Introduction to Neuroevolution
Instructor: Bradly Alicea, e-mail: freejumper@yahoo.com
Meeting place: TBA, Meeting time: TBA

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).

<table>
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<tr>
<th>Grading Scale:</th>
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<tbody>
<tr>
<td>Item</td>
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<tr>
<td>Assignment #0</td>
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<tr>
<td>Assignment #1</td>
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<td>Assignment #2</td>
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<td>Assignment #3</td>
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<td>Assignment #4</td>
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<td>Final Exam</td>
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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:

<table>
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<th>Section 1: Introduction</th>
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<tr>
<td>Date and Topic</td>
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<td>Week 1: Introduction</td>
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### Section A: What is neuroevolution and why should I care?
Session B: Review of terminology, concepts, outline of course.

### 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).

Assignment #2: **simulation assignment**.

#### 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**.
### Section 3: Focus on brain anatomy and evolution

<table>
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<th>Week 6 &amp; 7: Brain anatomy and evolution – concepts</th>
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<tr>
<td>Session A and B (6): Phenotypic changes: allometric and isometric scaling, architectonic changes, neuronal and ion channel specialization, epigenetic matching.</td>
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<tr>
<td>Session A and B (7): “Genotypic” changes: developmental, activity-dependent, and reactive gene expression.</td>
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| 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. |

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<tr>
<th>Week 7 &amp; 8: Brain anatomy and evolution – model systems</th>
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<tr>
<td>Session A: spatial cognition and evolution of the eye in vertebrates.</td>
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<tr>
<td>Session B: learning and memory in Aplysia, language in primates.</td>
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| 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”

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<th>Weeks 9 and 10: Sexual differentiation, plasticity, and development.</th>
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<td>Sessions A and B (9): hormonal effects on the nervous system (organizational vs. activational). Sexual selection.</td>
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<td>Sessions B (Week 9) and A (Week 10): Preconditioning</td>
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<p>| 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. |</p>
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<tr>
<th>Week 10 &amp; 11: Evolution of the brain.</th>
<th>Sessions A and B (10): introduction to Evolution of Development (evo-devo).</th>
<th>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.</th>
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<tr>
<td>Week 11 &amp; 12: Evolution of the periphery: muscle, bone, and motility.</td>
<td>Sessions A and B (11): Neuromechanics.</td>
<td>To understand the basics of genomics and molecular biology of the brain. Should be able to relate these concepts to brain development, function, and biodiversity.</td>
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<td>Week 15: Sociality, physiological regulation, and plasticity.</td>
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<td>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.</td>
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<td>Final Exam</td>
<td>Should be able to pass this without too much difficulty.</td>
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Further reading list for selected topics (all readings should be provided either on library reserve or in .pdf form on the class website):

General:


Web resource: http://williamcalvin.com/BrainForAllSeasons/


Web Resource: http://www.mindcreators.com/NeuralDarwinism.htm


Web resource: http://accidentalmind.org/


Web resource: http://cognet.mit.edu/library/erefs/mitecs/

**Comparative Neuroevolution:**


**Intelligence in silico:**


**Phylogeny of the Nervous System:**


**Sexual Differentiation, Plasticity, and Development:**


Physiological Consequences/Correlates of Neuroevolution:


Neuromechanics:


Genomics and Molecular Biology:


**Molecular Basis of Behavior and Cognition:**


**Sociality, Sexual Selection, and Brain Evolution:**


**Digital Evolution and Experimental Methods:**


**Evolvability and Robustness:**


**Facilitated Evolution:**


**Perspectives: Notes on Evolution and Phylogeny**

<table>
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<tr>
<th>Neutral Processes vs. Natural Selection:</th>
<th>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.</th>
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<td>Hard vs. Soft Heredity:</td>
<td>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.</td>
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<tr>
<td>Homologues vs. Paralogues:</td>
<td>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.</td>
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**Perspectives: Notes on Intelligence (e.g. adaptive behavior) Benchmarks**

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<tr>
<th>“Hopeful Monster” intelligence</th>
<th>“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.</th>
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<tr>
<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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<tr>
<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</td>
<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

\[ FV = \left( \frac{M_n}{M_l} \right) \times \left( \frac{D_n}{D_l} \right) \]

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>
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<tr>
<th>Model</th>
<th>Description</th>
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<tr>
<td>Nuclear-to-Layered Hypothesis:</td>
<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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<tr>
<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 within 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

<table>
<thead>
<tr>
<th>Lability:</th>
<th>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)?</th>
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<td>changes in the function, size, or shape of a trait between species and across generations.</td>
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<th>Plasticity:</th>
<th>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?</th>
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<tr>
<td>changes in function, size, or shape of a trait within the life history of the organism.</td>
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Comparative Neural System Resources

Fishes/Reptiles:


Birds:


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

[http://www.youtube.com/watch?v=dbwRHIuXqMU&feature=related](http://www.youtube.com/watch?v=dbwRHIuXqMU&feature=related)

Wild: [http://www.youtube.com/watch?v=xwVhrrDvwPM](http://www.youtube.com/watch?v=xwVhrrDvwPM)

Murids (e.g. Mice):


**Rats:**

![Rat Image]


**Cetaceans:**

![Cetacean Image]

Bats:


Primates/Hominids:


Insects:


Cnidarians (e.g. jellyfish):


Cephalopods (e.g. octopus and cuttlefish):


Neural control of Octopus Arms: 

Flies, Moths, and Cuttlefish: spineless tales provide strong backbone to human brain research: 
http://www.sciencedaily.com/releases/2006/08/060816020648.htm