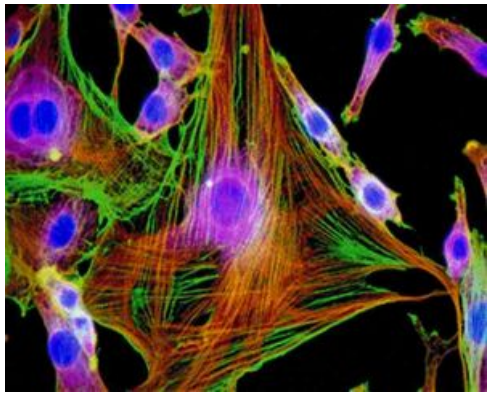
lecture 3
the complexity of evolution

jeremy gunawardena



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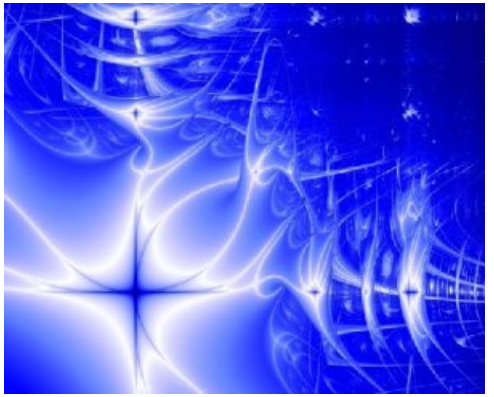


“A Systems Approach to Biology”, UBA Buenos Aires, 11-22 June 2018

syllabus

1. the role of mathematics in biology

2. homeostasis of the organism

3. the complexity of evolution 

4. weak linkage and learning

5. timescale separation and the linear framework

evolution and systems biology

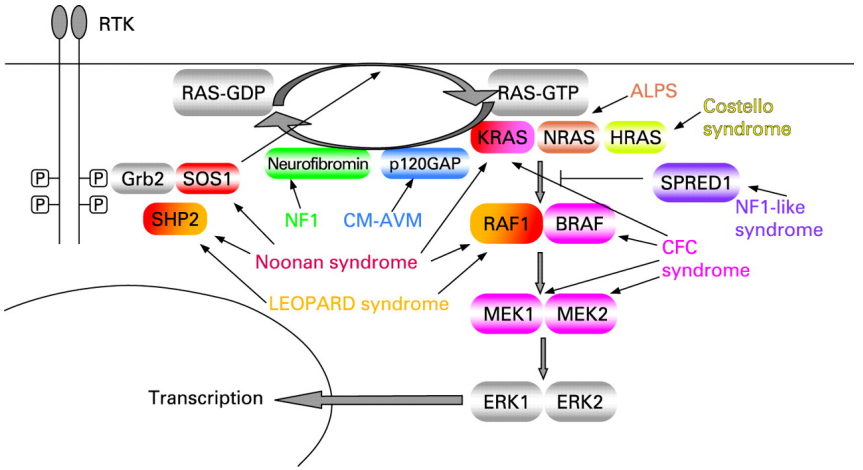
systems biology

how do we get from dead molecules to living organisms?

how do the collective interactions of molecular components give rise to the phenotype of the organism?

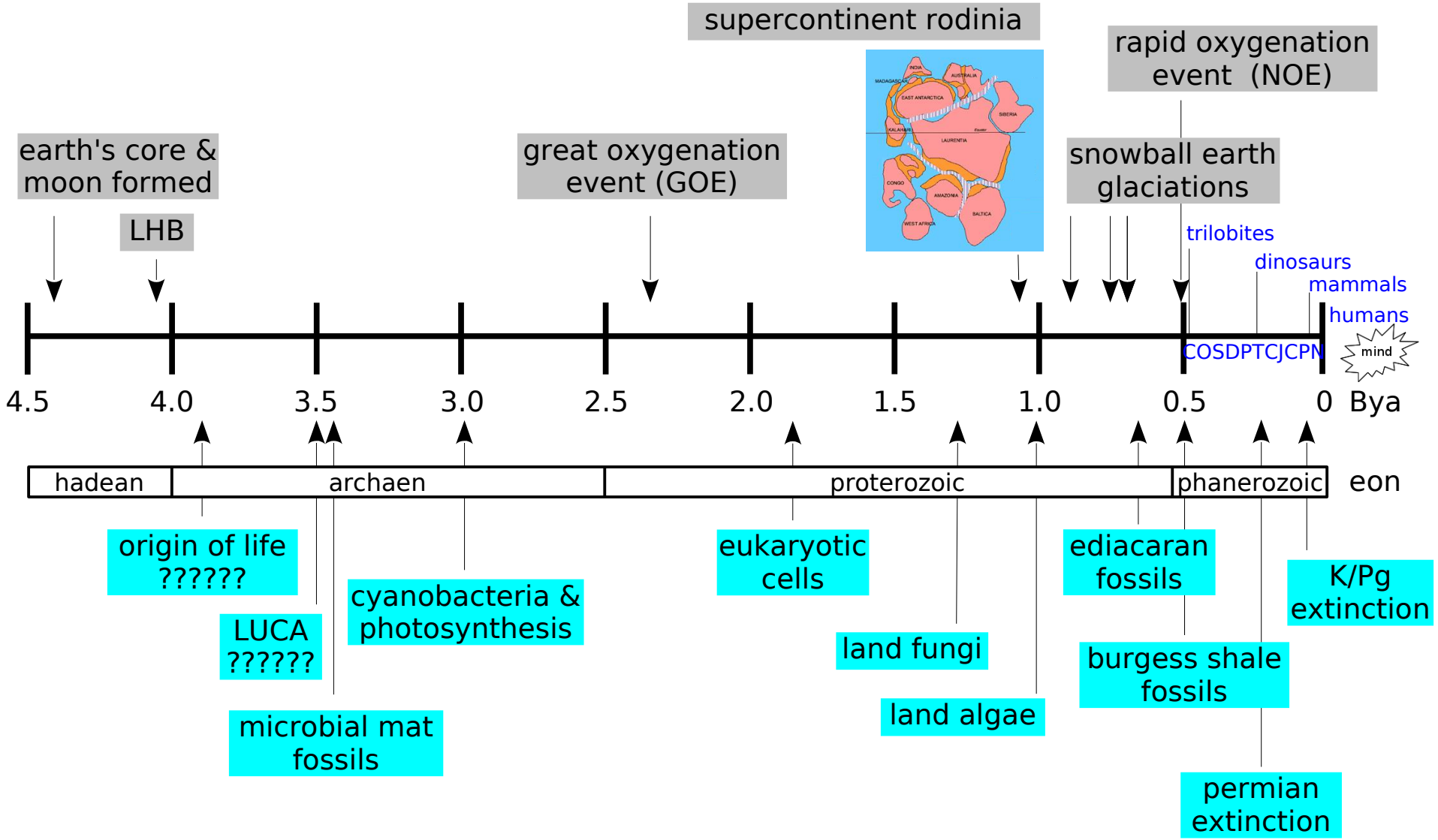
biological systems are evolved, not engineered

if we are to understand why the are the way they are, we must also understand the forces from which shaped them over historical time



1. the scope of evolution

life and times on planet earth

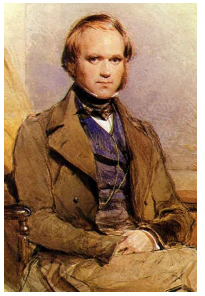


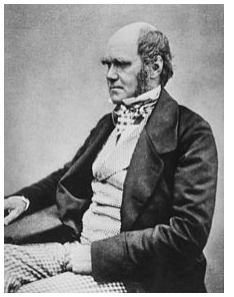
http://www.bevpease.force9.co.uk/ki.maps.Cont-Drift.htm
https://en.wikipedia.org/wiki/Timeline_of_the_evolutionary_history_of_life
with thanks to doug erwin

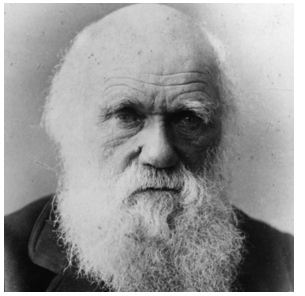
2. natural selection & complexity

charles darwin

“You care for nothing but shooting, dogs and rat-catching and you will be a disgrace to yourself and all your family”







1809 - 1882

1805 - 1865

Museo Municipal de Ciencas Naturales
“Carlos Darwin”, Punta Alta

“This wonderful relationship in the same continent between the dead and the living, will, I do not doubt, hereafter throw more light on the appearance of organic beings on our earth, and their disappearance from it, than any other class of facts.”

https://beagleproject.wordpress.com/

natural selection

“ ... any being, if it vary however slightly in any manner profitable to itself, under the complex and sometimes varying conditions of life, will have a better chance of surviving and thus be naturally selected. From the strong principle of inheritance, any selected variety will tend to propagate its new and modified form.”

darwinian dynamics arises when a trait whose variation is heritable increases the relative reproductive success of an entity (cell, organism). the trait can then spread.

“*How extremely stupid not to have thought of that!*” T H Huxley

but it is not so simple ...

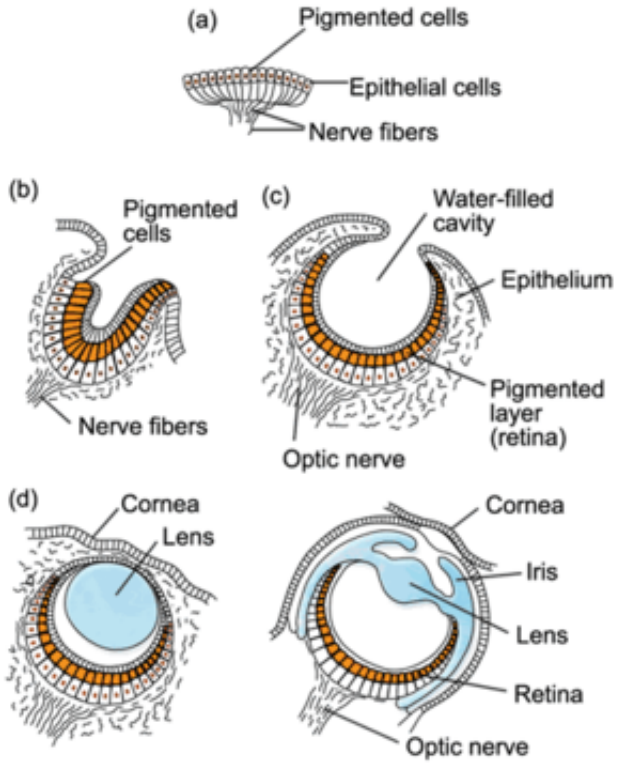
- “*if it vary however slight*” - how do variations arise?
- “*under the ... varying conditions of life*” - how do conditions change?
- “*the strong principle of inheritance*” - what is that?
- **organisms develop and die; only populations can *evolve***

“The face of Nature may be compared to a yielding surface, with ten thousand sharp wedges packed close together and driven inwards by incessant blows, sometimes one wedge being struck, and then another with greater force”

Charles Darwin, **On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life**, John Murray, London, 1859

the evolution of complexity

how can complex functionality like the eye emerge in nature?



"To suppose that the eye, with all its inimitable contrivances ... could have been formed by natural selection, seems, I freely confess, absurd in the highest possible degree."

"With these facts, here far too briefly and imperfectly given ... I can see no very great difficulty (not more than in the case of many other structures) in believing that natural selection has converted the simple apparatus of an optic nerve merely coated with pigment and invested by transparent membrane, into an optical instrument as perfect as is possessed by any member of the great Articulate class."

arthropods

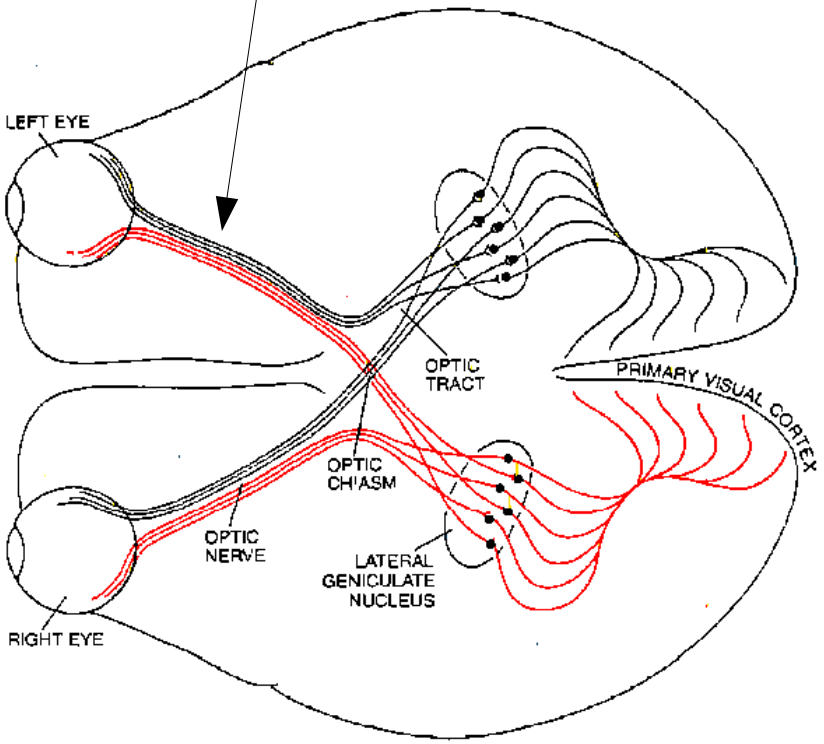
Darwin, **On the Origin of Species**, John Murray, London, 1859

the complexity of evolution

BUT we do not perceive with our eyes but with our brain

mutation improves eye resolution

new information conveyed to the brain



what does the brain do?

how does the brain know how to interpret the new information? how does it convert it into a selective advantage for the organism?

how does evolution avoid the need for multiple changes – to both eye and brain – in order to gain a selective advantage?

the modern answer I

“Charles Darwin confronted the problem of explaining the evolution of complex pieces of biological machinery. His answer was that a structure like an eye is built up by a process of stepwise change from a primitive ancestral state, such as a simple group of light-receptive cells, leading eventually to the complicated vertebrate system of lens, iris, retina, optic nerve, etc. The consensus among evolutionary biologists is that Darwin’s interpretation has successfully stood the test of time, although the news has apparently not reached Kansas.”

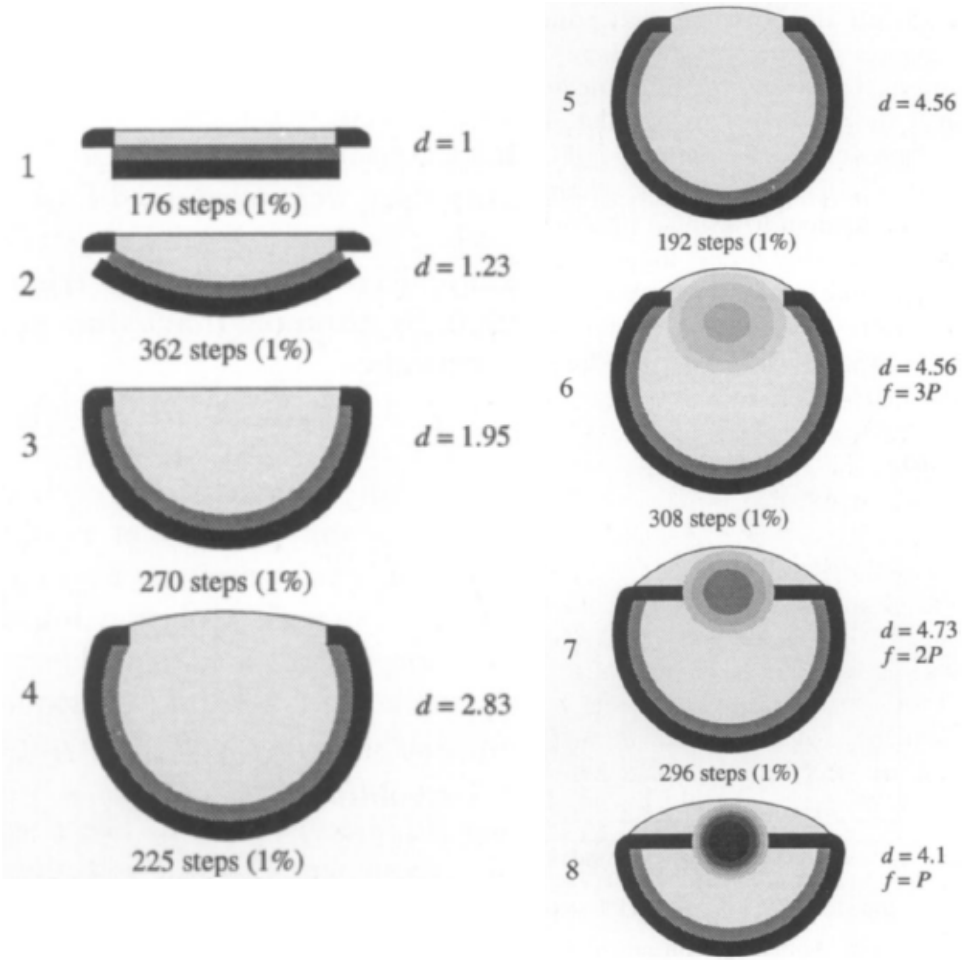
Brian Charlesworth, “*On the origins of novelty and variation*”, Science, **310**:1619-20 2005 – book review of Kirschner & Gerhart's **Plausibility of Life**.

the modern answer II

mark ridley, and also richard dawkins, refer to work of nilsson & pelger

according to ridley

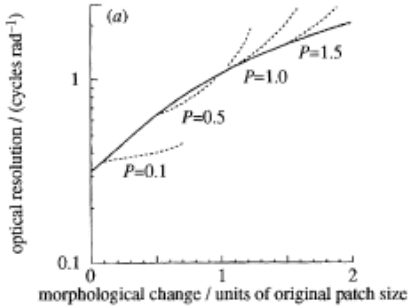
"Nilsson and Pelger allowed the shape of the model eye to change at random, in steps no more than 1% change at a time ... The model eye then evolved in the computer, with each new generation formed from the optically superior eyes in the previous generation; changes that made the optics worse were rejected, as selection would reject them in nature."

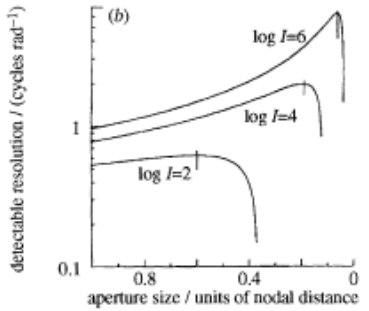


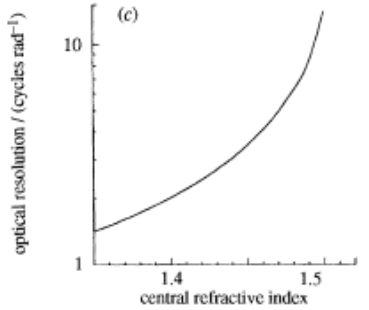
Mark Ridley, **Evolution**, 2nd ed, Blackwell Science, 1996; see also Richard Dawkins, **The Blind Watchmaker**, Norton, 1988; Nilsson, Pelger, "*A pessimistic estimate of the time required for an eye to evolve*", Proc Roy Soc Lond B, **256**:53-8 1994

but when you look more closely

there is no evolution, only small parametric changes in three models of the eye







"The relative effects that depression and constriction have on the eye's optical resolution are compared in figure 1a"

"We would thus expect selection first to favour depression and invagination of the light-sensitive patch, and then gradually change to favour constriction of the aperture."

$$\nu_{\max} = (0.375P/A)\,[\ln(0.746A^2\sqrt{I})]^{\frac{1}{2}},$$

"We can now use this relation to plot resolution against aperture diameter (figure lb)."

"When the aperture has reached the diameter which is optimal for the intensity at which the eye is used, there can be no further improvement of resolution unless a lens is introduced."

"The effect this has on resolution was calculated by using the theory of Fletcher et al. (1954) for an ideal graded-index lens (figure 1 c)"

this is the same argument as darwin made, with models replacing actual eyes

the complexity of evolutionary science

1. why has evolutionary biology not answered the complexity question?

2. why do evolutionary biologists think they have answered it?

3. how can complex functionality like the eye emerge in nature?

Does evolutionary theory need a rethink?

Researchers are divided over what processes should be considered fundamental.

POINT

Yes, urgently

Without an extended evolutionary framework, the theory neglects key processes, say Kevin Laland *and colleagues.*

COUNTERPOINT

No, all is well

Theory accommodates evidence through relentless synthesis, say Gregory A. Wray, Hopi E. Hoekstra *and colleagues.*

9 OCTOBER 2014 | VOL 514 | NATURE

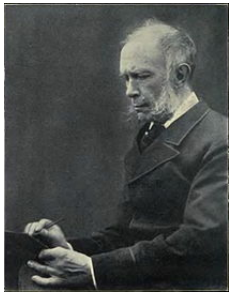
3. heredity & population genetics

the problem of inheritance

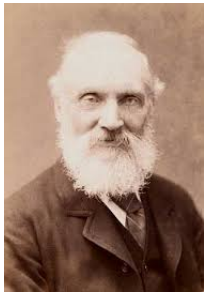
traits usually vary continuously in a population (height, for instance)

in darwin's time, inheritance was supposed to be a form of **blending**

the physicists (fleeming jenkin, william thomson) pointed out that, under blending inheritance, the height of an offspring will lie somewhere between the heights of its parents. variations in height will tend to revert to the mean of the population and will not spread to fix the new variation.



1833-1885



1824-1907

“I saw, also, that the preservation in a state of nature [as opposed to under domestication] of any occasional deviation of structure, such as a monstrosity, would be a rare event; and that, if preserved, it would generally be lost by subsequent intercrossing with ordinary individuals. Nevertheless, until reading an able and valuable article in the 'North British Review' (1867), I did not appreciate how rarely single variations, whether slight or strongly-marked could be perpetuated”

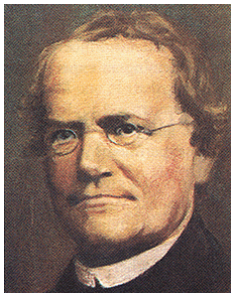
although a theory of “ancestral heredity” of continuous traits was developed (the “biometry” of galton & pearson), it remained difficult to explain natural selection.

Darwin, **On the Origin of Species**, John Murray, London, 5th Edition, 1869

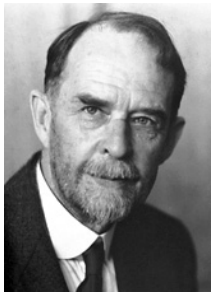
the rediscovery of mendelian genetics

genes were mathematical abstractions which explain data from experiments on crossing

"Frankly, these are questions with which the working geneticist has not much concern himself ... There is no consensus of opinion as to what the genes are—whether they are real or purely fictitious."



1822 - 1884

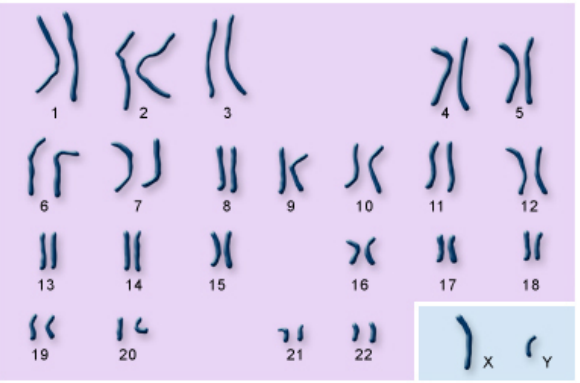


1866 - 1945

1902 - 1992

but they are closely associated in some way with chromosomes ...

"Pairing chromosomes, heteromorphic in two regions, have been shown to exchange parts at the same time they exchange genes assigned to those regions."

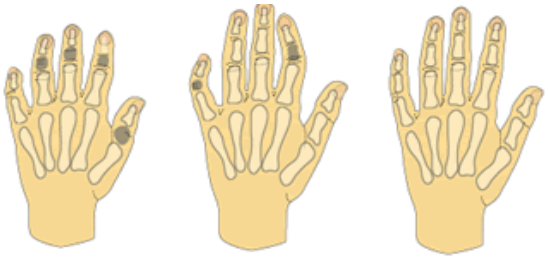


Morgan, "*The relation of genetics to physiology and medicine*", Nobel Lecture 1934

Creighton, McClintock, "*A correlation of cytological and genetical crossing over in Zea mays*", PNAS **17**:492-7 1931.

genetics becomes mathematical

how do allele frequencies change over time in populations, through inheritance and recombination?

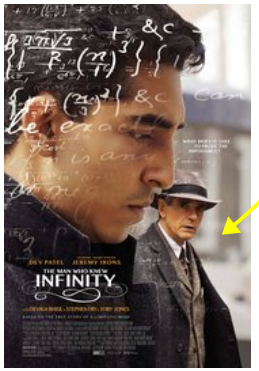


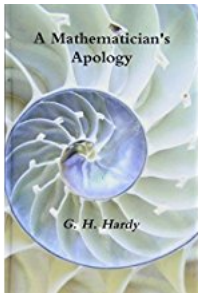
shortness of digits

A1 A4 normal

1877-1947

"To THE EDITOR OF SCIENCE: I am reluctant to intrude in a discussion concerning matters of which I have no expert knowledge, and I should have expected the very simple point which I wish to make to have been familiar to biologists. ... Mr. Yule is reported to have suggested, as a criticism of the Mendelian position, that if brachydactyly is dominant '<u>in the course of time one would expect, in the absence of counteracting factors, to get three brachydactylous persons to one normal</u>'. It is not difficult to prove, however, that such an expectation would be quite groundless."





G H Hardy, "*Mendelian proportions in a mixed population*", Science, **28**:49-50 1908.

https://www.peds.ufl.edu/divisions/genetics/teaching/hand_malformations.htm

hardy's calculation

two alleles (a, A) at a single locus

probabilities/frequencies

genotypes $\mathrm{AA}(P) \quad \mathrm{Aa}(Q) \quad \mathrm{aa}(R) \qquad P+Q+R=1$

alleles $\mathrm{A}\left(P+\frac{Q}{2}\right) \qquad \mathrm{a}\left(R+\frac{Q}{2}\right)$

under random mating in an infinite population with non-overlapping generations, in the absence of selection, mutation, migration, etc, the next generation looks like

genotypes

AA	Aa	aa
$\left(P+\frac{Q}{2}\right)^2$	$2\left(P+\frac{Q}{2}\right)\left(R+\frac{Q}{2}\right)$	$\left(R+\frac{Q}{2}\right)^2$

alleles $\mathrm{A}\left(P+\frac{Q}{2}\right) \qquad \mathrm{a}\left(R+\frac{Q}{2}\right)$ no change

the genotype frequencies become stable as soon as they satisfy $Q^2=4PR$ which happens after only a single generation

hardy-weinberg equilibrium

single locus, n alleles

alleles $A_1(p_1), A_2(p_2), \cdots, A_n(p_n)$

under random mating with no selection, mutation, migration, etc, the genotype frequencies become stable after one generation

their values are given by the respective terms in the expansion of

$$(p_1 + \cdots + p_n)^2$$

genotypes $A_iA_i(p_i^2)$ $A_iA_j(2p_ip_j)$

once introduced into a population, a neutral allele remains there indefinitely, it is not “blended” away.

C Stern, “*The Hardy-Weinberg law*”, Science, **97**:137-38 1943.

human polymorphisms at HW equilibrium

population genetics has been extremely successful at explaining data on variation

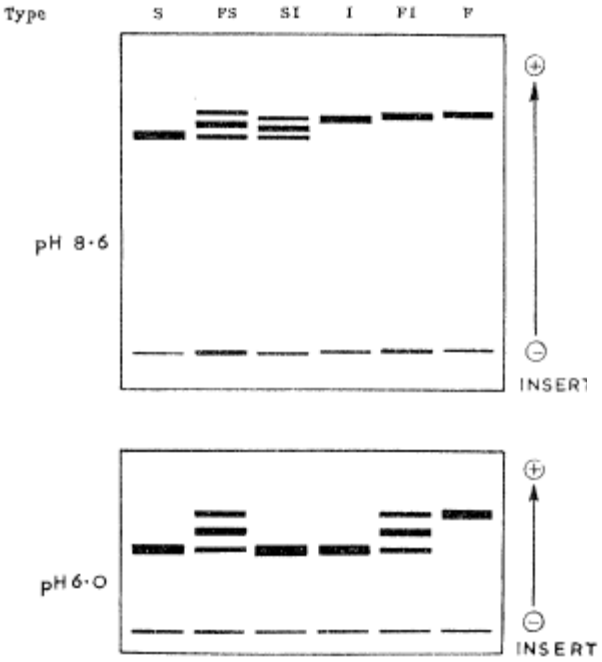


TABLE 9. OBSERVED AND EXPECTED NUMBERS OF PLACENTAL ALKALINE PHOSPHATASE TYPES IN A POPULATION SAMPLE ASSUMING A HARDY–WEINBERG EQUILIBRIUM **F I S** ($p = 0{\cdot}27$, $q = 0{\cdot}09$ and $r = 0{\cdot}64$)

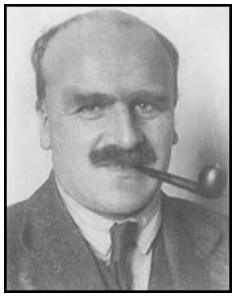
placental alkaline phosphatase type	expected incidence		expected numbers in population sample	observed numbers in population sample
S	r^2	0·410	135·9	141
SF	$2pr$	0·346	114·7	111
F	p^2	0·073	24·2	28
SI	$2qr$	0·115	38·2	32
FI	$2pq$	0·049	16·1	15
I	q^2	0·008	2·7	5
totals	$(p+q+r)^2$	1·001	331·8	332

Harris, "*Enzyme polymorphisms in man*", Proc Roy Soc Lond B, **164**:289-310 1966

4. the modern synthesis

natural selection in population genetics

how do allele frequencies change in populations under the influence of natural selection?


1890-1962 *1892-1964* *1889-1988*

two alleles (a, A) at a single locus:

selection coefficient

dominance

genotypes	AA	Aa	aa
relative fitness	*1 - s*	*1 - hs*	*1*

change in frequency (*p*) of allele A

$$\Delta p = \frac{pqs[ph + q(1-h)]}{1 - 2pqhs - q^2 s}$$

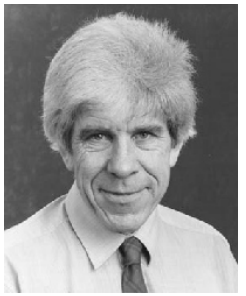
not only variation of discrete traits (represented by discrete alleles A/a) but also of continuous traits (height) can be explained as the additive effect of genes at many loci

John Gillespie, **Population Genetics**, JHU Press, 2004; Sean Rice, **Evolutionary Theory: Mathematical and Conceptual Foundations**, Sinauer Associates, 2004

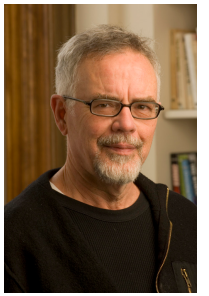
the triumph of the gene

inclusive fitness – selection of an allele may arise, not just through an individual organism, but also through other organisms (such as close relatives) which have the same allele

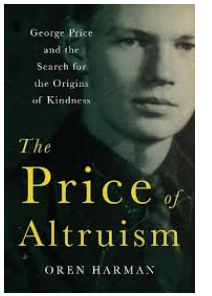
"I will give up my life for 2 brothers or 8 cousins" J B S Haldane



1936-2000



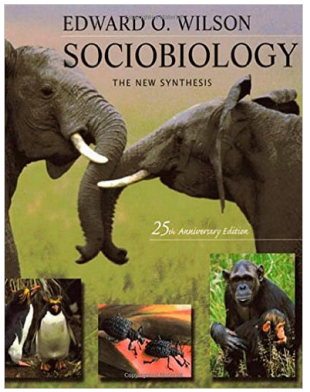
b. 1943

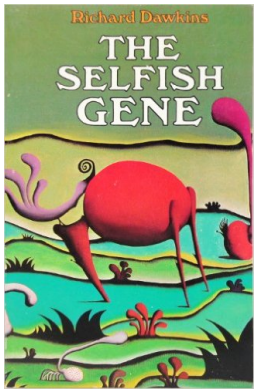


1922-1975

genomic conflict – selective advantage can arise for alleles which exploit other's genetically-related organsims (parent-offspring, siblings, etc)

reciprocal altruism – "tit for tat" – and the use of **game theory** to analyse how ecologica strategies can arise through natural selection

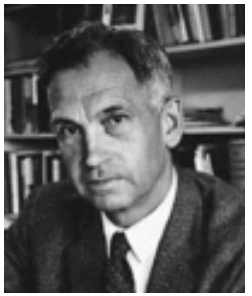




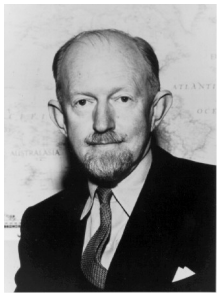
the modern ("neo-darwinian") synthesis

naturalists, field biologists and paleontologists showed that variation in nature was consistent with laboratory genetics and with the predictions of population genetics

1900-1975

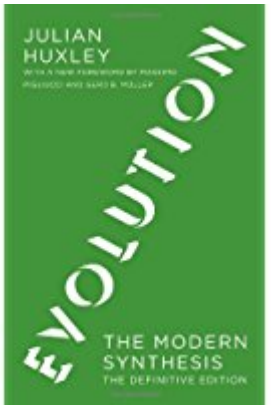


1904-2005



1902-1984

"Nothing in biology makes sense except in the light of evolution"

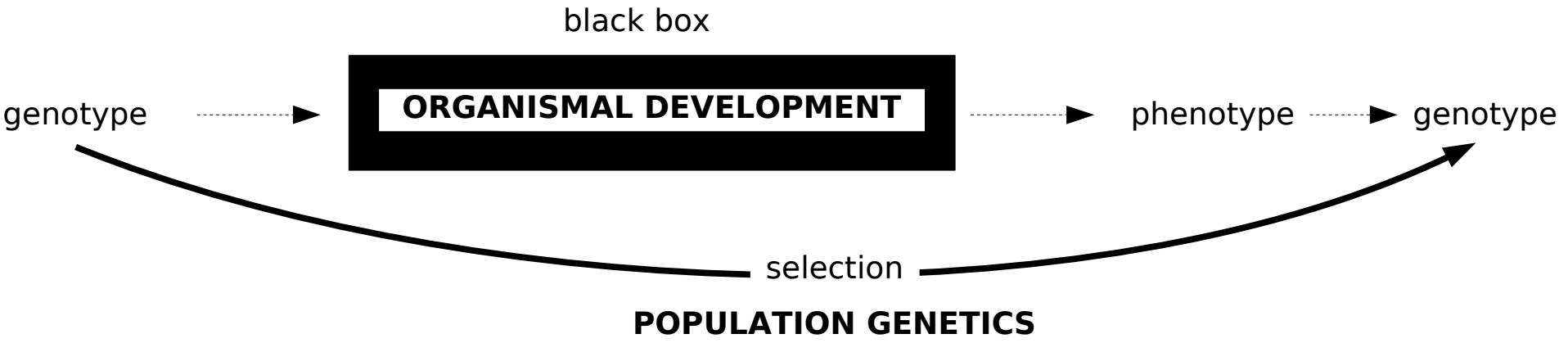


1887-1975

"Nothing in evolution makes sense except in the light of population genetics"

Ernst Mayr & William Provine, **The Evolutionary Synthesis: Perspectives on the Unification of Biology**, Harvard Univ Press, 1980; Dobzhansky, Amer Biol Teach **35**:125-9 1973; Lynch, PNAS **104**:8597-604 2007

the price of a successful theory



selection is assumed to act on the genotype, when it actually acts on the phenotype. the organism is a black box whose development is inaccessible to the theory

selection appears as a parameter, not as a variable. population genetics does not tell explain how selection arises but only how allele frequencies change.

$$\Delta p = \frac{pqs[ph + q(1-h)]}{1 - 2pqhs - q^2 s}$$

dynamical variables – p, q

parameters – s, h

the initial conditions are taken for granted – the necessary allele is assumed to exist at some frequency in the population. how such an allele arises in the first place is not part of the theory.

5. how does selection arise?

ecological selection

evidence for strong selection came from field studies of animal behaviour in their natural ecological context

Edmund Brisco Ford, **Ecological Genetics**, Methuen & Co, 1964

1901-1988

example: bernard kettlewell's experiment on “industrial melanism” in the peppered moth *Biston betularia*

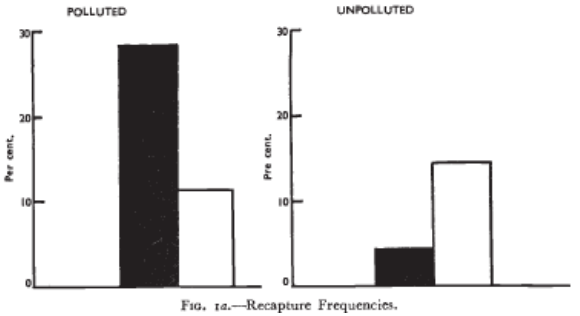


Fig. 12.—Recapture Frequencies.

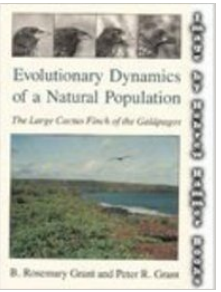
Kettlewell, “*Further selection experiments on industrial melanism in the Lepidoptera*”, Heredity, **10**:287-301 1956; Cook, Grant, Saccheri, Mallet, “*Selective bird predation on the peppered moth: the last experiment of Michael Majerus*”, Biol Lett **8**:609-12 2012; see also http://www.open.ac.uk/library/digital-archive/clip/clip%3Asci_clip14 - see 3.30mins

ecological selection

john endler with
Poecilia (guppy)

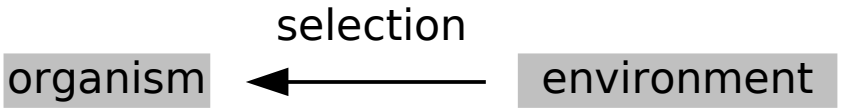
hopi hoekstra with
Peromyscus (deer mouse)

peter & rosemary grant with
Geospiza (Darwin's finches)



natural selection exists in the wild; selection can be strongly variable over time; natural populations can evolve very rapidly in response to selection

BUT the organism is passive and the ecological environment is assumed to act upon the organism to generate the selective “force”



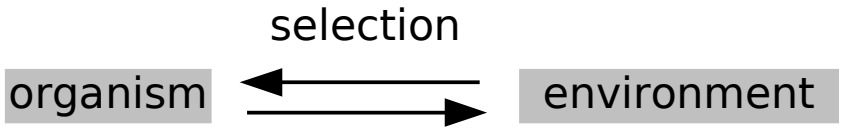
Reznick, Bryga, Endler, Nature, **346**:357-359 1990; Schluter, Trends Ecol Evol **16**:372-80 2001; Linnen, Hoekstra, Cold Spring Harb Symp Quant Biol **74**:155-68 2009

the organism as agent – niche construction

the role of behaviour in evolution has been associated with Lamarckian views about the inheritance of acquired traits

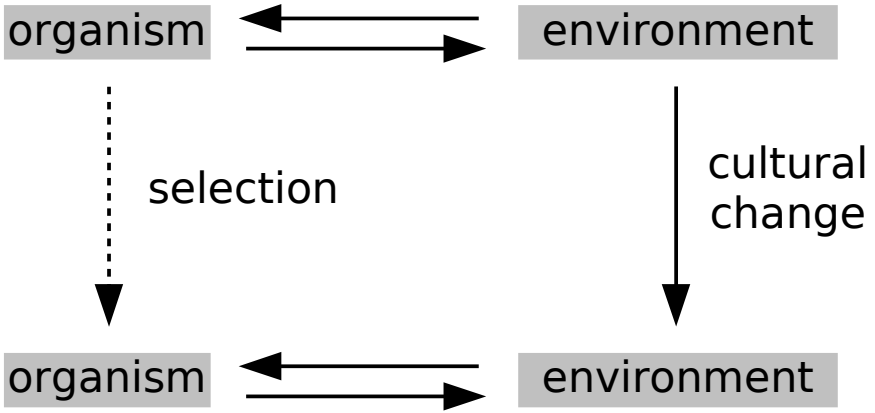
but organisms can actively change their environment – (re)construct their ecological niche – and thereby influence selective processes

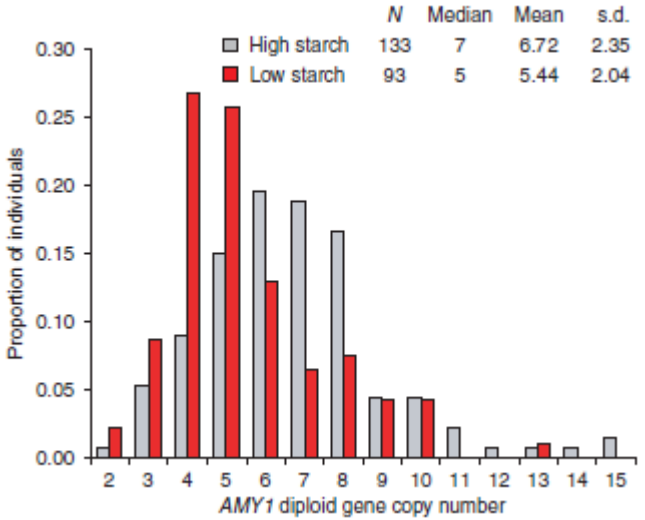
vogelkop bowerbird (*Amblyornis inornata*) and its bower

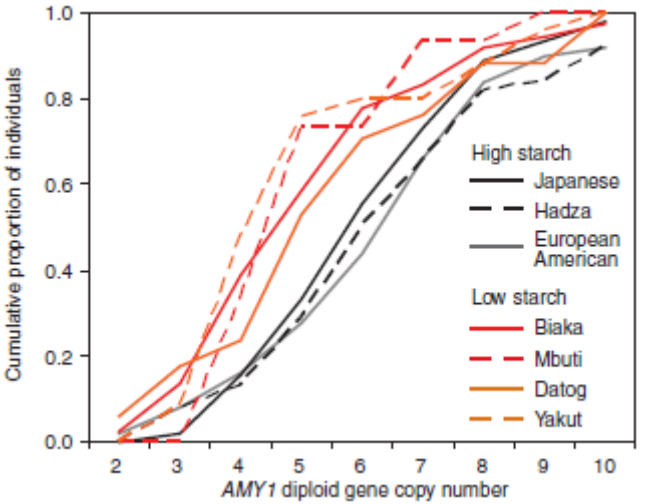


Odling-Smee, Laland, Feldman, **Niche Construction: The Neglected Process in Evolution**, Princeton Univ Press 2003.

the organism as agent – gene-culture coevolution







Laland, Odling-Smee, Myles, "*How culture shaped the human genome: bringing genetics and the human sciences together*", Nat Rev Genet, **11**:137-48 2010; Perry et al, "*Diet and the evolution of human amylase gene copy number variation*", Nat Genet **39**:1256-60 2007

evolutionary wars

1. why has evolutionary biology not answered the complexity question?

2. why do ridley and dawkins think they have answered it?

> *"At the heart of this exchange lie differences in perspective ... The skeptics probably represent the majority position: evolutionary processes are those that change gene frequencies. Advocates of NCT, in contrast, ... conceive of evolutionary processes more broadly, as anything that systematically biases the direction or rate of evolution. ... The skeptics among us embrace adaptationism, see natural selection as the ultimate source of organism-environment fit, have a gene-centered view of evolution ... NCT enthusiasts, in contrast are frequently sympathetic to a structuralist tradition that stems from developmental biology (e.g., Waddington 1959), which emphasizes not only constraints on adaptation but also the evolutionary significance of processes other than selection."*

conventional evolutionary thinking focusses only on the dynamical variables in population genetics – gene frequencies – and views the selection parameter as something that can be chosen at will, as justified by ecological selection.

Scott-Phillips et al, "*The niche construction perspective: a critical apprasial*", Evolution **68**:1231-43 2013; Laland et al versus Wray et al, "*Does evolutionary theory need a rethink?*", Nature **514**:161-4 2014