Evolution and Computation

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The Algorithm as a Lens

- It started with Alan Turing, 60 years ago
- Algorithmic thinking as a novel and productive point of view for understanding and transforming the Sciences
- Major theme of the Simons Institute
- …and of this symposium
- This talk: Evolution

Evolution before Darwin

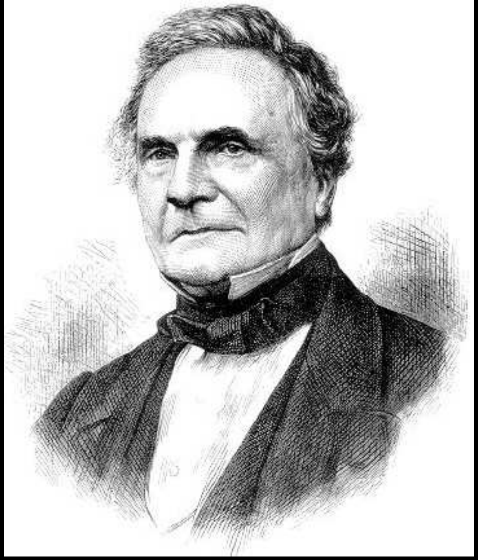
- Erasmus Darwin

Before Darwin

- J.-B. Lamarck

Before Darwin

- Charles Babbage



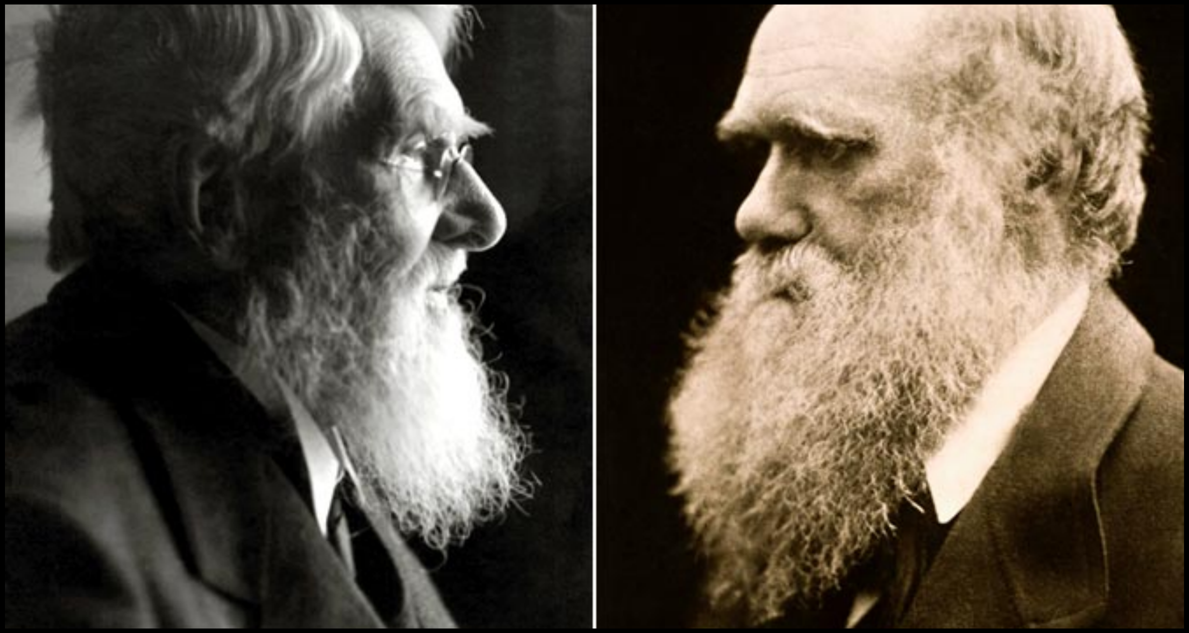
[ca. 1820, paraphrased]

"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.:

- How does novelty arise?
- What is the role of sex?

Cryptography against Lamarck

- A. Weismann

[ca. 1880, paraphrased]

"The mapping from genotype to phenotype is one-way"

Genetics

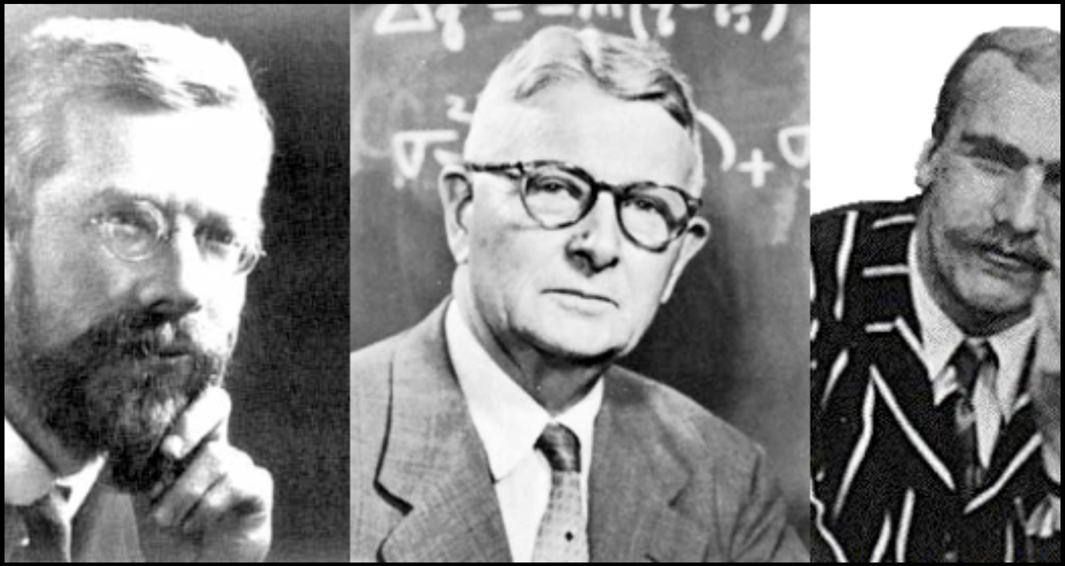
- Gregor Mendel [1866]
- Number of citations
  between 1866 and 1901:

3

The crisis in Evolution 1900 - 1920

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

The “Modern Synthesis” 1920 - 1950



Fisher – Wright - Haldane

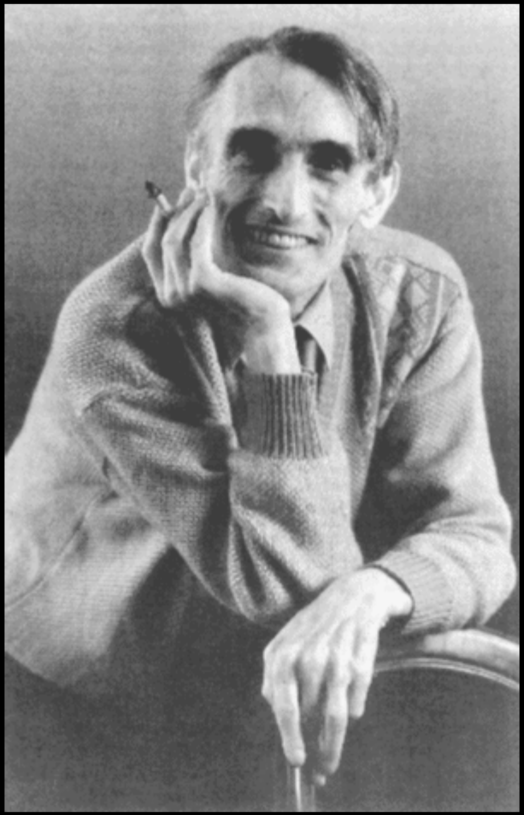
Big questions remain e.g.:

- How does novelty arise?
- What is the role of sex?

Disbelief

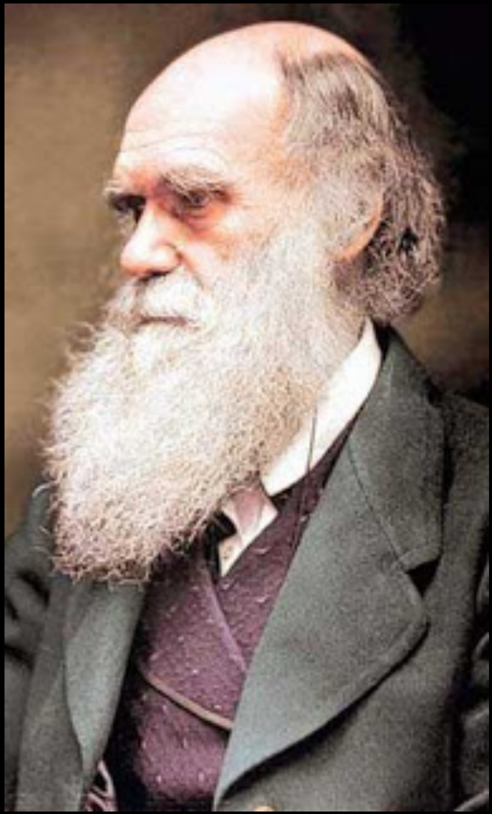
"Our thesis is that Neo-Darwinism cannot explain the basic phaenomena of evolution on the basis of physico-chemistry"

Schützenberger, 1966



Disbelief at the top

"The eye to this day gives me a cold shudder."



Disbelief, algorithmic version

"What algorithm could have achieved

all this

in a mere 10^{12} steps?"

(surprise: we have an answer…)

Valiant's Evolvability

" How do you find a 3-billion long string in 3 billion years?"

L. G.Valiant

Computationally-inspired model of Evolution shown to amount to a weak form of learning

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: The Fisher-Wright model

- Fitness landscape of a 2-gene organism

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

Rows: alleles of gene A

Entries: fitness of the combination

Columns: alleles of gene B

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

Pointer Dogs

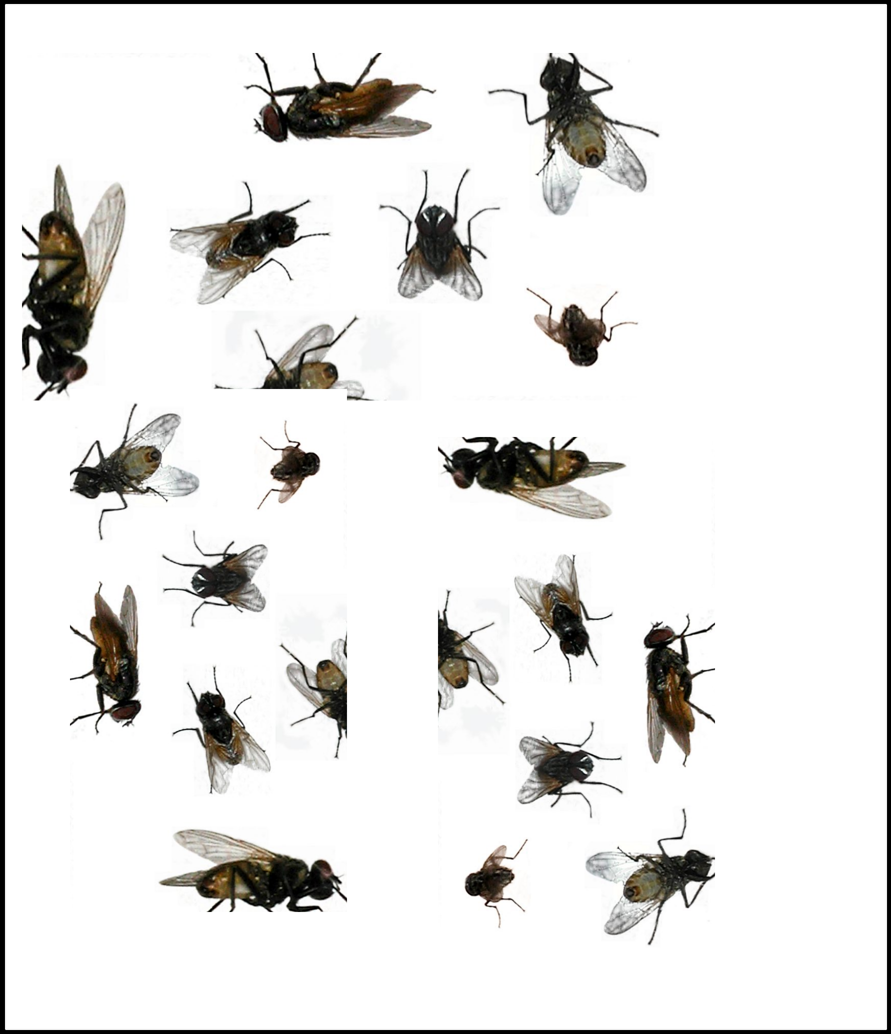
Pointer Dogs

C. H. Waddington

Waddington's Experiment (1952)

Generation 1

Temp: 20° C



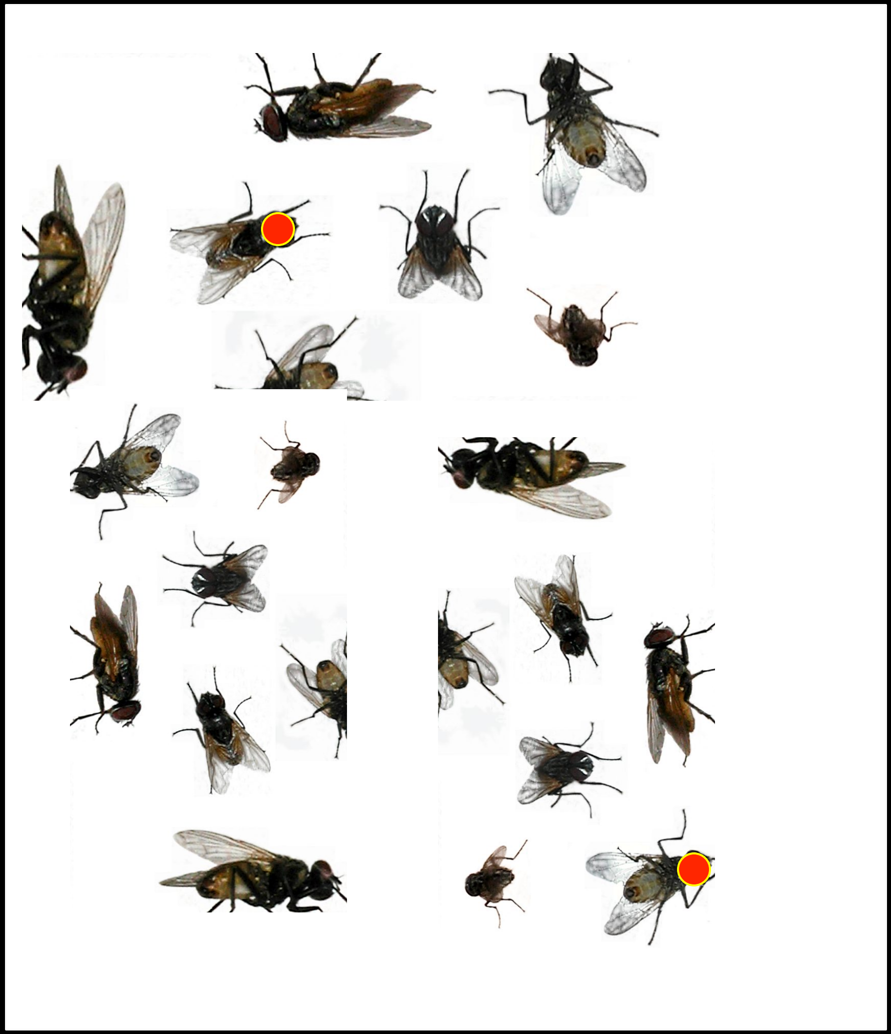
Waddington's Experiment (1952)

Generation 2-4

Temp: 40° C

~15% changed

Select and breed those



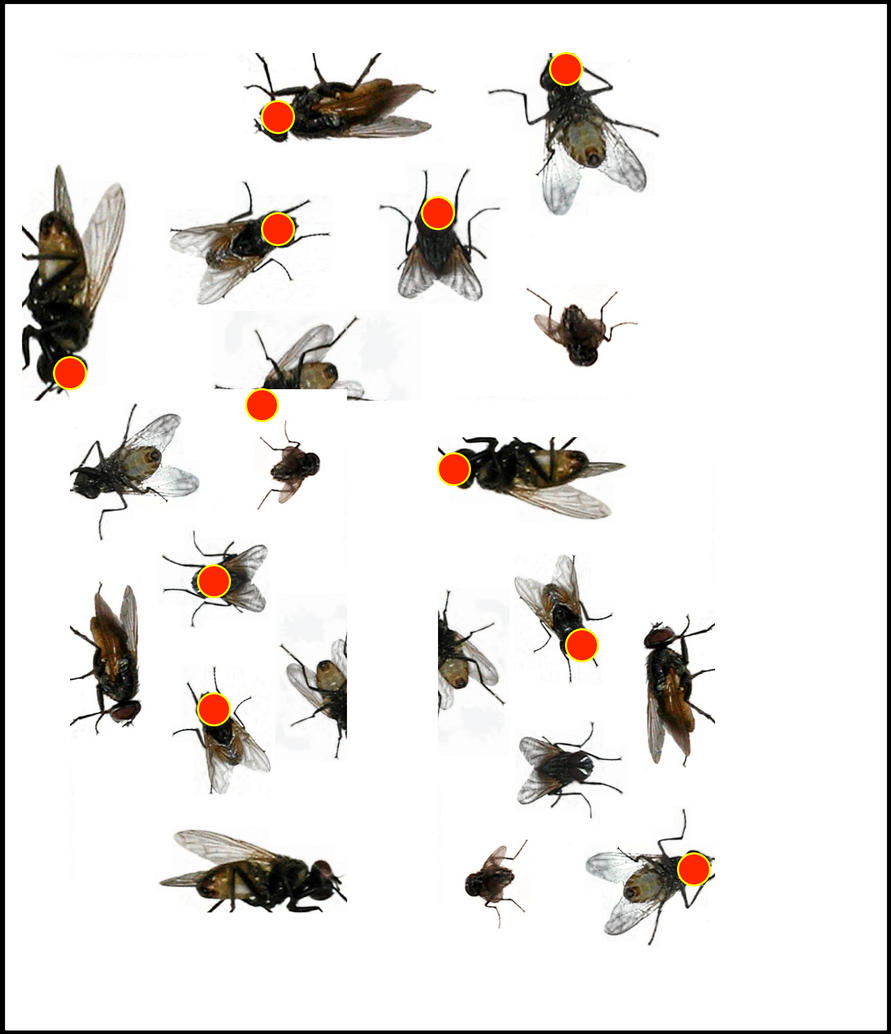
Waddington's Experiment (1952)

Generation 5

Temp: 40° C

~60% changed

Select and breed those



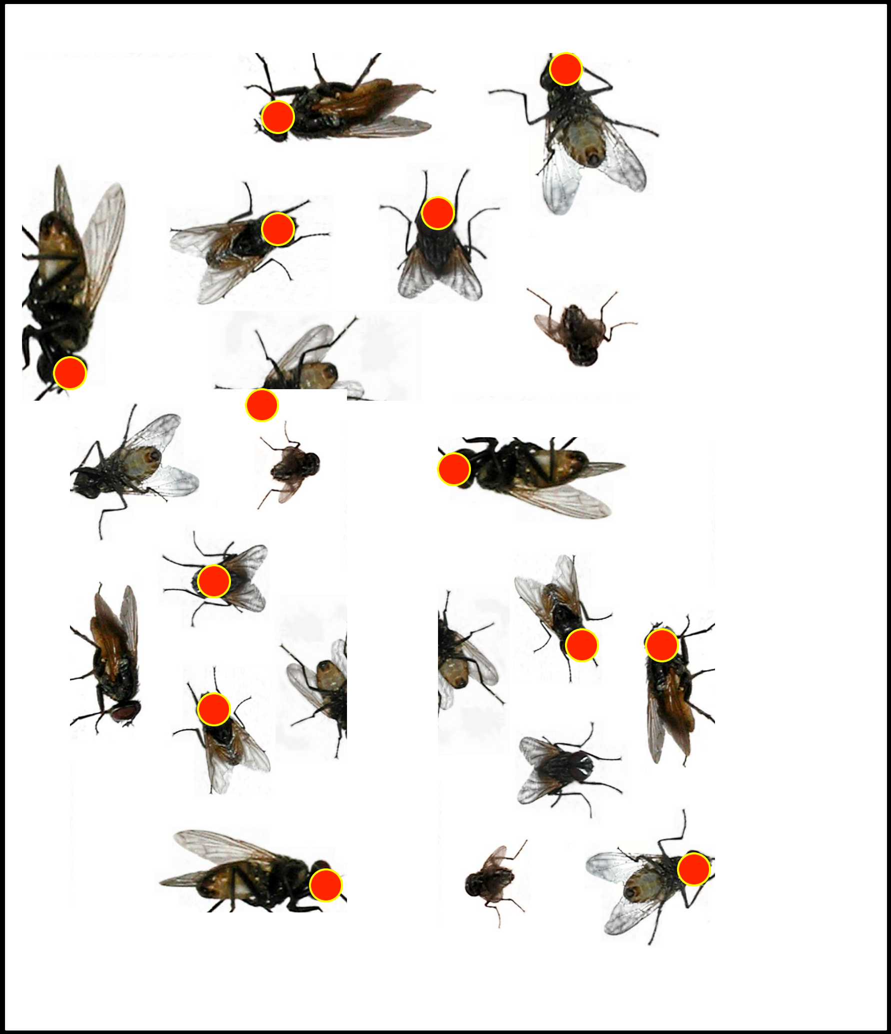
Waddington's Experiment (1952)

Generation 6

Temp: 40° C

~63% changed

Select and breed those



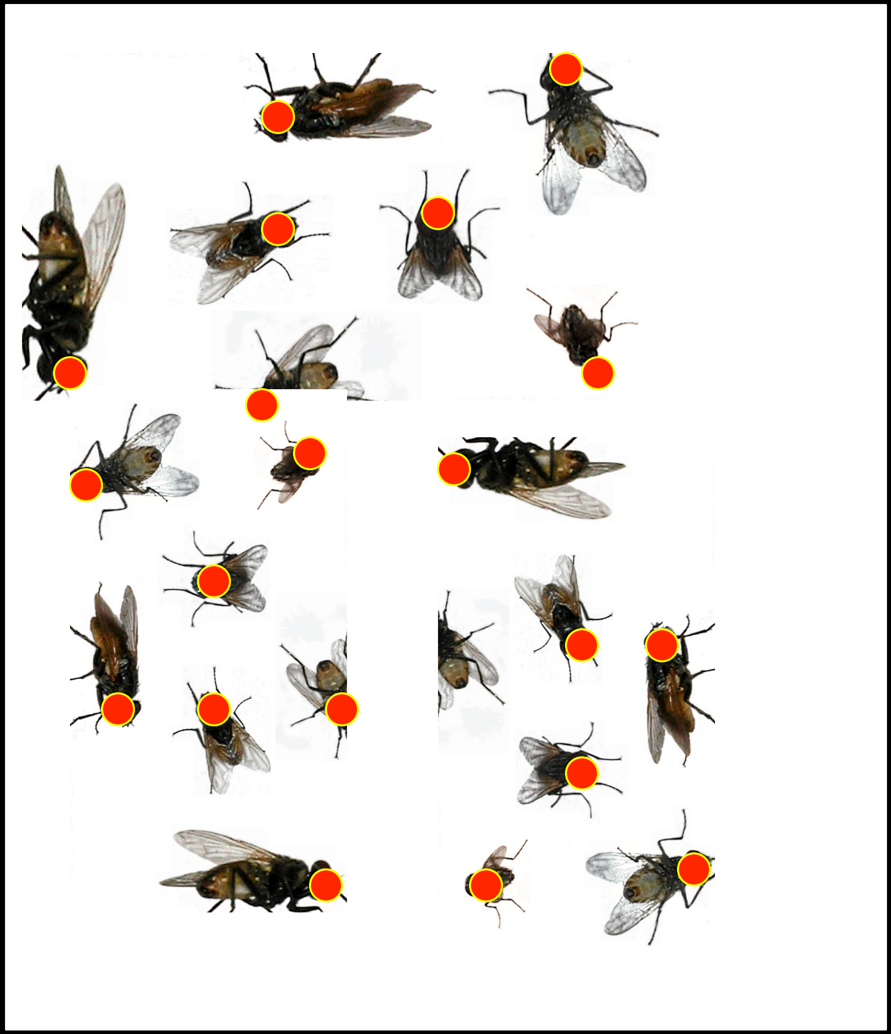
Waddington's Experiment (1952)

(…)

Generation 20

Temp: 40^{o} C

~99% changed

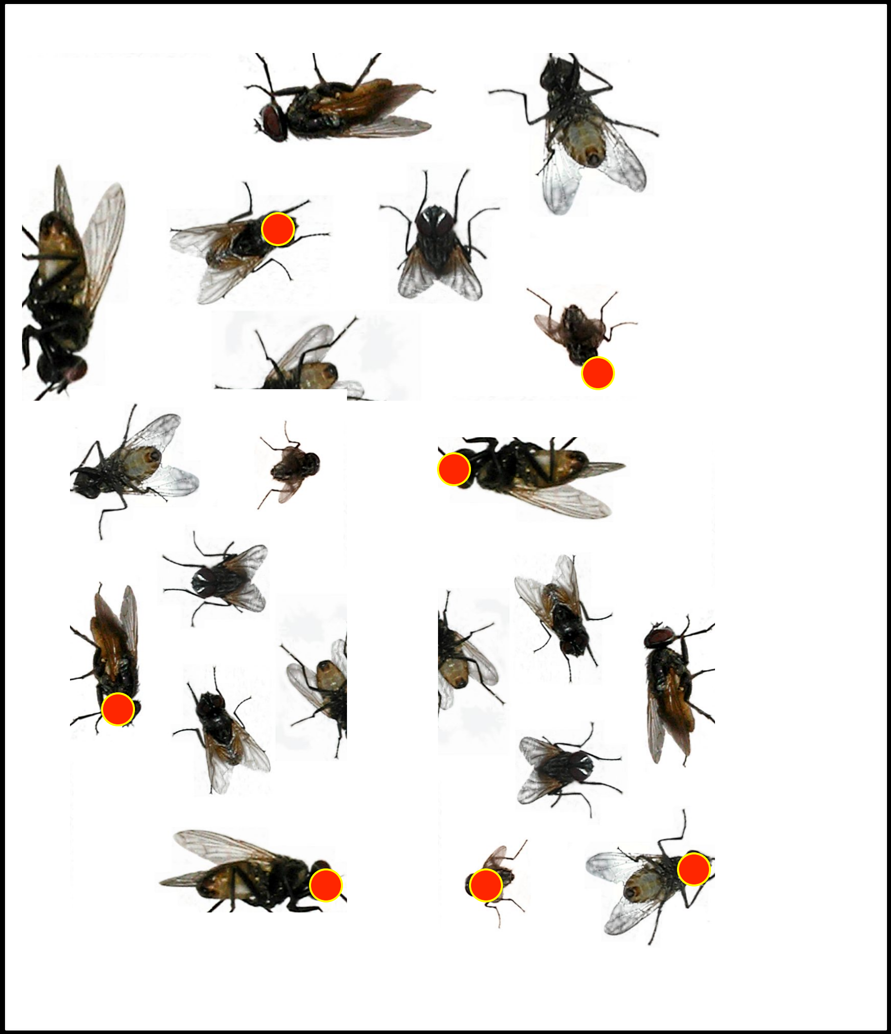


Surprise!

Generation 20

Temp: 20° C

~25% stay changed!!



- Adapt ome
  geneti

Is There a Genetic Explanation?

Function f (x, h) with these properties:

- Initially, $\text{Prob}_{x \sim p[0]}$ [f (x, h = 0)] ≈ 0%
- Then $\text{Prob}_{p[0]}$[f (x, 1)] ≈ 15%
- After breeding $\text{Prob}_{p[1]}$[f (x, 1)] ≈ 60%
- Successive breedings, $\text{Prob}_{p[20]}$[f (x,1)] ≈ 99%
- Finally, $\text{Prob}_{p[20]}$[f (x, 0)] ≈ 25%

A Genetic Explanation

- Suppose that "red head" is this Boolean function of 10 genes and "high temperature"

"red head" = "$x_1 + x_2 + \ldots + x_{10} + 3h \geq 10$"

- Suppose also that the genes are independent random variables, with p_i initially half, say
- All properties of the Waddington experiment satisfied
- [Stern *AN* 1958]

Arbitrary Boolean Functions

- What if we have an arbitrary function of genes (no environmental variable h)
- Suppose the satisfying genotypes have a fitness advantage ($1 + \varepsilon$ *vs.* 1, say)
- Will this trait be fixed eventually?

Arbitrary Functions: ***Yes!***

Theorem: Any Boolean function of genes which confers an evolutionary advantage will be eventually fixed (with high probability)

(2013; with Adi Livnat, Aviad Rubinstein, Greg Valiant, Andrew Won)

Which means that…

- "With sex, all moderate-sized Boolean functions are evolvable."
- *"Look, Ma, no mutations!"*
- Novel complex traits can emerge, through sex, in the whole population, without "Fisherian propagation"

Neutral Theory and Weak Selection

- Kimura 1970: Evolution proceeds not by leaps upwards, but mostly "horizontally," through statistical drift

- Weak selection: the values in the fitness matrix are very close, say in $[1 - \varepsilon, 1 + \varepsilon]$

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*
- Surprise: It can be done!
- [Hannan 1958, Cover 1980, Winnow, Boosting, no-regret learning, MWUA, …]

Multiplicative weights update

- 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
- MWUA solves: zero-sum games, linear programming, convex programming, network congestion,…

Disbelief

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

(2013, with E. Chastain, A. Livnat, U. Vazirani)

Finally…

- ***Variance preservation:*** MWUA is known to maximize entropy
- The curious successes of Evolution and MWUA: Two mysteries united
- ***This*** is the role of sex in Evolution

Sooooo…

- The theory of life is deep and fascinating
- And rife with interesting technical problems that are unexpectedly computational
- How robust? (Strong selection? Complex landscapes?)
- Environment? Mutations?
- Test?

Thanks!