Brain Development and Evolution

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January 17, 2014
Since all vertebrate brains have this in common, it could be a crucial prerequi-site to higher intelligence...or a frozen accident. Should AI be *inspired* by this biological fact??

*The Evolution of Man* (Ernst Haeckel, 1893).
A low-risk route to complexification, since key functionalities (e.g. F) are still present during the exploratory period when variants of A arise and their phenotypic consequences are tested.
Hox Genes: a conserved modular component

- *Evolving Brains* (J. Allman, 1999)
On the development of neuromeres to migration areas in the vertebrate cerebral tube (H. Bergquist & B. Kallen, 1953)
Vertebrate Brain Archetype

Principles of Brain Evolution (G. Streidter, 2005)
Evolving a Hierarchical Controller

Neural Tube

Forebrain
Midbrain
Cerebellum
Hindbrain
Spinal Cord

Frontal
Motor
Sensory

Hippocampus
Basal Ganglia
Cerebellum
Brainstem
Spinal Cord

Motor Output
Sensory Input

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Neural Darwinism: Exploratory Growth in Neural Devp

RNA
Survival of the Best Networkers

Genetic differences (w.r.t. genome size or DNA content) cannot account for quantitative, topological differences in mammalian brains.

Genes mainly affect bodies + initial (but not final) sizes of neuron populations.

Brain topologies grow to fit these conditions.

Evolutionary transitions often involve redimensioned brains to fit evolving bodies.

As relative sizes of brain regions change, so do their functional influences.
Deacon’s Rule

Large = Well Connected = Influential

Since a Darwinian-like process in brain development determines the relative sizes of functional brain regions and their patterns of connection, there is reason to suspect that a Darwinian-like functional consequence should result...if one brain structure is relatively enlarged compared to another, this should translate into both displacement of connections during development and displacement of computational influence in adulthood. More inputs equals more votes influencing the computational outcome...*(Symbolic Species, pg. 221)*
Displacement Theory

Neuron Groups

Sensory Inputs

Motor Outputs

Displacement

The Symbolic Species (Terrence Deacon, 1997)
AI gets many ideas from psychology and (more recently) neuroscience.

But what aspects of brain evolution, development and dynamics (e.g. learning) are artifacts of:

- The entire evolutionary history of life on earth.
- The physical and energetic constraints on cerebral growth, development and behavior.

And what aspects are vital prerequisites to adaptive, intelligent behavior in a population of simple, interconnected processing elements?

These are hard questions.

However, there are interesting general principles of evolution that apply to brains and could very well apply to Evolving ANNs (EANNS) too.
In a Perfect, Evolving World...

Genotypes

P1 \sim P2

Immature Phenotypes

P1 \sim P2

Mature Phenotypes

P1 \sim P2

Inheritance => Robustness

Variation => Adaptability

Capacity to generate heritable, selectable phenotypic variation. Two key aspects:

- Reduce potential lethality of mutations (robustness)
- Reduce number of mutations necessary for significant phenotypic change (adaptability)

This hints of edge-of-chaos or complex-regime dynamics: small genetic perturbations yield a power-law distribution of phenotypic effects.
**Genotypes** & Organic Processes that:
- have **modular** components and mechanisms that are easily **duplicated** and **differentiated**, while supporting **weak linkage**, and **exploratory growth**, and exhibiting **robustness** and **adaptability** (to changes in other modules), will produce

**Phenotypes** that are:
- **robust** and **adaptive** to genetic and environmental change, meaning
- they survive and proliferate even when conditions are dynamic (on many time scales).
Conserved Core Processes

- 3 billion years
  - Energy metabolism, 60 building blocks, and membrane formation
  - DNA replication and translation
- 2 billion years
  - microfilaments and microtubules, contractile activity
  - meiosis, sexual reproduction
- 1 billion years
  - cell-cell signalling pathways, cell adhesion
  - apical-basal cell polarization
- 550 million years
  - anterior-posterior and dorsal-ventral axis formation
  - complex regulatory processes

Variation achieved by altering relationships (e.g., regulatory links) between core processes.
Core components and processes facilitate variation via regulatory change (rather than changes to the core) by:

- Reducing number of **necessary** regulatory changes.
- Increasing number of **possible** regulatory targets for change.
- Reducing lethality of genetic change.
- Increasing genetic variation in the population.

A core with these properties facilitates variation and thus **deconstrains** evolution ⇒ there are many viable, attainable routes to phenotypic novelty.

Can we incorporate this in Bio-AI: Swarm Intelligence, Artificial Immune Systems, Evolving ANNs, etc.?
Constraint Satisfaction Problems (CSP)

\[(a \lor \neg b) \land (c \lor d)\]

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*Viable solutions in bold font.*
Deconstraint

\[(a \lor \neg b) \land (b \lor c \lor d) \equiv (a \lor c \lor d)\]

Possible States

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*Viable solutions in bold font.*

- Evolution is now highly constrained by the existing (successful) core processes.
- Deconstraint = facilitating more **combinations** of these building blocks.
In the face of a perturbation, the outer layer changes (adaptability) to maintain the inner layer (robustness)

- Robust - able to achieve viable phenotypes despite environmental or genetic change.
- Adaptive - able to modify the phenotype in response to environmental or genetic change while maintaining other important factors
- Weak linkage, exploratory growth and modularity support both.
- Robustness & Adaptability are closely related.
Modularity, Robustness and Flexibility

- **Modularity** (in genotypes, gtype-ptype mapping, and phenotypes) → perturbations have only local effects → robustness.
- **Modules** = building blocks → many combos possible → design flexibility.
Simple (enabling) signals are easily produced by many sources; complex instructive signals are not.

Components relying on enabling signals can flexibly link to many other components.
Simple enabling signals of environmental origin can, with simple mutations, become innately generated.

The genotype assimilates aspects of the phenotype-environment interaction: **it economizes on flexibility.**
Tags, Weak Linkage, and Evolvability

Tags can promote weak linkage, depending upon the matching algorithm.
EA chromosome encodes operons, which consume and produce chemicals.

Cell = container for operons and chemicals.

Weak Linkage: Flexible relationships between operon inputs and outputs → diverse GRN behaviors → diverse structures.
(Left) Chemical concentrations determine cell types. (Right) Signals and receptors determine ANN topology (Eggenberger, 1997).
Neural populations and their connections grow to fit the bodies structure and dynamics.

Robust - If the C neurons are displaced, the A’s can still find them.

Adaptive - If C’s displace a lot or change their affinity, then B’s may link to them instead of (or in addition to) the A’s.

One component may change via mutation, but the others adjust via exploration → No need for intricate and improbable coevolution.
Assume corresponding concentration gradients.

Informed exploration: The starting concentration imprinted on the growing axon guides its search for a similar level in the target layer.

This produces a biased, but imperfect topology.

Note the errant $D \rightarrow W$ and missing $B \rightarrow X$ links.
Emergent Fine-Tuning of Topological Maps

During learning, synaptic tuning is driven by experience, which reflects the statistical structure of the body and environment.

To activate, the bottom-layer neurons require 2 active inputs within a short time window.
D fires but W does not, so D-W synapse weakens.

This is a noncontinuous stimulus (less common in the real world), but it does suffice to fire W and D, so the D-W synapse strengthens.
Moving Patterns also Tune the Map

D fires after W, so more depression of D-W synapse

Network After Learning

Non-topographic connections weaken so much that they wither away.
Local signaling in developing fruit-fly brain causes proneural cells to differentiate into sensory-organ precursor (SOP) and non-SOP cells.

- All non-SOP cells have at least one SOP neighbor.
- No SOP cells are neighbors.

A similar mechanism allows the distributed solution of Minimal Independent Set (MIS) problems in graph theory.
Distributed Minimal Independent Set (MIS) Algorithm

- \( p = \frac{1}{D} \)
- if \( p \geq 1 \) exit
- Repeat \( M\log_2 N \) times:

**Round 1**
- With probability \( p \) do:
  - Broadcast message \( B \) to all neighbors(\( n \))
  - \( \text{state}(n) \leftarrow 1 \)
- If \( n \) receives \( B \) in round 1, then \( \text{state}(n) \leftarrow 0 \)

**Round 2**
- If \( \text{state}(n) = 1 \) (i.e., \( n \) broadcast \( B \) but did not receive \( B \) in round 1):
  - Add \( n \) to LEADER list.
  - Broadcast \( B \) to all neighbors(\( n \)).
- If \( n \) receives \( B \) in round 2, then add \( n \) to non-LEADER list.

- \( p \leftarrow 2p \); GOTO Step 2
Sample MIS solutions

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Facilitated Variation in EANNs

- **Modularity**
  - Most EANNs treat individual neurons or neural layers as genetic units that become phenotypic/functional units as well.
  - Through evolution and/or learning, functional neural modules often emerge.

- **Weak Linkage**
  - The basic signal among neurons is understood by all.
  - Simple tags allow many types of neurons and layers to hook up during devp.

- **Exploratory Growth**
  - Abstract versions of Neural Darwinism and Displacement.
  - Detailed models of axonal growth in some ALife systems.
Robustness
- Design of genotype and gtype → ptype mappings should be carefully considered to avoid extreme sensitivity to mutation.
- Stochastic aspects of connecting neurons and initializing weights → poor inheritance.

Adaptivity - Traditionally strong, since ANNs are designed for learning via synaptic change.
By incorporating modularity (duplication and differentiation), weak linkage, and appropriate abstractions of exploratory growth, AI researchers hope to achieve phenotypes that:

- are **robust** to many genetic changes,
- but exhibit **novel variations** in response to occasional genetic changes, and
- can **adapt** to dynamic environments (e.g., via synaptic change).