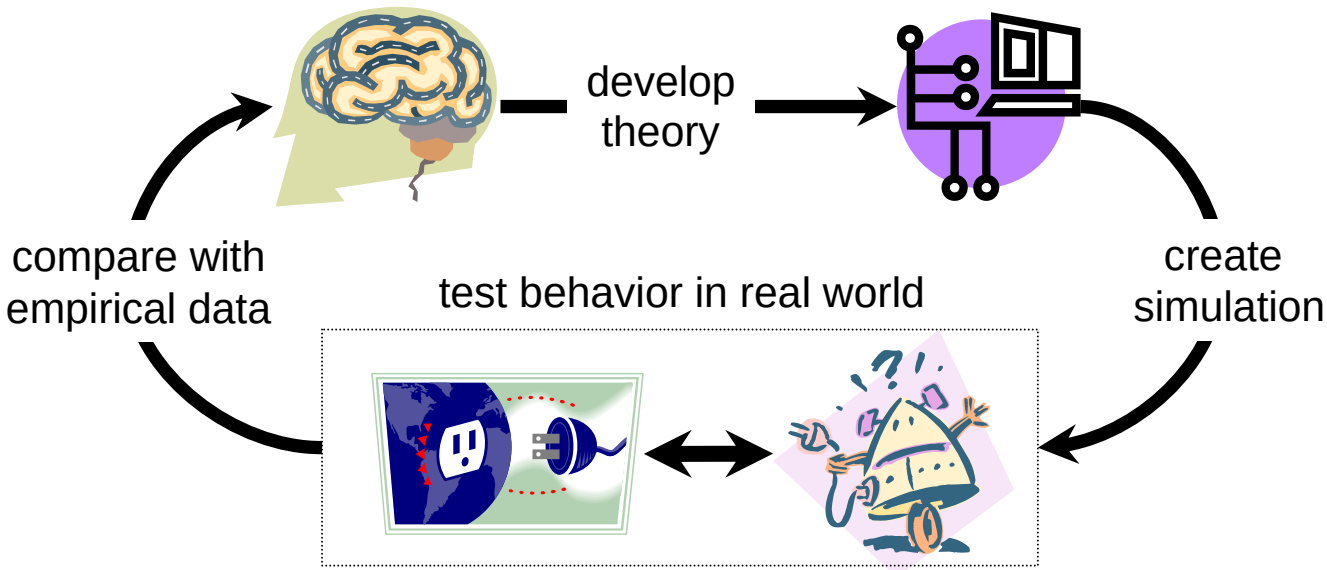
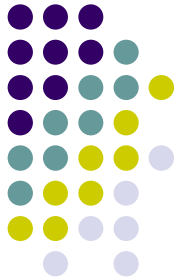
Brain-Based Devices

Studying Cognitive Functions with Embodied Models of the Nervous System

Jeff Krichmar
The Neurosciences Institute
San Diego, California, USA
http://www.nsi.edu/nomad

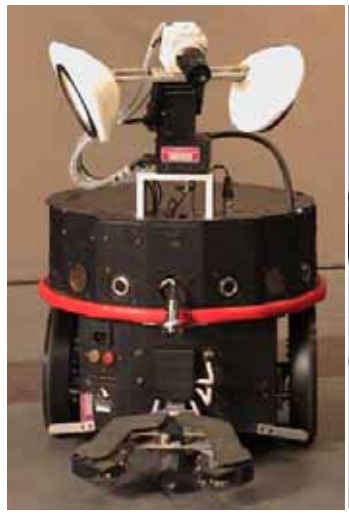


Brain-Based Device Hall of Fame



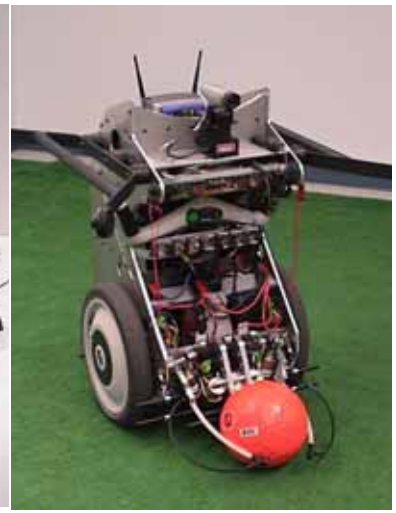
Darwin IV-VI
1992 - 1998

Darwin VII-VIII
1999 - 2002



Darwin IX-XI
2003 - 2007

BrainWorks
2004 - 2006



Brain-Based Devices: Design Principles and Constraints

- **The design should be constrained by these principles:**
  - **Incorporate a simulated brain with detailed neuroanatomy and neural dynamics.**
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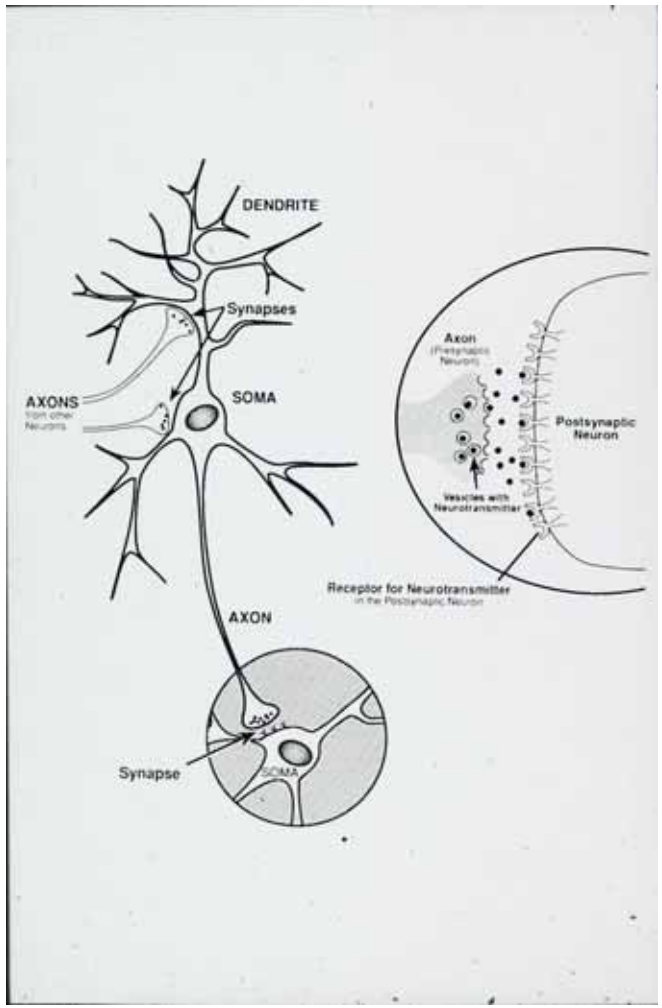
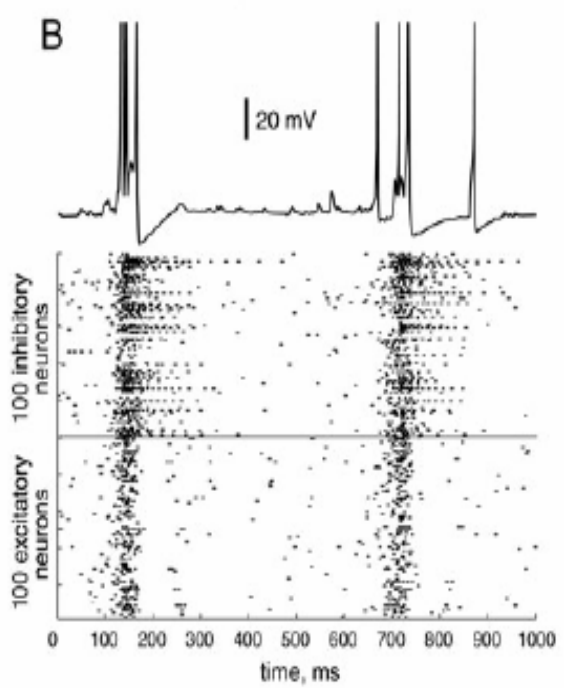
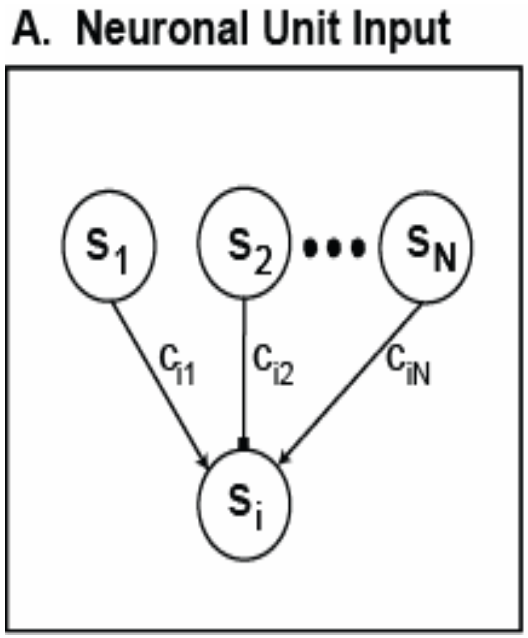
Neurodynamics and Neuroanatomy

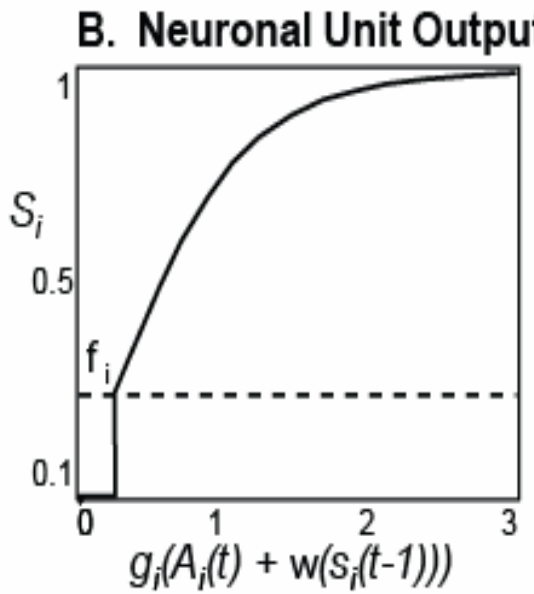


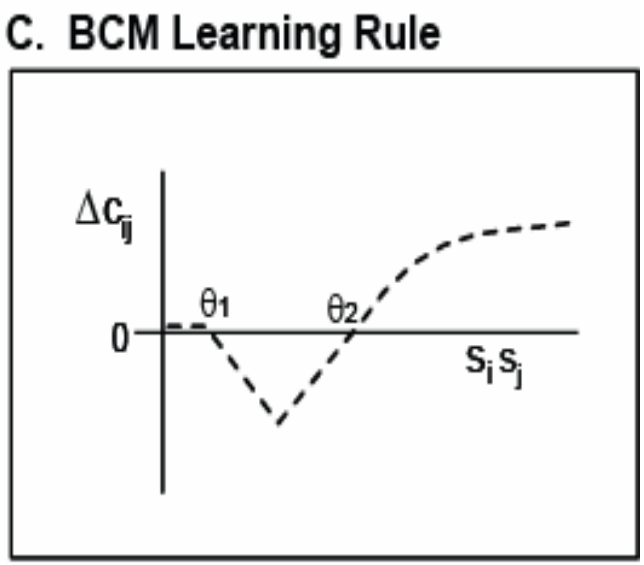


Mean Firing Rate Model

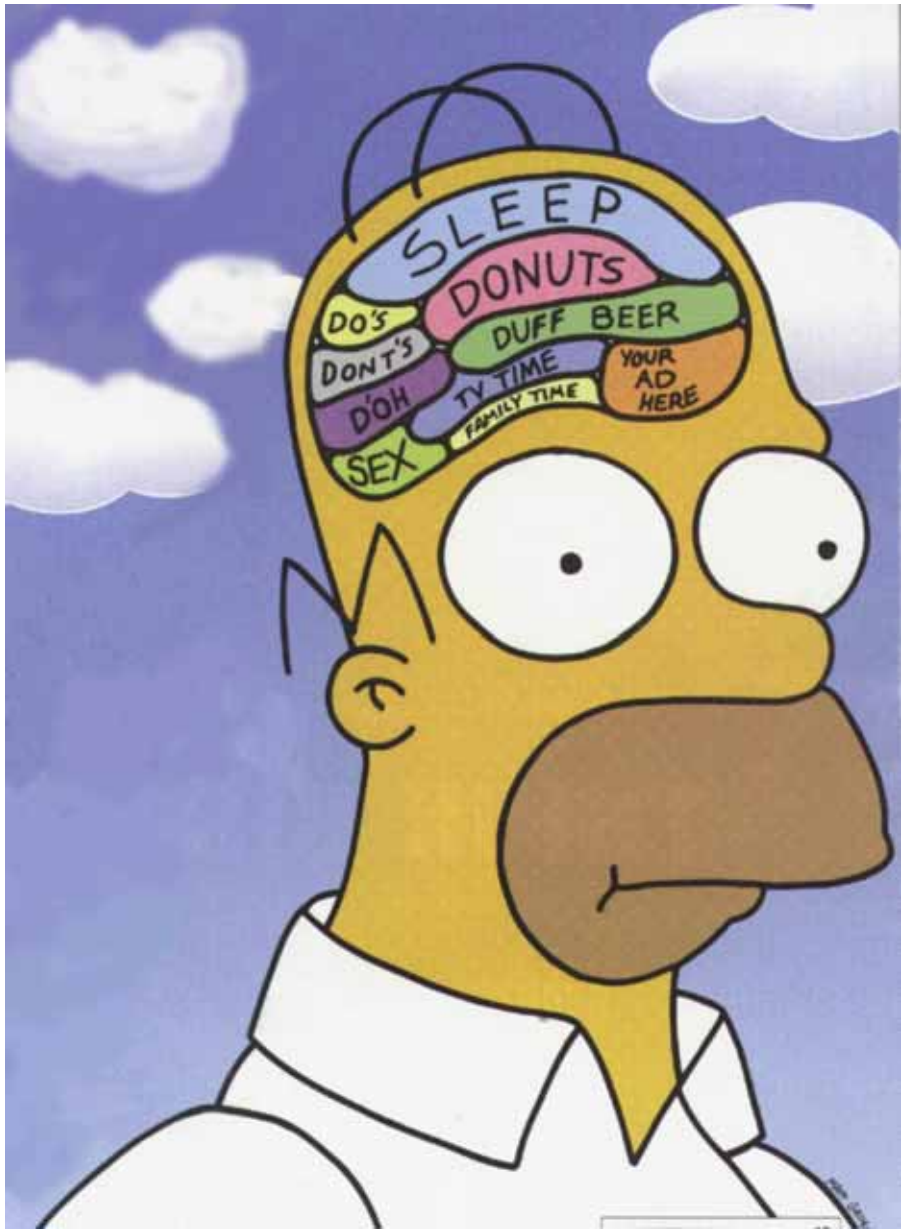
- **An efficient algorithm for network models**

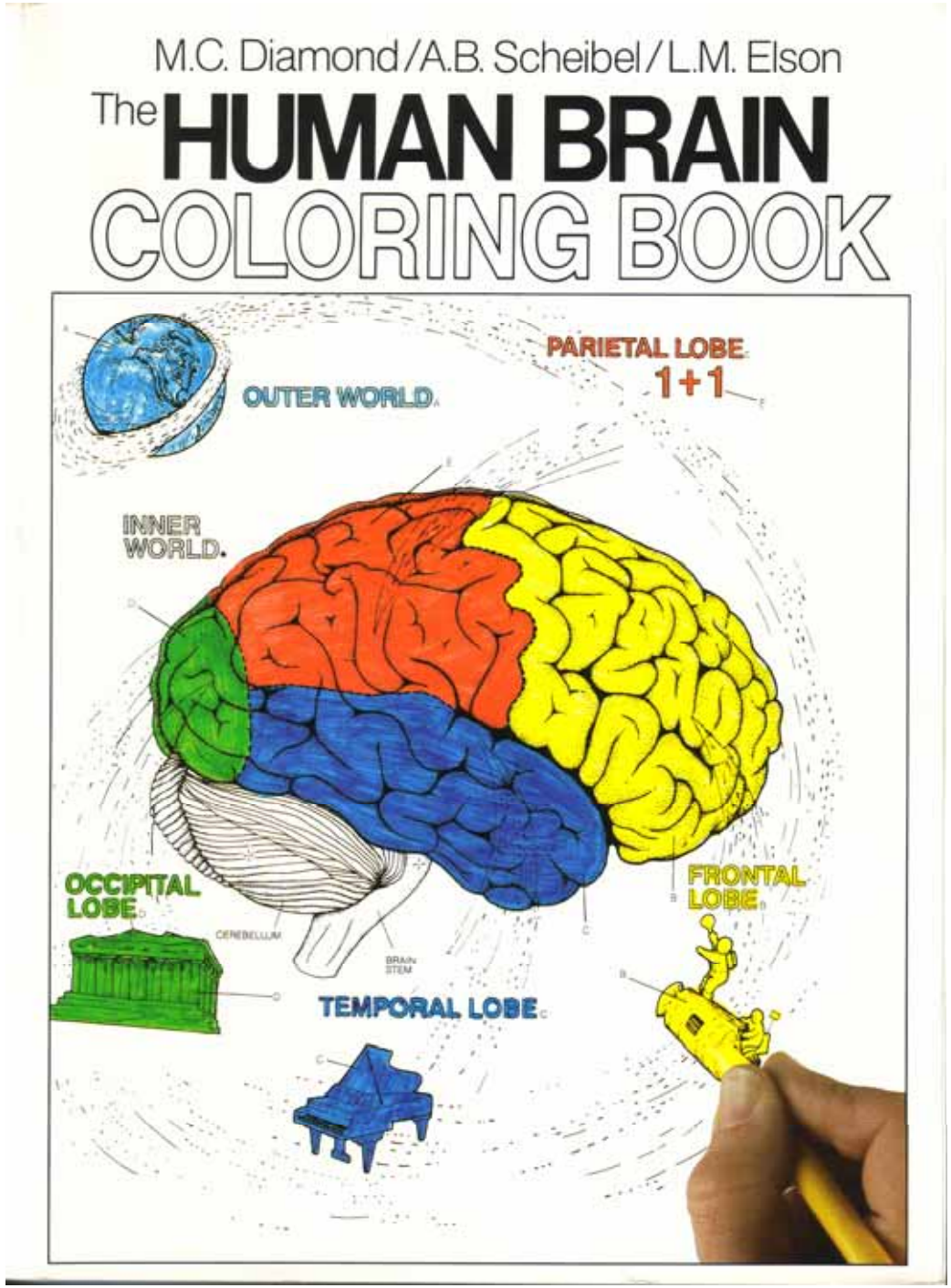




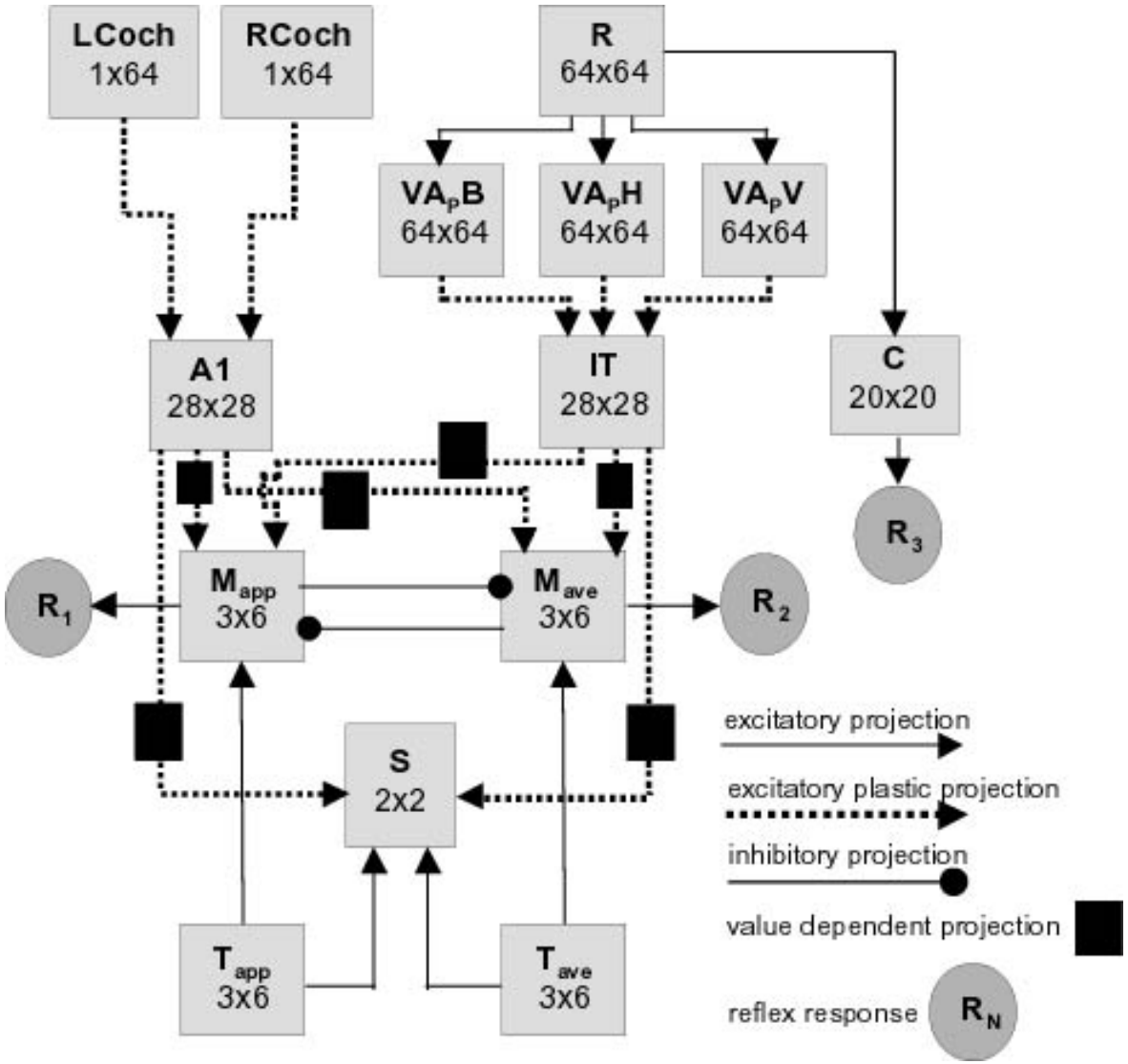


$$A_i = \sum_{j=1}^{N} c_{ij} s_j$$


SLEEP
DONUTS
DO'S
DUFF BEER
DONT'S
TV TIME
YOUR AD HERE
D'OH
FAMILY TIME
SEX


M.C. Diamond / A.B. Scheibel / L.M. Elson
The HUMAN BRAIN
COLORING BOOK
OUTER WORLD.
PARIETAL LOBE.
1+1
INNER WORLD.
OCCIPITAL LOBE.
FRONTAL LOBE.
CEREBELLUM
BRAIN STEM
TEMPORAL LOBE.

Functional Neuroanatomy of Darwin VII



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Perceptual Categorization
“the world is an unlabeled place”

Fabre-Thorpe, *Phil. Trans. R. Soc. Lond.* B (2003) **358**, 1215–1223

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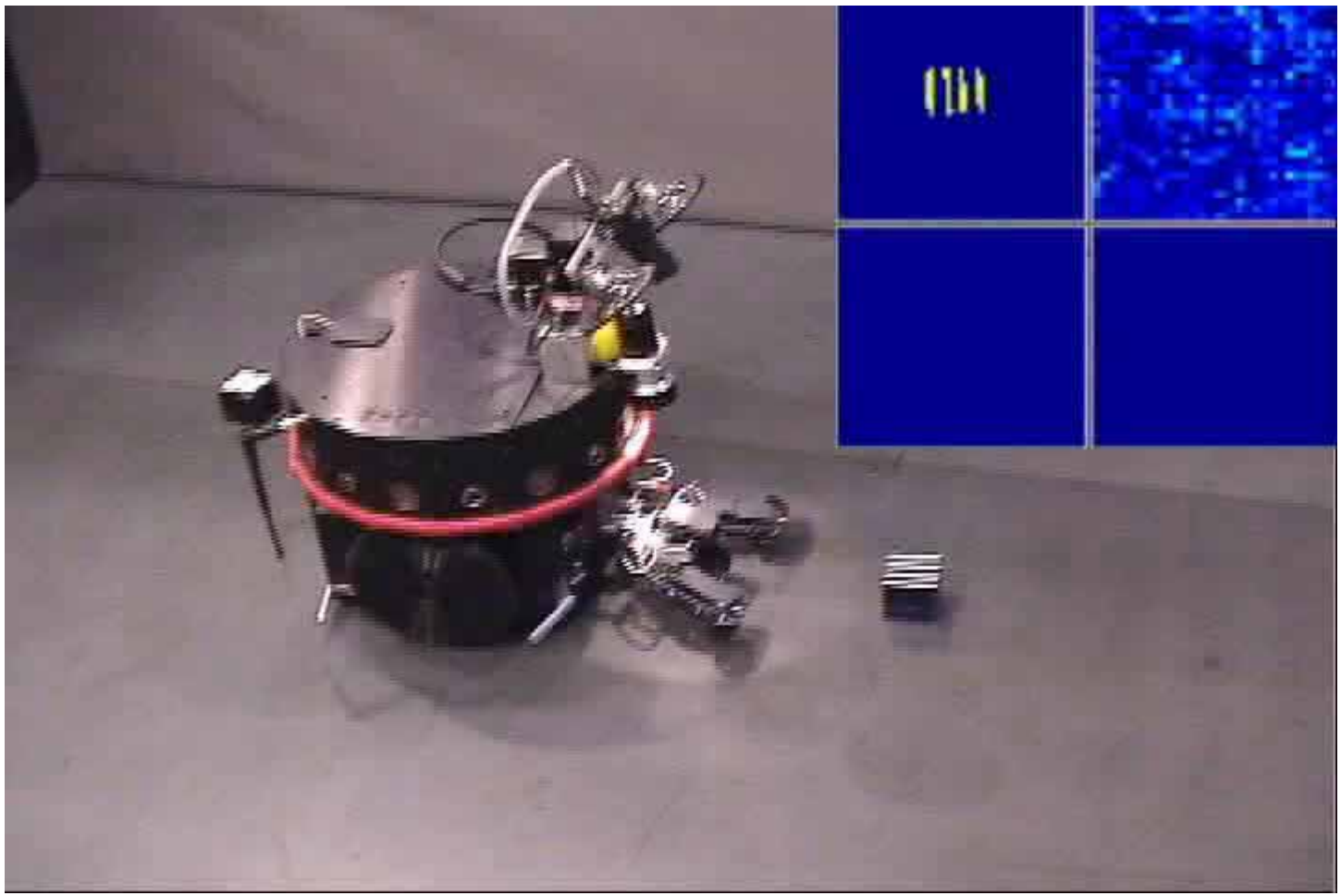
Darwin VII - Before Learning



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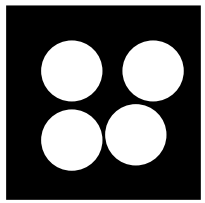
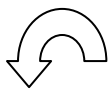
Darwin VII: Learning and Conditioning

	Innate (UCS)	Must Learn (CS)	Behavioral Response (UCR/CR)
Bad Tasting			unlearned – taste,  learned – no taste, 
Good Tasting			unlearned – taste,  learned – taste, 

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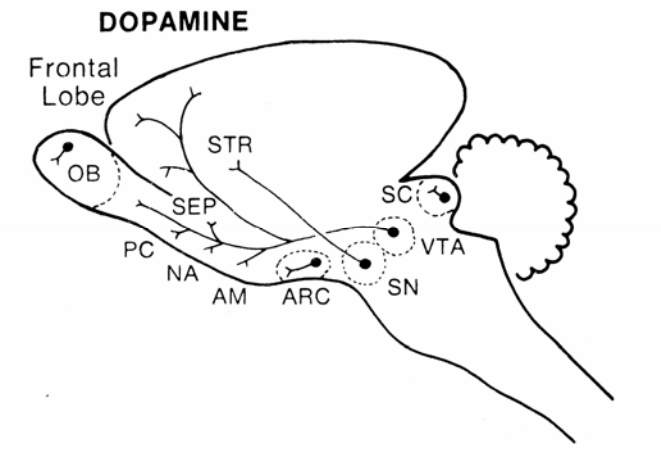
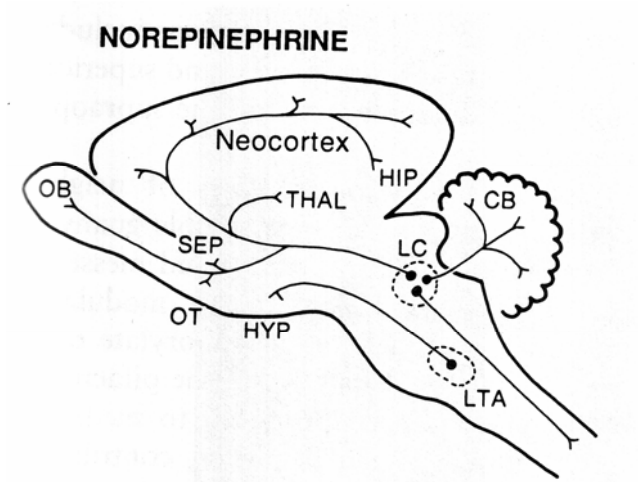
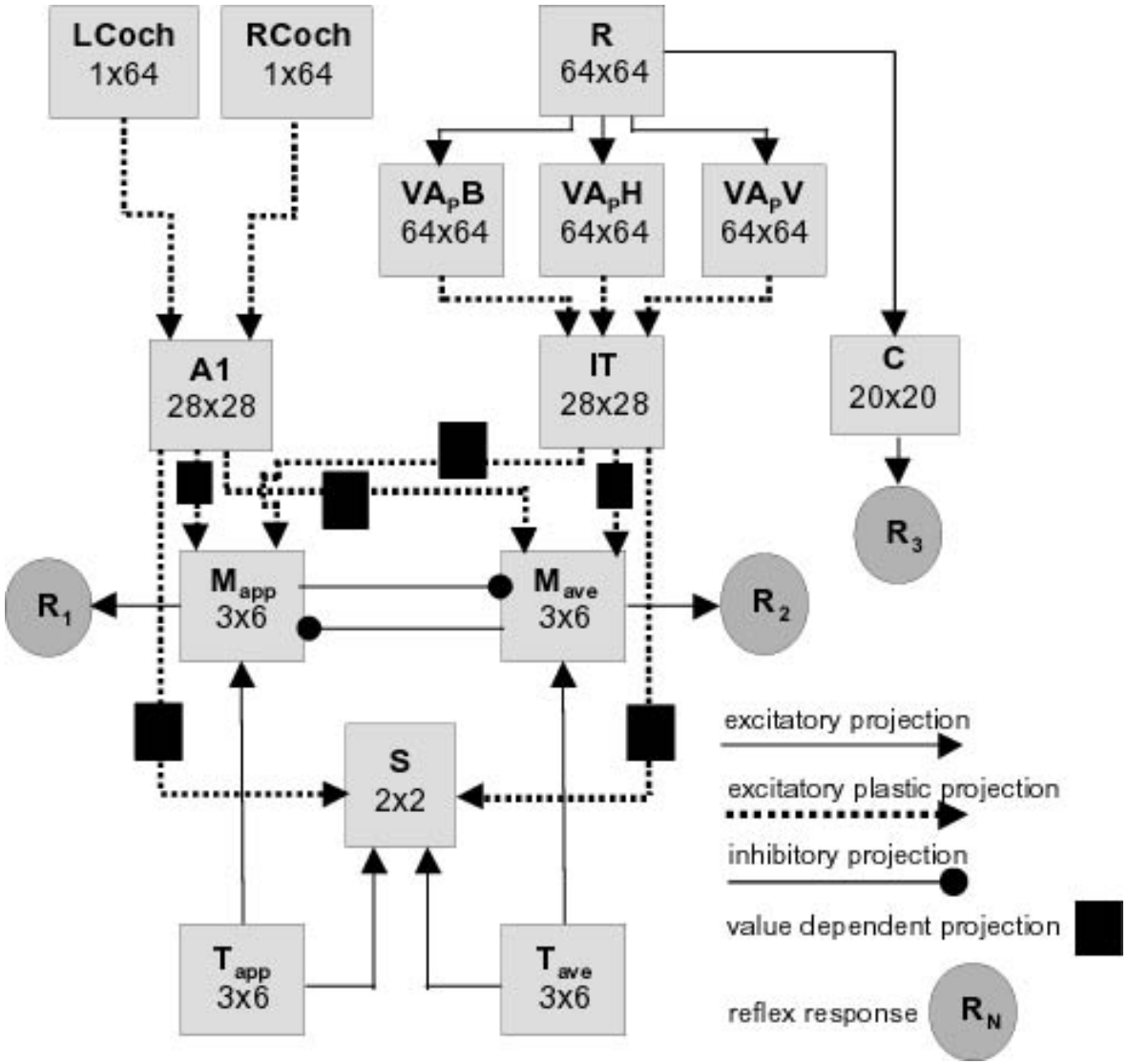
Value Systems

- **Organisms adapt their behavior through value systems:**
  - **Non-specific, modulatory signals to the rest of the brain.**
  - **Biases the outcome of synaptic efficacy in the direction needed to satisfy global needs.**

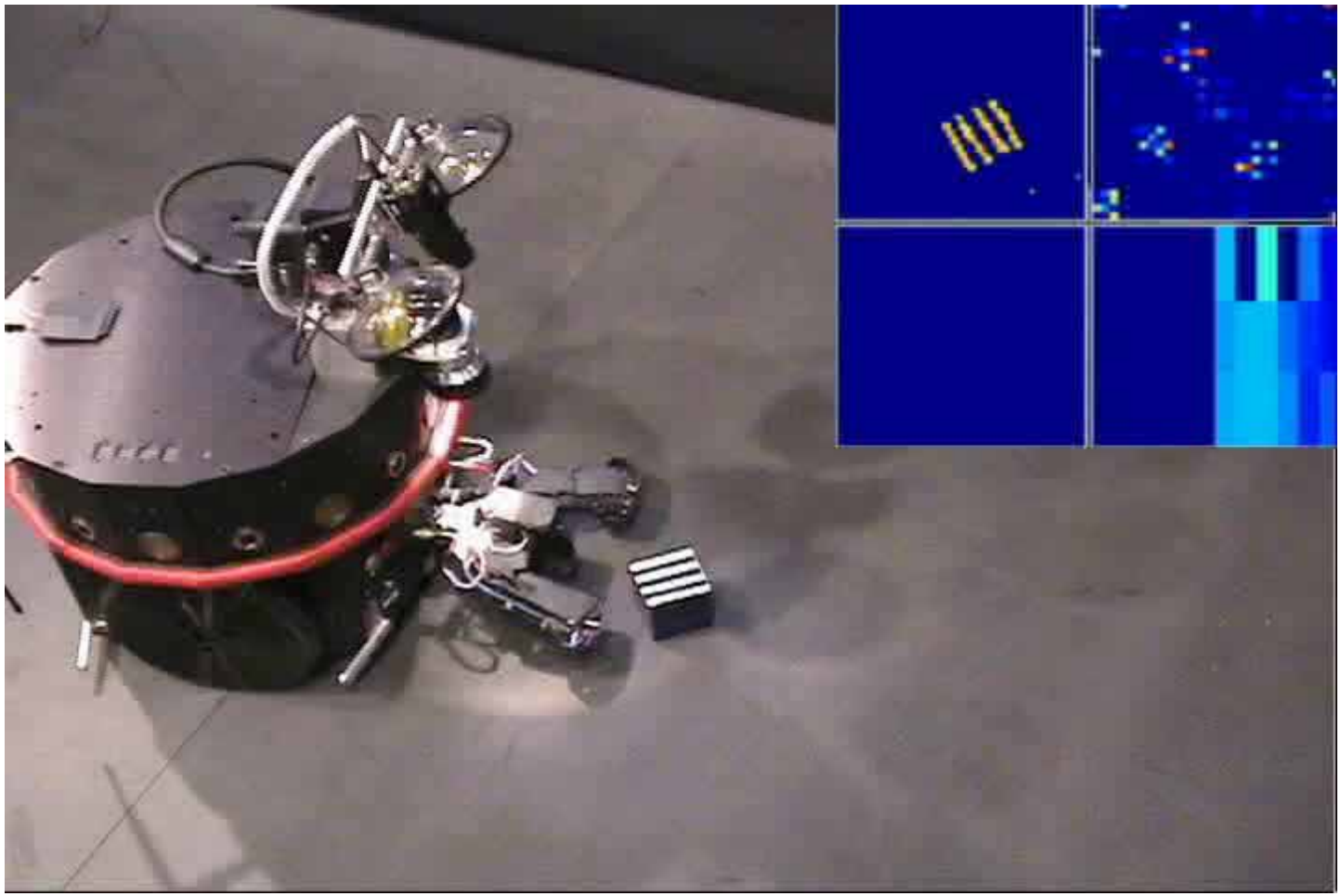




Functional Neuroanatomy of Darwin VII



Darwin VII - After Learning



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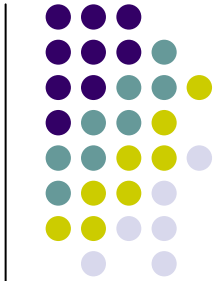
Episodic and Spatial Memory in a Brain-Based Device

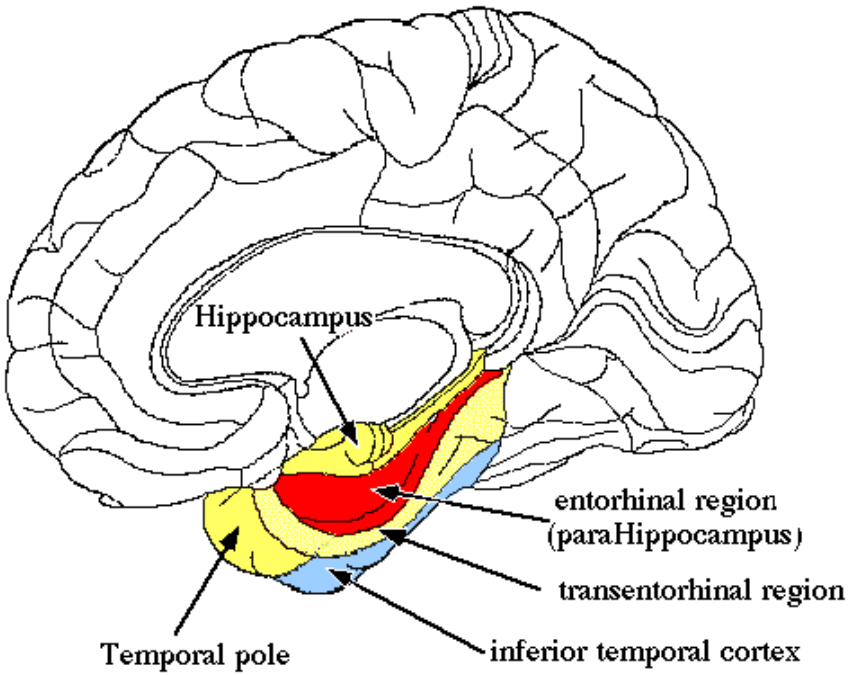


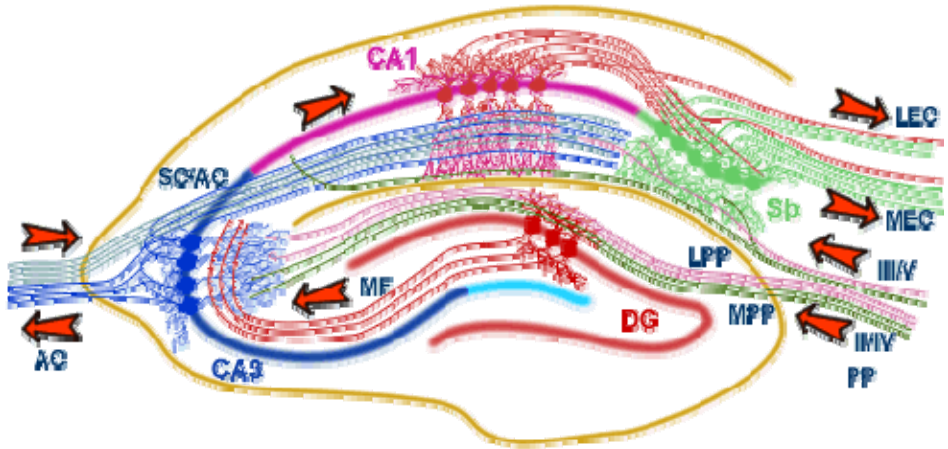
- **Episodic memory requires:**
  - **putting together the ‘what’, ‘when’ and ‘where’ of events.**
  - **the integration of multimodal information over time.**
- **In humans and other vertebrates, the hippocampus is crucial for the rapid acquisition and persistence of such memories.**


ADAM SANDLER
DREW BARRYMORE
Imagine having to win over
the girl of your dreams...
every friggin' day.
50 FIRST DATES
REMEMBER THE DATE
VALENTINE'S DAY


GUY PEARCE CARRIE-ANNE MOSS JOE PANTOLIANO
MEMENTO
otnemem.com

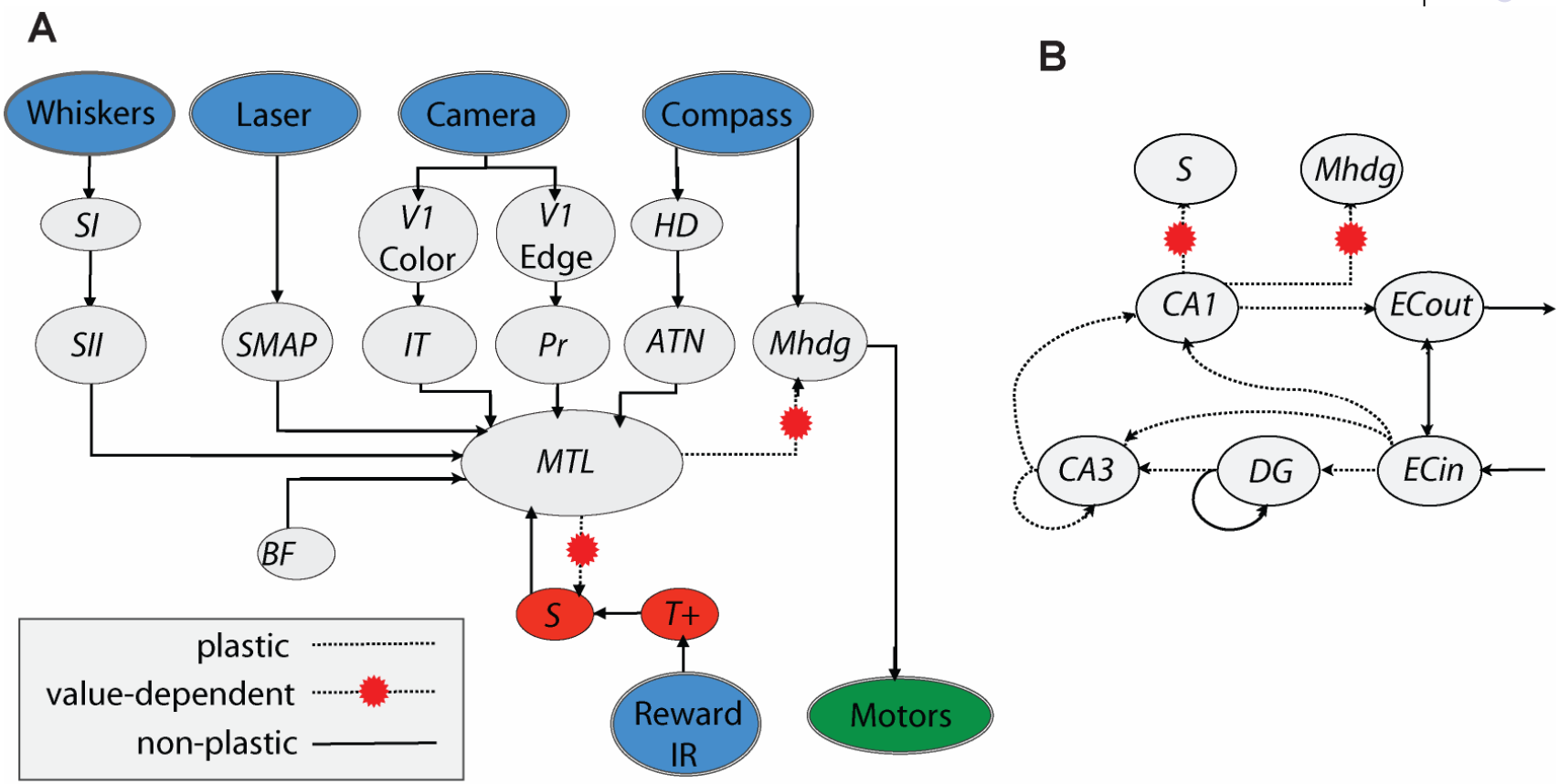
Hippocampus and its Surrounding Regions





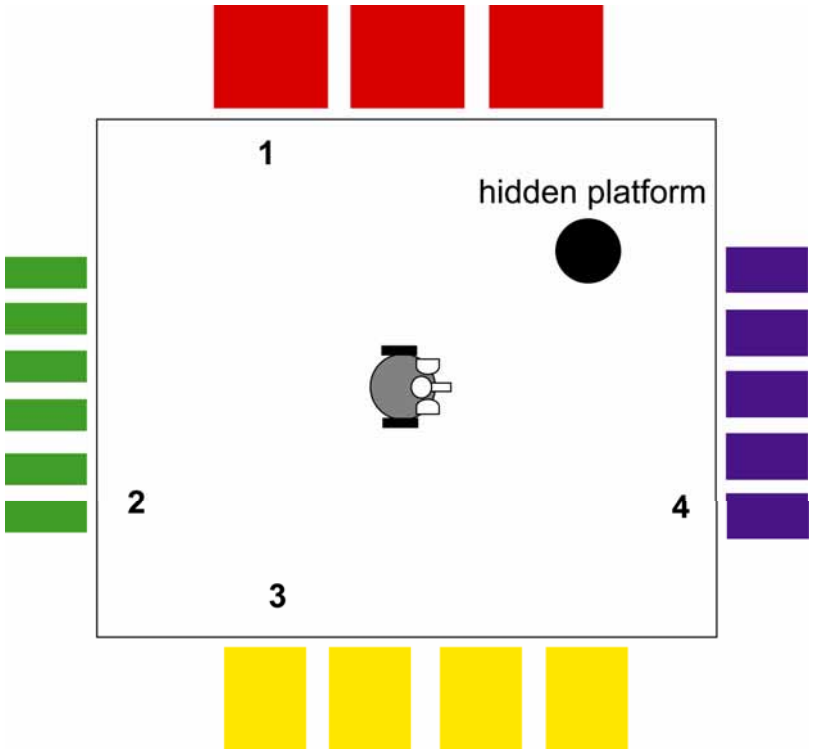
Darwin X and XI

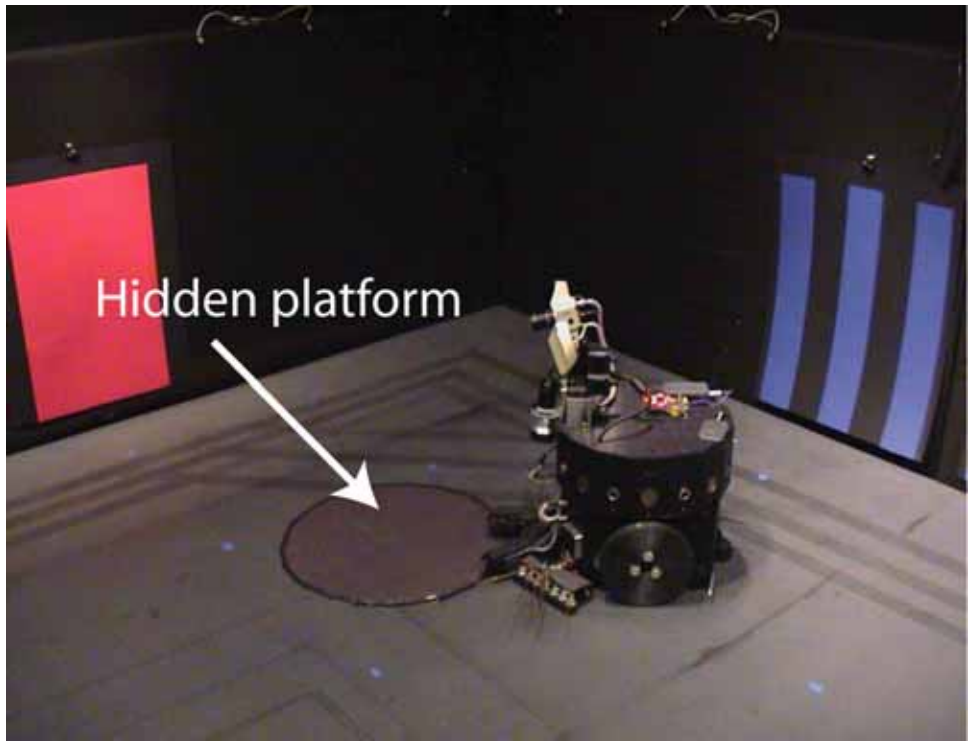
Neural Simulation and Network Architecture



- **57 neural areas, 80,000 neuronal units, and 1.2 million synaptic connections.**

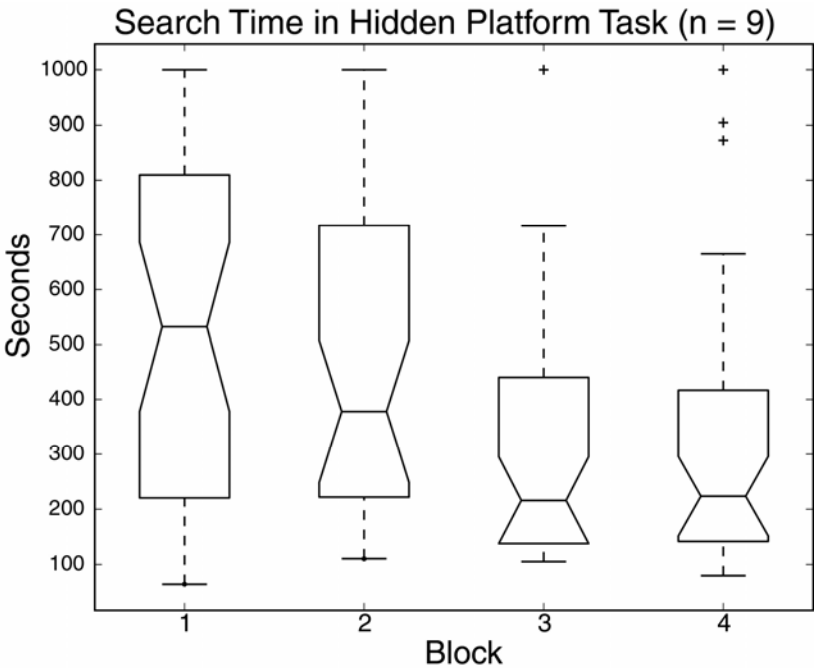
Test of Spatial Memory in BBDs: The Hidden Platform Task

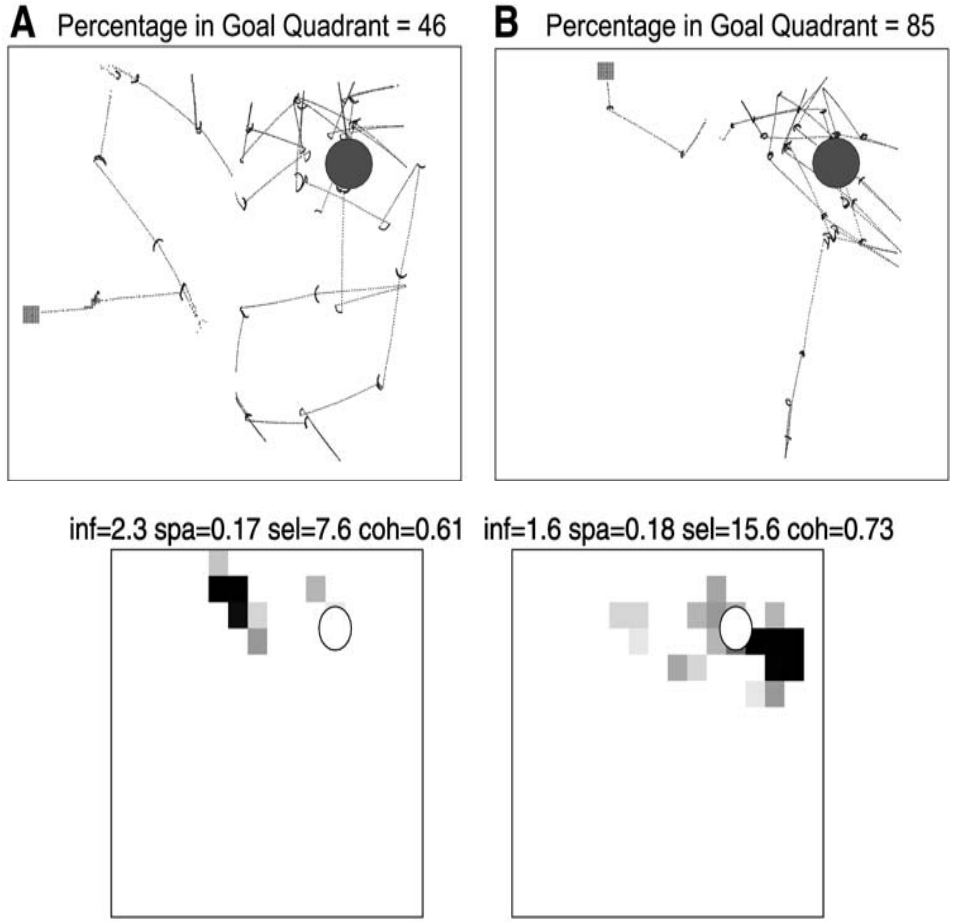




Performance in the Hidden Platform Task

Darwin X: Behavioral Results and Neuronal Activity

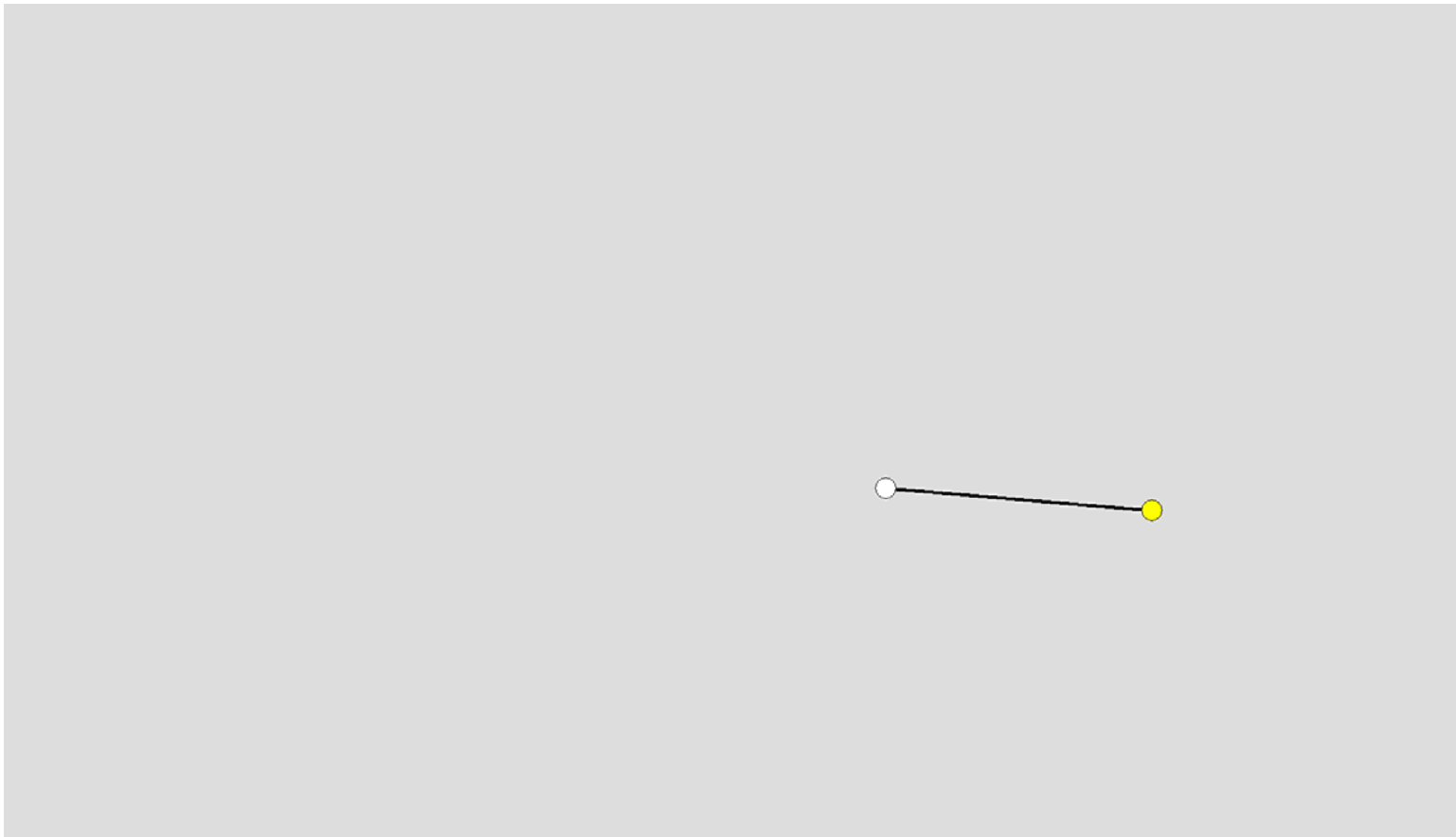




Analyzing Neural Dynamics Underlying Behavior

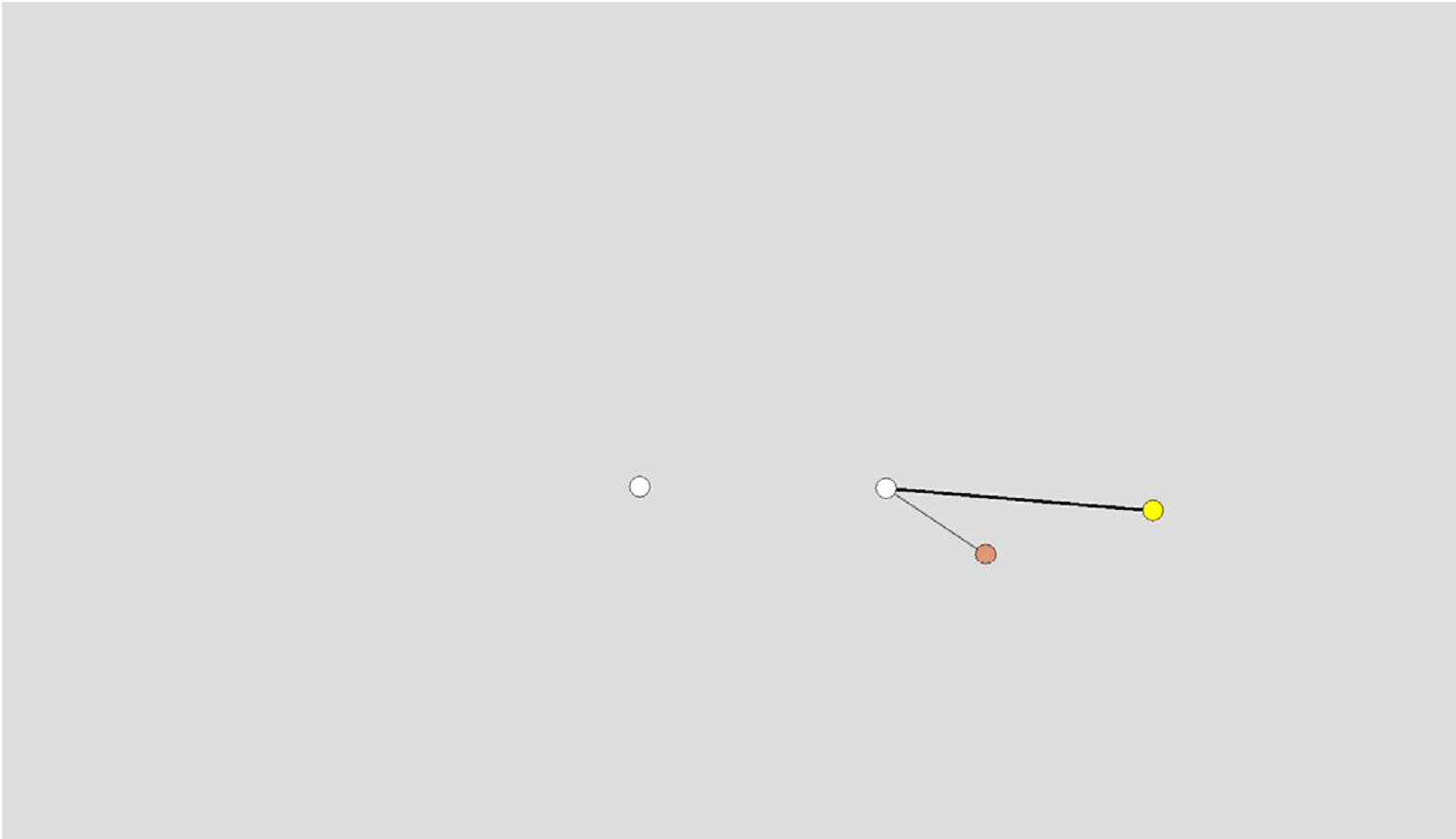
- **Developed novel methods for analyzing large scale neuronal networks:**
  - **Backtrace - trace functional pathways by choosing unit at a specific time and recursively examining all neuronal units that led to the observed activity in this reference unit.**
    - **JL Krichmar, DA Nitz, JA Gally, and GM Edelman (2005) *Proc Natl Acad Sci USA*, 102: 2111-2116.**
  - **Causality - a time series analysis that distinguishes causal interactions within and between neural regions.**
    - **AK Seth (2005) *Network*,16, 35-54.**
    - **JL Krichmar, AK Seth, DA Nitz, JG Fleischer, and GM Edelman (2005) *Neuroinformatics*, 3, 197-221.**

Backtrace from CA1 Reference Unit (t = -0.2s)



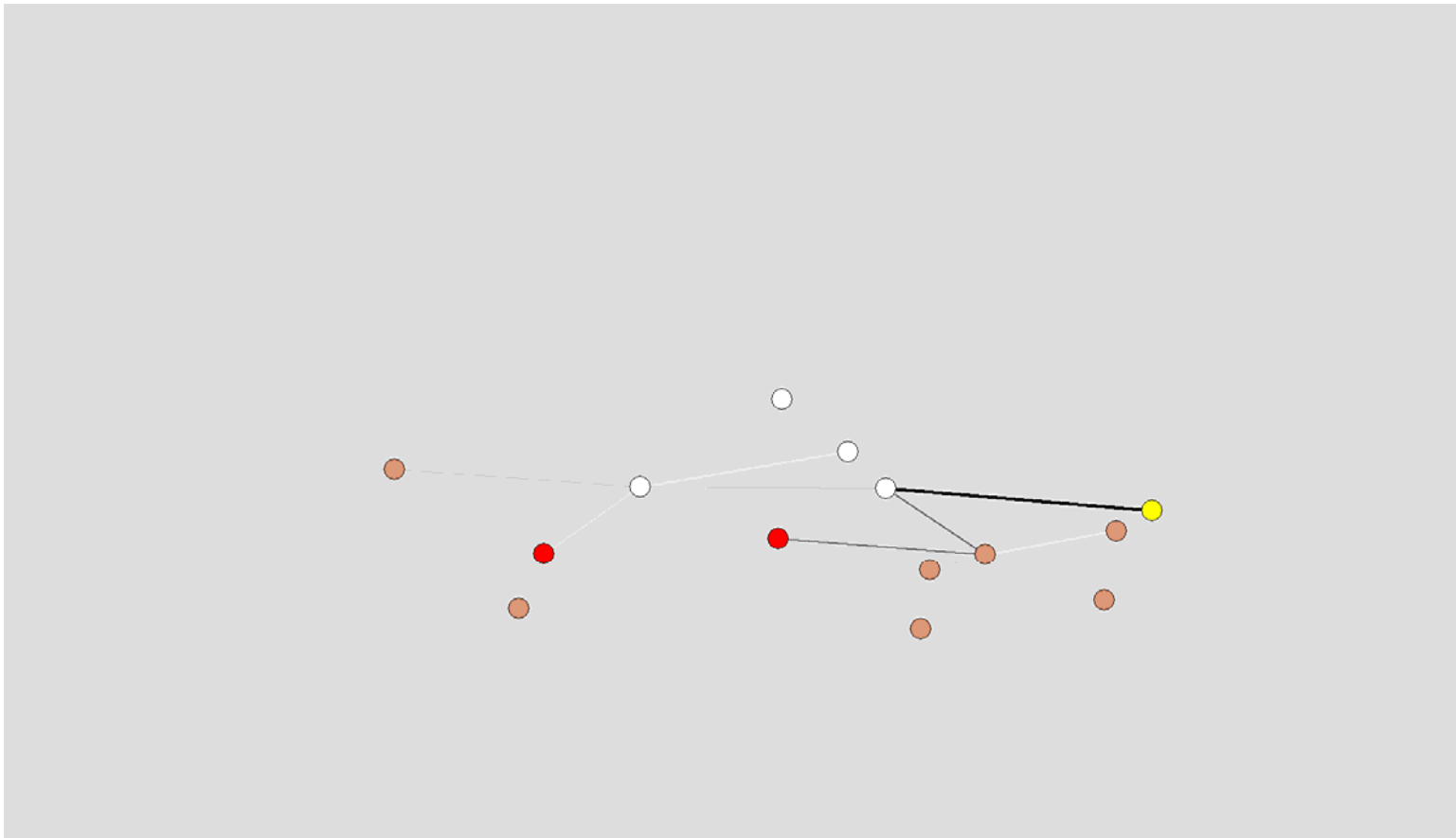
Reference unit – place field and strong connection to correct motor response.

Backtrace from CA1 Reference Unit (t = -0.4s)

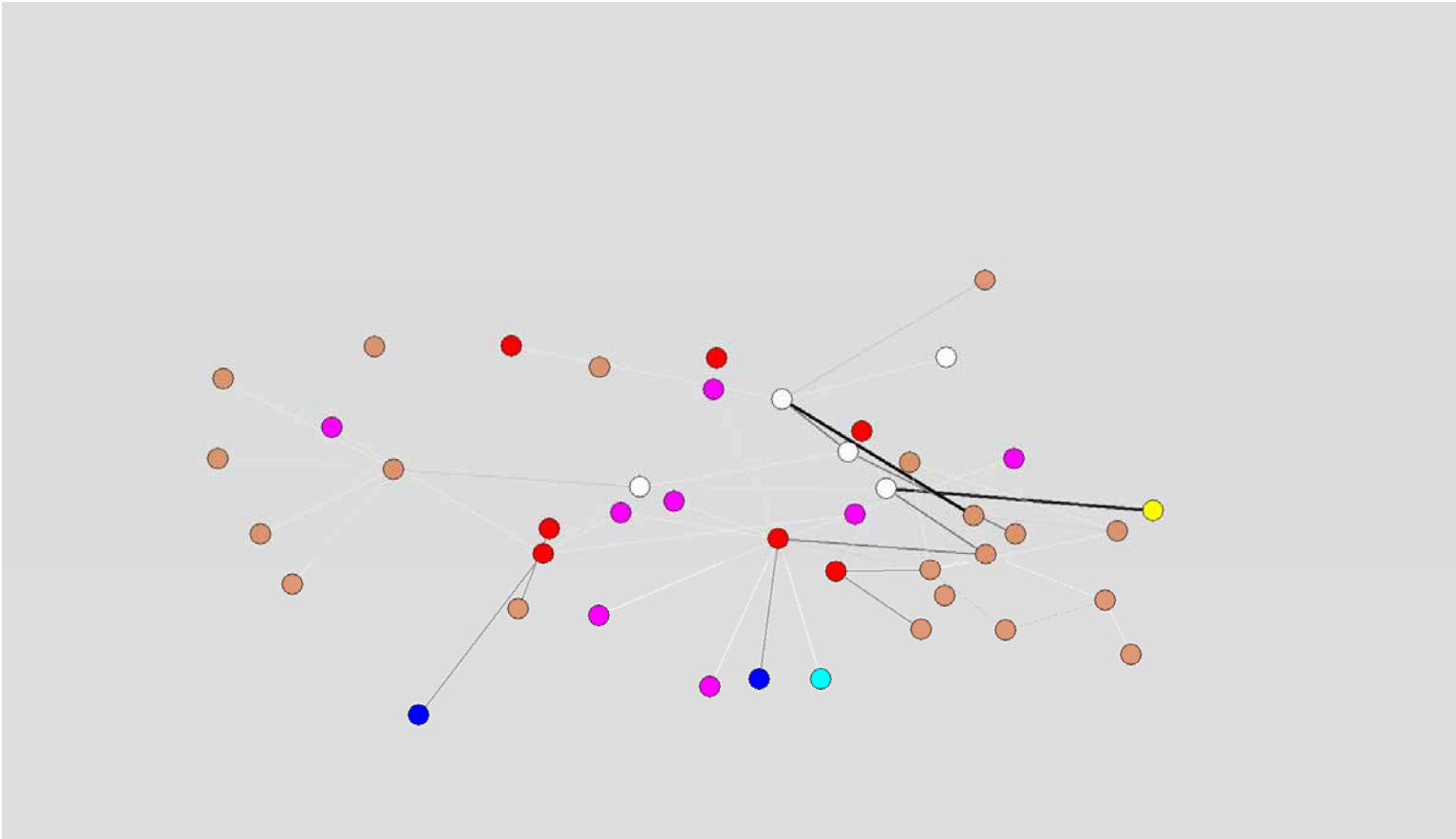


Specificity – 57% overlap of neuronal units in other backtraces with the same reference unit.

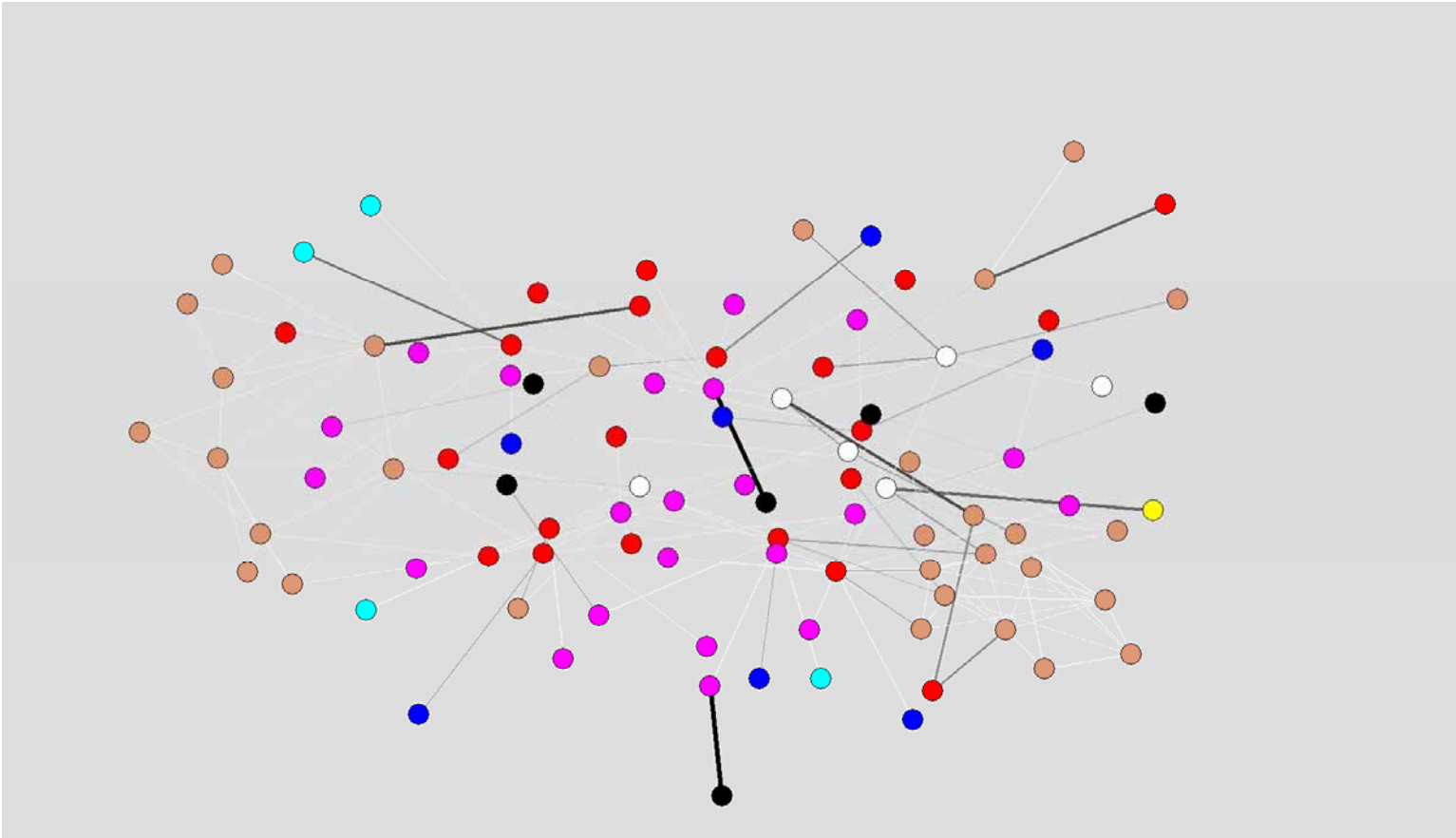
Backtrace from CA1 Reference Unit (t = -0.6s)



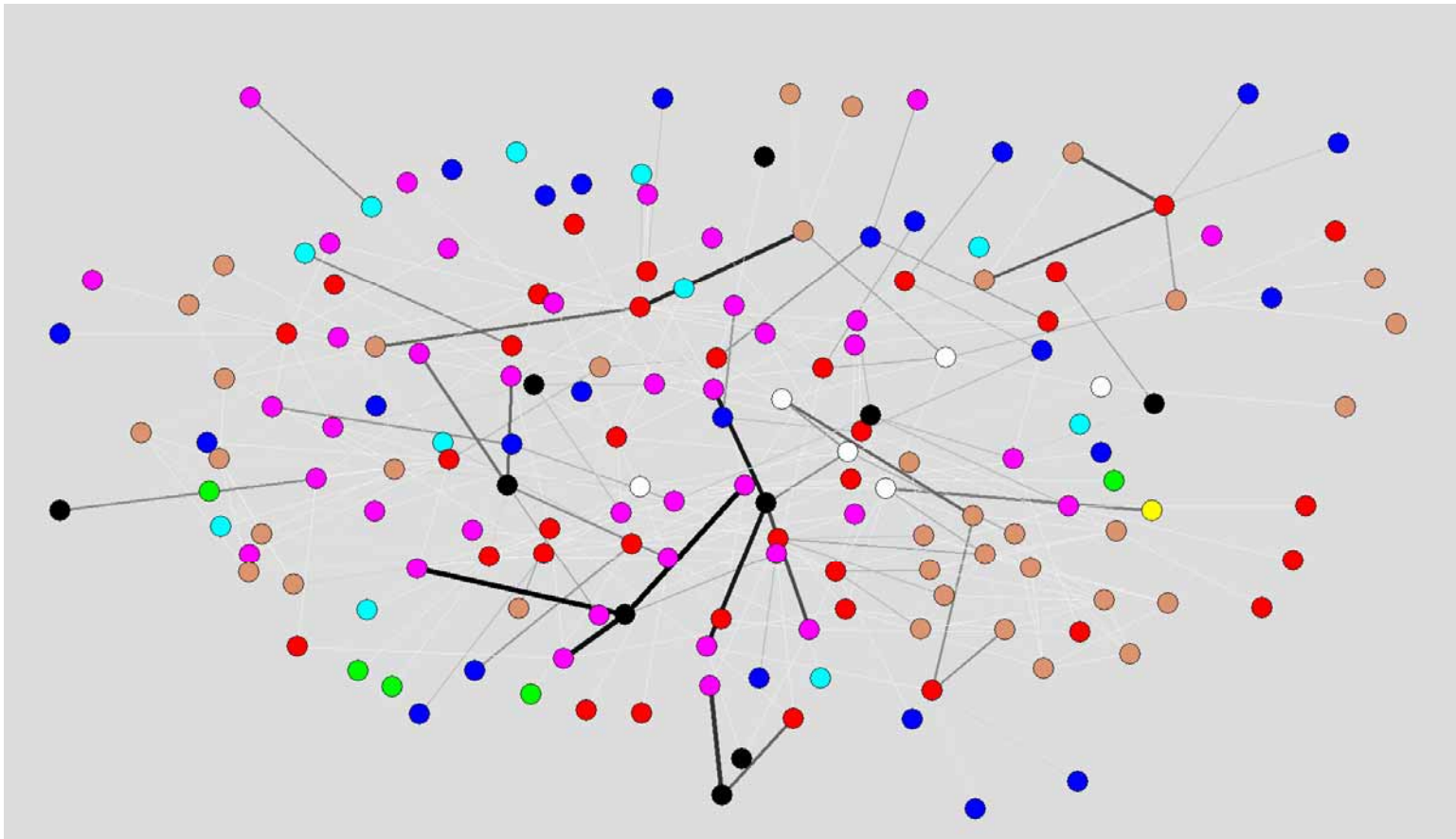
Backtrace from CA1 Reference Unit (t = -0.8s)



Backtrace from CA1 Reference Unit (t = -1.0s)

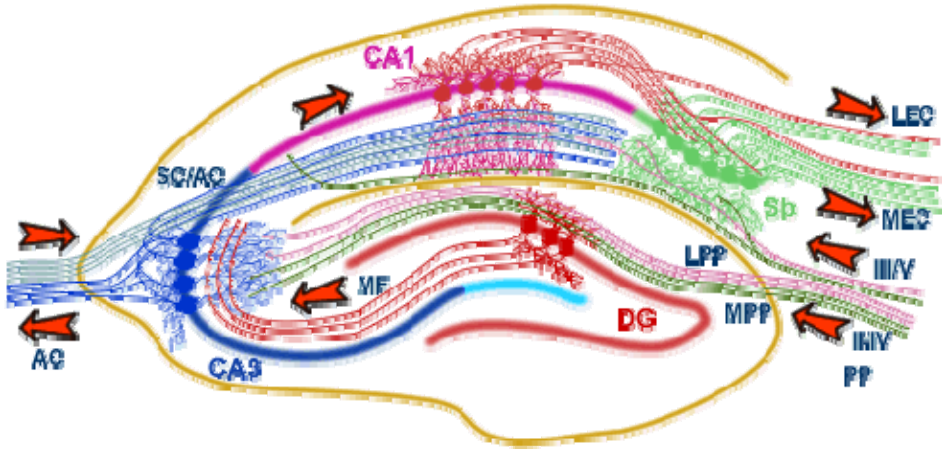


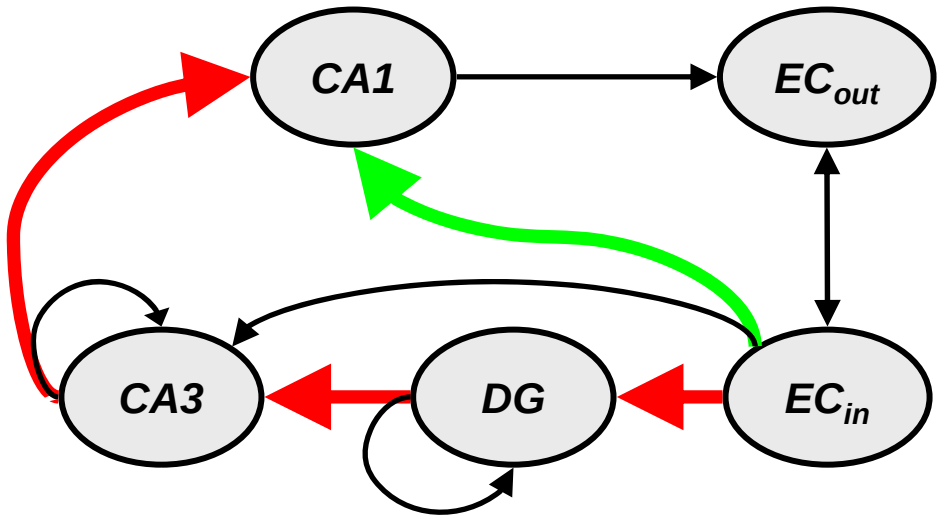
Backtrace from CA1 Reference Unit (t = -1.2s)



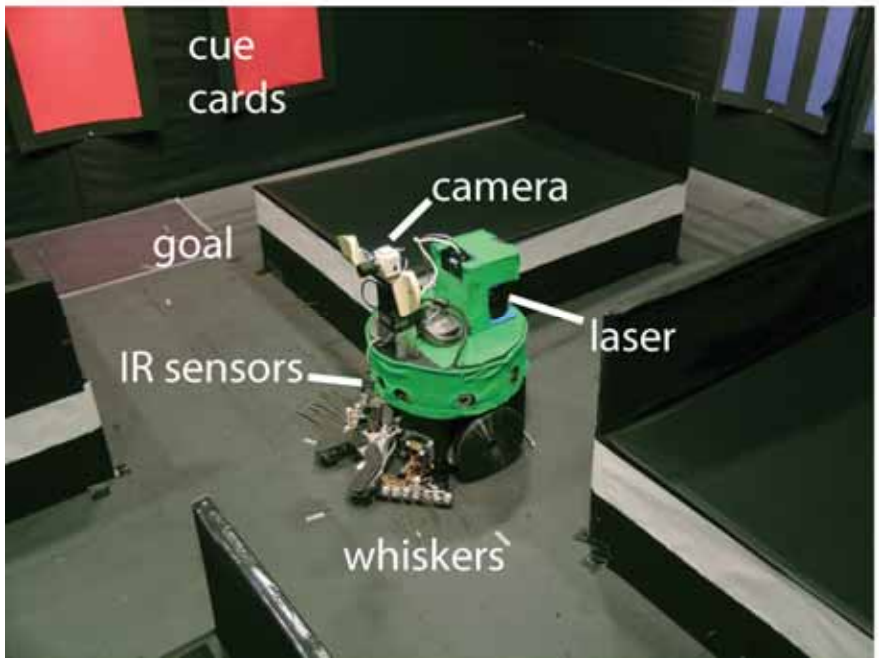
Degeneracy – 32% overlap of neuronal units in other backtraces with the same reference unit.

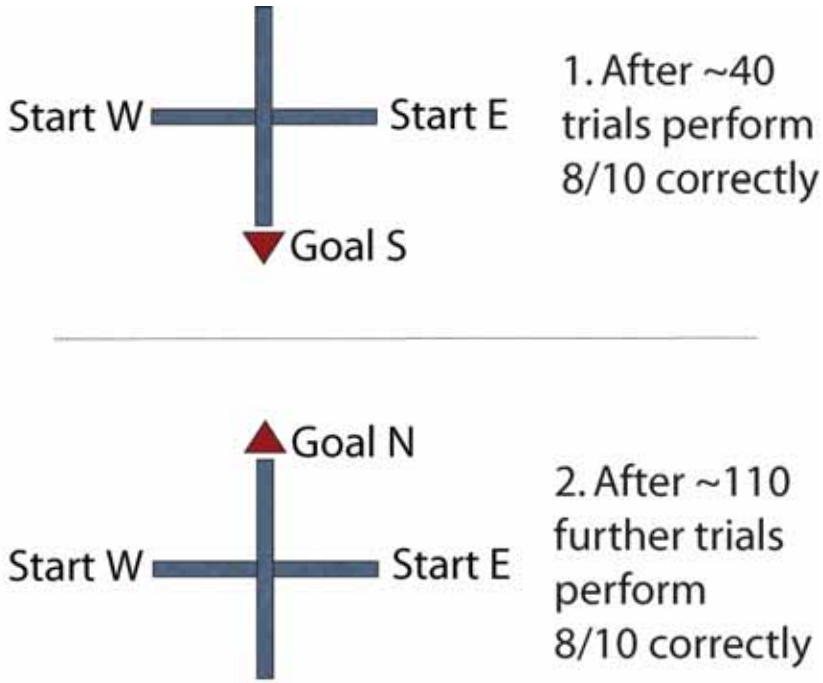
Functional Hippocampal Pathways Identified by the Backtrace Networks





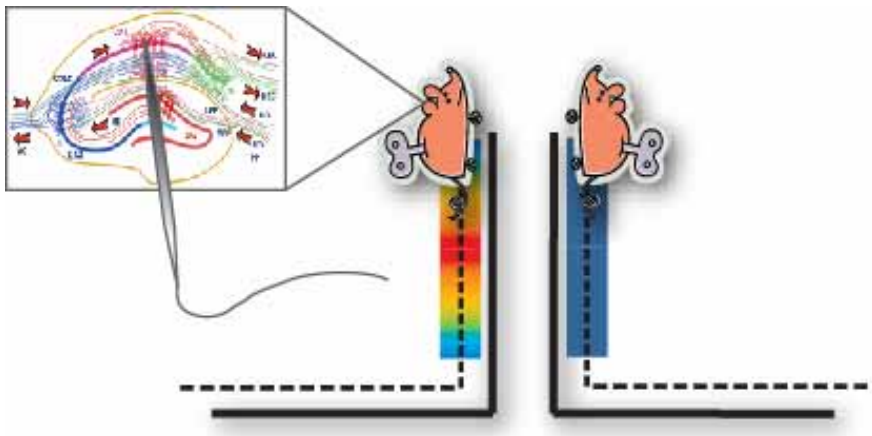
Darwin XI
Test of Episodic Memory
The Plus Maze





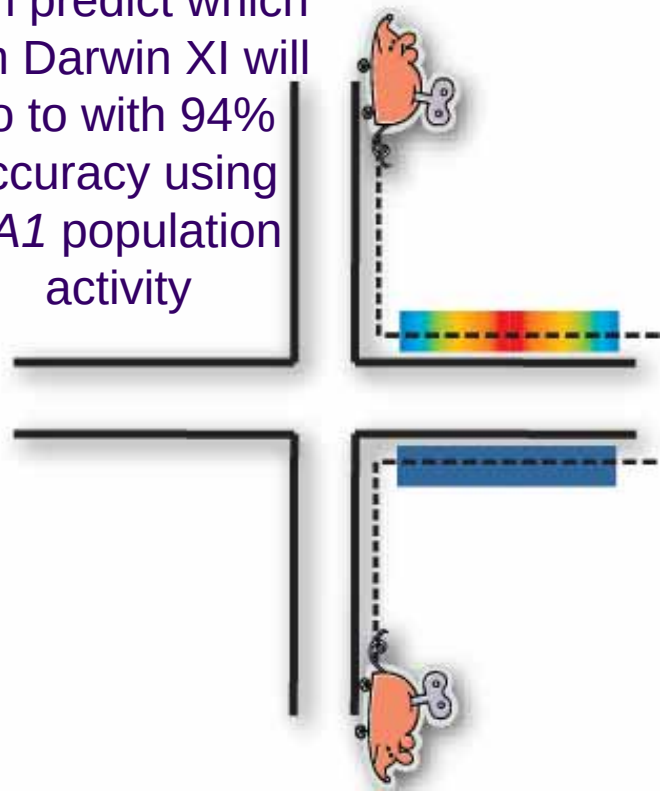
JG Fleischer, JA Gally, GM Edelman, JL Krichmar (2007) *Proc Natl Acad Sci USA, 104*, 3556-3561.

Neural Correlates of Current, Recent Past, and Imminent Future Events

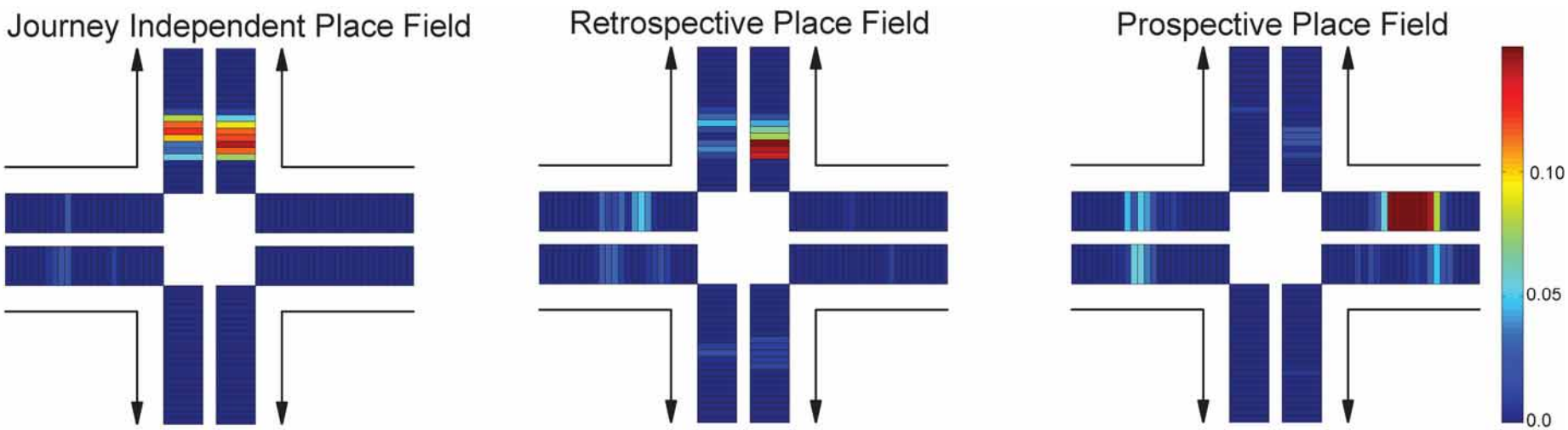


Can predict which arm Darwin XI came from with 83% accuracy using *CA1* population activity

Can predict which arm Darwin XI will go to with 94% accuracy using *CA1* population activity

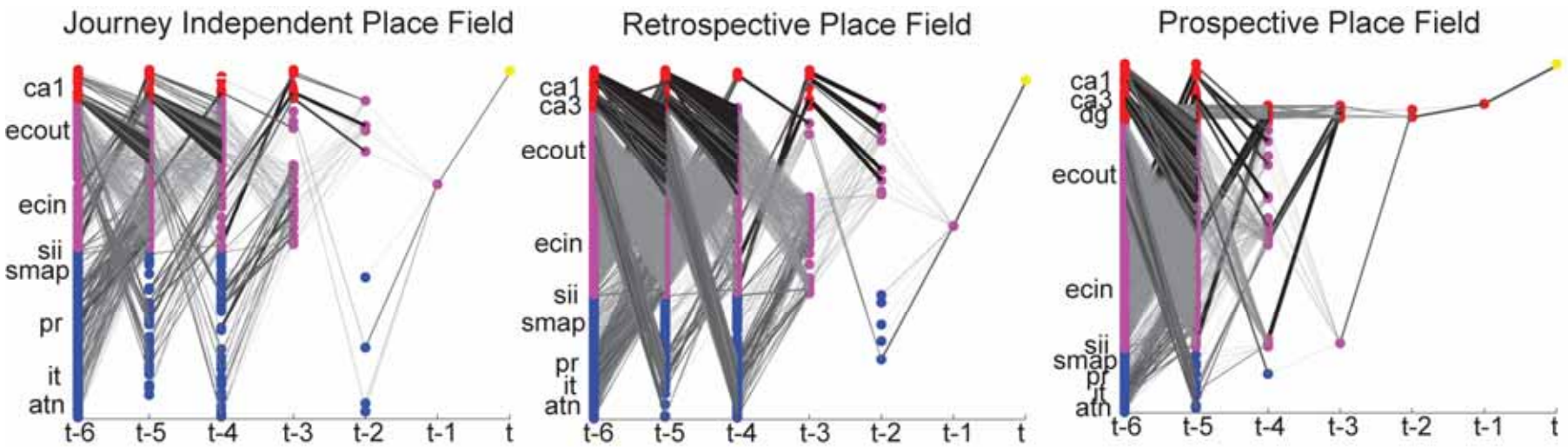


Neural Correlates of Current, Recent Past, and Imminent Future Events



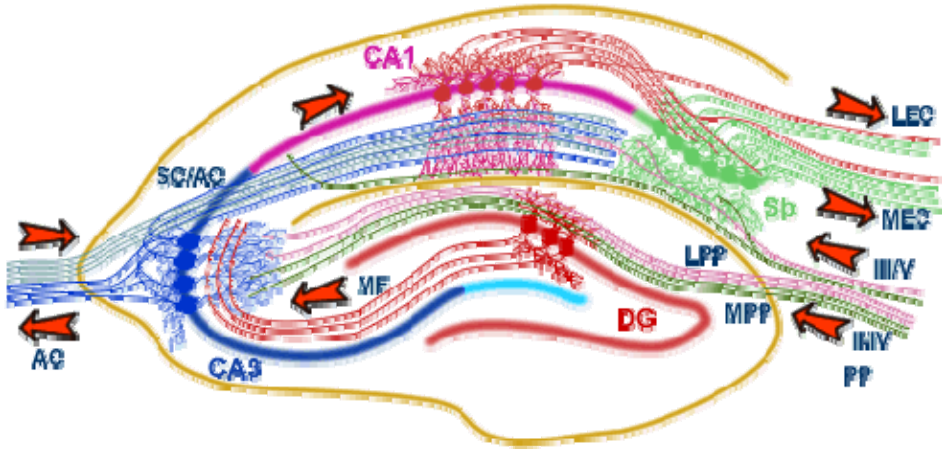
- **Darwin XI CA1 place fields**
  - **384 journey-dependent and 303 journey-independent**
    - **similar distribution to findings in rodent hippocampus**
    - **2304 total CA1 neuronal units**

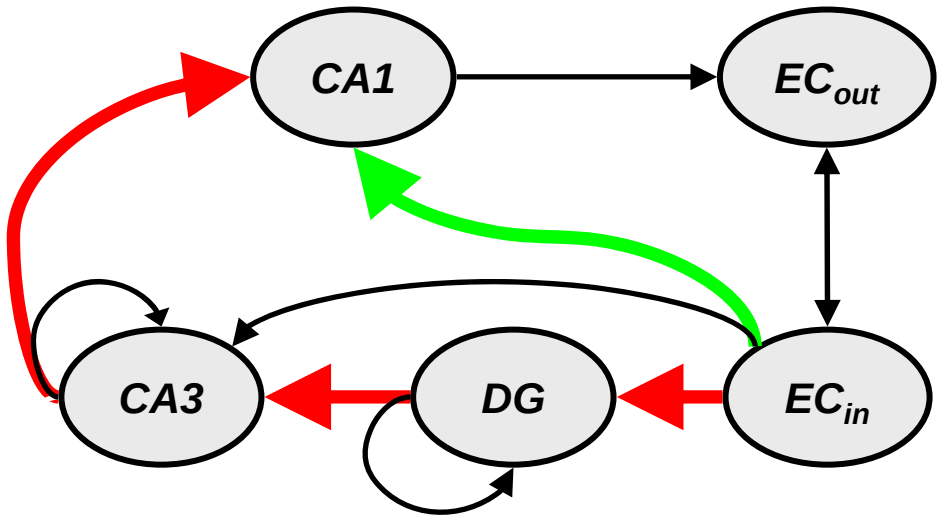
Network Dynamics of Current, Recent Past, and Imminent Future Events



- **Darwin XI Backtraces from CA1 place units show:**
  - **Significantly higher hippocampal influence on journey-dependent responses.**
  - **Strong entorhinal cortex influence on network dynamics.**

Functional Hippocampal Pathways Identified by the Backtrace Networks



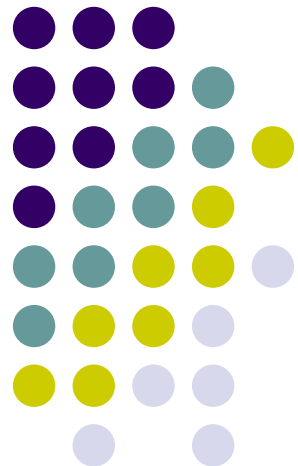


Darwin X and XI Models of the Hippocampus and its Surrounding Regions

- **Demonstrated spatial and episodic memory in a Brain-based Device**
  - **Acquired and recalled multimodal memories.**
  - **Developed goal-directed behavior.**
  - **Contextually and temporally sensitive responses.**
- **Analysis of network dynamics**
  - **Strong functional role of the entorhinal cortex.**
  - **Hippocampus necessary for:**
    - **novel environments.**
    - **context-dependent responses.**
  - **Degenerate pathways to neural responses that lead to behavior.**

Brain-Based Devices

Practical Applications

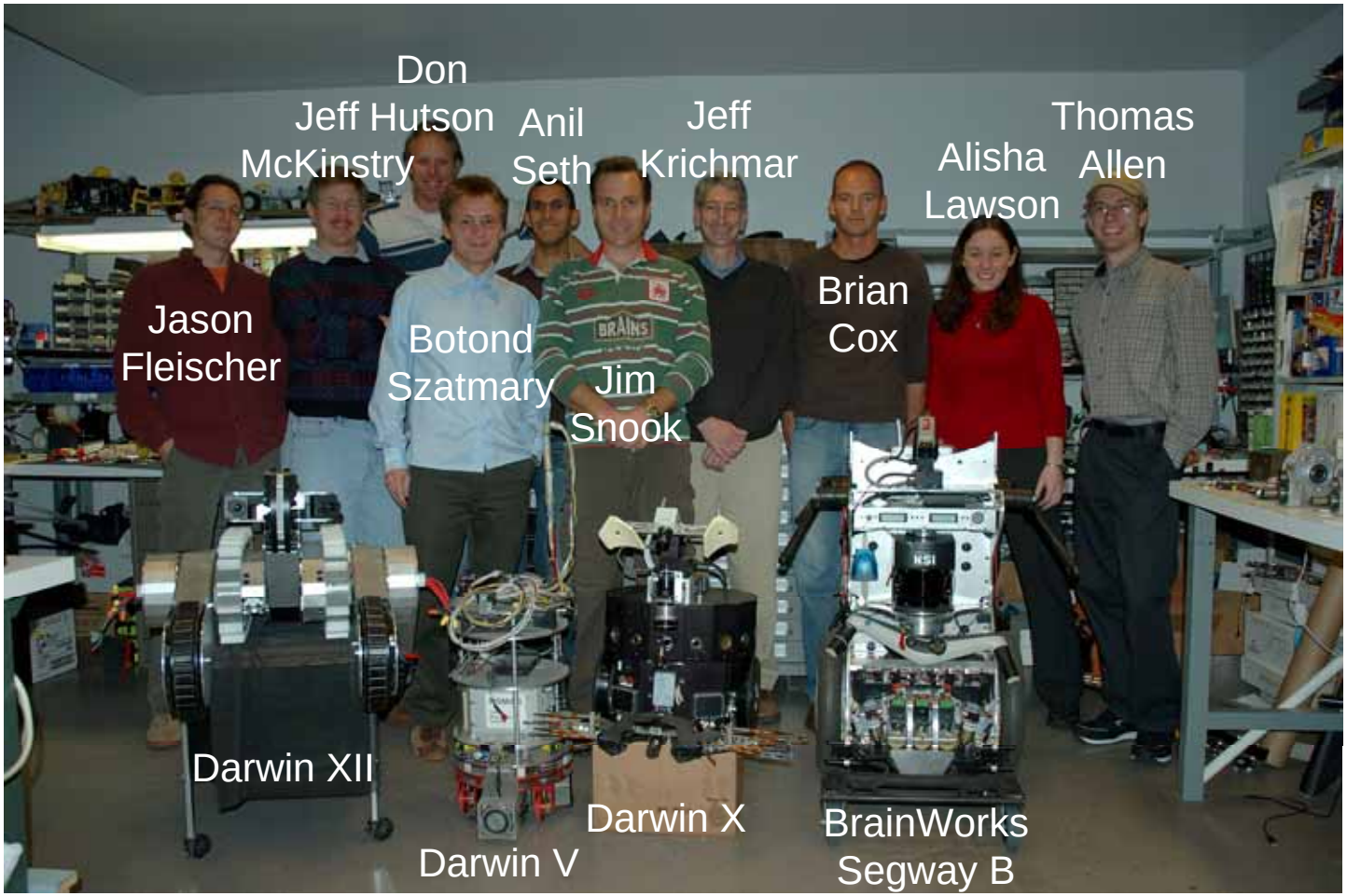


A New Challenge

- By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer champion team. -


RoboCup US Open
Segway Soccer League
Atlanta, Georgia
May 8-10, 2005

Build A Brain Team



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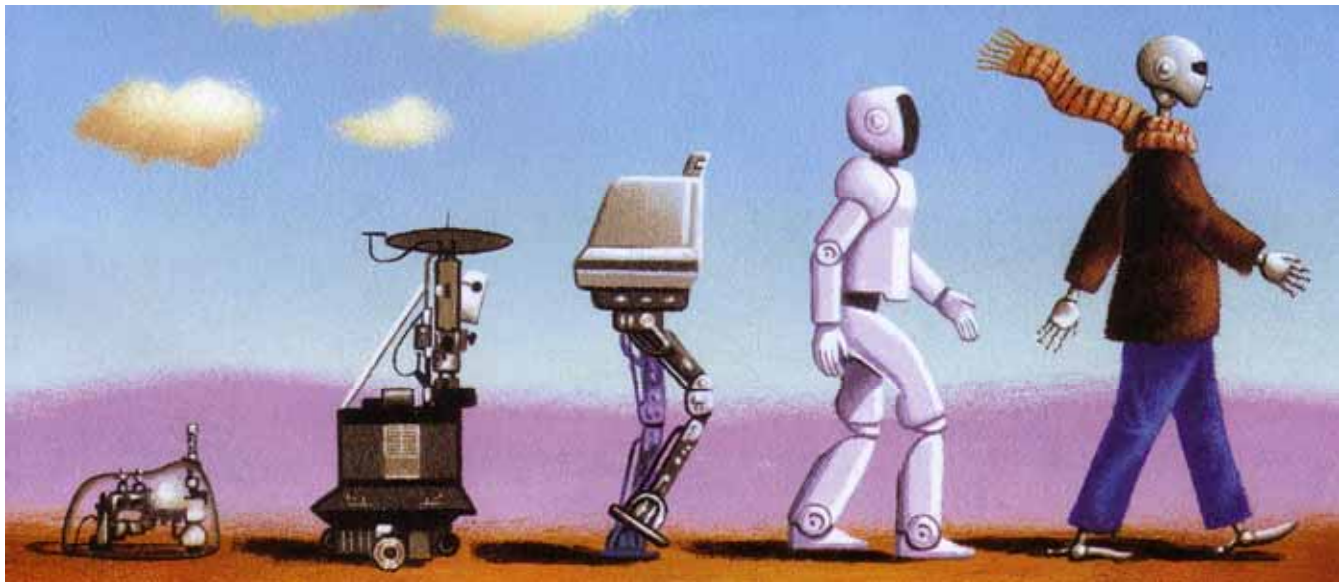
The Brain is Embodied and the Body is Embedded in the Environment



- **Higher brain functions depend on the cooperative activity of an entire nervous system:**
  - **its morphology, its dynamics, and its interaction with the environment.**
  - **provide heuristic bases for studying the brain.**
  - **may ultimately become a new and powerful class of *Intelligent Machines*.**
- **More information: http://www.nsi.edu/nomad**