SAND2008-1193P

Applications of Neurosystems Engineering ECE-595

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February 20, 2008

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Lecture Objectives

- What is Systems Engineering?
- How can systems engineering approaches be applied to develop Neurosystems?
- Examples of Neurosystem Engineering applications
- Discussion

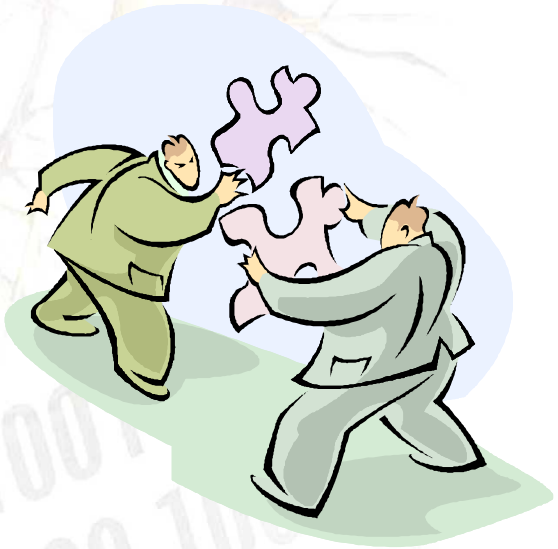
Speaker Background Info

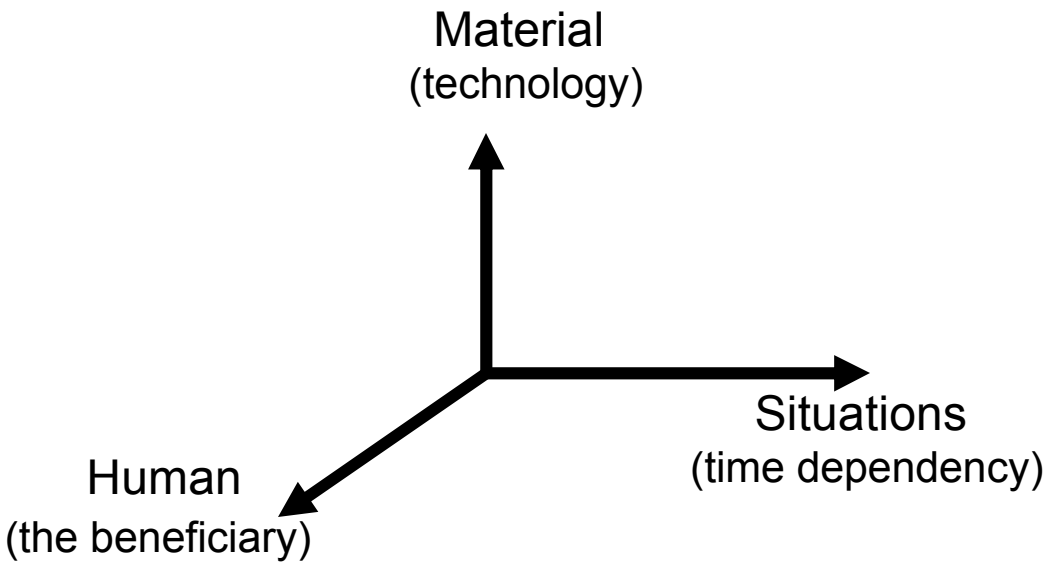
- Technical background in Signal and Image Processing: Ph.D. in EECS from MIT.

- Been at Sandia for 21 years
  - developed autonomous sensors, automatic pattern recognition algorithms, adaptive microsystems
  - Managed the Micro-electro-optical-mechanical engineering group (MESA)
  - Served as Deputy Director responsible for SNL Engineering Programs
  - Currently manage a group of about 75 people: we develop systemetics and cognition technologies for national security applications

What is a System?

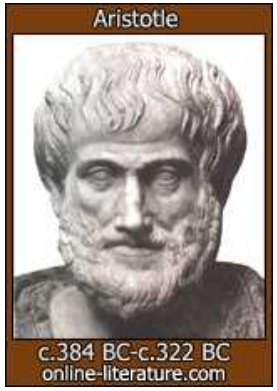
- A *system* is an arrangement, set, or collection of *real or abstract* things, connected or related, in such a manner as to form an entirety or whole.





Systems include material, situational, and human aspects

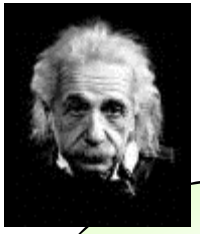
In a well-designed system, “the whole is more than the sum of its parts”

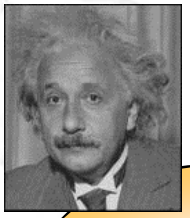


Systems thinking is a discipline in both Science and Engineering

- Systems Science
  - ***General System Theory***: Foundations, Development, Applications by Ludwig von Bertalanffy, Braziller, 1968
  - International Society for Systems Sciences
    - WWW page: http://isss.org/index-old.html
- Systems Engineering
  - ***Introduction to Systems Engineering*** by Andrew P. Sage, Wiley Series in Systems Engineering and Management, 2000
  - International Council on Systems Engineering
    - WWW page: http://www.incose.org/

Systems Science uses the Scientific Method





Fact

Theory

Hypothesis

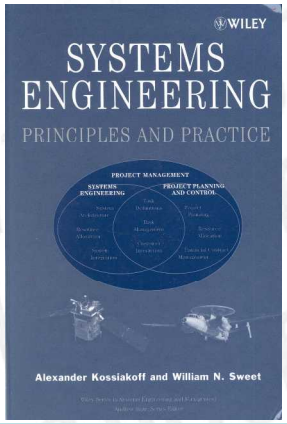
Idea

Reject Concept

after Engi, 2007

What is Systems Engineering?

Systems Engineering* is an interdisciplinary science-based engineering approach to the design, development, qualification, and release of complex products that, when followed, assures customer requirements and needs will be satisfied throughout the product's lifecycle.



*** Adapted from the INCOSE definition.**

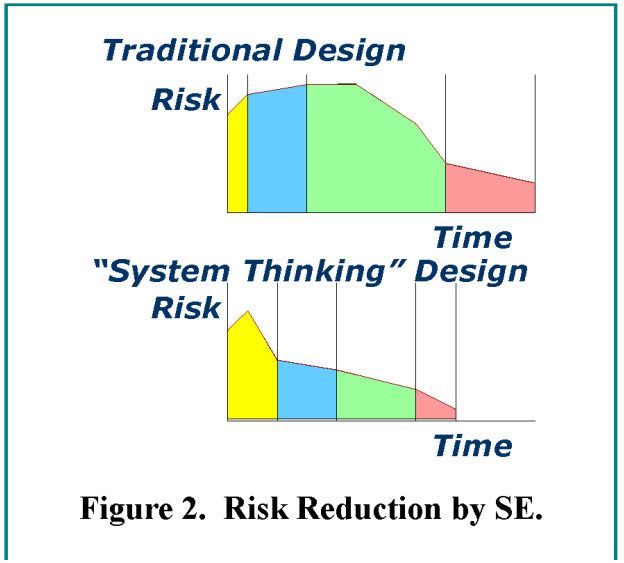
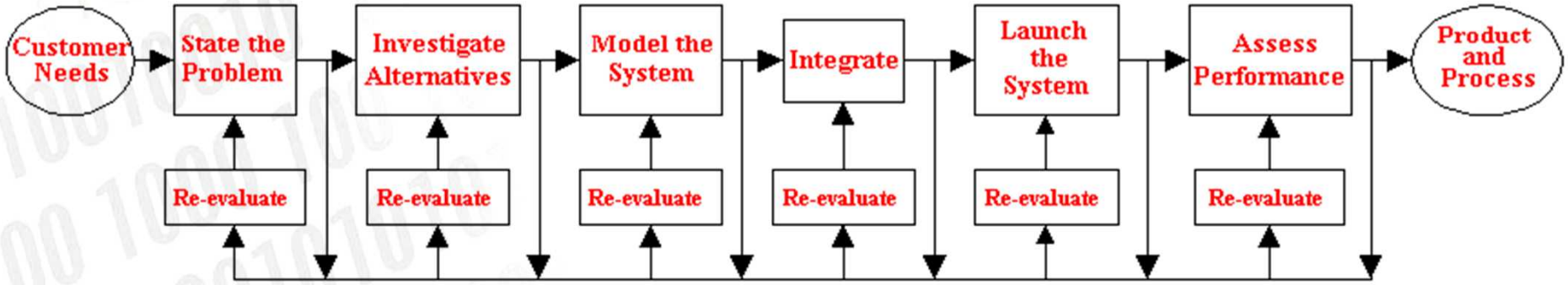


Figure 2. Risk Reduction by SE.

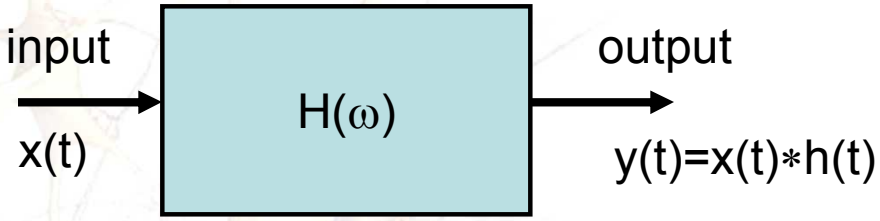
Systems Engineering Methodology

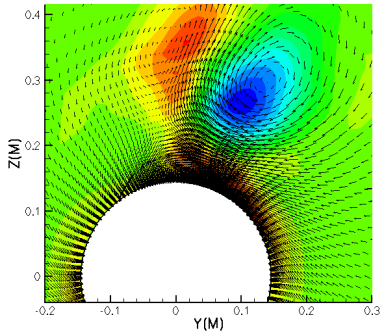
- **S**tate the problem
- **I**nvestigate alternatives
- **M**odel the system (both the operational view and the system view),
- **I**ntegrate the system
- **L**aunch the system
- **A**ssess the performance, and
- **R**e-evaluate the design.

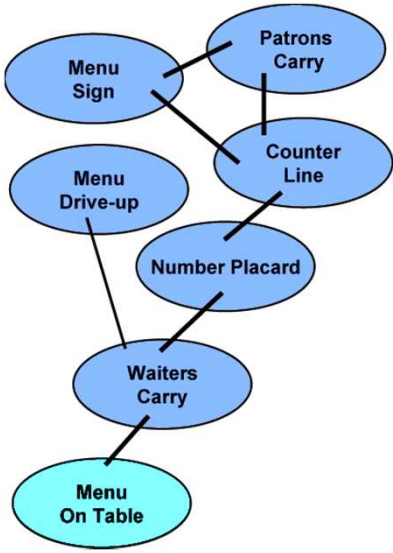


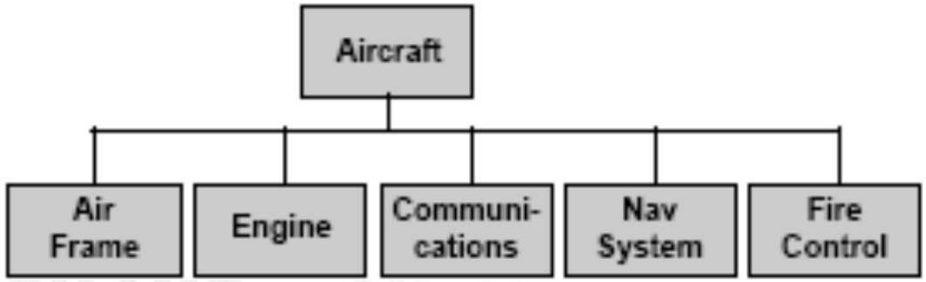
after Bahill and Gissing (1998).

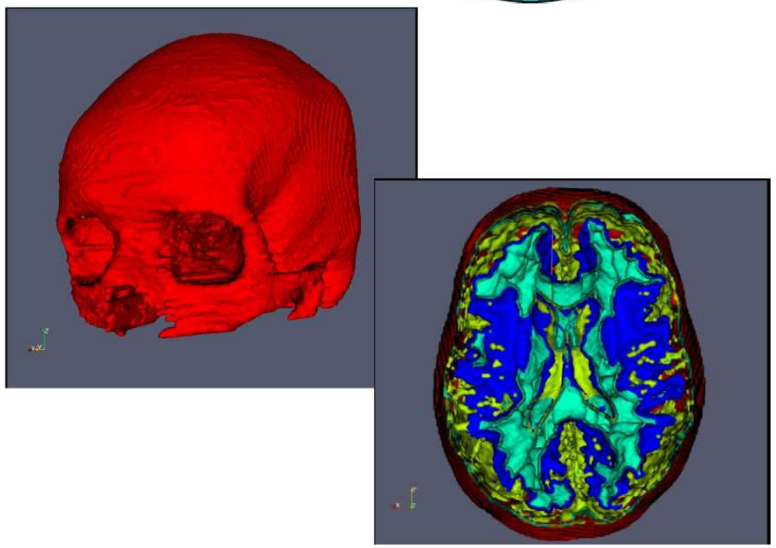
Models are the Key-to-Success in developing and proving innovative systems



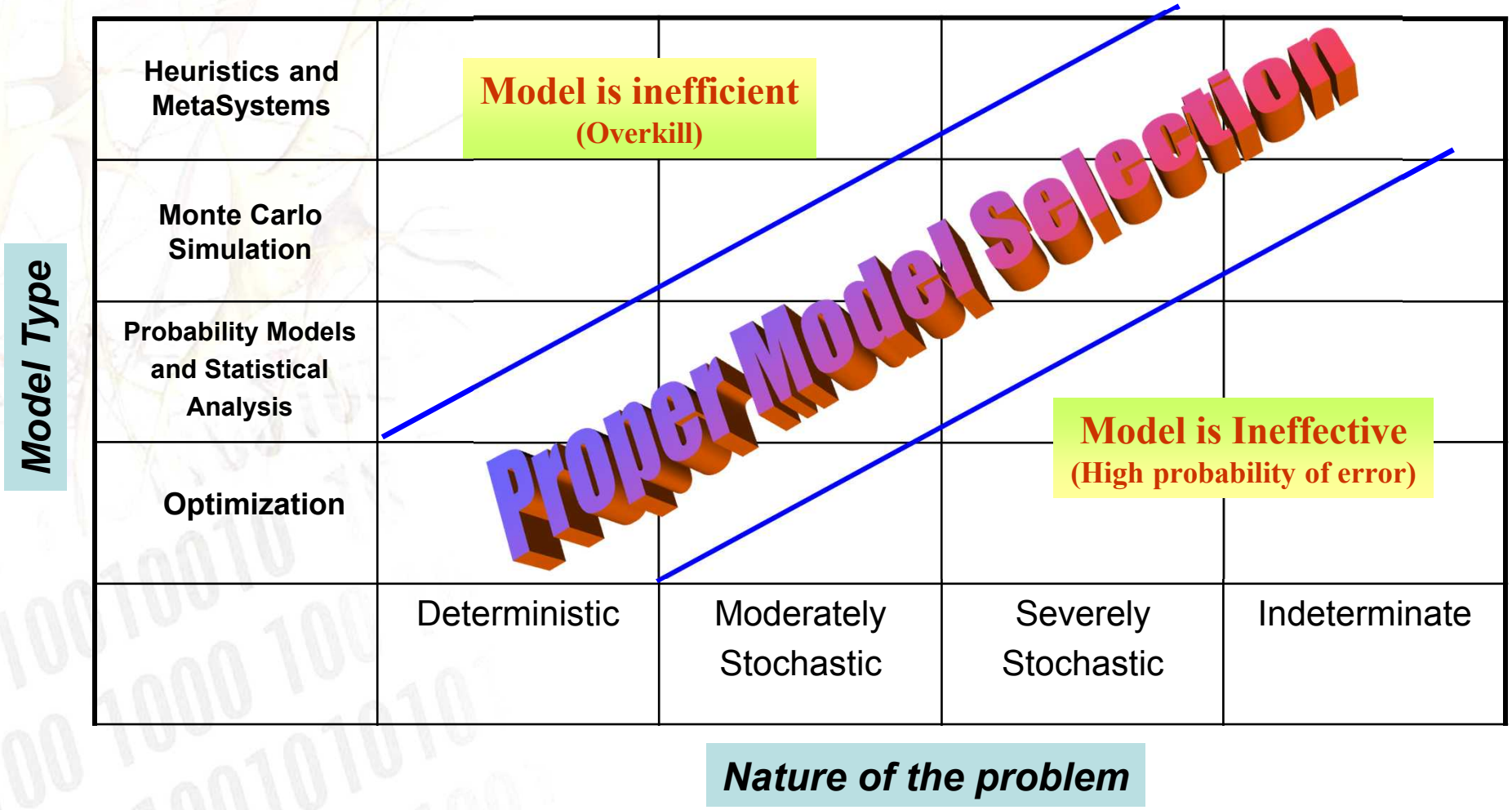




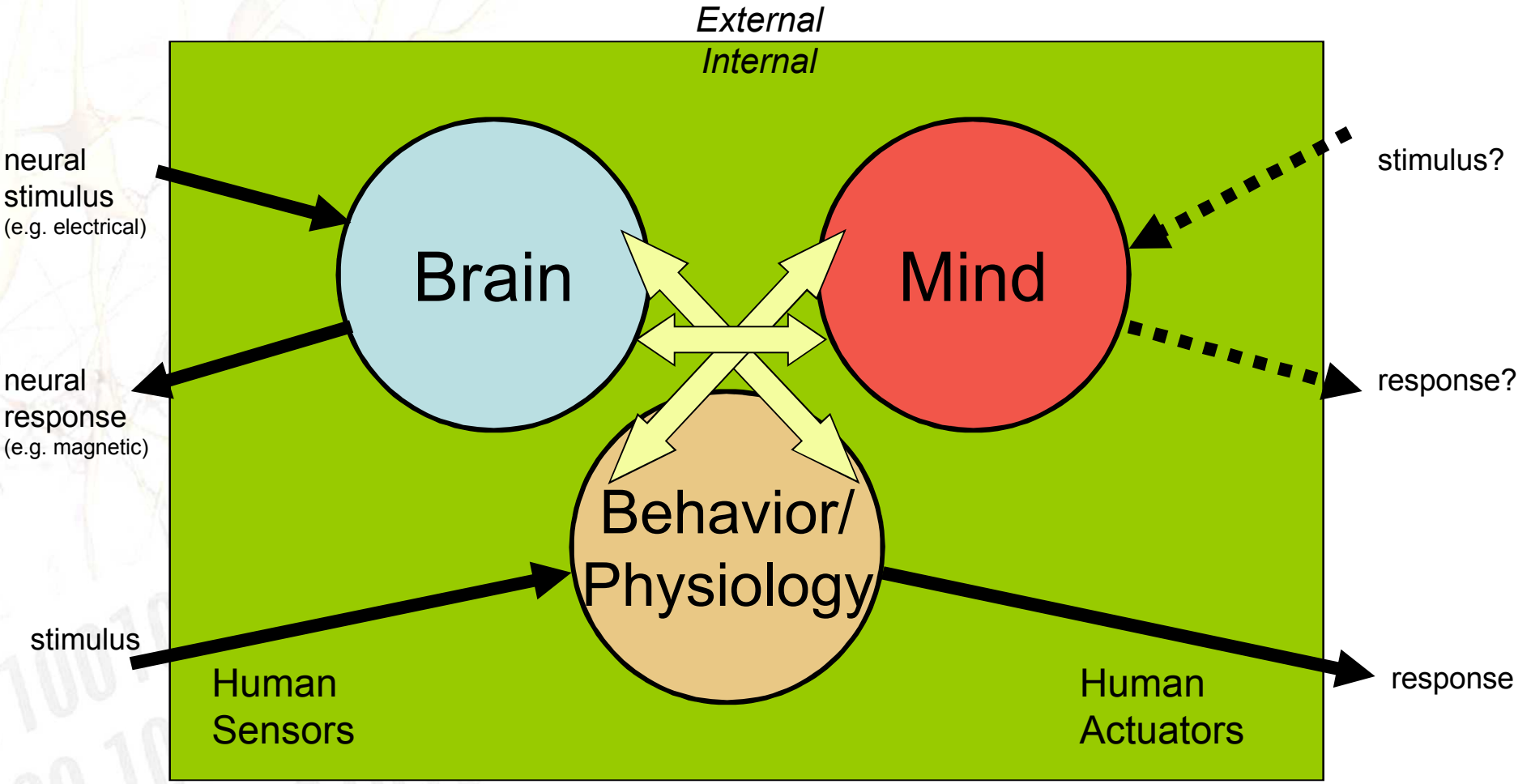




Models must be chosen carefully in order to represent the problem-at-hand



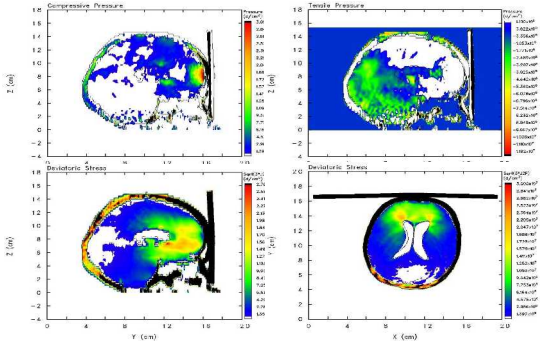
Modeling the Human as a System



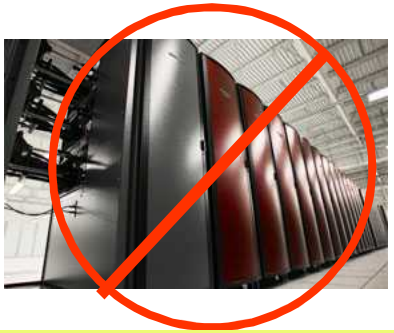
By the nature of the beast, the human represents a complex and stochastic system-of-systems …

Human Modeling Challenges

- Skin Conductance (a.k.a. polygrapgh)
  - The skin is a low-bandwidth actuator and sensor
  - < kHz data rates per probe site
  - 10's of kBytes of data storage needed for polygraph-like applications



- Full-Fidelity Electro-Magnetic Brain Model
  - Would need to model all neurons, synapses, and associated electro-chemistry
  - >> kHz data rates per synapse: but 1000's of synapses per neuron, and billions of neurons!
  - Peta-Bytes (yes > 10^15 bytes) of data storage required!

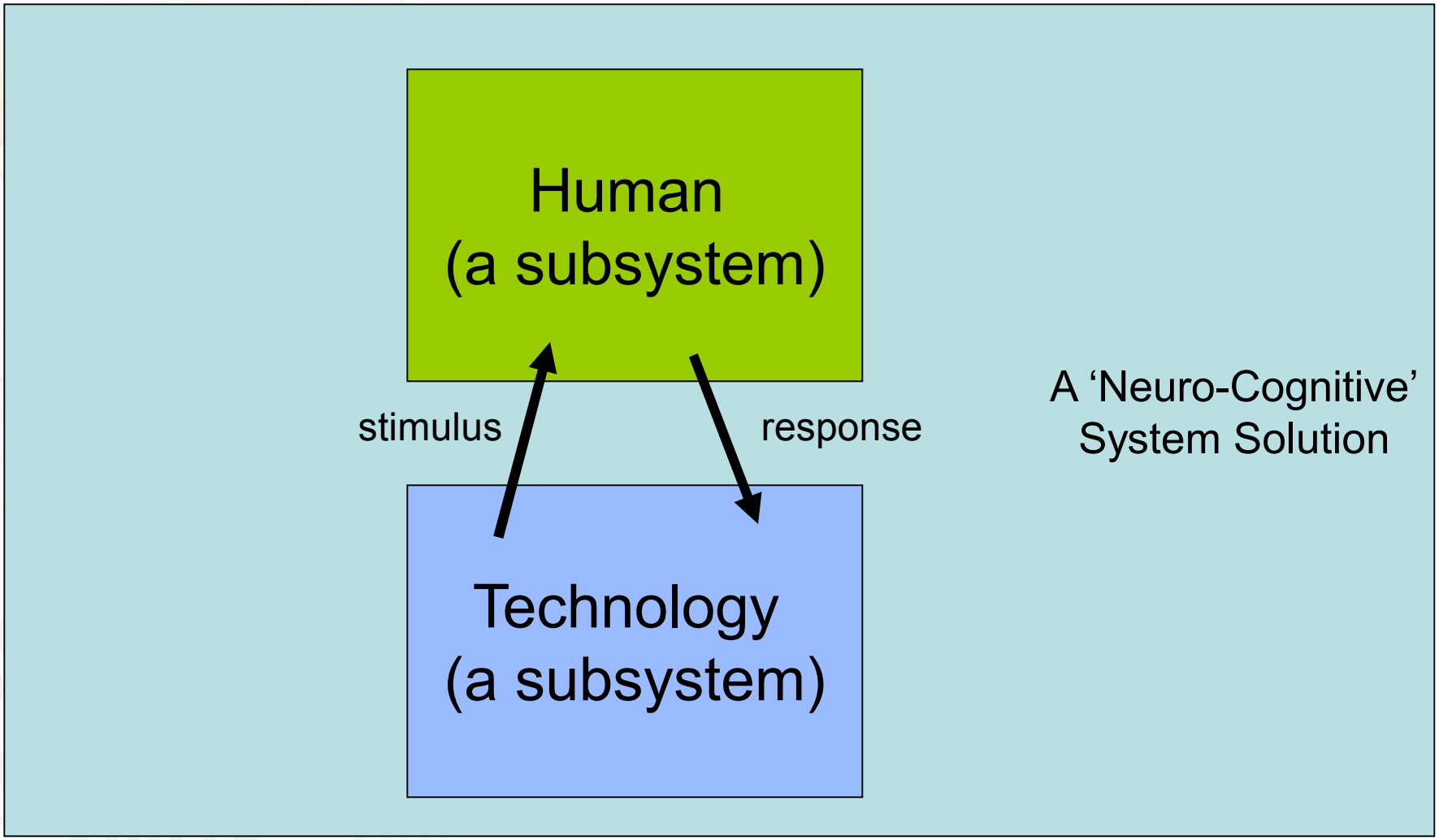


Shannon's Information Theory tells us that the Human Brain is grand numerical challenge

So, given today's technologies, can we engineer credible and practical Neurosystems?

… Three Application Areas will now be discussed …

Application #1: Augmenting Human Performance



Example: Enhancing the performance of a vehicle operator









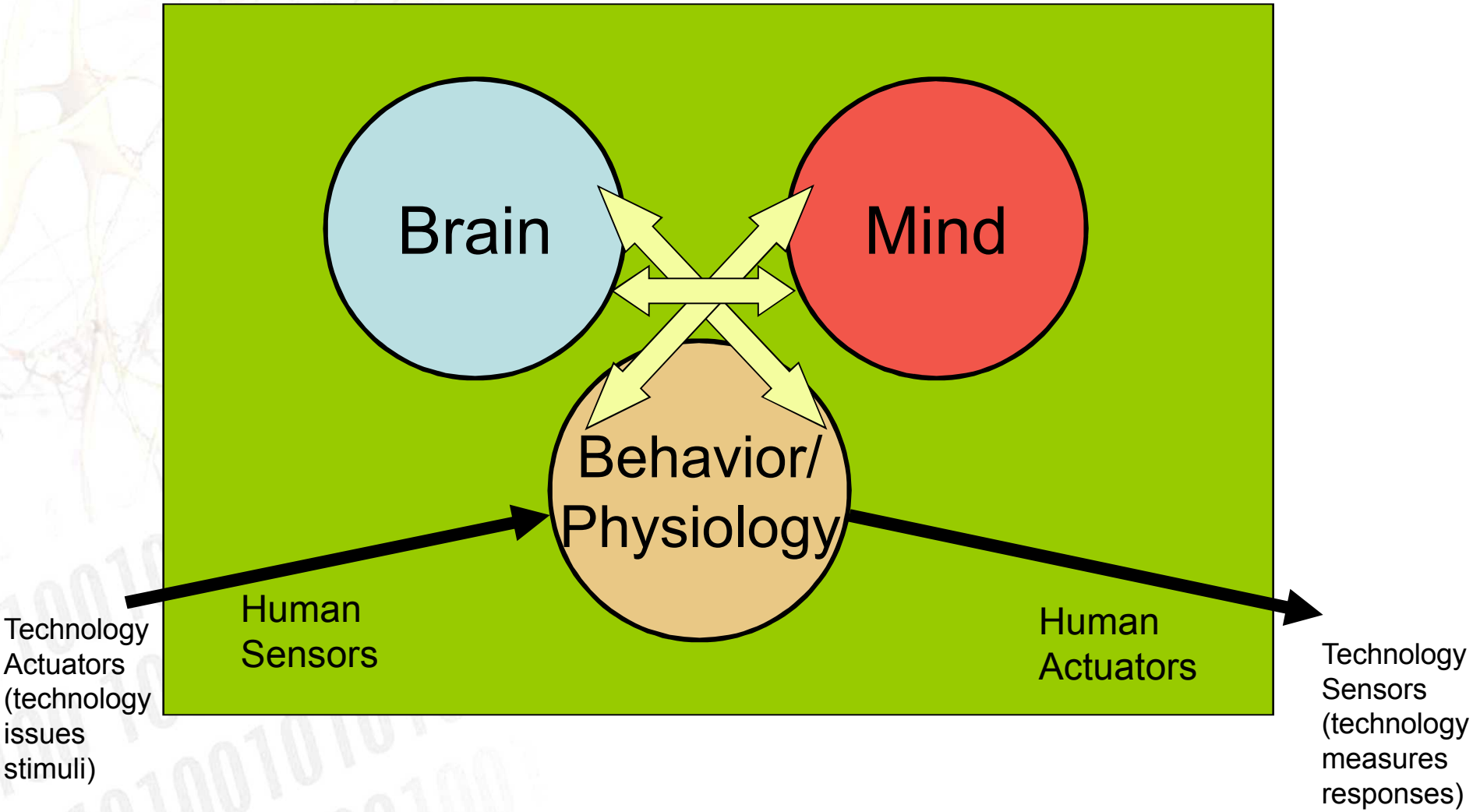
Various Human-Machine interfaces can be considered to address this challenge

Driving Under Duress …

Approach

- Estimate the impact on vehicle operators by exploiting:
  - Physiology:
    - Measuring body's response to stress
  - Physics:
    - Determine how physical conditions impact crew
  - Machine Learning:
    - Use knowledge of the past to generalize and predict impact of future situations
- All systems must operate in real time and in real-world conditions

Interfacing the 'Human Sensors and Actuators' with Technology Sensors and Actuators



Technology Actuators and Human Sensors

- Visual Displays
- Audio Alerts
- Seat and Steering Wheel stimulation

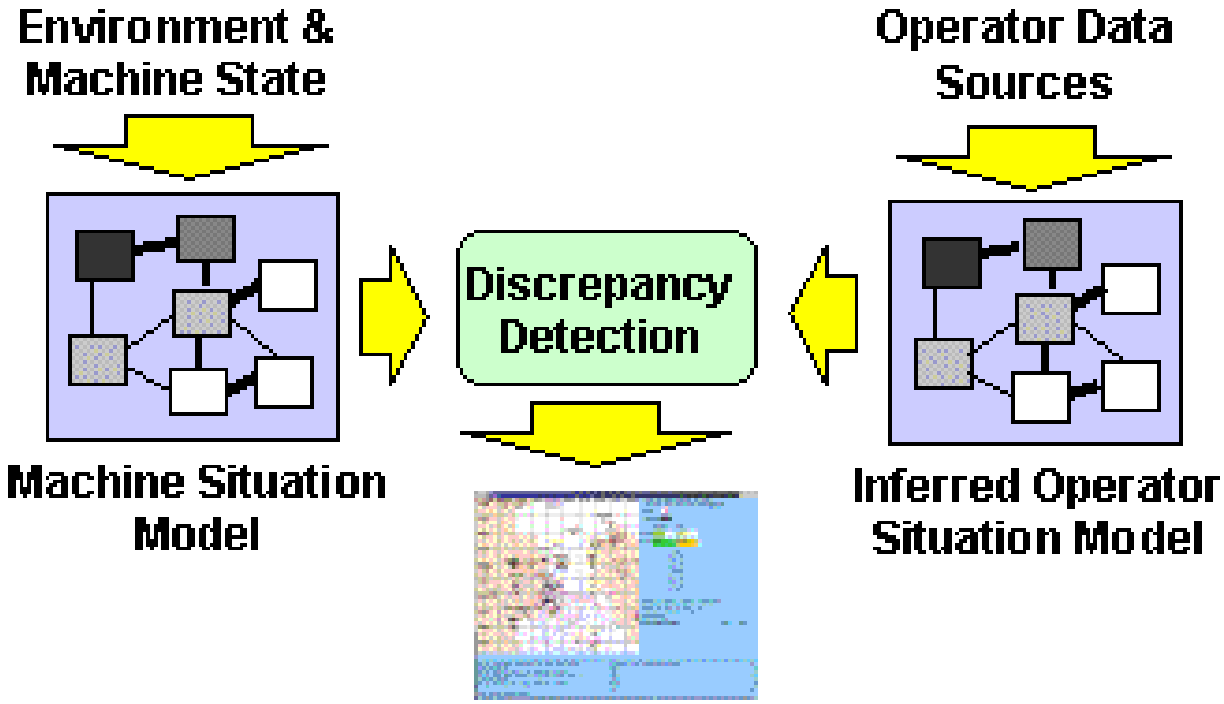
- Eye
- Ear
- Peripheral Nerves

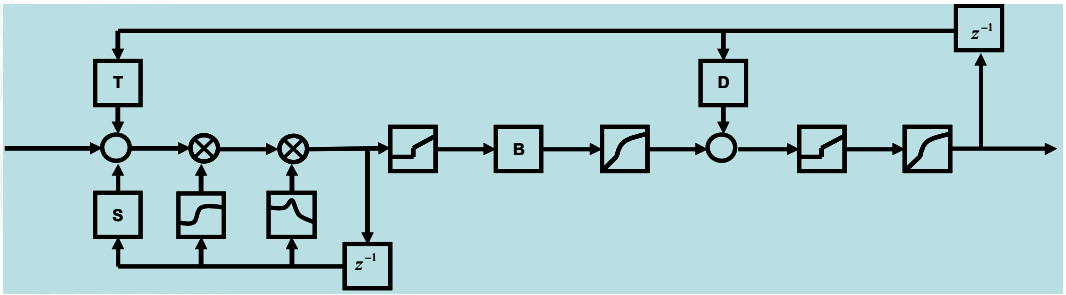
Technology Sensors and Human Actuators

- Eye Tracking
- Steering Sensing
- Accelerator/Brake Sensing

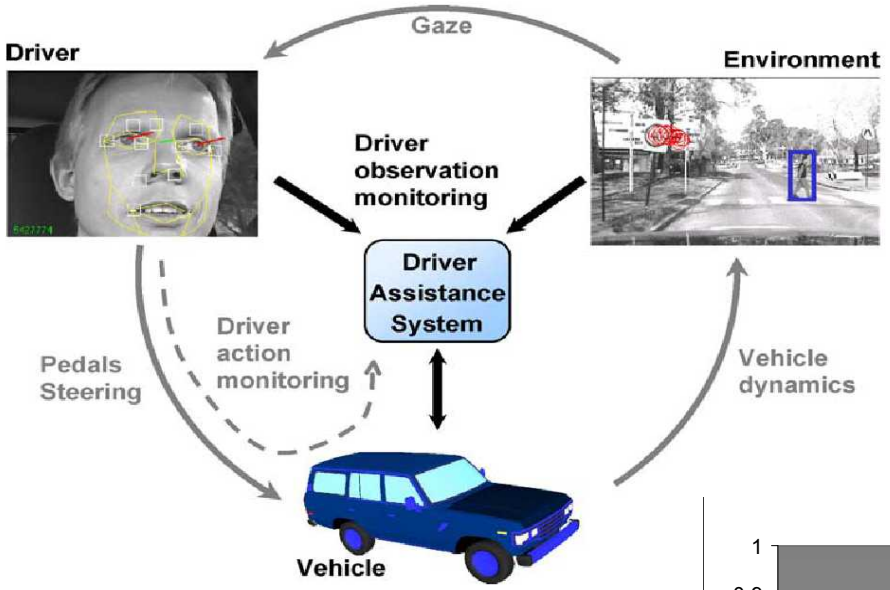
- Eye motors
- Hand motors
- Foot motors

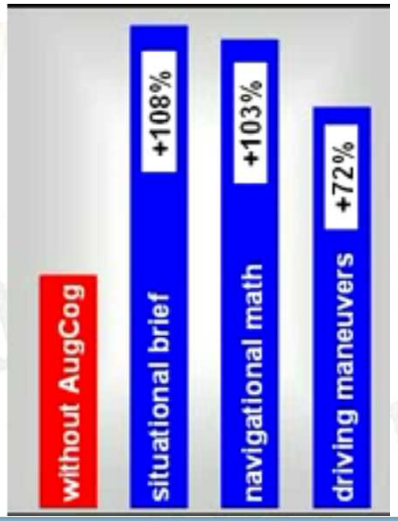
Algorithms are used to process the sensors and create feedback control





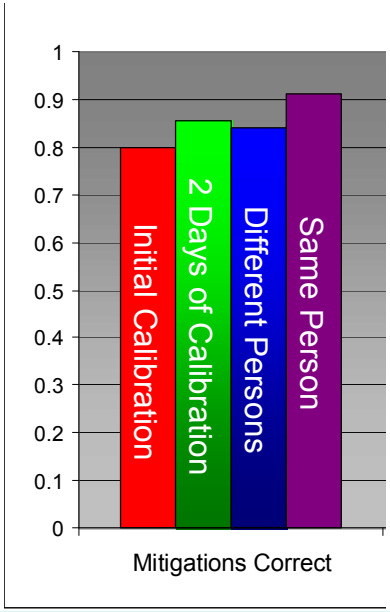
Some Results

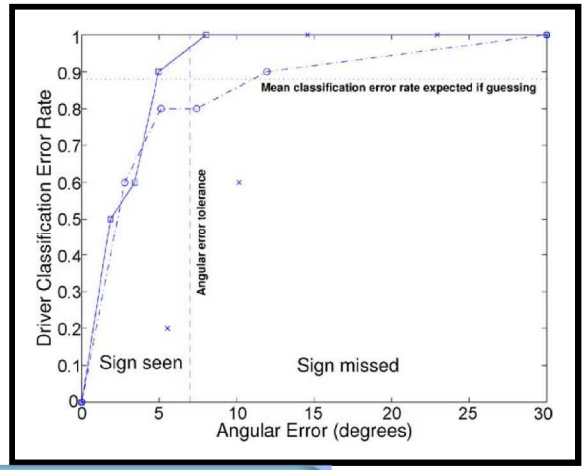




(c) '40' seen. Car speeding.

(d) '40' missed. Car speeding.





Results suggest that a 2x improvement in driver's safety performance may be possible

Human Performance Augmentation Using Neural Methods?

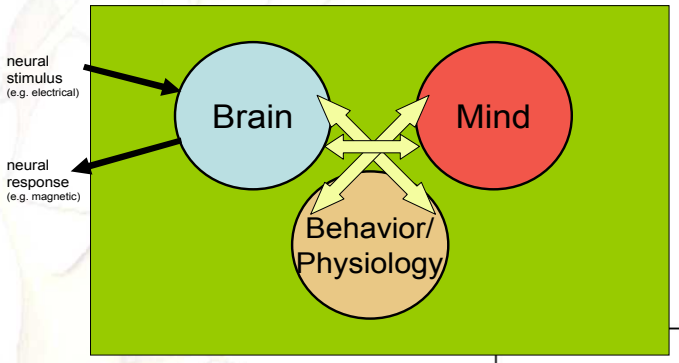
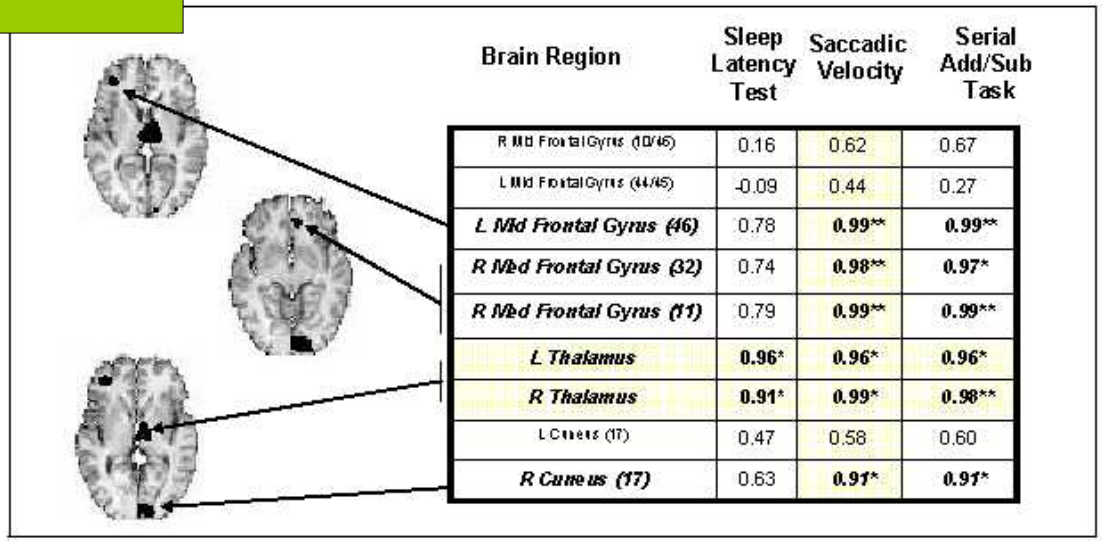


TABLE I. PROPOSED ALERTNESS-COGNITIVE STATES

Hyper Awake
Awake
Drowsy-Sleepy
Light Sleep
Deep Sleep
Stupor
Coma
Deceased

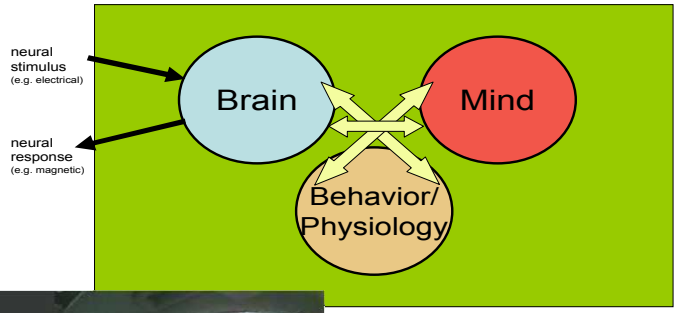


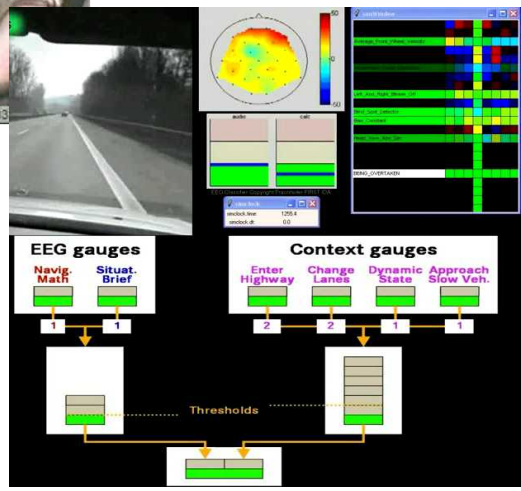
Brain Region	Sleep Latency Test	Saccadic Velocity	Serial Add/Sub Task
R Mid Frontal Gyrus (10/46)	0.16	0.62	0.67
L Mid Frontal Gyrus (44/45)	-0.09	0.44	0.27
L Mid Frontal Gyrus (46)	0.78	**0.99****	**0.99****
R Med Frontal Gyrus (32)	0.74	**0.98****	**0.97***
R Med Frontal Gyrus (11)	0.79	**0.99****	**0.99****
L Thalamus	**0.96***	**0.96***	**0.96***
R Thalamus	**0.91***	**0.99***	**0.98****
L Cuneus (17)	0.47	0.58	0.60
R Cuneus (17)	0.63	**0.91***	**0.91***

Figure 1. Human brain images showing areas of decreasing brain activity (annotated in black) across 72 hours of sleep deprivation that correlate with increasing sleepiness (decreased sleep latency), slowing in saccadic eye movements (decreased velocity), and impaired complex cognitive task performance (decreased accuracy, speed, and throughput on sustained attention, working memory, and arithmetic math performance) (25). Significant correlations are denoted (*$P \leq 0.05$; **$P \leq 0.01$).

EEG Sensors may be useful in Human Performance Augmentation

- EEG measurements have been explored as potential feedback sensors
  - limited studies have used EEG data in real-world conditions in real time
  - We often have a noisy electromagnetic environment
  - Driving conditions are unconstrained and experiments last ~5 hours
  - Subjects are moving around, looking around, being jostled, and occasionally talking
- Nonetheless, it was found that there was up to a 93% correlation of EEG measurements with the driver's cognitive state (alert, tired, sleeping) *Dixon et al 2006.*

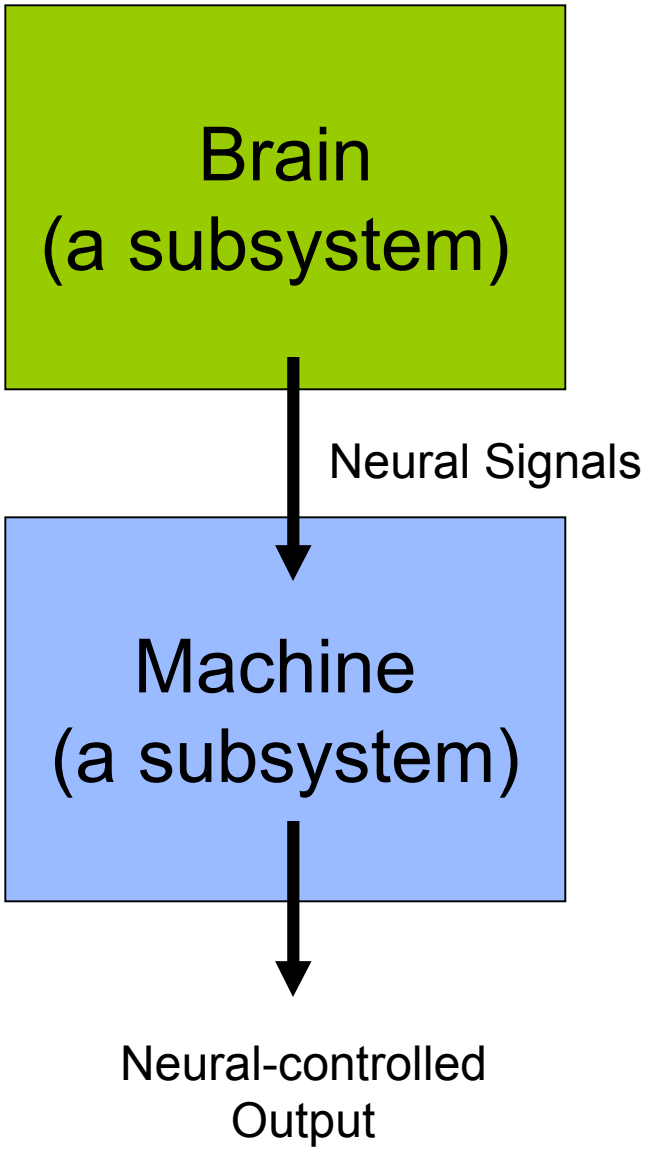




While there have been some studies that explore EEG as a potential human-interface sensor, there has not been, to our knowledge, exploration of direct electrical brain stimulation as an actuator for human performance augmentation

Application #2: Neural Machine Control

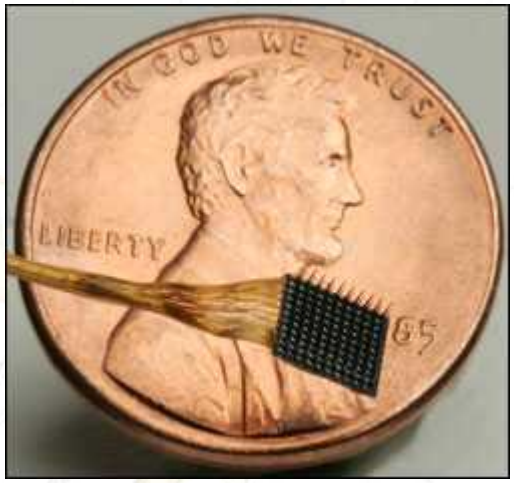
- Today, all machines are controlled through the human peripheral actuators
  - primarily the hand and/or foot (knobs, pedals, switches, the mouse, etc)
- Additional peripheral actuators are actively being explored: e.g. eye-tracking
- But is it possible to directly control a machine from neural interfaces?

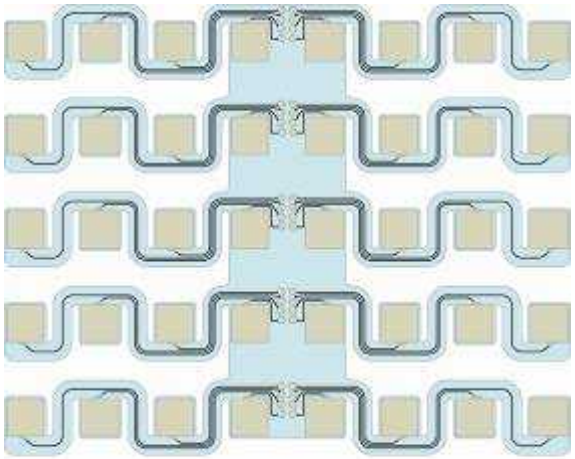


Neural-Machine-Control Concept

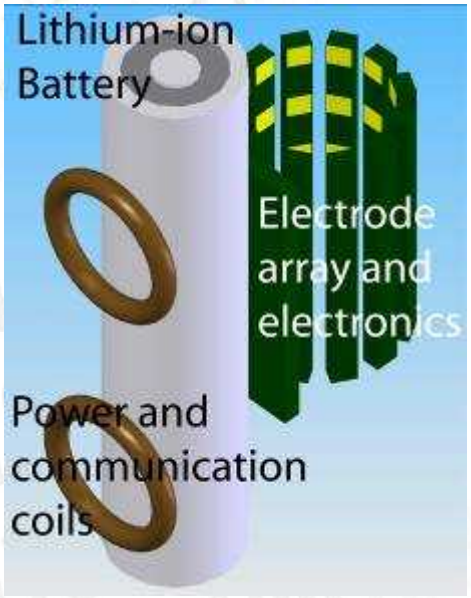
from Cyberkinetic Inc. ‘The BrainGate Technology’

Neural Implants can act as sensors

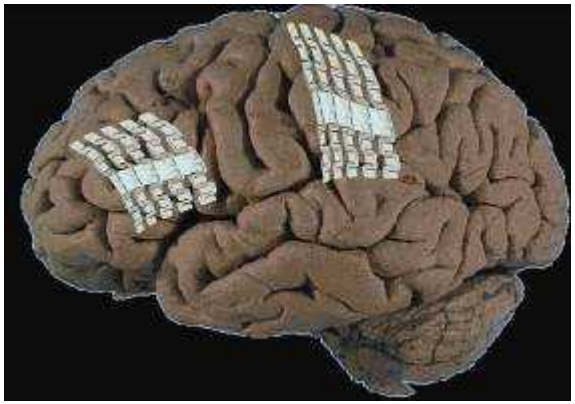




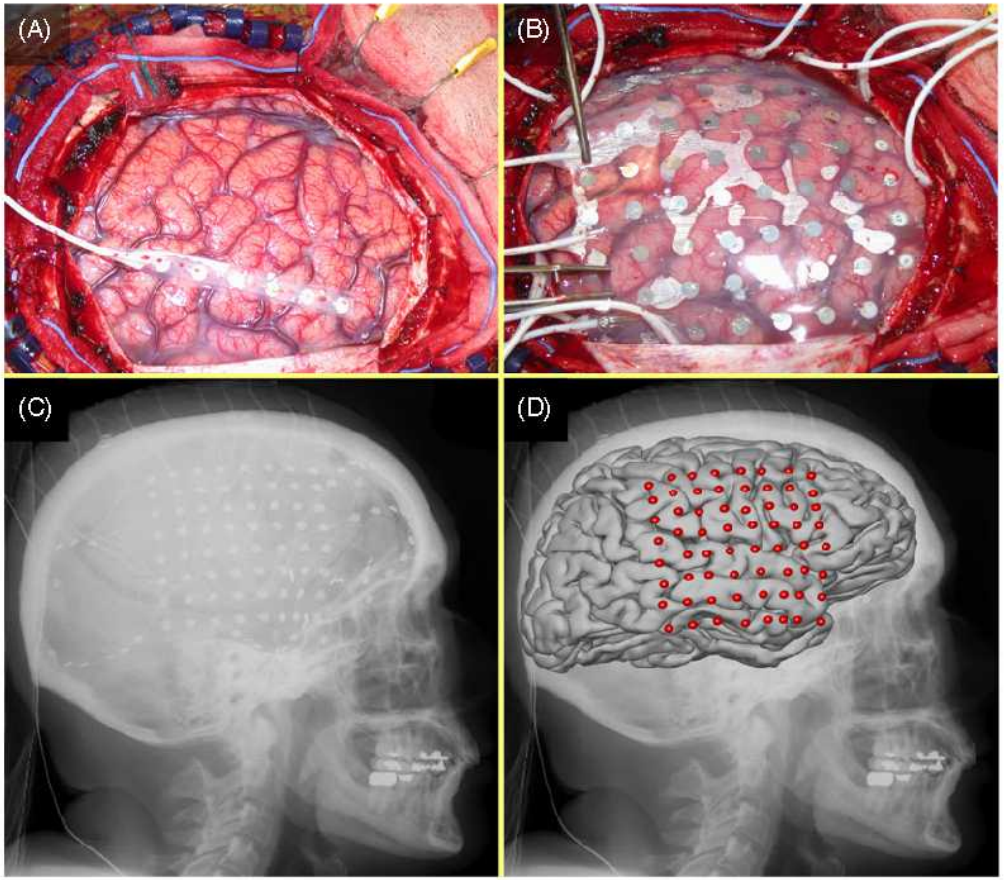
Implantable Compliant Electrode array for use in cortical recording and stimulation.
(Sandia National Labs)



Power and communication can be wireless-through-the-skin



Scientific Experiments show promise



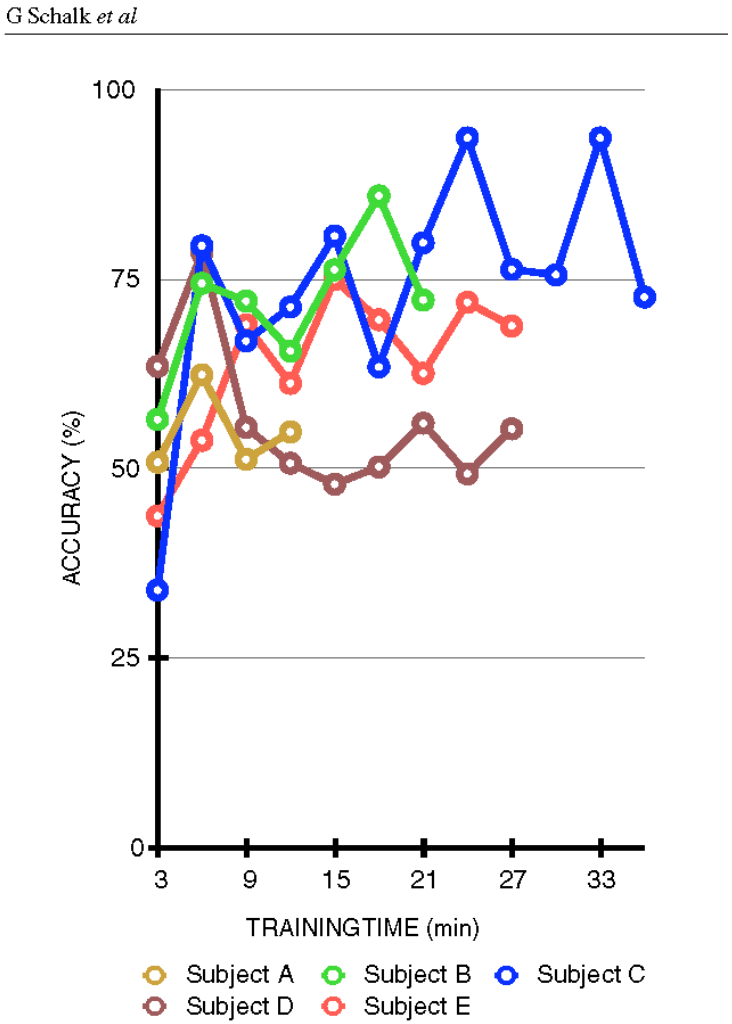
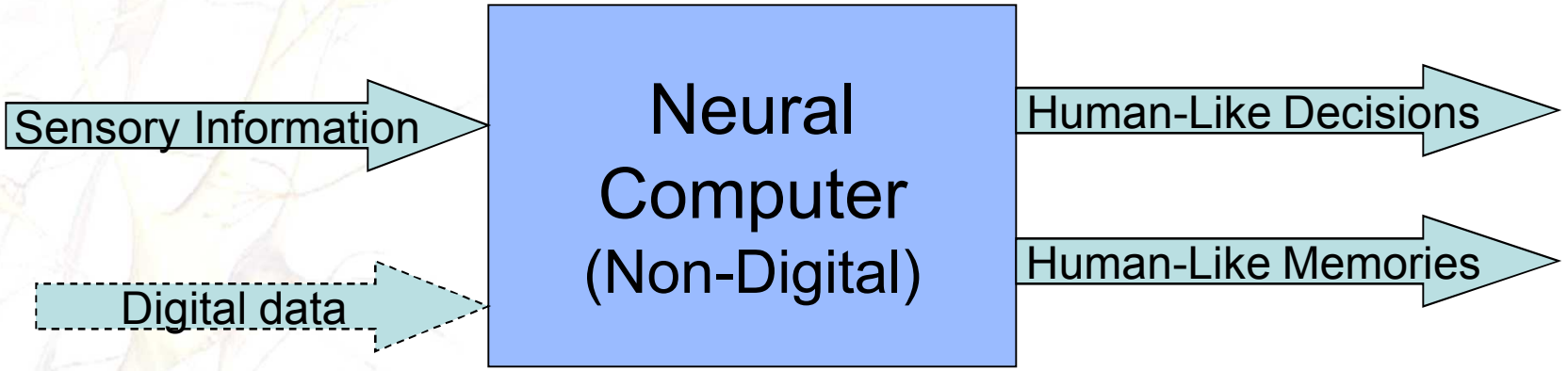


Figure 5. Learning curves for ECoG control of the two-dimensional cursor movement using motor actions or imagery (see text).

Application #3: Neural Computers



- Can we create technology that fully emulates the computational prowess of the human brain?
- What would it look like?

Neural Computers are not ‘Neural Networks’

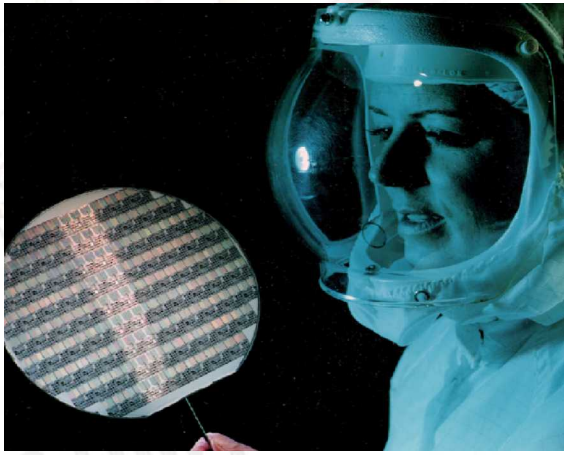
- ‘Neural Networks’ are essentially digital algorithms that try to implement a computational model of the brain

- By **Neural Computers** we mean a manufactured brain (biological, inorganic or both) that is based on neural and synaptic building blocks

Neural Computers: manufactured in silicon or biologically grown?

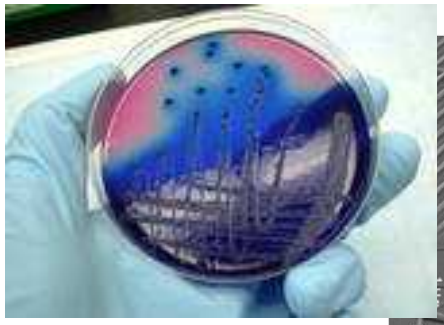
Silicon 'Semiconductor' Methods

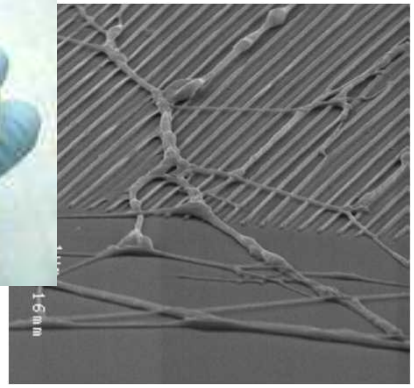
- Novel building-blocks will be needed
  - 'Neuristors'
  - 'Synaptic Interconnects'



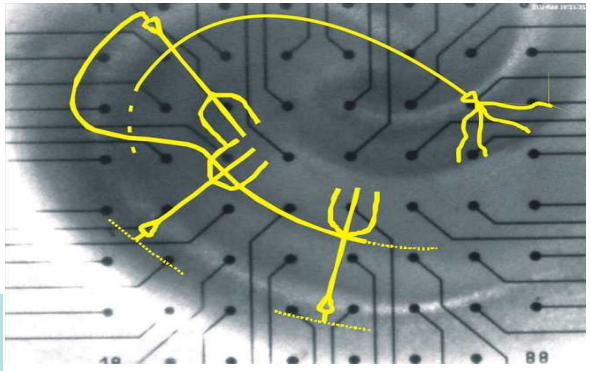
Biological Methods

- Grown in 'Petri dishes'
- analogous to genetic cloning





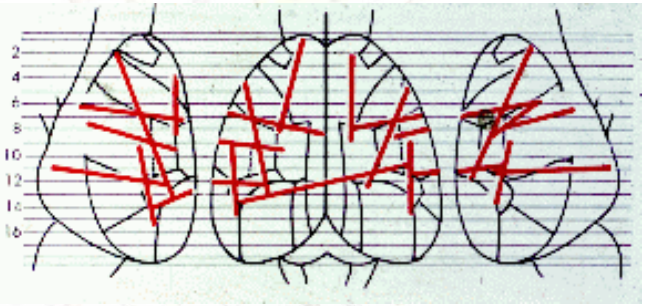
Hybrid Methods

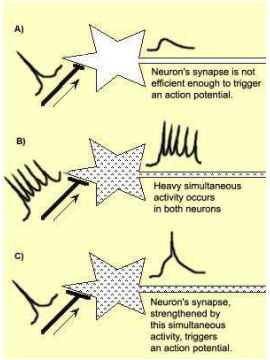


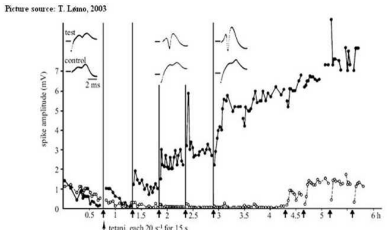
Is this Science Fiction?

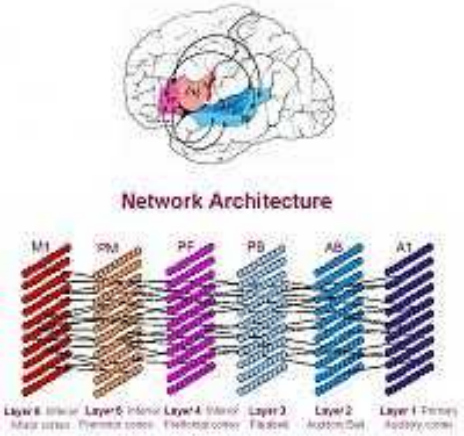
Despite decades of research, no one has cracked the neural code

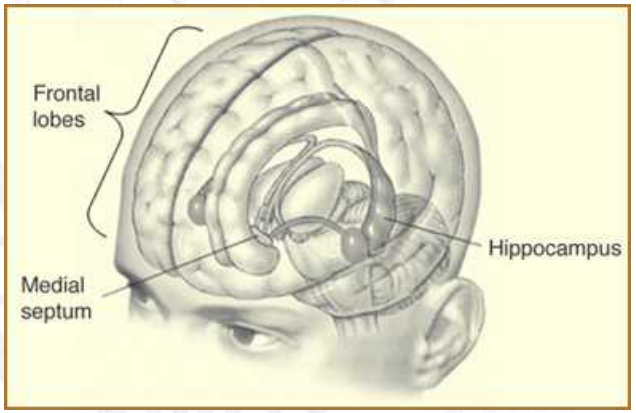
How memories are stored within networks of neurons has been one of the most prominent questions within cognitive neuroscience.

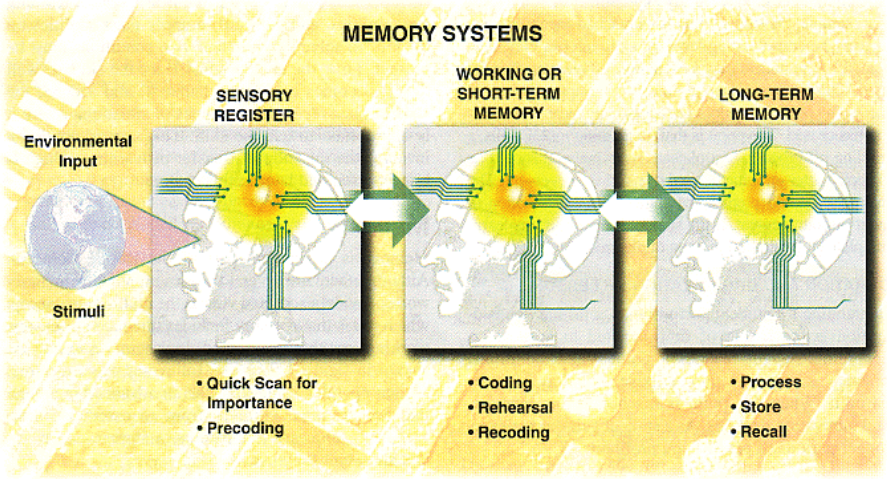




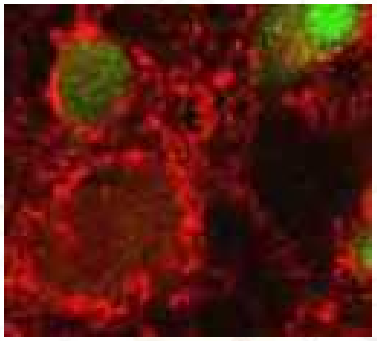




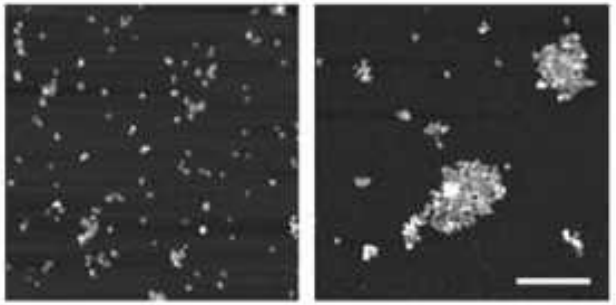




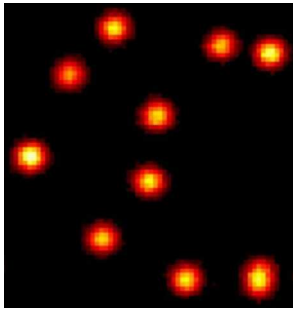
In vivo nanoscale measurement and modeling set the stage for major scientific breakthroughs



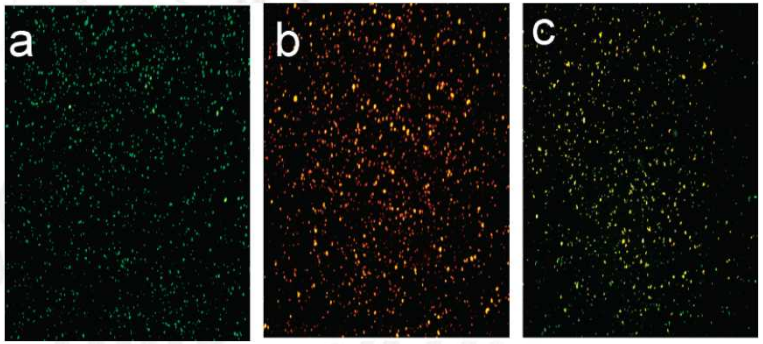
Pre-synaptic uptake of quantum dots
Fan et al, 2006



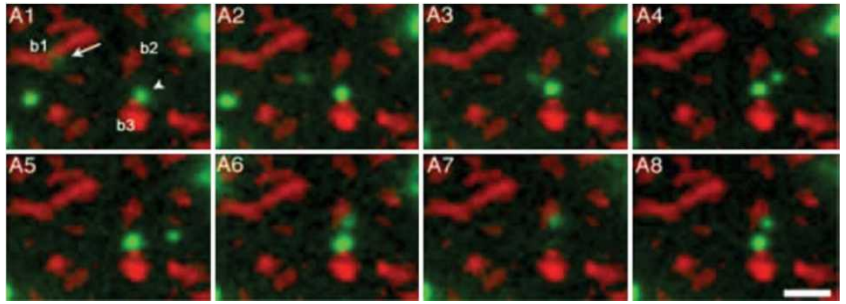
MRI contrast agents for detecting calcium uptake
Jasanoff, 2007



Particle flux accompanying synaptic activity
Lounis, 2007



Color changes correspond to enzymatic activity
Shi et al, 2007

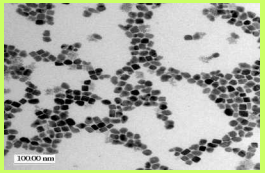


Tracking membrane migration of glycine receptors
Dahan, 2006

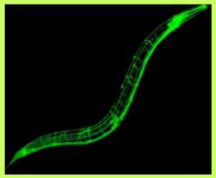
There is an opportunity to make a unique and profound contribution to cognitive neuroscience

Our objective is to develop and demonstrate nanoscale measurement and modeling techniques for studying the interactions that underlie memory storage within a network of neurons.

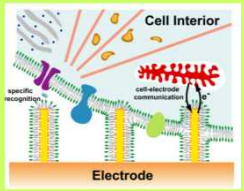
Establish foundation for synthesis suitable nanoparticles



Establish biofunction-alization



Develop techniques for volume measurement



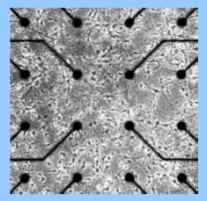
Nanoscale Measurement Track

Computational Modeling

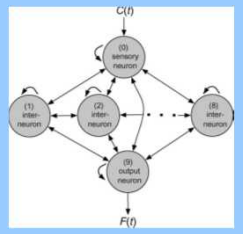
Establish requirements for neural circuit modeling

Select modeling framework

Testing with microarray data

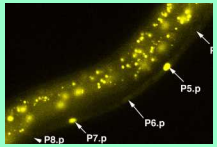


Implement nematode model in Xyce

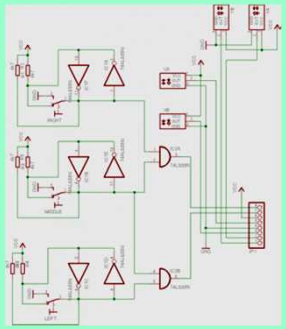


Nanoscale measurement and modeling

Conduct *in vivo* measurement

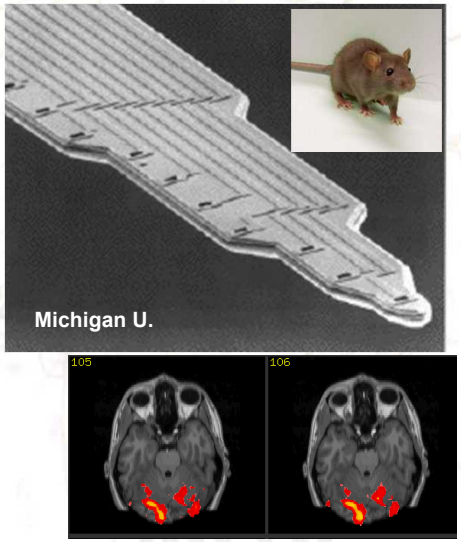


Model neural circuit from *in vivo* measurement

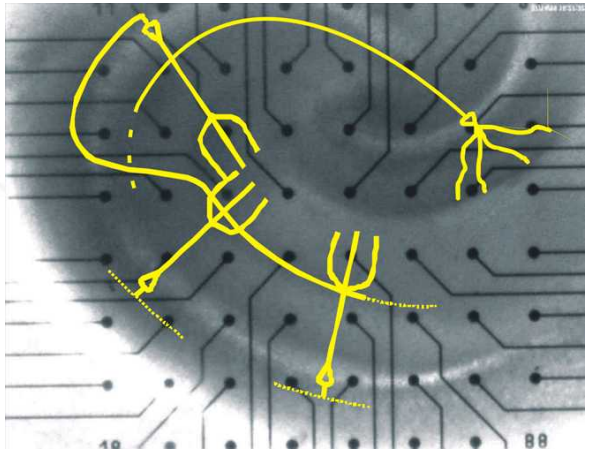


A Neurosystems Engineering Approach will be required to develop Neural Computers

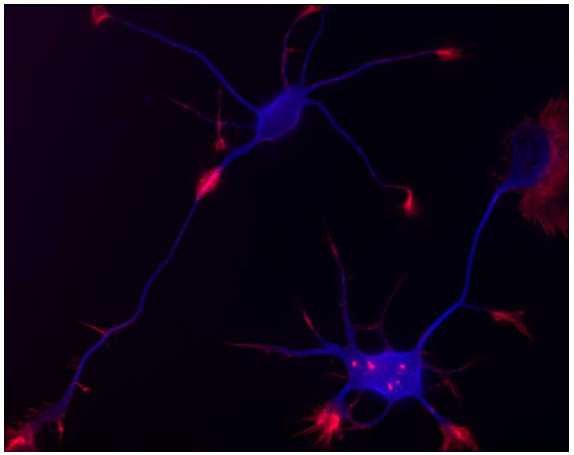
All current methods are lacking in regards to understanding core processes involved in network architecture and function, and specifically in regard to strategies to *repair, build, or enhance network performance*



***In vivo* measurements**
- Cannot modify network structure, long-term recordings are difficult; complexity of whole brain is an intractable problem



Brain slices (quasi- *in vivo*)
- Cannot modify network structure; manageable complexity, short-term (acute-24 hours, organotypic-6 months), measurement resolution not sufficient

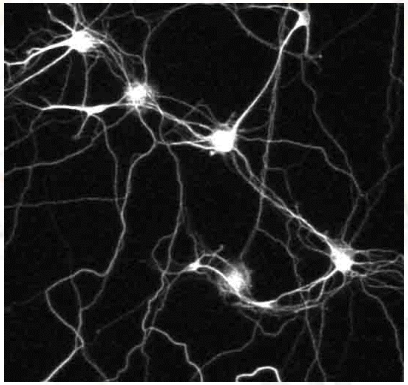


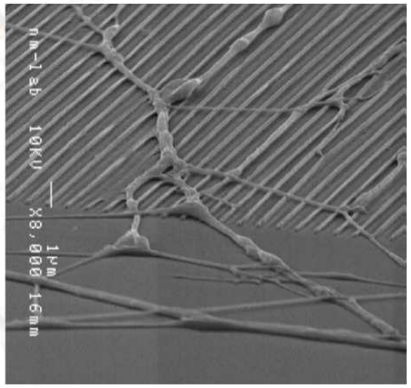
Dissociated neurons (*in vitro*)
- Cannot control network structure, thus biological replicates are impossible; long-term (> 1 year) simplified problem, but maybe too simple

Neural engineering is required to understand how tissue structure and function are related, and how neural tissue can be repaired, built or enhanced

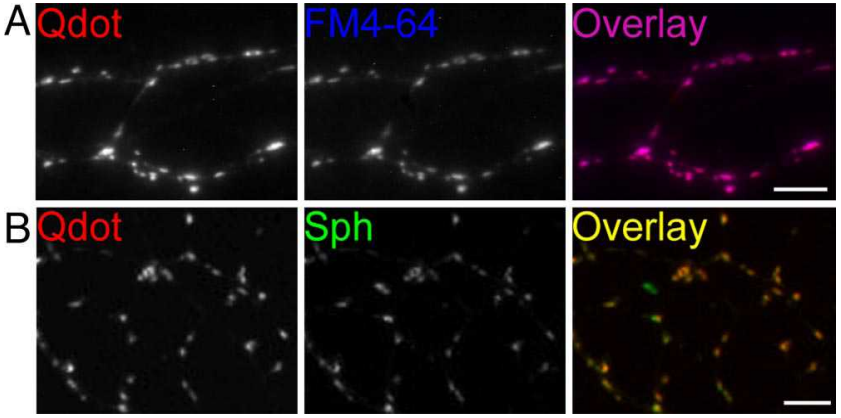
A Neurosystems Hypothesis

Neurotechnologies, specifically **micro/nano-engineering methods**, can be used to **repair/manufacture** neural tissue and **enhance** the performance of neural tissue networks. Micro/nano-engineering methods can also be used to interrogate neural function…

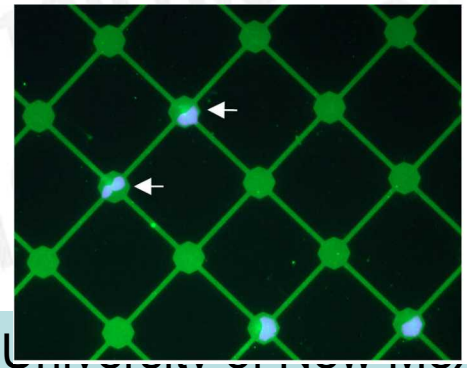


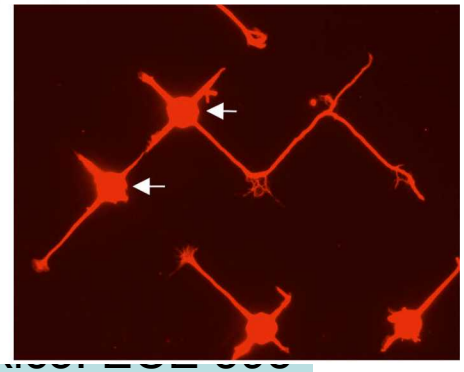


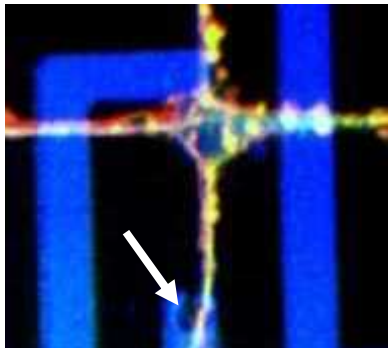
Johansson, Biomater 2006, 27, pg. 1251

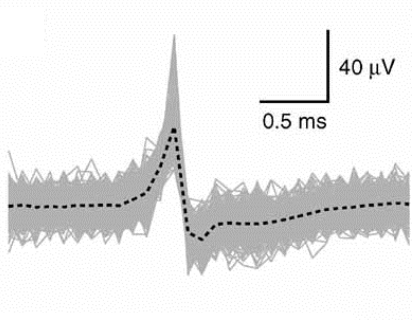


Zhang, PNAS 2007, 104, pg. 17843



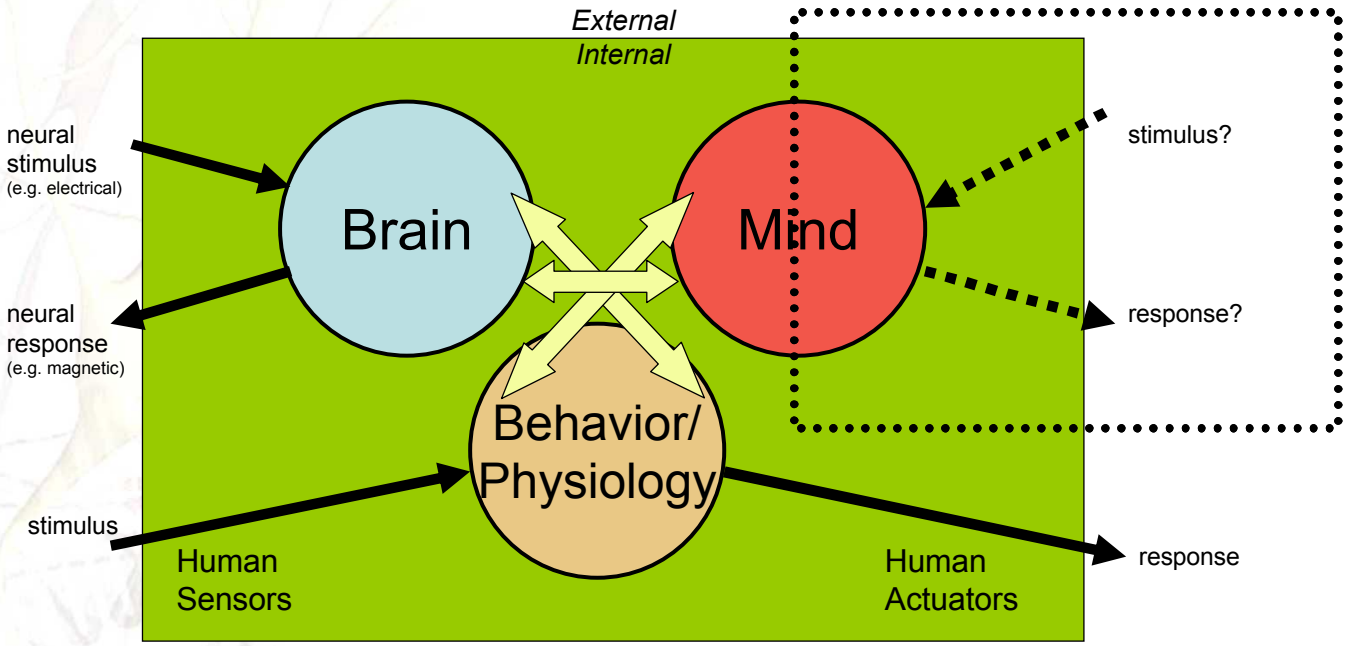






James, IEEE Trans Biomed Eng 2004, 51, pg. 1640

Closing Thought: Will we discover a way to bypass the Brain or the Physiology to get directly at the Mind?



The Mind (our thoughts) are primarily composed of perceptual constructs

- Sounds, Words, Quasi-Images, etc.
- We know full-well how to influence the Mind via the human sensors (sing a song)
  - Is there a bypass mechanism?
  - And if so, is it bi-directional - so that we could read one's thoughts?

Summary

- Systems Thinking is the key to innovation …
  - via the scientific method
  - via representative and valid system models
  - via formal systems engineering and project management
- Given the complexity of the human-system, a Neurosystems Engineering approach will be required
- Neurosystems Applications are within our grasp
  - Augmented Cognition Systems are starting to be fielded.
  - Brain-Machine Interfaces have been conceptually demonstrated
  - The building blocks for Neural Computers are just being discovered
  - Someday, we may even be able to unlock the Mind …