Developmental biology and evolutionary theory

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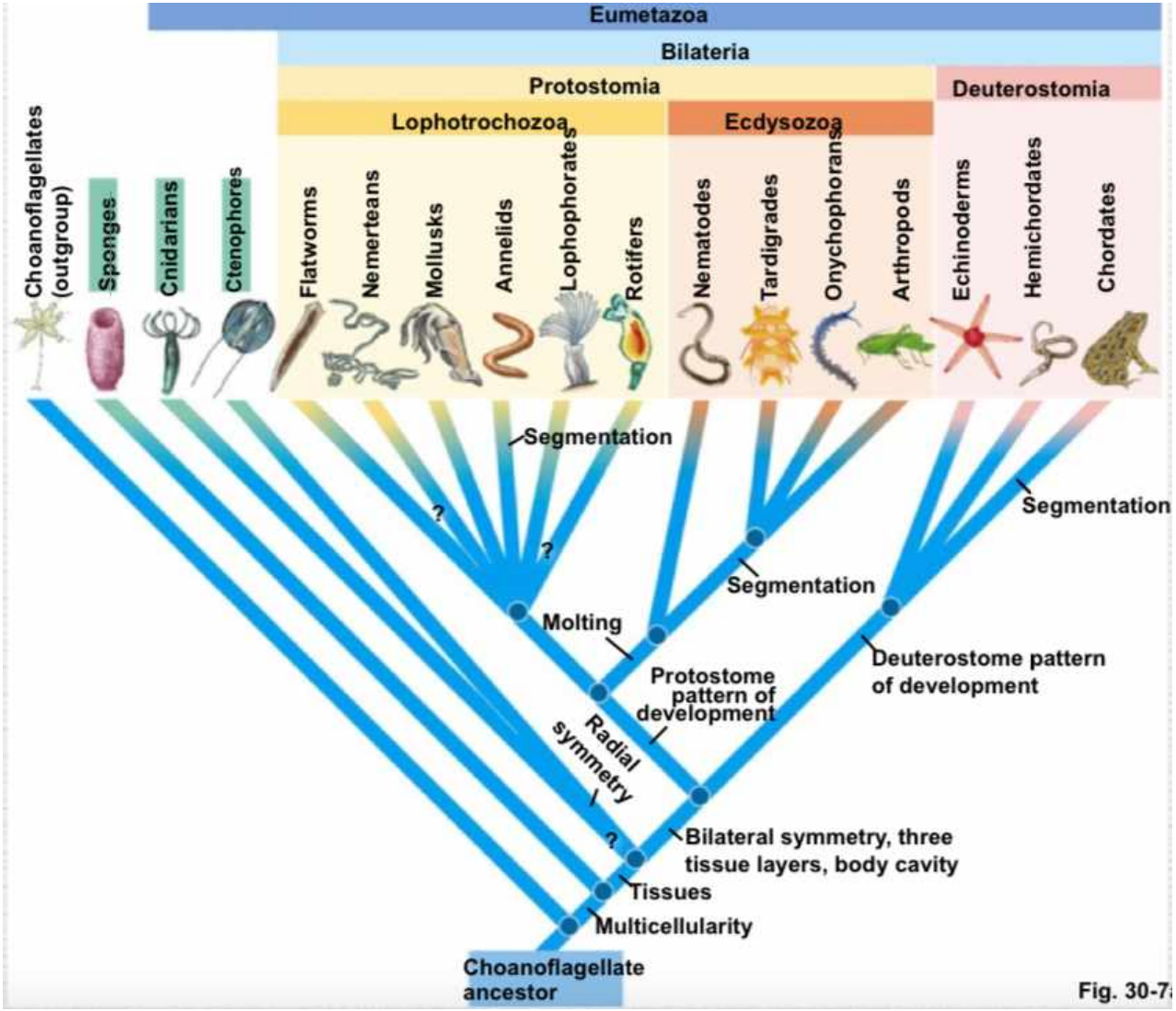
Workshop "*Flags, Landscapes, Signalling*"
IMSC Chennai, 17 May 2024

~100 million species

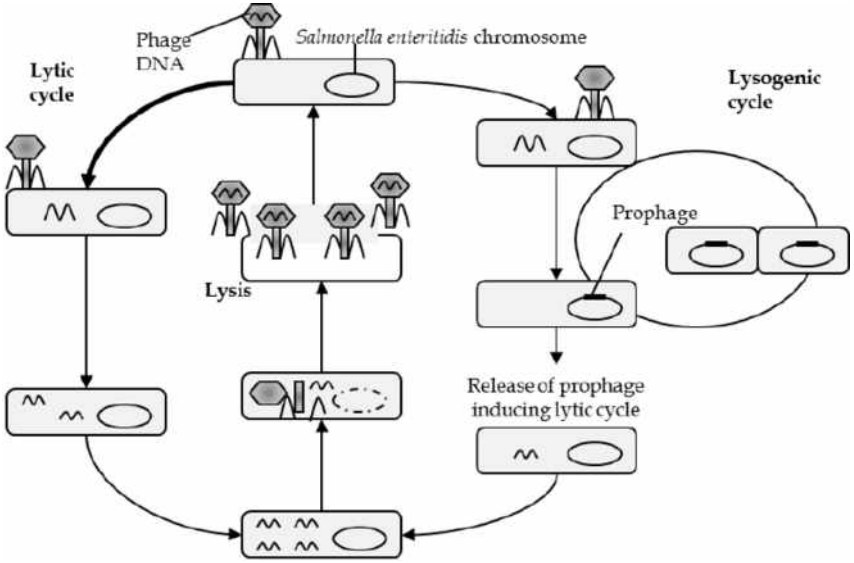
https://www.nationalgeographic.com/science/article/110824-earths-species-8-7-million-biology-planet-animals-science

~35 major animal body plans (phyla)

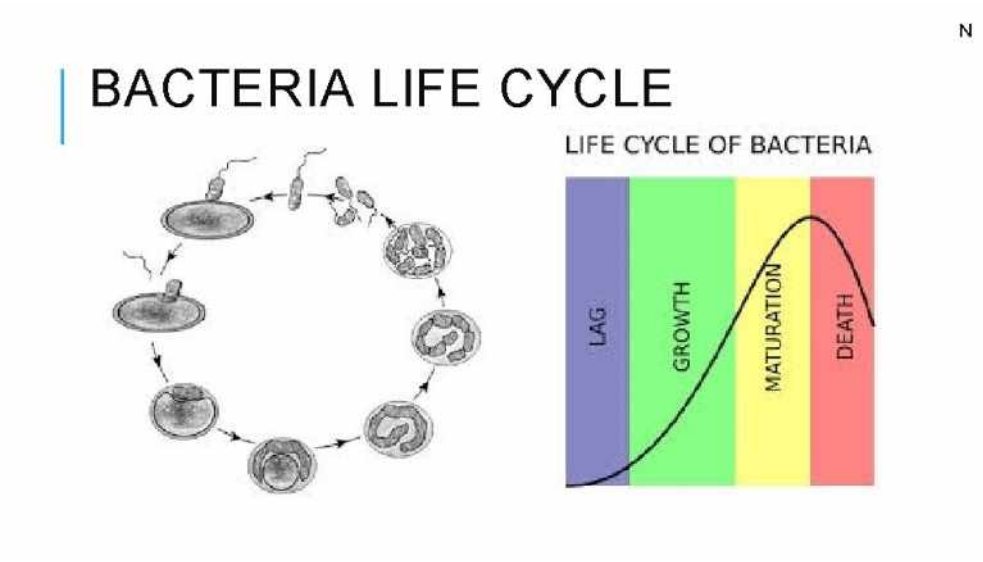


https://quizlet.com/284078930/phyla-list-the-12-phylum-diagram/

Living matter: life cycle (1)

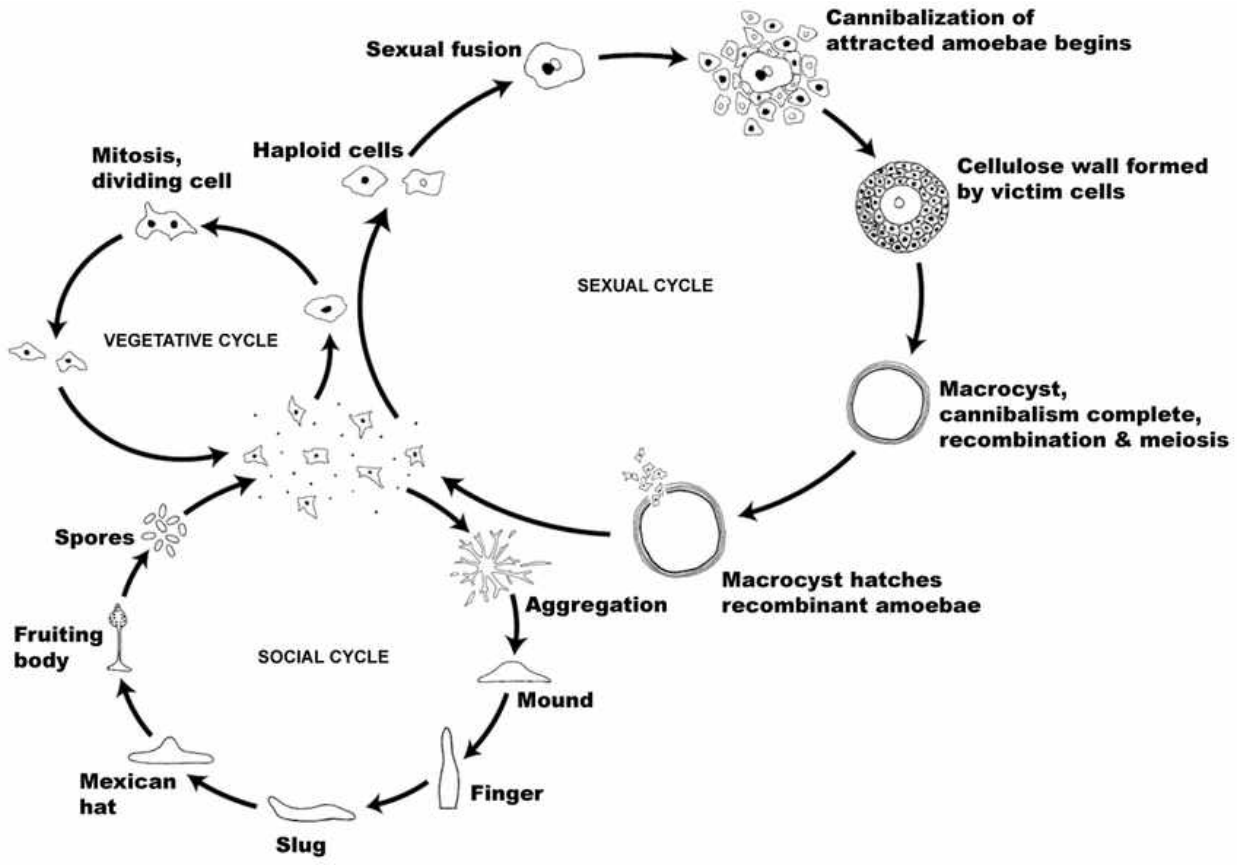


https://www.researchgate.net/figure/Life-Cycle-of-Bacteriophages-Bacteriophages-are-capable-of-entering-either-a-lytic_fig1_221928639



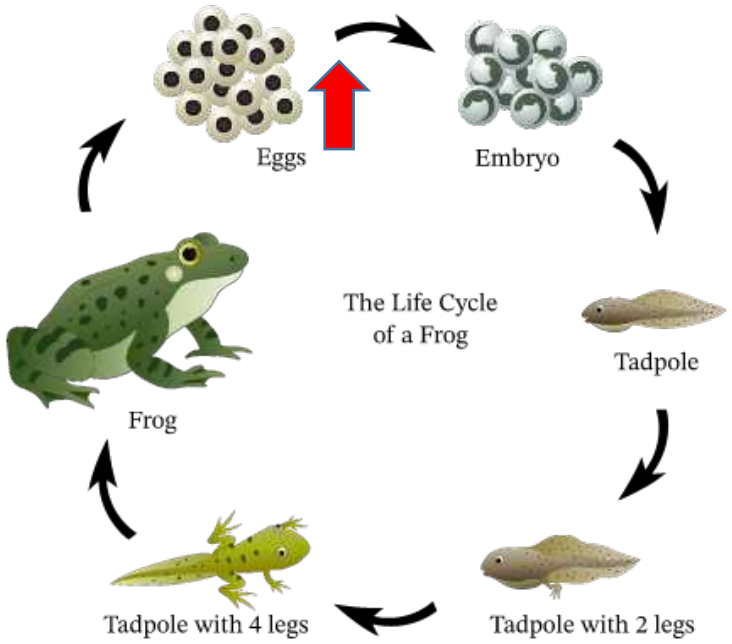
https://slidetodoc.com/bacteria-and-archaea-jess-alicia-natalia-j-three/

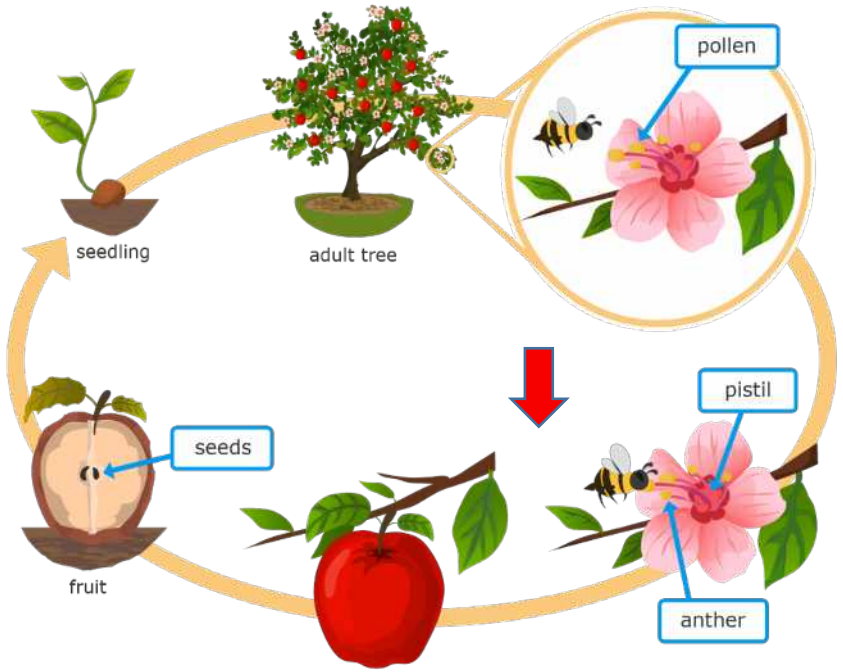
Living matter: life cycle (2)



https://www.researchgate.net/figure/The-life-cycle-of-Dictyostelium-discoideum-Most-of-its-life-this-haploid-social-amoeba_fig9_45114679

Living matter: life cycle (3)

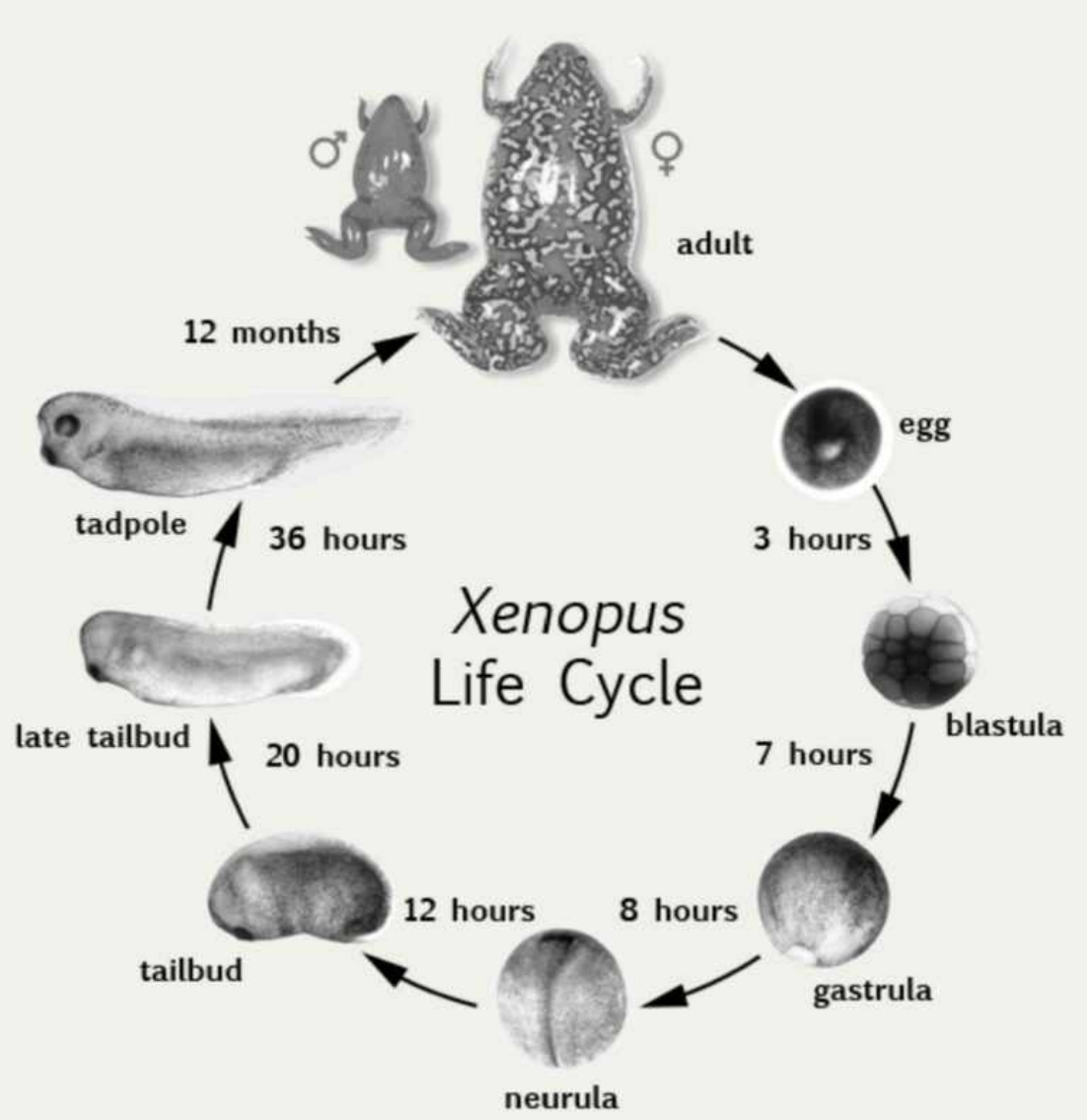




Red arrows➔ fertilisation

https://www.nagwa.com/en/worksheets/585198653583/; https://www.ixl.com/science/grade-6/flowering-plant-and-conifer-life-cycles;

Development = Life cycle

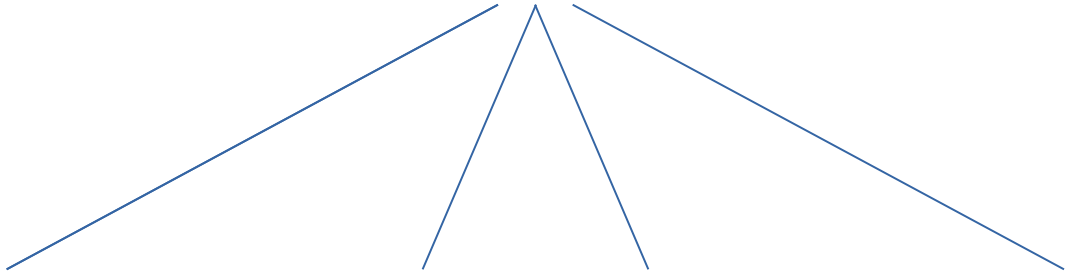


https://bionomous.ch/articles/automating_sorting_xenopus_oocytes_embryos/

Development = multicellular development?*

Spatial and temporal coordination between individual cells:
"clocks" and "maps"

What a cell does depends on



Its location *Past history* *Interactions* *Time*

*Ciliates as prominent counter-examples

Temporal regulation of development*

Nucleus:cytoplasm ratio
(frog, asynchrony and zygotic gene transcription)

No. of rounds of DNA replication
(ascidian, larval tail muscle AchE)

Cytoplasmic oscillator
(chick, somite formation)

*Not considered any further in this talk

Development and Evolution – often viewed as same thing over different time scales

Two threads in development: epigenesis (Aristotle, Harvey) and preformation (Bonnet, aphid), rough analogy to Lamarckian, env-driven evolution and present-day genetic view.

Comparing development and evolution

Similarities

Dramatic changes

Underpinned by laws of physics and chemistry

Gene-based inheritance

Importance of environment

Importance of chance – contingency and randomness

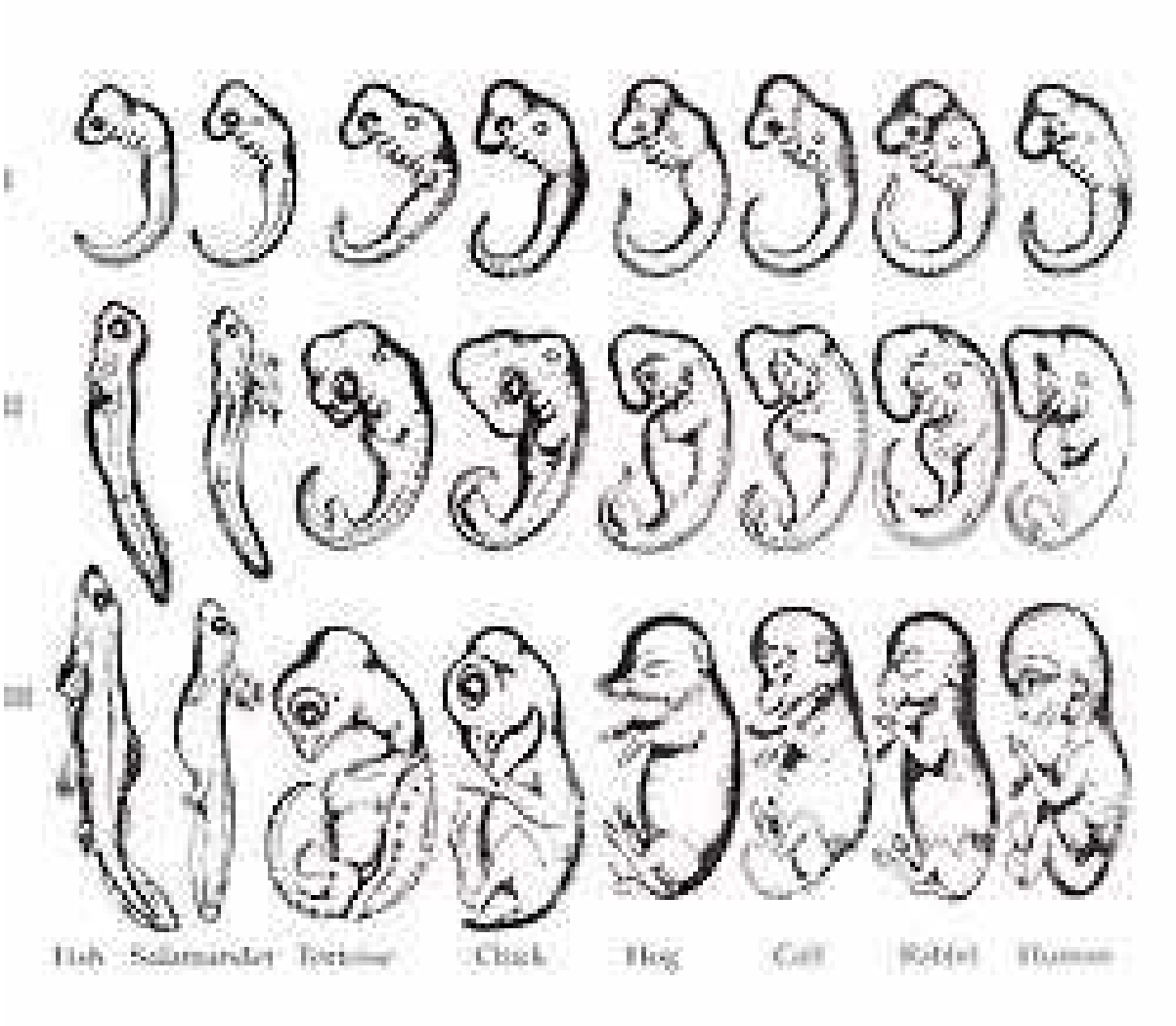
Dissimilarities

Vastly differing time scales

Genetics/Epigenetics

Repeated/Unique

Comparative embryonic development



Romanes's 1892 copy of Ernst Haeckel's controversial drawings;
https://en.wikipedia.org/wiki/Embryo_drawing

Darwin in *The Origin of Species* (1859)

Embryology rises greatly in interest, when we thus

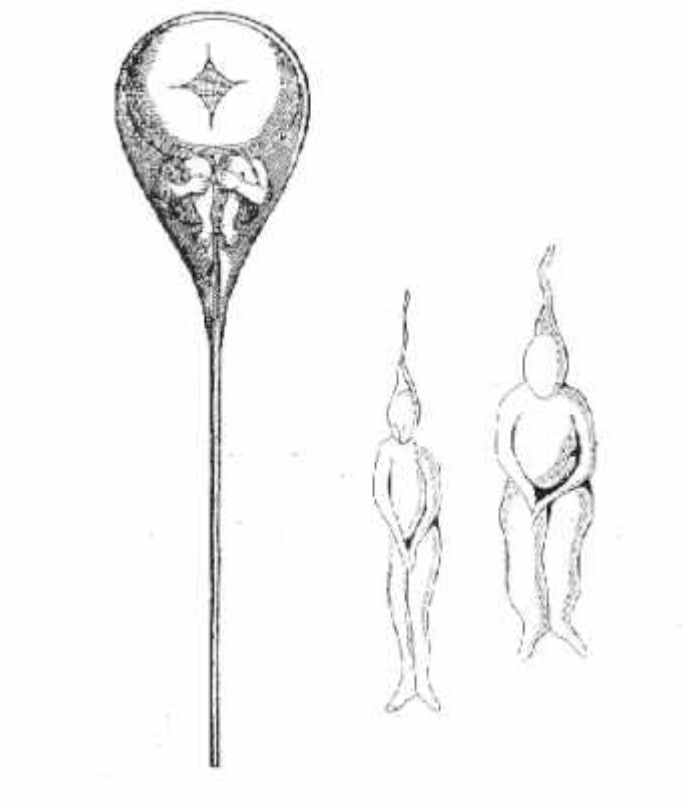
look at the embryo as a picture, more or less obscured,

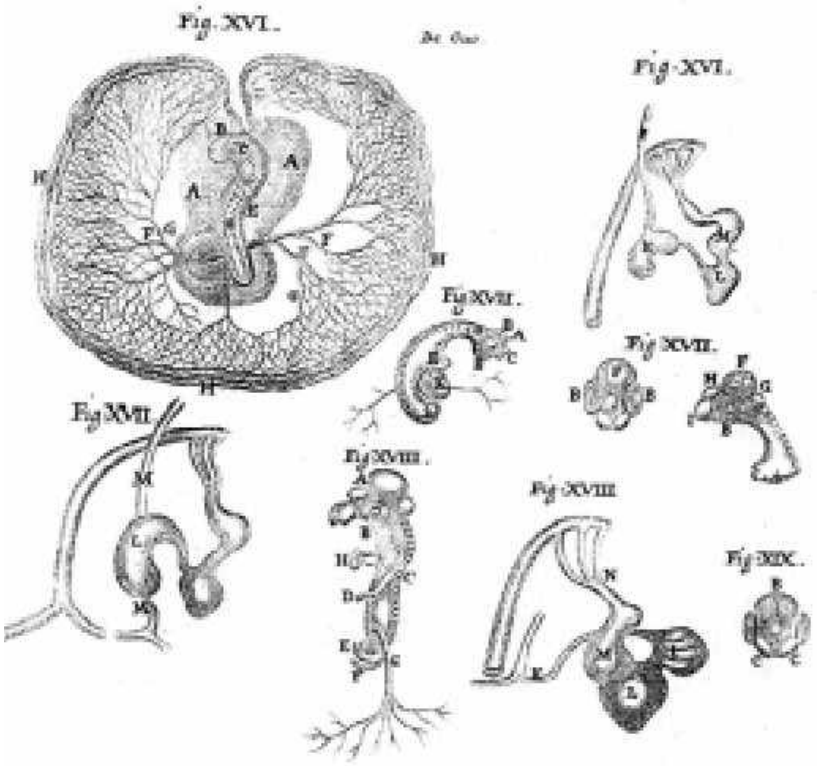
of the common parent-form of each great class of animals.

(Chapter 13)

Preformation and Epigenesis

Determinist/contingent (evolution), mosaic/regulative (development), genes/environment (both)





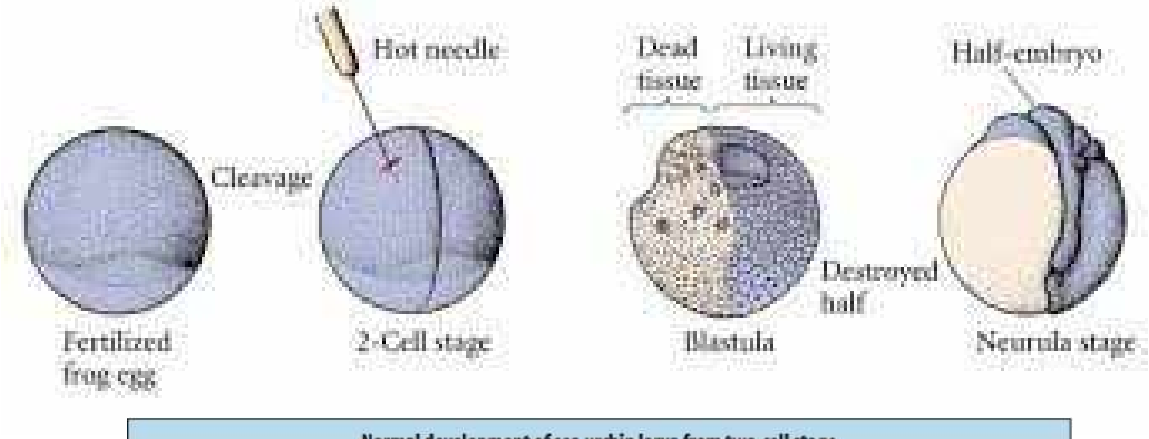
Nicolaas Hatsoeker, 1695

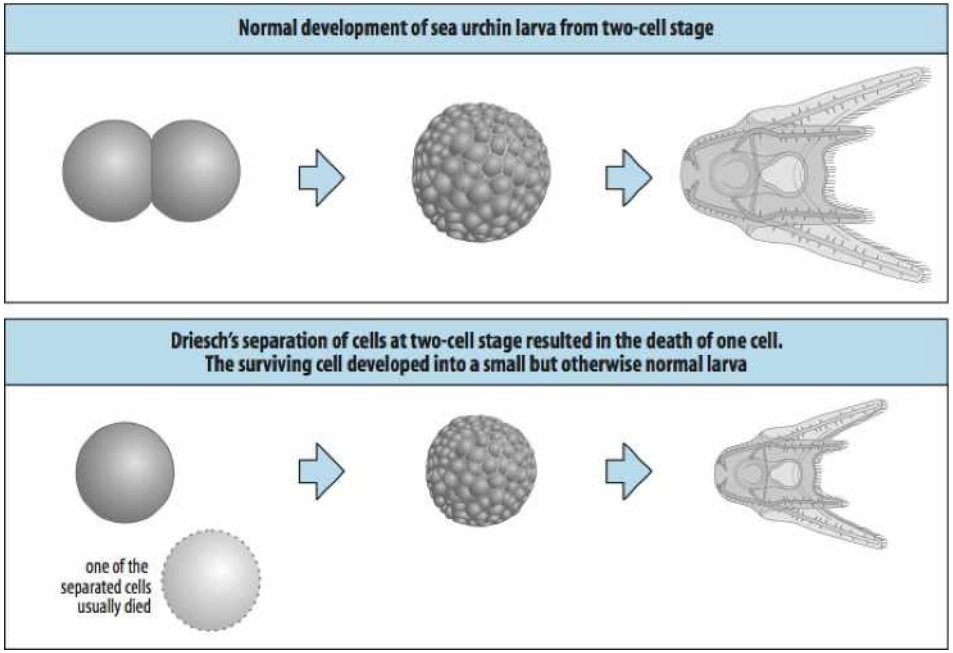
https://en.wikipedia.org/wiki/Preformationism#/media/File:Preformation.GIF;

Marcello Malphigi (1628-1694) drawing of chick development (https://www.researchgate.net/publication/12266336_The_rise_of_embryology_in_Italy_From_the_Renaissance_to_the_early_20th_century/figures).

Roux and Driesch: the fate of single blastomeres

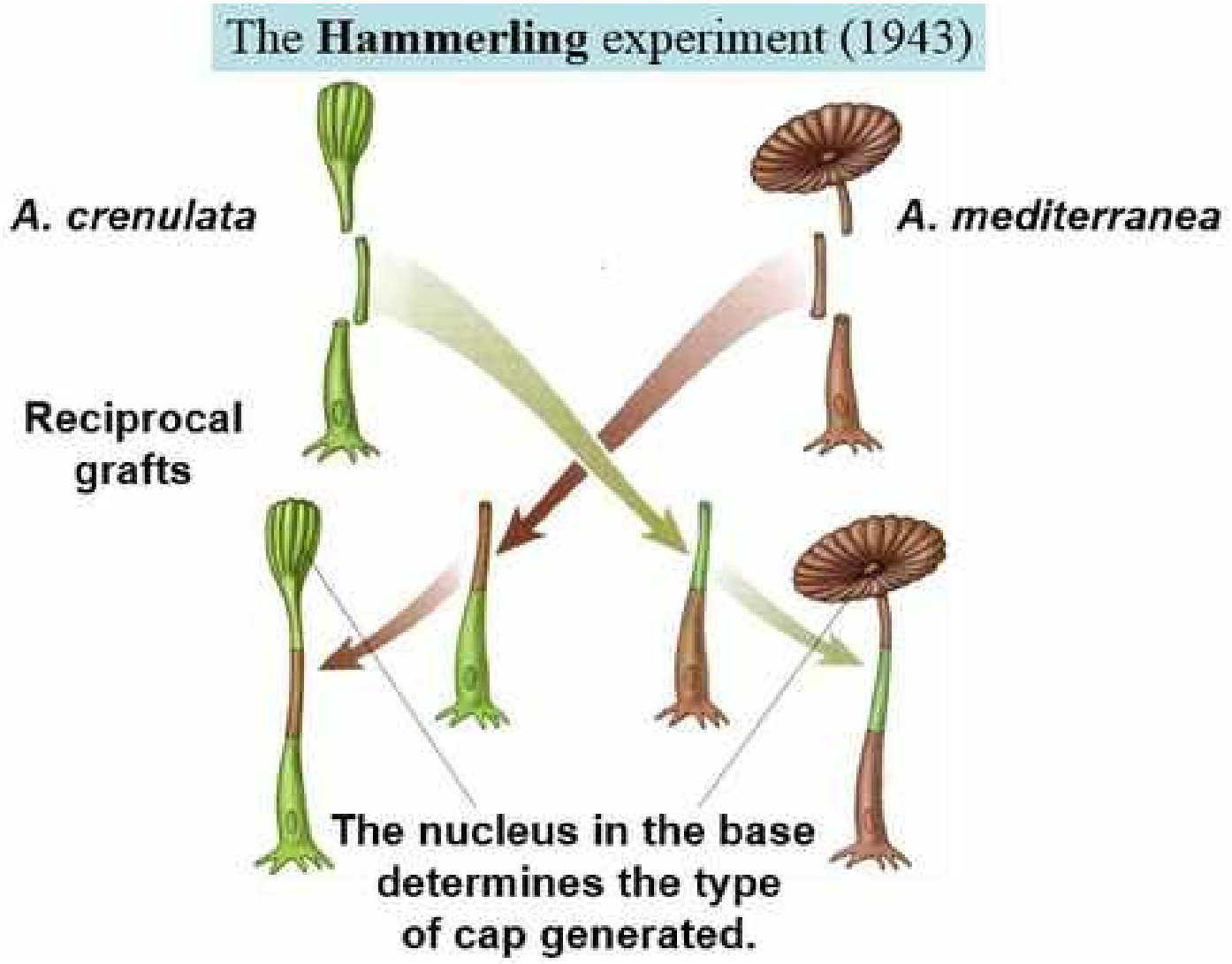
(preformation and epigenesis)





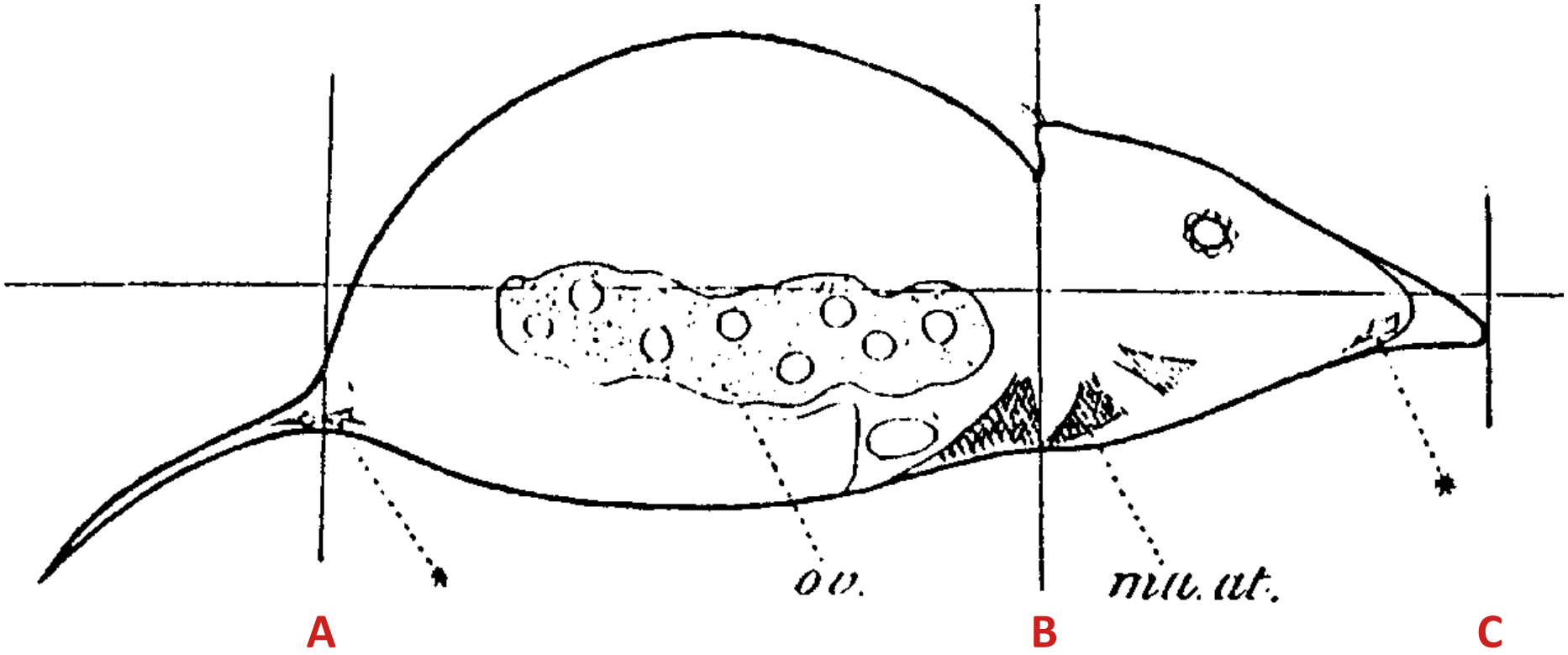
https://documen.site/download/experimental-embryology_pdf;
https://bastiani.biology.utah.edu/courses/3230/db%20lecture/Lectures/a2Concepts.html

Genes and pattern: Acetabularia cap



https://quizlet.com/39544971/genetics-dna-flash-cards/

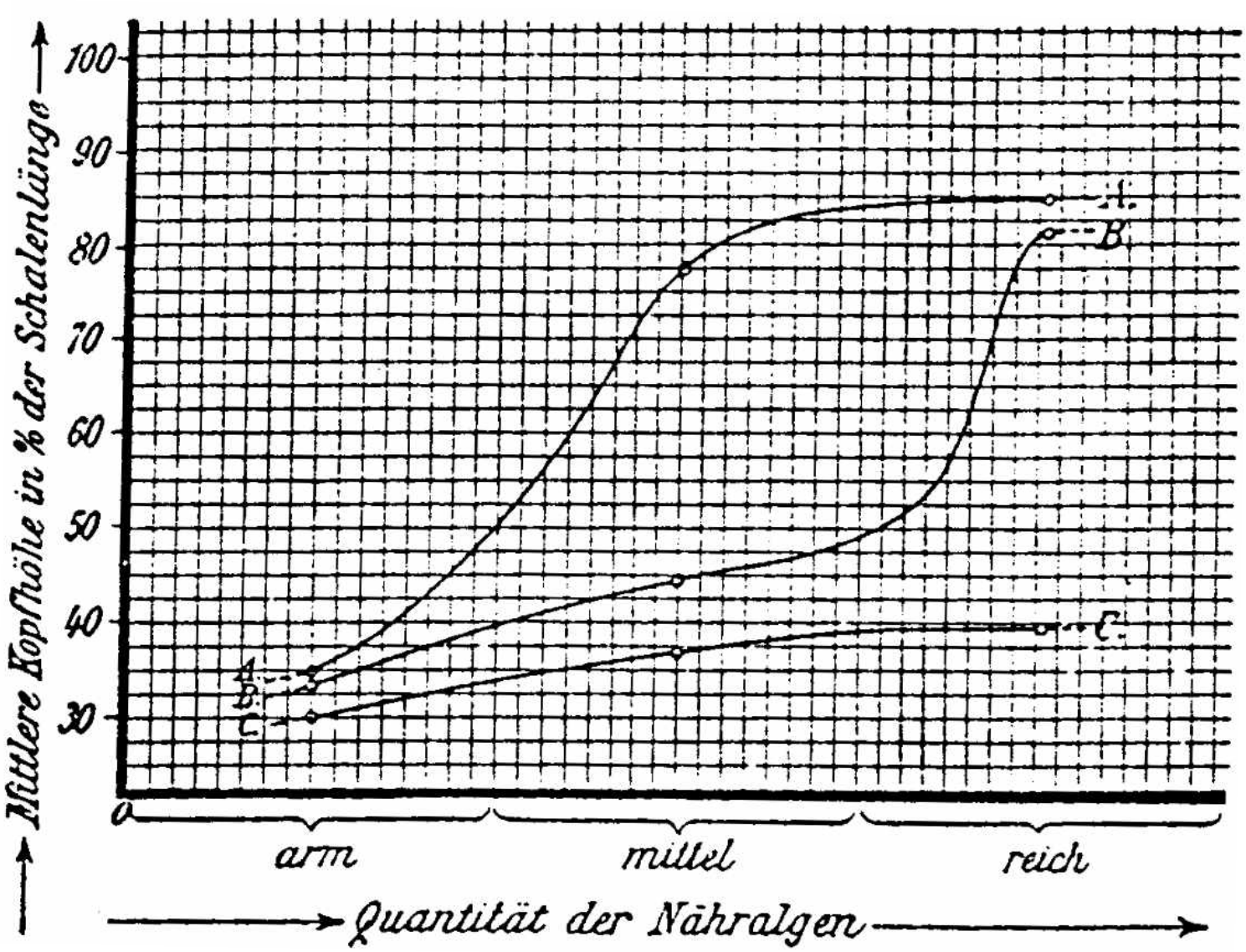
Woltereck: selection on environment-induced effect



(Fresh water crustacean *Hyalodaphnia*;
Phenotype BC/AC or 'relative head height' in %;
selective agent: nutrition)

Woltereck, 1909; see Sarkar, Biol Phil 14 (1999);
Nanjundiah (2020) https://doi.org/10.1016/B978-0-12-817996-3.00035-9

The reaction norm (Woltereck 1909)



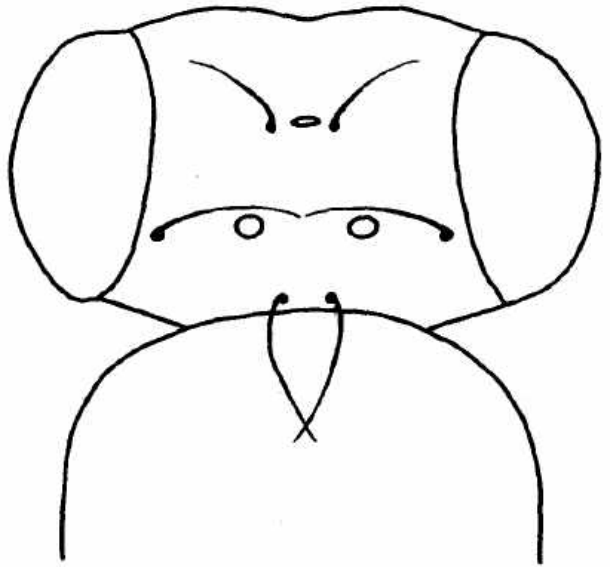
Curves not parallel: non-linear interaction of 'nature' and 'nurture'

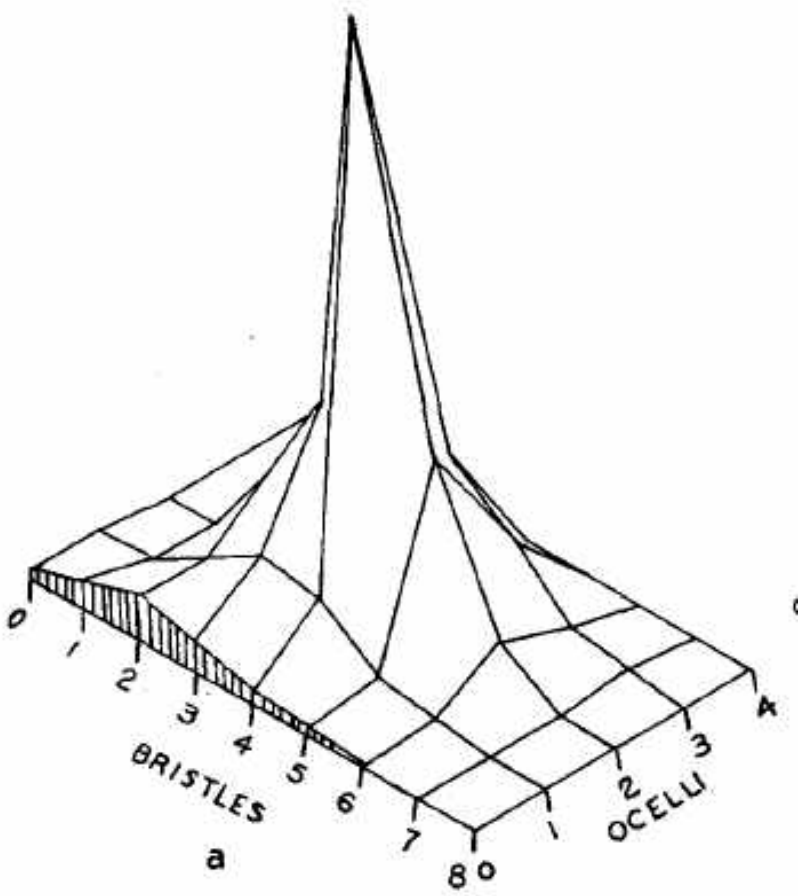
Natural selection stabilises the phenotype
(Schmalhausen, Waddington)

Selection can act on the mean as well as variance

Canalisation

Selection can canalise a novel phenotype





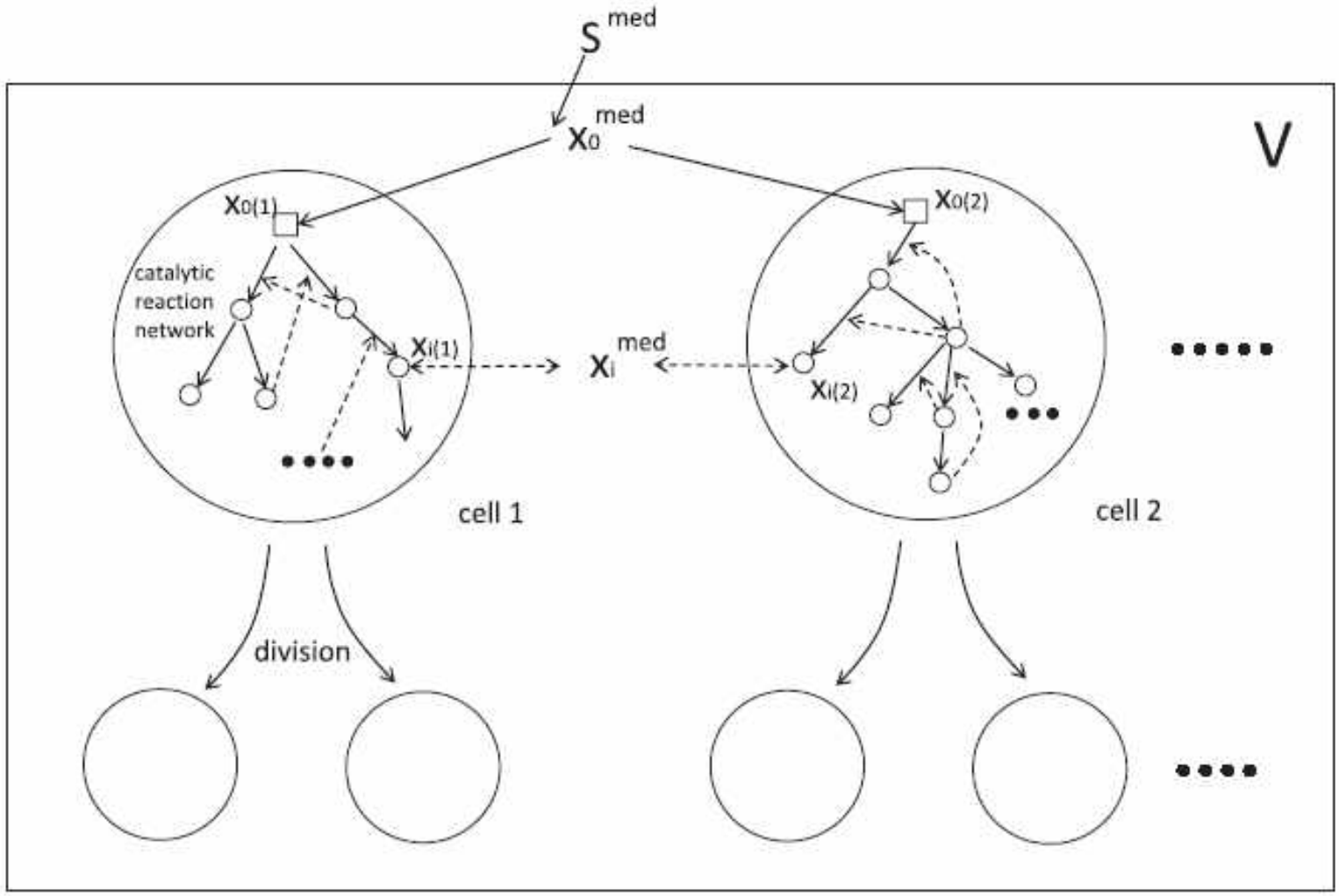
WT (3 ocelli, 6 bristles)

Selection for 2 posterior oc., 4 br.

(Does not work for asymmetry)

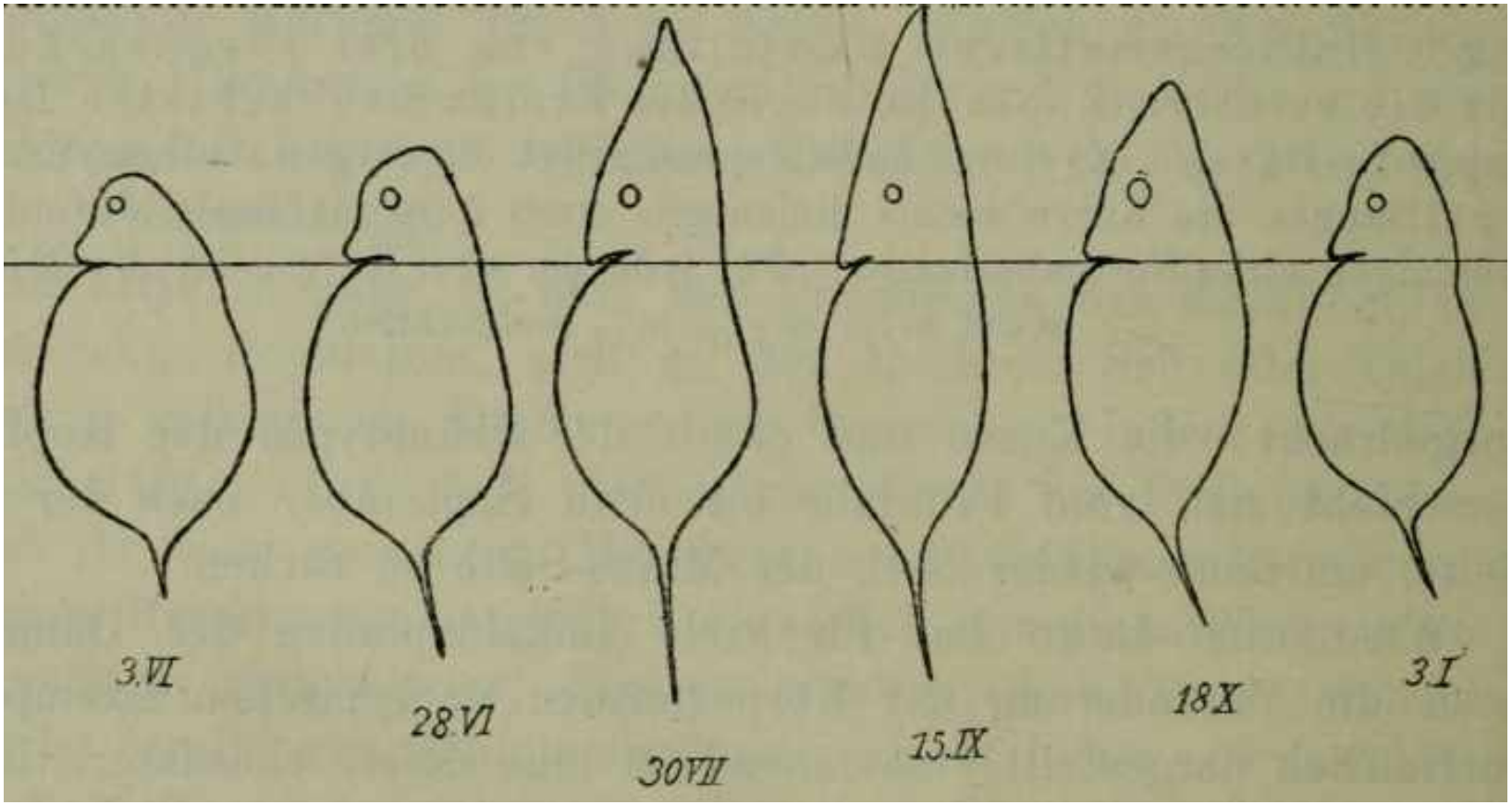
D. subobscura; J. Maynard Smith and K. C. Sondhi (1960) Genetics 45 (8): 1039–1050

Mutual dependence ➔ Co-existence



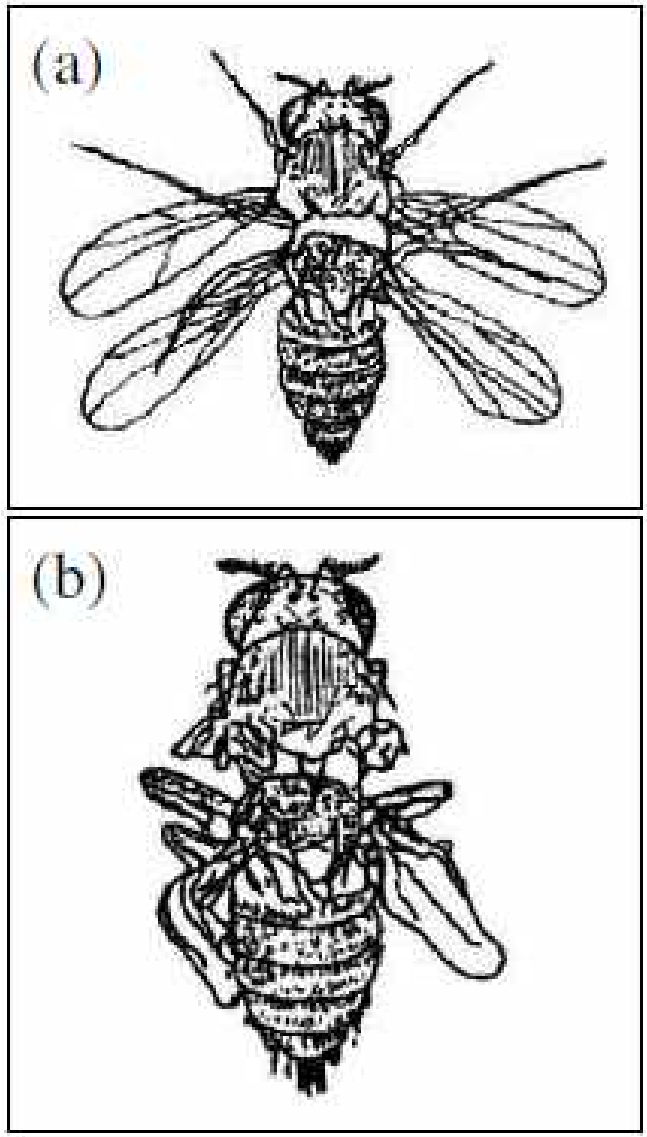
Annual range of Hyalodaphnia morphs

(assimilated morph similar, also to other species of Daphnia)



Woltereck, R.: 1909, 'Weitere experimentelle Untersuchungen über Artveränderung, speziel über das Wesen quantitativer Artunterschiede bei Daphnien', *Verhandlungen der deutschen zoologischen Gesellschaft* **19**, 110–173., p. 122

Genetic assimilation of four-winged phenotype

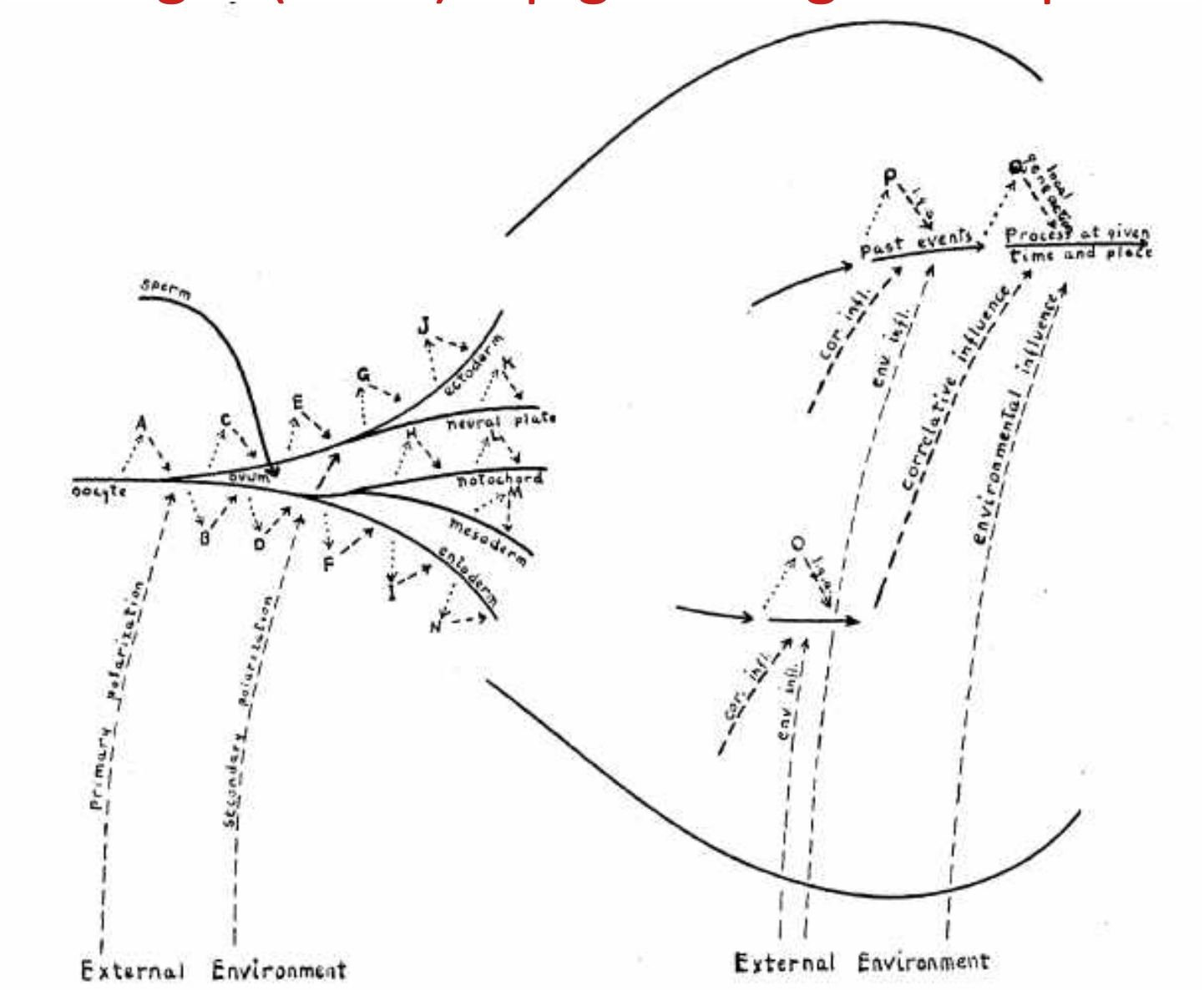


Ultrabithorax mutant

Four-winged fly
(halteres removed)

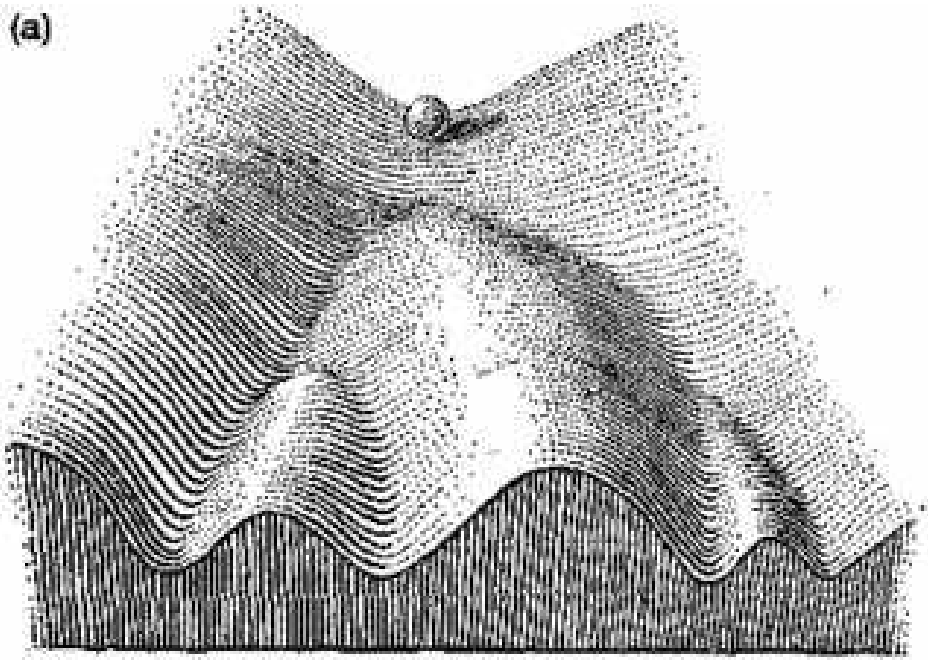
C H Waddington (1961). Genetic Assimilation, *Adv. Genet.*, 10: 257–293.

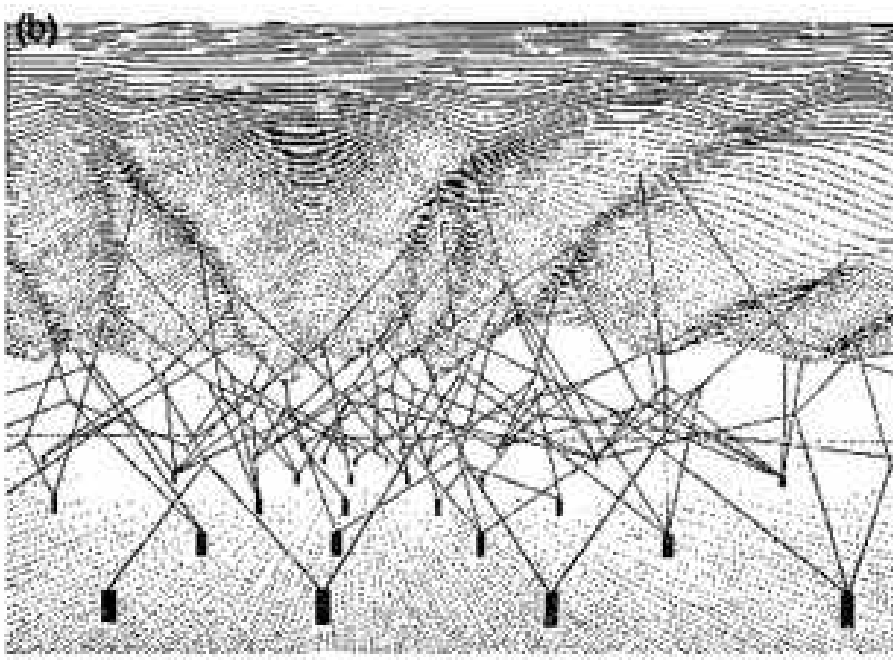
Wright (1934): Epigenetic genescape



Wright S, *Am. Natural,* Vol.68, pp.25–53, 1934.

C. H. Waddington (1939): Epigenetic landscape

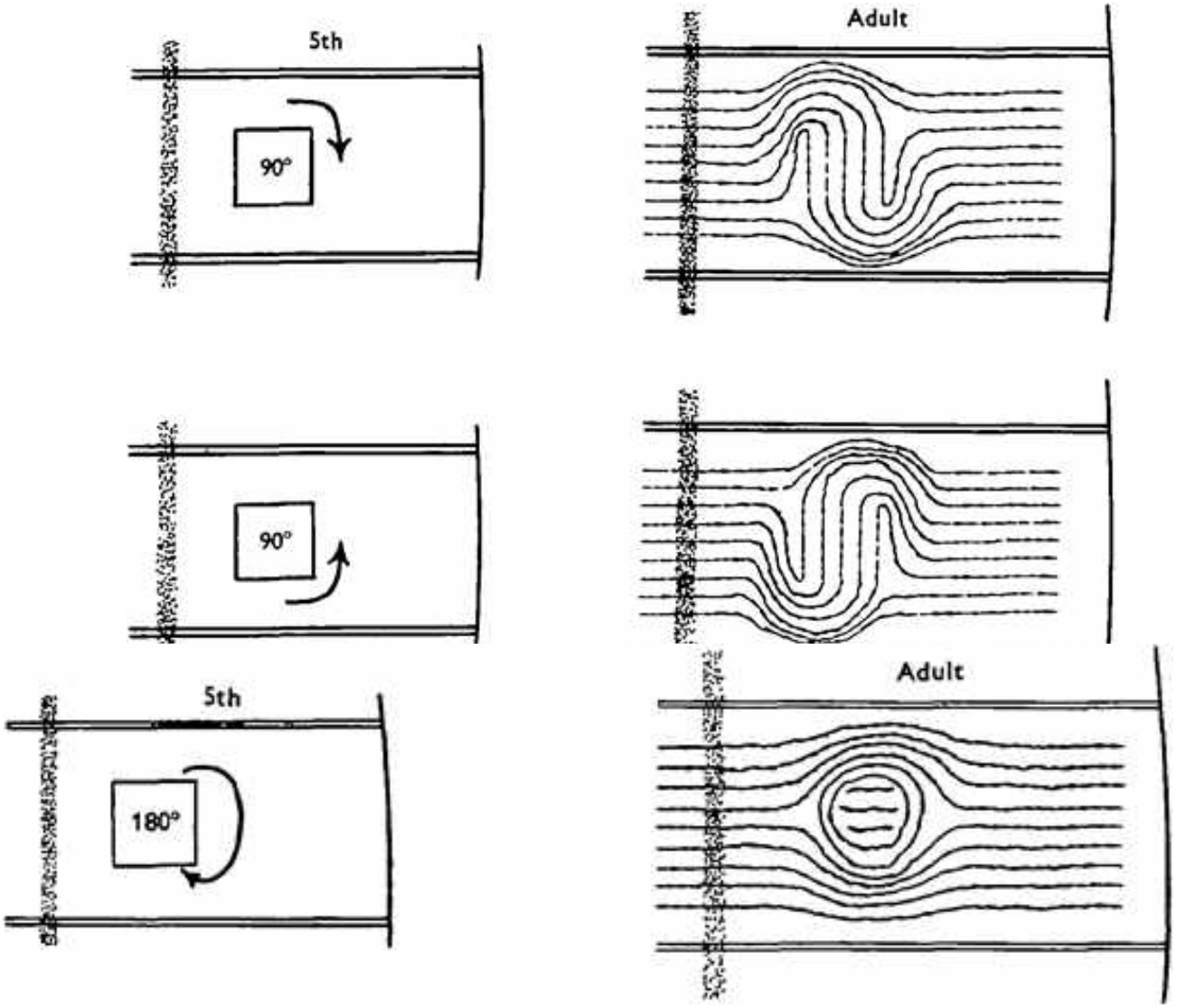




Waddington (1939) An Introduction to Modern Genetics; (1940) Organizers and Genes; (1957) The Strategy of the Genes

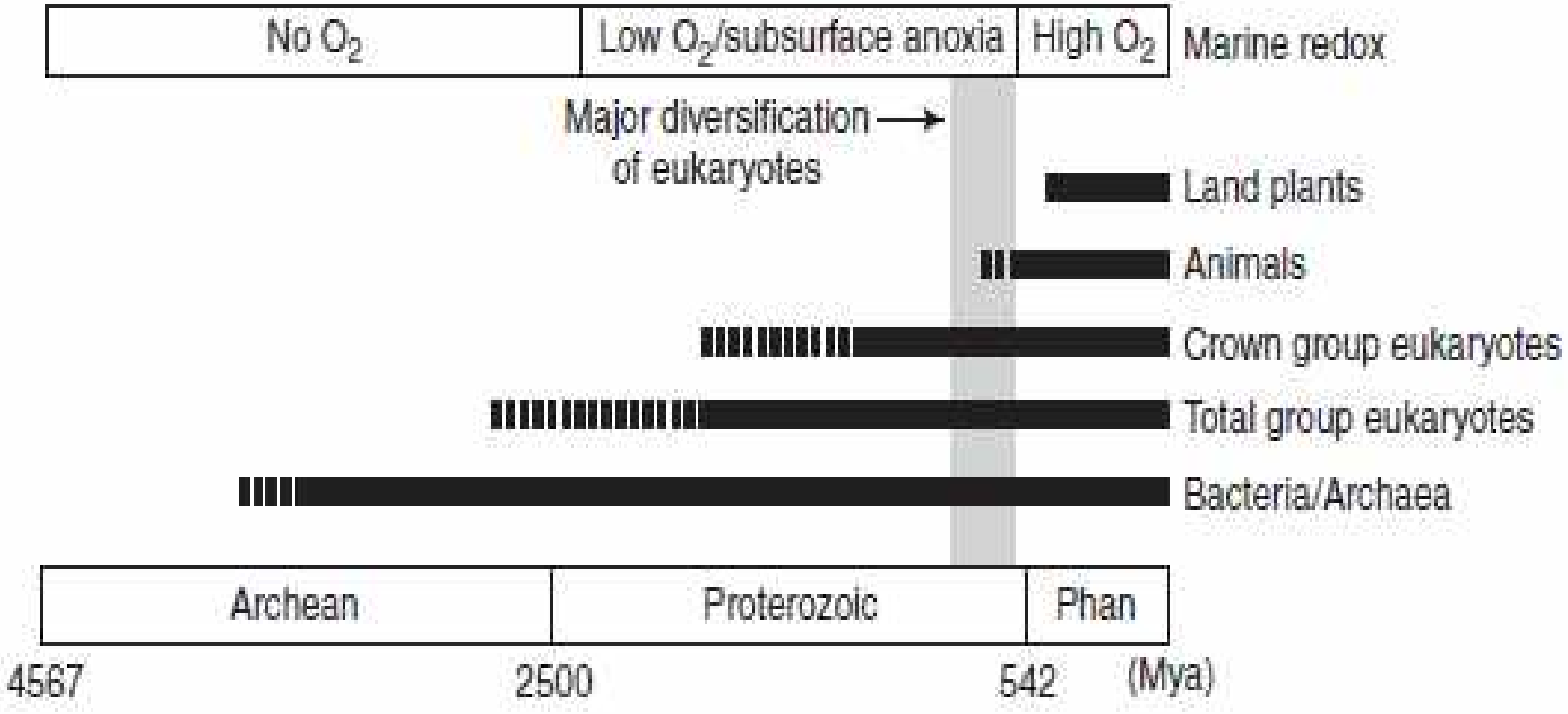
Graded variation

(gradient in Rhodnius cuticle)



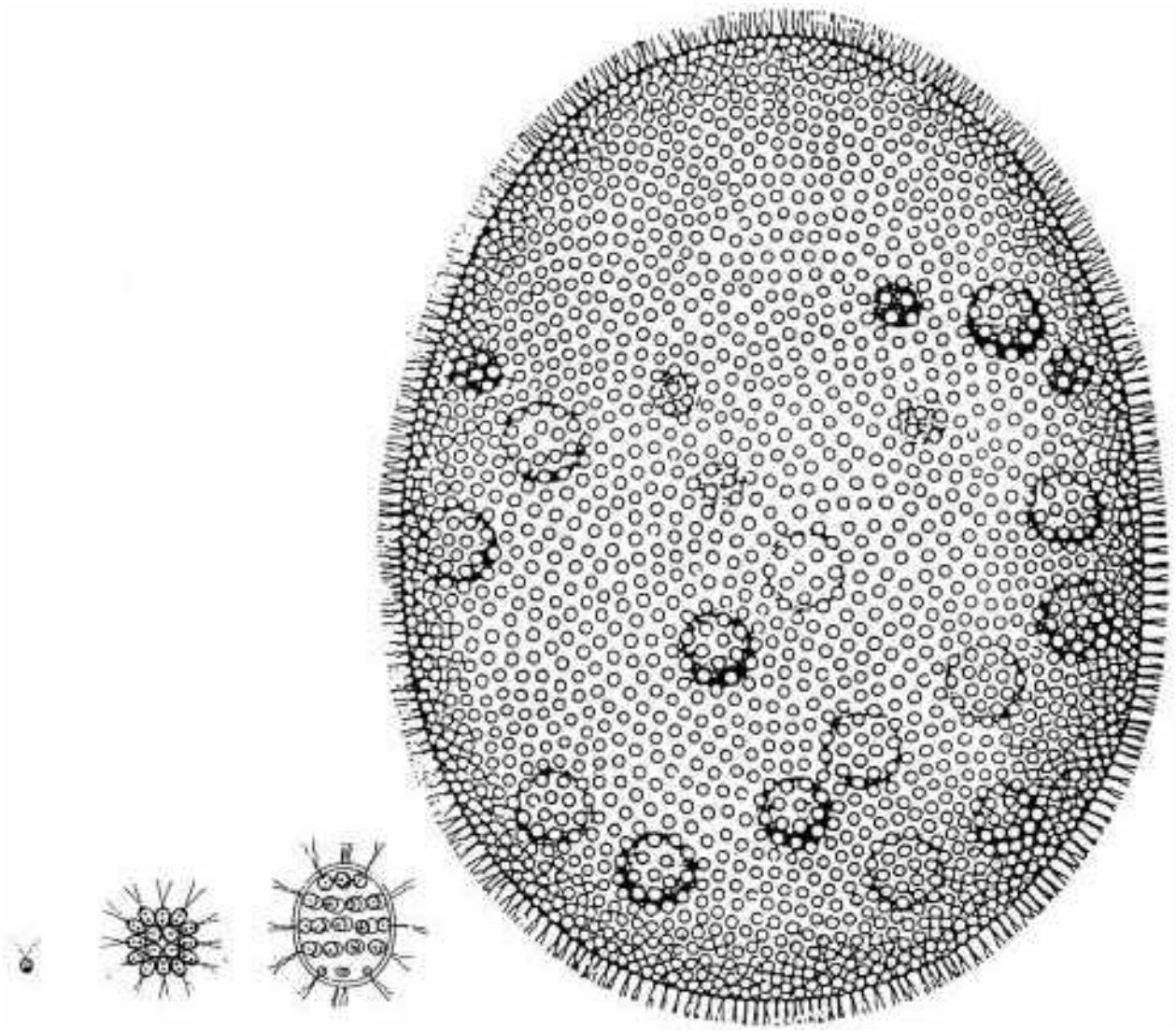
M. Locke (1959) J Exp Biol (1959) 36 (3): 459–477.

Origin of multicellularity



A. H. Knoll, "Paleobiological Perspectives on Early Eukaryotic Evolution" (Cold Spring Harbor Press 2014)

Chlamydomonas, Gonium, Pleodorina and Volvox



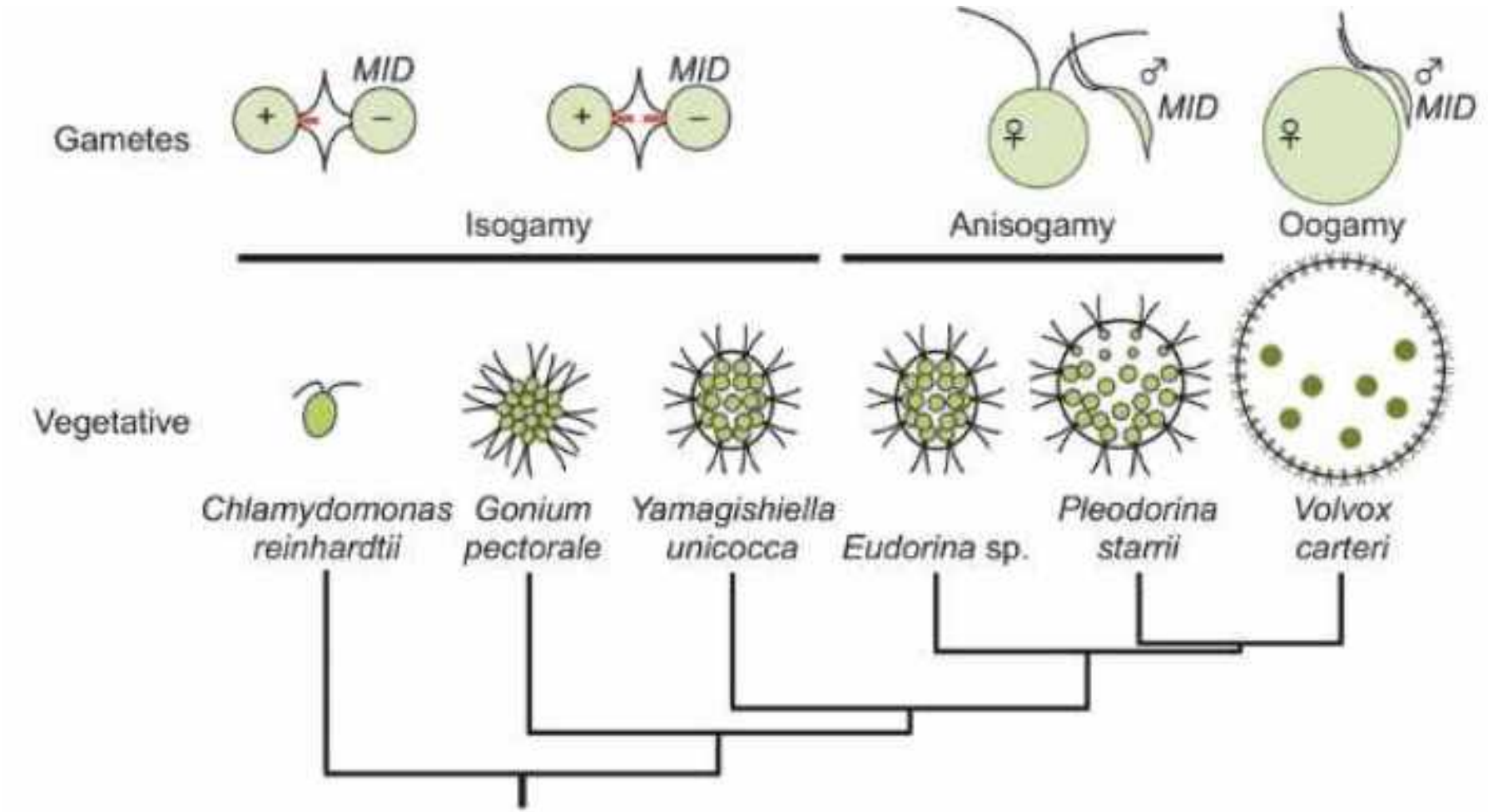
Bonner J Biosci 2003

Gonium (16 cells): All somatic→
All reproductive

Eudorina (16 or 32):
Small→ like Gonium;
Large→ 4 anterior somatic cells

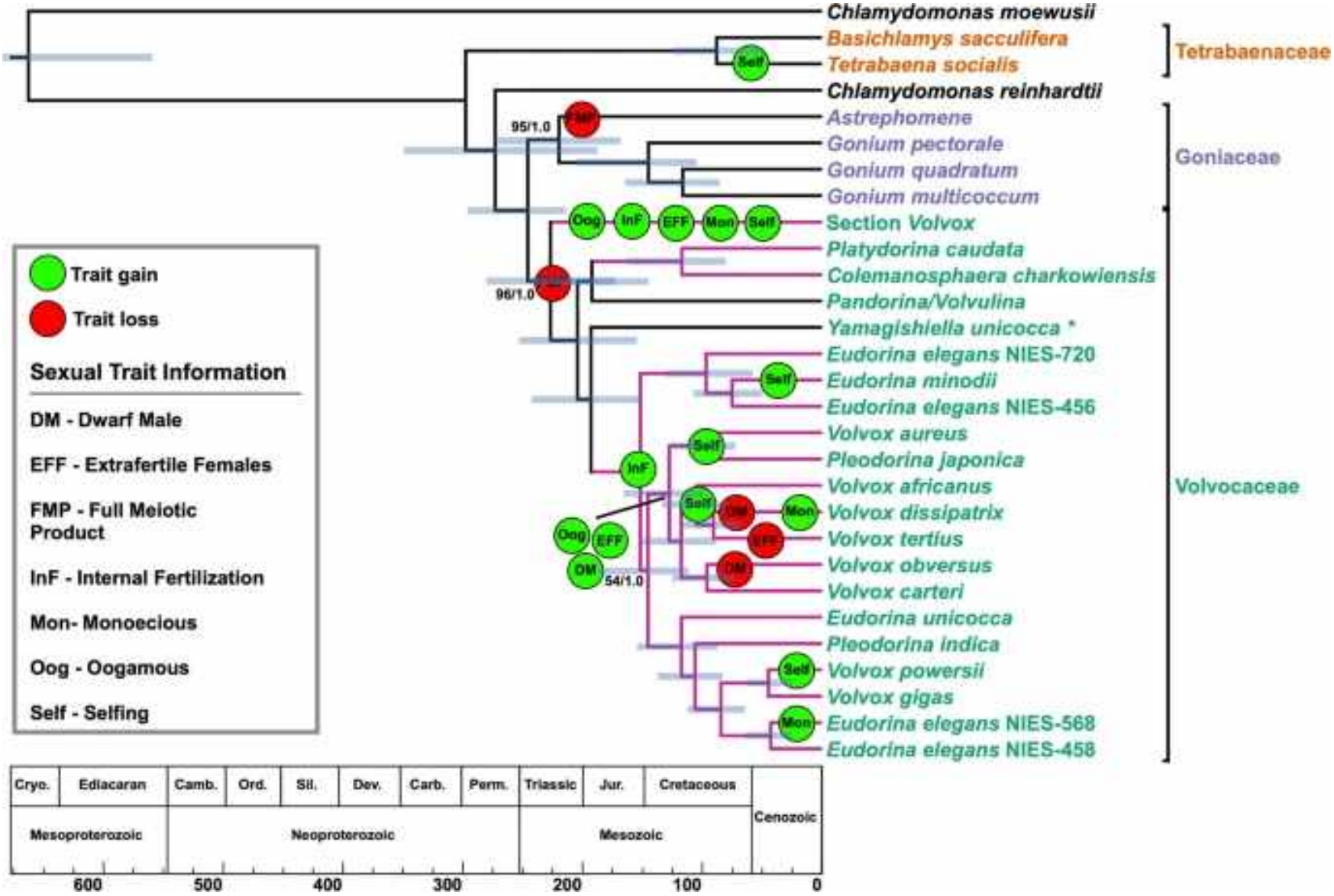
Pleodorina (~32 or more):
Permanent division of labour; soma:germ line increases with size

Hypothetical volvocine phylogeny: simple to complex



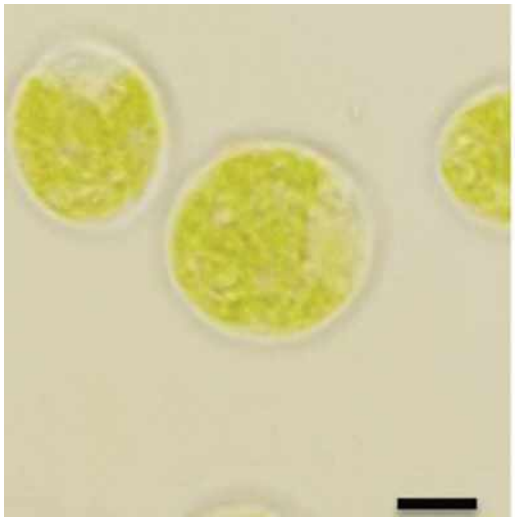
Hamaji et al. 2016 G3 Genes Genomes Genetics 6(5) DOI: 10.1534/g3.115.026229

Actual volvocine phylogeny falsifies hypothesis



Based on 263 nuclear genes; Lindsey et al. BMC Biol 22, 79 (2024)

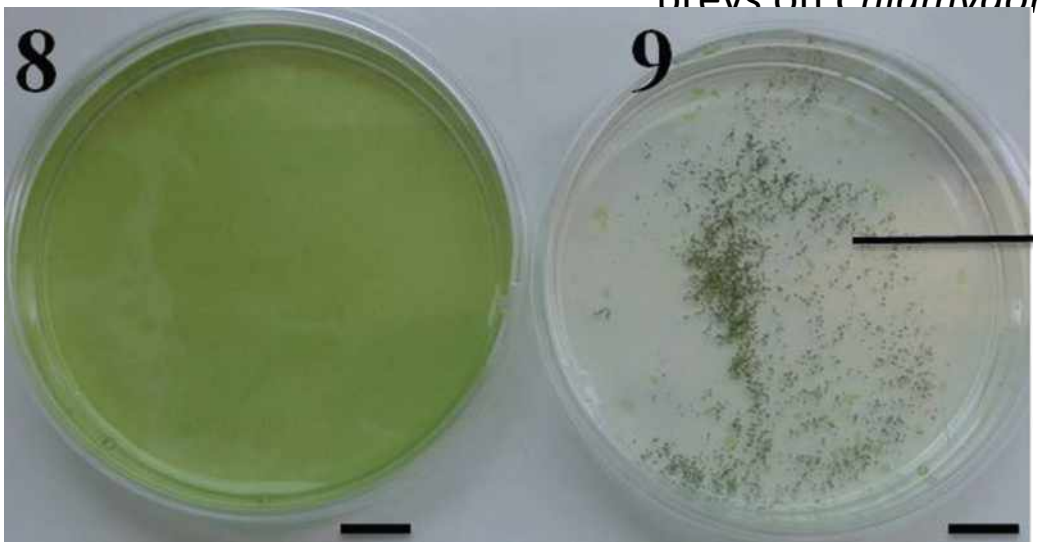
Chlamydomonas predation → chimaeric aggregates



C. reinhardtii

C. moewusii

Peranema (ciliate)
preys on *Chlamydomonas*

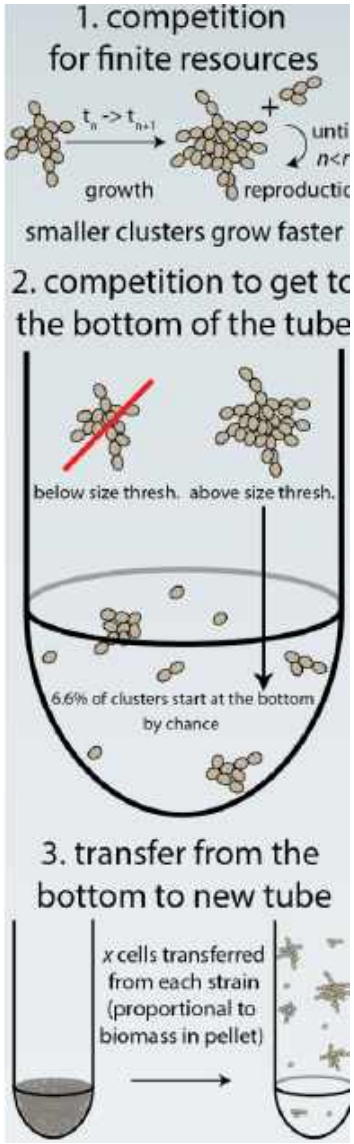


Single cells

Aggregates

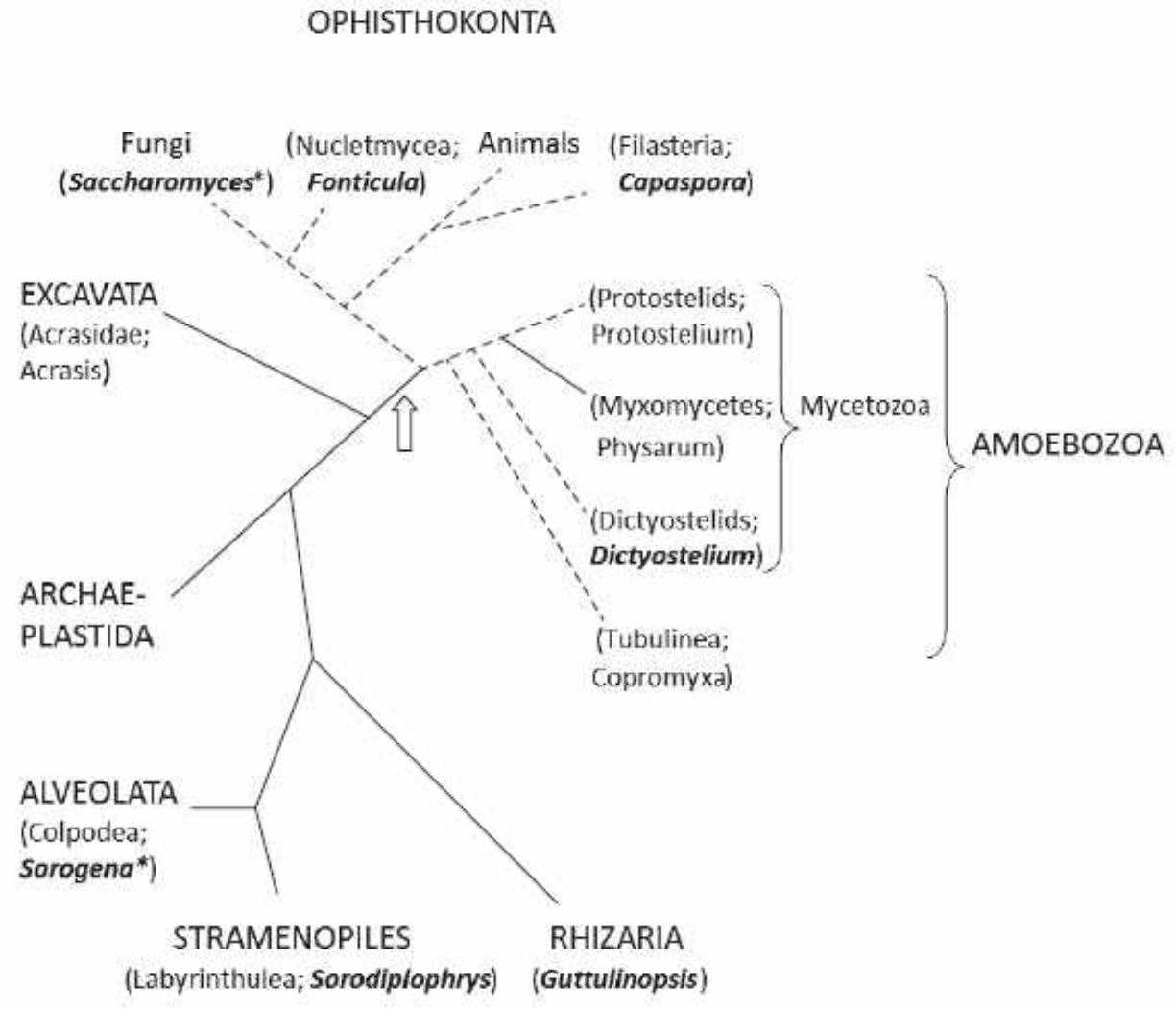
(Sathe & Durand, 2015)

Synthetic multicellularity in yeast



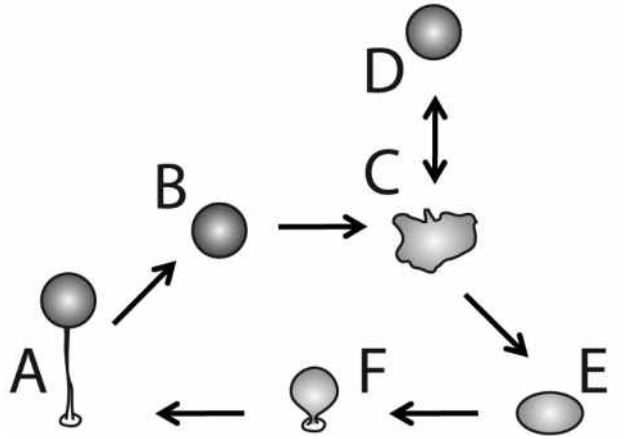
Ratcliff, in “Multicellularity” (Niklas and Newman, eds., MIT Press 2016)

Independent origins of aggregative multicellularity

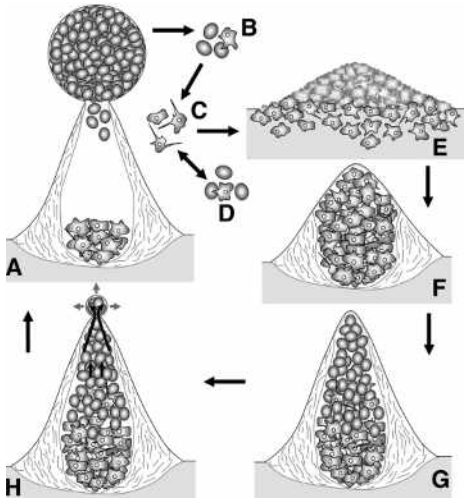


(All amoeboid except Sorogena, which is a ciliate; after Brown and Silberman, 2012)

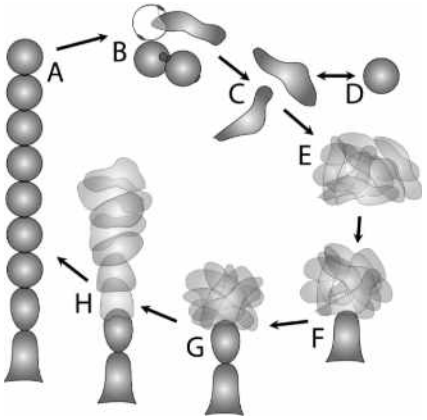
Preadaptations + Self-organisation→ Multicellularity



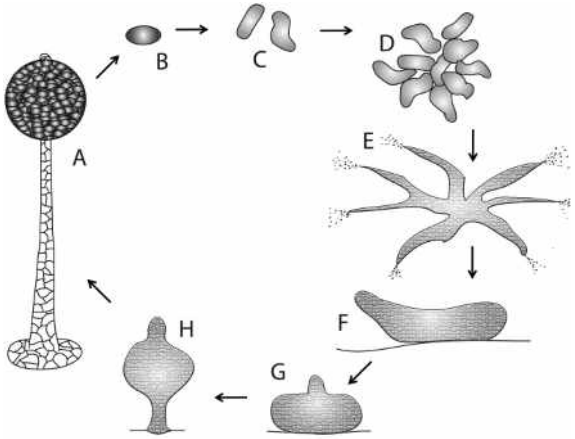
Protostelium (Amoebozoa)



Fonticula (Opisthokonta)



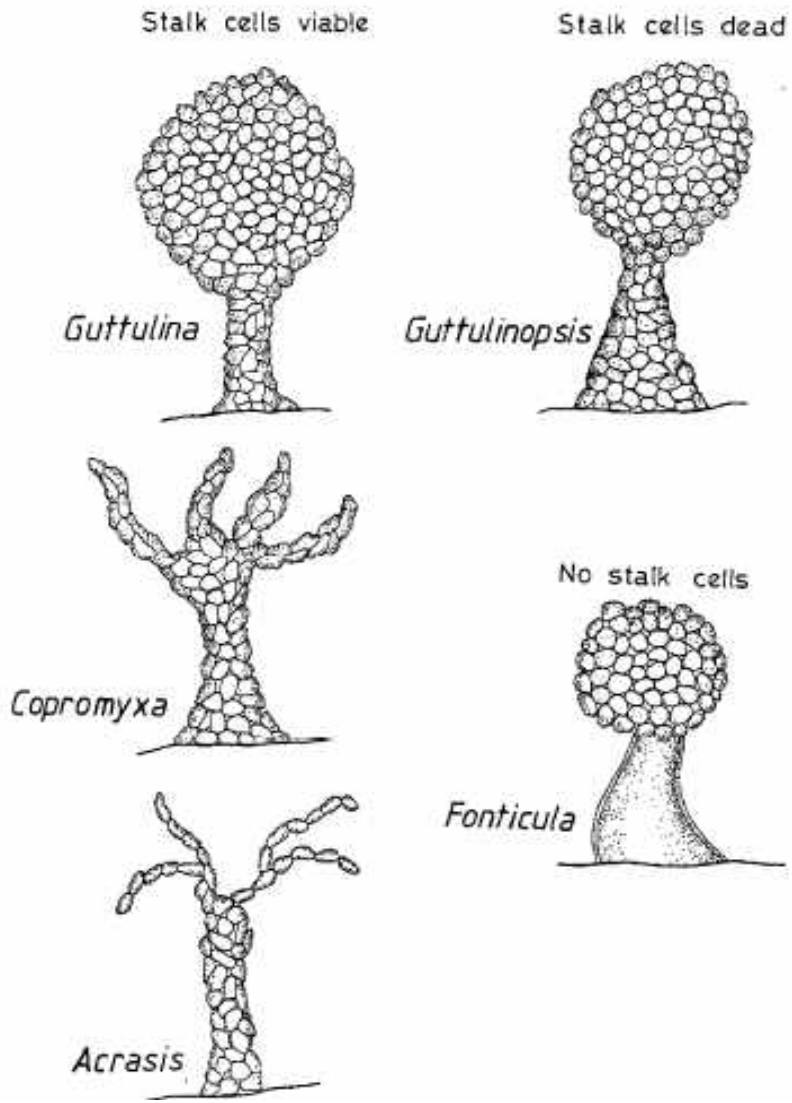
Acrasis (Excavata)



Dictyostelium (Amoebozoa)

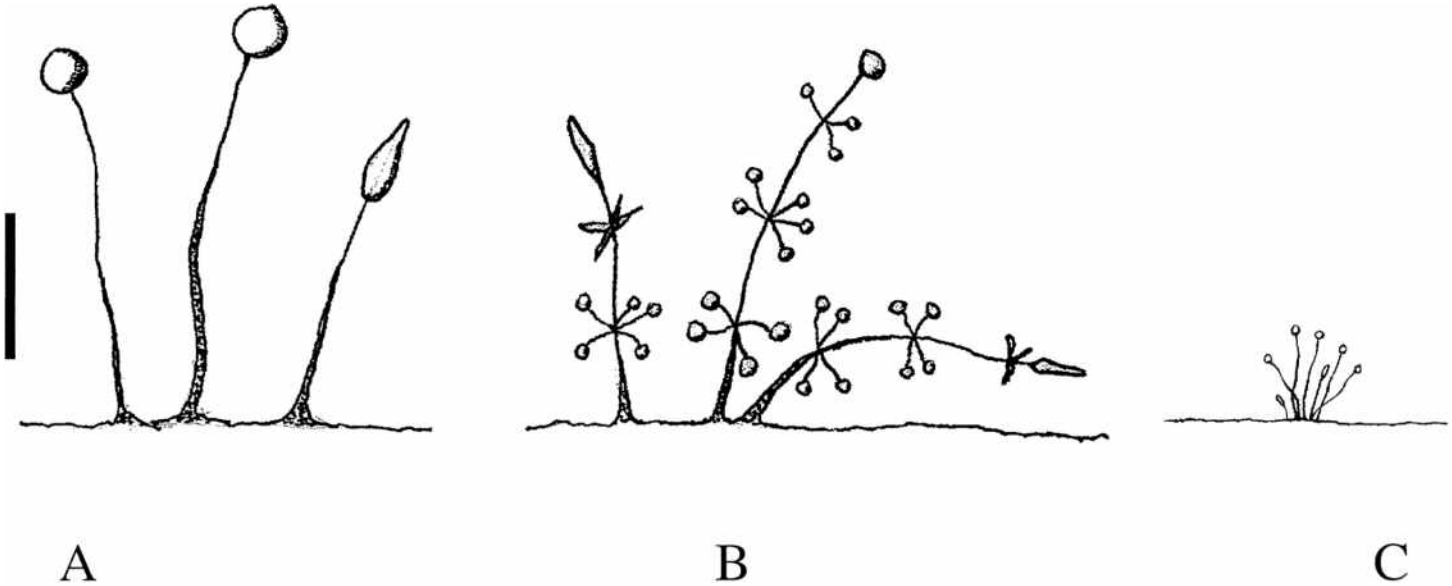
Brown, 2010, PhD thesis, University of Arkansas

Convergent evolution of aggregative multicellularity



(Bonner, 'The cellular slime molds', 1967; https://www.researchgate.net/figure)

Facultative terminal morphologies



Dictyostelium*
(cellular stalk)

Polysphondylium
(cellular stalk + branching)

Acytostelium*
(acellular stalk)

Swanson; http://faculty.scf.edu/swansoa/aboutme.htm

(Polyphyletic distribution; * *D. lacteum*: like A when many cells, like C when few cells)

‘Developmentally essential’ or ‘Multicellularity’ genes?

385 DEGs (absence → no development; growth unaffected):
80% in unicellular relatives
72% in non-Amoebozoan species
37 not shared by all four CSMs

186 MGs (upregulated 3x, manipulation→ aberrant development):
33 lack orthologue in at least one of other three CSMs
20 lack orthologue in all three
50% of ~2400 3x upregulated genes in all species lack orthologue in any of remaining three

Schilde et al. 2016, Gloeckner et al. 2016

Protein-coding genes in D. *discoideum*

Beta integrin, retinoblastoma, Wnt, STAT, beta catenin, presenilin, Src homology domain proteins, homeobox genes

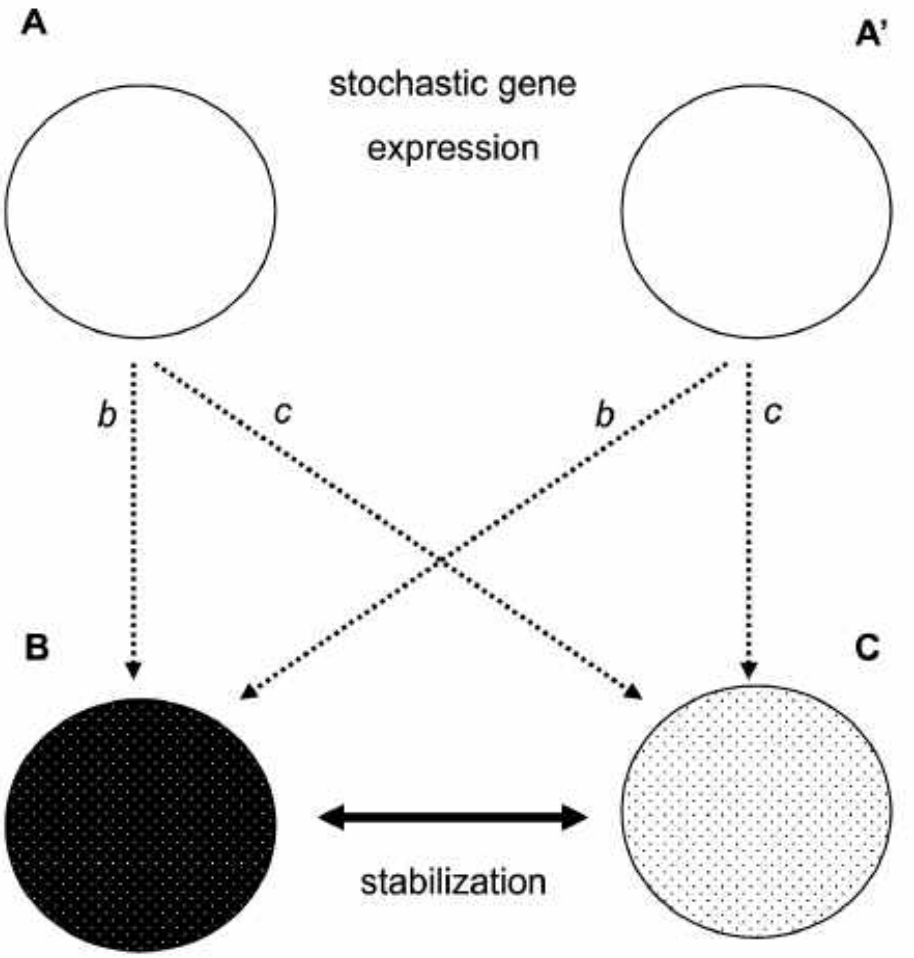
Also, gene regulation by non-coding RNAs

What is the wild type in *D. discoideum*?

Strain	Origin	Gross developmental phenotype	Extracellular phosphodiesterase activity
NC4	Decomposing forest leaf (Raper 1984)	Wild type	Plates: peaks during aggregation Suspension: peaks before starvation, much lower at aggregation phase
V-12	Forest leaf litter (Raper 1984)	Wild type	–
M1	Subclone of V-12	Normal (i.e., like wild-type).	Plates: negligible during aggregation Suspension: peaks before starvation, much lower at aggregation phase
M2	Subclone of V-12	Normal	Suspension: peaks before starvation, much lower at aggregation phase
Ax2	Spontaneous axenic mutant, isolated from NC4 in two steps	Normal	Suspension: peaks before starvation, much lower at aggregation phase
aggr50-3 (rev)	Spontaneous revertant of nonaggregating, mutant aggr50 (parent V-12)	Aggregates normally	Suspension: peaks before starvation, much lower at aggregation phase
ga86 and ga88	Independently derived UV-induced mutants of V-12	Very large aggregation territories	Suspension: enzyme activity barely detectable

VN, J Exp Zool (Mol Dev Evol). 2019;1–10.

Selection-stabilization model of differentiation:
Noise followed by competition ('biased random walk')



Kupiec, J-J (2014). Cell differentiation is a stochastic process subjected to natural selection. (Towards a Theory of Development, pp. 155-173)

Stochastic differentiation: haematopoietic stem cells

...gradually acquire lineage characteristics along multiple directions without passing through discrete hierarchically organized and demarcated progenitor populations

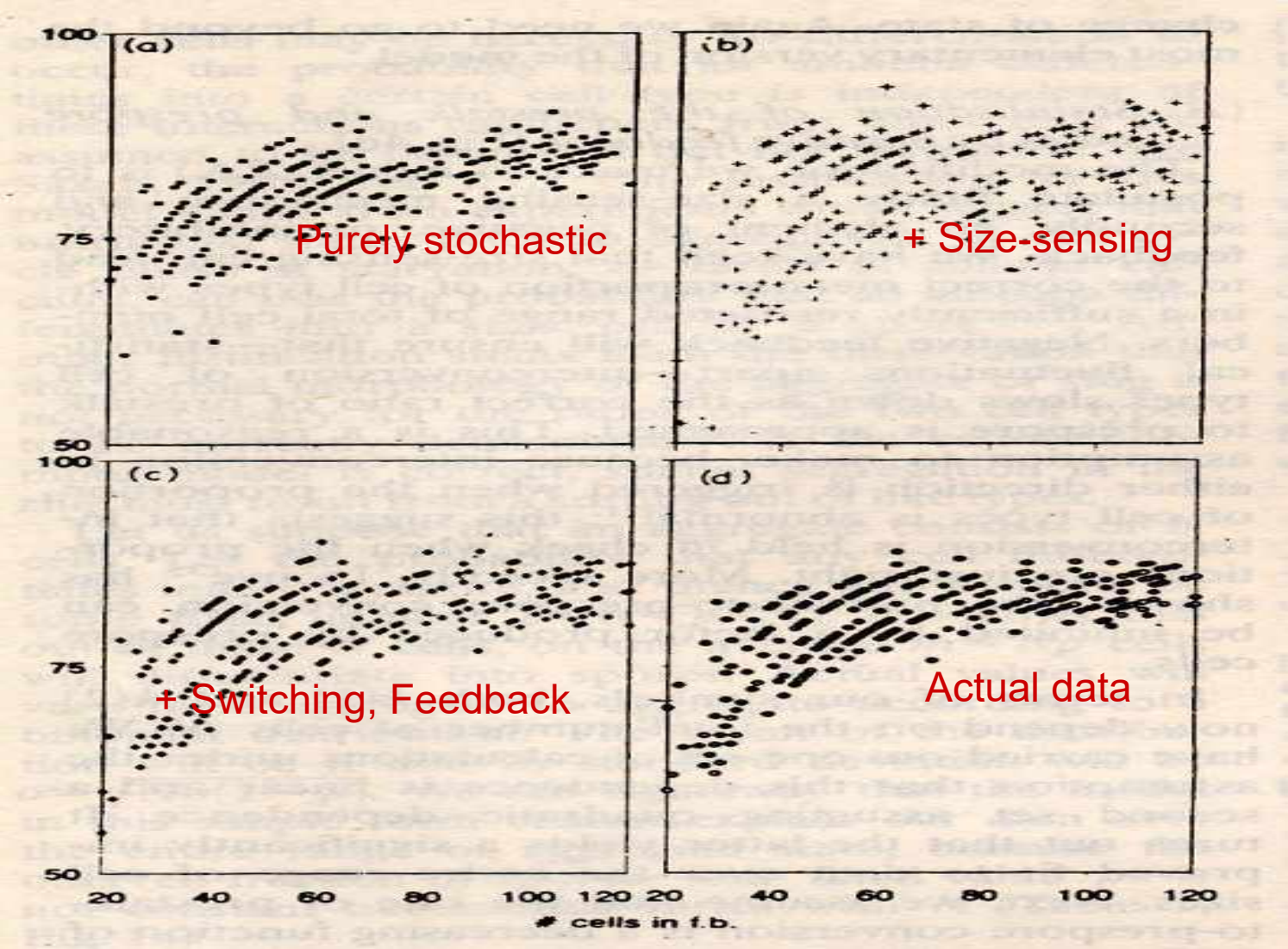
...a rapid and global nonspecific chromatin decompaction precedes the global up-regulation of gene expression ...regulatory actions stabilize and maintain the activity of a subset of genes.. remaining part of the genome becomes repressed again after chromatin recompaction.

Kupiec J-J (1997) A Darwinian theory for the origin of cellular differentiation, Mol Gen Genet 255: 201-208; (2014) Cell differentiation is a stochastic process, "Towards a theory of development", chap.10; Parmentier et al. (2022) PLoS Biol. 20(10): e3001849.

Developmental noise and stochastic differentiation:

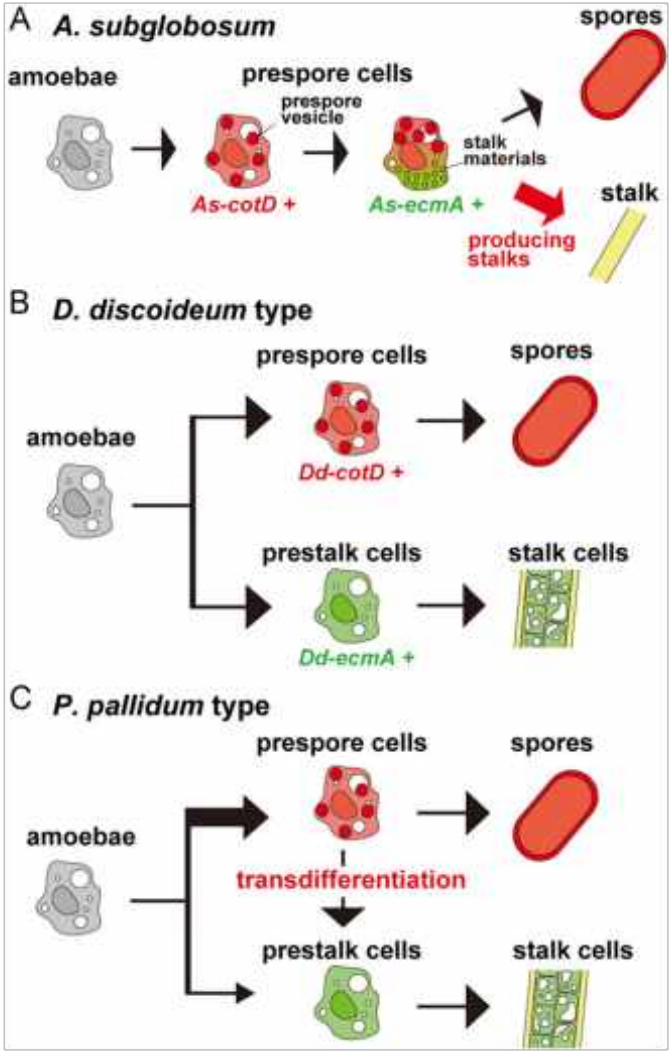
Dictyostelium discoideum

% spores vs. no. of cells in f.b.



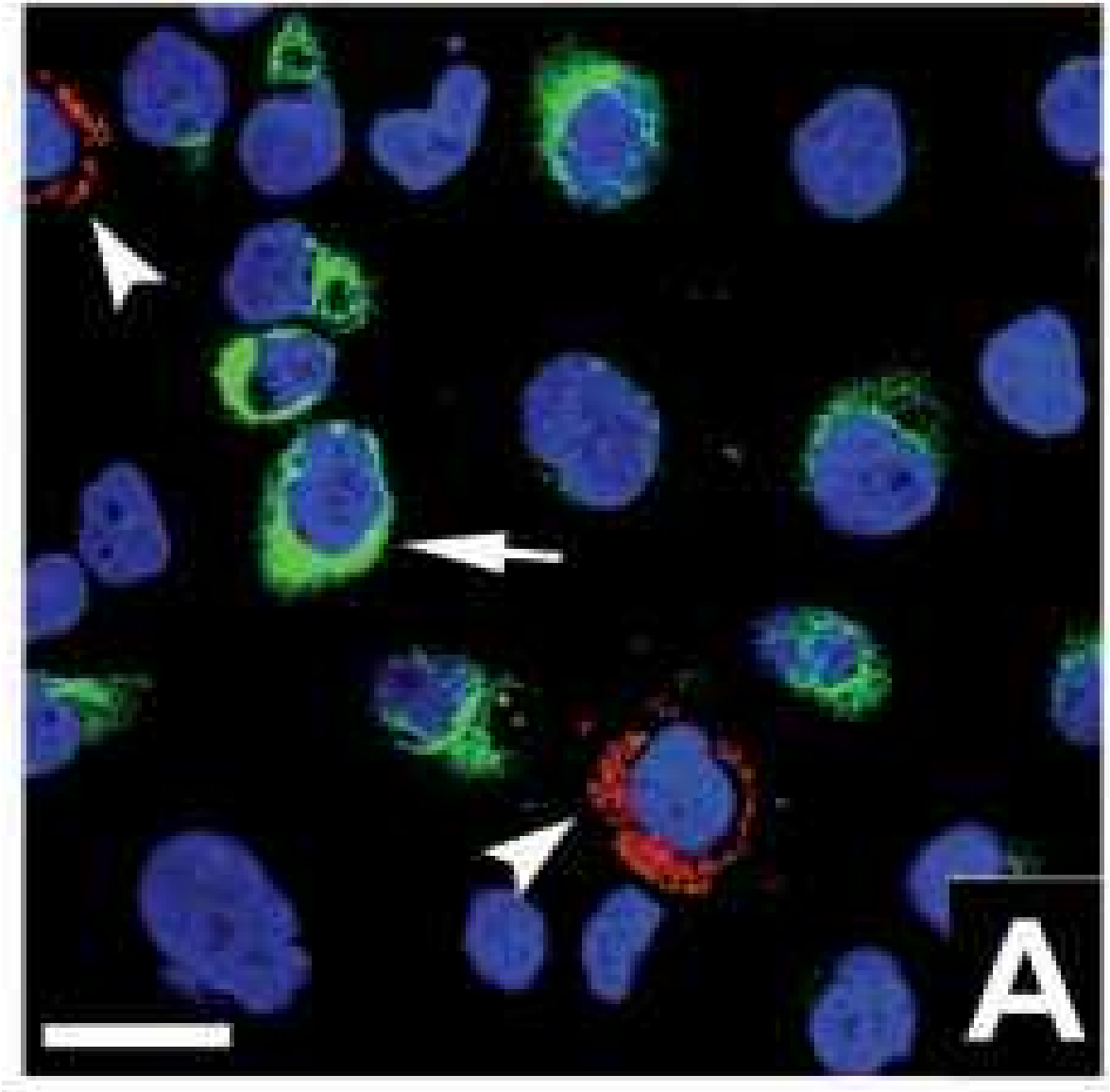
Nanjundiah and Bhogle 1995 Ind J Biochem Biophys 32(6):404-416

Temporal → Spatial division of labour



(a): All cells become pre-spores, some express 'prestalk' genes and produce stalk;
(b): early divergence of cell types; (c): all cells start as psp, some change to prestalk;
Mohri et al. Dev Biol. 2013

Stochastic differentiation of complementary cell types



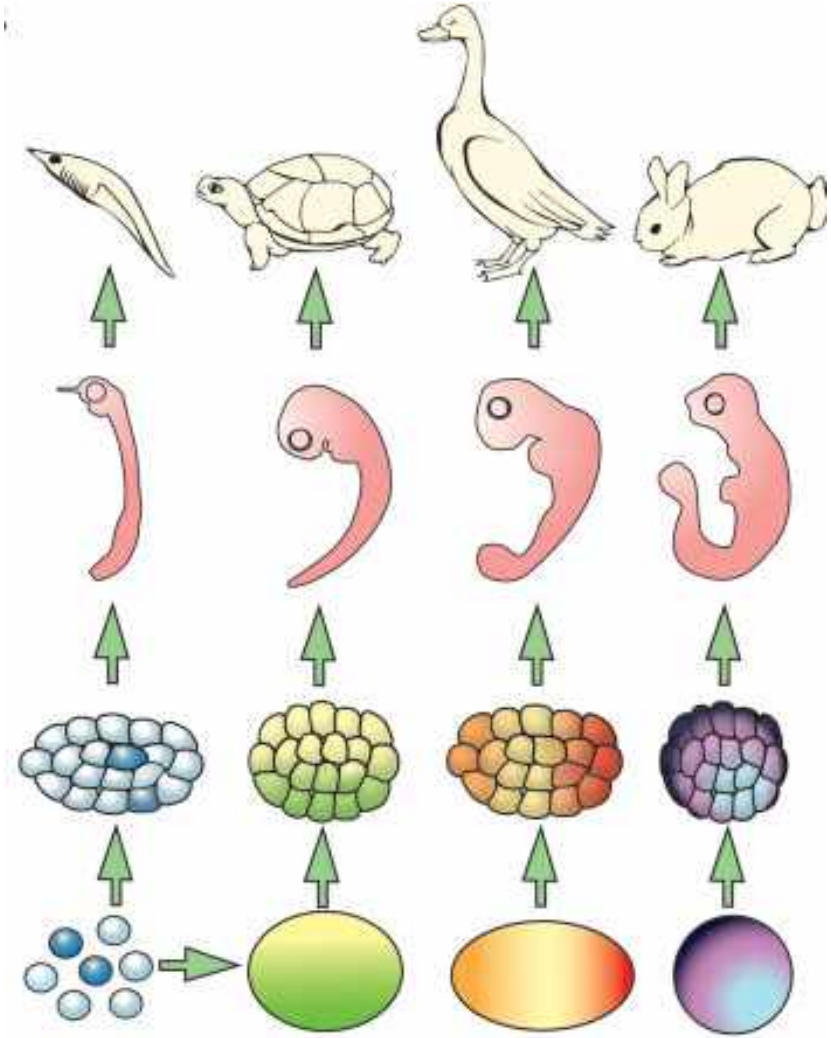
Pancreatic cell line

FGF2 (chemo-attractant)

FGF2-receptor

Hardikar et al. (2003) PNAS 100 (12): 7117–7122

“The chicken came before the egg”



Newman, 2011; J. Exp. Zool. (Mol. Dev. Evol.) 316:467–483

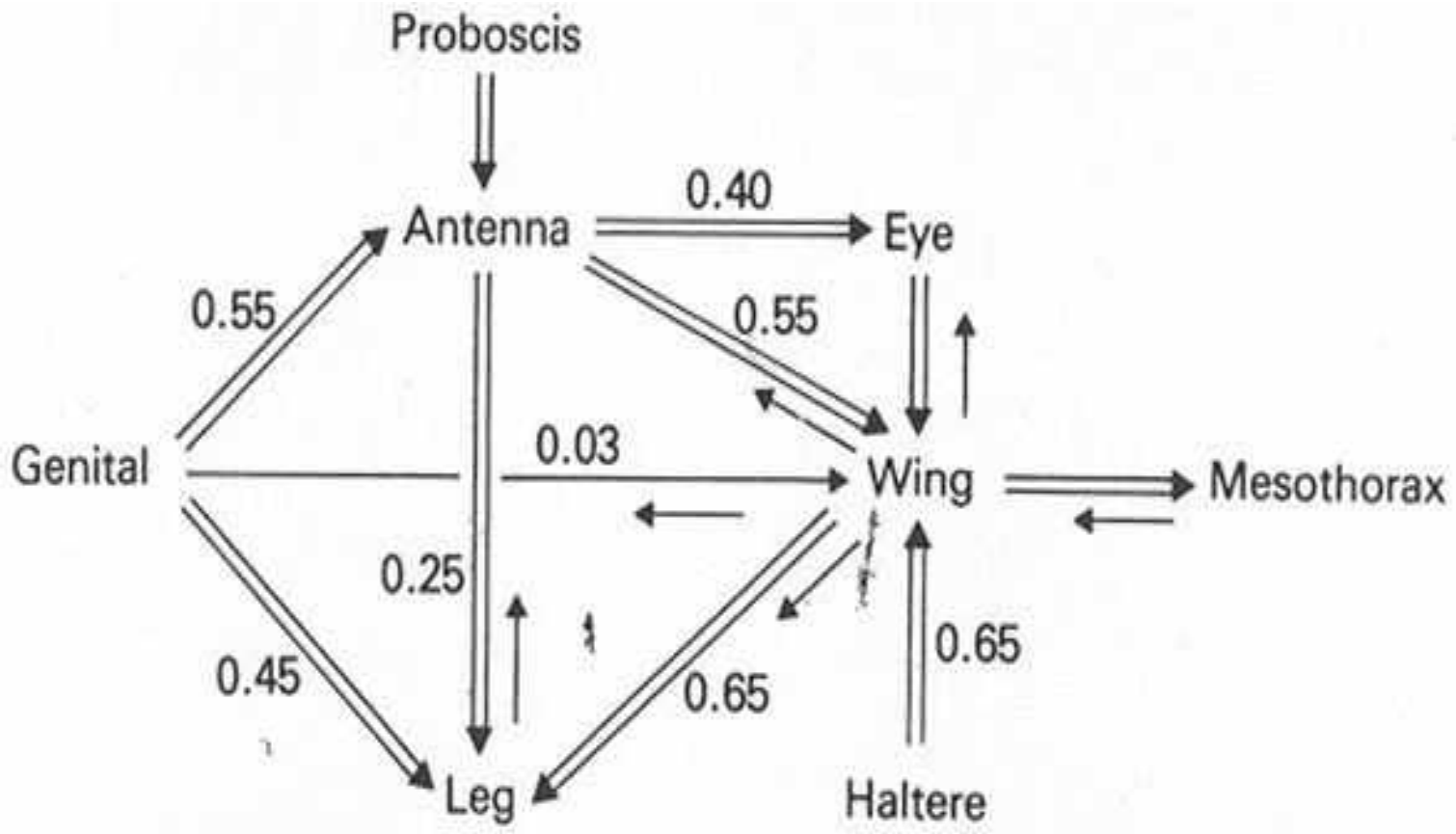
Stochastic differentiation

"... gene expression is unstable. It occurs stochastically and produces different cell types. In the second step gene expression is stabilized by means of cellular interactions."

"The origin of cellular differentiation is explained as an adaptation of cells to metabolic gradients created by substrate diffusion inside growing cell populations."

Kupiec 1997

Transdetermination in Drosophila



"Animal physiology and development"; http://slideplayer.com/slide/6856479/

Chimera between goat and sheep
(divergence 5-7 Myr ago)

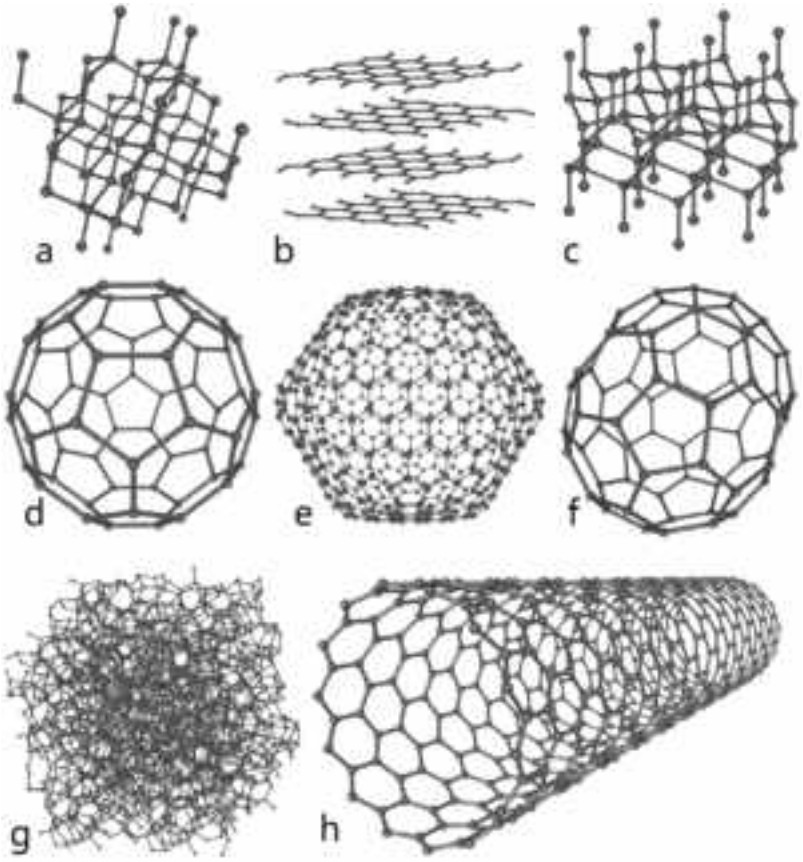
Fehilly et al. *Nature* **307**: 634–636, 1984

Chimera between quail and chick
(diverged 38MYr ago)

(Data: Pereira et al., Mol. Biol. Evol. 23(9):1731–1740. 2006)

Le Douarin, *Nature 286: 663-669, 1980*

Allotropes of carbon



a) diamond, b) graphite, c) lonsdaleite, d) C_{60} buckminsterfullerene, e) C_{540}, Fullerite f) C_{70}, g) amorphous carbon, and h) single-walled carbon nanotube.
(https://en.wikipedia.org/wiki/Allotropes_of_carbon)

Null hypothesis: “Internal” view

Preadaptation

→

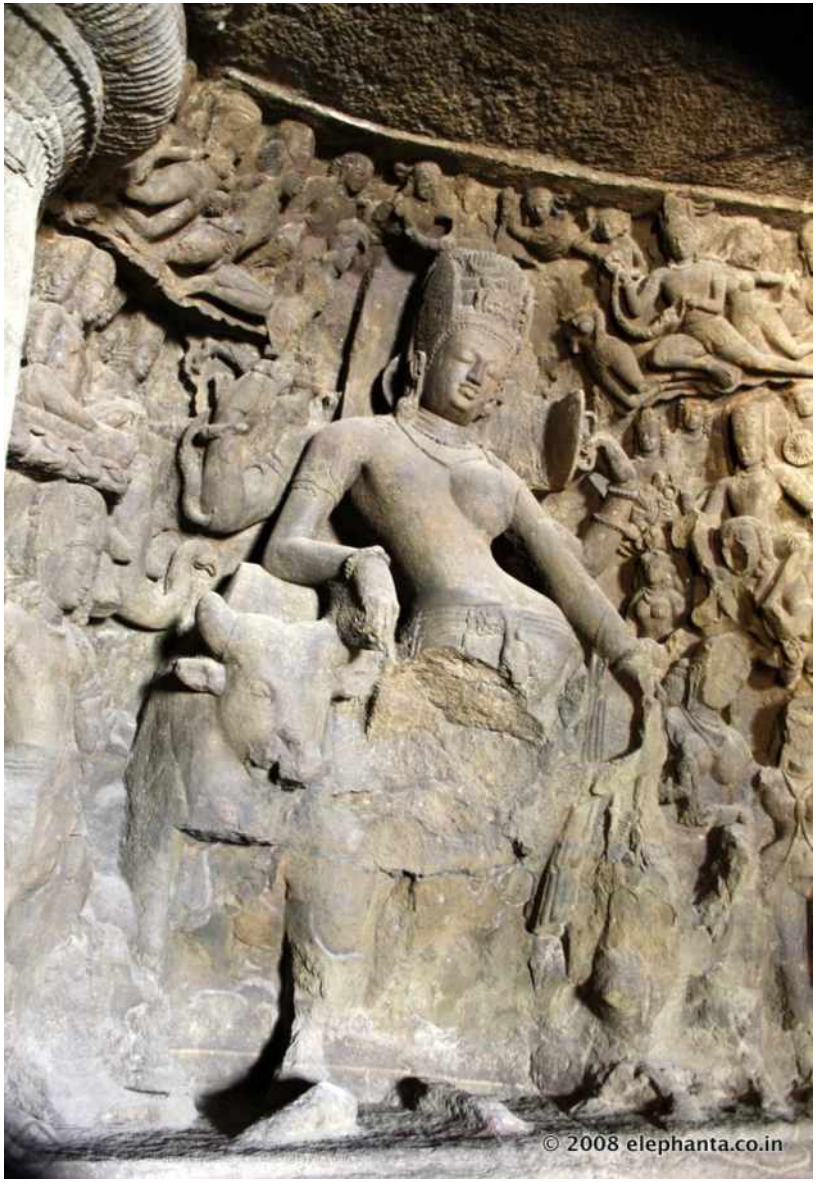
Self-organisation

→

Natural selection for best adapted phenotype

→

Secondary genetic change, stabilises best adapted outcome



https://elephanta.co.in/ardhanarishvara-at-elephanta/ardhanariswara-panel