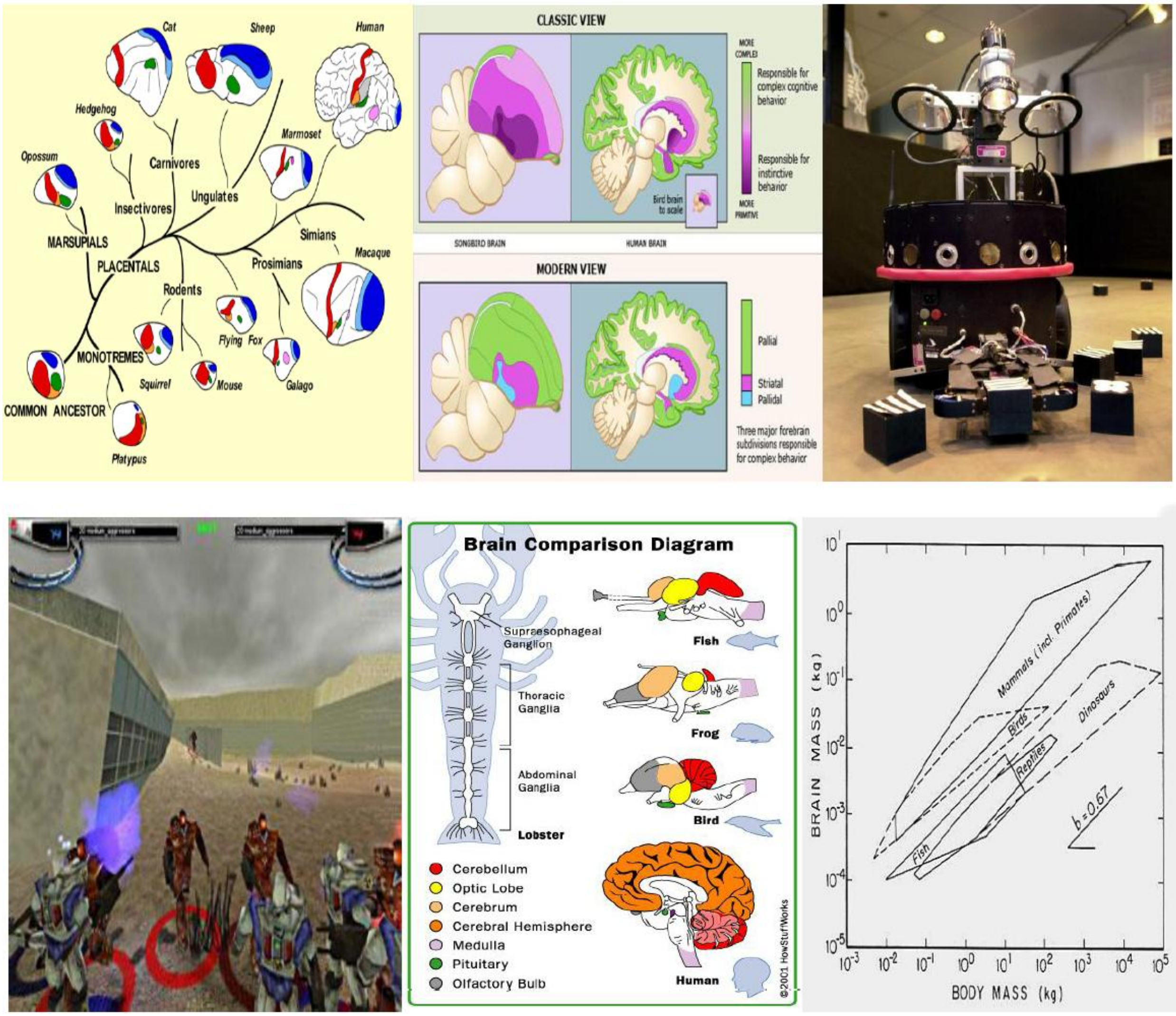
Introduction to Neuroevolution

Instructor: Bradly Alicea, e-mail: freejumper@yahoo.com

Meeting place: TBA, Meeting time: TBA



Pictures, clockwise from upper left: a diagram of Mammalian neocortical brain evolution; a comparison of bird and human brains before and after a taxonomic revision; Darwin VII (a robot design based on evolutionary principles); a trait-body size scaling of brain size across vertebrate taxa; comparison of major brain centers between lobsters and vertebrate species; NERO, a neural network-based virtual environment simulation that produces adaptive network connectivity.

What is Neuroevolution and why should I care? Several scientific luminaries can give you an idea:

"It is not the strongest of the species that survives, nor the most intelligent, but the one most responsive to change" - Charles Darwin

"Nothing in Biology Makes Sense Except in the Light of Evolution" - Theodosius Dobzhansky

"As long as our brain is a mystery, the universe, the reflection of the structure of the brain will also be a mystery" - Santiago Ramon y Cajal

"We're inquiring into the deepest nature of our constitutions: How we inherit from each other. How we can change. How our minds think. How our will is related to our thoughts. How our thoughts are related to our molecules" - Gerald M. Edelman

What kind of background do I need for this class?

A background in biology is useful but not required. In addition, there will be a significant technological component, and students will be introduced to mathematical concepts. To get the most out of this class, you must keep an open mind and be persistent, qualities that will serve you well in general.

How fair is the grading?

The grading is as fair as it gets. There is one exam (a final), as this is a problem-based, hands-on course. There are four homework assignments, each due 1.5 weeks after assigned. There is also a single quiz at the beginning of the course. Pay attention to this assignment, as it may help your final grade (e.g. pre-emptive extra credit).

Grading Scale:

Item	Percentage of Grade
Assignment #0	Tie-breaker
Assignment #1	15%
Assignment #2	15%
Assignment #3	20%
Assignment #4	15%
Final Exam	35%

What will we cover?

The list of topics is broad but integrative. The lesson plan will move between basic concepts and more detailed problems. There will be several "introduction" lectures interspersed throughout the course, with a more detailed follow-up in subsequent lectures.

Materials will be provided either through the class website or put on reserve in the library. Supplementary materials (study guides, course packs, lecture notes, podcasts, and video clips) will all be made available either in .pdf or .mpeg format via the class website.

Schedule of Topics and Assignments:

Section 1: Introduction

Date and Topic	Goals	Assignments
Week 1: Introduction	To acquire a basic understanding of the course	Download and Review: Basic Terminology Handout.

Session A: What is neuroevolution and why should I care? Session B: Review of terminology, concepts, outline of course.	layout and the field of neuroevolution.	
Weeks 1 & 2: Basics of Evolution Session A: phylogeny and systematics of nervous systems. Session B: population and developmental processes.	To acquire an introductory toolkit (e.g. terminology and analytic tools).	Online Exercise (Assignment #0): Terminology quiz (open-note).

Section 2: Genes, brains, and intelligence

Week 3: Genes, Circuits, and Behavior: a question of scale? Session A: review of evidence, recent developments. Session B: mapping genotype to phenotype.	To understand the linkages between different scales of analysis. Also to appreciate the effects of one scale of analysis on another. Should be able to explain what "level of selection" refers to.	Assignment #1: basic phylogenetics assignment.
Week 4: A benchmark for intelligence I. Session A: birds and bees, cetaceans and humans (and octopii, oh my): case studies in cognition. Session B: bridging the gap between "hopeful monsters".	To understand basics of human and animal intelligence. Also to appreciate how intelligence is related to "descent with modification" and biodiversity (e.g. phylogenetic processes).	
Weeks 4 & 5: A benchmark for intelligence II: Session A: what does ecology have to do with it? Culture, niche, and environmental selection. Case study: Hominids in the Pleistocene.	To understand linkages between ecology, behavior, and observed intelligence. Should have familiarity with several animal and in silico (e.g. robotic and artificial intelligence) model systems.	Assignment #2: simulation assignment.

Session B: intelligence *in silico*.		

Section 3: Focus on brain anatomy and evolution

Week 6 & 7: Brain anatomy and evolution – concepts Session A and B (6): Phenotypic changes: allometric and isometric scaling, architectonic changes, neuronal and ion channel specialization, epigenetic matching. Session A and B (7): "Genotypic" changes: developmental, activity-dependent, and reactive gene expression.	An introductory-level understanding of concepts required to appreciate the literature in this area. Relevant concepts include: growth, development, adaptation, activity-dependent plasticity, reactive plasticity, phenotypic specialization, and biodiversity.	
Week 7 & 8: Brain anatomy and evolution – model systems Session A: spatial cognition and evolution of the eye in vertebrates. Session B: learning and memory in Aplysia, language in primates.	To understand and appreciate the model systems in modern brain science. Focus will be on rediscovering them in light of an evolutionary perspective.	Assignment #3: applying concepts to model systems assignment.

Section 4: Brain anatomy "in action"

Weeks 9 and 10: Sexual differentiation, plasticity, and development. Sessions A and B (9): hormonal effects on the nervous system (organizational vs. activational). Sexual selection. Sessions B (Week 9) and A (Week 10): Preconditioning	Focus will be on reconsidering them in light of concepts learned in Weeks 6 and 7. Know the difference between sexual and environmental selection, and their corresponding roles in shaping the nervous system.	

(the effects of acute environmental stressors on the brain). Sessions A and B (10): introduction to Evolution of Development (evo-devo).		
Week 11 & 12: Evolution of the periphery: muscle, bone, and motility. Sessions A and B (11): Neuromechanics. Sessions A and B (12): functional morphology and evolution.	To understand and appreciate how the phenotype (e.g. an animal's body) shapes and affects cognition and brain function. Should be able to understand why motility evolved in both basal and derived neural systems, and what an artificial selection experiment is.	
Week 13 & 14: Genomics and molecular biology of the brain. Session A and B (13): introduction to molecular biology. Sessions A and B (14): introduction to evolutionary genomics.	To understand the basics of genomics and molecular biology. Should be able to relate these concepts to brain development, function, and biodiversity.	Assignment #4: basic genomics assignment.
Week 15: Sociality, physiological regulation, and plasticity.	To understand the basic impact of sociality on brain morphology and physiological regulation.	

Section 5: Future directions

Week 16: Evolvability of the brain and neural systems. Session A: introduction to evolvability. Session B: digital evolution.	To understand the basics of computational methods used to assess how evolvable a specific neural system is. Should have literacy in digital representations of biological systems and computational modeling.	Study for Final Exam. Review session/materials TBA
Final Exam	Should be able to pass this without too much difficulty.	

Further reading list for selected topics (all readings should be provided either on library reserve or in .pdf form on the class website):

General:

Allman, J.M. (1999). Evolving Brains. W. H. Freeman, New York, NY.

Butler, A.B. and Hodos, W. (2005). Comparative Vertebrate Neuroanatomy. Wiley and Sons, New York, NY.

Calvin, W.H. (2002). A Brain for All Seasons: human evolution and abrupt climate change. University of Chicago Press, Chicago.
Web resource: http://williamcalvin.com/BrainForAllSeasons/

deWaal, F.B.M. and Tyack, P.L. (2003). Animal Social Complexity: intelligence, culture, and individualized societies. Harvard Press, Cambridge, MA.

Dusenbery, D.B. (1992). Sensory Ecology: how organisms acquire and respond to information. W.H. Freeman, Chicago.

Edelman, G.M. (1987). Neural Darwinism: the theory of neuronal group selection. Basic Books, New York.
Web Resource: http://www.mindcreators.com/NeuralDarwinism.htm

Kaas, J., Striedter, G., Bullock, T., Preuss, T., Rubenstein, J., and Krubitzer, L. (2006). Evolution of Nervous Systems (four-volume set). Academic Press, New York.

Linden, D.J. (2007). The Accidental Mind: how brain evolution has given us love, memory, dreams, and god. Harvard Press, Cambridge, MA.
Web resource: http://accidentalmind.org/

MacLean, P.D. (1990). The Triune Brain in Evolution. Springer, Berlin.

McNeill, A.R. (1996). Optima for Animals. Princeton, Princeton, NJ.

Odling-Smee, F.J., Laland, K., and Feldman, M.W. (1999). Niche Construction: the neglected process in evolution. Princeton, Princeton, NJ.

Sanes, D.H., Reh, T.A., and Harris, W.A. (2005). Development of the Nervous System. Academic Press, New York, NY.

Streidter, G. (2006). Principles of Brain Evolution. Sinauer, Sunderland, MA.

Swanson, L.W. (2003). Brain Architecture: Understanding the Basic Plan. Oxford University Press, Oxford, UK.

Wilson, R.A. and Keil, F.C. (2001). The MIT Encyclopedia of the Cognitive Sciences. MIT Press, Cambridge, MA.
Web resource: http://cognet.mit.edu/library/erefs/mitecs/

Comparative Neuroevolution:

Calarco, J.A., Xing, Y., Caceres, M., Xiao, X., Pan, Q., Lee, C., Preuss, T.M., and Blencowe, B.J. 2007. Alternative splicing differences between humans and chimpanzees affect transcripts from functionally diverse genes. Genes and Development, 21(22), 2963-2975.

Kaas, J.H. (1989). The evolution of complex sensory systems in mammals. Journal of Experimental Biology, 146(1), 165-176.

Lefebvre, L., Sol. D (2008). Brains, lifestyles and cognition: are there general trends? Brain, Behavior and Evolution, 72, 135-144.

Preuss, T.M. (2001). The discovery of cerebral diversity: an unwelcome scientific revolution. In "Evolutionary Anatomy of the Primate Cerebral Cortex". D. Falk and K. Gibson eds. pgs. 138-164. Cambridge University Press, Cambridge, UK.

Preuss, T.M. (2000). Taking the measure of diversity: Comparative alternatives to the model-animal paradigm in cortical neuroscience. Brain, Behavior and Evolution, 55, 287-299.

Intelligence *in silico*:

Reger, B.D., Fleming, K.M., Sanguineti, V., Alford, S., and Mussa-Ivaldi, F.A. (2000). Connecting Brains to Robots: An Artificial Body for Studying Computational Properties of Neural Tissues. Artificial Life, 6(4), 307-324.

Valsalam, V., Bednar, J.A., and Miikkulainen, R. (2007). Developing Complex Systems Using Evolved Pattern Generators. IEEE Transactions on Evolutionary Computation, 11(2), 181-198.

Phylogeny of the Nervous System:

Allman, J., Hakeem, A., and Watson, K. (2002). Two Phylogenetic Specializations in the Human Brain. The Neuroscientist, 8(4), 335-346.

Eisthen, H.L. and Nishikawa, K.C. (2002). Convergence: Obstacle or Opportunity? Brain, Behavior, and Evolution, 59, 235-239.

Krubitzer, L. and Kaas, J. (2005). The evolution of the neocortex in mammals: how is phenotypic diversity generated? Current Opinion in Neurobiology, 15, 444-453.

Zakon, H.H. (2002). Convergent Evolution on the Molecular Level. Brain, Behavior, and Evolution, 59, 250-261.

Sexual Differentiation, Plasticity, and Development:

Gidday, J.M. (2006). Cerebral preconditioning and ischaemic tolerance. Nature Reviews Neuroscience, 7(6), 437-448.

Hofman, H.A. (2003). Functional Genomics of Neural and Behavioral Plasticity. Journal of Neurobiology, 54, 272-282.

Krubitzer, L.A., and Kahn, D. (2003). Nature versus nurture revisited: an old idea with a new twist. Progress in Neurobiology, 70, 33-52.

McEwen, B.S. (1981). Sexual differentiation of the brain. Nature, 291, 610.

Physiological Consequences/Correlates of Neuroevolution:

Aiello, L.C. and Wheeler, P. (1995). The expensive-tissue hypothesis: the brain and the digestive system in human and primate evolution. Current Anthropology, 36, 199–221.

Balaban, E. (1997). Changes in multiple brain regions underlie species differences in complex, congenital behavior. PNAS USA, 100, 4873–4878.

Guoa, J.H., Huanga, Q., Studholmeb, D.J., Wua, C.Q., Zhao, Z. (2005). Transcriptomic analyses support the similarity of gene expression between brain and testis in human as well as mouse. Cytogenetics and Genome Research, 111, 107-109.

Meizel, S. (2005). The sperm, a neuron with a tail: 'neuronal' receptors in mammalian sperm. Biological Reviews of the Cambridge Philosophical Society, 80(4), 673.

Sol, D, Bacher, S., Reader, S.M., and Lefebvre, L. (2008). Brain size predicts the success of mammal species introduced into novel environments. American Naturalist, 172, S63.S71

Neuromechanics:

Nishikawa, K., Biewener, A.A., Aerts, P., Ahn, A.N., Chiel, H.J., Daley, M.A., Daniel, T.L., Full, R.J., Hale, M.E., Hedrick, T.L., Lappin, A.K., Nichols, T.R. Quinn, R.D., Satterlie, R.A., and Szymik, B. (2007). Neuromechanics: an integrative approach for understanding motor control. Integrative and Comparative Biology, 47(1), 16-54.

Full, R.J. and Koditschek, D.E. (1999). Templates and anchors: neuromechanical hypotheses of legged locomotion on land. Journal of Experimental Biology, 202(23), 3325-3332.

Genomics and Molecular Biology:

Choi, C.Q. (2006). RNAi? A new targeted silencer? Gene silencing causes marked behavior changes, may help map brain circuitry. http://www.the-scientist.com/news/display/23730/

Larsen, D.D. and Krubitzer L. (2008) Genetic and epigenetic contributions to the cortical phenotype in mammals. Brain Research Bulletin, 75(2-4), 391-397.

Perry, G.H. Dominy, N.J., Claw, K.G., Lee, A.S., Fiegler, H., Redon, R., Werner, J., Villanea, F.A., Mountain, J.L., Misra, R., Carter, N.P., Lee, C. and Stone, A.C. (2007). Diet and the evolution of human amylase gene copy number variation. Nature Genetics, 39, 1256-1260.

Robinson, G.E. (1999). Integrative animal behavior and sociogenomics. Trends in Ecology and Evolution, 14(5), 202-205.

Molecular Basis of Behavior and Cognition:

Hill, R.S. and Walsh, C.A. (2005). Molecular insights into human brain evolution. Nature, 437, 64-67.

Kandel, E.R. (2001). The molecular biology of memory storage: a dialogue between genes and synapses. Science. 294, 1030-1038.

Pollard, K.S., Salama, S.R., Lambert, N., Lambot, M-A., Coppens, S., Pedersen, J.S., Katzman, S., King, B., Onodera, C., Siepel, A., Kern, A.D., Dehay, C., Igel, H., Ares, M., Vanderhaeghen, P. and Haussler, D. (2006). An RNA gene expressed during cortical development evolved rapidly in humans. Nature, 443, 167-172.

Wang, H-Y., Chien, H-C., Osada, N., Hashimoto, K., Sugano, S., Gojobori, T., Chou, C-K., Tsai, S-F., Wu, C-I., and Shen, J. (2006). Rate of Evolution in Brain-Expressed Genes in Humans and Other Primates. PLoS Biology, 5(2), e13.

Sociality, Sexual Selection, and Brain Evolution:

Byrne, R.W. and Corp, N. (2004). Neocortex size predicts deception rate in primates. Proceedings of the Royal Society B, 271, 1693–1699.

Dunbar, R.I.M. and Shultz, S. (2007). Evolution in the Social Brain. Science, 317(5843), 1344-1347.

Korzan, W.J. and Summers, C.H. (2007). Behavioral Diversity and Neurochemical Plasticity: Selection of Stress Coping Strategies That Define Social Status. Brain, Behavior, and Evolution, 70, 257-266.

Pagel, M.D. and Harvey P.H. (1988). How mammals produce large-brained offspring. Evolution, 42, 948–957.

Schillaci, M.A. (2006). Sexual Selection and the Evolution of Brain Size in Primates. PLoS One, 1(1), e62.

Digital Evolution and Experimental Methods:

Garland, T. (2003). Selection experiments: an under-utilized tool in biomechanics and organismal biology. In “Vertebrate Biomechanics and Evolution”, pgs. 23-49. V.L. Bels, J.P. Gasc, and A. Casinos eds. BIOS, Oxford, UK.

Lenski, R.E., Ofria, C., Pennock, R.T., and Adami, C. (2003). The evolutionary origin of complex features. Nature, 423, 139-144.

McKinley, P., Cheng, B.H.C., Ofria, C., Knoester, D., Beckmann, B., and Goldsby, H. (2008). Harnessing Digital Evolution. IEEE Computer, 41(1), 54-63.

Evolvability and Robustness:
Adami, C. (2006). Reducible Complexity. Science, 312(5770), 61-63.

Lenski, R.E., Barrick, J.E., and Ofria, C. (2006). Balancing Robustness and Evolvability. PLoS Biology, 4(12), e428.

Facilitated Evolution:
Gerhart, J. and Kirschner, M. (2007). The theory of facilitated variation. PNAS USA, 104(1), 8582-8589.

Gerhart, J. and Kirschner, M. (2005). Plausibility of Life: resolving Darwin's dilemma. Yale University Press, New Haven, CT.

Parter, M., Kashtan, N., and Alon, U. (2008). Facilitated Variation: How Evolution Learns from Past Environments To Generalize to New Environments. PLoS Computational Biology, 4(11), e1000206.

Perspectives: Notes on Evolution and Phylogeny

Neutral Processes vs. Natural Selection:	Neutral processes are changes in gene frequencies due to genetic drift, while natural selection is a changes in gene frequencies due to environmental or sexual selection. In natural populations, each of these processes play a significant role in shaping the biodiversity we observe today. Which process has contributed more to brain evolution or the evolution of cognition? We will attempt to consider this question by learning how these forces of evolution operate.
Hard vs. Soft Heredity:	There are two forms of heredity that play a role in shaping natural variation: hard and soft mechanisms. Hard hereditary mechanisms involve genes that are protected from environmental mutations and other direct influences on the expression of traits. By contrast, soft heredity involves cellular agents and epigenetic factors which can influence how traits are expressed independent of the traditional forces of evolution. We will consider both types of heredity as complementary aspects of neuroevolution.
Homologues vs. Paralogues:	Homologues are alternate versions of a gene shared among species by virtue of a common ancestor. Paralogues are genes that exhibit homology but are not true homologues due to gene duplication or functional changes. Which type of gene has contributed more to the evolution of similar brain structures and behaviors across species? We will use the example of the Fox gene family in birds and Primates to get at this question.

Perspectives: Notes on Intelligence (e.g. adaptive behavior) Benchmarks

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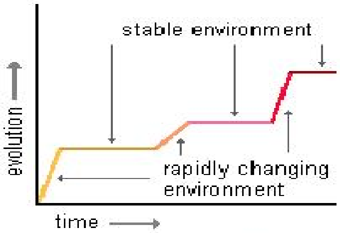
<td>“Hopeful Monster” intelligence



</td>
<td>“Hopeful monsters” are large-scale changes observed when comparing closely-related species. The presumption is that some mechanism exists to initiate large-scale change in a single evolutionary step. How this relates to extremely intelligent taxonomic groups (e.g. hominids, corvids, cetaceans, bees) remains unclear.</td>
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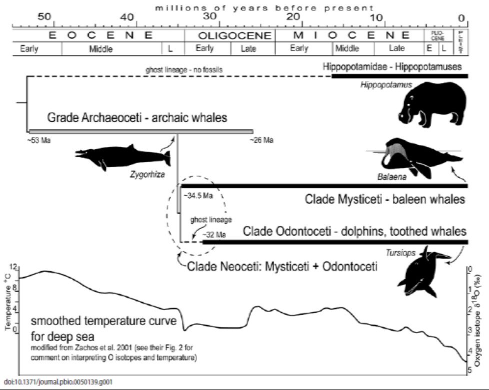
<td>Specialized intelligence



</td>
<td>Some species, such as bats and electric fish, have developed adaptive behavior based on sensory and morphological specializations. Even within humans, it is said that multiple specialized forms of intelligence exist that make us all different but complementary. How these specialties and this variation got there in evolution is unclear.</td>
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<td>Intelligence and cultural evolution</td>
<td>The role of sociality and culture in intelligence is also an open question. Most of the highly intelligent taxonomic groups also exhibit high degrees of sociality. Focusing on human evolution, many changes such as the cooking of food, making of tools, and the transition to agriculture have had profound effects on brain size and intelligence.</td>
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<tr>
<td>Simulated (machine) intelligence


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<td>How to build a truly autonomous intelligent machine remains an open question. For our purposes, Niko Tinbergen (the famous ethologist) poses four questions regarding the presence of a trait: how does it get there in evolution, how does it get there in development, what is its structure and what is its function. Consider how you would build an intelligent system with this in mind.</td>
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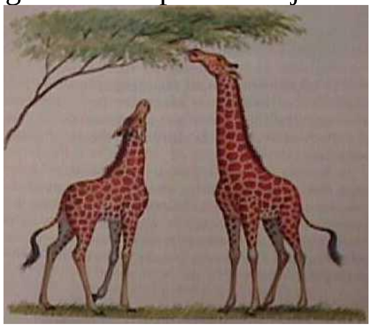
Perspectives: Facilitated Evolution

Intellectuals ranging from Lamarck to Baldwin have come up with ideas regarding the effect of physiological adaptation and learning on evolutionary change across generations. The classical example is of the giraffe’s neck. Lamarck postulated that the giraffe’s neck got the way it through the cumulative effects of reaching behavior. After Darwin, it was understood that neck length was a heritable trait under natural selection, and that only those giraffes with sufficiently long necks were able to survive and reproduce.

Thus, until recent empirical (molecular biological techniques) and theoretical (evo-devo) developments, perspectives involving the role of what might be called life-history adaptations in producing macroevolutionary patterns have not been widely accepted. One idea that is taking root is called facilitated evolution. According to this theory, environmental factors produce changes in the underlying biological system that can facilitate differential survival and reproduction. The following highlighted concepts are major features of this theory.



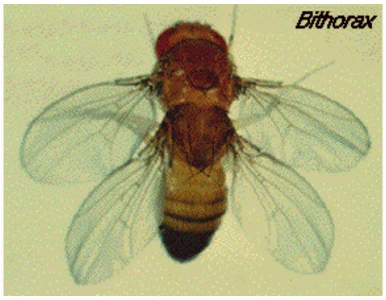
Facilitated variation (FV) can be described mathematically as

$$\mathbf{FV = (M_n/M_l) * (D_n/D_l)}$$

where M_n are the number of non-lethal mutants, M_l is the number of lethal mutants, D_n is the phenotypic distance of non-lethal mutants from the wildtype, and D_l is the phenotypic distance of lethal mutants from the wildtype (see Parter et.al, 2008).

This result suggests that as variation is facilitated, both M_n and D_n become large. Non-wildtype variants become more abundant and more dissimilar as FV is maximized. In addition, this equation proposed by Parter et.al suggests that the relationship between abundance and phenotypic distance is multiplicative.

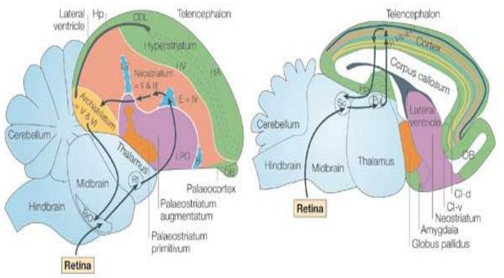
Weak regulatory linkage: in gene clusters such as the *Hox* family, tight physical linkage is required for proper gene expression and developmental function. One consequence of relaxed linkage is the production of lethal mutant phenotypes which are highly unfit. The *bithorax* mutant of the fruit fly (*Drosophila*) is one such example. In this case, the thoracic segment is duplicated, leading to an extra set of wings and severe impairments in flight performance.



Exploratory behavior: the matching of a signal to a target (e.g. targeted innervations). In the Streidter book, this process of motorneuron axons projecting to muscles in target tissues is called epigenetic matching. Another definition of exploratory behavior is weak regulatory linkage that results in non-lethal variation. In FV equation, M_n/M_l is maximized.

Reduced pleiotropy: Pleiotropy is the presence of multiple effects from a single gene. In facilitated evolution, the number of multiple effects is reduced so that the total amount of variability produced by a gene or gene family is focused in a certain direction.

Perspectives: Major Models and Issues in Brain Evolution

<table>
<tr>
<td>Nuclear-to-Layered Hypothesis:

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<td>Karten (1991). Characterizes homologous regions in bird pallium and 6-layered cortex in mammals. This is one in a number of hypotheses meant to explain the diversity observed across vertebrates as a single evolutionary system.</td>
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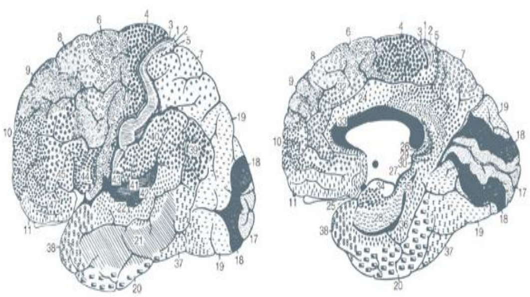
<td>Parcellation:
</td>
<td>Ebbetson (1980). Specialized function calls for a proliferation of cortical regions. Species that have visual, auditory, or somatosensory specializations have greater amounts of cortex devoted to them.</td>
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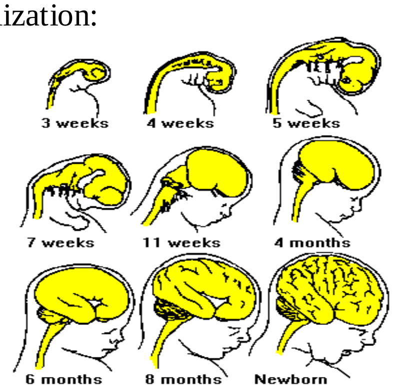
<td>Encephalization:

</td>
<td>Enlargement of the brain. Brain volume scales to body size in many vertebrate species, and a change in that scaling relationship represents enlargement or (sometimes!) shrinkage. Change is due to changes in growth during development, gene expression patterns, or heritable factors.</td>
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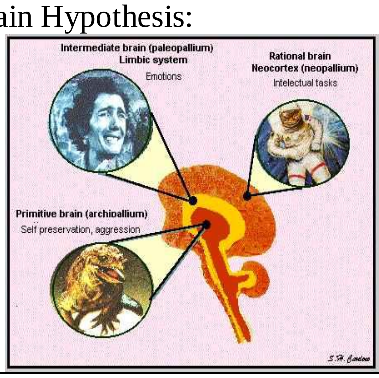
<td>Triune Brain Hypothesis:

</td>
<td>MacLean (1990). In mammals, the 6-layered cortex, midbrain, and brainstem are all distinct subsystems that have their own evolutionary history and functionality. The popular conception of the "lizard brain" is based on this theory.</td>
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Sexual Selection: 	Sexual selection has two dimensions: one is intersexual (males vs. females in a species), and the other is intrasexual (competition between males or females win a species). Like environmental selection, sexual selection favors individuals with high reproductive fitness. The difference between the two forms of selection rests on two criteria: 1) transmissibility (e.g. sex-linked traits) and 2) functionality (e.g. organs used in mating and copulation).

Perspectives: Differences Between Lability and Plasticity in the Brain

Lability: changes in the function, size, or shape of a trait between species and across generations.	What are the cumulative effects of evolutionary changes on the brain? How are they expressed in a comparative sense (e.g. across species vs. within species)?
Plasticity: changes in function, size, or shape of a trait within the life history of the organism.	What are the cumulative effects of exercise or aging on the brain? How are they expressed in terms of the brain and mind observed in vivo?

Comparative Neural System Resources

Fishes/Reptiles:

 

Kotrschal, K., van Staaden, M.J., and Huber, R. (1998). Fish brains: evolution and functional relationships. Reviews in Fish Biology and Fisheries, 8, 373-408.

Rodríguez, F., López, J.C., Vargas, J.P., Broglio, C., Gómez, Y., and Salas, C. (2002). Spatial memory and hippocampal pallium through vertebrate evolution: insights from reptiles and teleost fish. Brain Research Bulletin, 57(3-4), 499-503.

Birds:

Jarvis E.D., Güntürkün, O., Bruce, L., Csillag, A., Karten, H., Kuenzel, W., Medina, L., Paxinos, G., Perkel, D.J., Shimizu, T., Striedter, G., Wild, J.M., Ball, G.F., Dugas-Ford, J., Durand, S.E., Hough, G.E., Husband, S., Kubikova, L., Lee, D.W., Mello, C.V., Powers, A., Siang, C., Smulders, T.V., Wada, K., White, S.A., Yamamoto, K., Yu, J., Reiner, A., and Butler, A.B. (2005). Avian brains and a new understanding of vertebrate brain evolution. Nature Reviews Neuroscience, 6, 151-159.

Avian Brain Nomenclature Consortium: http://avianbrain.org/
Sol, D., Duncan, R.P., Blackburn, T.M., Cassey, P. and Lefebvre, L. (2005). Big brains, enhanced cognition, and response of birds to novel environments. PNAS USA, 102, 5460-5465.

Crow tool use video clips:
Laboratory:
http://www.youtube.com/watch?v=esfo6Wh-Ty8

http://www.youtube.com/watch?v=dbwRHIuXqMU&feature=related

Wild:
http://www.youtube.com/watch?v=xwVhrrDvwPM

Murids (e.g. Mice):

Mouse Brain Atlas (anatomical structures): http://www.mbl.org/atlas170/atlas170_frame.html

Allen Brain Atlas (gene expression and anatomical structures): http://www.brain-map.org

CalTech Mouse Atlas (developmental changes via MRI): http://mouseatlas.caltech.edu/

Rats:

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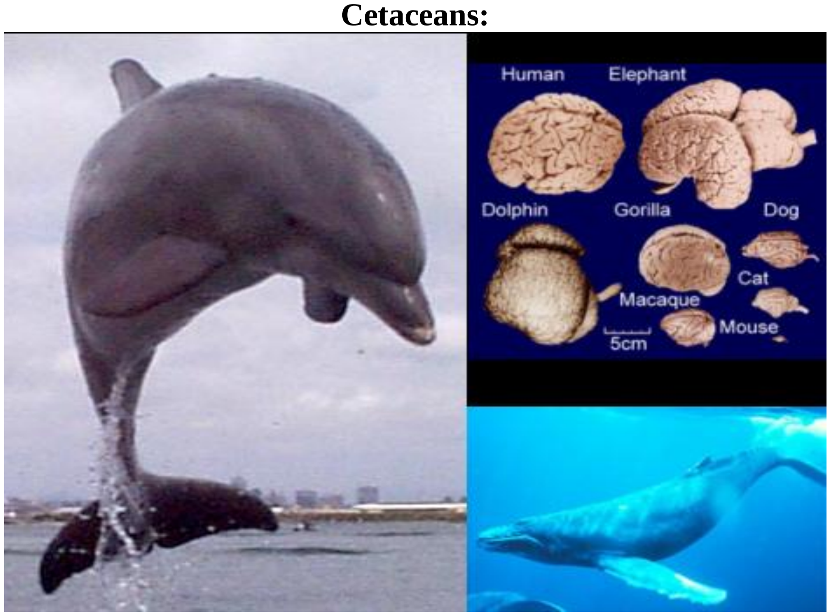
Cetaceans:



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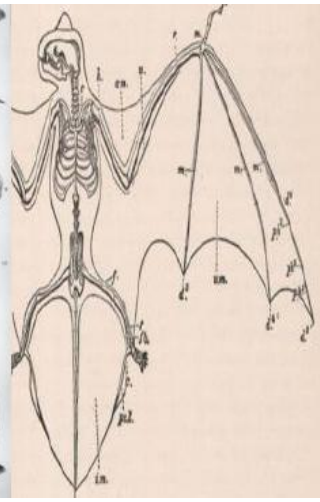
Bats:



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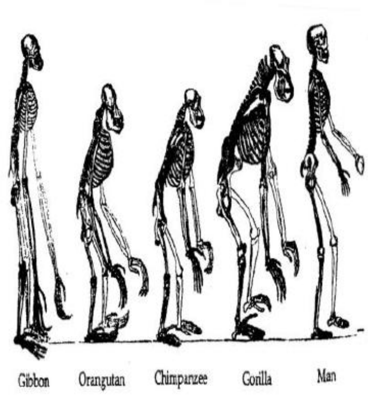
Primates/Hominids:



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Wang, Y-Q. and Su, B. (2004). Molecular evolution of microcephalin, a gene determining human brain size. Human Molecular Genetics, 13(11), 1131-1137.

Insects:

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Anderson, P.A.V. (2004). Cnidarian neurobiology: what does the future hold? Hydrobiologia, 530-531, 107-116.

Cephalopods (e.g. octopus and cuttlefish):

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