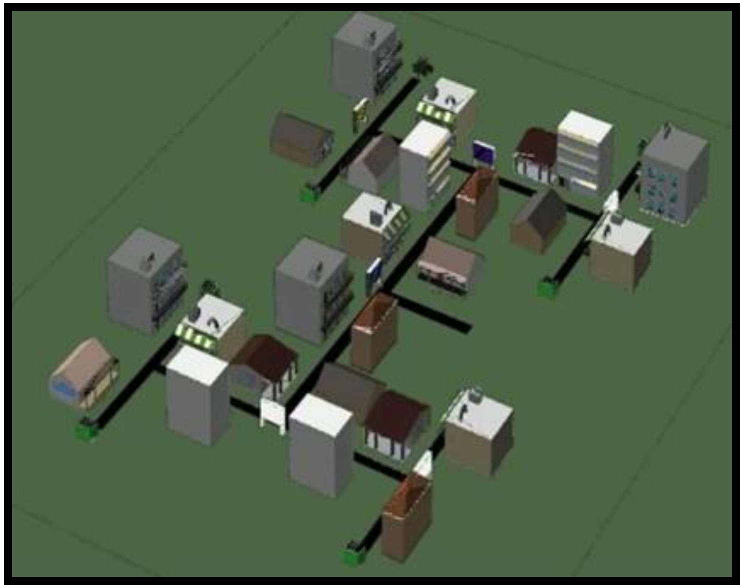


Laurence C. Jayet Bray, Sridhar R. Anumandla, Corey M. Thibeault, Roger V. Hoang, Philip H. Goodman, Sergiu M. Dascalu, Bobby D. Bryant, and Frederick C. Harris, Jr. "Real-time human-robot interaction underlying neurorobotic trust and intent recognition" Neural Networks, 32:130-137, 2012.

Robotic Interface

- Constructed using Webots 5
- Motions were programmed in C++ using the provided interfaces and the communication was accomplished using the NCSTools C++ client





Trust

- Behavior between a humanoid neurorobot and human actor
  - Oxytocin release
    - Social reinforcement
    - Reduction of inhibition
- Experiment has two conceptual phases:
  - Learning
  - Challenge

Paradigm

Learning

Robot Initiates Action

1. Robot brain initiates arbitrary sequence of motions

Human Responds

2. Human moves object in either a similar ("match"), or different ("mismatch") pattern

Match: robot learns to trust

Mismatch: don't trust

Challenge (at any time)

Human Acts

3. Human slowly reaches for an object on the table

Robot Reacts

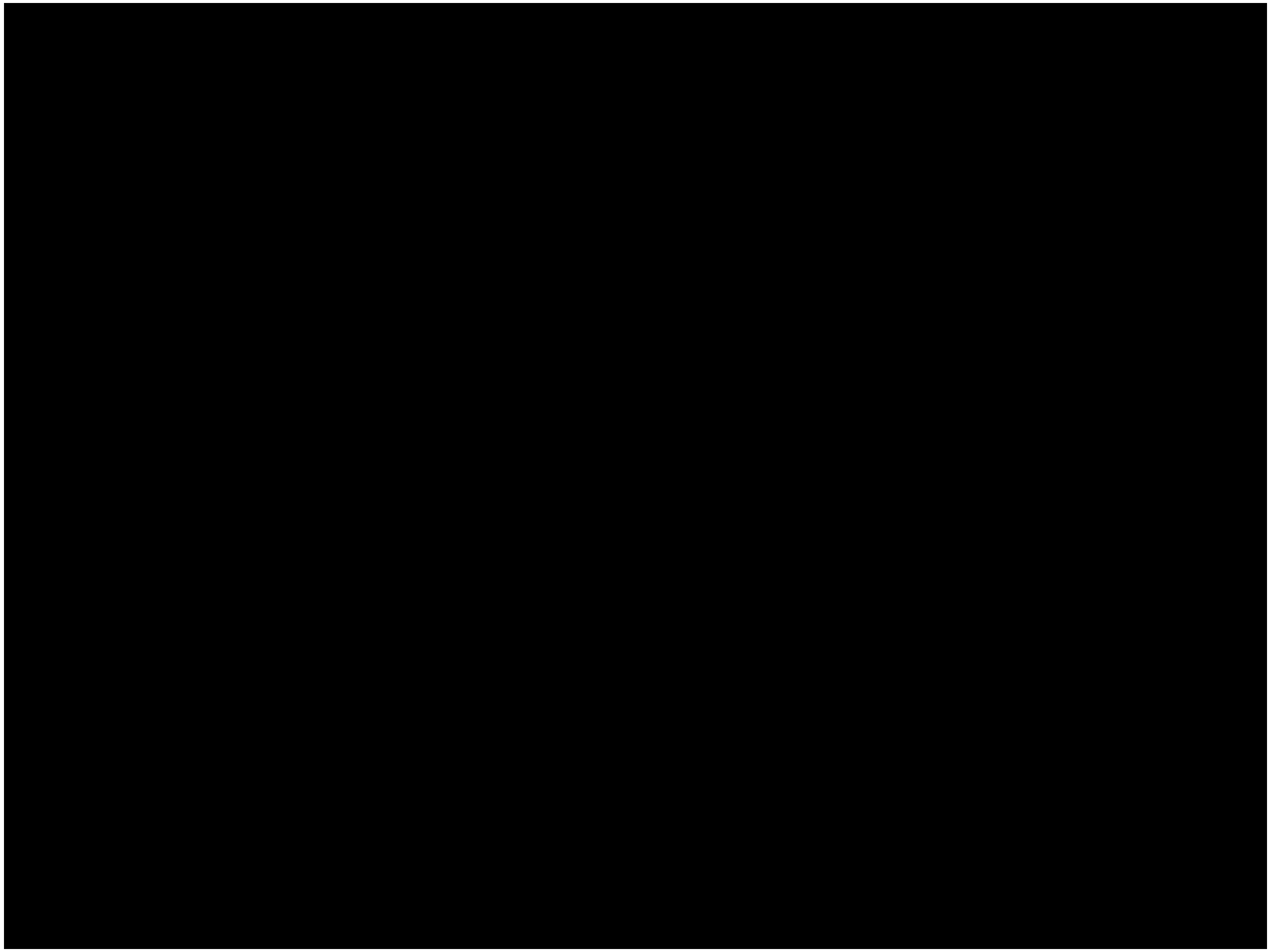
4. Robot either "trusts", (assists/offers the object), or "distrusts", (retract the object).

trusted

distrusted

Sridhar R. Anumadla, Laurence C. Jayet Bray, Corey M. Thibeault, Roger V. Hoang, Sergiu M. Dascalu, Frederick C Harris, Jr., and Philip H. Goodman "Modeling Oxytocin Induced Neurorobotic Trust and Intent Recognition in Human Robot Interaction" In Proceedings of the IJCNN (2011) July 31-Aug 5, 2011, San Jose, CA.

Concordant Motions Video

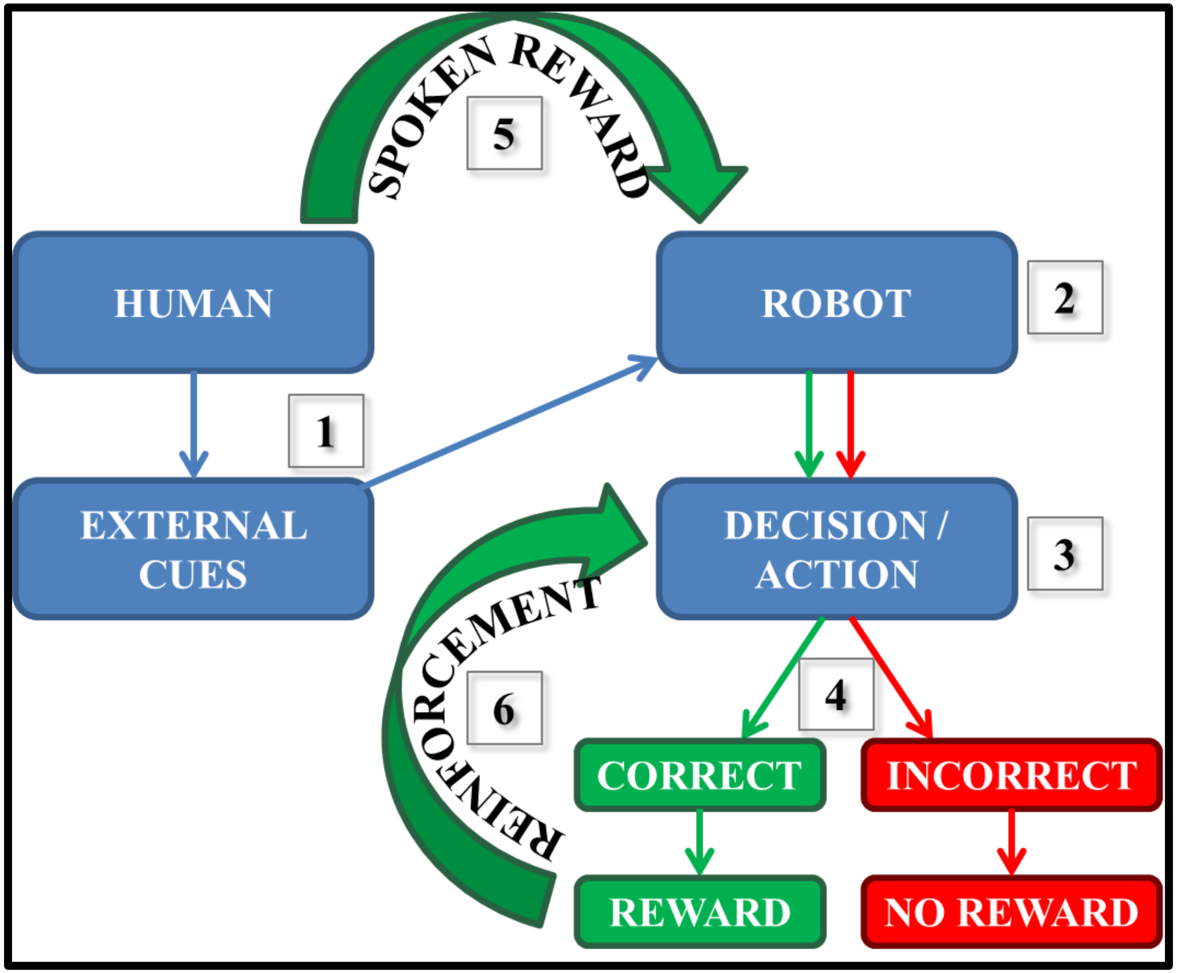


Discordant Motions Video

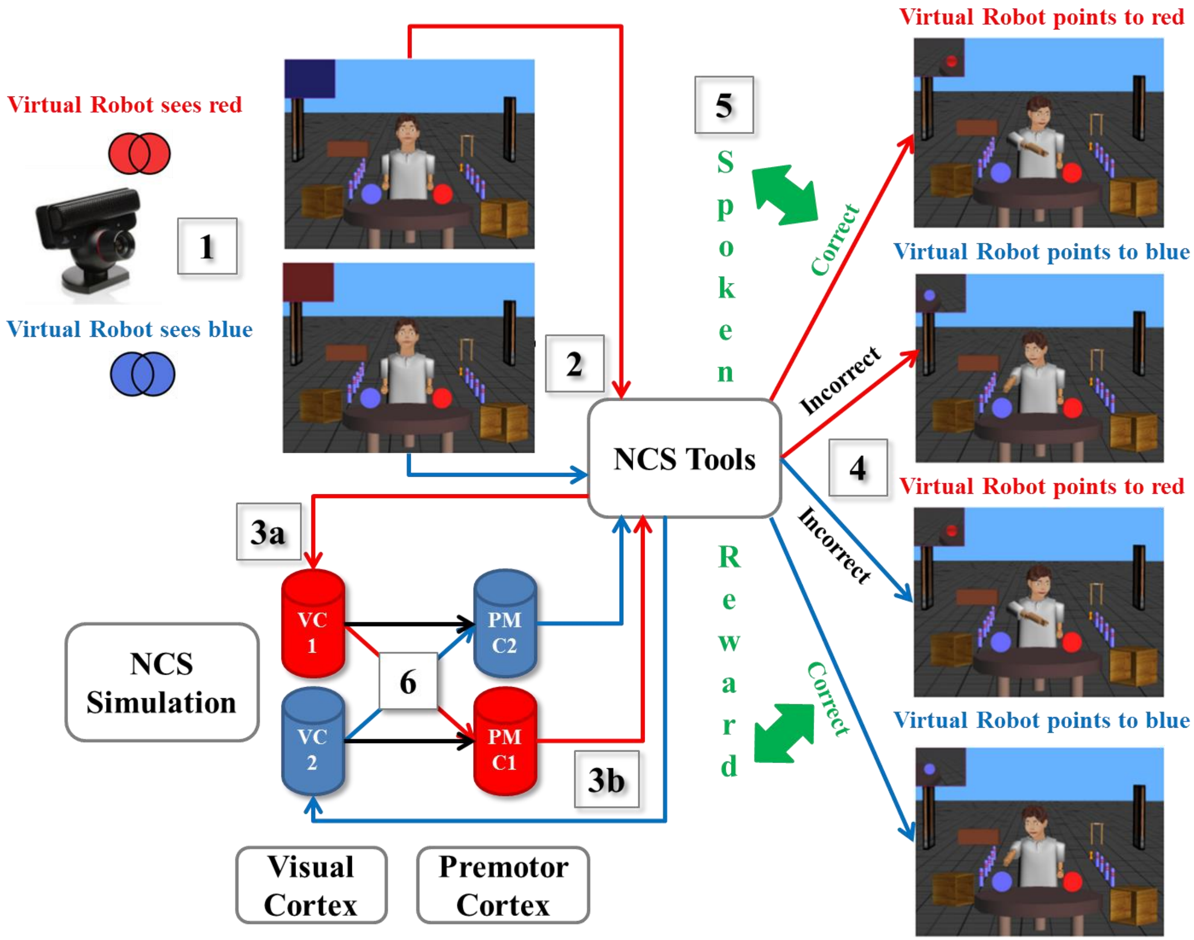
Emotional Speech

- Allows for more natural interaction between humans and robots
    - Determine the ideal behavior from a simple reward feedback
- Emotional Speech processor
    - Successfully distinguished “sad” and “happy” utterances
- Integrated into neurorobotic scenario
    - The robot received a spoken reward if the correct decision was made
- Step toward the combination of human emotions and virtual neurorobotics

Reward-based Learning Through ESP



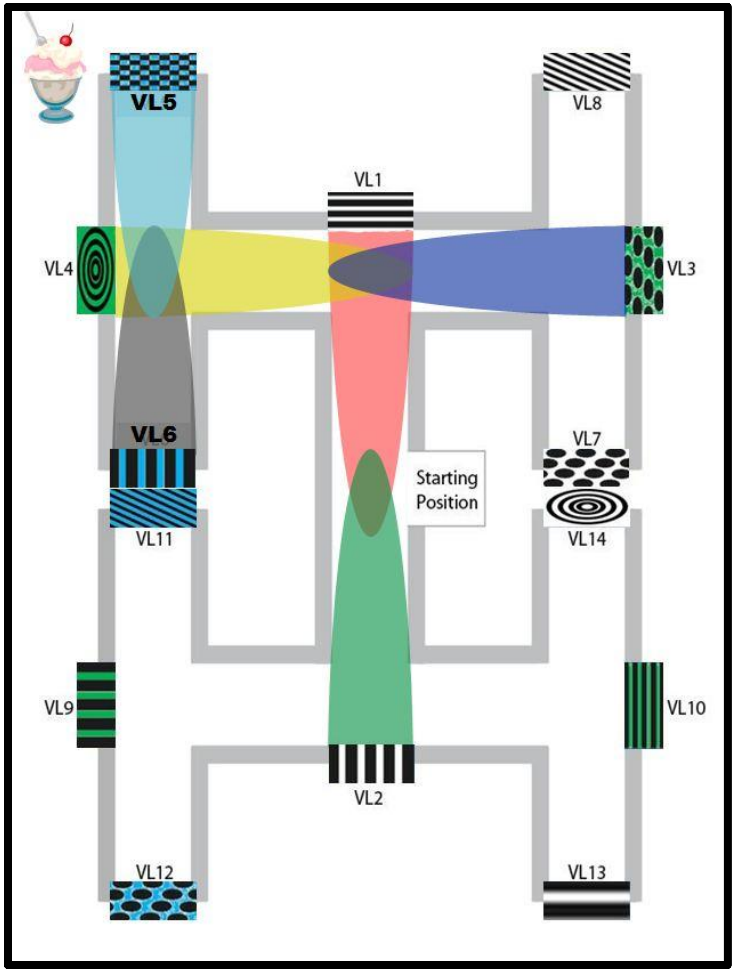
Reward-based Learning Through ESP



Navigation

- Navigate to familiar location
  - Prefrontal Cortex
  - Hippocampus (CA1 and Subiculum)
  - Entorhinal cortex
- Computational system representing a navigating rodent
- Reward at the end of a sequence of 3 turns
- Showed learning performance without biased decisions
- Short-term memory

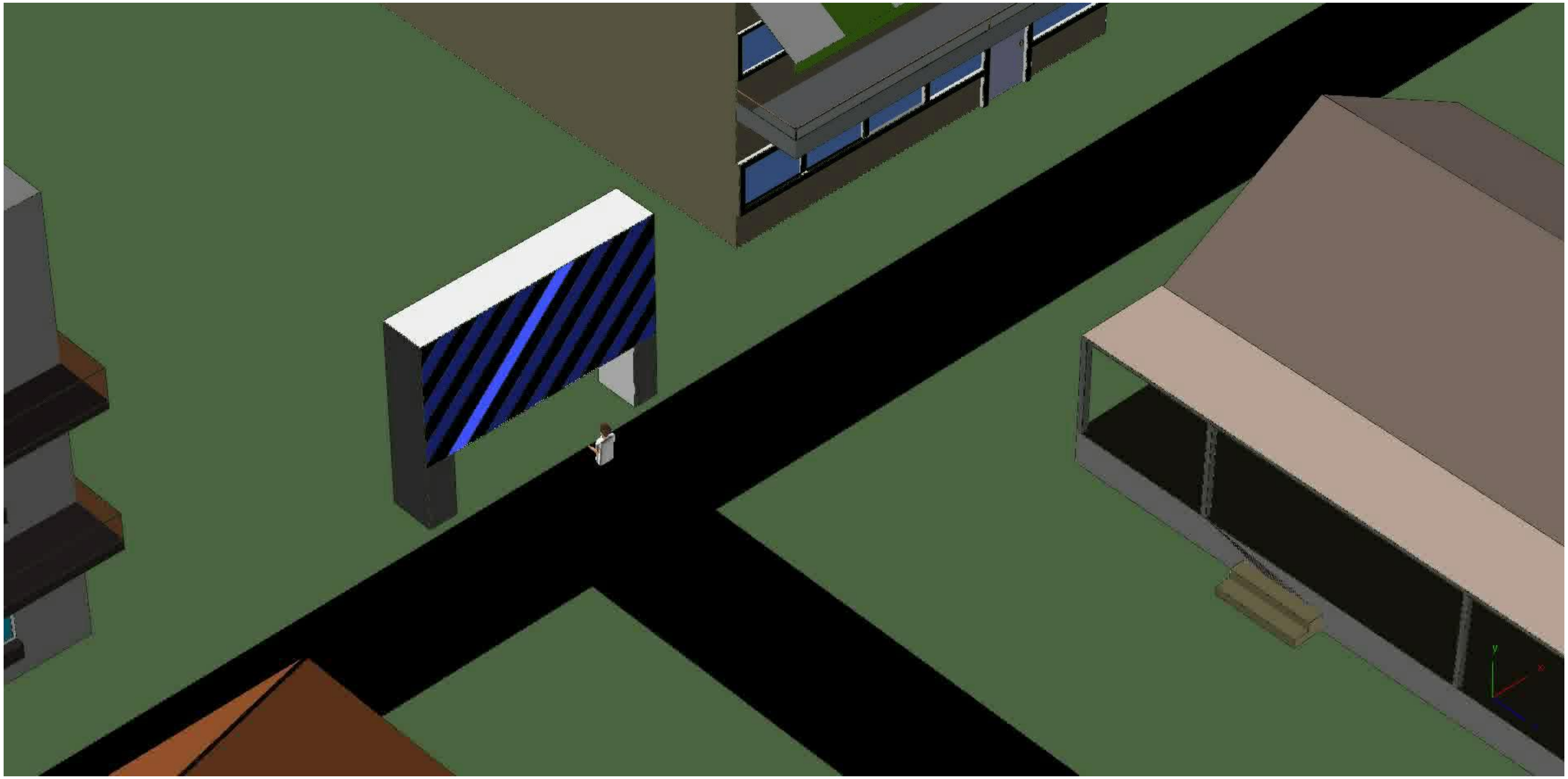
Paradigm



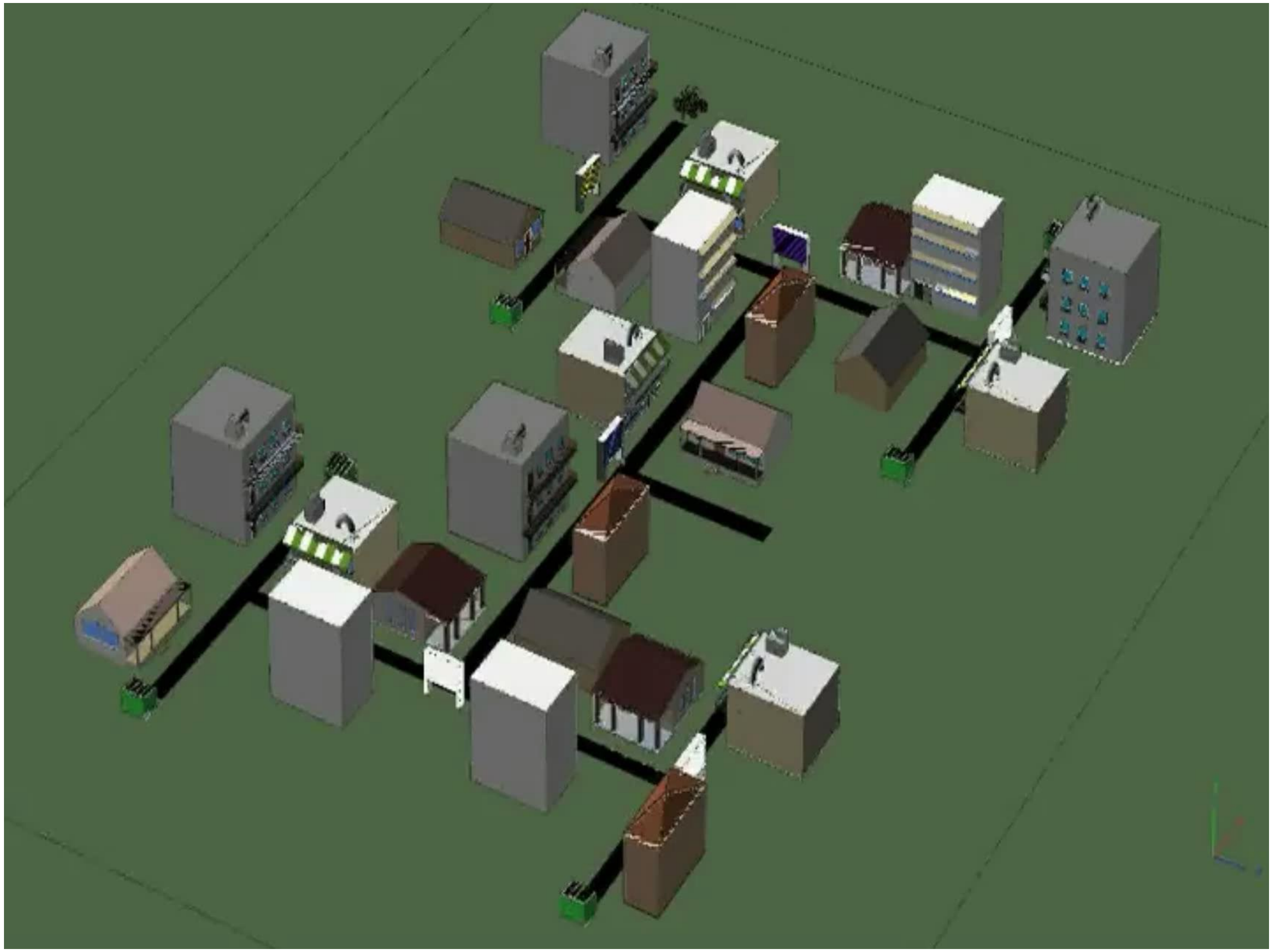
Jayet Bray L. A Circuit-Level Model of Hippocampal, Entorhinal and Prefrontal Dynamics Underlying Rodent Maze Navigational Learning. Ph.D. Dissertation. University of Nevada, Reno, 2010.

Navigation Video

Incorrect Choice



Navigation Video
Correct Choice



Future Directions
Simulator & Tools

- Near Term:
  - GUI-based brain model builder and visualizer
  - Multi-Scale modeling
  - Input language options
- Long Term:
  - Simulated fMRI data

Acknowledgments

- Office of Naval Research

- DARPA Synapse project and HRL