Cognitive Modeling and Robust Decision Making

5 March 2012

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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.

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:

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

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

3) Categorization/classification algorithms: \textit{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
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)

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?
Neuronal Basis of Cognition
(Aurel Lazar, Columbia EECS)

Neural Population Coding Hypothesis

“Brain as A/D and D/A Signal Converters”

- Continuous waveform \( u(t), t \in \mathbb{R} \), is represented as a set of discrete values \( u(kT), k \in \mathbb{Z} \), with \( T = 2^{-p} \). 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.
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.
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?
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.
Goal:
Advance research on machine intelligence architectures that derive from cognitive and biological models of human intelligence.

Challenges and Strategy:
• 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.
**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).
**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.
Joint Initiative with AFRL/RH in Neuroergonomics Research
(Parasuraman, George Mason U Psy)

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

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

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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
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
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

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