

Welcome  
to Lecture 14

*Computation and the Brain*

**What happened last Wednesday**

## Great lecture by Francesco Fumarola

- Recalling from a list of  $N$  words
- We remember  $M < N$  of them
- We seem to be able to recall  $\sim \sqrt{N}$

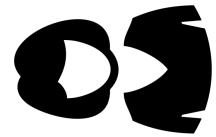
Language: A tale of two island girls  
and their mothers, grandmothers, etc.



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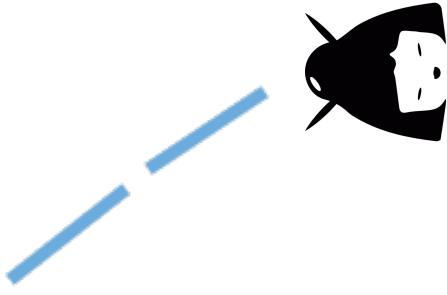
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English and Japanese are  
separated by the changes  
effected by about four  
thousand mothers teaching  
language to their children



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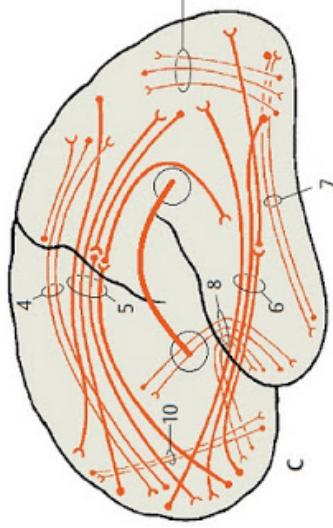
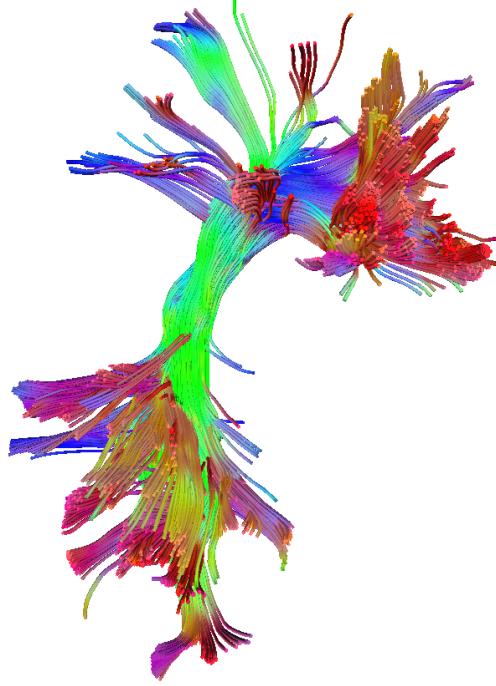
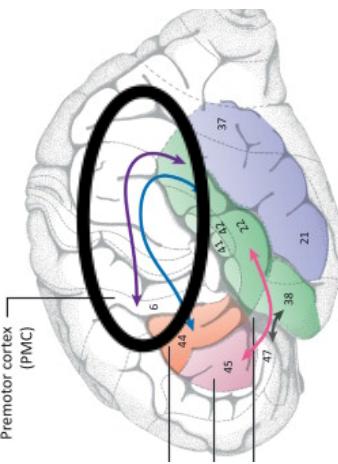
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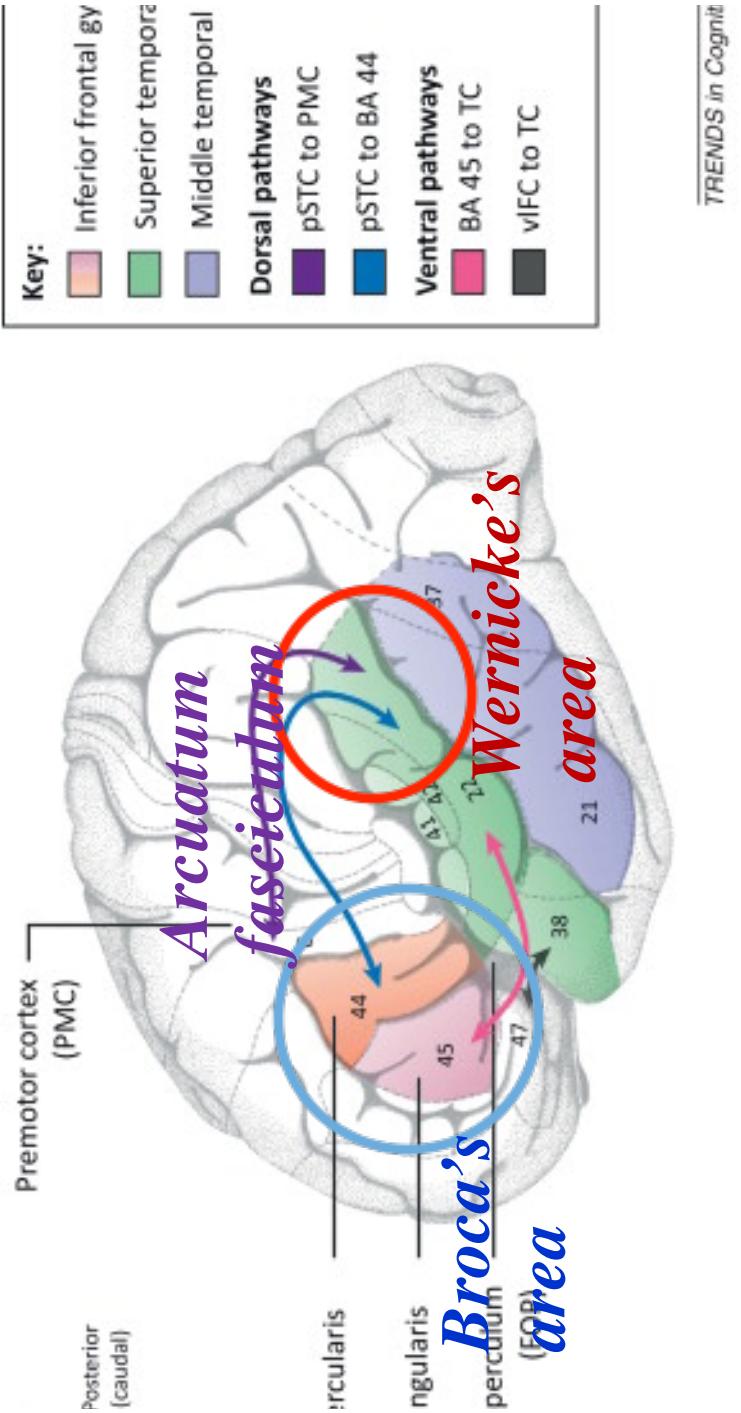
# Was there a neural Bing Bang?

- Our left and right hemispheres are anatomically asymmetric
- Seems to be specific to humans

- Main locus of asymmetry: the *arcuatum fasciculum*



# The Language hemisphere



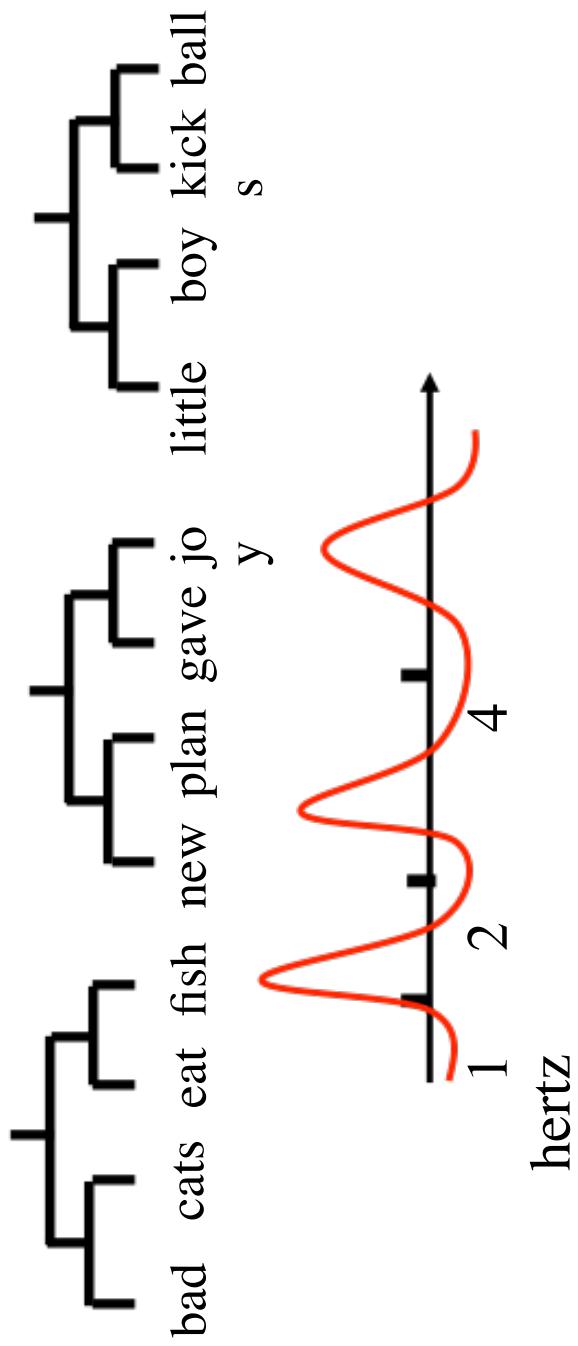
# The Chomsky hierarchy

Four increasingly general kinds of (recursive, infinitary) grammars

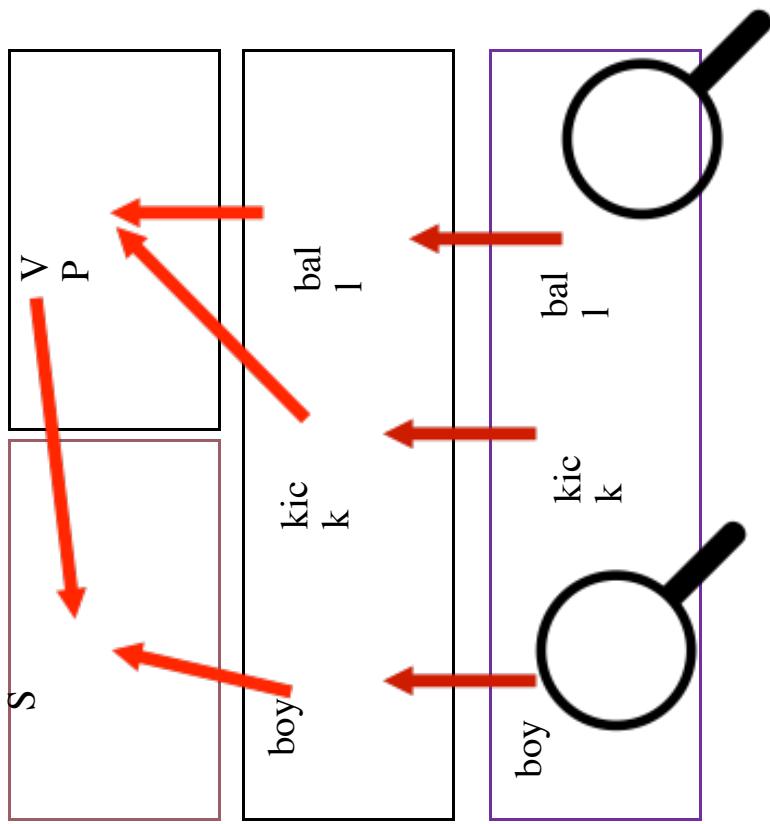
(**Assume only caps occur in lhs**)

1. Regular or right-linear:  $A \rightarrow a \ b \ B$
2. Context-free:  $S \rightarrow a \ B \ b \ S$
3. Context-sensitive:  $SB \rightarrow S \alpha B \beta \ B \gamma \ B \delta \ B \epsilon \ B \ z \ B \ y \ B \ x \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \ B \ m \ B \ l \ B \ k \ B \ j \ B \ i \ B \ h \ B \ g \ B \ f \ B \ e \ B \ d \ B \ c \ B \ b \ B \ a \ B \ t \ B \ u \ B \ v \ B \ w \ B \ r \ B \ s \ B \ p \ B \ q \ B \ n \B$
4. General:  $ScD \rightarrow Ba$

# The Poepel experiment



# *a brain architecture for syntax*



# Today:

- Talk by Dr. Alison Hanson
- Preliminary presentations of projects!**
- Evolution (...and Computation, of course)
- Discussion on Consciousness?

# Evolution

Evolutionists flock  
to Darwin-shaped  
wall stain

(from **The Onion**)



# 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*”

## *1959: 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 most questions left unanswered, e.g.:

- How does novelty arise?
- How is heredity “done”?
- If selection is important, why is there diversity?
- 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

# Key insight

- For Darwin, **fitness** was the degree to which an organism is in harmony with its environment
- For Neo-Darwinists, fitness is a **number**
- Roughly, **the expected number of surviving offspring** this organism is to produce

Fisher's reconciliation of discrete vs  
continuous traits: The law of large numbers



## Selection on a single locus

- Assume **haploid** (one version of each chromosome; diploid similar)
- Suppose a locus L has two **alleles**, A and B
- If there is **no difference** in fitness → **genetic drift**
- Frequency of alleles is a random walk
- Result: one of the alleles will be extinct in about  $2N_e$  generations
- $N_e = \text{effective population size}$

## Selection on a single locus (cont.)

- Suppose the fitness of A is greater than that of a. If at first frequency of A is high it will be extinct after  $1/\delta$  generations.
- **Evolutionary sweep of A**

Then how is diversity replenished?  
(Lewontin's paradox...)

- One possible answer: **heterozygote advantage**
- In a diploid organism (the norm) allele combination AB may be more fit than both AA and BB
- Example: malaria and thalassemia
- Does not seem so widespread

All this assumes that genes do not interact

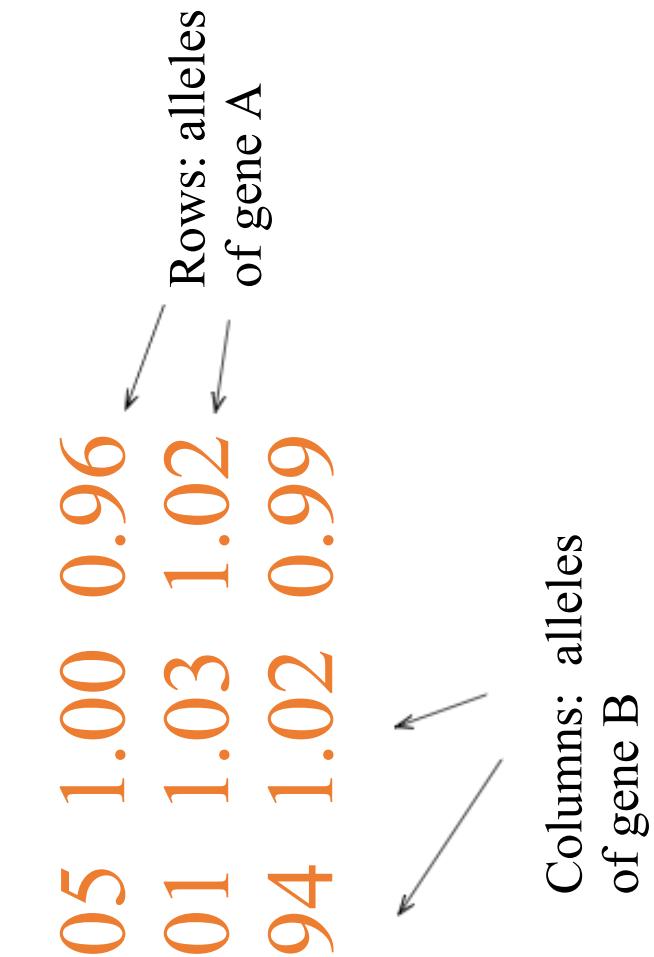
- But genes do...
- Gene A, alleles A1, A2, A3
- Gene B, alleles B1, B2, B3
- Maybe A1-B1 is the best combination

# Two gene interaction (infinite, panmictic, H/A population)

Entries: fitness

of the genotype  
(exp. # offspring,  
normalized)

1.05	1.00	0.96
1.01	1.03	1.02
0.94	1.02	0.99



# The Fisher-Wright-Haldane model: **frequencies at current generation**

0.33	0.33	0.33	0.33
0.33	1.05	1.00	0.96
0.33	1.01	1.03	1.02
0.33	0.94	1.02	0.99

## The Fisher-Wright-Haldane model: **frequencies at the next generation**

	0.33	0.35	0.32
0.34	1.05	1.00	0.96
0.34	1.01	1.03	1.02
0.31	0.94	1.02	0.99

Brilliant theory, a deluge of data  
-- and yet most important questions unanswered

- Why so much genetic diversity?
- What is the role of sex/recombination?
- *Is Evolution optimizing something?*

# Disbelief

*“Our thesis is that Neo-Darwinism cannot explain the basic phenomena of evolution on the basis of physico-chemistry”*



Schützenberger, 1966

# Disbelief at the top



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

*Charles Darwin ca. 1875*

# Disbelief, CS version

“What algorithm could have achieved  
*all this*  
in a mere 1012 steps?”

(surprise: there is an answer....)

Btw: 100 generations later?

1.05	1.00	0.96
1.01	1.03	1.02
0.94	1.02	0.99

100 generations later!

0.24	0.30	0.63	0.07
0.73	1.05	1.00	0.96
0.03	1.01	1.03	1.02
0.94	1.02	0.99	

Mixability Theory of the Role of Sex: [LPPF 2007]:

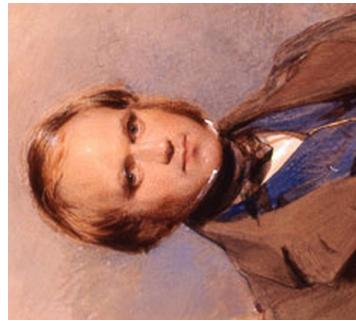
***good mixers are selected***



Contrast: In asexual species  
the fittest genotype wins

1.05	1.00	0.96
1.01	1.03	1.02
0.94	1.02	0.99

# Pointer Dogs



# Pointer Dogs

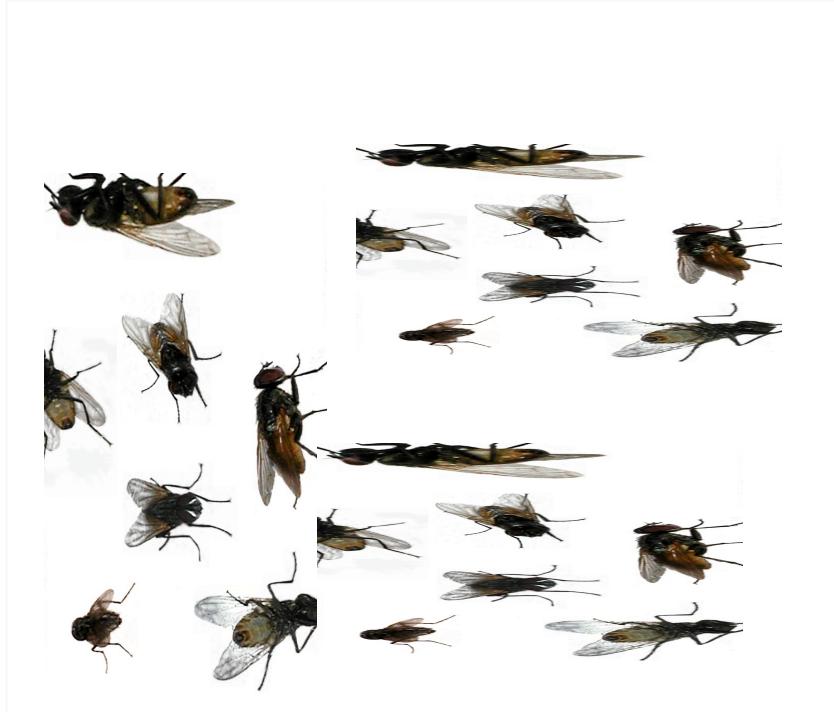


C. H. Waddington

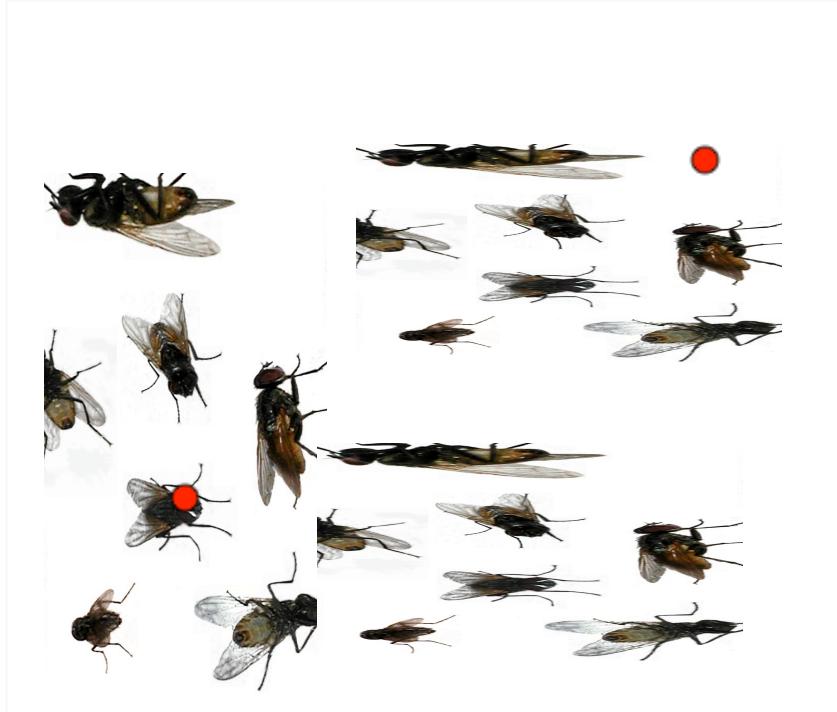


# Waddington's Experiment (1952)

Generation 1  
Temp: 200 °C



# Waddington's Experiment (1952)



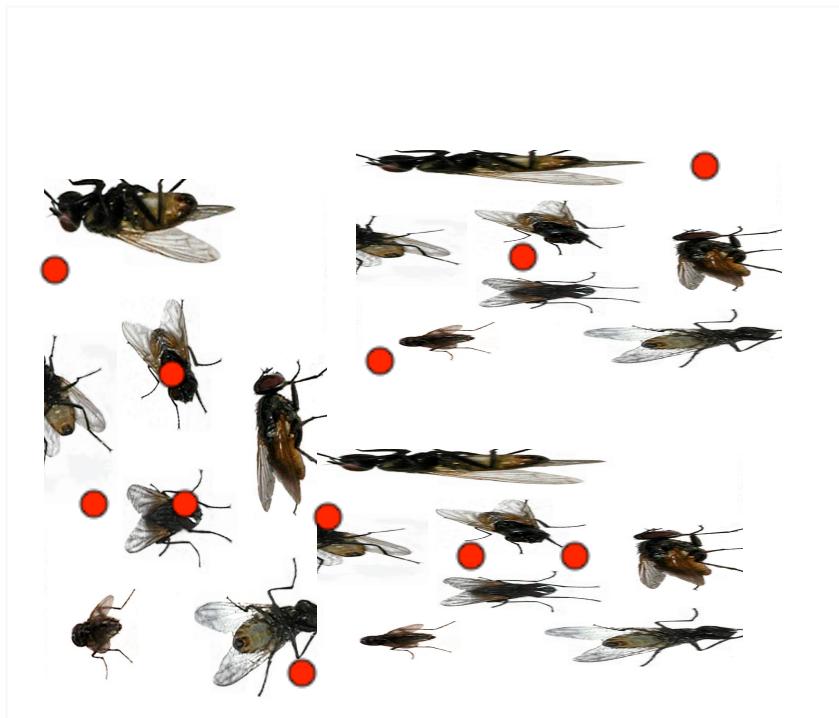
Generation 2-4

Temp: **400 C**

~15% changed

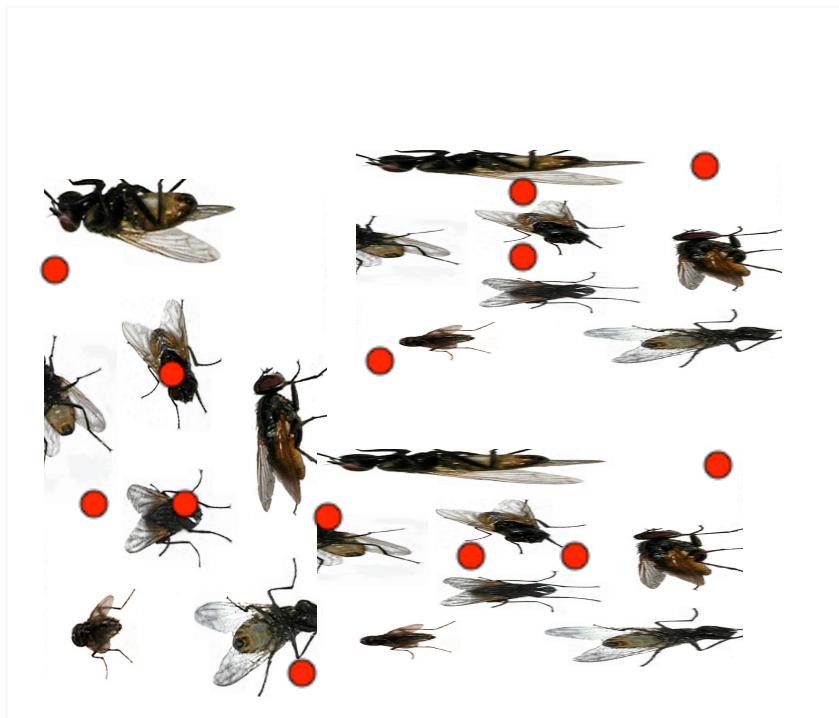
Select and breed  
those

# Waddington's Experiment (1952)



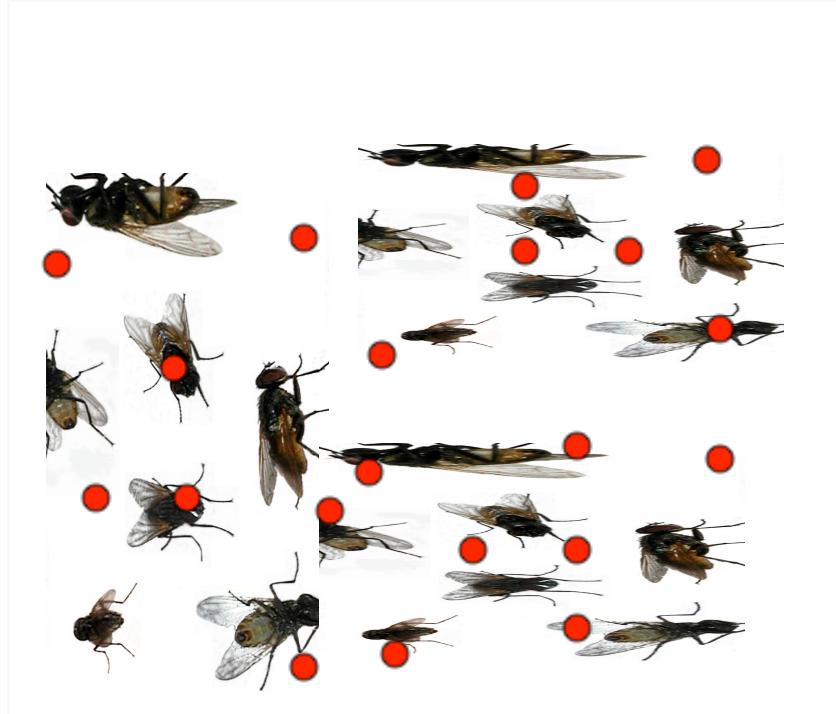
Generation 5  
Temp: **400 C**  
~60% changed  
Select and breed  
those

# Waddington's Experiment (1952)



Generation 6  
Temp: **400 C**  
~63% changed  
Select and breed  
those

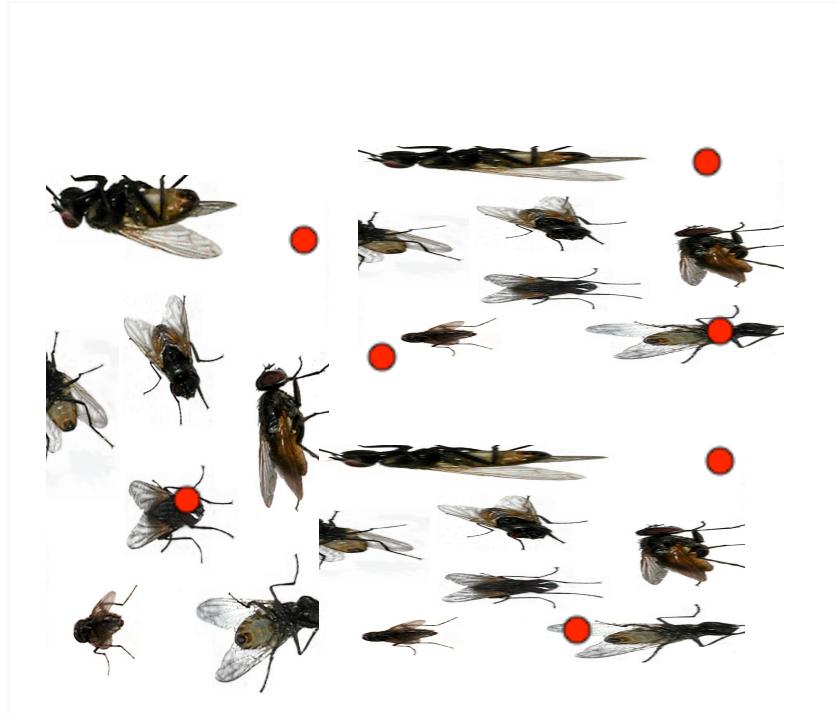
# Waddington's Experiment (1952)



(...)  
Generation 20  
Temp: **400** C  
~99% changed

Surprise!

Generation 20  
Temp: 200 C  
~25% stay changed!!



# Genetic ASS

- Adaptations to th



# Is There a Genetic Explanation?

Boolean function  $f(x, h)$  with these properties:

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

## A Genetic Explanation

- Suppose that “red head” is this Boolean function of 10 genes and.  $h = \text{“high temperature”}$ :  
**‘red head’ = ‘x1 + x2 + ... + x10 + 3h ≥ 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 ( $1 + \epsilon$  vs. 1, say)
- Will this trait be fixed eventually?

## Arbitrary Functions:

**Theorem [2013 FOCS]:** Any Boolean function of genes which confers an evolutionary advantage will be eventually fixed (with high probability)

Which means that...

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

# Evolution and ML

- Q: ‘*What algorithm could have done all this! in a mere 1012 steps?*’
- A: The equations for the evolution of a population of genotypes are tantamount to the genes playing a repeated game, with the alleles as strategies, through **multiplicative weights updates (aka AdaBoost)**!

**...but it gets better!**

Furthermore, by convex duality:

$x_{t+1}$  is the  $x$  that maximizes

$$\phi(x) = s \sum_i x_i + H(x)$$

entropy  
cumulative fitness

# Evolution

- Vast challenging subject
- Very close to home
- Many mysteries and open questions
- Computation brings in new insights