Punctuated Equilibria and the Origin and Evolution of Development

Stuart A. Newman
New York Medical College

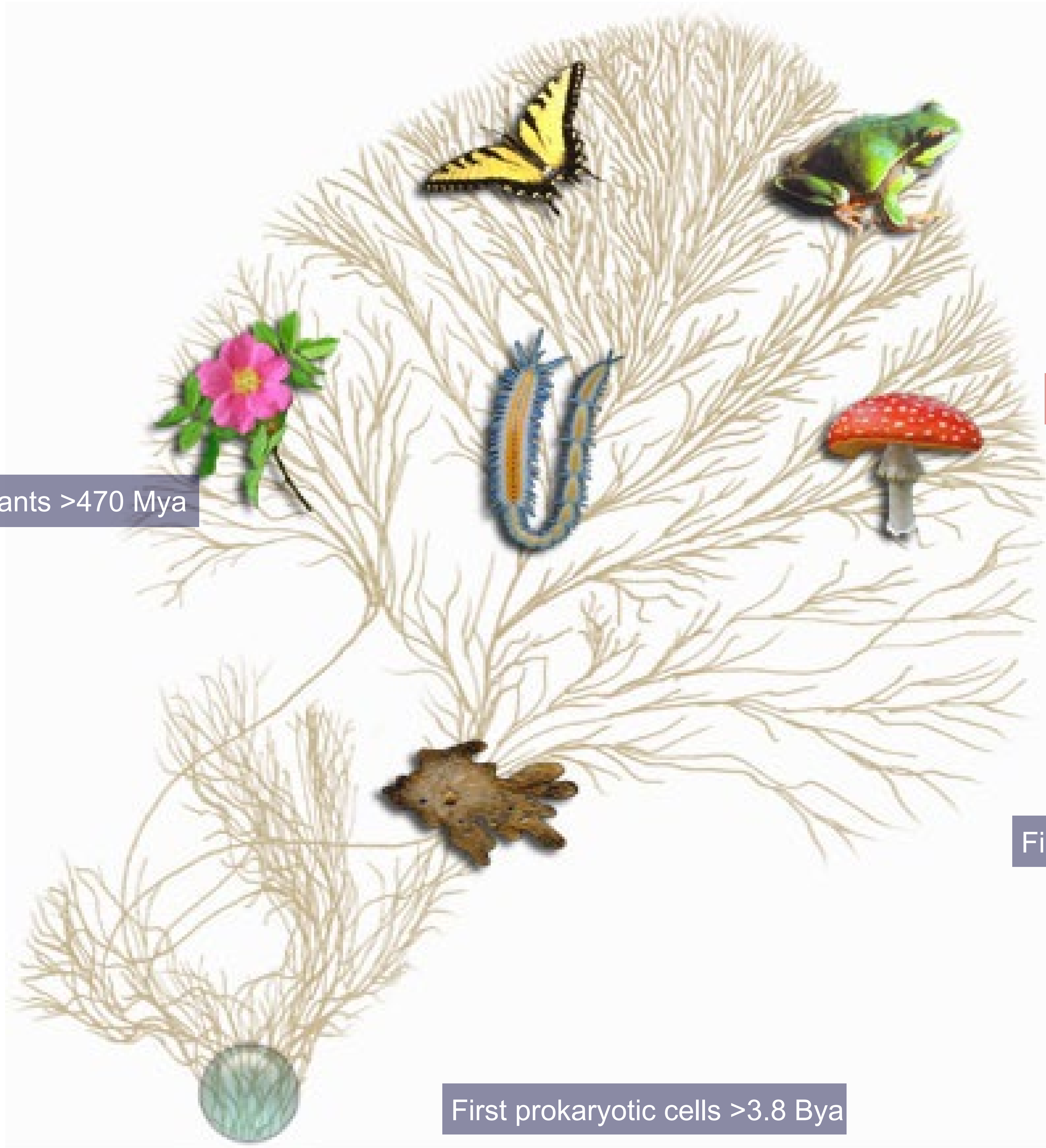
"Punctuated Equilibrium: 50 Year Later"

Geological Society of America

Denver, Colorado

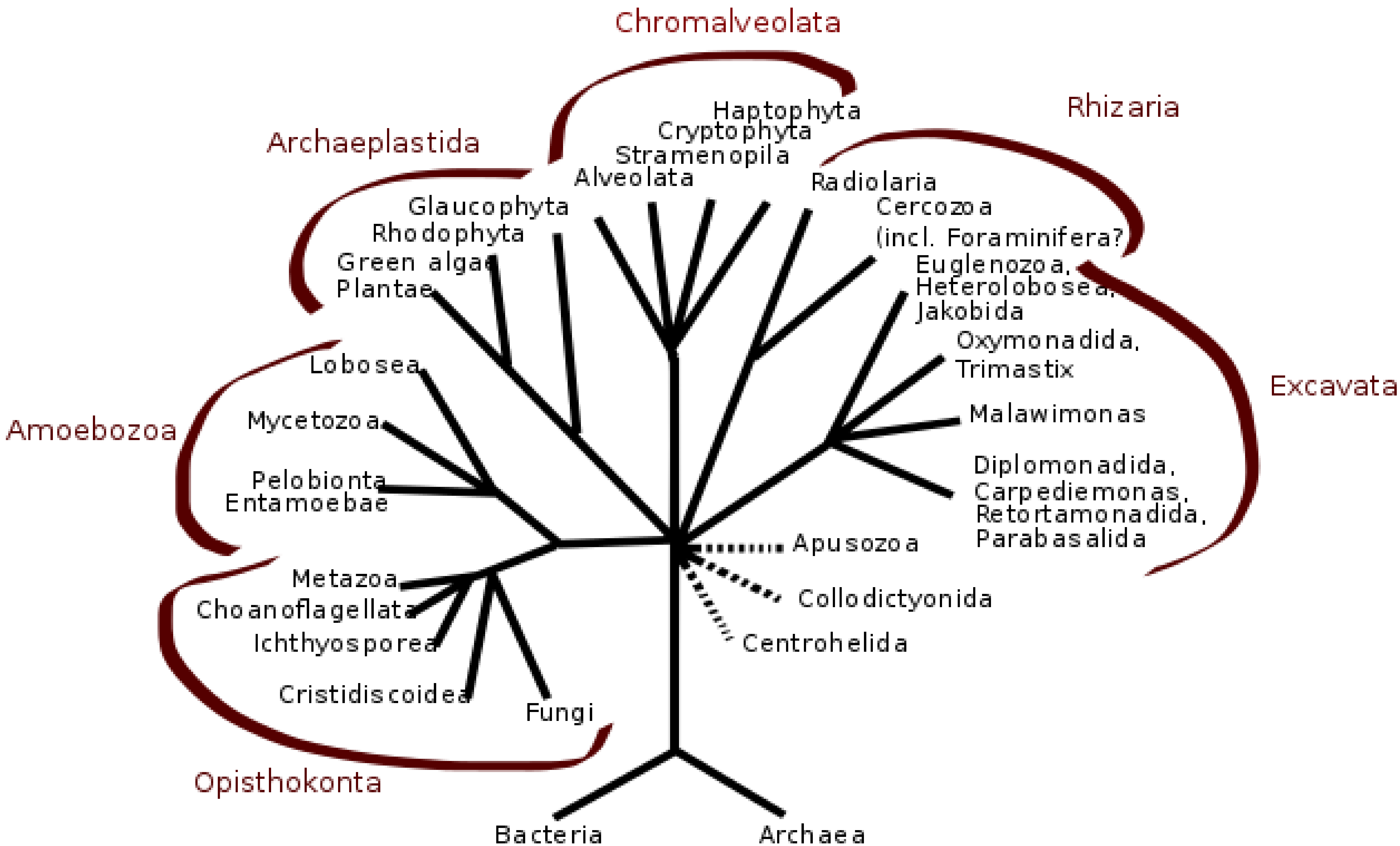
October 10, 2022

Diversification of cellular and multicellular life



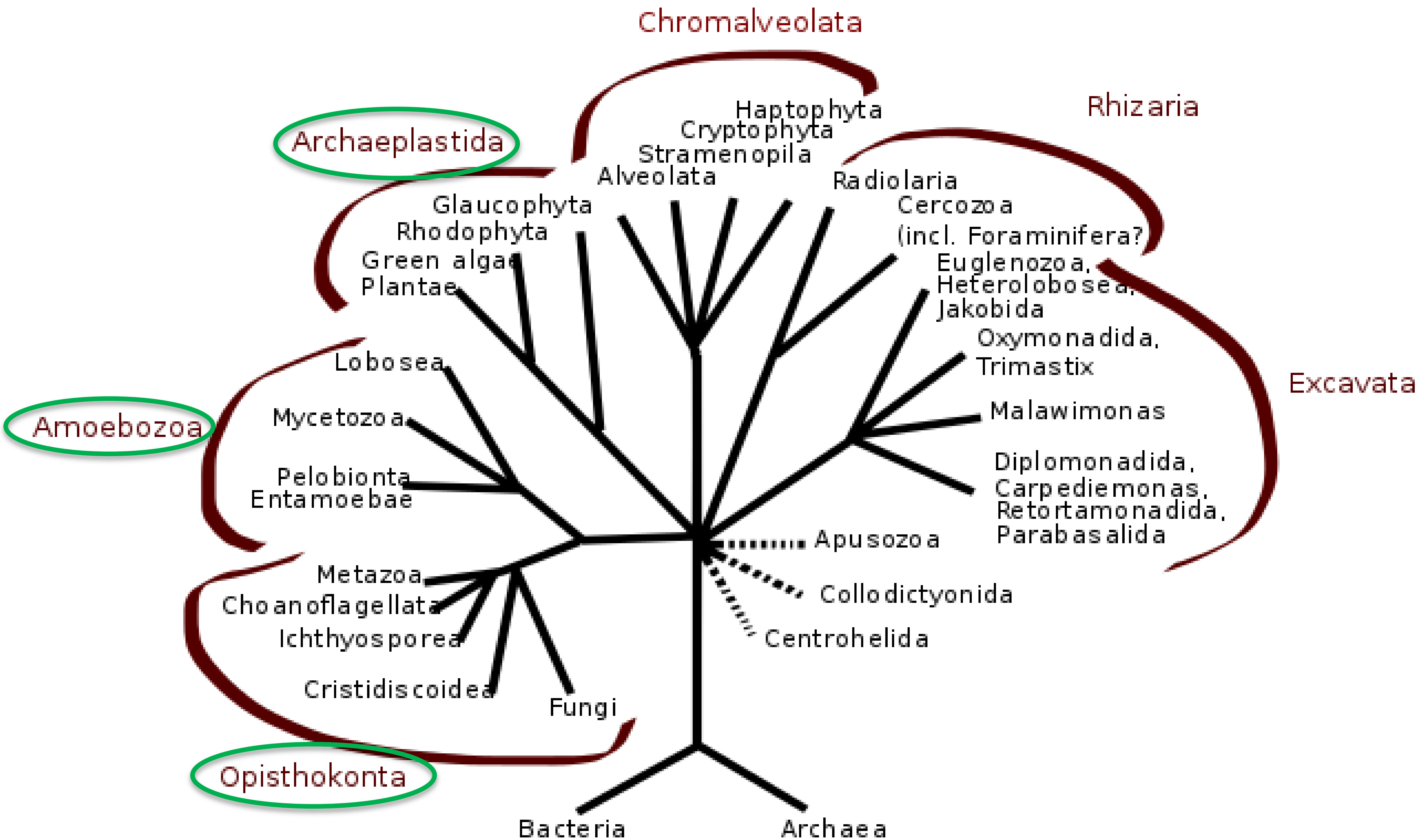
Tree of Life Web Project
http://tolweb.org/tree/

Major eukaryotic groups



Based on Simpson & Roger *Curr Biol* (2004)

Groups with multicellular forms



Based on Simpson & Roger *Curr Biol* (2004)

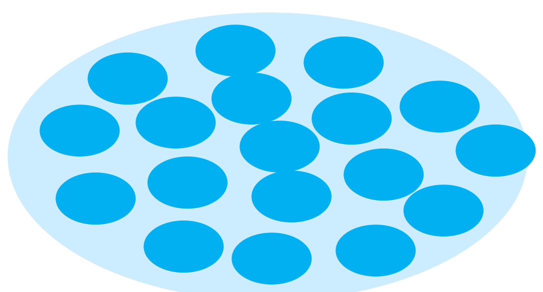
Proposition

Much of multicellular evolution, rather than resulting from cycles of gradual selection for adaptive advantage, was driven by the inherent physical properties of multicellular matter.

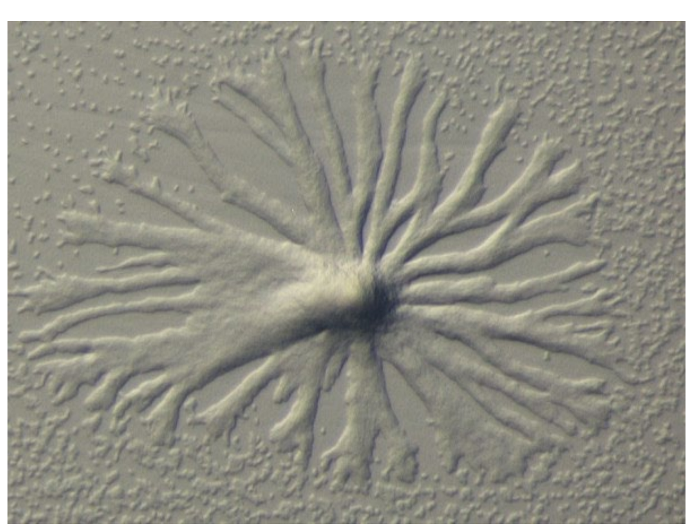
Nonliving materials exhibit characteristic **morphological motifs** that depend on their composition and the mesoscale physical processes mobilized by the respective materials.

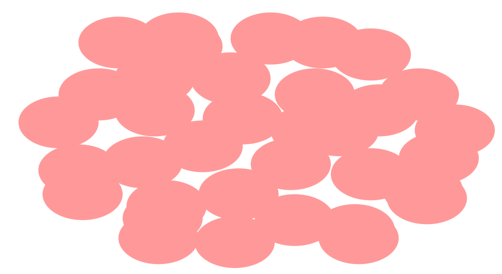
For example, nonliving **liquids** can generate waves and vortices and mineral **solids** have varied crystal structures.

Varieties of multicellular materials

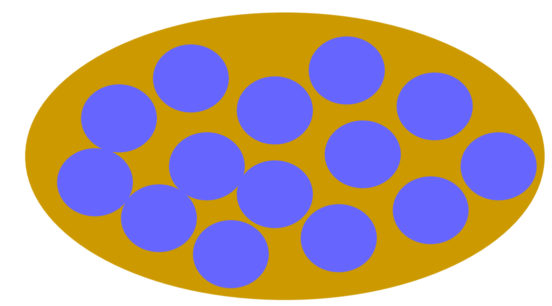


Passive liquid multicellular forms: separate motile cells in compliant matrix (dictyostelids)

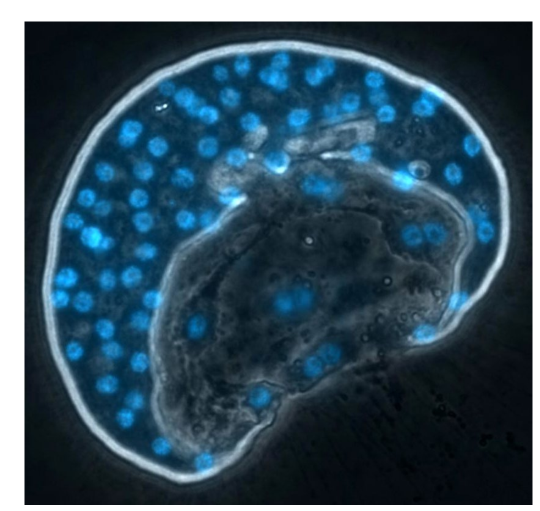


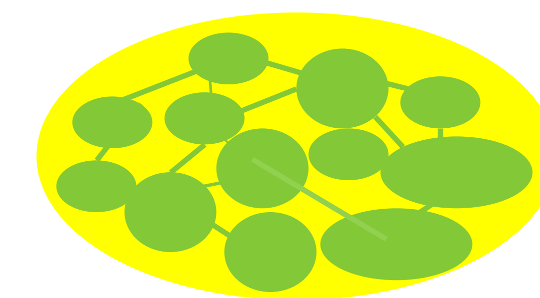


Active liquid multicellular forms: directly linked motile cells (animals)



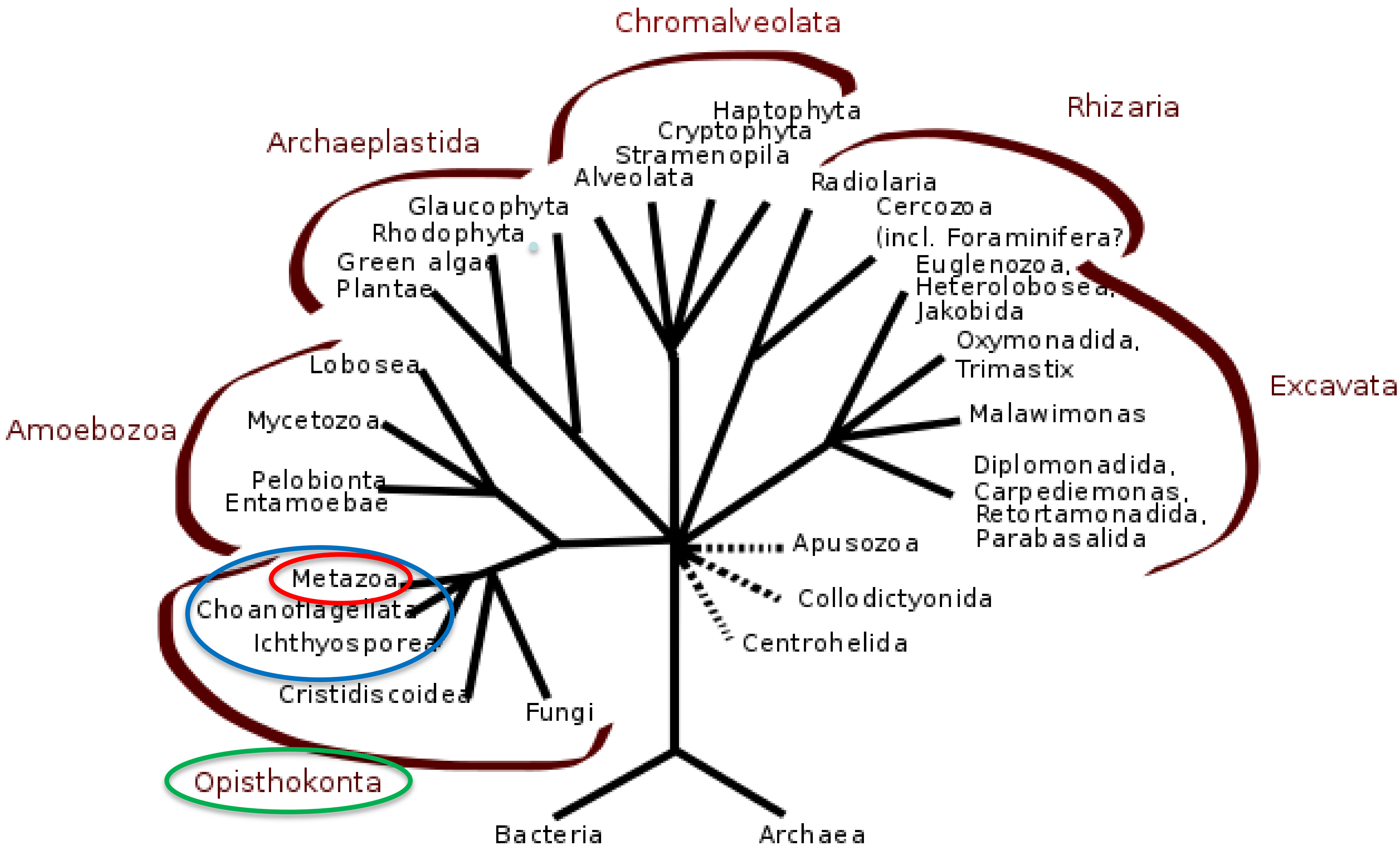
Inert solid multicellular forms: nonmotile cells in a noncompliant matrix (nonmetazoan holozoans)





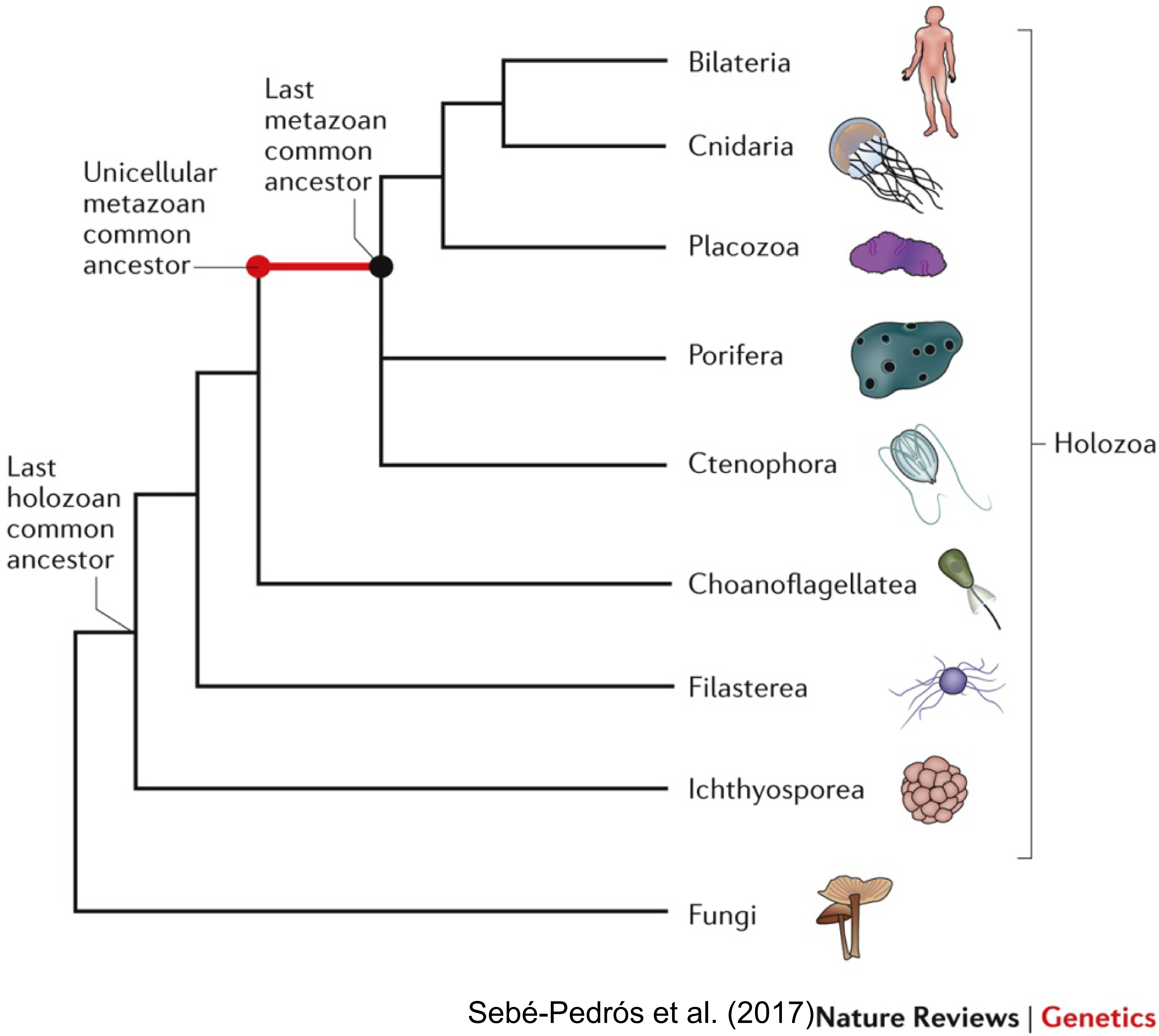
Active solid multicellular forms: shape-changing, communicating cells in a stretchable, “meltable” matrix (plants)

Animals and their close relatives



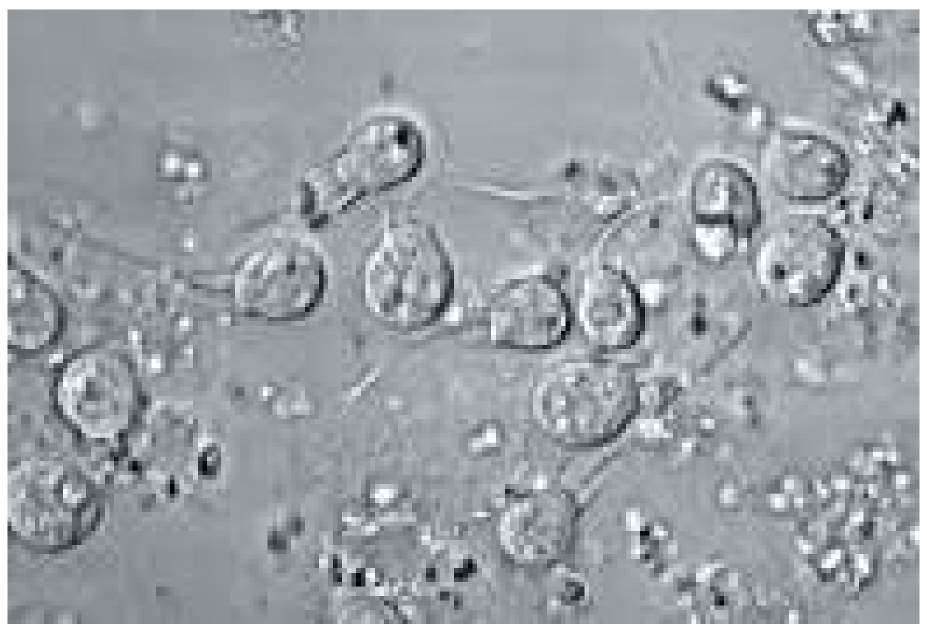
Based on Simpson & Roger *Curr Biol* (2004)

Origin of metazoans (animals)

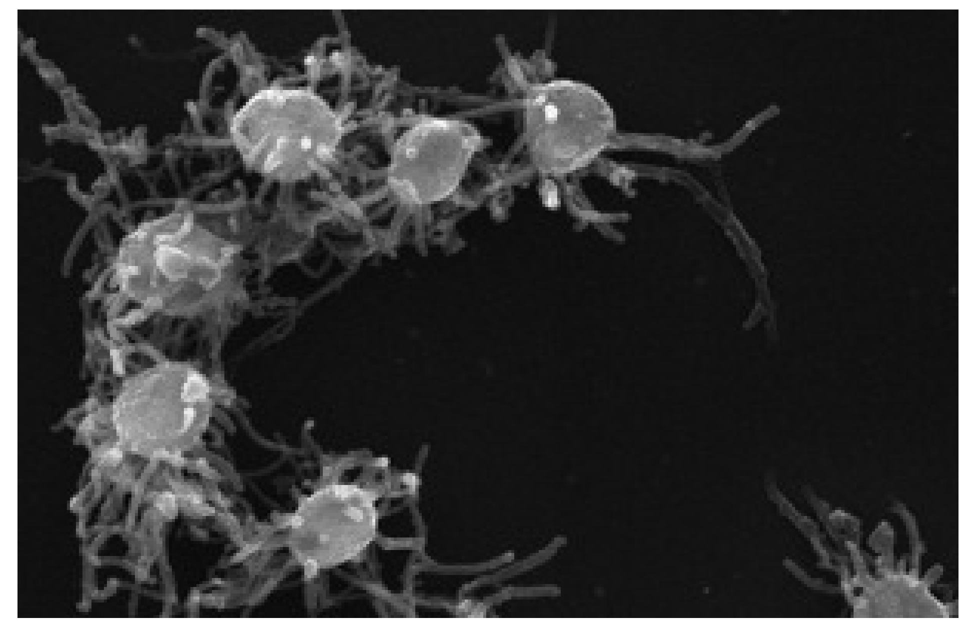


Sebé-Pedrós et al. (2017)

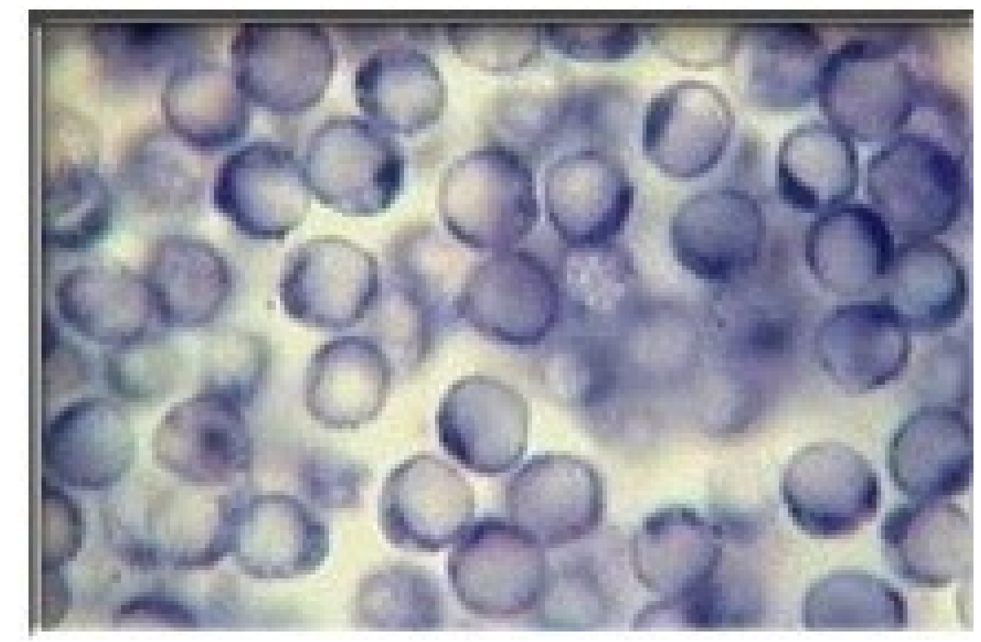
Animal morphogenesis and pattern formation employ repurposed genes



Monosiga



Capsaspora



Ichthyosporea

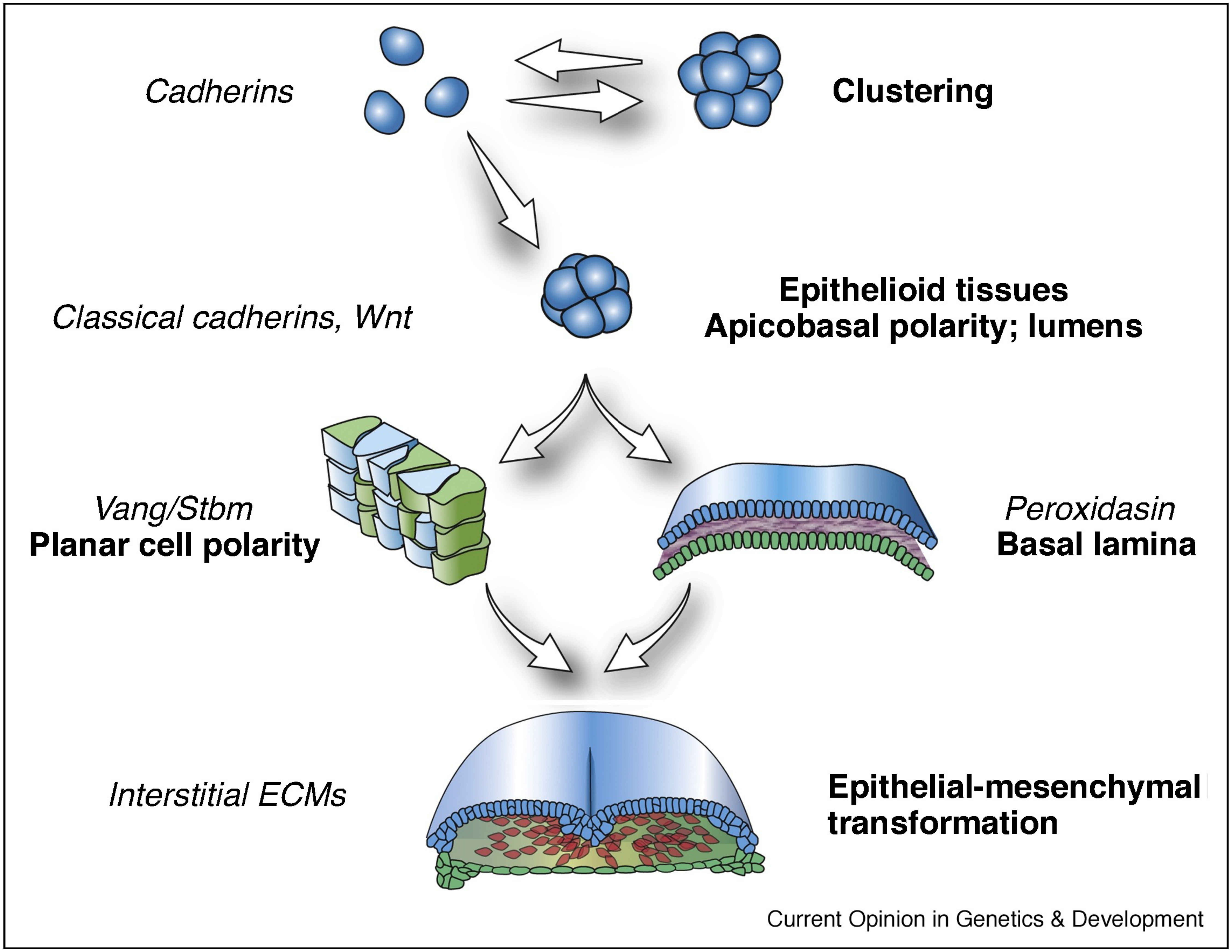
One or more of the extant holozoans and (by inference) the unicellular ancestors of the metazoans, contain(ed) genes specifying members of the metazoan developmental-genetic toolkit which eventually came to mediate adhesion and other cell-cell interactions.

King *et al.*, *Nature* 451:783; 2008

Shalchian-Tabrizi *et al.*, *PLoS ONE* 3:e2098; 2008

Sebé-Pedrós *et al. eLife 2:* e01287; 2013

Novel genes were also required for metazoan origination and development

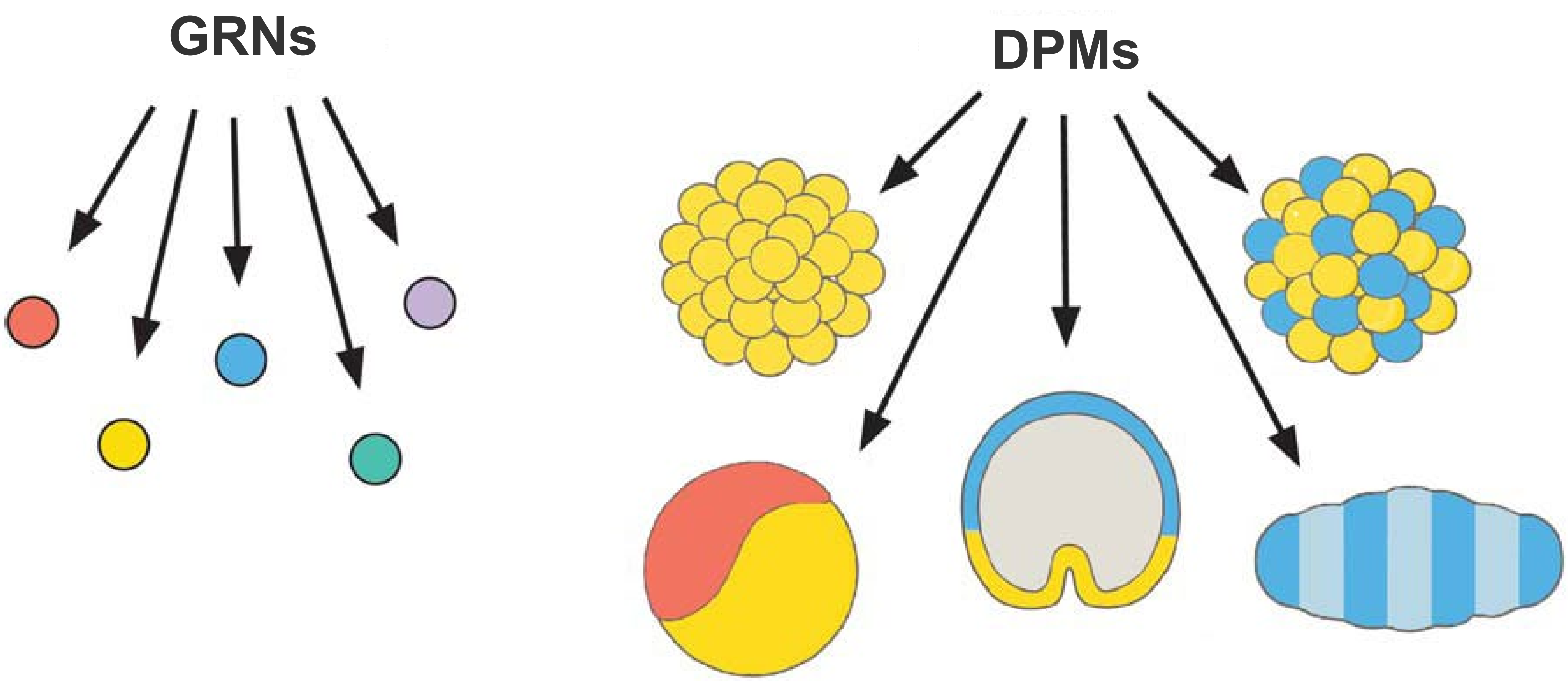


SN, *COGDE*, 2019

Dynamical Patterning Modules

Definition: DPMs are **specific molecules and pathways** that mobilize **specific physical forces or effects** to shape and pattern multicellular aggregates.

Gene regulatory networks (GRNs) mediate **cell differentiation**; dynamical patterning modules (DPMs) mediate **pattern formation and morphogenesis**

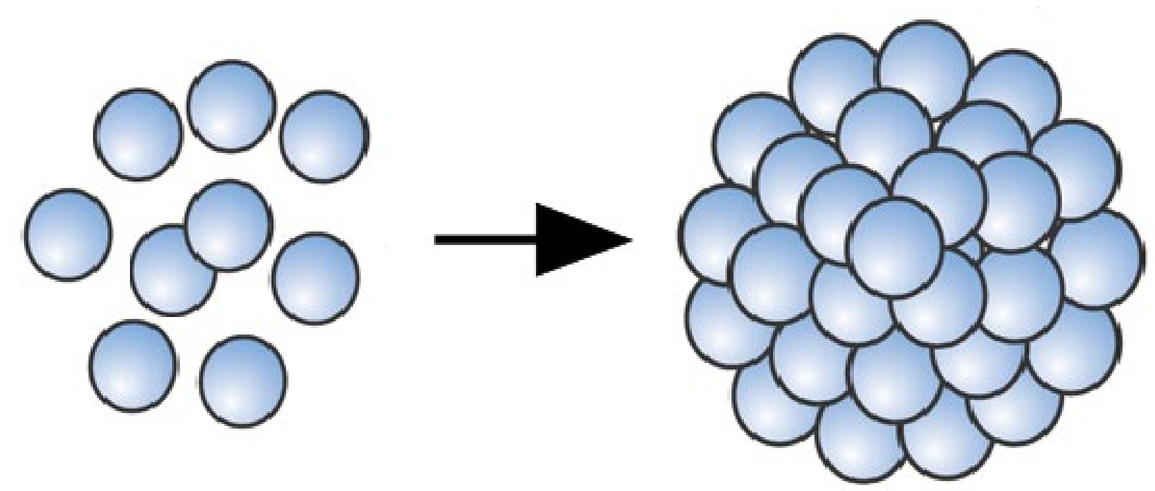


Newman et al. *J. Biosci.*; 2009

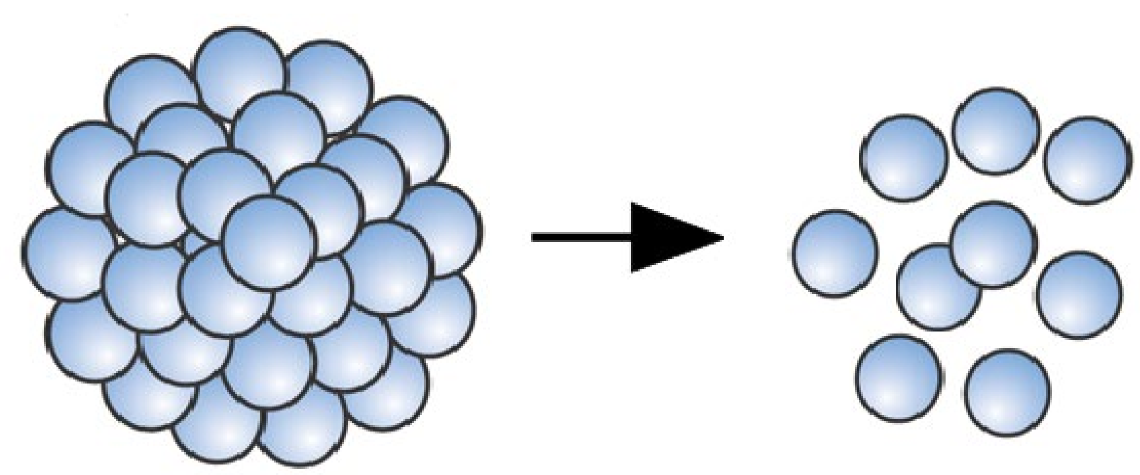
Repurposed and novel toolkit gene products mobilize **mesoscale physical effects** in the multicellular context

The most fundamental DPM: *ADH*

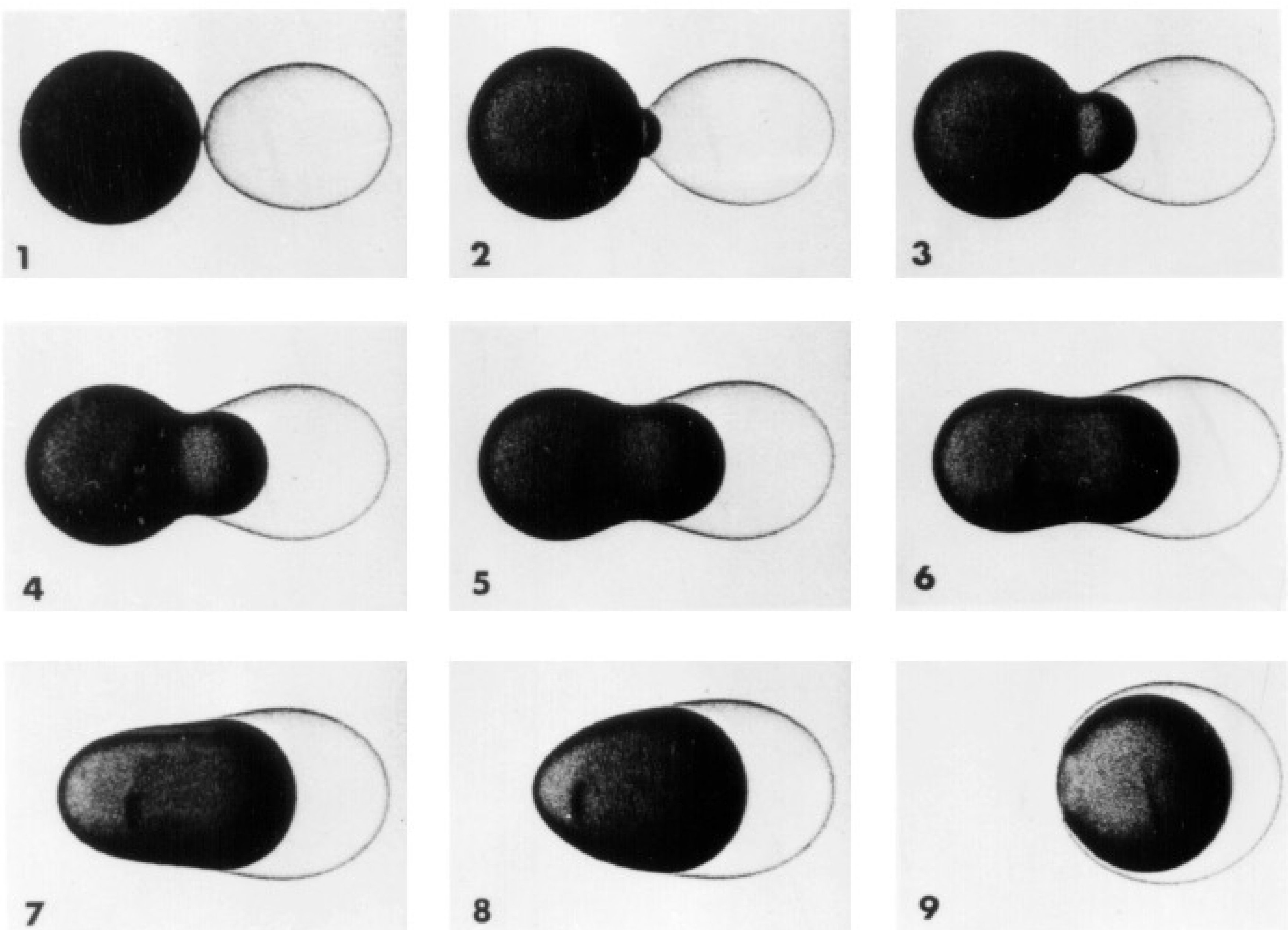
Aggregation is the necessary condition for multicellularity



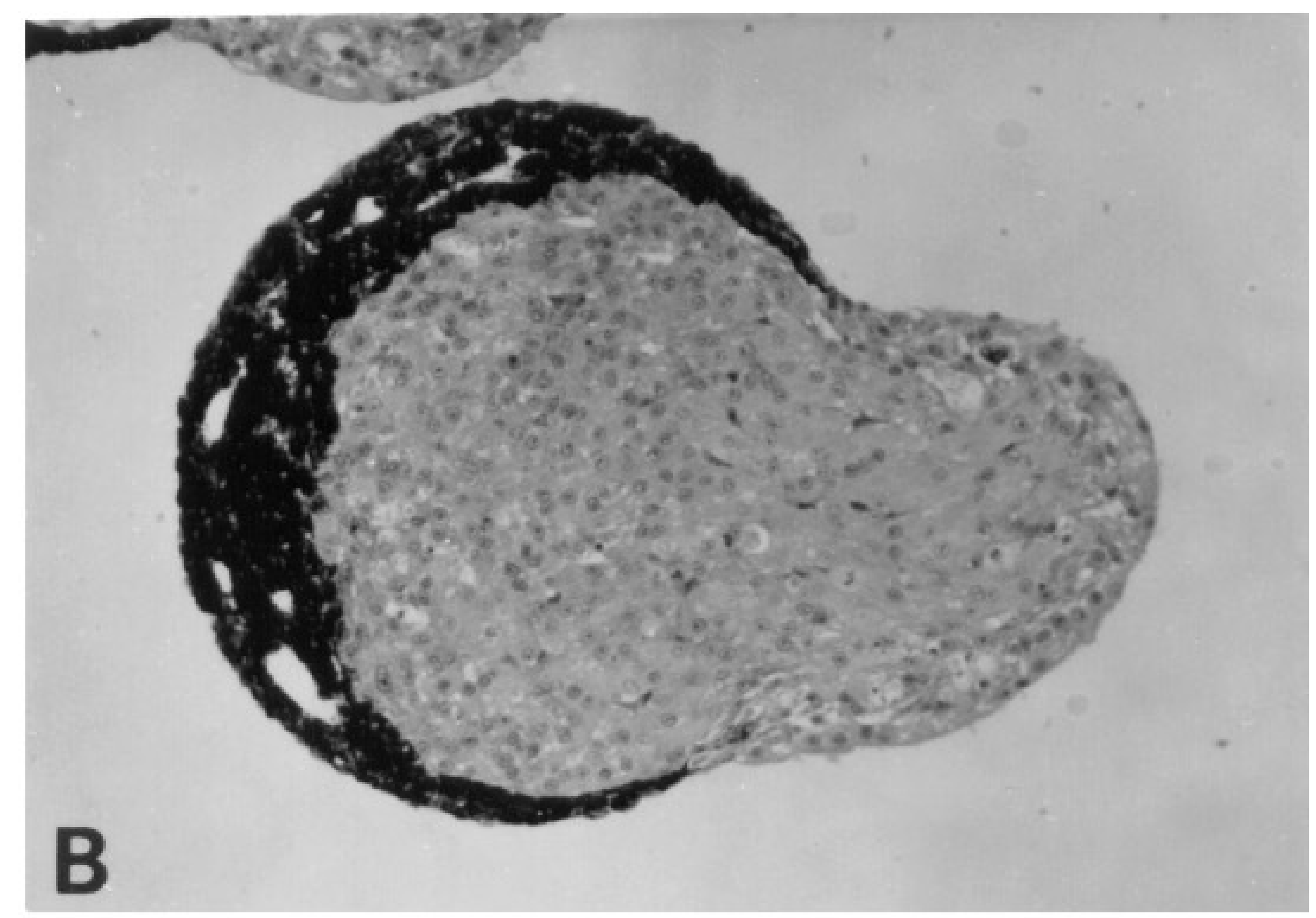
Its inverse is *epithelial-mesenchymal transformation*



Differential adhesion/cohesion: phase separation and engulfment behavior in liquids and tissues

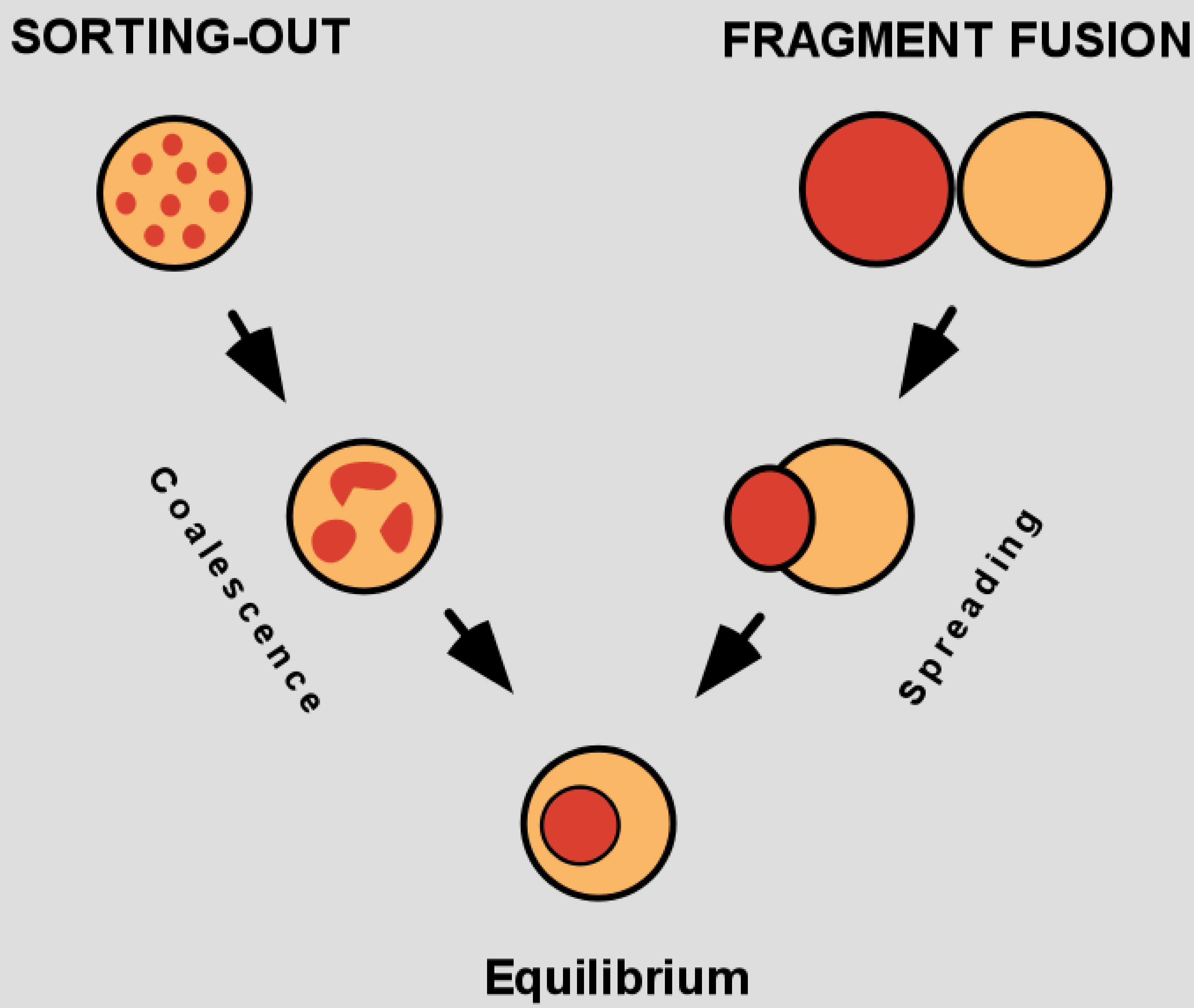


Torza and Mason *Science* 163: 813; 1969



Armstrong, *Crit Rev Biochem Mol Biol* 24:119; 1989

Differential adhesion/cohesion can lead to cell sorting and tissue layering



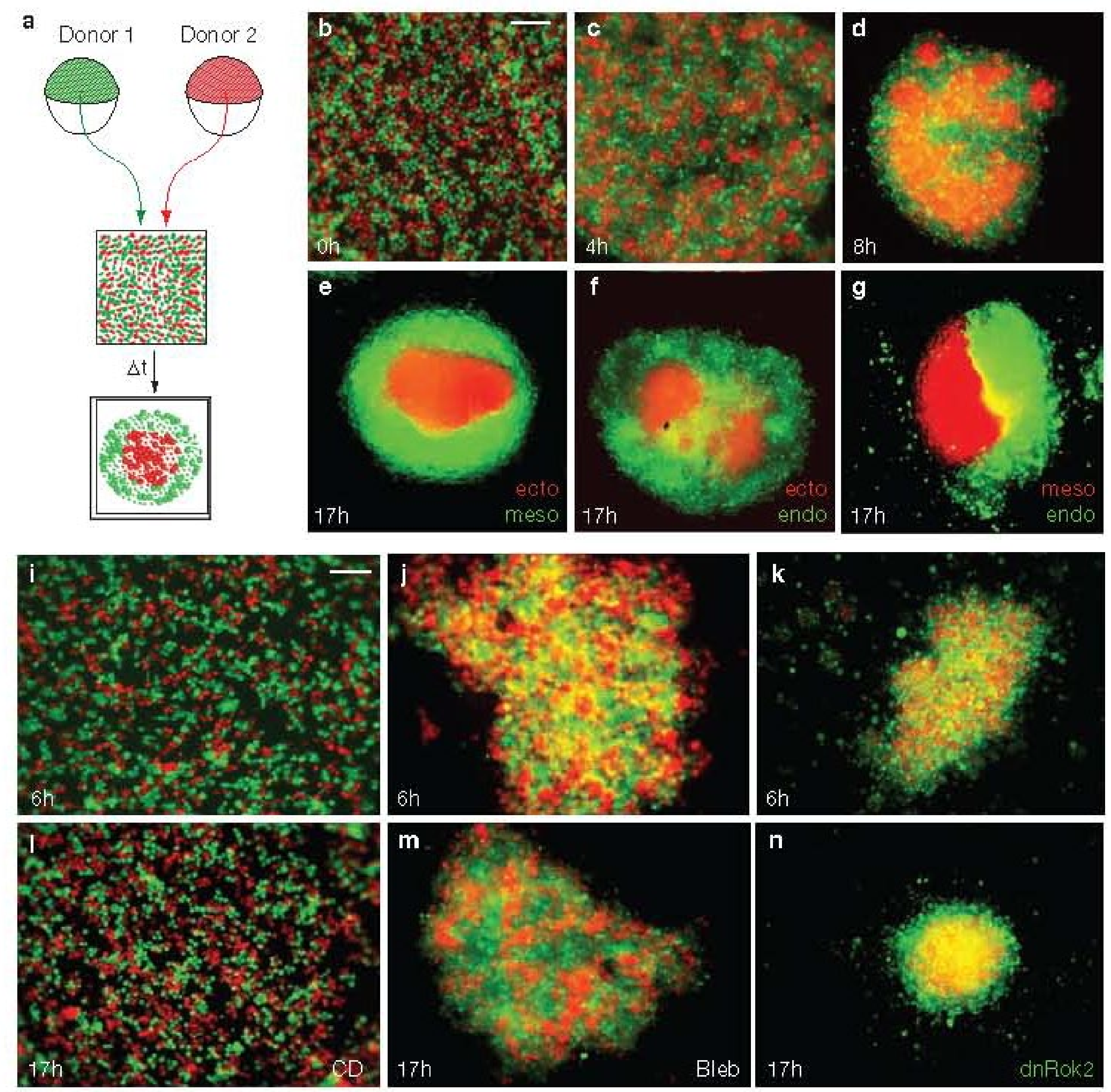
Based on Steinberg *Symp Soc Dev Biol*, 1978
See also Maître and Heisenberg *Curr Biol*, 2013

NATURE CELL BIOLOGY VOLUME 10 | NUMBER 4 | APRIL 2008

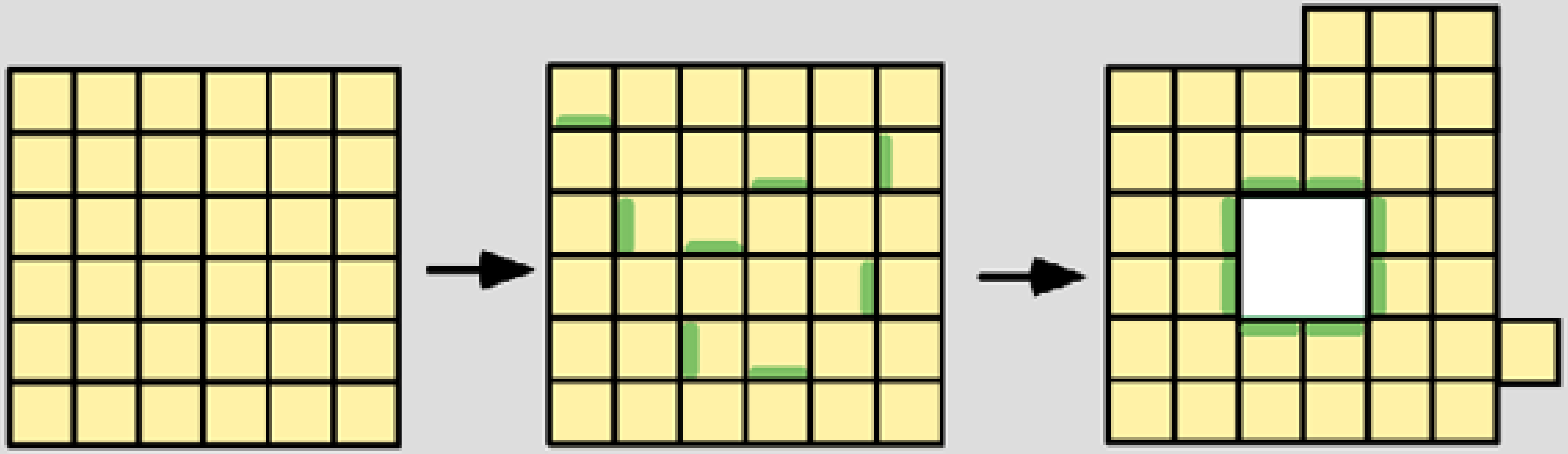
Tensile forces govern germ-layer organization in zebrafish

M. Krieg[1], Y. Arboleda-Estudillo[1,2], P.-H. Puech[3], J. Käfer[4], F. Graner[4], D. J. Müller[1,5] and C.-P. Heisenberg[2,5]

Understanding the factors that direct tissue organization during development is one of the most fundamental goals in developmental biology. Various hypotheses explain cell sorting and tissue organization on the basis of the adhesive and mechanical properties of the constituent cells[1]. However, validating these hypotheses has been difficult due to the lack of appropriate tools to measure these parameters. Here we use atomic force microscopy (AFM) to quantify the adhesive and mechanical properties of individual ectoderm, mesoderm and endoderm progenitor cells from gastrulating zebrafish embryos. Combining these data with tissue self-assembly *in vitro* and the sorting behaviour of progenitors *in vivo*, we have shown that differential actomyosin-dependent cell-cortex tension, regulated by Nodal/TGFβ-signalling (transforming growth factor β), constitutes a key factor that directs progenitor-cell sorting. These results demonstrate a previously unrecognized role for Nodal-controlled cell-cortex tension in germ-layer organization during gastrulation.

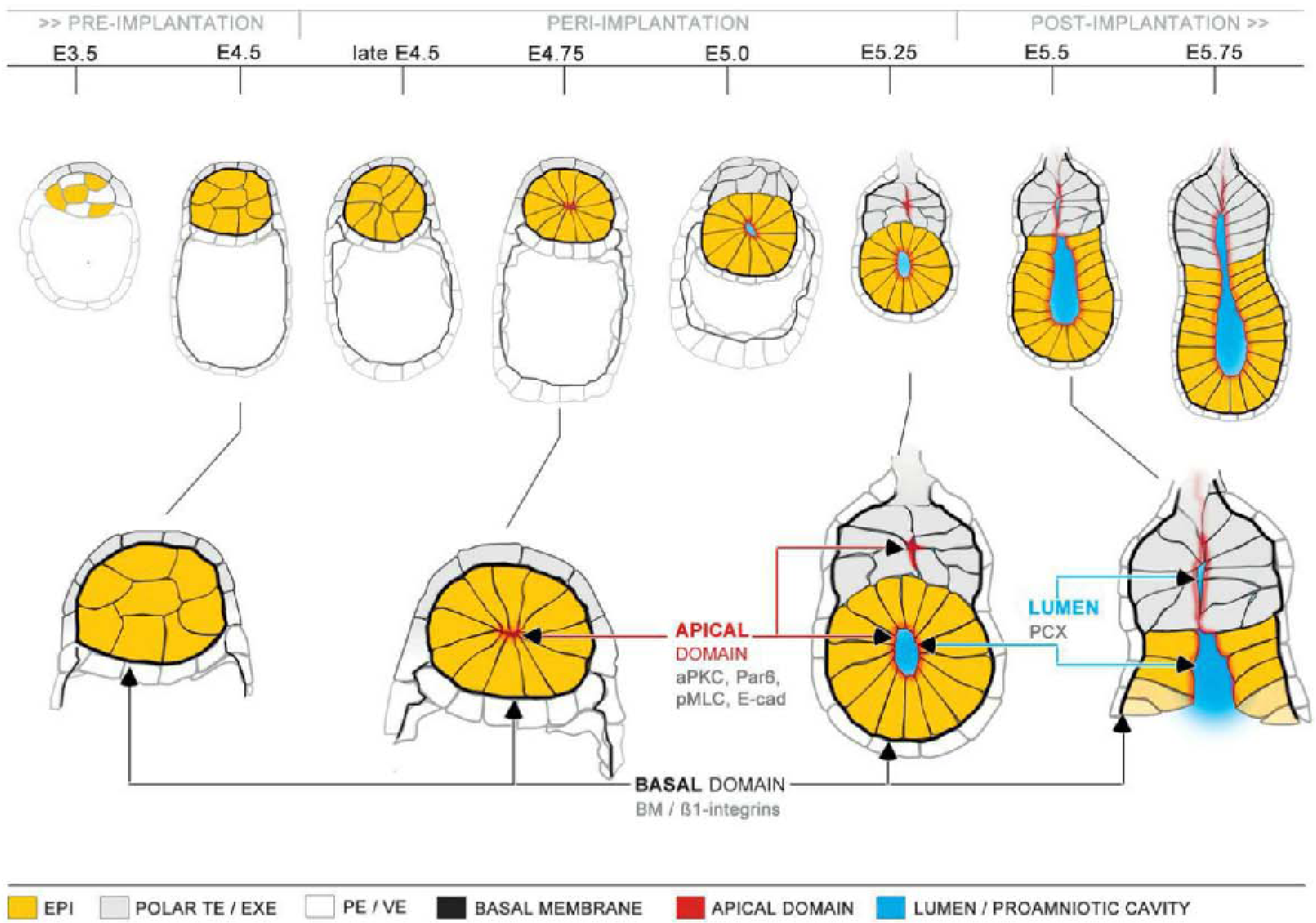


Lumens can automatically arise in clusters of cells that are apicobasally polarized with respect to adhesivity

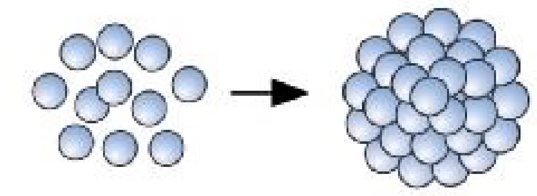
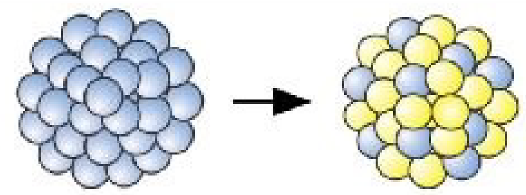
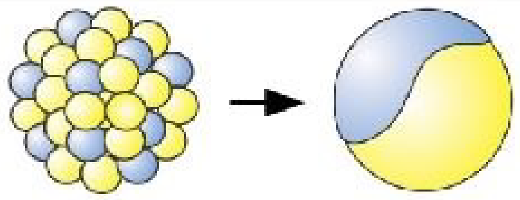
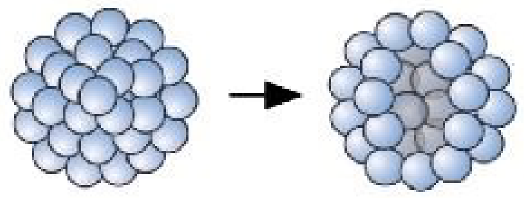
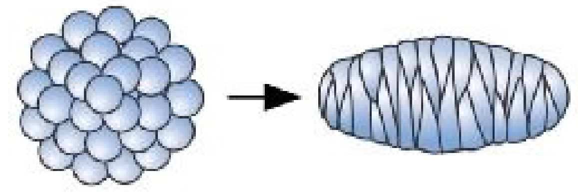
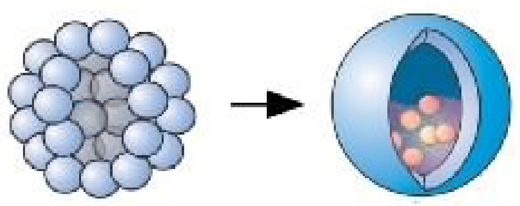
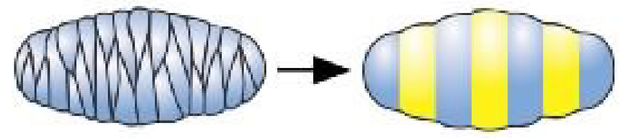
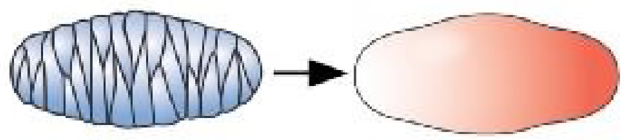
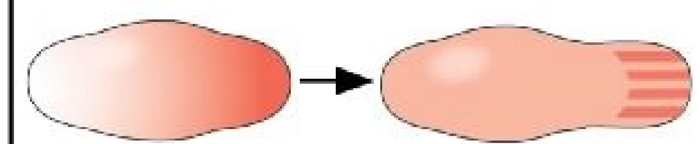


Self-Organizing Properties of Mouse Pluripotent Cells Initiate Morphogenesis upon Implantation

Ivan Bedzhov[1,2] and Magdalena Zernicka-Goetz[1,2,*]
[1]Wellcome Trust/Cancer Research UK Gurdon Institute, University of Cambridge, Tennis Court Road, Cambridge CB2 1QR, UK
[2]Department of Physiology, Development and Neuroscience, University of Cambridge, Downing Street, Cambridge CB2 3DY, UK
*Correspondence: mz205@cam.ac.uk
http://dx.doi.org/10.1016/j.cell.2014.01.023

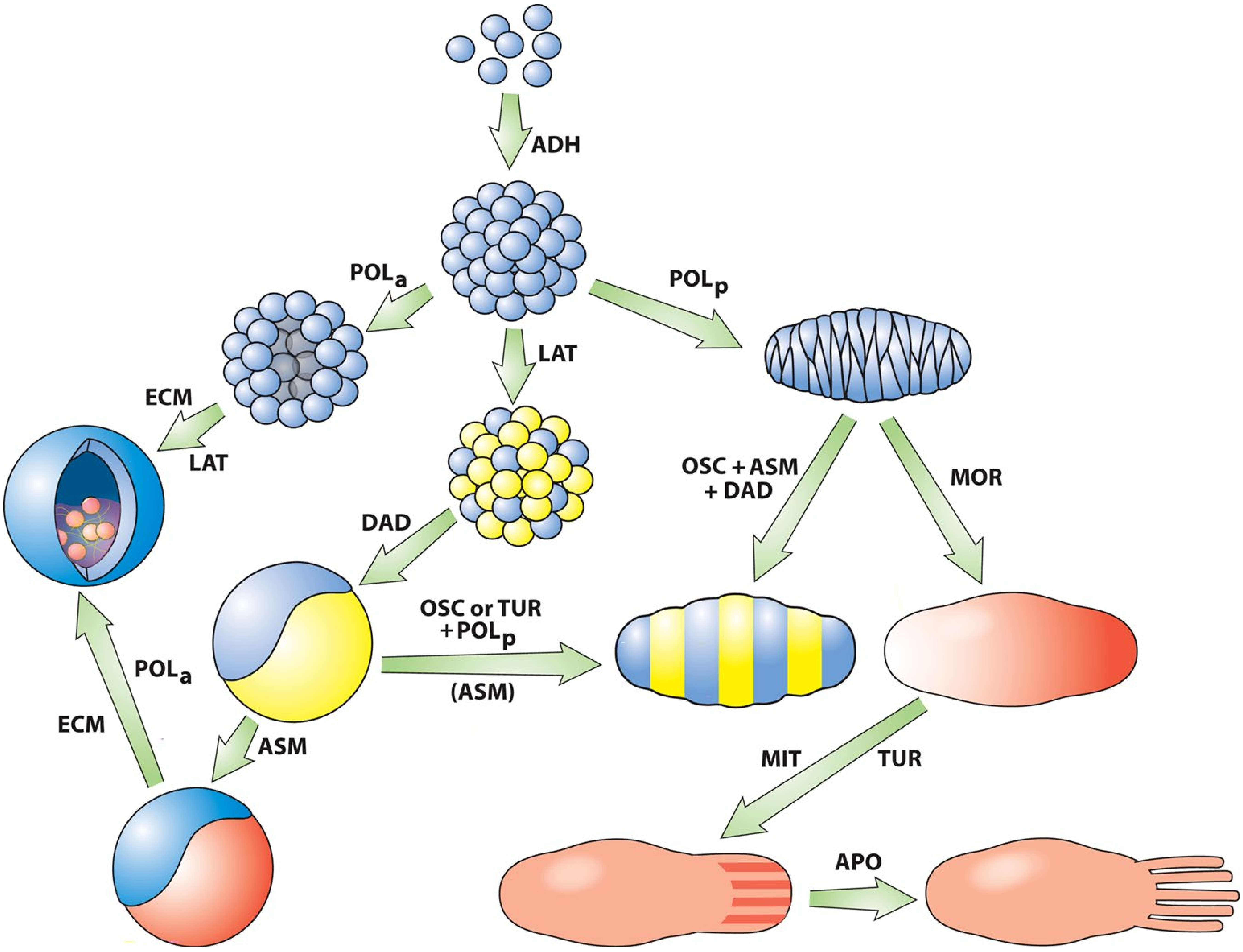


Cell *156*, 1032–1044, February 27, 2014 ©2014 Elsevier Inc.

DPM	molecules	physics	evo-devo role	effect
ADH	cadherins	adhesion	multicellularity	
LAT	Notch	lateral inhibition	coexistence of alternative cell states	
DAD	cadherins	differential adhesion	phase separation; tissue multilayering	
POL_a	Wnt	cell surface anisotropy	topological change; interior cavities	
POL_p	Wnt	cell shape anisotropy	tissue elongation	
ECM	chitin; collagen	stiffness; dispersal	tissue solidification; elasticity; EMT	
OSC	Wnt + Notch	synchrony of oscillation	morphogenetic fields; segmentation	
MOR	TGF-β/BMP; FGF; Hh	diffusion	pattern formation	
TUR	MOR + Wnt + Notch	dissipative structure	segmentation; periodic patterning	

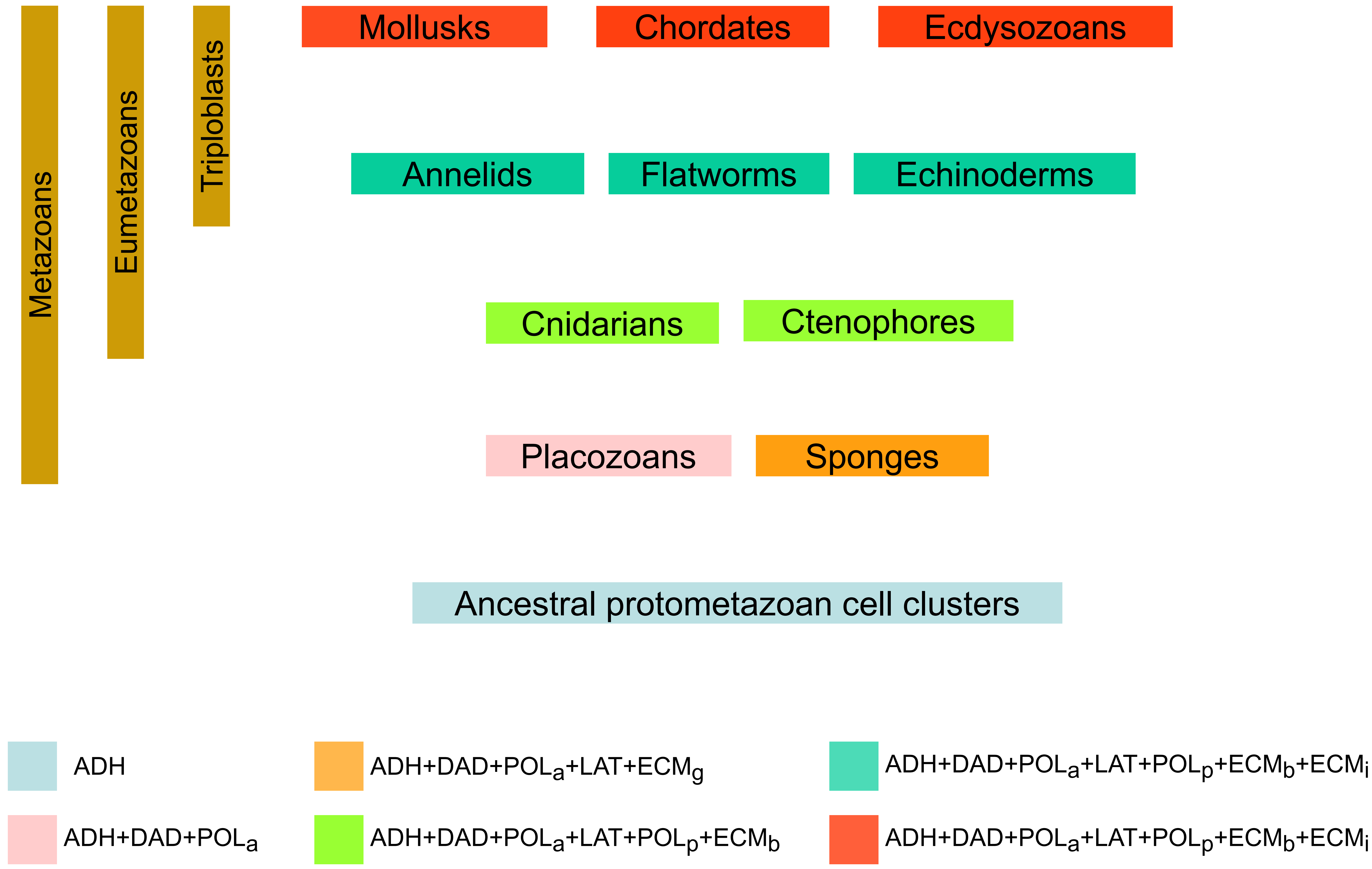
Newman and Bhat, *Phys. Biol.* 2008

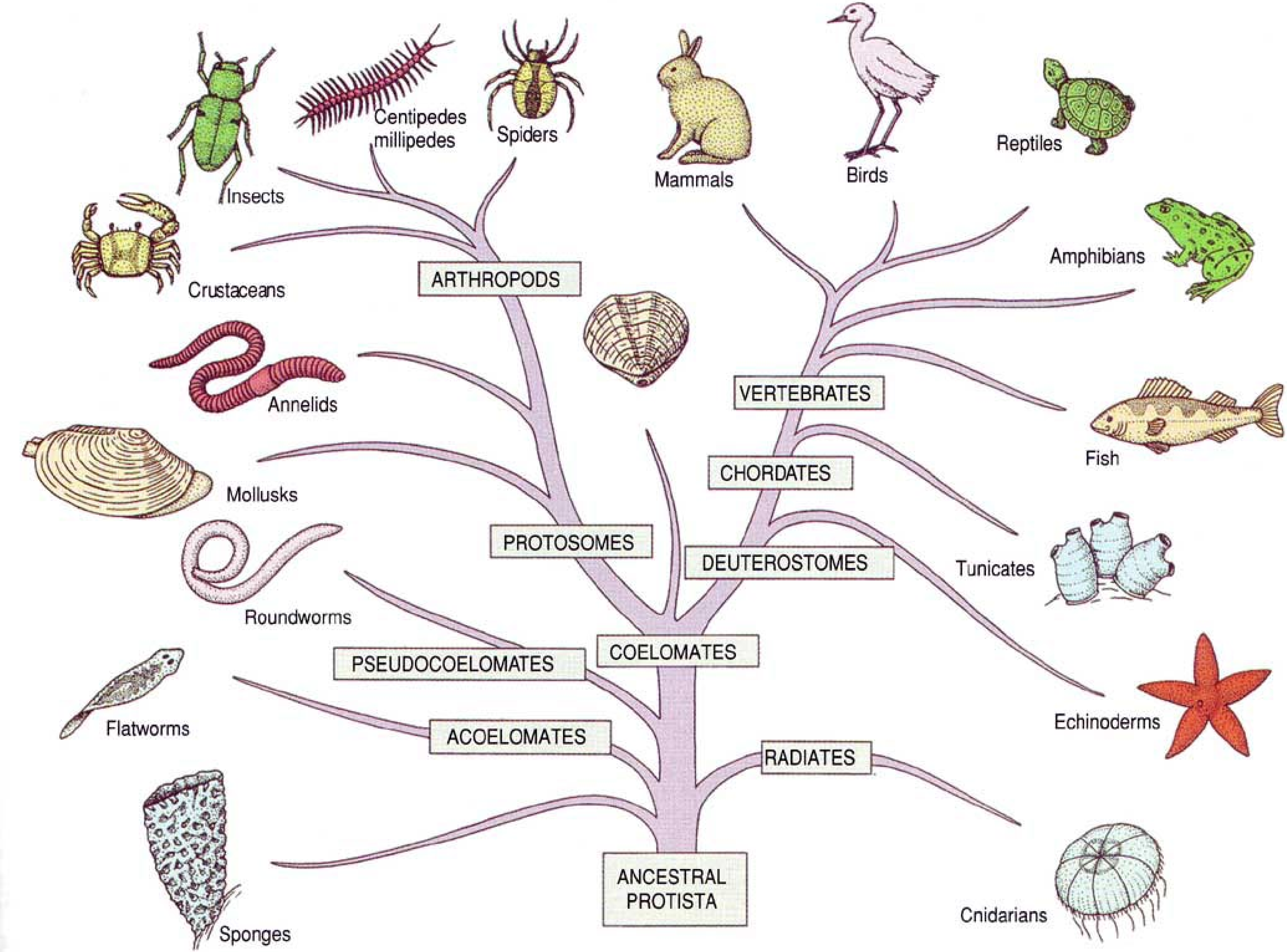
Combinatorial use of DPMs in metazoan origins



Newman & Bhat, *Int J Dev Biol*; 2009

Metazoan morphological complexity tracked successive addition of DPMs over evolution





Mark E. Nelson, Univ. Illinois

Conclusions

- The origination of multicellular forms was based on morphogenetic processes of mesoscale physics, mobilized by products of developmental "toolkit" genes.
- These "physico-genetic" mechanisms inescapably mediate saltational change and their morphological outcomes have therefore been qualitatively disparate and limited in range.
- **Punctuated equilibrium**, rather than **adaptive gradualism**, has thus been the inevitable mode of morphological evolution.

Key Collaborators

Mariana Benítez Keinrad, UNAM, Mexico City

Ramray Bhat, Indian Institute of Science, Bangalore, India

Karl Niklas, Cornell University, Ithaca, New York

Gerd Müller, Konrad Lorenz Institute, Klosterneuburg, Austria

Isaac Salazar-Ciudad, Centre de Recerca Matematica, Barcelona

Funding

John Templeton Foundation

Agency, Directionality & Function Program