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Brains as a Model for Thermodynamic Computing

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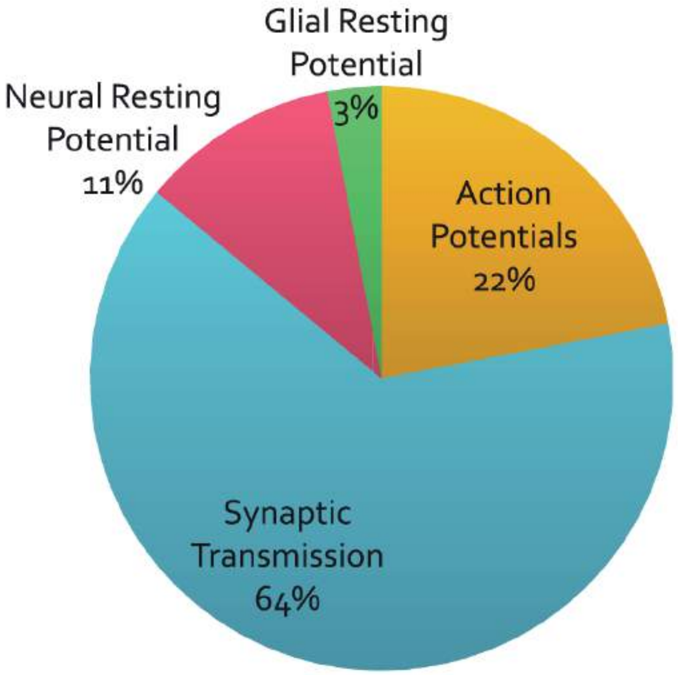
Brains Reduce Energy Consumption

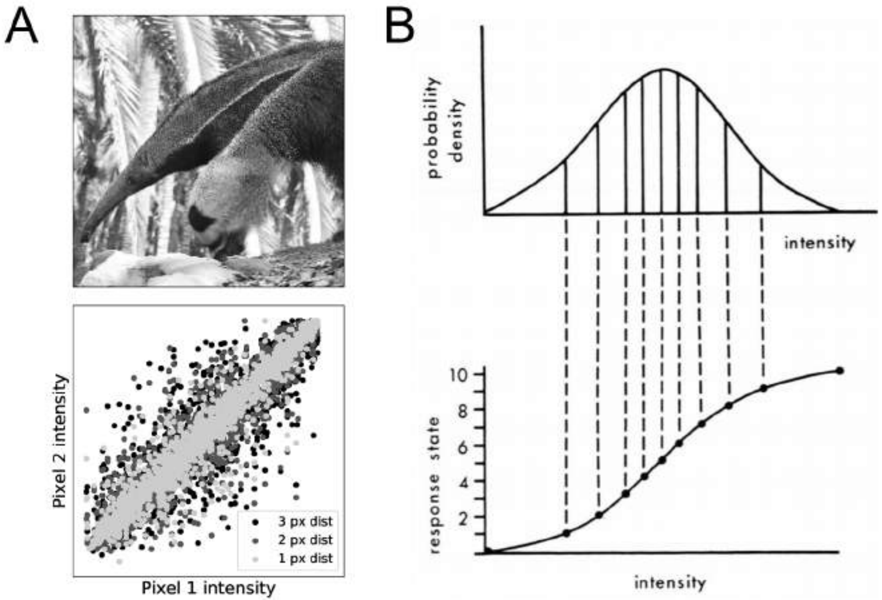
- At every level, the nervous system uses strategies to maintain high performance and information transfer, while minimizing energy expenditure.
- These range from ion channel distributions, to coding methods, to wiring diagrams (connectomes).



Sengupta, et al., PLoS Comp Bio, 2013.

Organisms Must Be Efficient to Survive

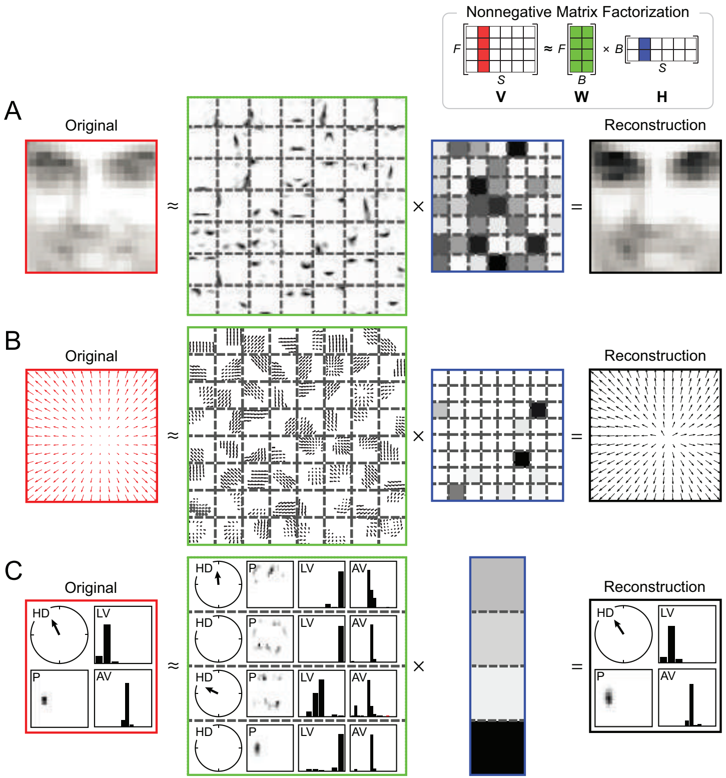
- Nervous systems adapt their responses to the regularities of their input to increase the amount of transmitted information.
  - Maximize efficiency (*reduce redundancy*).
  - Responses should be independent of one another (*decorrelation*).
  - A stimulus should involve only a small fraction of the available neurons (*sparse*).
  - Neurons should span the input space.



Louie & Glimcher, P.W. Ann N Y Acad Sci *1251*, 13-32, 2012.; H. Barlow. Network: Computation in Neural Systems, 12(3):241–253, 2001.; J. Atick. Network: Computation in Neural Systems, 3(2):213–251, 1992.

Sparse and Reduced Representations

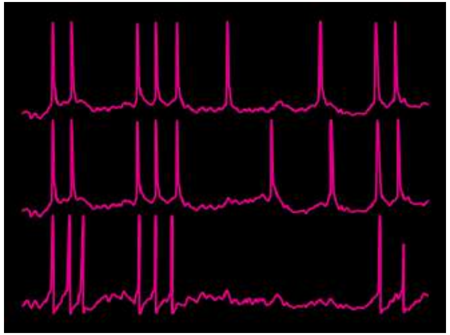
- Sparse coding and dimensionality reduction is a ubiquitous coding strategy across brain regions and modalities,
- Allows neurons to achieve nonnegative sparse coding (NSC) by efficiently encoding high- dimensional stimulus spaces using a sparse and parts-based population code.
- Reducing the dimensionality of complex, multimodal sensory streams is critically important for metabolically constrained brain areas to represent the world.

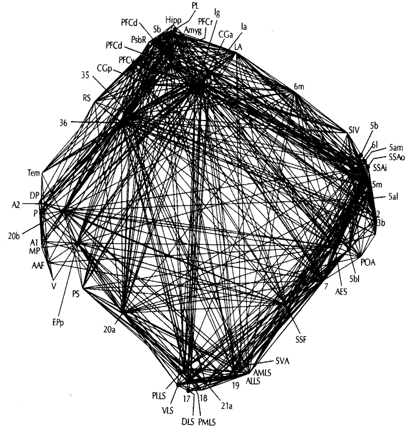


Beyeler, M., Rounds, E. L., Carlson, K. D., Dutt, N., & Krichmar, J. L. (2017). Sparse coding and dimensionality reduction in cortex. *bioRxiv*. doi:https://doi.org/10.1101/149880

Brains Use Sparse Communication

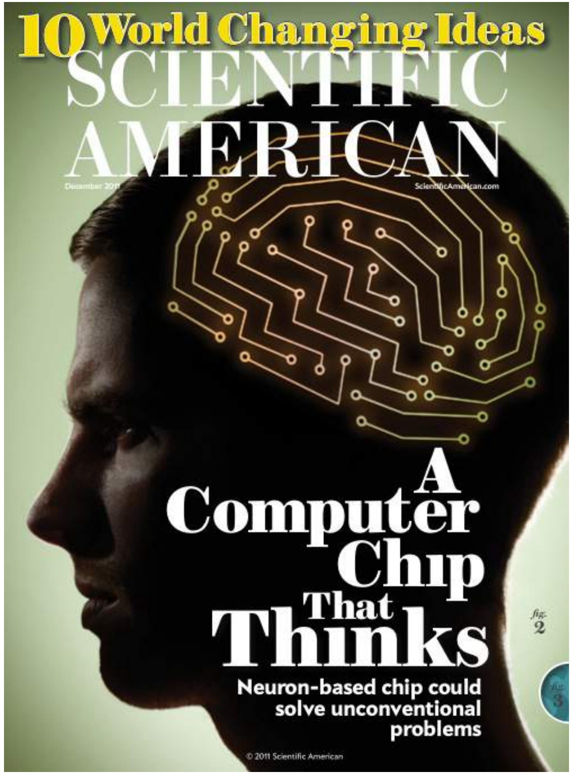
- The brain uses local analog computing and binary-spike communication.
  - Event-driven, asynchronous.
  - Minimal energy expenditure between spikes.
  - Low frequency output.
- The brain is a small world network.
  - Any two neurons are only a few hops away from each other.
  - Reduces wiring, but maximizes information processing.





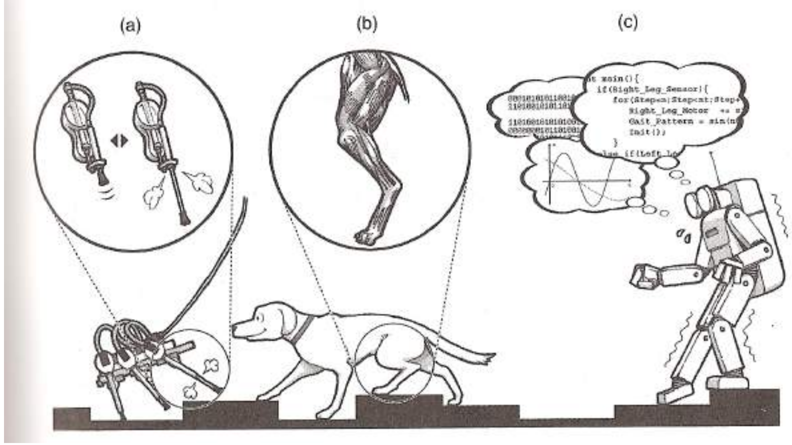
Karlheinz Meier, IEEE Spectrum, 2017.
Sporns, Tononi & Edelman, Cereb Cortex. 2000 Feb;10(2):127-41.

Neuromorphic Chips

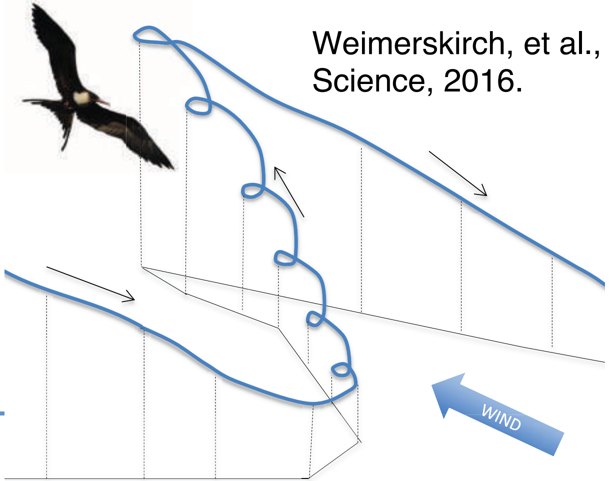


Embodiment: Non-Neural Theromodynamic Computing

- Morphological Computation
  - Certain processes are performed by the body that free up brain processing.



Pfeifer & Bongard, How the Body Shapes the Way We Think.



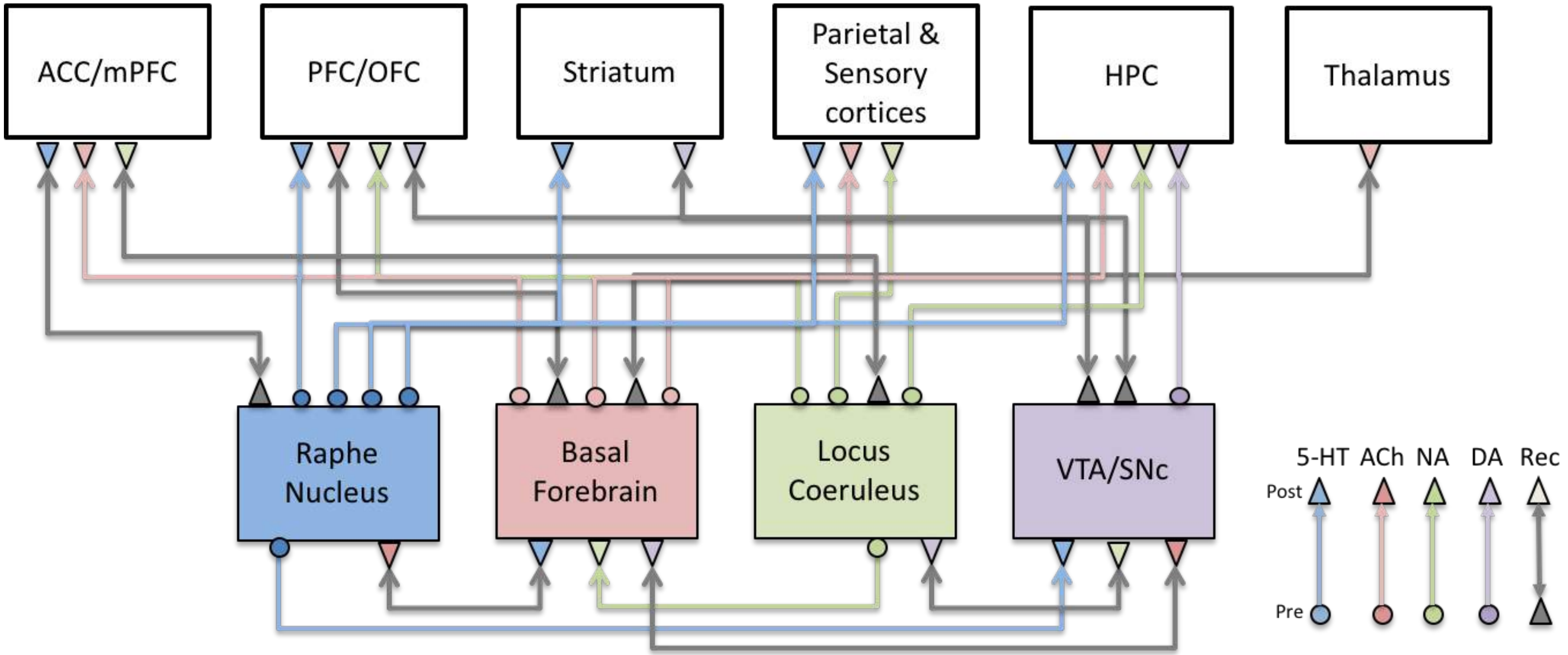
Weimerskirch, et al., Science, 2016.

Value and Prediction

- Intelligent agents are equipped with a value system which constitutes a basic set of assumptions about what is good or bad.
- Organisms adapt their behavior through value systems.
- Minimizing surprise, by predicting future outcomes, minimizes the expenditures required to deal with unanticipated events.

Neural Correlates of Value

DA – Reward prediction; 5-HT – Risk aversion;
ACh – Attention (Expected Uncertainty); NA – Attention (Unexpected Uncertainty)



Avery & Krichmar, Front. Neuro, 2017

Reducing Surprise Through Prediction

- Prediction is crucial for fitness in a complex world and a fundamental computation in cortical systems.
- This requires the construction and maintenance of an internal model.
- The brain maintains internal models for a wide range of behaviors; from motor control to language processing.

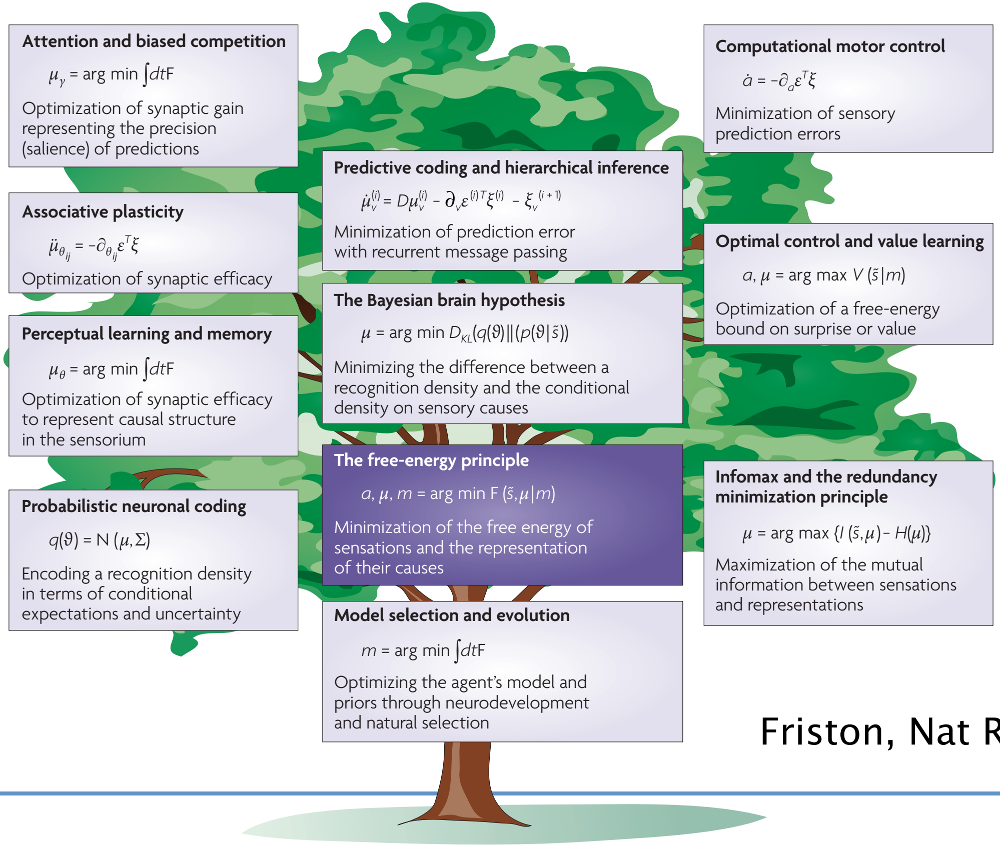
Krichmar, Hwu, Zou & Hylton, Cognitive Computation and Systems, In Press.

Clark (2013) *Behav Brain Sci*; Hickok, Houde & Rong (2011) Neuron; Richert, Fisher, Piekniewski, Izhikevich, & Hylton (2016), arXiv:1608.06277.

Biological Organisms Minimize Free Energy

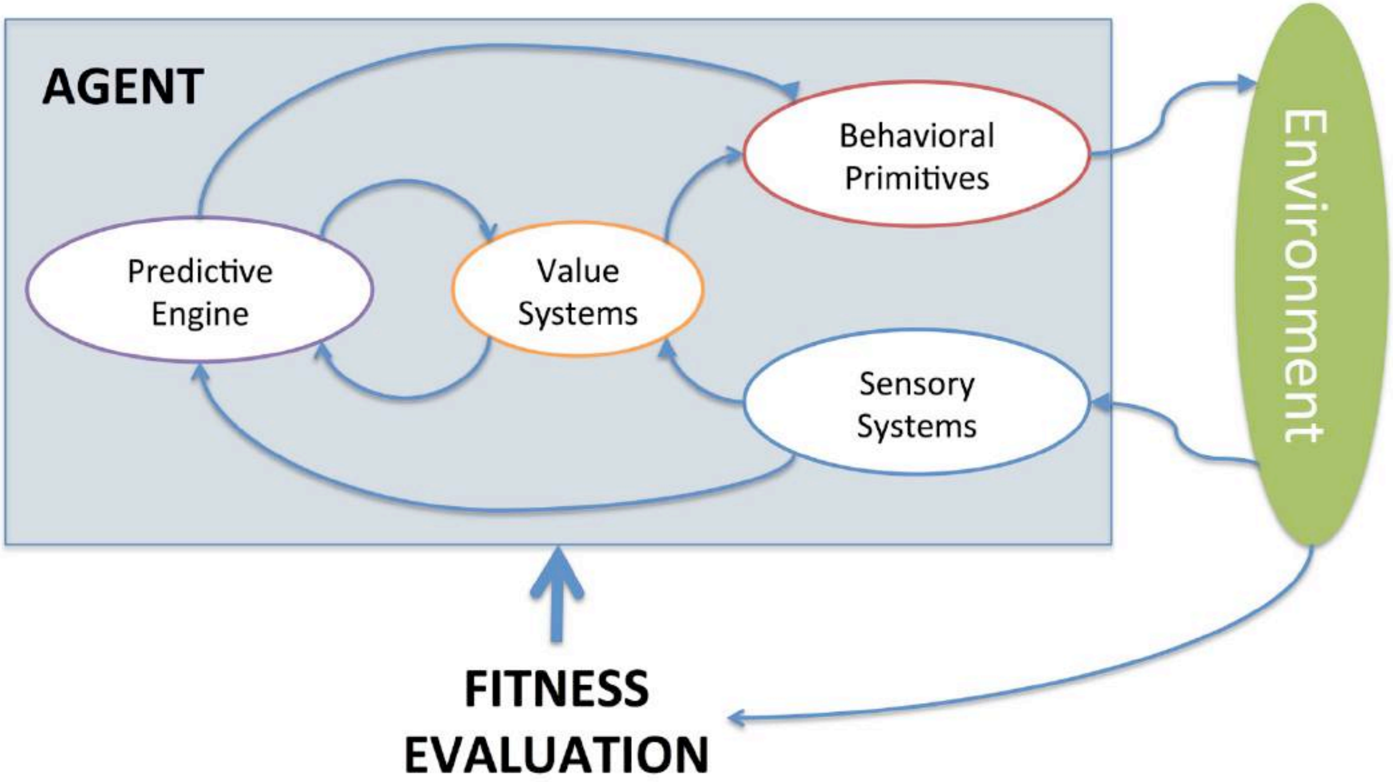
- Natural systems must adapt or evolve to resist a tendency toward disorder in an ever-changing environment (Ashby, 1947).
- Any self-organizing system that is at equilibrium with its environment must minimize its free energy (Friston, 2010).

Free Energy Principle - Unifying Brain Theory



Friston, Nat Rev Neurosci, 2010

Biomimetic Architecture for Thermodynamic Computing



Biomimetic Architecture for Thermodynamic Computing

- A closed loop system where the control (artificial brain) is closely coupled with the body (robot) and the world (environment).
  - The agent has innate values, derived from the environment and value systems, which send signals to the brain to adapt behavior.
  - Since value is inversely proportional to surprise, predicting value is key to the agent's fitness.
- The world is dynamic, the agent must adapt its behavior to survive.
  - Fitness Evaluation is the metric for evolving these algorithms
    - How long the system can perform without intervention.
    - How successful the system is in the task environment.
    - How energy efficient the system is in performing a task.

More to Explore

- Beyeler, M., Rounds, E.L., Carlson, K.D., Dutt, N., and Krichmar, J.L. (2017). Sparse coding and dimensionality reduction in cortex. bioRxiv.
  - https://www.biorxiv.org/content/early/2017/06/14/149880
- Krichmar, J., Severa, W., Khan, S., Olds, J. (2018). Making BREAD: Biomimetic strategies for Artificial Intelligence Now and in the Future. arXiv.
  - https://arxiv.org/abs/1812.01184

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Back row: Hirak Kashyap, Alexandro Ladron, Celeste Crowder, Emre Neftci, John Shepanski, Georgios Detorakis
Front row: Nikil Dutt, Ting-Shou Chou, Jeff Krichmar, Xinyun Zou, Tiffany Hwu

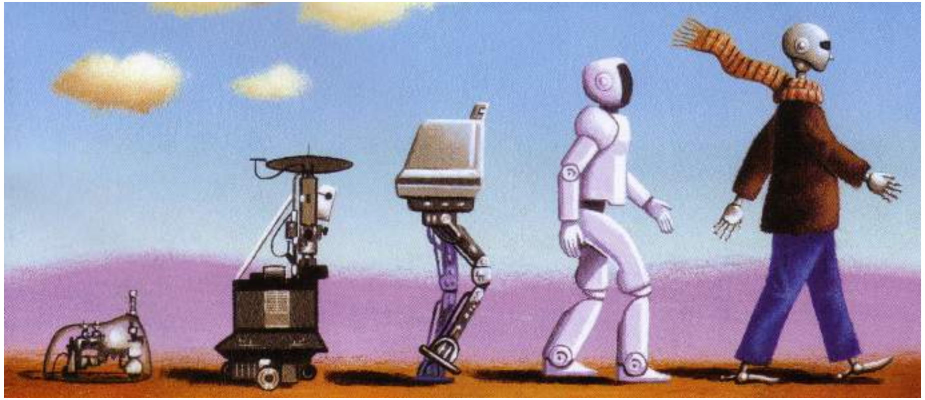
Todd Hylton UCSD

Tom Conte Georgia Tech

Yiorgos Makris UT Dallas

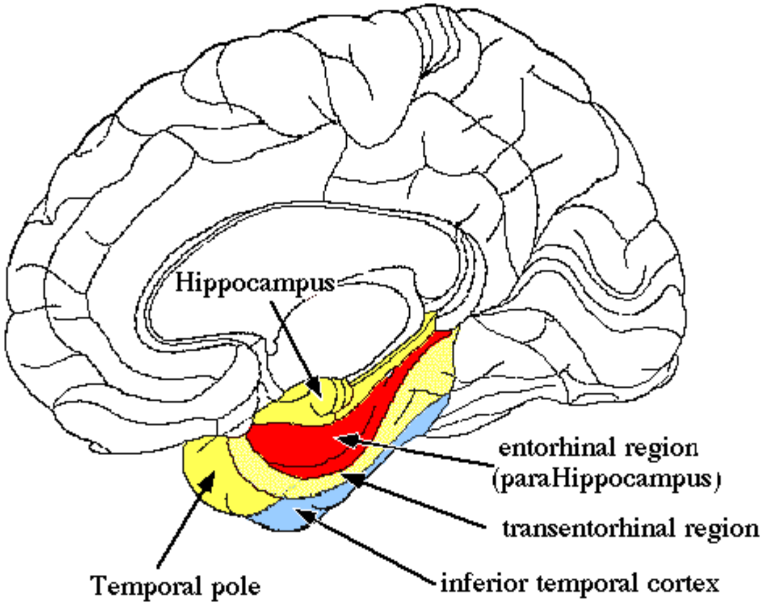
http://www.socsci.uci.edu/~jkrichma/

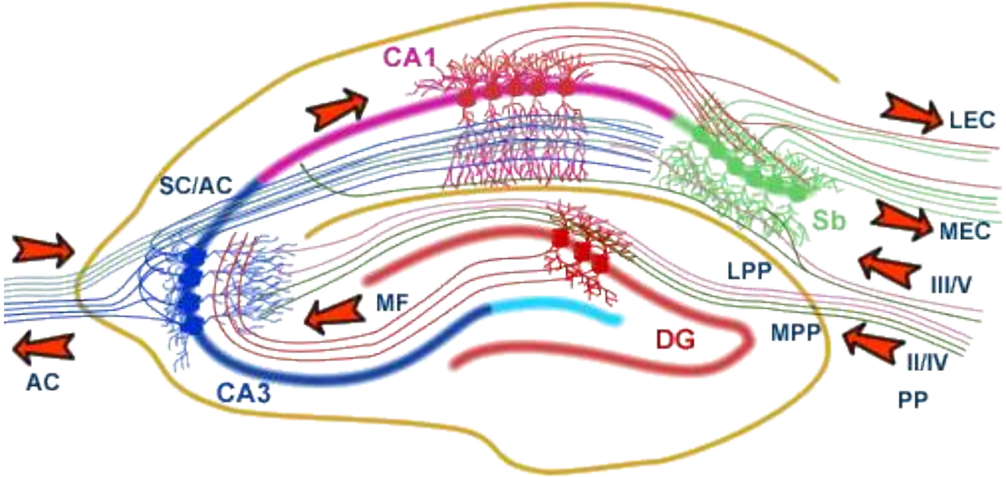
Future Outlook…



- To get a truly cognitive system one must study and be inspired by the brain and body of natural systems.
- Biological intelligence is an existence proof and currently our only working model.
- Following this will ultimately lead to intelligent cognitive robots and assistants.

Hippocampus – Learning and Memory

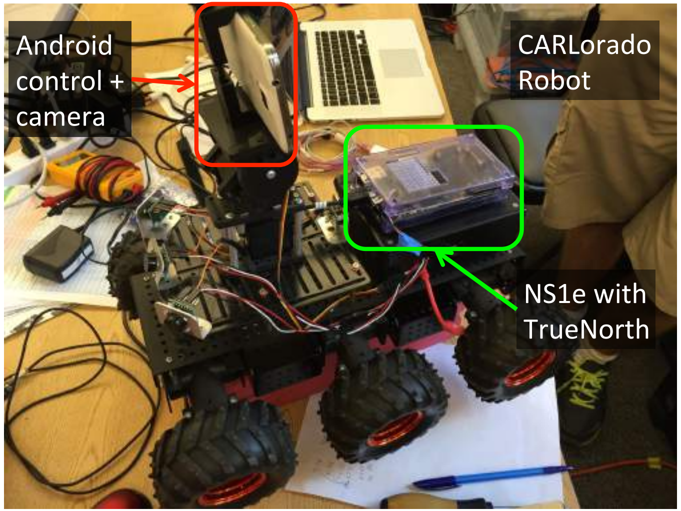




Hippocampus – Learning and Memory

Krichmar, J.L., Nitz, D.A., Gally, J.A., and Edelman, G.M. (2005). PNAS, *102*, 2111-2116.

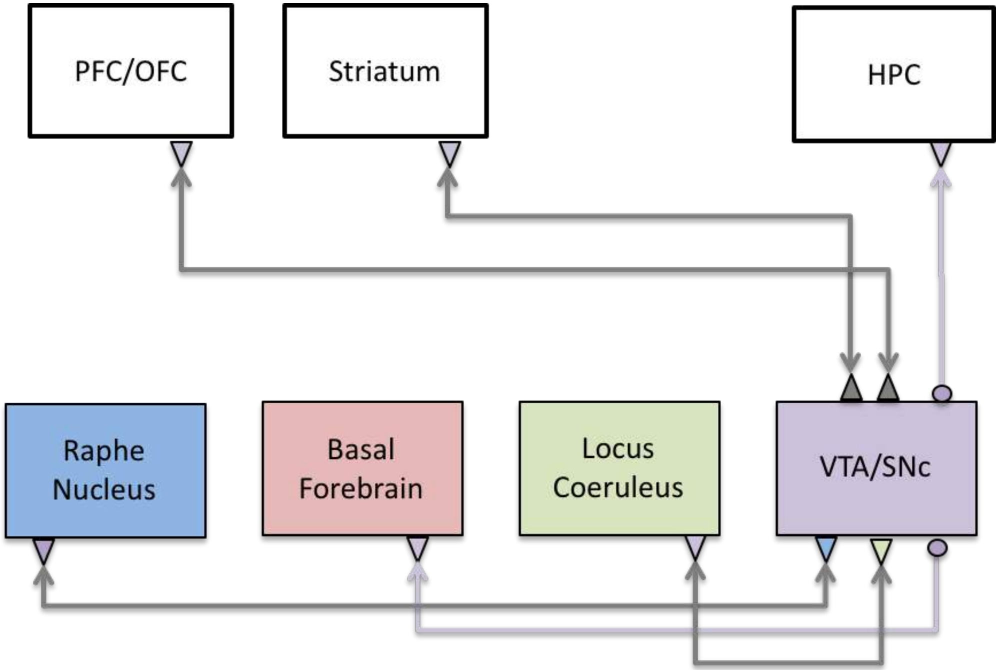
Self-Driving using CNNs on Neuromorphic Hardware



Hwu, T., Isbell, J., Oros, N.,& Krichmar, J. IJCNN 2017

Neural Correlates of Value

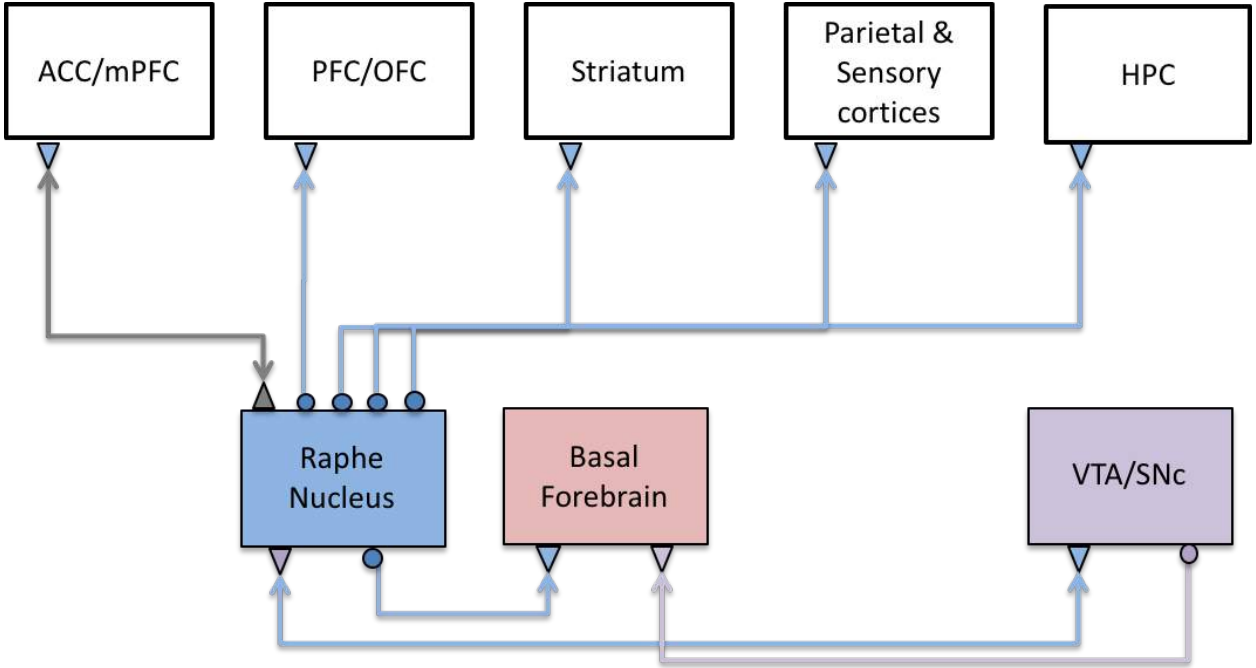
Dopamine – Reward, Saliency, Novelty, Invigoration



Avery & Krichmar, Front. Neuro, 2017

Neural Correlates of Value

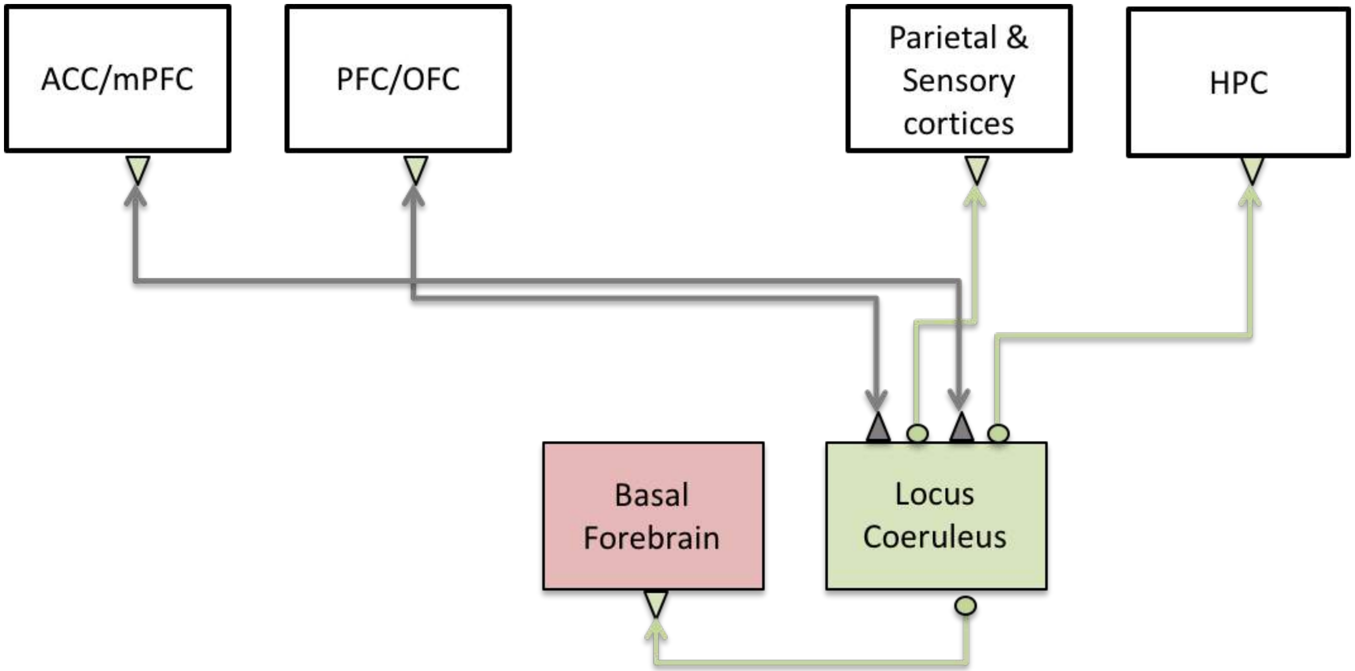
Serotonin – Harm Aversion, Anxious States, Withdrawal



Avery & Krichmar, Front. Neuro, 2017

Neural Correlates of Value

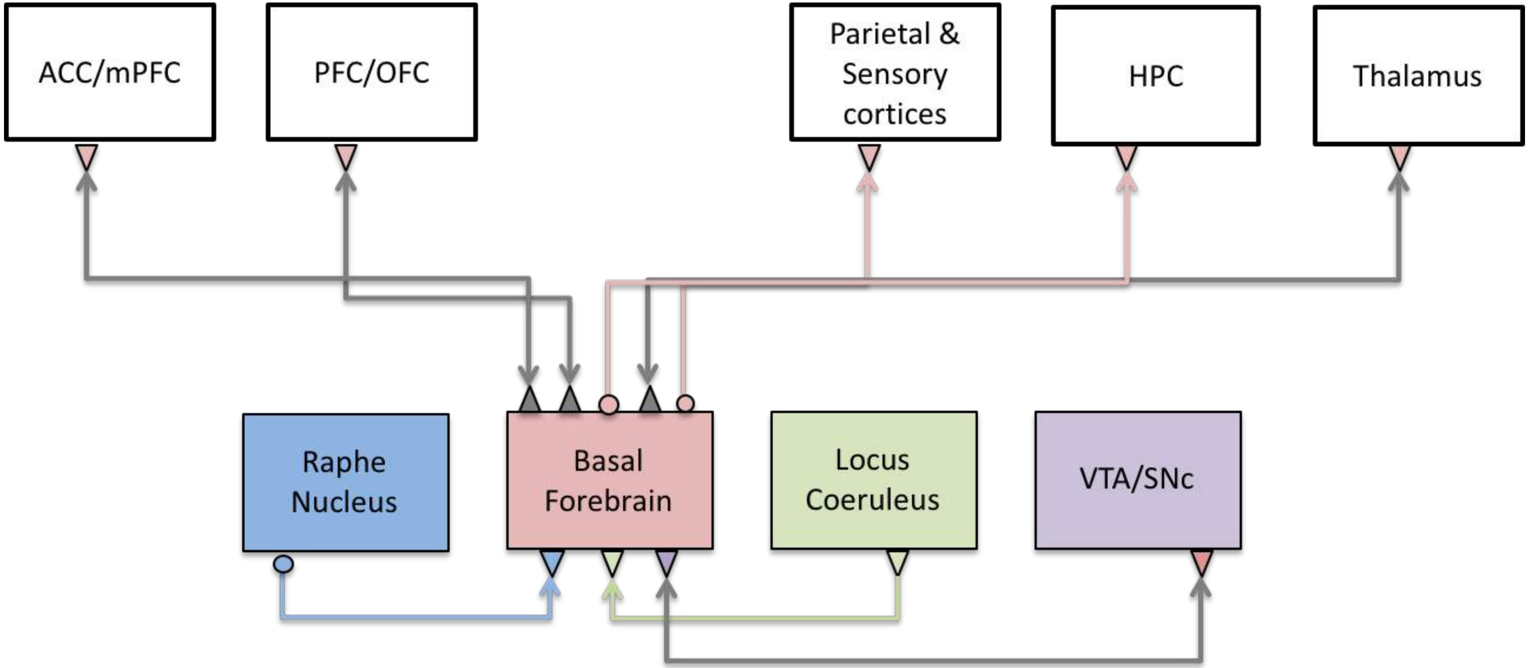
Norepinephrine – Vigilance, Unexpected Uncertainty



Avery & Krichmar, Front. Neuro, 2017

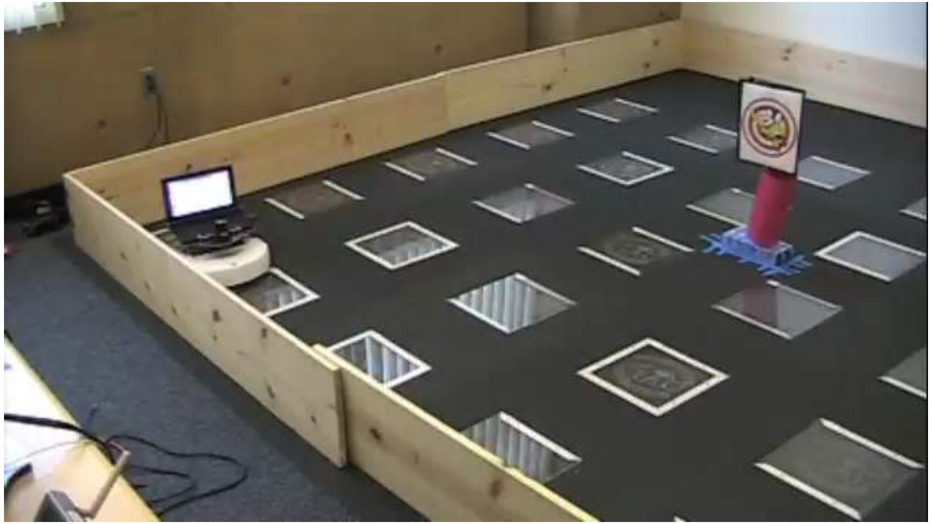
Neural Correlates of Value

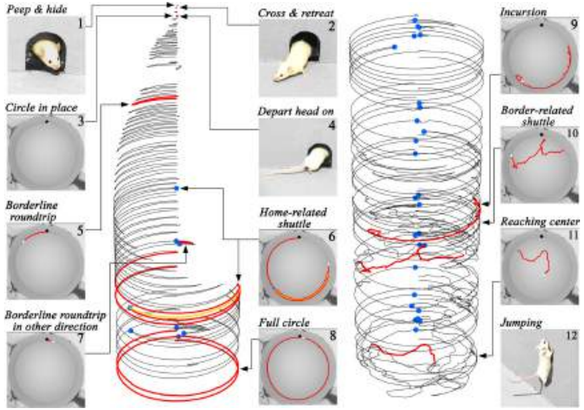
Acetylcholine – Memory Consolidation, Attention, Expected Uncertainty

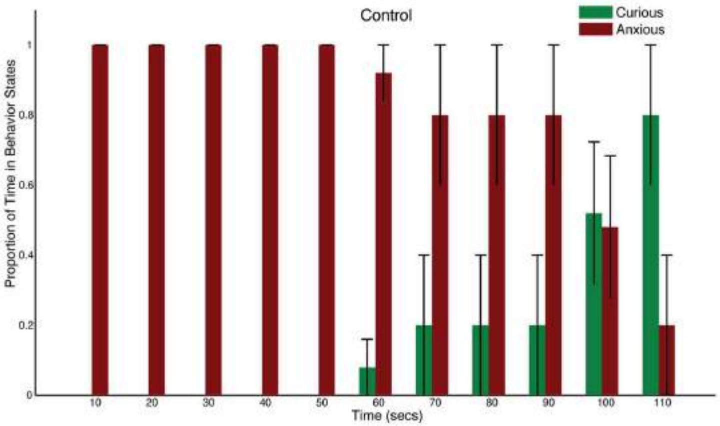


Avery & Krichmar, Front. Neuro, 2017

Value-Based Neurorobot



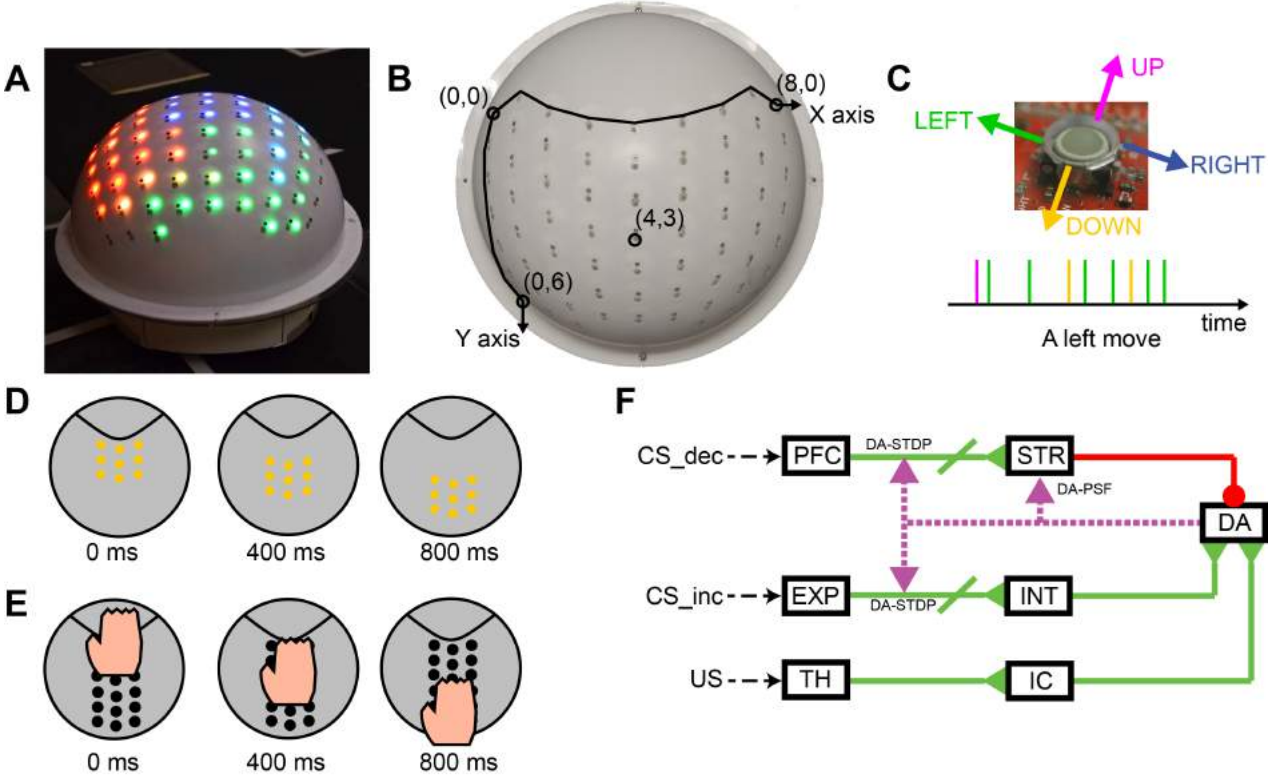




- Open Field Test for Rodents and Robots
  - Gold standard test for anxiety and obsessive compulsive disorders in animal models.
  - Typical behavior
    - Anxious – stay close to the walls until convinced it is safe.
    - Curious – make crossings in the open and explore novel objects.

Krichmar, Front. Neurorobot, 2013

Predicting User Preferences with a Tactile Robot



Chou, T.-S., Bucci, L. D.,& Krichmar, J. L. Front. Neurorobot, 2015.

Predicting User Preferences with a Tactile Robot

Mental Imagery

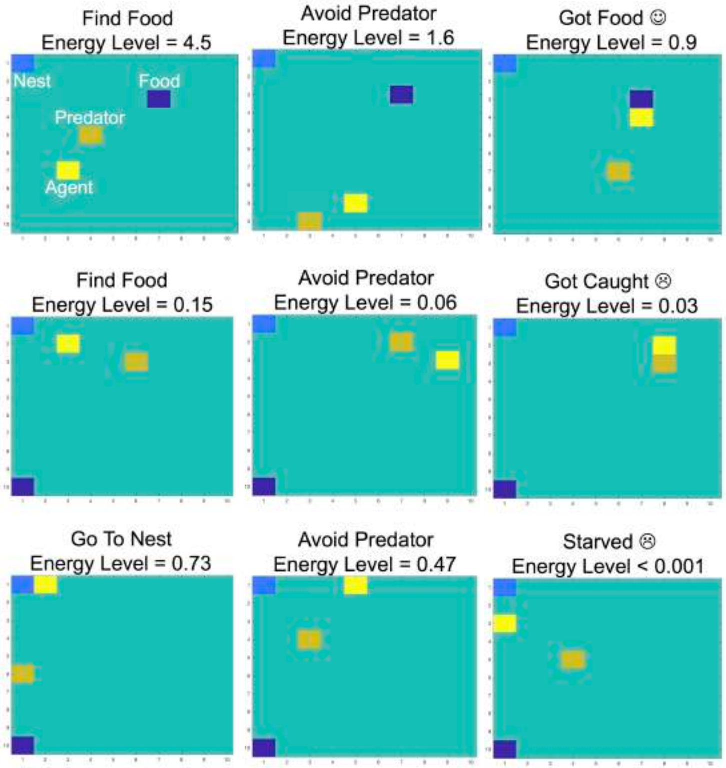
- Mental simulation can predict outcomes and overcome uncertainty.
- Mentalizing
  - Ability to understand another's state and plan accordingly
- Mental imagery is thought to be an important component for developing artificial systems that are cognitive or conscious.

Vernon, Metta, & Sandini (2007) *IEEE Transactions on Evolutionary Computation*

Chella and Manzotti (2011). Artificial Consciousness. Perception-Action Cycle: Models, Architectures, and Hardware 1, 637-671.

Predicting Value through Mental Imagery

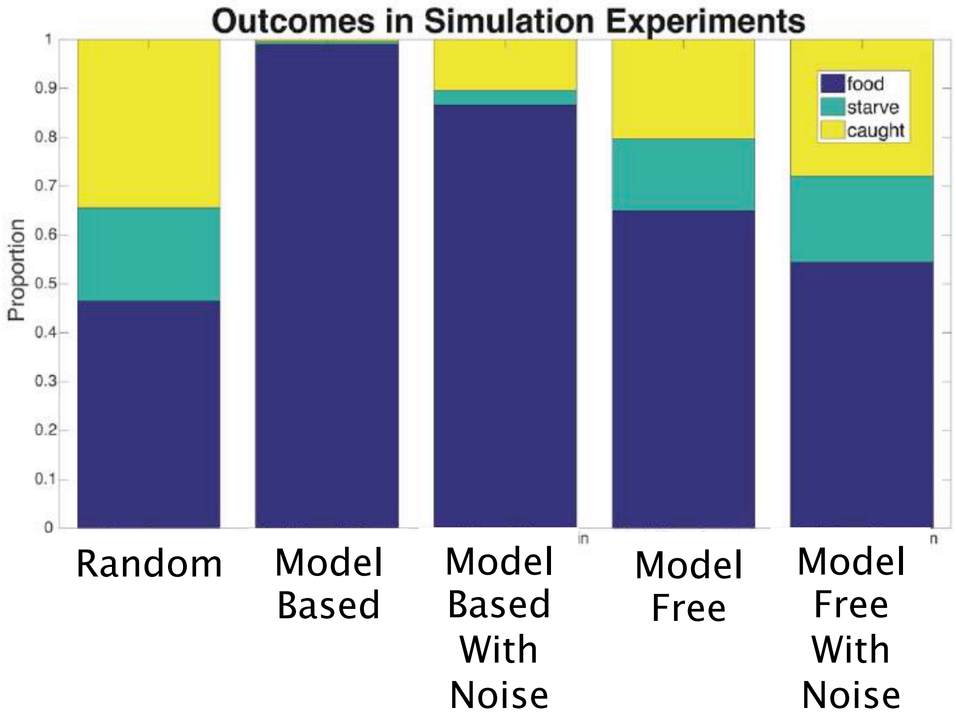
- Developed a simple model based algorithm to recursively "imagine" how the effects of its own actions would affect another's actions.
- Designed a predator-prey scenario
  - Agent maximizes positive value
    - Acquiring food.
  - Minimizes negative value
    - Eaten by a predator.
    - Starving.



Krichmar, Hwu, Zou & Hylton (Submitted) *Frontiers in Neurorobotics.*

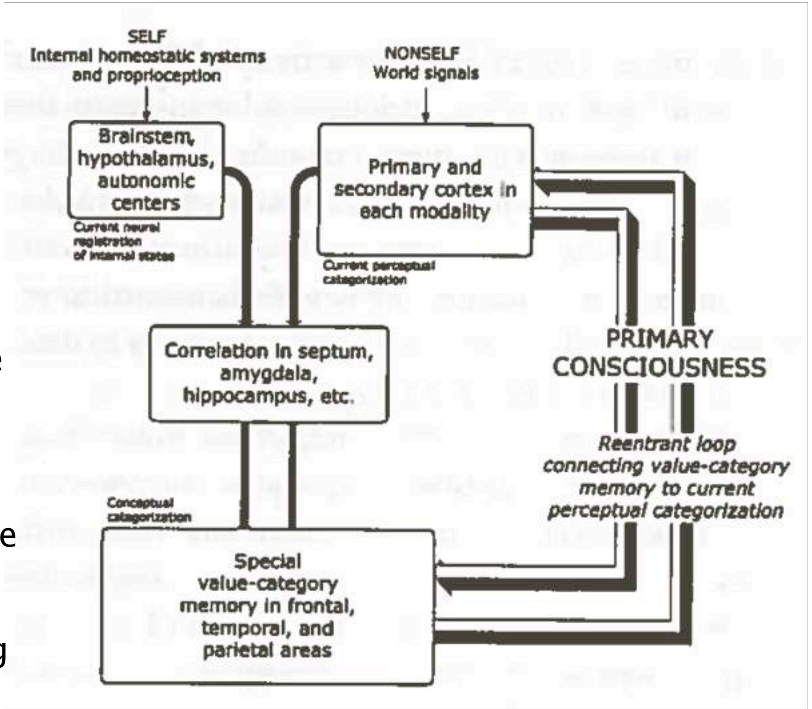
Predicting Value Through Mental Imagery

- Model-based system that could mentalize outperformed a model-free reinforcement learning algorithm.
- Highlights advantage of planning ahead before taking actions in dynamic, noisy environments.



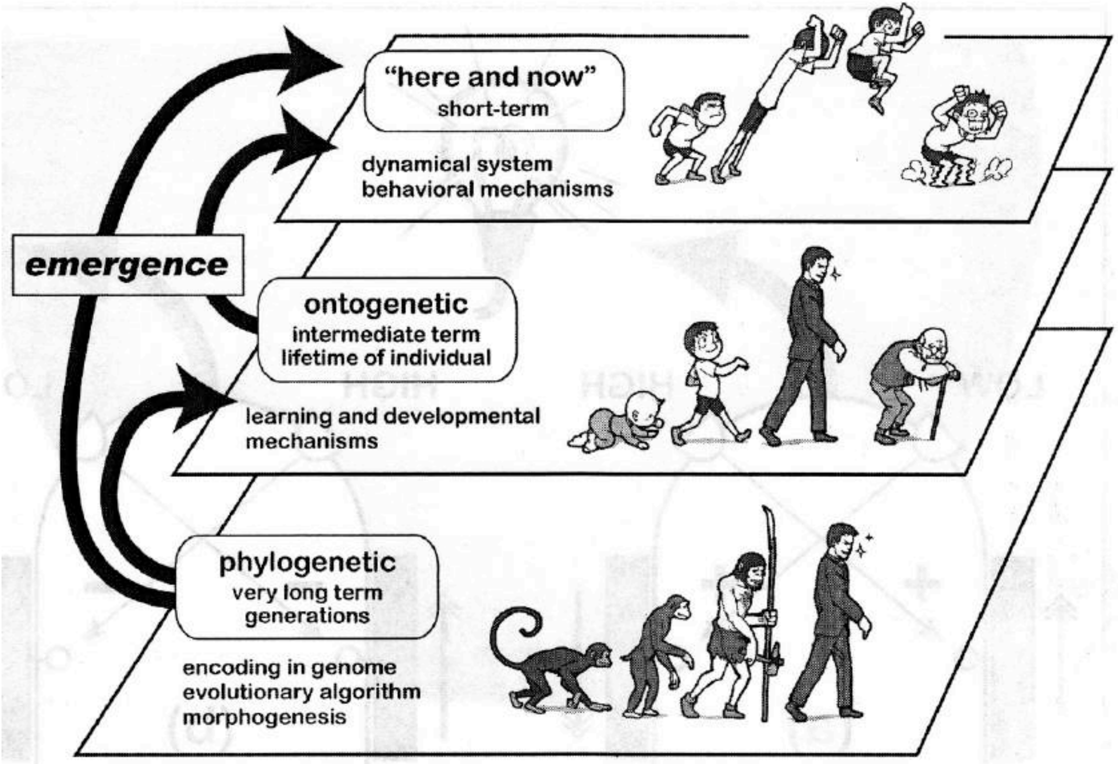
Theory of Neuronal Group Selection

- Plasticity is modulated by value
  - Signaled by neuromodulatory systems and hormonal systems.
  - Predicted by frontal cortex and limbic system.
- Value systems control which neuronal groups are selected and which actions lead to evolutionary fitness
  - Predicting outcomes that lead to positive value and avoid negative value. In this sense, predicting value is inversely proportional to surprise.
- From a nonequilibrium thermodynamic perspective
  - Value is associated with those actions that minimize the increase of entropy (e.g., feeding, predicting outcomes, gathering information).
  - Efficient movement, efficient alert sensory scanning of the environment, and foresight.



Edelman, Neural Darwinism, 1993.

Emergence of Cognition Occurs at Multiple Timescales



Pfeifer & Bongard, How the Body Shapes the Way We Think.

Brain Computing Facts

- That 1.3 kilogram lump of neural tissue you carry around in your head accounts for about 20 percent of your body's metabolism.
  - An average basal metabolism of 100 watts, each of us is equipped with the biological equivalent of a 20-Watts supercomputer.
  - Today's most powerful computers, running at 20 million Watts, can't come close to matching the brain.
- The brain has relatively shallow but massively parallel networks.
  - At every level, from deep inside cells to large brain regions, there are feedback loops that keep the system in balance and change it in response to activity from neighboring units.
  - The ultimate feedback loop is through the muscles to the outside world and back through the senses.

Fred Rothganger, IEEE Spectrum 2017