

Computational Intelligence

Master in Artificial Intelligence

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Introduction to Evolutionary Computation

Natural Selection

(adapted from *The Origin of Species*)

IF there are organisms that reproduce
offspring inherit traits from their progenitor(s)
there is a variability of traits
there is selective pressure for limited resources*

AND

AND

AND

THEN individuals with *less-adapted traits*** will die
without reproducing

AND

individuals with *more-adapted traits*** will prosper &
reproduce

* the environment cannot support all members of a growing population

** as determined by the environment

Natural Selection

Selective (environmental) pressure is due to:

- Access to food or water
- Climate conditions
- Fooding/Hunting
- Breeding areas
- Predators (esp. Humans)
- Mating (finding a mate)
- ...

Origins of the Theory of Natural Selection

Year	Event
1831-6	Second expedition of the HMS Beagle, visiting mainly South America and Pacific islands (e.g. Galapagos)
	<i>The Voyage of the Beagle</i> published by Charles Darwin
1839	
1842	Darwin's unpublished draft of his theory
1858	Article sent to Darwin by Alfred Russel Wallace
	describing his own theory of natural selection
1859	<i>On the Origin of the Species</i> published by Darwin
1865	Mendel published <i>Experiments in Plant Hybridization</i>
	(in German) setting the foundations of Genetics
1869	<i>The Malay Archipelago</i> published by Russel Wallace
	and dedicated to Darwin

It's a long and winding road ...

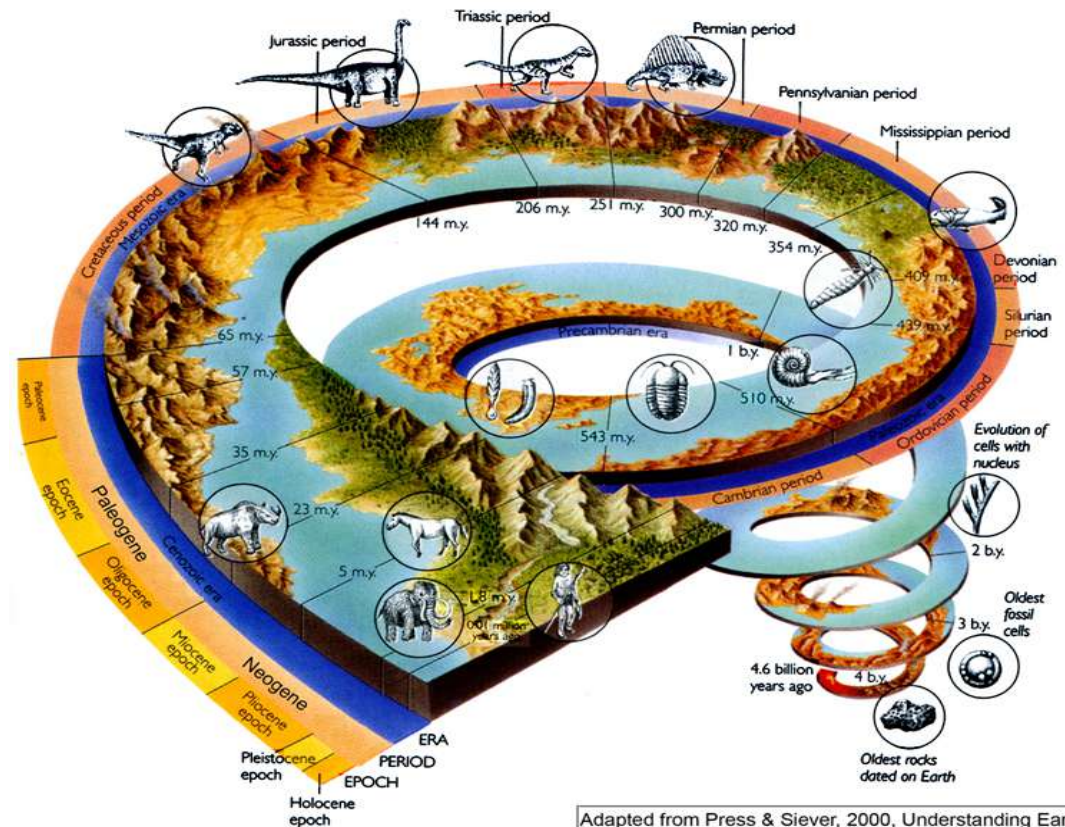
History of life

Interaction of different biological (physical/behavioral) **processes** operating on **individuals** and **species**

These **processes** are:

- Reproduction
- Mutation
- Competition
- Selection

collectively leading to
EVOLUTION



Adapted from Press & Siever, 2000, Understanding Earth

What is EVOLUTION? (I)

Evolution is **change** (structural, physiological, behavioral) which occurs over time through **interaction** with the **environment**

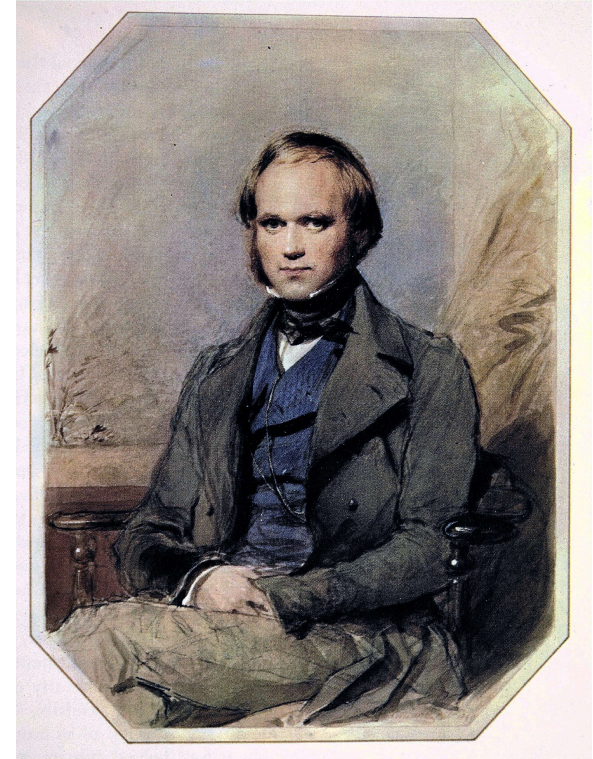
- What major mechanisms are responsible for evolution? **mutation** and **natural selection**
- **Mutations**
 - Caused by a copying error in the sequence of A, C, G and T nucleotides when DNA is copied
 - This error may cause a change in a protein leading to a modification in the individual that is inheriting the gene
- For example, the new instruction for us humans could be "build a baby with a slightly longer middle finger"
- Since the change is random and unpredictable, it is very difficult to tell *a posteriori* which gene(s) may have been involved

What is EVOLUTION? (II)

Charles Darwin (and independently **Alfred Russel Wallace**) suggested that evolution occurs, and was the first to suggest a plausible mechanism and to present an overwhelming case in its favour (accumulated over the years).

Careful!

- Darwin used the word **selection** but nature doesn't care about who gets “selected” for survival
- Evolution has **no goal**. Certain individuals survive because they have structural, physiological, behavioral or other characteristics that prevent them from being eliminated *before* reproduction, or by sheer luck (see later)



What is EVOLUTION? (III)

Darwin defined evolution as “**descent with modification**”

He didn't know about genetics ...

(he couldn't know that these characteristics were caused by **mutations** and that they could be passed on through the **genes**)

How does it work?

After a mutation changes an individual, the environment determines if the change gives the individual an advantage. If the new trait is helpful, the mutated individual is more likely to survive, reproduce and **pass the new trait to offspring**.

Natural selection is not the only mechanism that changes organisms over time ... but it is the only known process that makes organisms *adapt* over time.

What is EVOLUTION? (IV)

Mutation is not the only source of genetic variation.

Many other mechanisms interact: **genetic drift**, **gene flow**, and **symbiosis**:

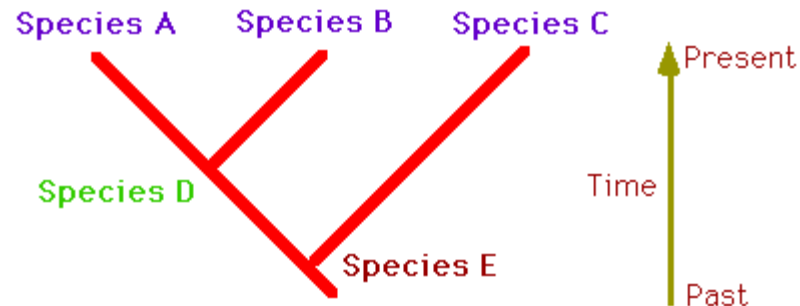
- **Genetic drift** happens when random events cause gene frequencies to vary between generations (more important in small populations) **Example: a truck-bus accident**
- **Gene flow** (or migration) is the movement of genes in a species from one population to another as the result of inter-breeding. **Example: evidence of gene flow between cultivated plants and their wild relatives.**
- **Symbiosis** is the cooperative (close and often long-term) interaction between different organisms. **Example: in the ocean, when shrimp and gobies clean fish, receiving nutrients.**

What is EVOLUTION? (and V)

A **phylogenetic tree** shows the inferred evolutionary relationships among various biological species —their phylogeny— based upon similarities and differences in their physical or genetic characteristics

Hypothesis: all species alive today have evolved from simpler, more primitive forms of life. Since every living thing uses the same genetic code, life descended from a distant common ancestor that had that code:

Descent with modification



A **cladogram** (from Greek *clados* (branch) and *gramma* (character))

Evidence for descent with modification

Biogeography

Functional morphology

Paleontology

Comparative embryology

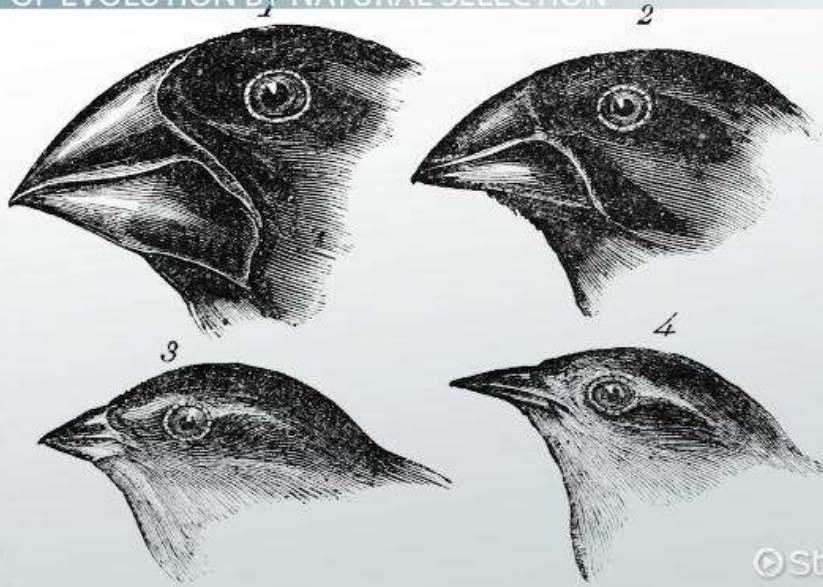
Animal and plant breeding

Molecular biology



Evidence from **biogeography**: an example

THEORY OF EVOLUTION BY NATURAL SELECTION



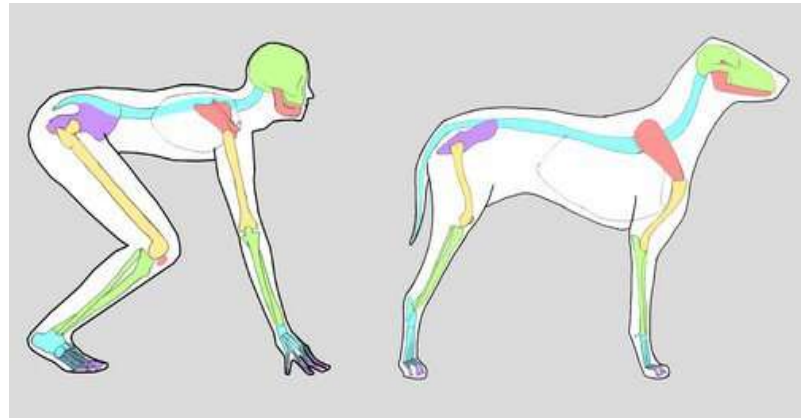
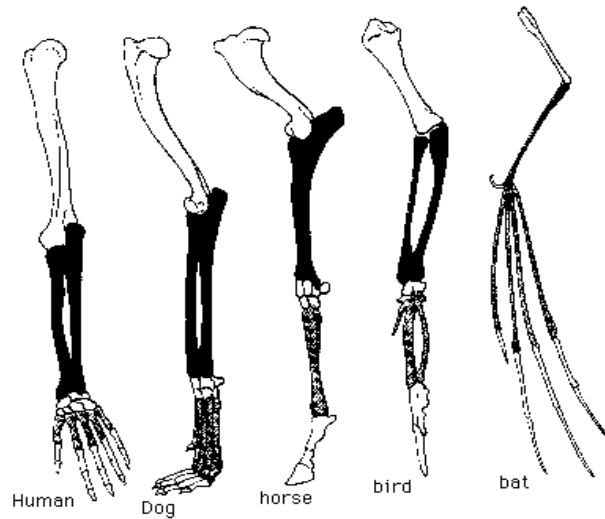
Each island has a slightly different species of finch, all of which appear close to a single species found on the South American mainland.

The finch has adapted to take advantage of feeding in different ecological niches.

For example, the finches who eat grubs have a thin extended beak to poke into holes in the ground and extract the grubs.

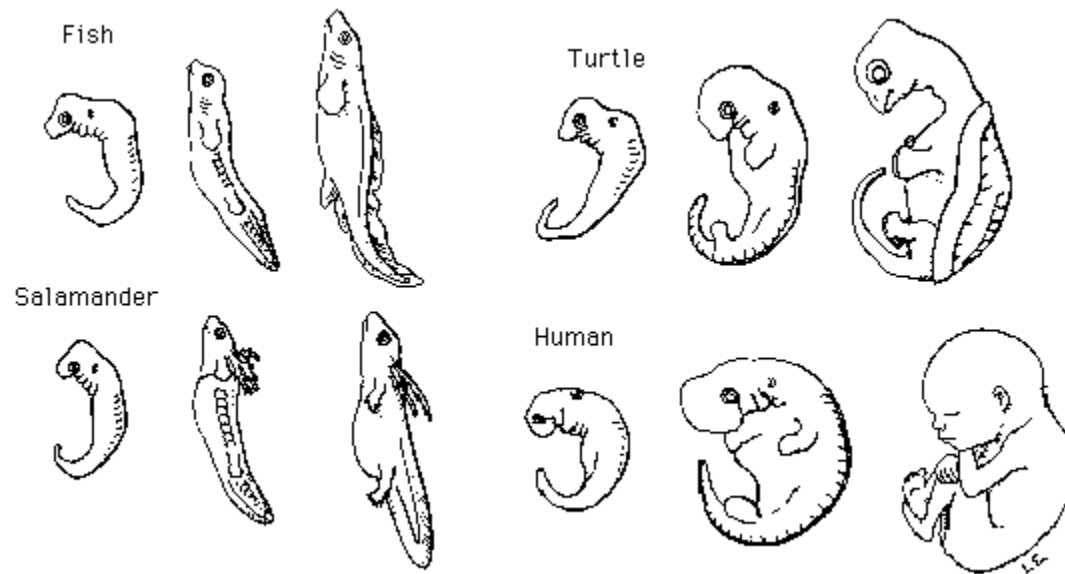
Molecular basis of beak evolution: Developmental research in 2004 found that [bone morphogenetic protein 4](#) (BMP4), and its differential expression during development resulted in variation of beak size and shape among finches.

Evidence from functional morphology: an example



Homologous structures are anatomical resemblances representing variations on a structural theme present in a common ancestor.

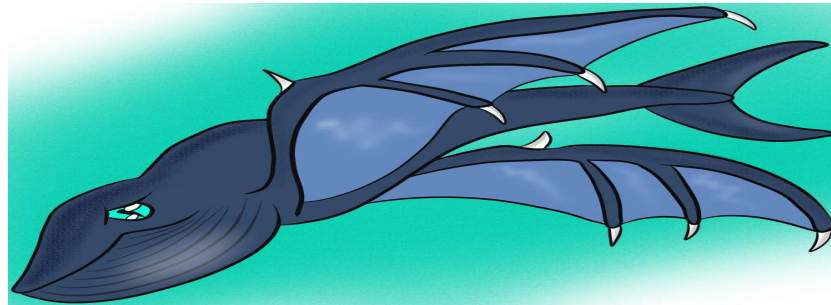
Evidence from comparative embryology: an example



Early **embryos** of very different organisms closely resemble each other

Evidence from molecular biology: an example

The **biochemistry** of a **bat** is much closer to that of a **whale**, rather than that of a **bird** ... not expected unless bat and whale have a more recent common ancestor than bat and bird



Example: paternity testing (how do you tell who's dad?)

- ➔ **DNA profiling** (aka genetic fingerprinting) can determine whether two individuals are biologically parent and child, or the likelihood of someone being a biological grandparent to a grandchild

Modern examples of natural selection “in action”

Rabbits & myxomatosis

In 1859, 24 cute and cuddly rabbits were brought to Australia. By 1886, the army of rabbits was advancing at over 66 miles a year, smashing through “rabbit-proof” barriers. They spanned entire Australia by 1907. In the 1940s, it was estimated that rabbit population was as high as 800 million.



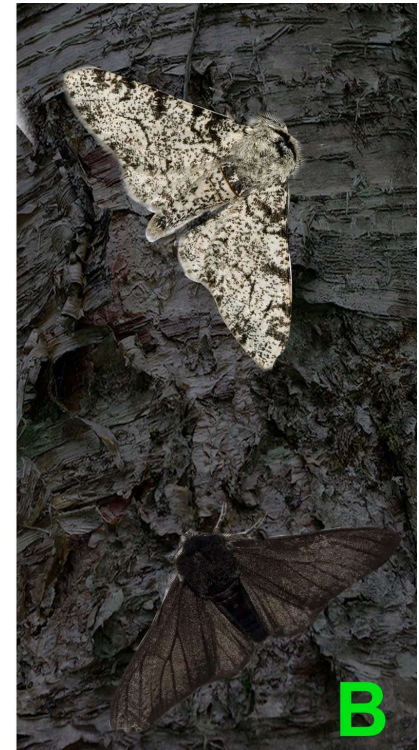
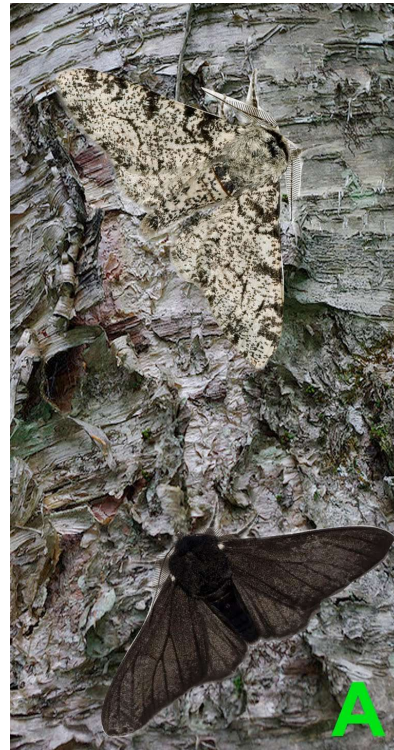
Myxomatosis was introduced in 1950, with an initial mortality rate of 99.9%, quickly dwindling to 95%. Mortality rate today is about 40%.

Modern examples of natural selection “in action”

The peppered moth

The black and patterned (peppered) moth populations changed drastically during the **Industrial Revolution** in England. Soot blackened the trees and killed the lichen growing on the trees. The new environment elicited changes in the number of both peppered and black moths (B)

As pollution controls were put in place, the lighter form of the moth prevailed again (A)

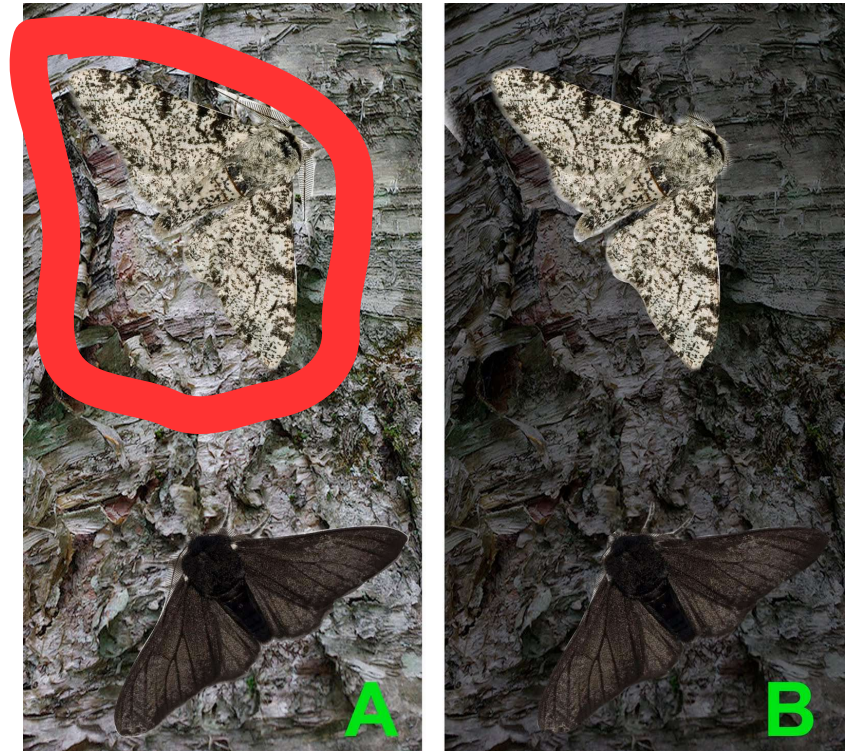


Modern examples of natural selection “in action”

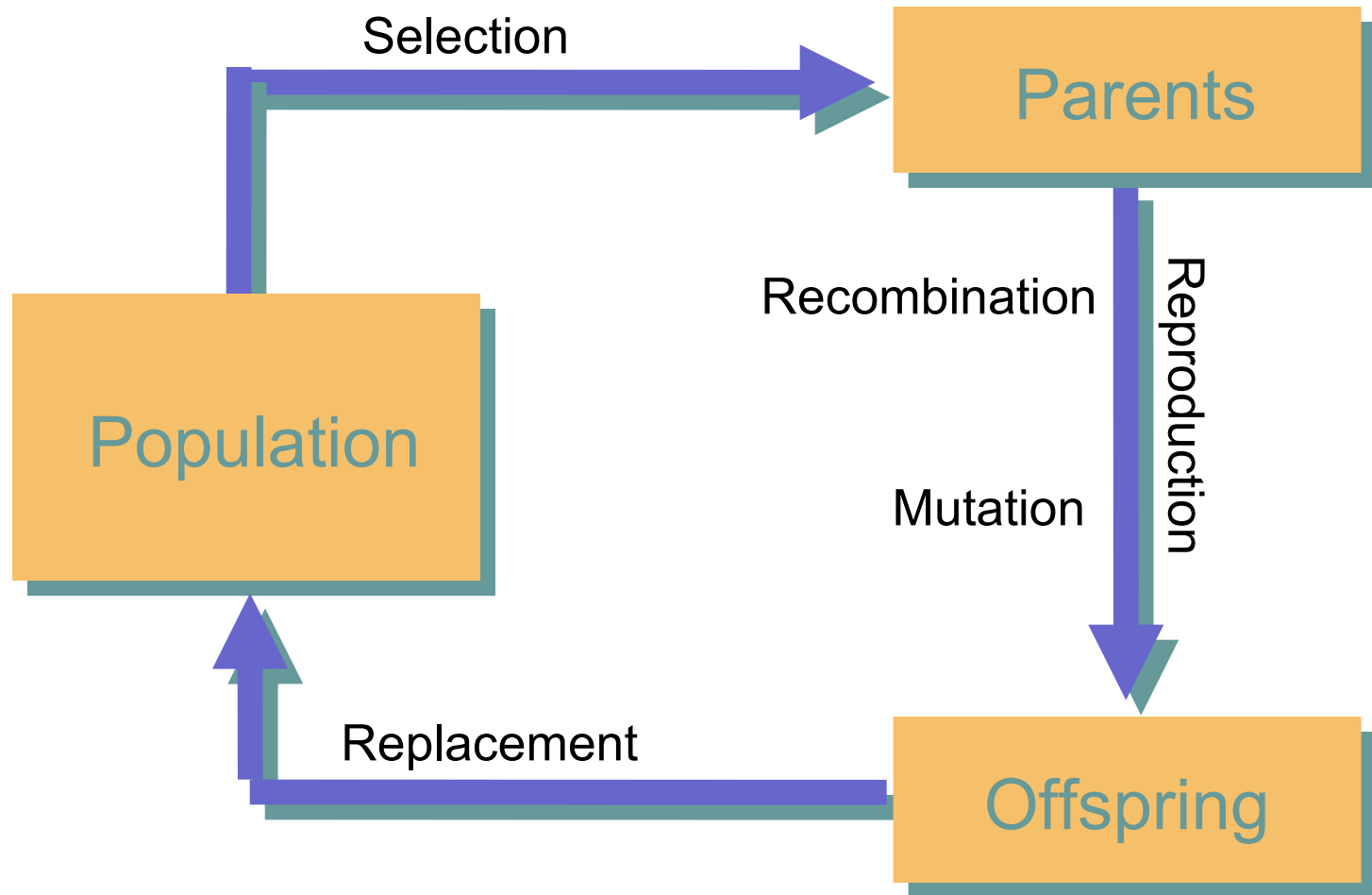
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The evolutionary cycle in Nature



Some biological terms used in EC

- **Genotype**: The molecular basis of inheritance as defined by genes and chromosomes.
- **Phenotype**: The actual appearance of the living beings.
- **Species**: A group of organisms capable of inter-breeding and producing fertile offspring.
- **Chromosome** (or **individual**): a candidate solution to the problem to be optimized.
- **Gene**: single variable to be optimized.
- **Locus** (plural *loci*): the specific location of a gene or position on a chromosome.
- **Allele**: possible assignment of a value to a variable (a locus in a gene).
- **Fitness [function]**: capability of an individual of certain genotype to reproduce.

What is an Evolutionary Algorithm?

An EVOLUTIONARY ALGORITHM is a computer simulation in which a population of abstract representations of candidate solutions (**individuals**) to an optimization problem are stochastically **selected**, **recombined**, **mutated**, and then removed or kept, based on their relative **fitness** to the problem:

1. maintain population of individuals
2. select individuals according to fitness
3. breed (“recombine/cross over”) them & mutate the offspring
4. form a new generation using the offspring and the old one

Basic evolutionary algorithm

$t := 0$

Initialize $P(t)$

Evaluate $P(t)$

WHILE NOT (termination condition) **DO**

$t := t+1$

 Select $P'(t)$ from $P(t-1)$

 Recombine and/or Mutate $P'(t)$

 Evaluate $P'(t)$

 Form $P(t)$ by using $P'(t)$ and $P(t-1)$

END

The 7 main components of an EA

- **coding function** to represent potential solutions as valid chromosomes
- **fitness function** to evaluate the goodness of individuals
- **initialization method** to create the initial population
- **selection operator** to determine which individuals will undergo variation
- **replacement strategy** to decide which individuals will be allowed in the next generation
- **genetic variation operators** (mutation, recombination) to perform the variation
- **termination criterion** to stop the process

Behaviour of components

- Selection, replacement and fitness
DECREASE diversity in a population
- Genetic operators (mutation, recombination)
INCREASE diversity in a population

exploration \longleftrightarrow exploitation

Fitness functions (informal ideas)

“However many ways there may be of being alive, it is certain there are vastly more ways of being dead, or rather not alive.”

Richard Dawkins in *The Blind Watchmaker*

“As things get better, increases in fitness show diminishing returns: more food is better, but only up to a point. But as things get worse, decreases in fitness can take you out of the game: not enough food and you're dead.”

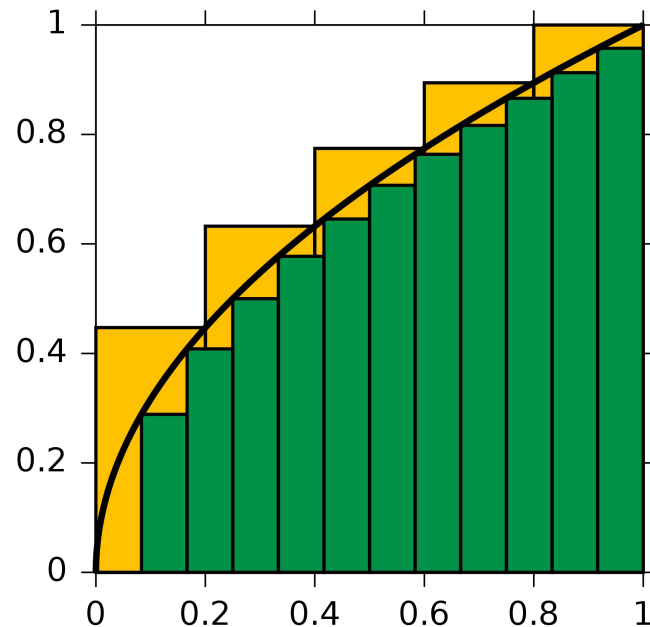
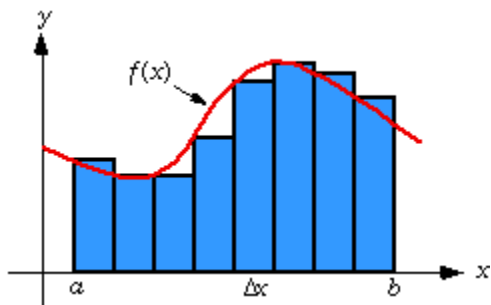
Tim Ketelaar, quoted in Steven Pinker's *How The Mind Works*

Fitness functions (formal ideas)

Design ideas:

Left: my “true” fitness function is very costly: use a surrogate

Right: my “true” fitness function is impossible to express or compute: use a bounding function (the tighter, the better)



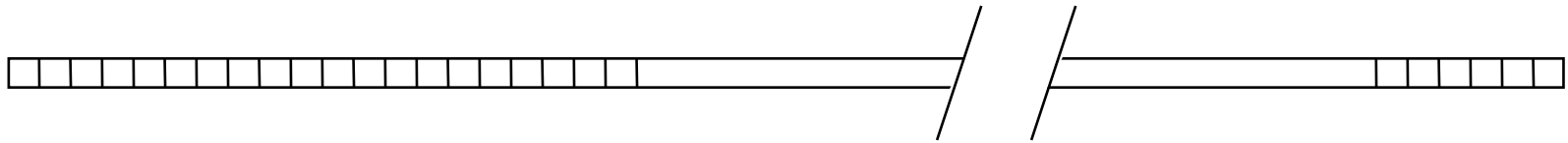
Termination criteria

- 1) Maximum number of generations
- 2) Maximum number of fitness function evaluations
- 3) Avg/max (relative) fitness function improvement below some tolerance (over a period of time)
- 4) Diversity below some tolerance (idem)
- 5) Closeness to optimum below some tolerance

or a **combination** thereof

The COP (counting ones problem)

Problem: a string of n binary variables, $x \in \{0, 1\}^n$:



Fitness:

$$F(x) = \sum_{i=1}^n f(x_i)$$

Objective: maximize the **number of ones** in the string.

Let's generalize it, give a solution and explore variations:

- Stochastic
- Weighted
- Deceptive

Replacement strategies

Suppose we maintain a population of $\mu \geq 1$ individuals
At each generation, they produce $\lambda \geq 1$ offspring

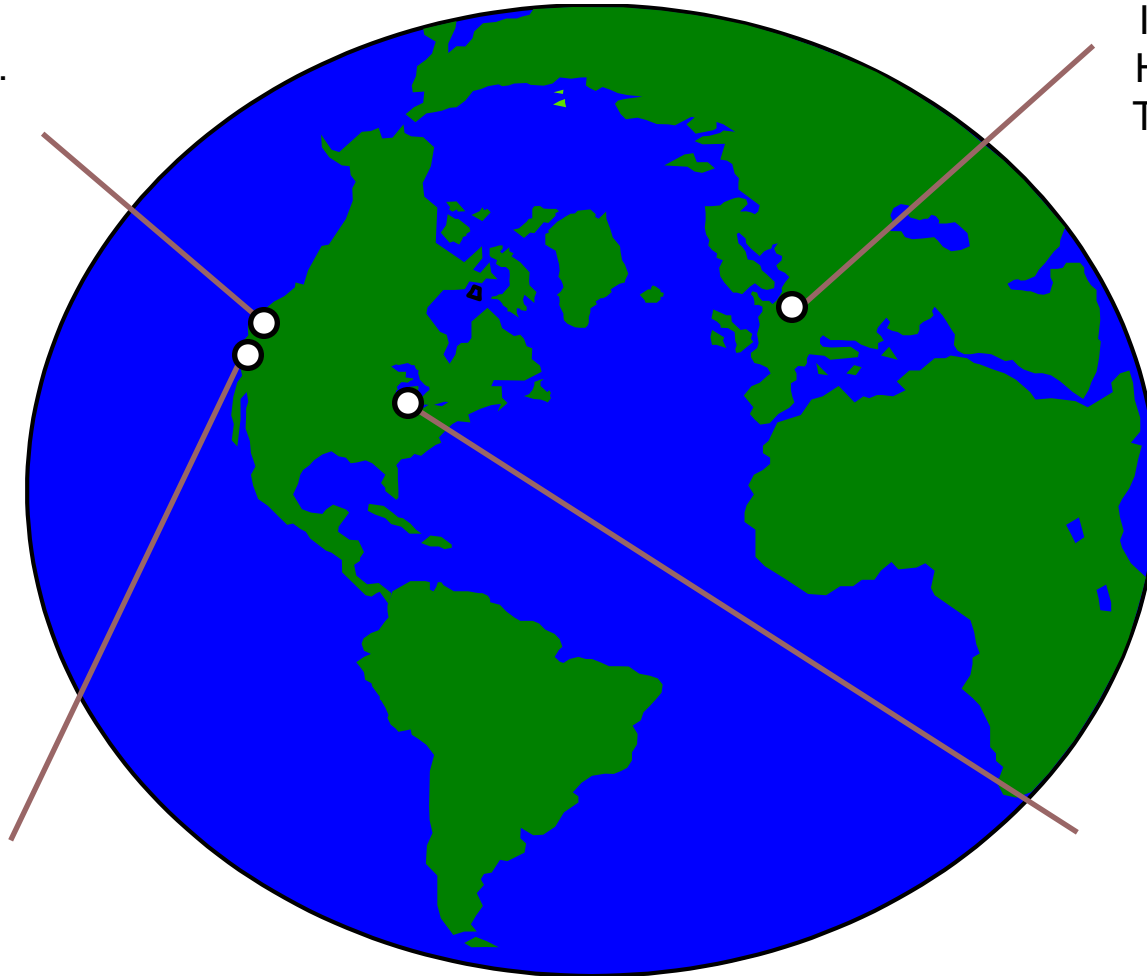
Two **strategies**:

- $(\mu + \lambda)$ – strategy “steady-state”
- (μ, λ) – strategy, $\lambda \geq \mu$ “generational”

The story so far

John Koza
Stanford Univ.
1988 (**GP**)

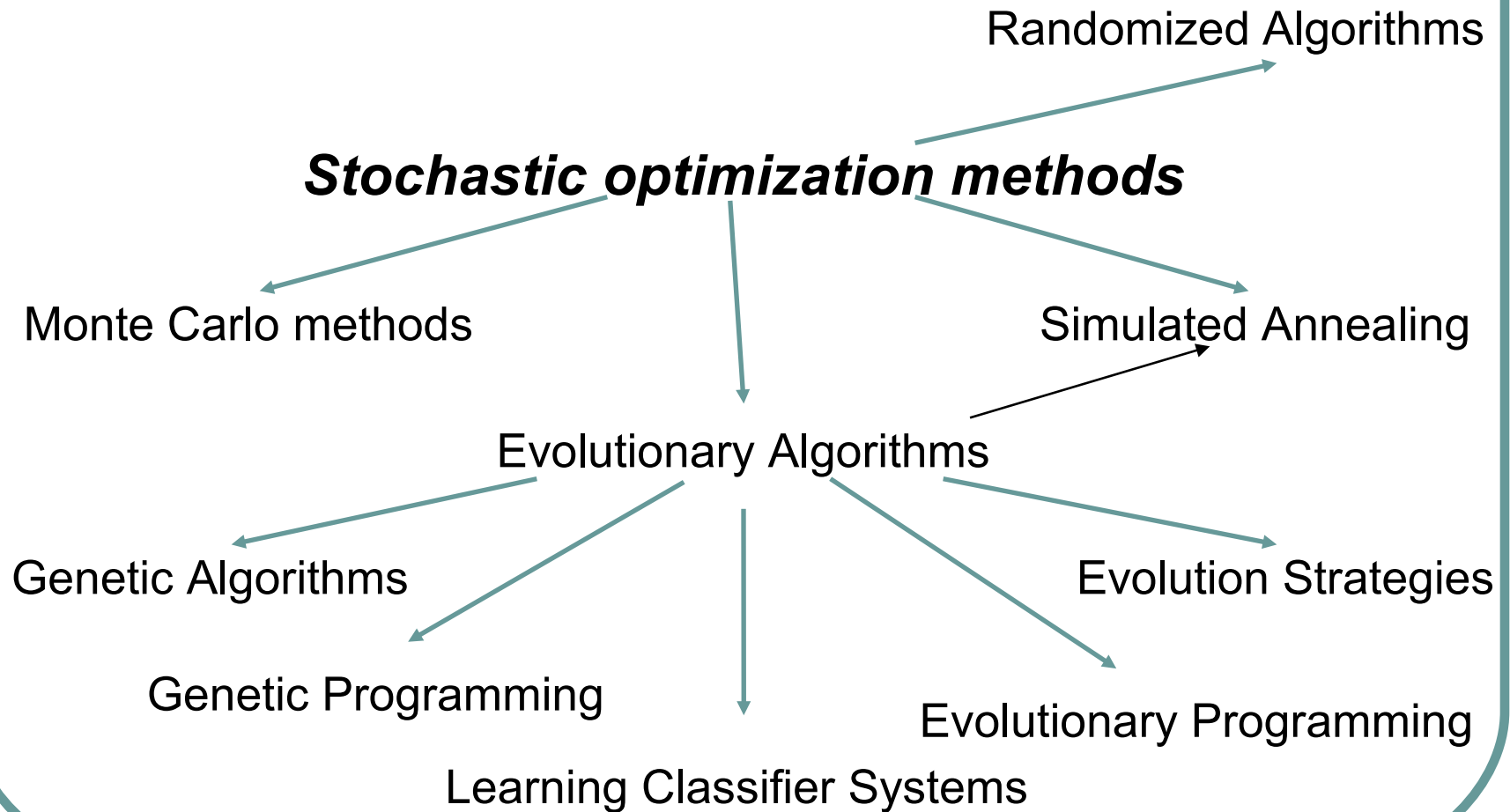
Ingo Rechenberg
Hans P. Schwefel
TU Berlin '65 (**ES**)



Larry Fogel
UCSD 1960
(**EP**)

John H. Holland
U. of Michigan
early '70s (**GA**)

Taxonomy of methods



Outline of various techniques

- **Genetic Algorithms (GA)** model standard genetic evolution
- **Genetic Programming (GP)**, based on genetic algorithms, but individuals are computer programs
- **Evolutionary Programming (EP)**, derived from the simulation of adaptive behavior in evolution (i.e. phenotypic evolution).
- **Evolution Strategies (ES)**, geared toward modeling the strategic parameters that control evolution itself (“evolution of evolution”)
- **Learning Classifier Systems (LCS)** aim at knowledge representation
- **Differential Evolution (DE)**, similar to genetic algorithms, differing only in the reproduction mechanism used
- **Neuro Evolution (NE)**, specifically aiming at evolving neural networks

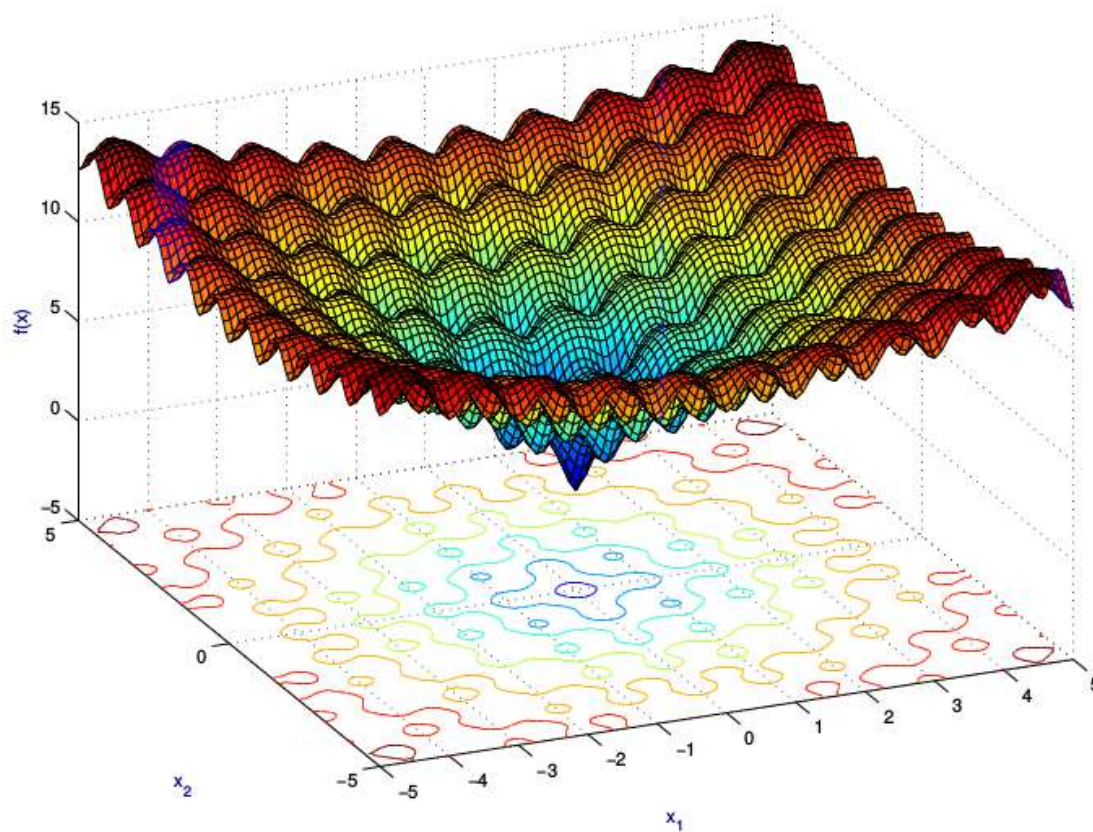
A fundamental difference ...

- Genetic Algorithms (bitstrings)
- Evolutionary Programming (finite-state automata)
- Evolution Strategies (real-valued vectors)
- Genetic Programming (computer programs)
- Neuro Evolution (neural networks)
- Learning Classifier Systems (if-then rules)

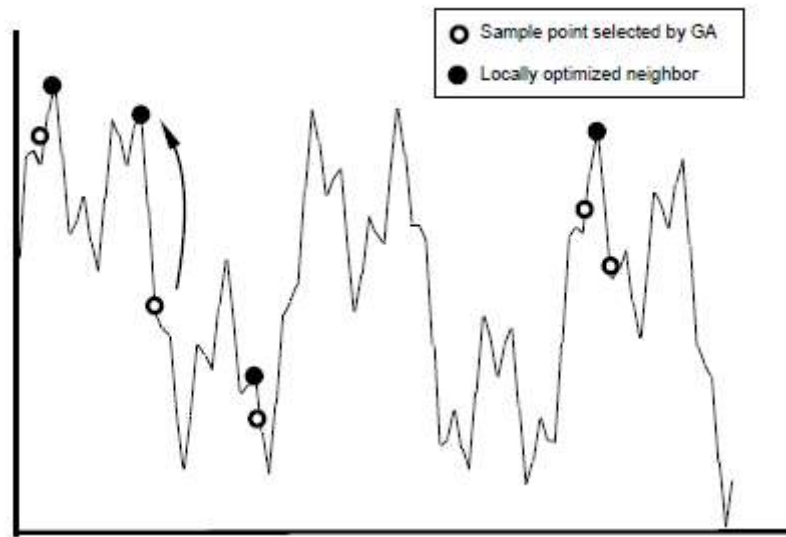
EAs vs derivative-based methods

- EAs can be **much slower** (but they are *any-time algorithms*)
- EAs are less dependent on **initial conditions** (still we need **several runs**)
- EAs can use alternative **error functions**:
 - Not continuous or differentiable
 - Including structural terms
- EAs do not get easily **stuck in local optima**
- EAs are better “**scouters**” (global searchers)
- EAs are worse “**tuners**” (local searchers)

Example: Ackley's function



Hybrid algorithms (aka memetic)



- The EA can be used to find a good set of initial solutions
- Hopefully a very good solution is on the basin of attraction of one of these points
- Iteration leads to “Lamarckian” evolution

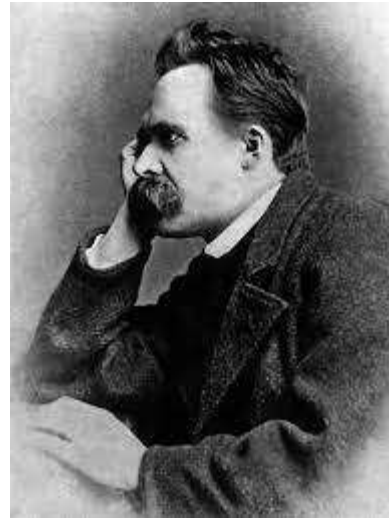
(from Belew, McInerney & Schraudolph: *Evolving Networks*)

And the Oscar goes to ...

“Species do not evolve to perfection, but quite the contrary. The weak, in fact, always prevail over the strong, not only because they are in the majority, but also because they are the more crafty.”

Friedrich Nietzsche,

in *The Twilight of the Idols*



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