A Pattern Language for Animal Form

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Second Life Embryo Course

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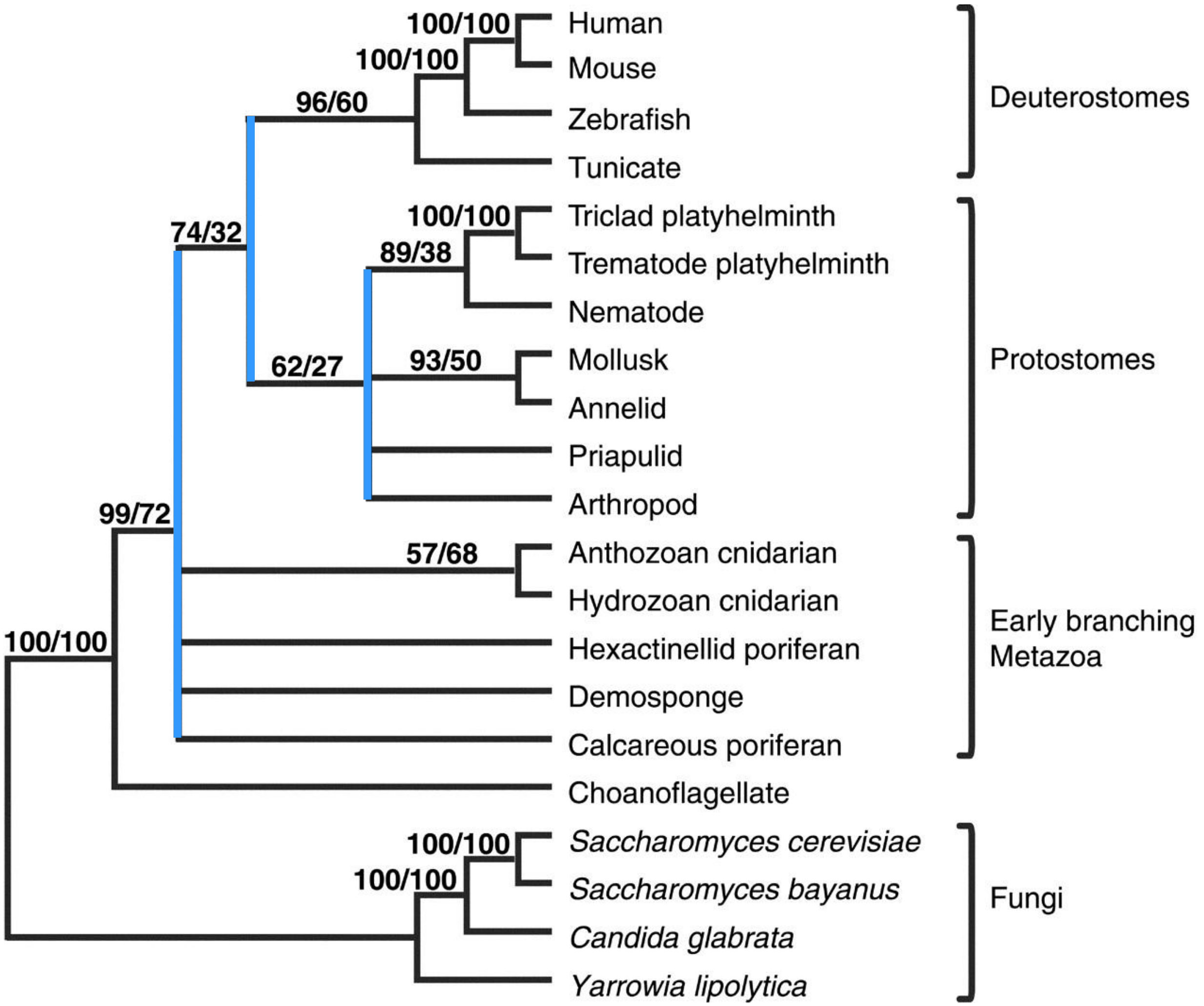
Animal Evolution and the Molecular Signature of Radiations Compressed in Time

Antonis Rokas,* Dirk Krüger,† Sean B. Carroll‡

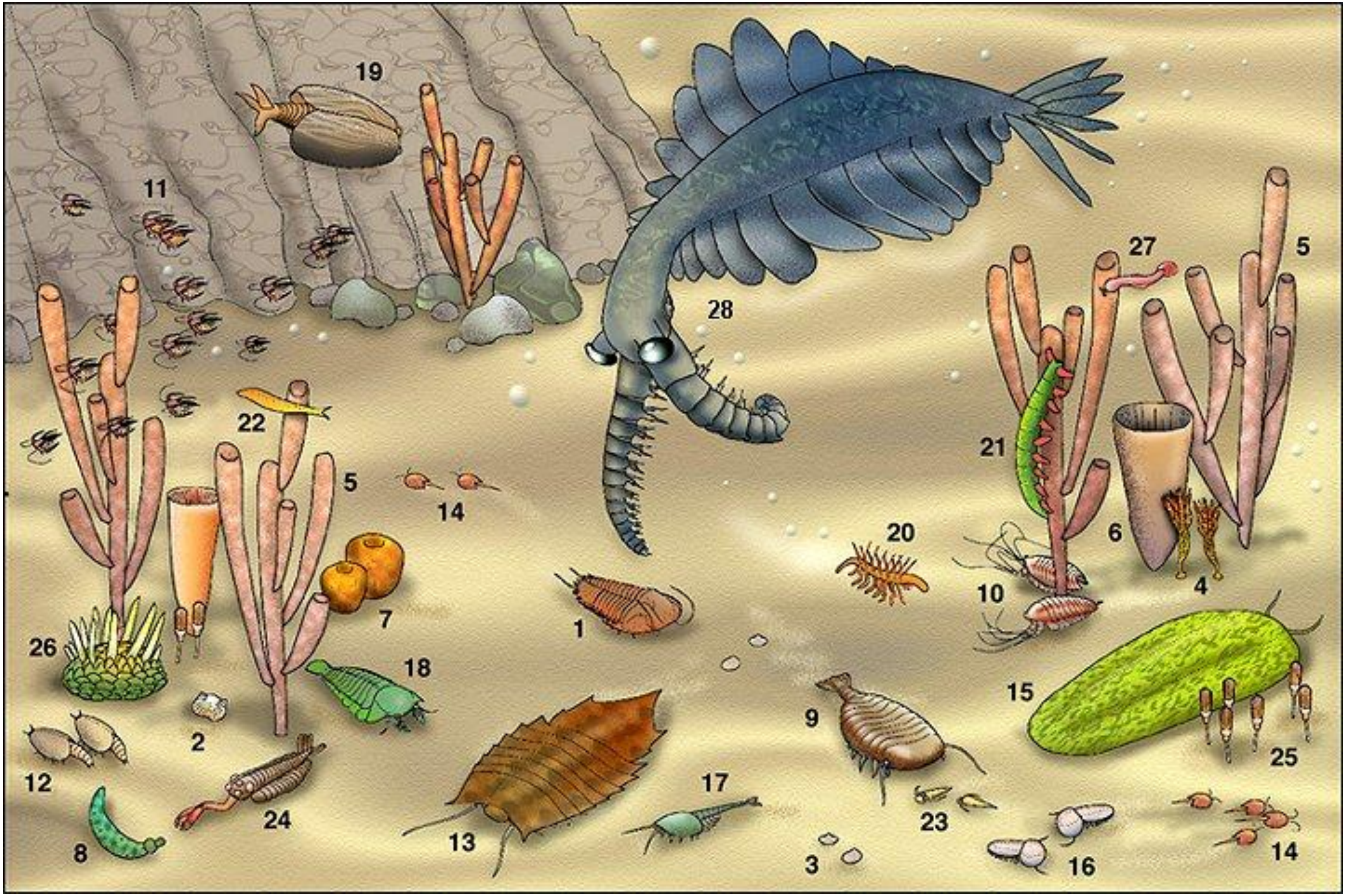
The phylogenetic relationships among most metazoan phyla remain uncertain. We obtained large numbers of gene sequences from metazoans, including key understudied taxa. Despite the amount of data and breadth of taxa analyzed, relationships among most metazoan phyla remained unresolved. In contrast, the same genes robustly resolved phylogenetic relationships within a major clade of Fungi of approximately the same age as the Metazoa. The differences in resolution within the two kingdoms suggest that the early history of metazoans was a radiation compressed in time, a finding that is in agreement with paleontological inferences. Furthermore, simulation analyses as well as studies of other radiations in deep time indicate that, given adequate sequence data, the lack of resolution in phylogenetic trees is a signature of closely spaced series of cladogenetic events.

Rokas et al., *Science*; 2005

The lack of resolution in phylogenetic relationships among major metazoan phyla



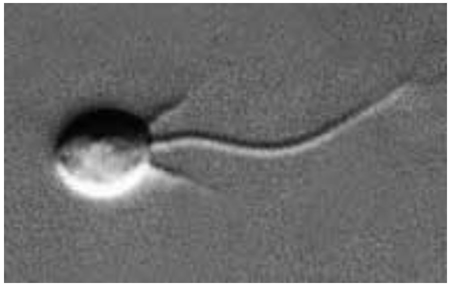
Rokas et al., *Science*; 2005



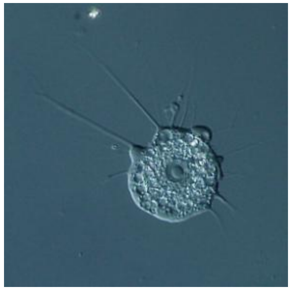
Reconstruction of the Burgess Shale Fauna by S.M. Gon III

http://www.trilobites.info/triloclass.htm

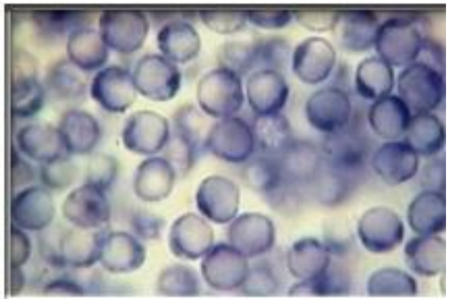
The phylum Choanozoa is a unicellular sister clade of the Metazoa



Monosiga brevicollis



Nuclearia



Mesomycetozoea

One or more of the choanozoans (and thus the unicellular ancestor of the Metazoa) contain genes specifying cadherins, C-type lectins, Notch and Hedgehog, members of the metazoan developmental-genetic toolkit.

King *et al.*, *Nature* 451:783; 2008
Shalchian-Tabrizi *et al*., *PLoS ONE* 3:e2098; 2008

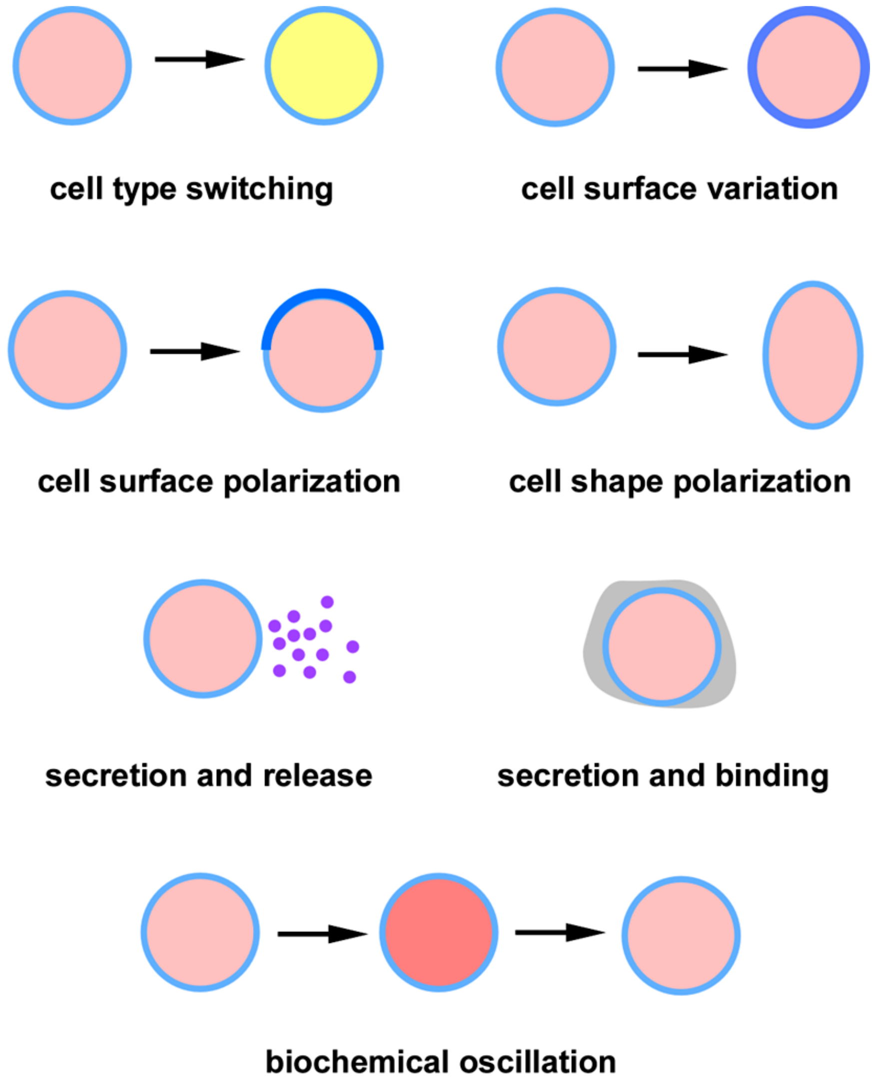
Proposition

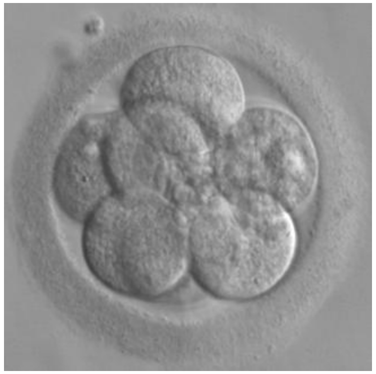
Metazoan form originated and rapidly diversified by the action of **Dynamical Patterning Modules (DPMs)**.

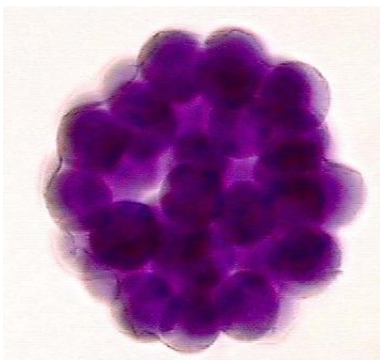
Definition: DPMs are complexes of proteins (and some polysaccharides) that mediate cell behavior or cell-cell interaction by mobilizing one or more physical forces or effects.

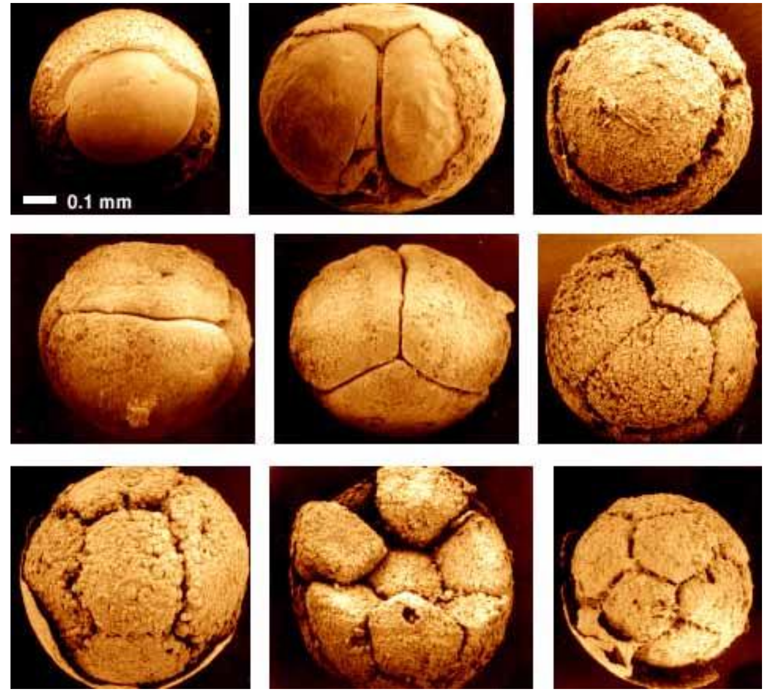
Hypothesis: DPMs originated when ancient cellular molecules (many of which were present in unicellular ancestors of the metazoa) assumed novel physical functions due to the change of scale and context in the multicellular state.

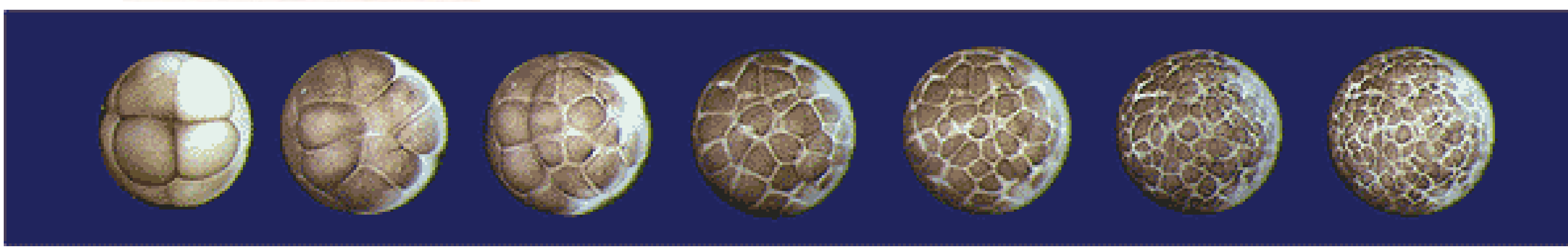
Some single-cell functionalities





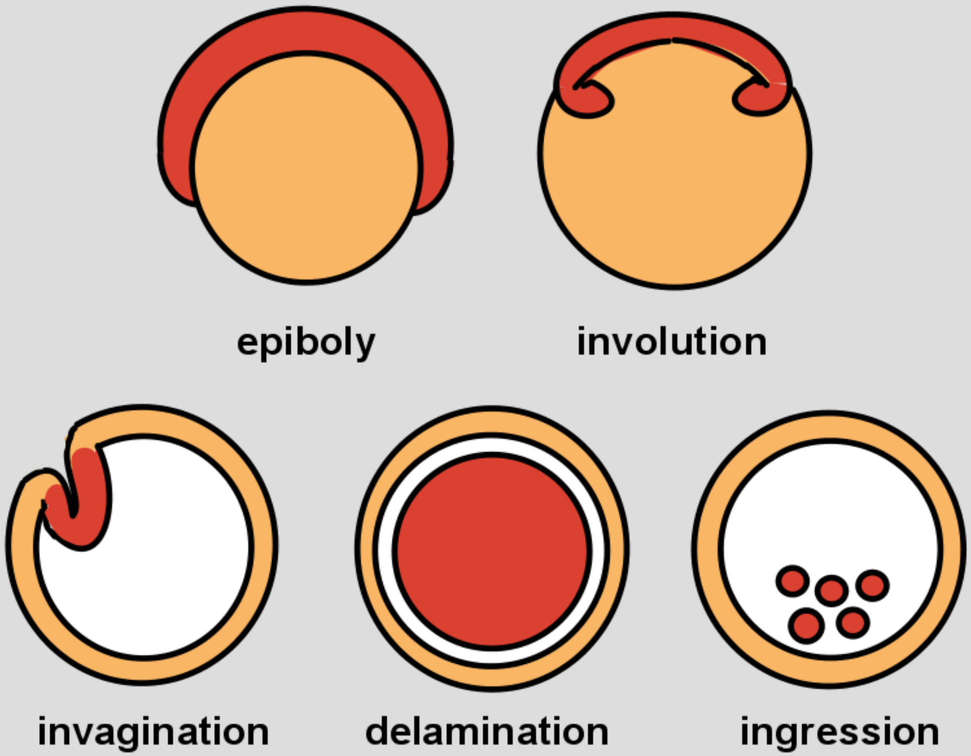




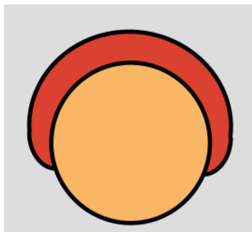


Upper left, Human morula; RWJMS IVF Program
Middle left, Starfish morula; K. Wynne, Tyler Junior College
Right, Fossil “embryos”; Ediacaran Doushantuo Formation; Shuhai Xiao, Virginia Tech
Bottom, Frog blastula; www.snv.jussieu.fr/bmedia/xenope1/xenope3.html

The main types of gastrulation

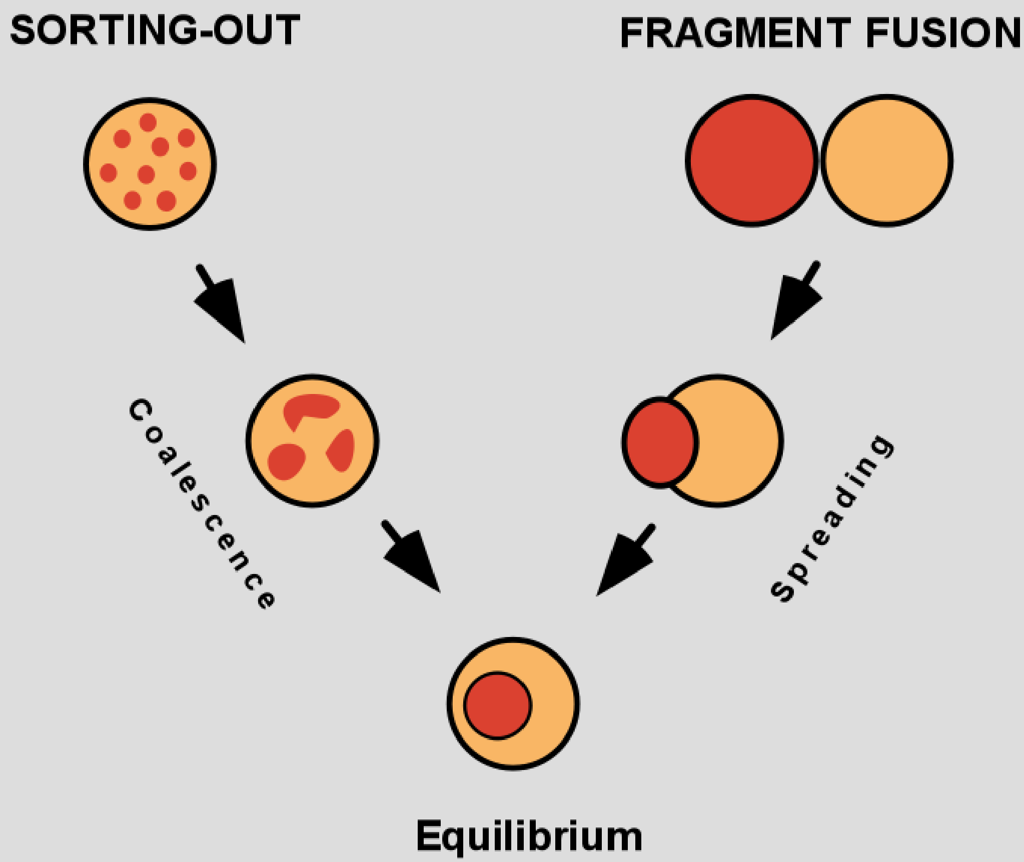


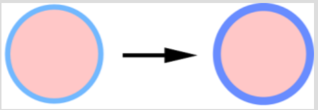
Gastrulation can involve engulfment-like tissue rearrangement (e.g., zebrafish)



AG Gajewski; University of Cologne

Differential adhesion of cell subpopulations leads to cell sorting and tissue engulfment

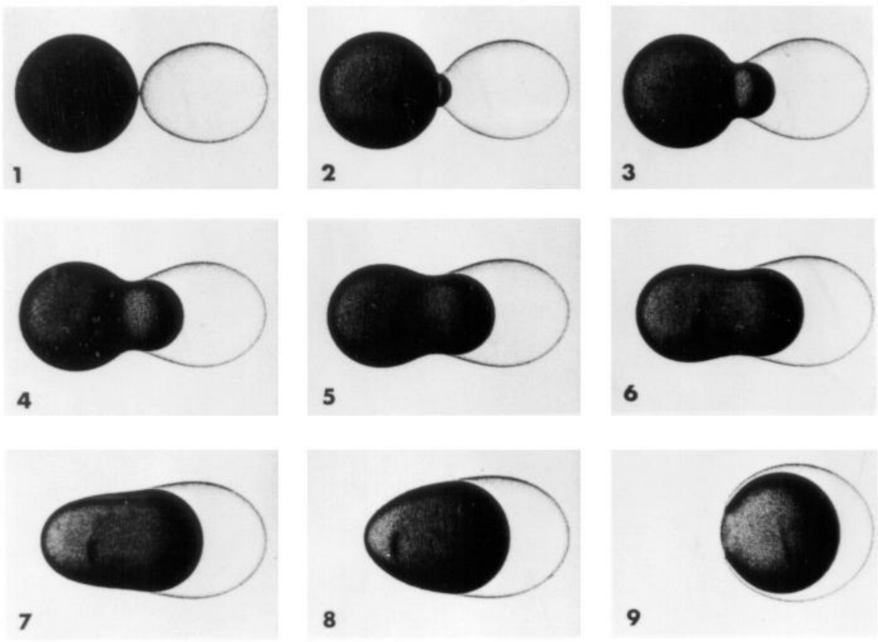




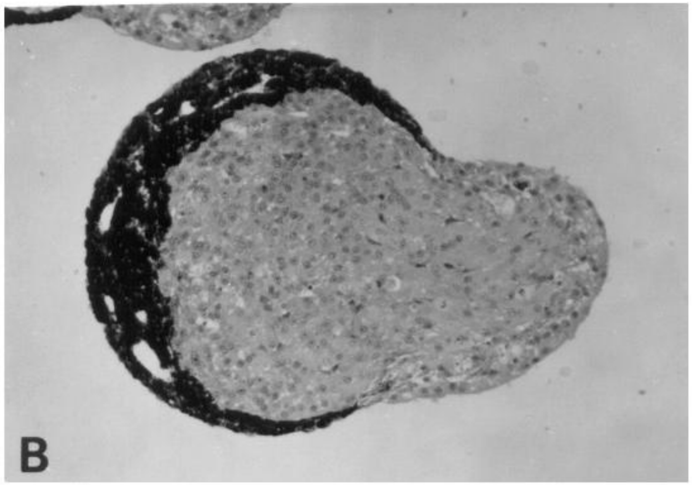
Toolkit molecules: cadherins; lectins

Based on Steinberg, 1978

Phase separation and engulfment behavior in liquids and tissues

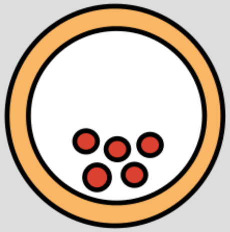


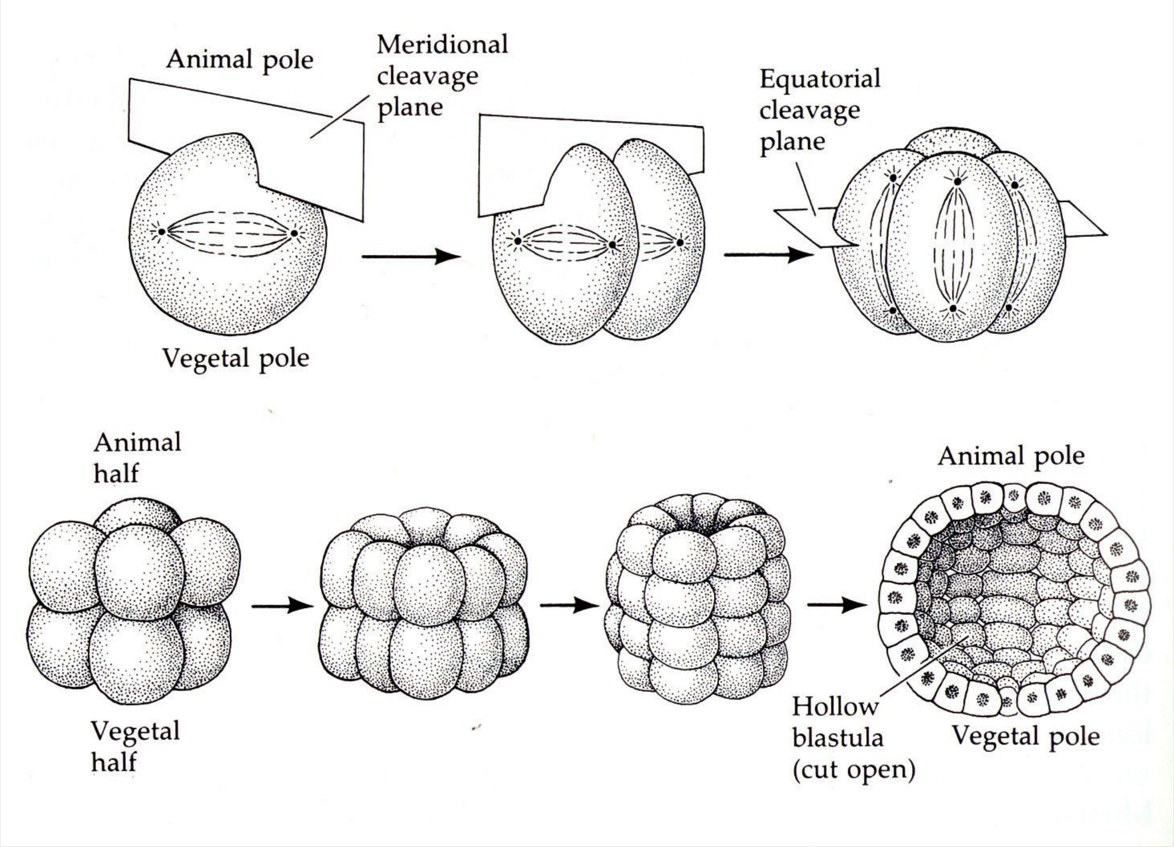
Torza and Mason *Science* 163: 813; 1969



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

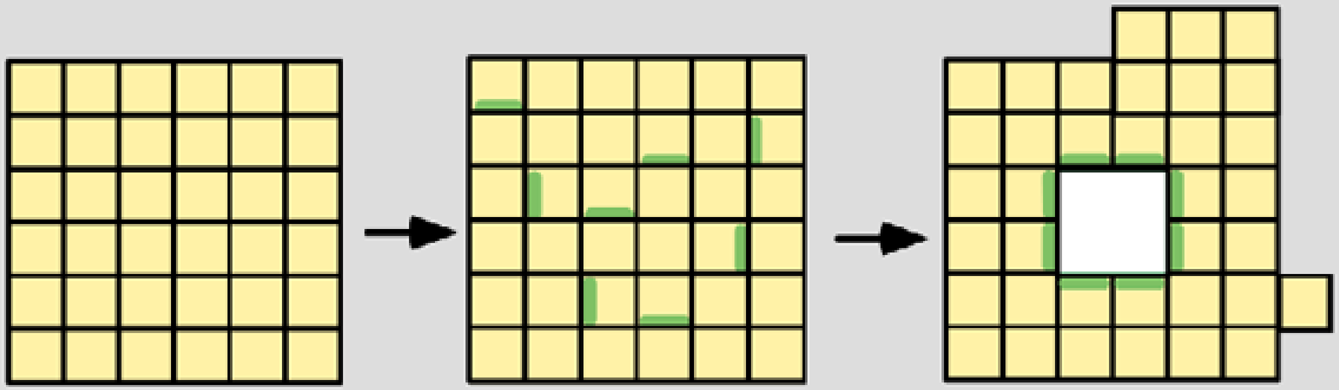
Gastrulation often involves lumen formation (e.g., sea urchins)

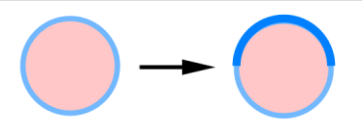




Gilbert, *Developmental Biology,* Sinauer, 2000

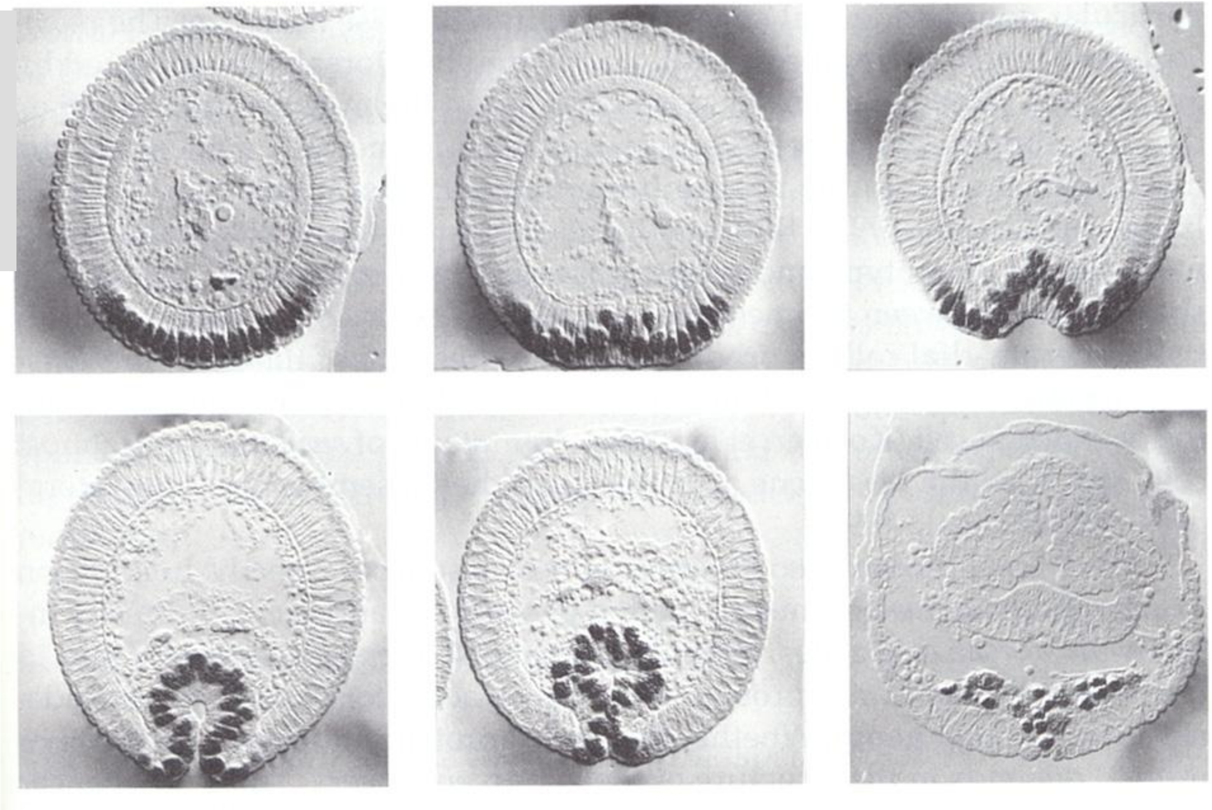
Lumens can automatically arise in clusters of cells that are individually (apico-basally) polarized





<u>Toolkit molecules</u>:
Wnt pathway

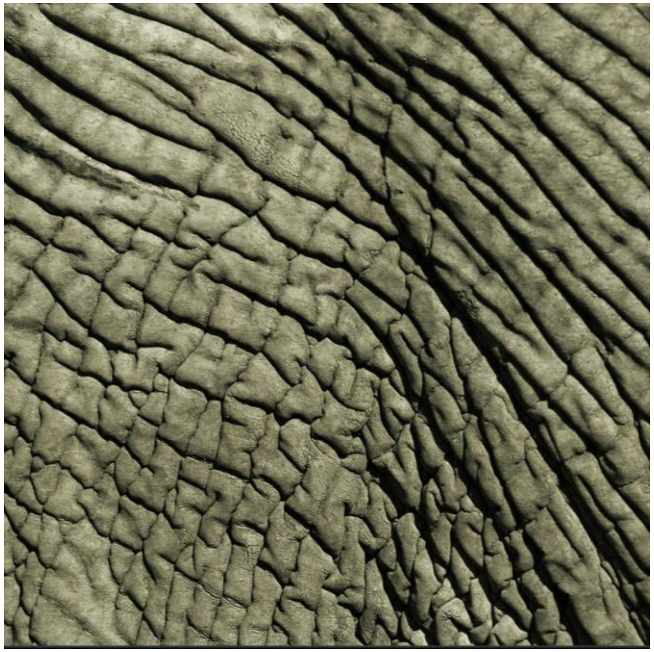
Gastrulation can involve buckling-like movements of tissue sheets (e.g., *Drosophila*)



Leptin, *In* Keller et al, eds.,
Gastrulation, Plenum; 1991

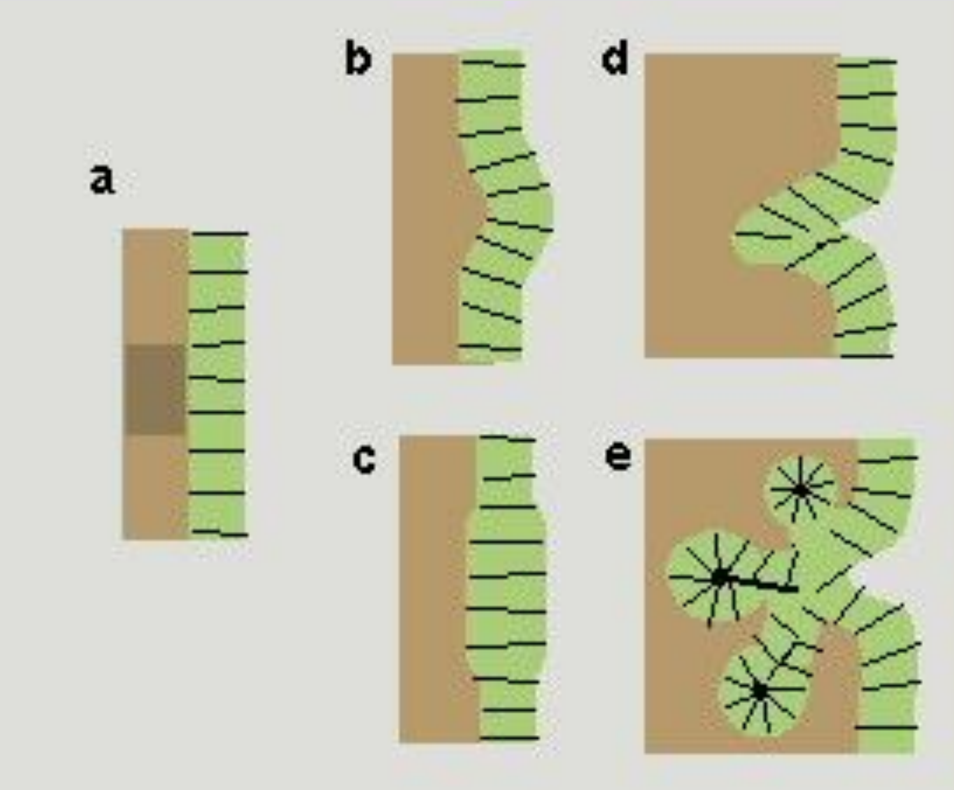
Buckling: dried paint and elephant skin

www.scottcamazine.com/



photography.nationalgeographic.com

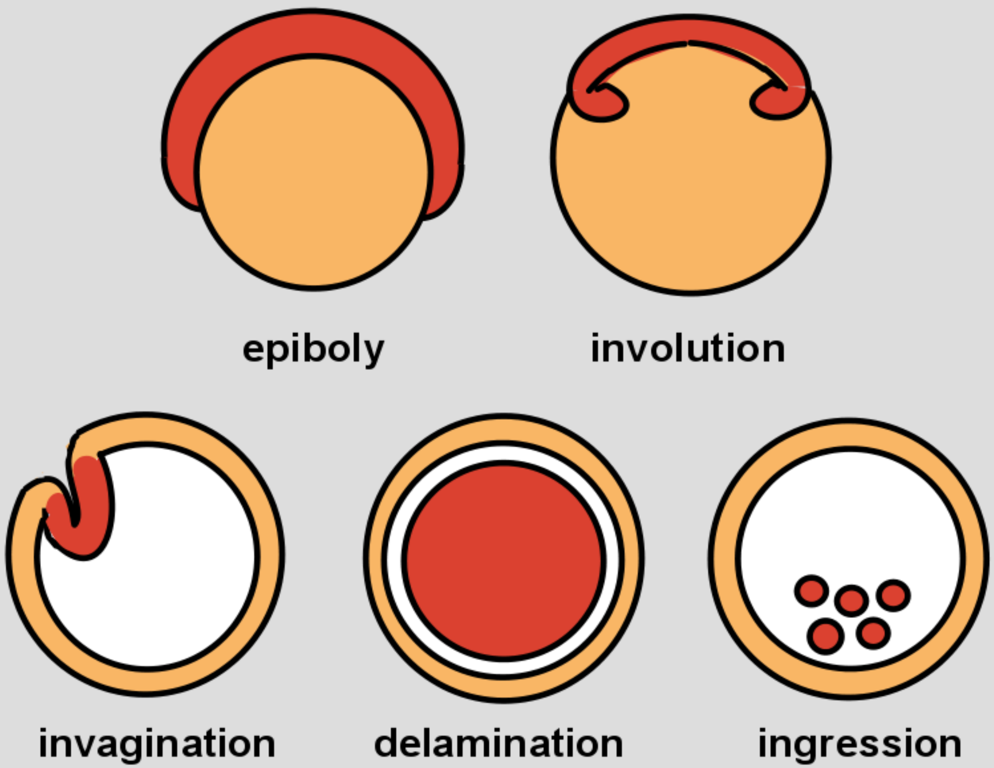
Modes of epithelial morphogenesis arising from position-dependent modulation of stiffness and viscoelasticity



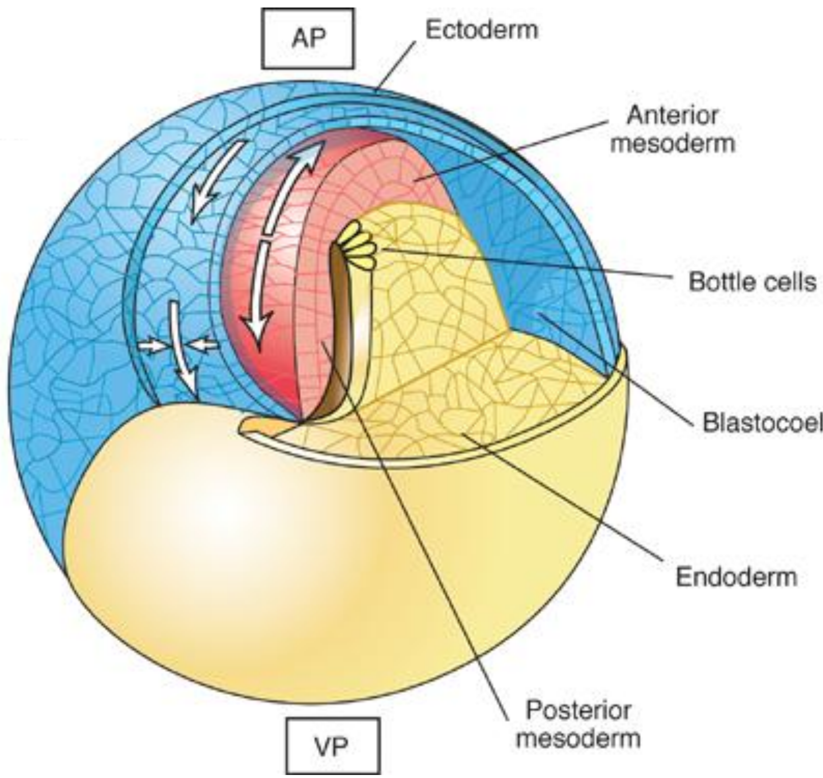
<u>Toolkit molecules</u>: collagen and other ECM molecules

Theory in: Gierer, *Q. Rev. Biophys*; 1977; Mittenthal and Mazo, *J. Theor. Biol*; 1983

Plausible physical bases of origination of gastrulation: differential adhesion (phase separation and engulfment), $\pm$ cell polarity, $\pm$ epithelial folding

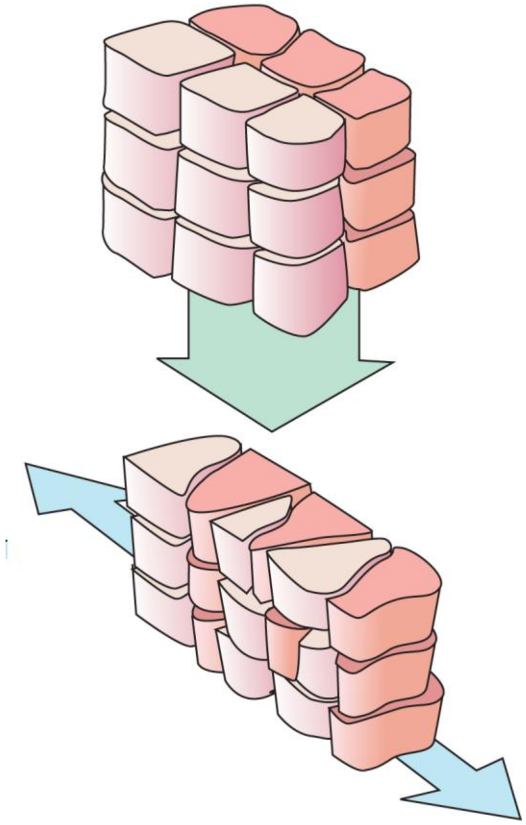


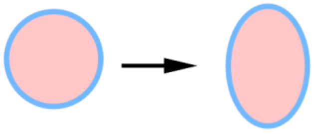
Embryos typically undergo elongation (e.g., during amphibian gastrulation)



Forgacs & Newman, *Biological Physics of the Developing Embryo*; 2005 (After Keller et al., 2000)

Tissue narrowing and elongation can arise from intercalation of (planar) polarized cells

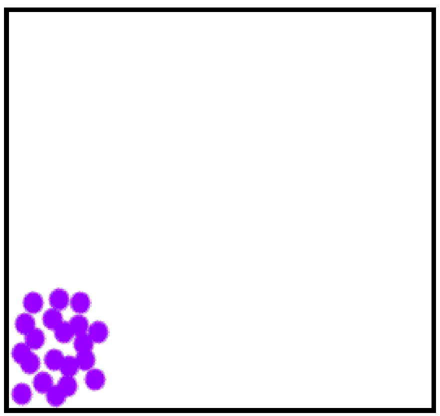




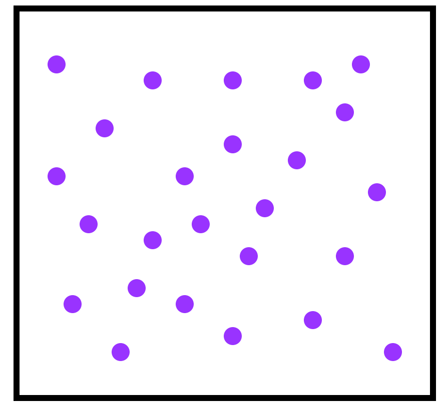
<u>Toolkit</u>
<u>molecules</u>:
noncanonical
Wnt pathway

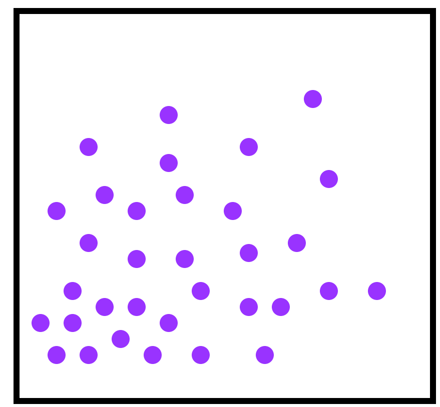
Forgacs & Newman, *Biological Physics of the Developing Embryo*; 2005 (After Keller et al.)

Diffusion, depending on rates, distances, etc., can…



even things out, or…

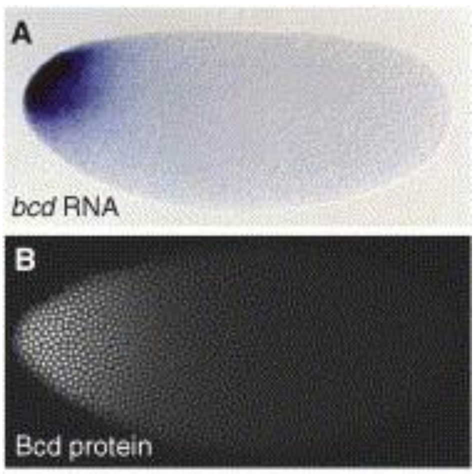




produce gradients

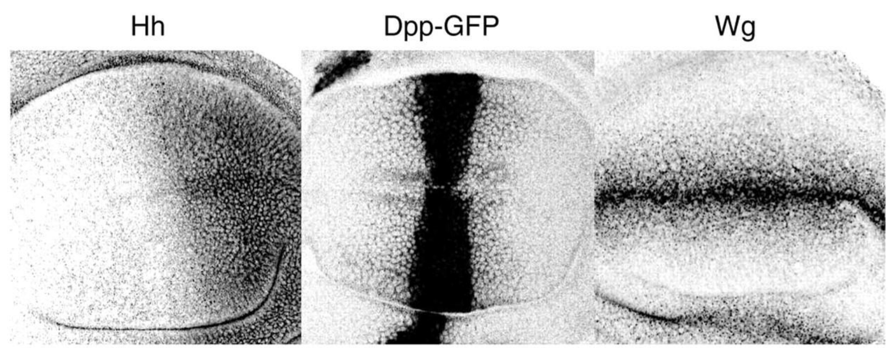
Morphogen gradients

Drosophila syncytial embryo

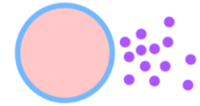


FlyEx database; © David Kosman and John Reinitz

Drosophila imaginal disk



Tabata and Takei; *Development*, 2004



<u>Toolkit molecules</u>:
Hh; FGF; BMP/TGFβ

"A morphogenetic field is a system of order such that the positions taken up by unstable entities in one part of the system bear a definite relation to the position taken up by other unstable entities in other parts of the system."

Joseph Needham, 1950

Chemical oscillation

W. Escudier, Académie d’Aix Marseille

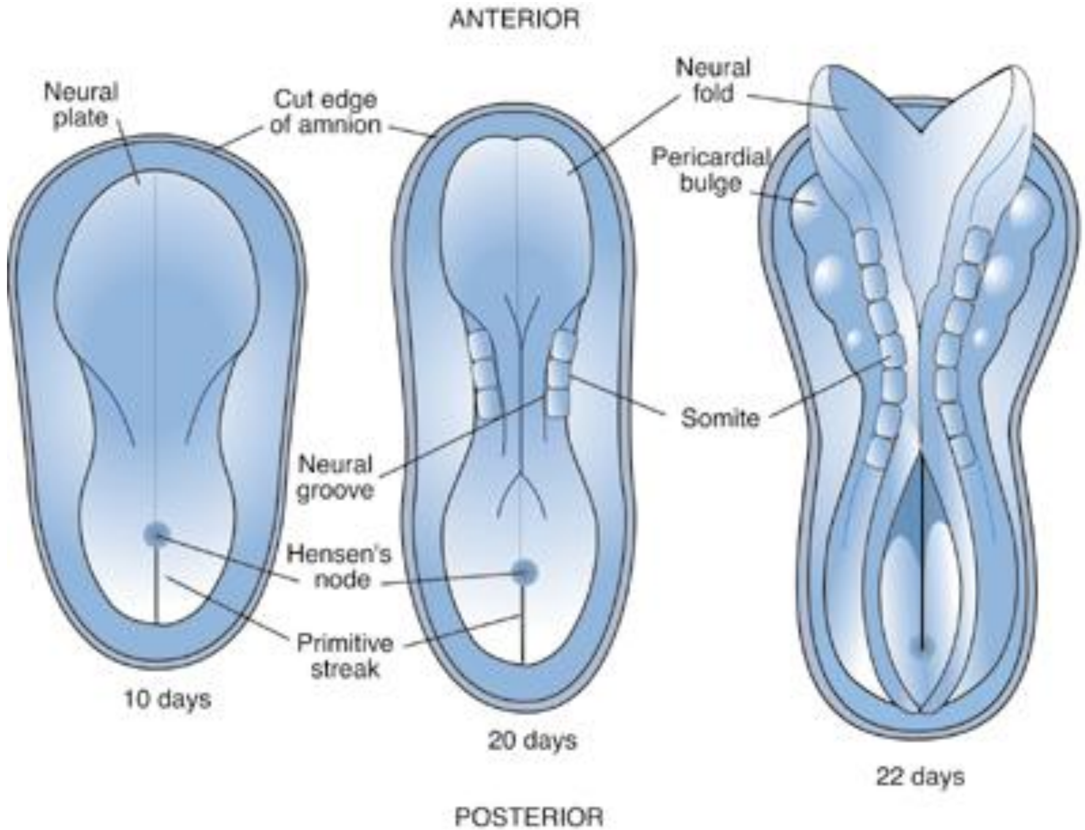
http://www.youtube.com/watch?v=Ch93AKJm9os

Synchronization of oscillators

A. Bahraminasab, Lancaster University, UK

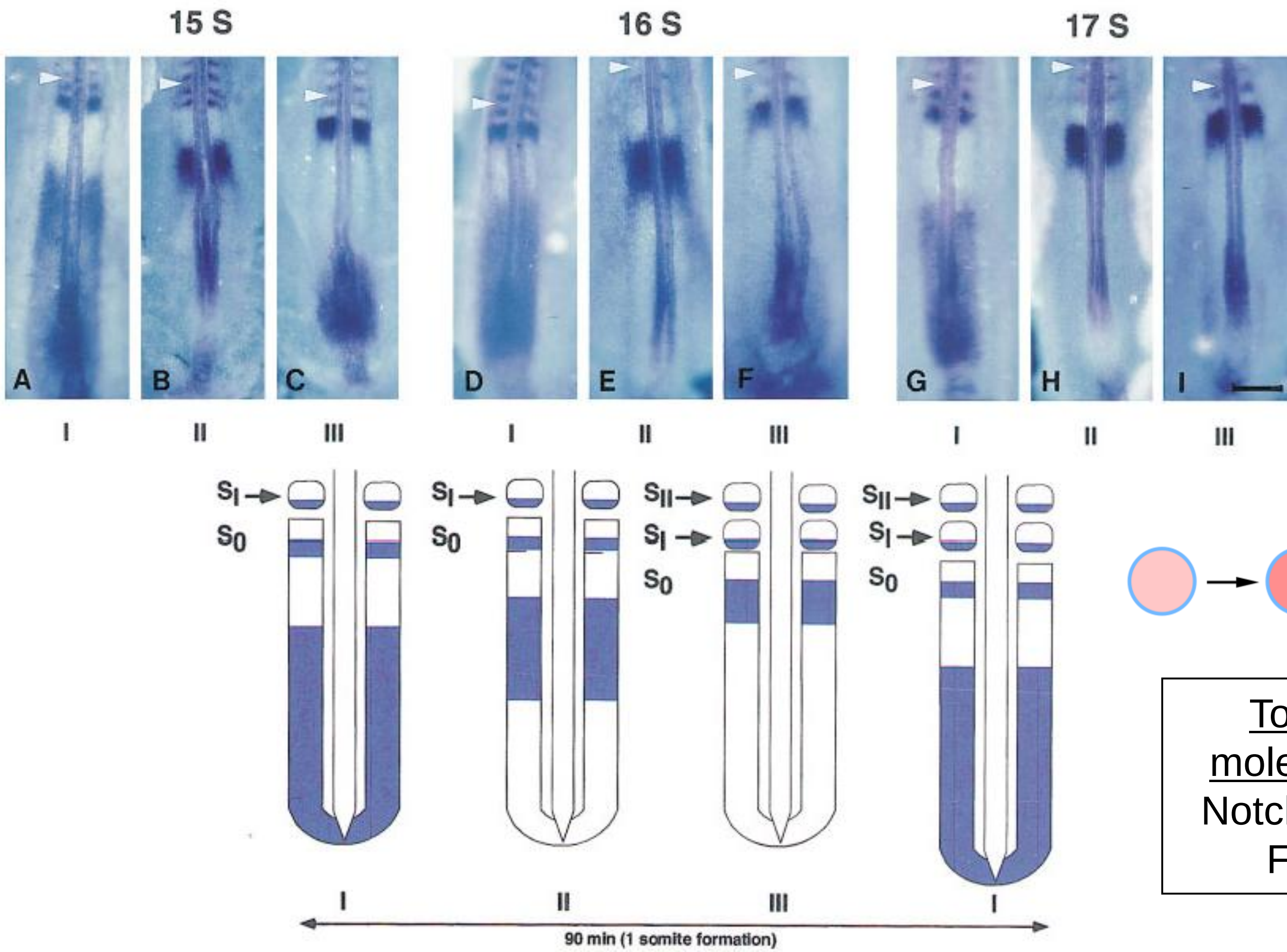
http://www.youtube.com/watch?v=W1TMZASCR-I

Somitogenesis: formation of paired segmental blocks of tissue along the vertebrate embryo midline



Forgacs & Newman, *Biological Physics of the Developing Embryo*; 2005

Somitogenesis results from synchronized biochemical oscillation interacting with a molecular gradient



<u>Toolkit molecules</u>: Notch; Wnt: FGF

Palmeirim et al., 1997

How did the metazoa originate?

• The described physical forces, effects and processes (adhesion/differential adhesion; surface and shape polarity; diffusion; chemical oscillation; LALI, etc.) are all “generic”: in principle, they could be mediated by many alternative gene products.

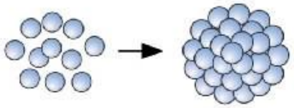
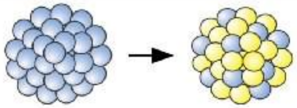
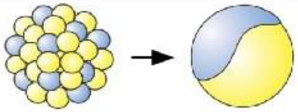
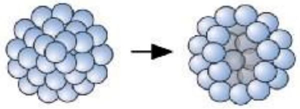
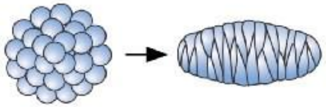
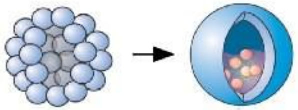
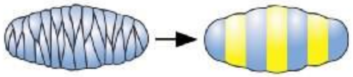
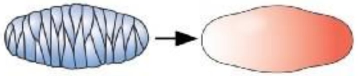
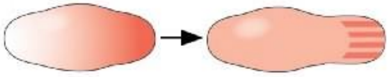
• The corresponding dynamical patterning modules could therefore have been invented again and again during the more than half a billion years of metazoan evolution. However…

The "molecular homology-analogy paradox"

Products of homologous genes (the "developmental-genetic toolkit") are used to generate corresponding body and organ pattern elements in distantly related animal species for which there is often no common ancestor with the corresponding morphological motif.

Resolution of the molecular homology-analogy paradox

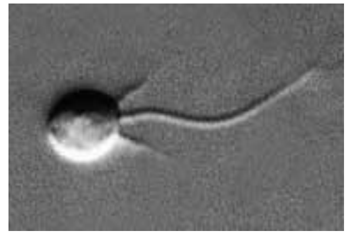
- The metazoan DPMs employ a subset of the toolkit gene products: cadherins, Notch and Wnt pathways, BMP, Hedgehog and FGF morphogens, collagen, chitin and hyaluronan ECMs, etc.
- Although most of these molecules and/or associated pathways were present in unicellular antecedents of the Metazoa, they did not mediate pattern formation and morphogenesis in those organisms.
- In the multicellular context and spatial scale, they became immediately active in these processes by virtue of the physics they brought into play.

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

Presence of basic DPMs in metazoan and related clades

Choanozoa:
(unicellular sister clade of Metazoa)



ADH; DAD: cadherins; C-type lectins

LAT: Notch (only some species)

MOR: Hh

ECM: collagen

All of above, plus

POL: Wnt

no Notch

Placozoa Porifera
(basal metazoans)

All of above, plus

MOR: TGF-β

POL: Wnt

Cnidaria:
(eumetazoans)

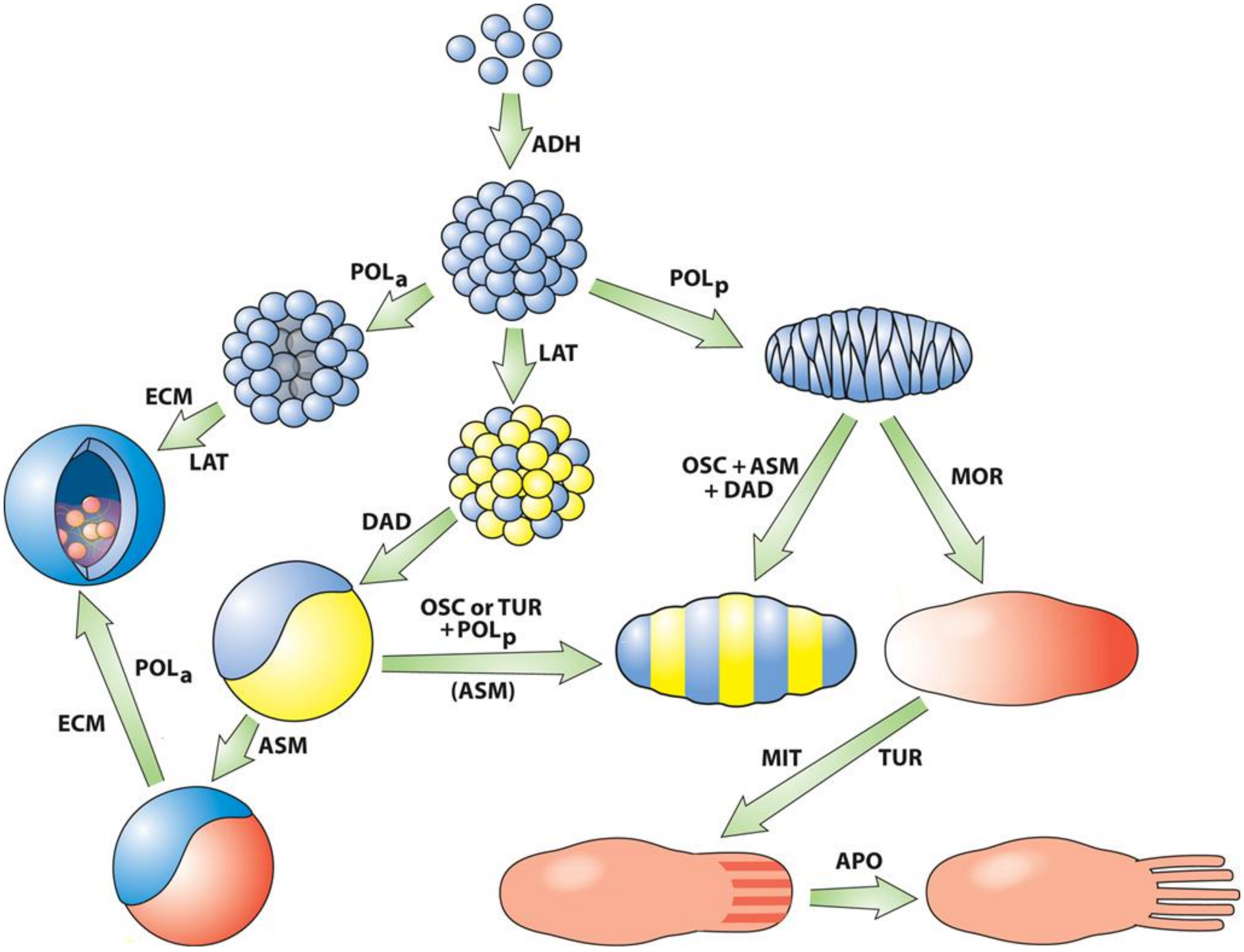
All of the above, plus

MOR: FGFs

Arthropods; chodates:
(Bilateria)

All of the above

Combinatorial use of DPMs in Metazoan origination



Newman & Bhat *Int J Dev Biol*; in press