Cognitive Modeling and Robust Decision Making

5 March 2012

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Integrity ★ Service ★ Excellence

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NAME: Jay Myung, PhD **Years as AFOSR PM: 0.75**

BRIEF DESCRIPTION OF PORTFOLIO:

Support experimental and formal modeling work in:

1) **Understanding cognitive processes underlying human performance in complex problem solving and decision making tasks;**
2) **Achieving maximally effective symbiosis between humans and machine systems in decision making;**
3) **Creating robust intelligent autonomous systems that achieve high performance and adapt in complex and dynamic environments.**

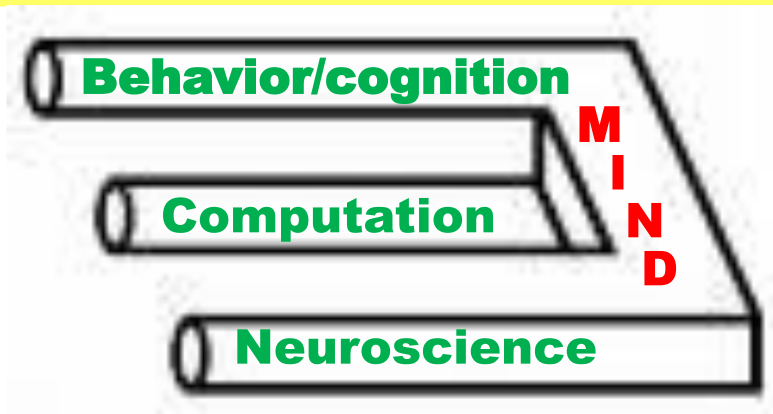
LIST SUB-AREAS IN PORTFOLIO:

- **Mathematical Modeling of Cognition and Decision (3003B)**
- **Human-System Interface and Robust Decision Making (3003H)**
- **Robust Computational Intelligence (3003D)**

Program Roadmap

Adaptive, Natural or Artificial, Intelligence as Computational Algorithms Requiring Interdisciplinary Approach

General purpose algorithms that the brain uses to achieve adaptive intelligent computation.



Mind as adaptive computational algorithm (software) running on the brain (hardware)

Behavior/Cognition: *extracting and defining the problem to be solved, consolidated as robust empirical laws.*

Computation: *solves a well-defined problem, in terms of optimization, estimation, statistical inference, etc.*

Neuroscience: *implementing the solution by the neural architecture (including hardware and currency).*

Computational Algorithms for Cognition and Decision

Challenge for an Adaptive Intelligent System to Solve:

Massive **Raw Data** → Useful **Information** → Actionable **Knowledge** → Robust **Decision**

(1) Neuronal signal processing algorithms: *optimal balance* between representation (encoding) and computation (decoding) in information processing of the brain.

(2) Causal reasoning and Bayesian algorithms: *optimal fusion* of prior knowledge with data/evidence for reasoning and prediction under uncertainty, ambiguity, and risk.

(3) Categorization/classification algorithms: *optimal generalization* from past observations to future encounters by regulating the complexity of classifiers while achieving data-fitting performance.

Program Trends

- Memory, Categorization, and Reasoning
- Optimal Planning/Control and Reinforcement Learning
- Mathematical Foundation of Decision Under Uncertainty
- Causal Reasoning and Bayesian/Machine Learning Algorithms
- Neural Basis of Cognition and Decision
- Computational Cognitive Neuroscience
- Computational Principles of Intelligence and Autonomy
- Cognitive Architectures
- Software System Architectures and Sensor Networks

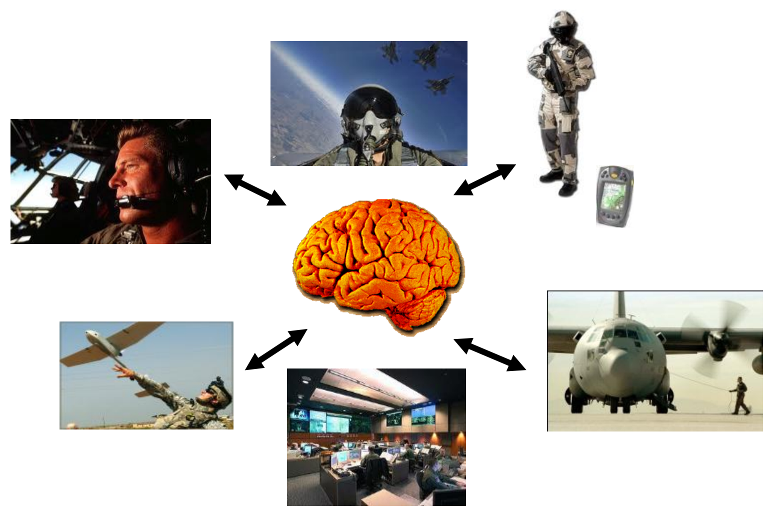
Mathematical Modeling of Cognition and Decision (3003B)

Goal:

Advance mathematical models of human performance in attention, memory, categorization, reasoning, planning, and decision making.

Challenges and Strategy:

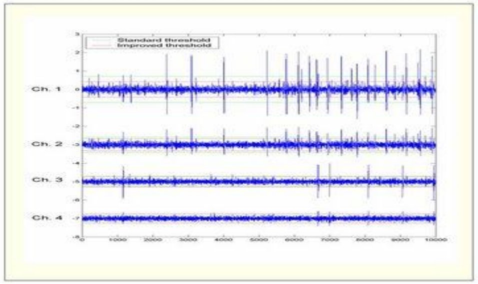
- **Seek algorithms for adaptive intelligence inspired by brain science**
- **Multidisciplinary efforts cutting across mathematics, cognitive science, neuroscience, and computer science.**



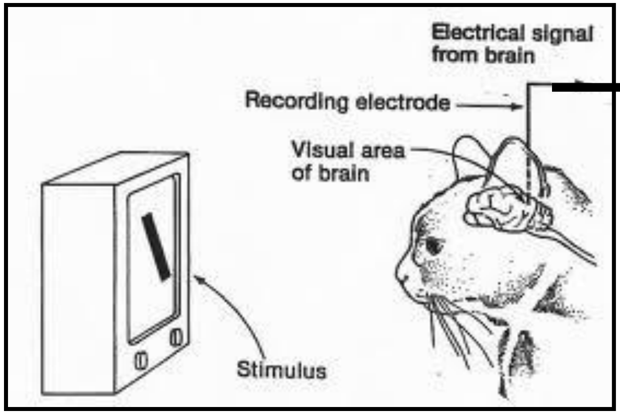
Neuronal Basis of Cognition
(Aurel Lazar, Columbia EECS)

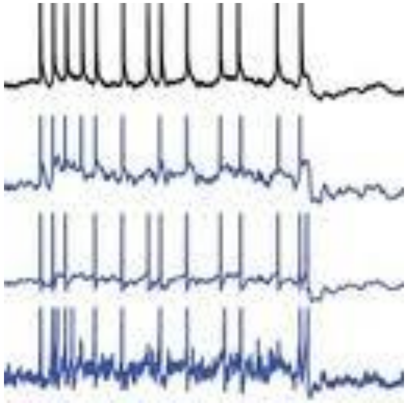
Prof. Aurel Lazar

Neuronal Signal Processing
(Hodgkin & Huxley, 1963, Nobel Prize)



"Cognition is an End-product of Neural Computation."

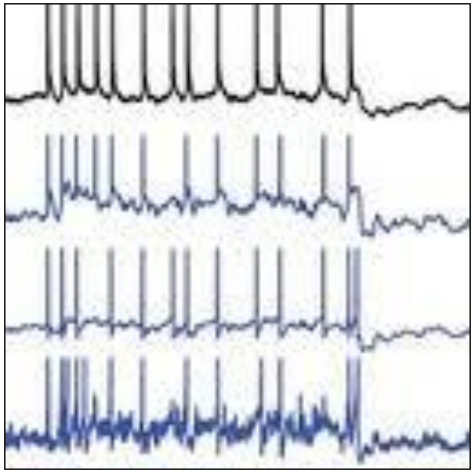




The Scientific Challenge: The Holy Grail of Neuroscience

- What is the neural code?

- Can we “reconstruct” cognition from neural spiking data?



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Neuronal Basis of Cognition
(Aurel Lazar, Columbia EECS)

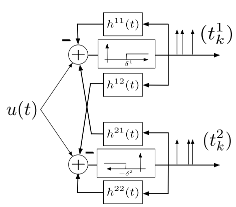
Neural Population Coding Hypothesis

Encoding with IAF/TAF Neurons with Feedback
Encoding of Video Streams with a Population of Neurons
Invariant Representations in the Time Domain
Conclusions

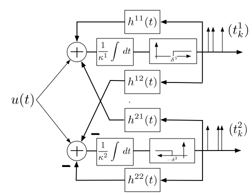
Encoding with Single Neurons
Encoding with ON-OFF Neurons

ON-OFF Neurons with Thresholding and Feedback
Models of ON-OFF Bipolar Cells in the Retina

Thresholding and Feedback



IAF and Feedback



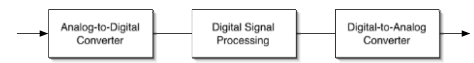
Aurel A. Lazar | Encoding Natural Scenes

"Brain as A/D and D/A Signal Converters"

Outline

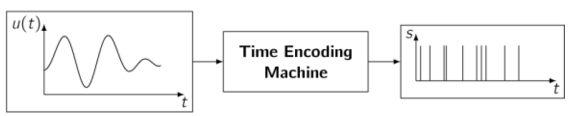
Information Representation and Processing
The Signal Processing Approach

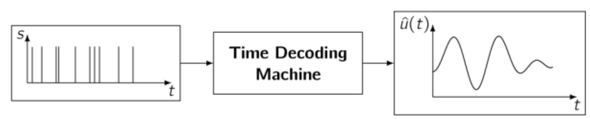
General signal processing chain with a digital signal processing core



- Continuous waveform $u = u(t)$, $t \in \mathbb{R}$, is represented as a set of discrete values $u(kT)$, $k \in \mathbb{R}$, with $T = \frac{\pi}{\Omega}$. The A/D converter is clocked.
- Processing is executed on a quantized version of the discrete samples $u(kT)$, $k \in \mathbb{Z}$.
- A continuous waveform is produced from the output of the DSP block.

Aurel A. Lazar | Encoding Natural Scenes

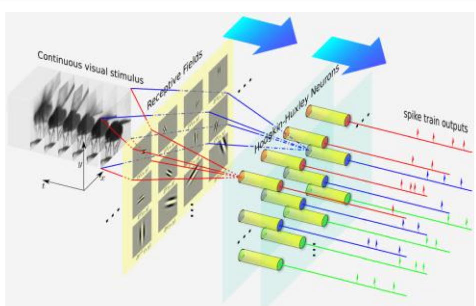




Encoding of Video Streams with Hodgkin-Huxley Neurons
Stimulus Recovery
Conclusions

The PIF t-Transform and its Inverse
Decoding Using the Conditional PRC
Population Encoding and Decoding Architectures

Video Time Encoding Machine Architecture



Aurel A. Lazar | Encoding Natural Scenes

Encoding of Video Streams with Hodgkin-Huxley Neurons
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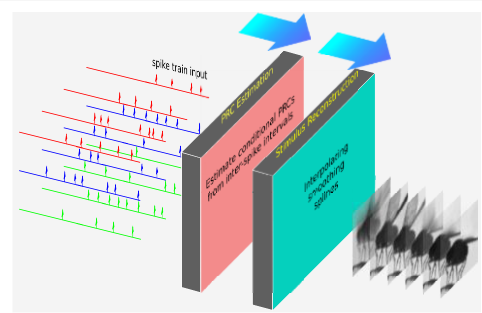
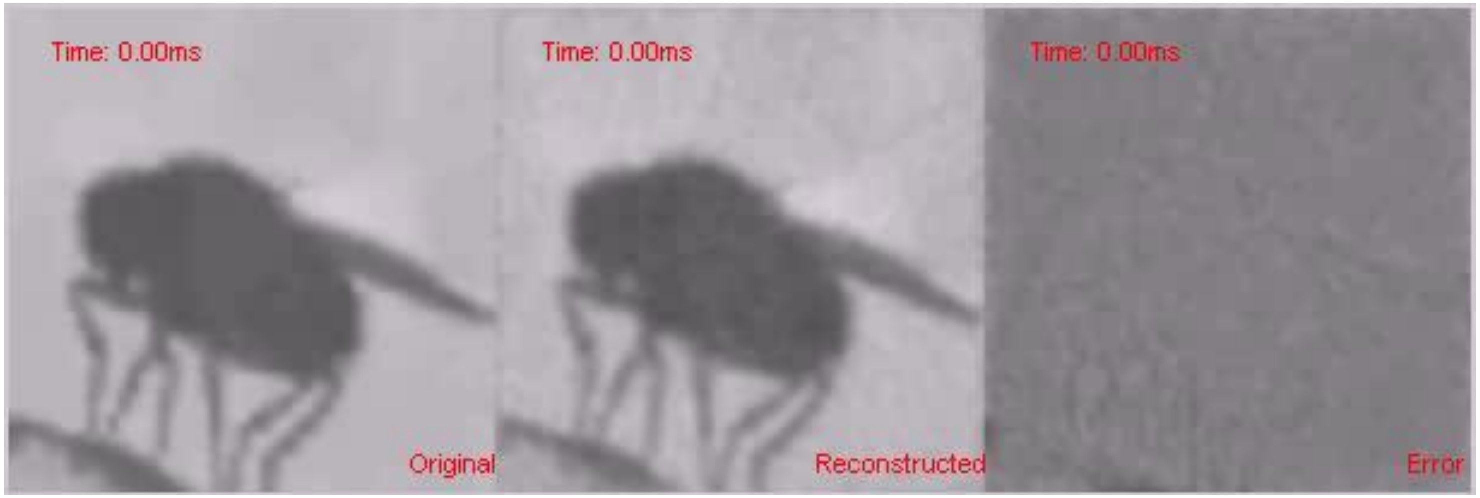


Aurel A. Lazar | Encoding Natural Scenes

Neuronal Basis of Cognition
(Aurel Lazar, Columbia EECS)

Video Stream Recovery from Spiking Neuron Model



• **First-ever demonstration of natural scene recovery from spiking neuron models based upon an architecture that includes visual receptive fields and neural circuits with feedback.**

• **Scalable encoding/decoding algorithms were demonstrated on a parallel computing platform.**

Human System Interface and Robust Decision Making (3003H)

Goal:

Advance research on mixed human-machine systems to aid inference, communication, prediction, planning, scheduling, and decision making.

Challenges and Strategy:

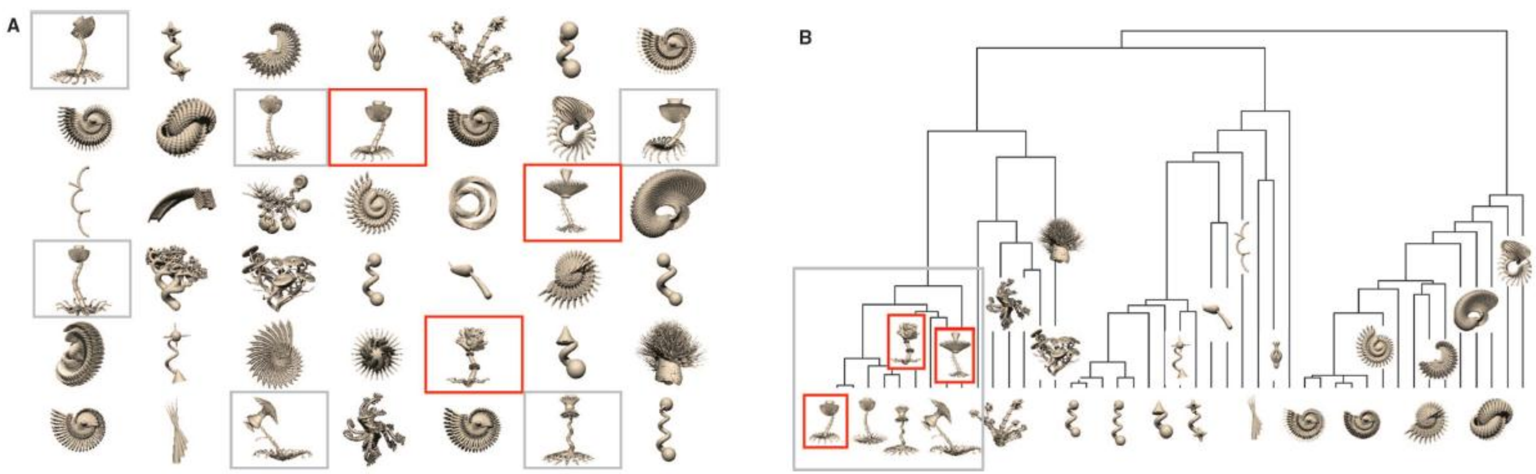
- **Seek computational principles for symbiosis of mixed human-machine systems with allocating and coordinating requirements.**
- **Statistical and machine learning methods for robust reasoning and strategic planning.**

Flexible, Fast, and Rational Inductive Inference (Griffiths YIP, Berkeley Psy)

Prof. Thomas Griffiths

The Problem:

• Understand how people are capable of fast, flexible and rational inductive inference.



The Scientific Challenge:

Develop a framework for making automated systems capable of solving inductive problems (such as learning causal relationships and identifying features of images) with the same ease and efficiency of humans.

Flexible, Fast, and Rational Inductive Inference (Griffiths YIP, Berkeley Psy)

A Bayesian Statistical Approach:

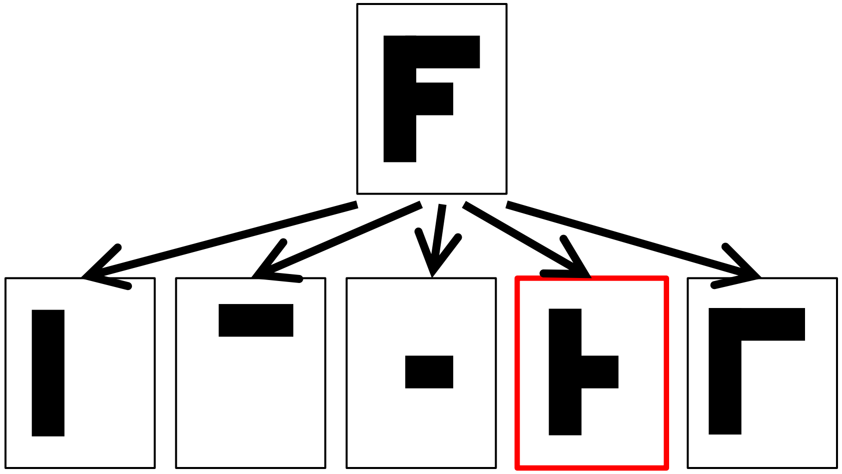
Analyze human inductive inference from the perspective of Bayesian statistics. Explore Monte Carlo algorithms and nonparametric Bayesian models as an account of human cognition. Test models through behavioral experiments.

Features:

Features are the elementary primitives of cognition, but are often ambiguous.

Inferring a feature representation is an ***inductive inference*** problem.

***Challenge*:** How do you form a set of **possible representations?**



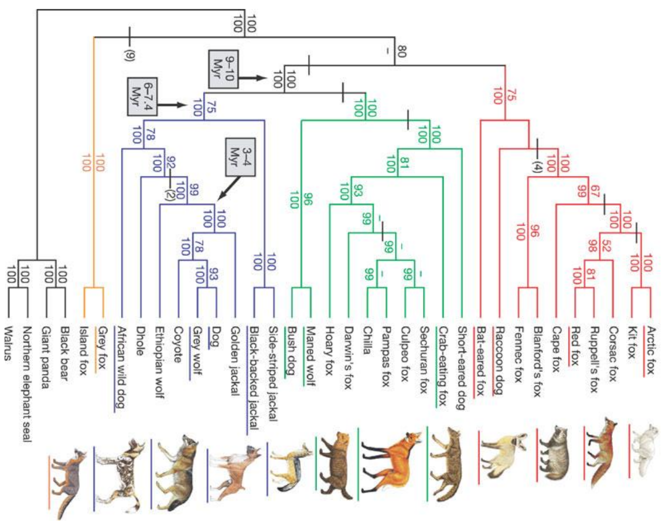
Flexible, Fast, and Rational Inductive Inference (Griffiths YIP, Berkeley Psy)

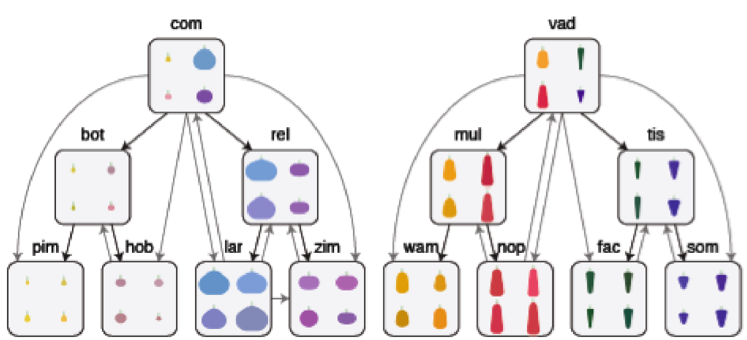
Nonparametric Bayesian Algorithms:

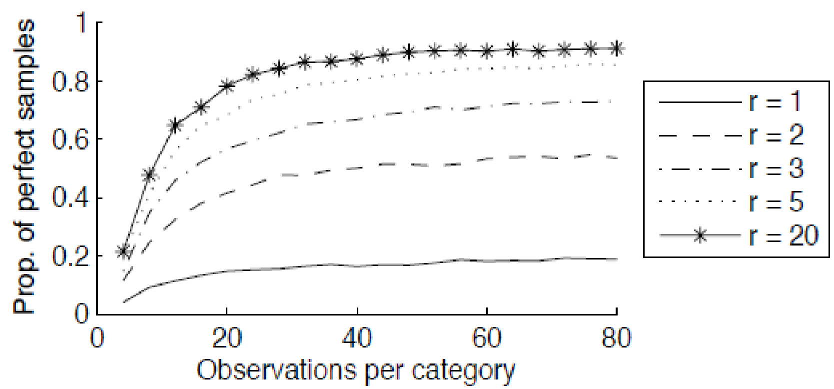
***Basic idea*:** Use flexible hypothesis spaces from nonparametric Bayesian models with potentially infinite many features.

Learning by examples: Combines structure of a bias towards *simpler* feature representations, but with the flexibility to grow in complexity as more data is observed.

Multi-level Category Learning



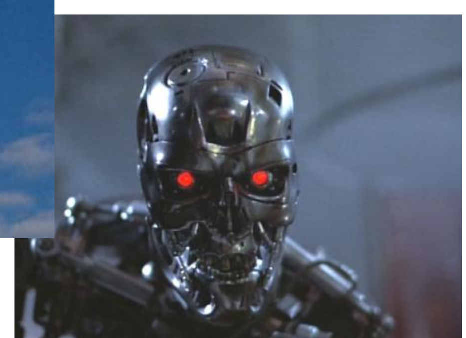




Robust Computational Intelligence (3003D)

<u>Goal:</u>
Advance research on machine intelligence architectures that derive from cognitive and biological models of human intelligence.

<u>Challenges and Strategy</u>:
- **Seek fundamental principles and methodologies for building autonomous systems that learn and function at the level of flexibility comparable to that of humans and animals.**

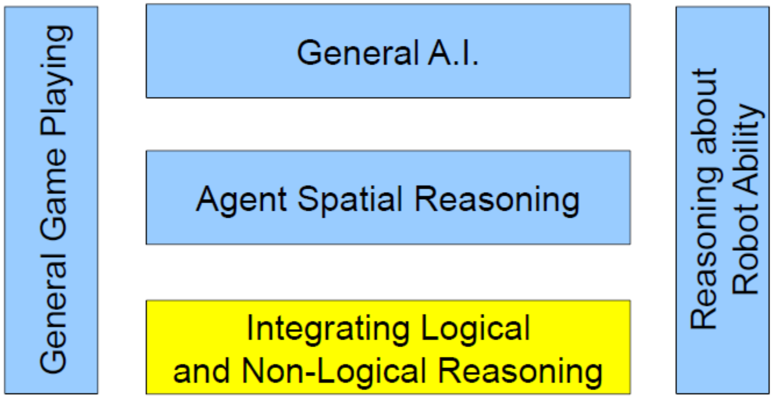


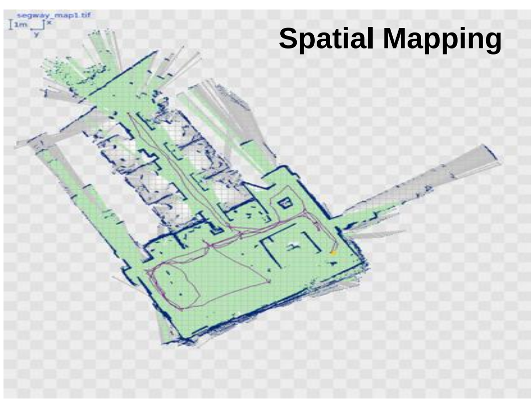
Practical Reasoning in Robotic Agents (Pagnucco, UNSW CS)

Objective: Extract summarized, actionable knowledge from raw data in complex problem domains (e.g., spatial mapping).

DoD benefits: Enables autonomous systems to automatically adapt to unfamiliar situations in the presence of erroneous information.

Technical approach: Formal A.I. methods for integrating logical and non-logical reasoning in robotic agents (e.g., MAVs).





Modeling Functional Architectures of Human Decision Making (Patterson, AFRL/RH)

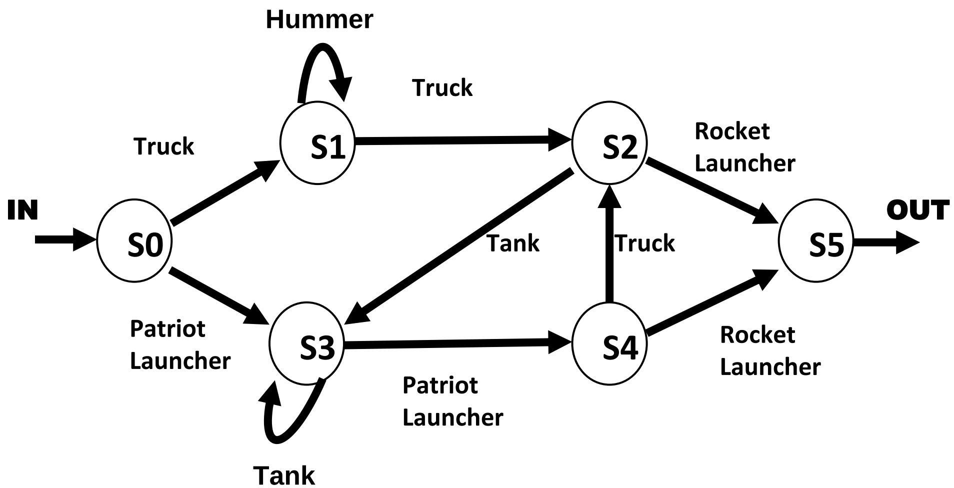
Objective: Understand functional architecture of human decision making.

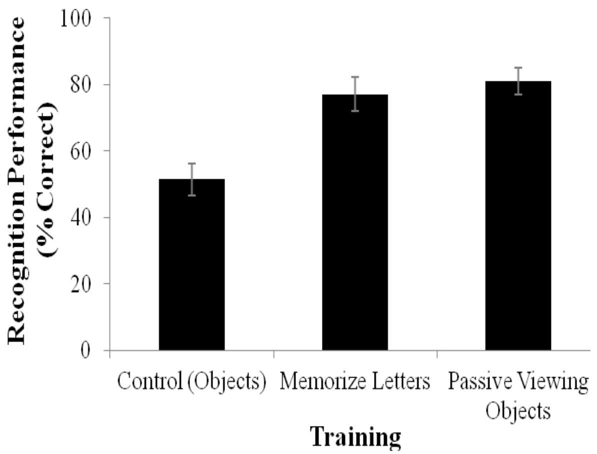
DoD benefits: Increased knowledge about designs of human-machine systems.

Technical approach: Combine analytical and intuitive decision making within formal tests of functional architecture.

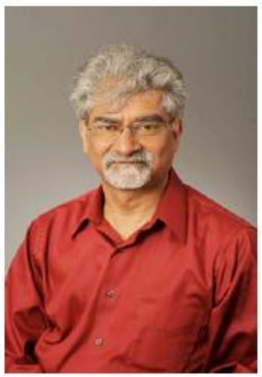
Intuitive Decision Making:

Synthetic Terrain Imagery & Object Sequences





CENTEC: Center of Excellence in Neuro-Ergonomics, Technology and Cognition (since July 2010)



Prof. Raja Parasuraman

- Goal: Support the Air Force mission of enhanced human effectiveness through
  - Research in neuroergonomics, technology, and cognition
  - Training of graduate students and postdoctoral fellows
  - Collaborations with scientists of AFRL/RH
- **"Direct transitions"** of university research to AFRL

NEUROADAPTIVE LEARNING, NEUROIMAGE, BEHAVIORAL GENETICS, ATTENTION, TRUST IN AUTOMATION, MULTI-TASKING, MEMORY, SPATIAL COGNITION

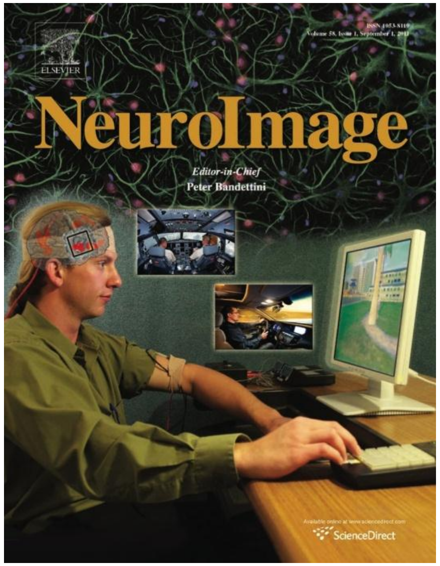
Other Organizations that Fund Related Work

- ONR (PM: Paul Bello)
  - Representing and Reasoning about Uncertainty Program
  - Theoretical Foundations for Socio-Cognitive Architectures Program
- ONR (PM: Tom McKenna)
  - Human Robot Interaction Program
- ONR (PM: Marc Steinberg)
  - Science of Autonomy Program
- ARO (PM: Janet Spoonamore)
  - Decision and Neurosciences Program
- NSF (PMs: Betty Tuller & Lawrence Gottlob)
  - Perception, Action & Cognition Program
- NSF (PM: Sven Koenig)
  - Robust Intelligence Program

Recent Highlights

CENTEC team (PI: R. Parasuraman, GMU)

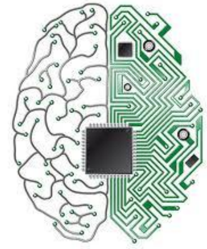
- **Special issue** in *Neuroimage* on neuroergonomics
- Joint papers by GMU and AFRL/RH scientists



Prof. T. Walsh team (NICTA, Australia)

- ***Eureka Prize*** for Peter Stuckey (Highest prize in CS in Australia)
- Best Paper Prize @ AAAI 2011

Program Summary
Transformational Impacts and Opportunities



The Basic Premise of Investment Philosophy

Cognition/Intelligence as computation algorithm:
Requires multidisciplinary research efforts to uncover brain algorithms, from *computer science*, *mathematics*, *statistics*, *engineering*, and *psychology*.

1. Neurocomputational foundation of cognition

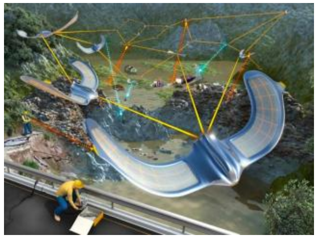
- We stand "almost" at the threshold of a major scientific breakthrough reminiscent of genetics in the 1950s, i.e., Watson & Click (1953; Nobel Prize, 1962).

2. Self-learning decision support systems

- Machine learning algorithms for inference and decision making capability comparable to that of humans.

3. Trust-worthy autonomous agents

- Capable of sense-making massive raw data for prediction, planning, communication, and decision.



Questions?

Thank you for your attention

Jay Myung, Program Manager, AFOSR/RSL

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Back-up Slides to Follow

Neuronal Basis of Cognition
(Aurel Lazar, Columbia EECS)

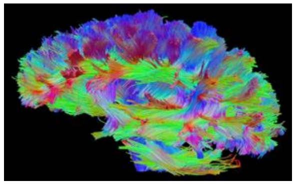
Six Disruptive Basic Research Areas

(Honorable Lemnios, Asst Sec Def. (R&E))

1. *Metamaterials and Plasmonics*
2. *Quantum Information Science*
3. ***Cognitive Neuroscience***
4. *Nanoscience and Nanoengineering*
5. *Synthetic Biology*
6. *Computational Modeling of Human and Social Behavior*

3. Cognitive Neuroscience:
More deeply understand and more fully exploit the fundamental mechanisms of the brain.

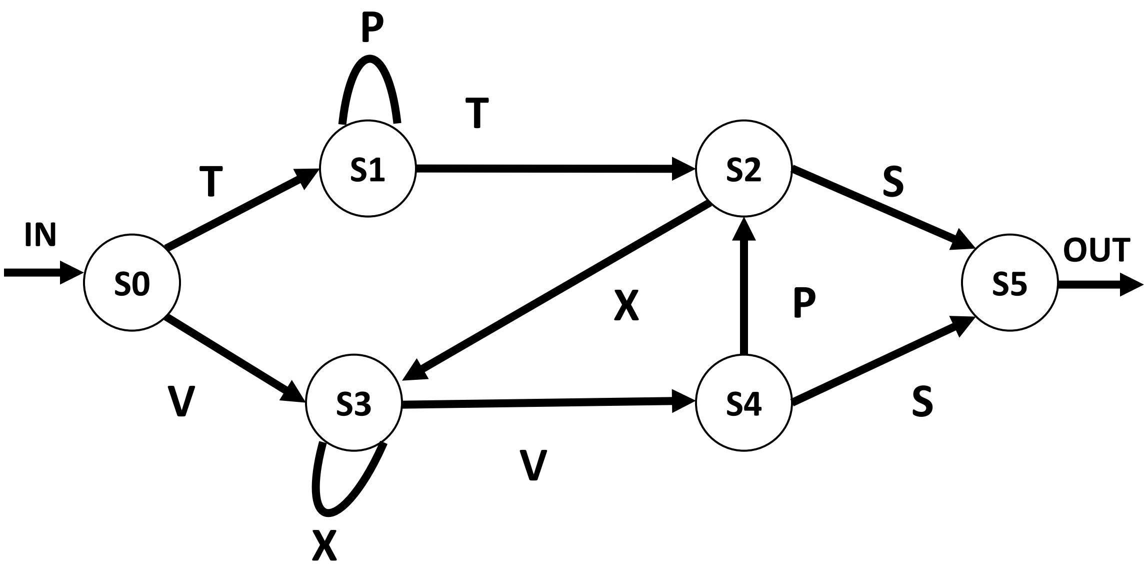
- Key Research Challenges:
  - **Solving the inverse problem of predicting human behavior from brain signals**
  - Translating clinical measurements & analyses to uninjured personnel
  - Developing models incorporating individual brain variability



IMPLICIT LEARNING of ARTIFICIAL GRAMMAR

(e.g., Reber, 1967)

Rules for ‘sentence’ construction: Finite State Algorithm



Sentences of length 6-8 used (34 total possible); examples: ***TPTXVPS; VXXVPS***

Participants learned the grammar with fewer errors than participants who learned random letter strings—but few could provide answers about the rules

Pattern 'chunks' can be abstracted via a rudimentary inductive process without explicit strategies

CHARACTERISTICS OF 2 PROCESSES

(derived from Evans, 2008)

<u>"System 1" (Intuitive)</u>	***<u>System 2" (Analytic)</u>***
***Situational Pattern Recog**	***Deliberative**
Unconscious	**Conscious**
Implicit	**Explicit**
Automatic	**Controlled**
Low effort	**High effort**
Rapid	**Slow**
High capacity	**Low capacity**
Holistic, *perceptual*	**Analytic, reflective**
Domain specific (inflexible)	**Domain specific & general (flexible)**
Contextualized	**Abstract**
Nonverbal	**Linked to language**
Independent of working memory	**Limited by working memory capacity**