

Computational Ideas and the Theory of Evolution

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“Nothing makes sense in life except in the light of evolution”

Theodosius Dobzhansky

“One curious aspect of evolution is that everybody thinks he understands it!”

Jacques Monod

Evolution before Darwin

- Erasmus Darwin



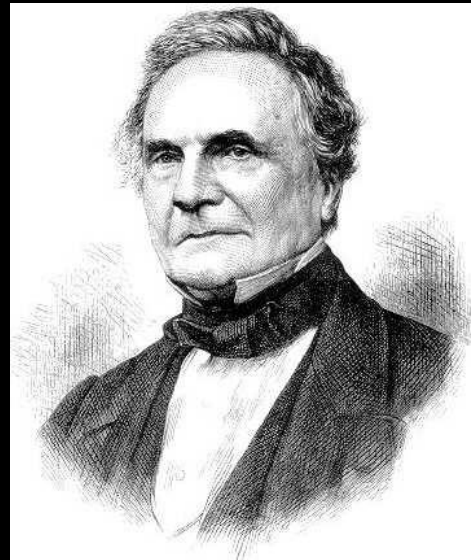
Before Darwin

- J.-B. Lamarck



Also before Darwin

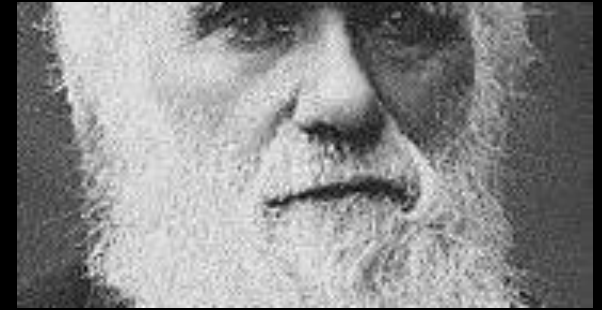
- Charles Babbage



[ca. 1820, paraphrased]

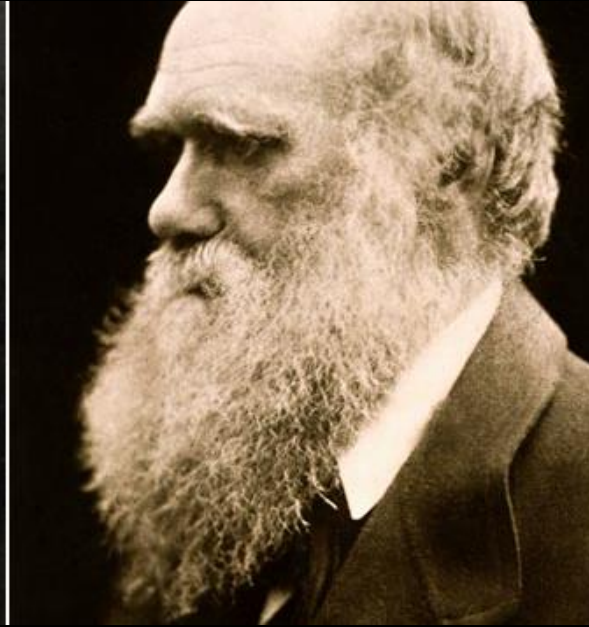
“God created not species, but the Algorithm for creating species”

The Origin of Species



- Natural Selection
- Common Ancestry
- Possibly the world's most masterfully compelling scientific argument
- The six editions: 1859, 1860, 1861, 1866, 1869, 1872

The Wallace-Darwin papers: Exponential Growth



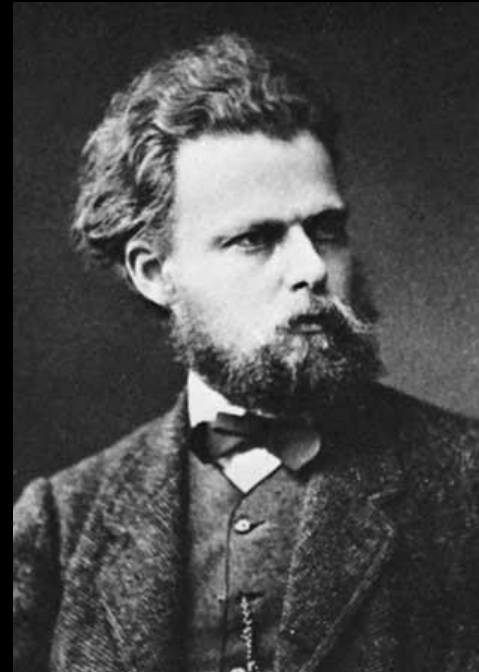
Brilliant argument, and yet many questions left unasked, e.g.:

- What is the role of sex?
- How do complex adaptations arise?
- How is diversity maintained?

Cryptography against Lamarck

- A. Weismann

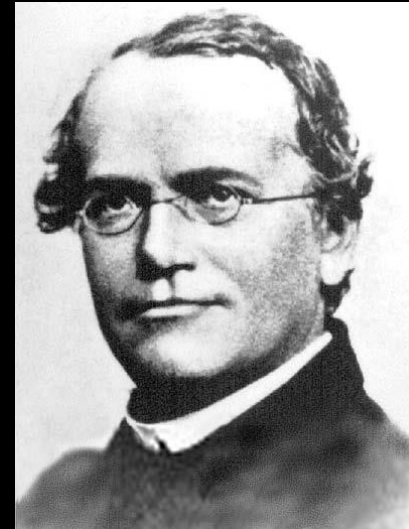
[ca. 1880, paraphrased]



“The mapping from genotype to phenotype is one-way”

Genetics

- Gregor Mendel [1866]
- Number of citations
between 1866 and 1901:



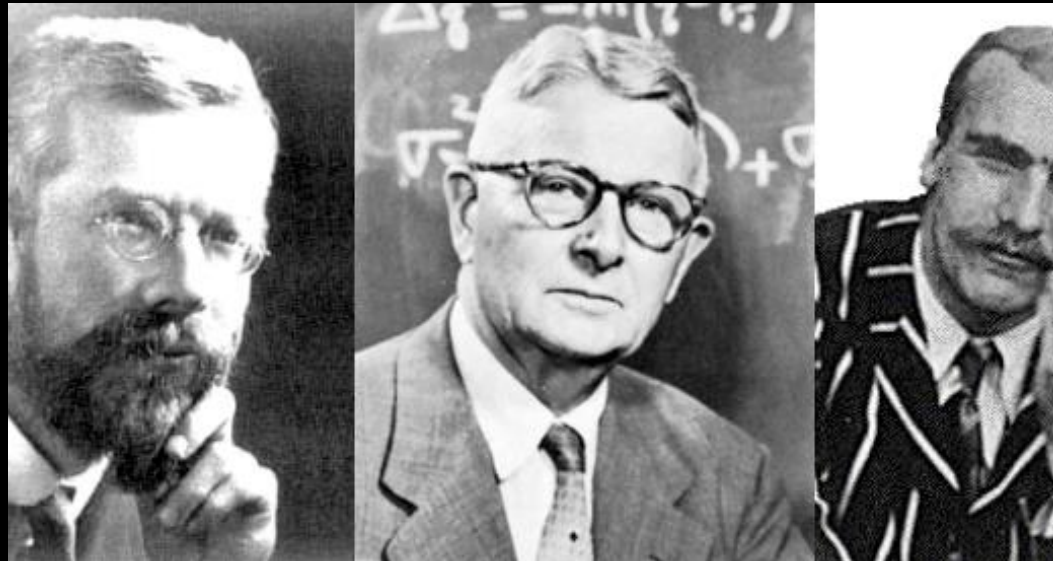
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The crisis in Evolution

1900 - 1920

- Mendelians vs. Darwinians
- Geneticists vs.
Biometricists/Gradualists

The “Modern Synthesis” 1920 - 1950



Fisher – Wright - Haldane

The Fisher-Wright model (frequencies)

^{.03} 3	^{.01} 2	^{.10} 4	^{.05} 5	^{.04} 4
^{.01} 1	^{.09} 0	^{.01} 0	^{.06} 7	^{.02} 2
^{.02} 2	^{.11} 1	^{.05} 0	^{.14} 4	^{.01} 3
^{.11} 1	^{.02} 8	^{.08} 1	^{.03} 3	^{.02} 2

The Fisher-Wright model

(frequencies, a generation later)

.04	.02	.07	.03	.07
3	2	4	5	4
.02	.05	.03	.04	.01
1	0	0	7	2
.01	.07	.02	.13	.11
2	1	0	4	3
.21	.02	.08	.05	.07
1	8	1	3	2

The Fisher-Wright model

- And then we have mutations, speciation, changes in the environment, etc...

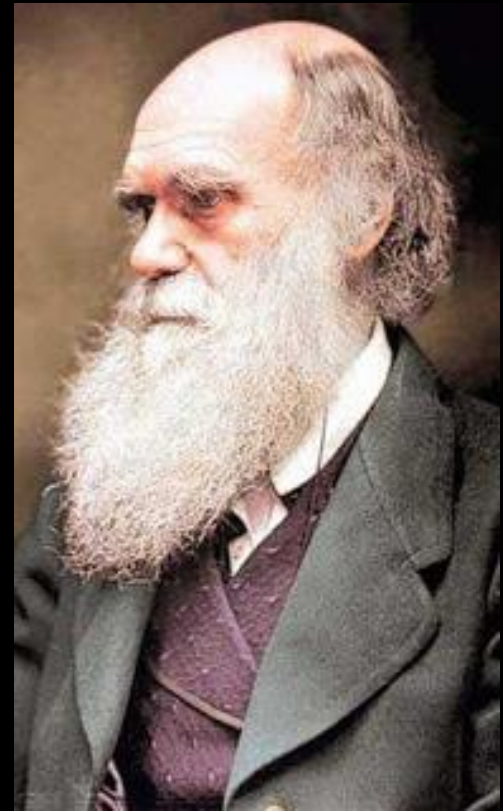
Big questions remain

e.g.:

- What is the role of sex?
- How is variation preserved?
- How do complex adaptations arise?
- *And how can this crude mechanism and model account for the miracle of Life we see around us?*

Disbelief at the top

“The eye to this day gives me a cold shudder.”



The Eye: the Problem of Complex Adaptations

Theorem: Any Boolean function of n genes which confers a small evolutionary advantage will be eventually fixed (with high probability), with polynomial population and number of generations

(FOCS 2014; with Adi Livnat, Aviad Rubinfeld, Greg Valiant, Andrew Won)



More Disbelief: Les Valiant

- *“How can you find a 3-billion long string in 3 billion years?”*
- Valiant’s theory of evolution as learning

Disbelief, algorithmic version

“What algorithm could have achieved

all this

in a mere 10^{12} steps?”

(surprise: we have an answer...)

Evolution and CS Practice: Genetic Algorithms [ca. 1980s]

- To solve an optimization problem...
- ...create a population of solutions/genotypes
- ...who evolve through mutations and sex...
- ...and procreate with success proportional to their objective function value
- Eventually, some very good solutions are bound to arise in the soup

...and in this corner...

Simulated Annealing

- Inspired by *asexual* reproduction
- Mutations are adopted with probability increasing with fitness/objective differential

The Mystery of Sex Deepens

- Simulated annealing (asexual reproduction) works fine
- Genetic algorithms (sexual reproduction) don't work
- In Nature, the opposite happens: Sex is successful and ubiquitous



A Radical Thought

- What if sex is a mediocre optimizer of fitness (= expectation of offspring)?
- What if sex optimizes something else?
- And what if this something else is its *raison d'être*?

Mixability!

- [Livnat et al, PNAS 2008]
- Simulations show that natural selection under **asex** optimizes fitness
- But under **sex** it optimizes *mixability*:
- = The ability of alleles (gene variants) to perform well with a broad spectrum of other alleles

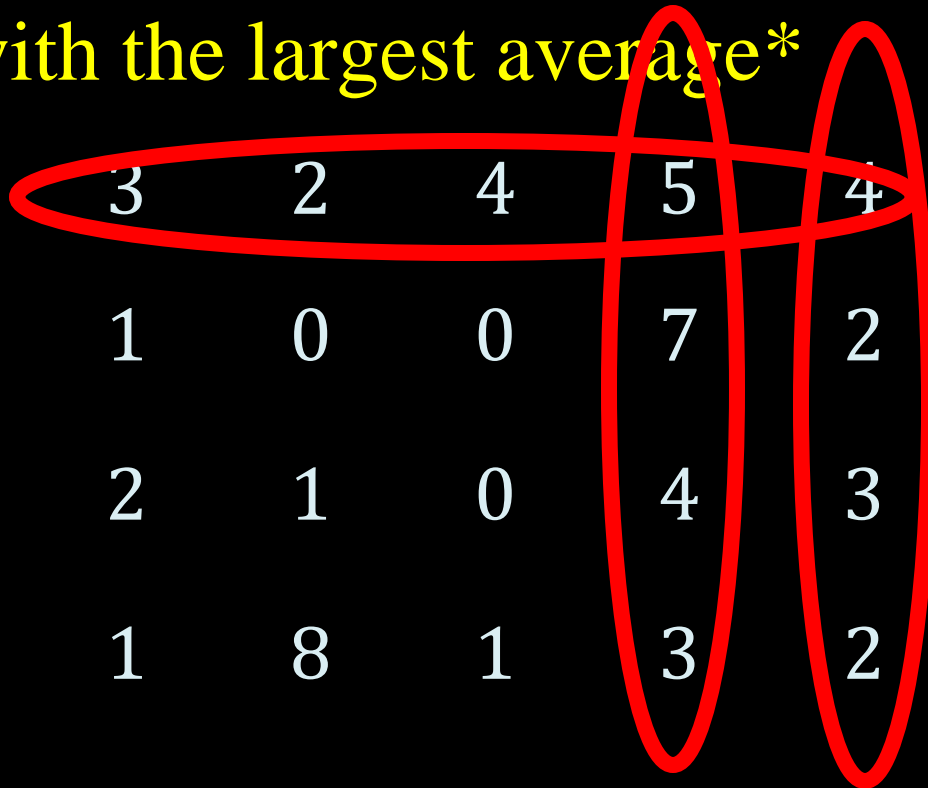
Explaining Mixability (cont)

- Asex will select the largest numbers

3	2	4	5	4
1	0	0	7	2
2	1	0	4	3
1	8	1	3	2

Explaining Mixability (cont)

- But sex will select the rows and columns with the largest average*

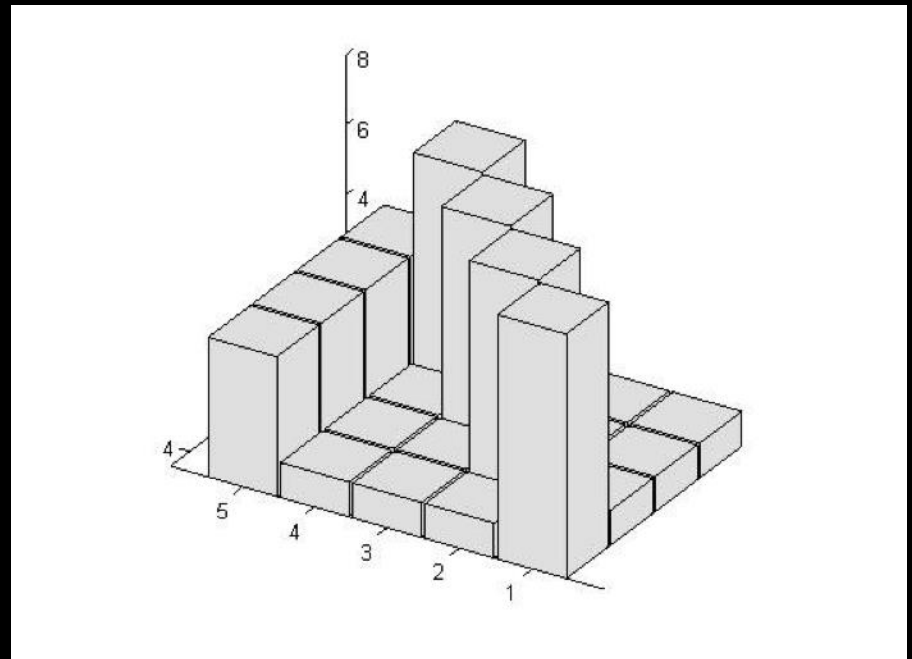


3	2	4	5	4
1	0	0	7	2
2	1	0	4	3
1	8	1	3	2

In pictures

[Livnat, P., Feldman
J. Th. Bio 2011]

Unless
peaks $> 2 \times$ plateau
the plateau
will prevail under sex



Changing the subject: The experts problem

- Every day you must choose one of n experts
- The advice of expert i on day t results in a gain $G[i, t]$ in $[-1, 1]$
- Challenge: Do as well as the best expert *in retrospect*

The experts problem

- Surprise: It can be done!
- A hard-to-believe fact which has been discovered again and again...
- [Hannan 1958, Cover 1980, Winnow, Boosting, no-regret learning, MWUA, ...]

Multiplicative updates

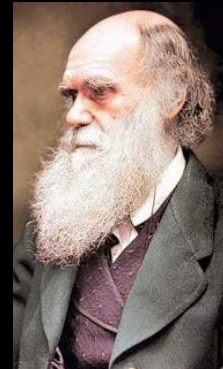
- Initially, assign all experts same weight/probability
- At each step, increase the weight of each by $(1 + \varepsilon G[i, t])$ (and then normalize)
- **Theorem:** *Does as well as the best expert*
- Also solves zero-sum games, convex programming, network congestion,...

Disbe



Computer scientists find it hard to believe that such a crude technique solves all these sophisticated problems

(cf: the other disbelievers)



Theorem: Under “weak selection,”
evolution of a species *is a game*

- the players are the genes
- the strategies are the alleles
- the common utility is the fitness of the organism (*coordination game*)
- the probabilities are the allele frequencies
- game is played through multiplicative updates

(2014, with E. Chastain, A. Livnat, U. Vazirani)

The mysteries of Evolution

- *Variation preservation*: what is each gene “optimizing” with MU?
- $x_g^{t+1} = \operatorname{argmax} \{ \text{???} \}$
- Answer: cumulative expected fitness + entropy of distribution x_g
- *genes appear to optimize a linear combination of performance plus variation...*

- The curious successes of Evolution and MWUA: Two mysteries united
- *This* is the role of sex in Evolution

Thank You!