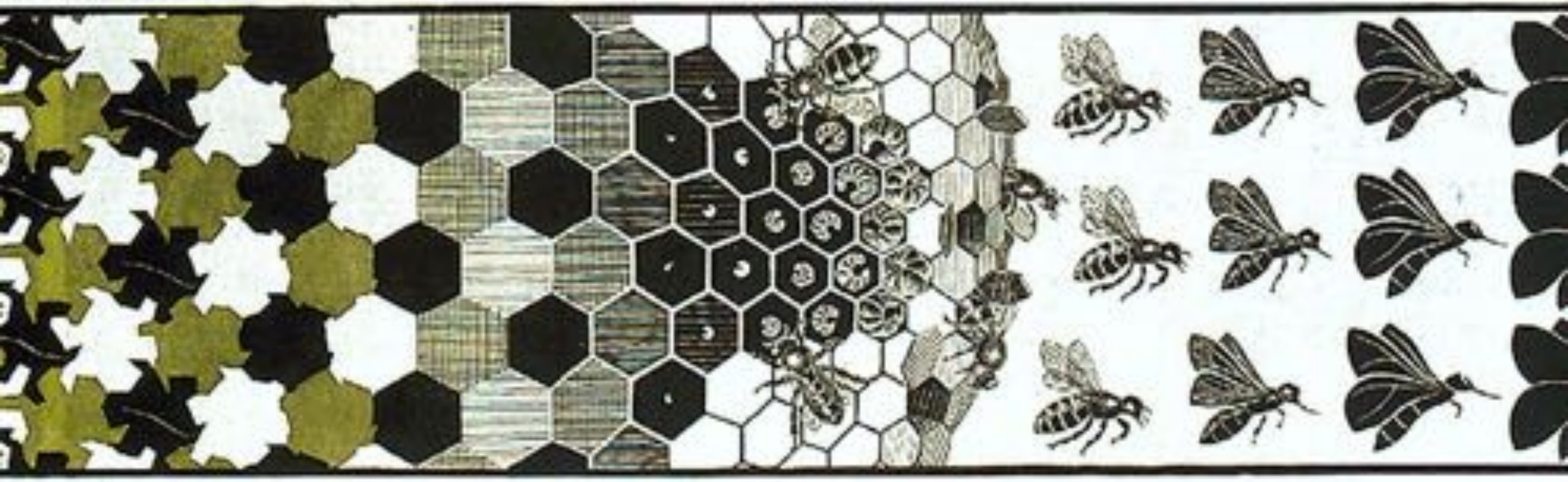
Metamorphosis



Laurel Sky Hiebert
Postdoc in Federico's Lab
June 4, 2015

Outline of lecture

Part 1: What is metamorphosis?
An overview of diversity of metamorphic types

Part 2: The mechanisms regulating metamorphosis
Focus on frogs and flies

Part 3: The evolution of metamorphosis
Is metamorphosis ancestral to all animals? Or has it evolved many times?

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Is metamorphosis ancestral to all animals? Or has it evolved many times?

Is this metamorphosis? A challenge!

RULES:

I will show photos of the life cycle of different organisms

Raise your hand if you think that the term “metamorphosis” applies

Is this metamorphosis?

Is this metamorphosis?

Is this metamorphosis?

Is this metamorphosis?

Is this metamorphosis?

How do biologists define metamorphosis?

What is metamorphosis?

C. D. Bishop,[*] D. F. Erezyilmaz,[†] T. Flatt,[‡] C. D. Georgiou,[§] M. G. Hadfield,[*] A. Heyland,[¶,**] J. Hodin,[1,††] M. W. Jacobs,[†,**] S. A. Maslakova,[**] A. Pires,[‡‡] A. M. Reitzel,[§§] S. Santagata,[**,¶¶] K. Tanaka[†] and J. H. Youson[***]

From the symposium "Metamorphosis: A Multikingdom Approach" presented at the annual meeting of the Society for Integrative and Comparative Biology, January 4–8, 2006, at Orlando, Florida.

Biologists have a variety of conceptions of metamorphosis

Table 1 Summary of the various conceptions of metamorphosis presented here

Author	Habitat shift	Major morphological change	Change in adaptive landscape	Rapid	Change in feeding mode	Pre metamorphic stage is post-embryonic	Usually pre-reproductive to reproductive stage transition	Transition is generally hormone-regulated	Is plant flowering metamorphic?
Cory Bishop			X			X	X		Yes
Deniz Erezyilmaz		X	[1]			X	X	X	Yes
Thomas Flatt	X	X	X		X	X	X		No
Christos Georgiou		X	X					X	Yes
Michael Hadfield	X	X	X		X	X			No
Andreas Heyland	X	X	X		X	X	X	X	No
Jason Hodin	X	X	X		X	X	X	X	Yes
Molly Jacobs	X	X	X	X[2]	X[2]	X[2]			No
Svetlana Maslakova	X	X	X		X	X			No
Tony Pires		X	X[3]			X	X		No
Adam Reitzel	X		X		X	X	X		No
Scott Santagata	X	X[4]	X			X			No
Kohtaro Tanaka	X	X	X			X			Yes[5]
John Youson	X	X	X		X	X	X	X	No[6]

So, there is no single definition of metamorphosis

But we call agree that it involves some change in form during development

The spectrum of metamorphic life cycles

Direct development

Indirect development

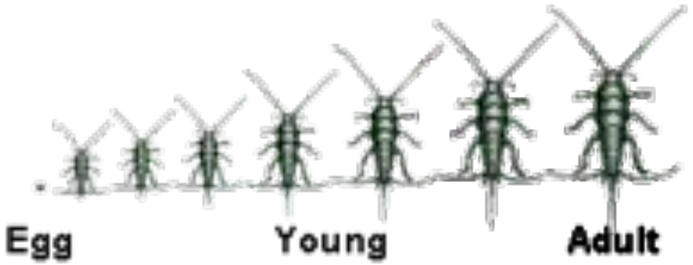
Just change in size

Change in *form*

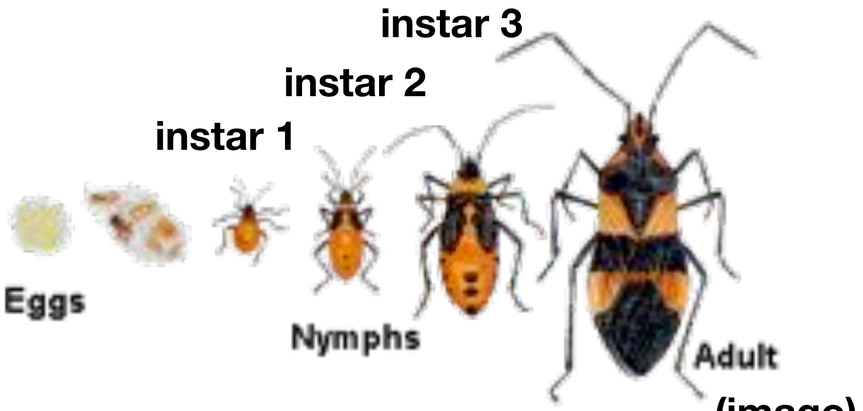
Let’s look at a diversity of metamorphic life cycles and see how they fit on this spectrum…

Insects display three different types of development

ametabolous insects



hemimetabolous insects



(imago)

holometabolous insects

larva pupa

adult

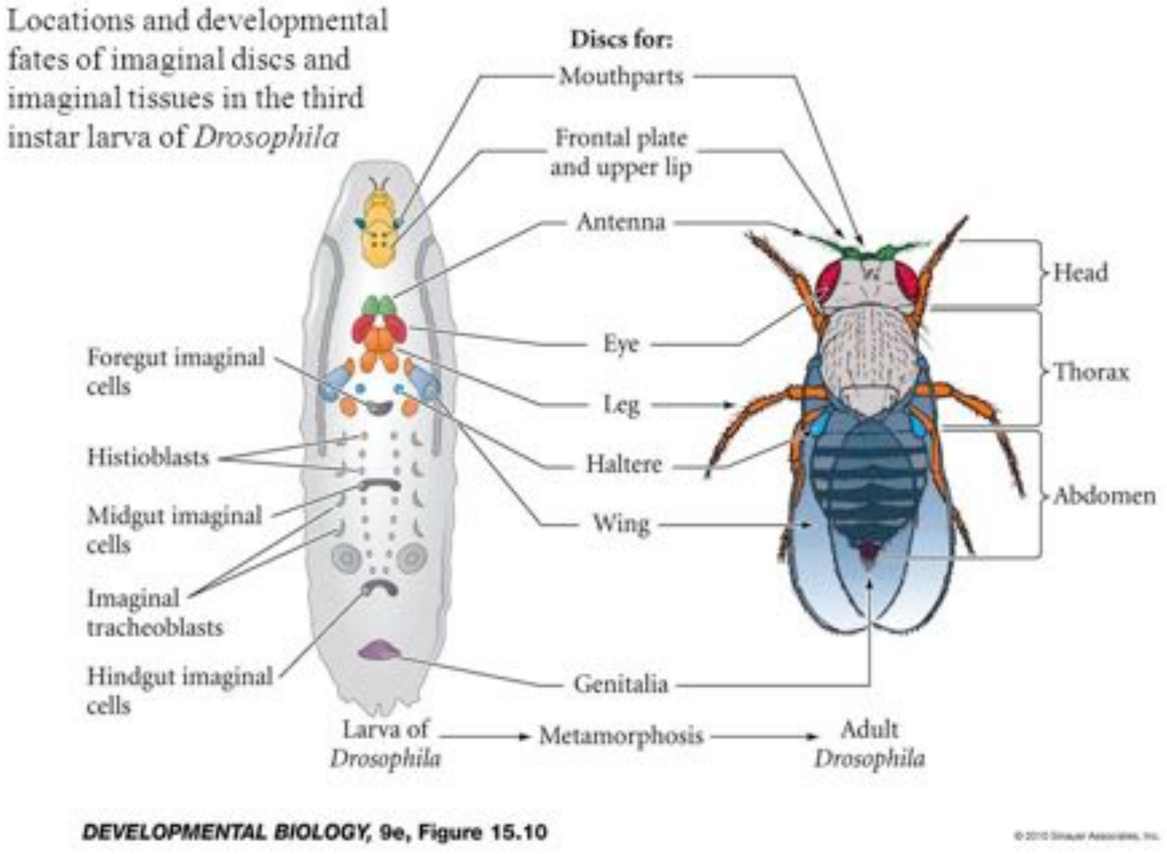
(each larval molt is called an instar)

Holometabolous insect imaginal discs

https://www.youtube.com/watch?v=rcAN4rkTmNU

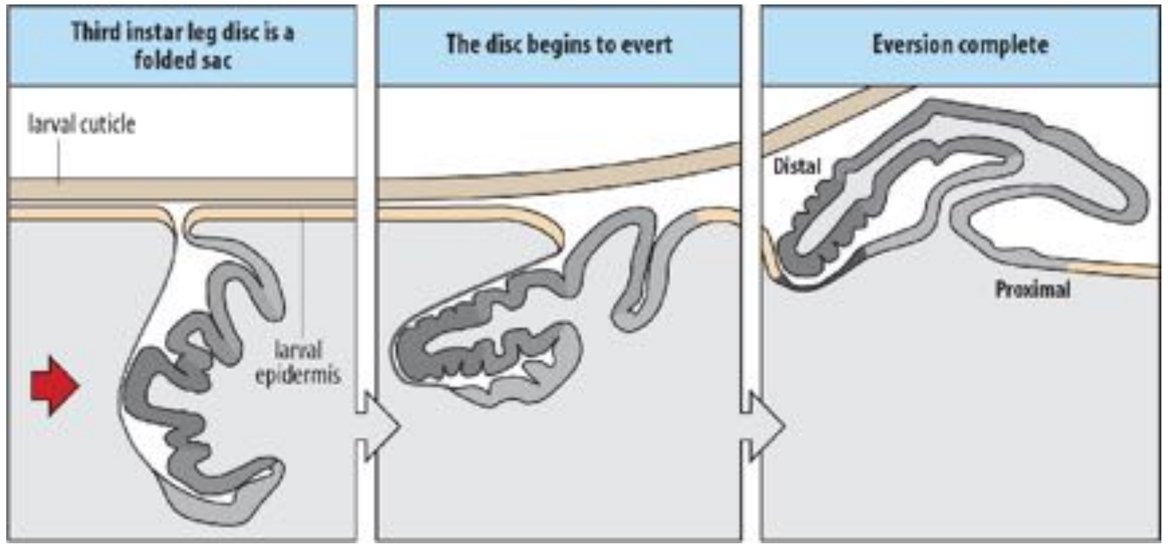
Insect imaginal discs (and cells) are tucked-away structures that form the adult

19 discs and a few other imaginal cells each become part of the adult

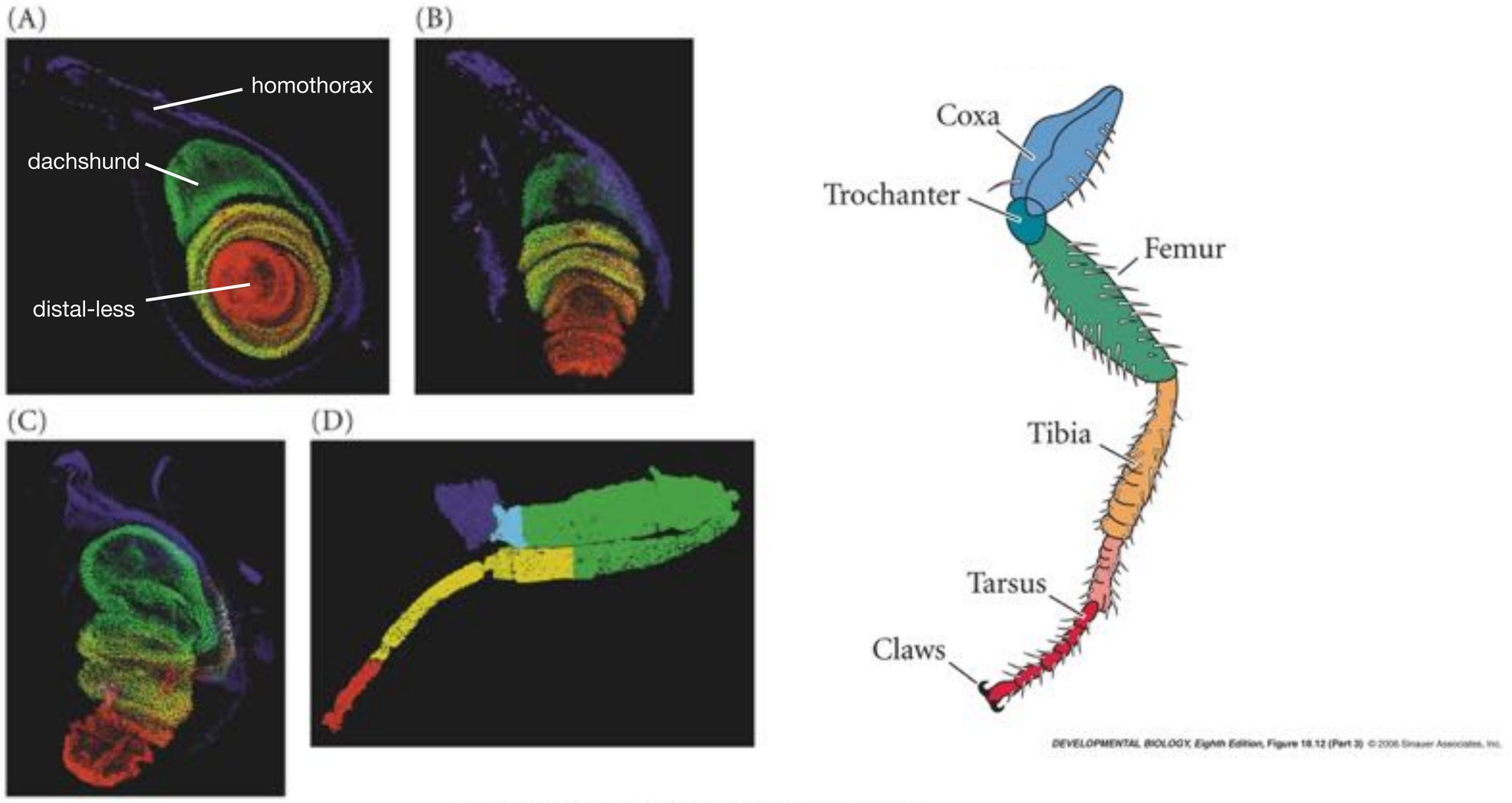


***DEVELOPMENTAL BIOLOGY*, 9e, Figure 15.10**

The discs are folded up inside and evert at metamorphosis



Fates of imaginal disc cells are driven by transcription factor expression: example: insect leg

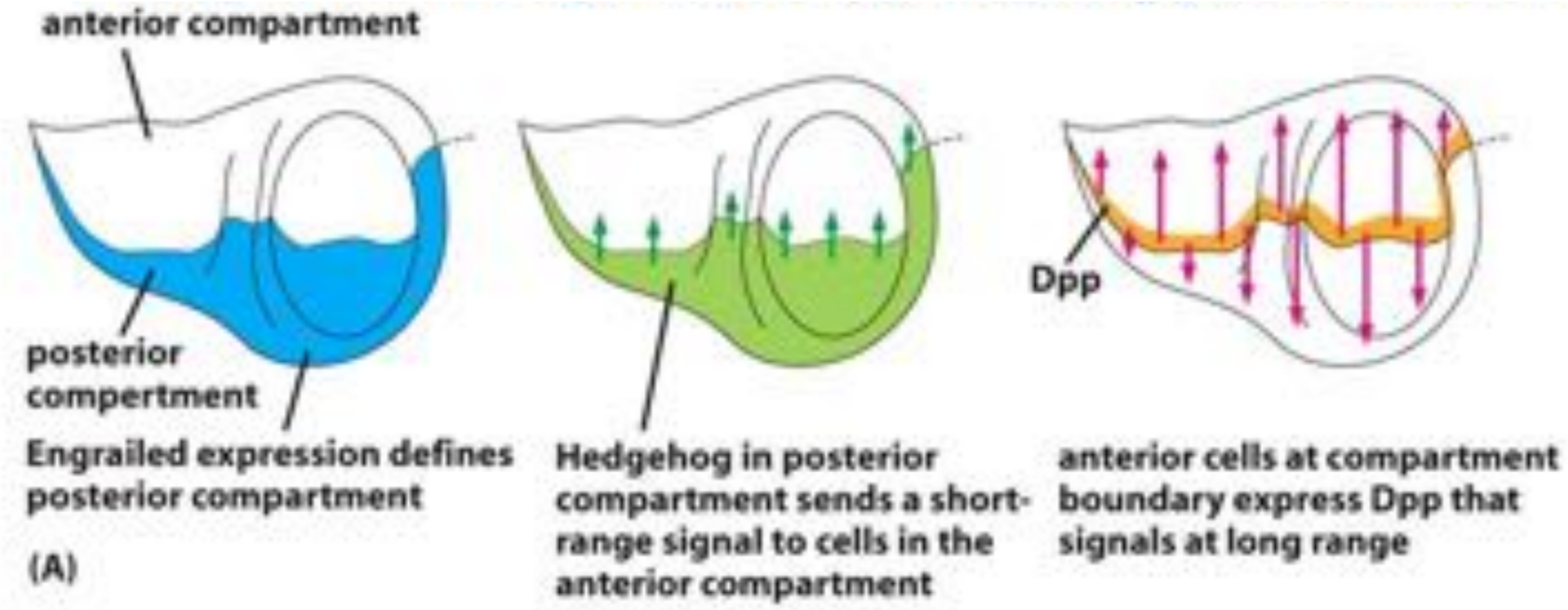


DEVELOPMENTAL BIOLOGY, Eighth Edition, Figure 18.12 (Part 3) © 2006 Sinauer Associates, Inc.

DEVELOPMENTAL BIOLOGY, Eighth Edition, Figure 18.13 © 2006 Sinauer Associates, Inc.

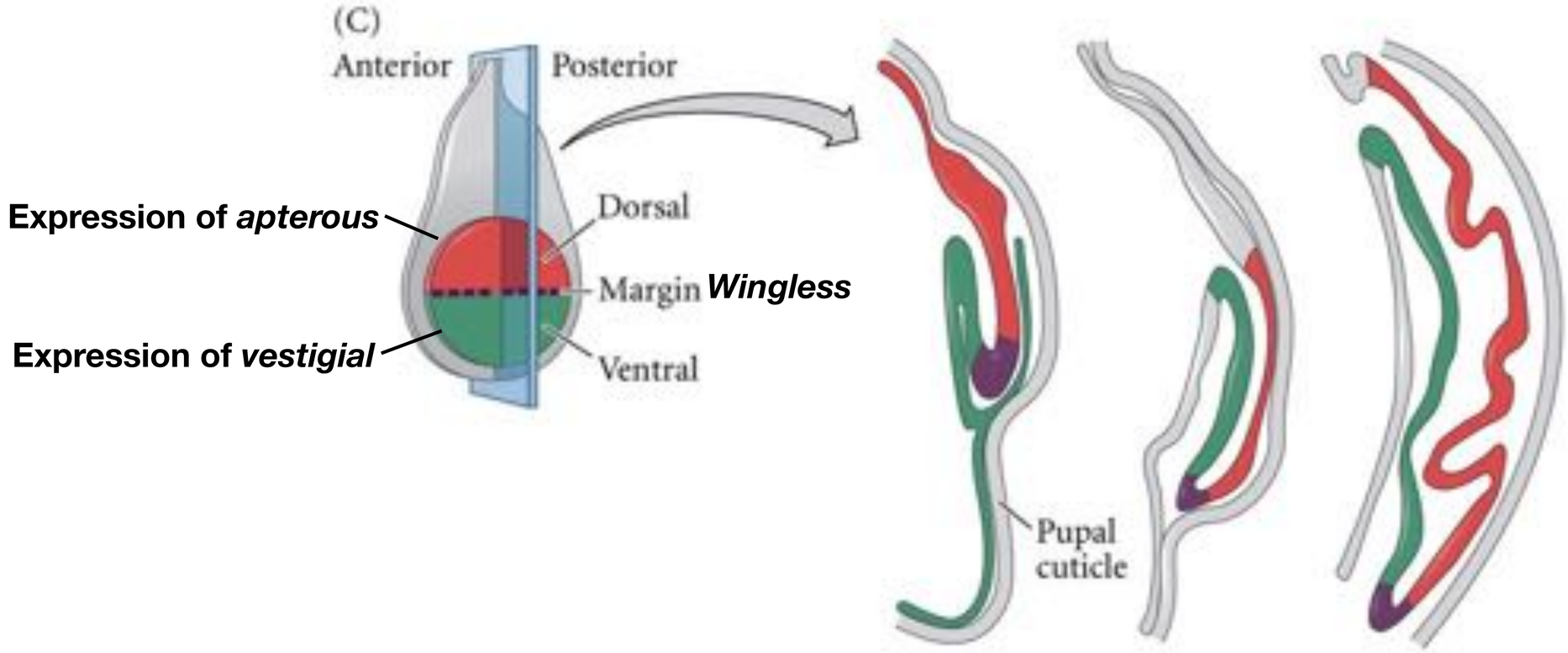
Patterning in the wing imaginal discs is accomplished by dividing discs into compartments of expression

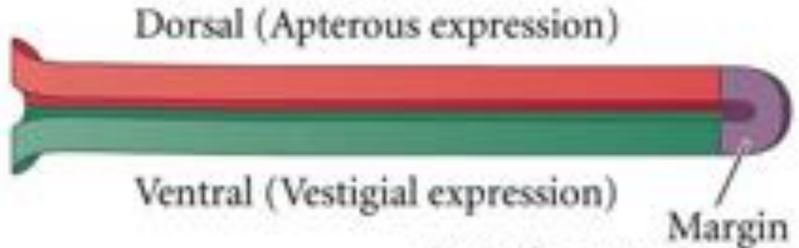
Anterior-posterior patterning



Patterning in the wing imaginal discs is accomplished by dividing discs into compartments of expression

Dorsal-ventral patterning





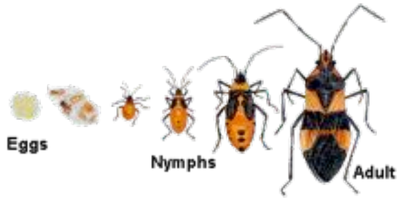
The spectrum of metamorphic life cycles

Direct developement

Indirect developement

ametabolous insects

hemimetabolous insects

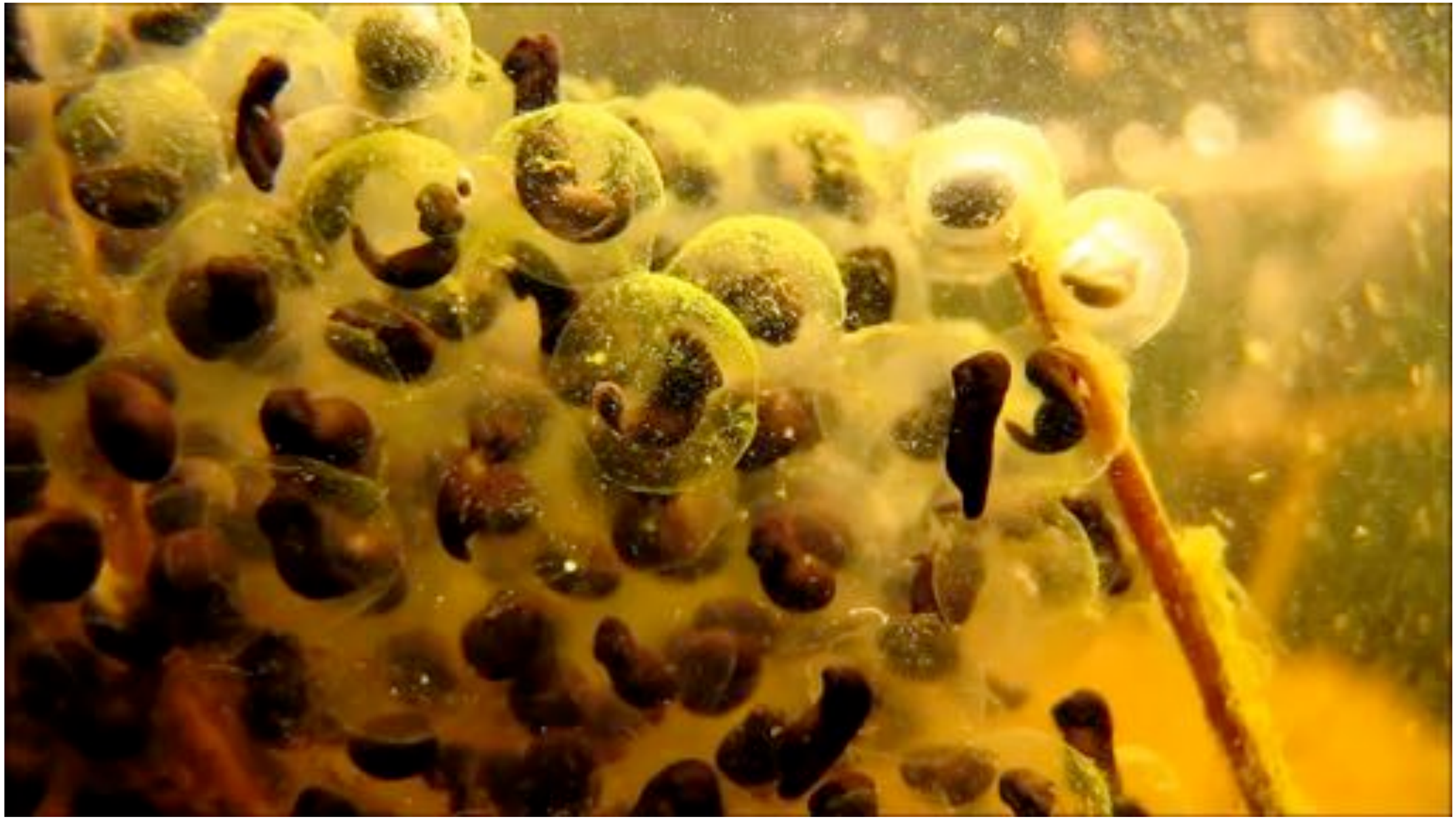


holometabolous insects

Metamorphic changes in anurans




System	Larva	Adult
Locomotory	Aquatic; tail fins	Terrestrial; tailless tetrapod
Respiratory	Gills, skin, lungs; larval hemoglobins	Skin, lungs; adult hemoglobins
Circulatory	Aortic arches; aorta; anterior, posterior, and common jugular veins	Carotid arch; systemic arch; cardinal veins
Nutritional	Herbivorous: long spiral gut; intestinal symbionts; small mouth, horny jaws, labial teeth	Carnivorous: Short gut; proteases; large mouth with long tongue
Nervous	Lack of nictitating membrane; porphyropsin, lateral line system	Development of ocular muscles, nictitating membrane, rhodopsin; loss of lateral line system
Excretory	Largely ammonia, some urea	Largely urea; high activity of enzymes of ornithine-urea cycle
Integumental	Thin, bilayered epidermis with thin dermis;no mucous glands or granular glands	Stratified squamous epidermis with adult keratins; well-developed dermis contains mucous glands and granular glands secreting antimicrobial peptides



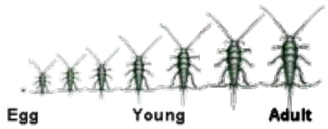
https://www.youtube.com/watch?v=wAcwjWi6l9Y

The spectrum of metamophic life cycles

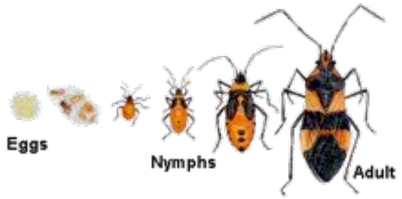
Direct developement

Indirect developement

ametabolous insects



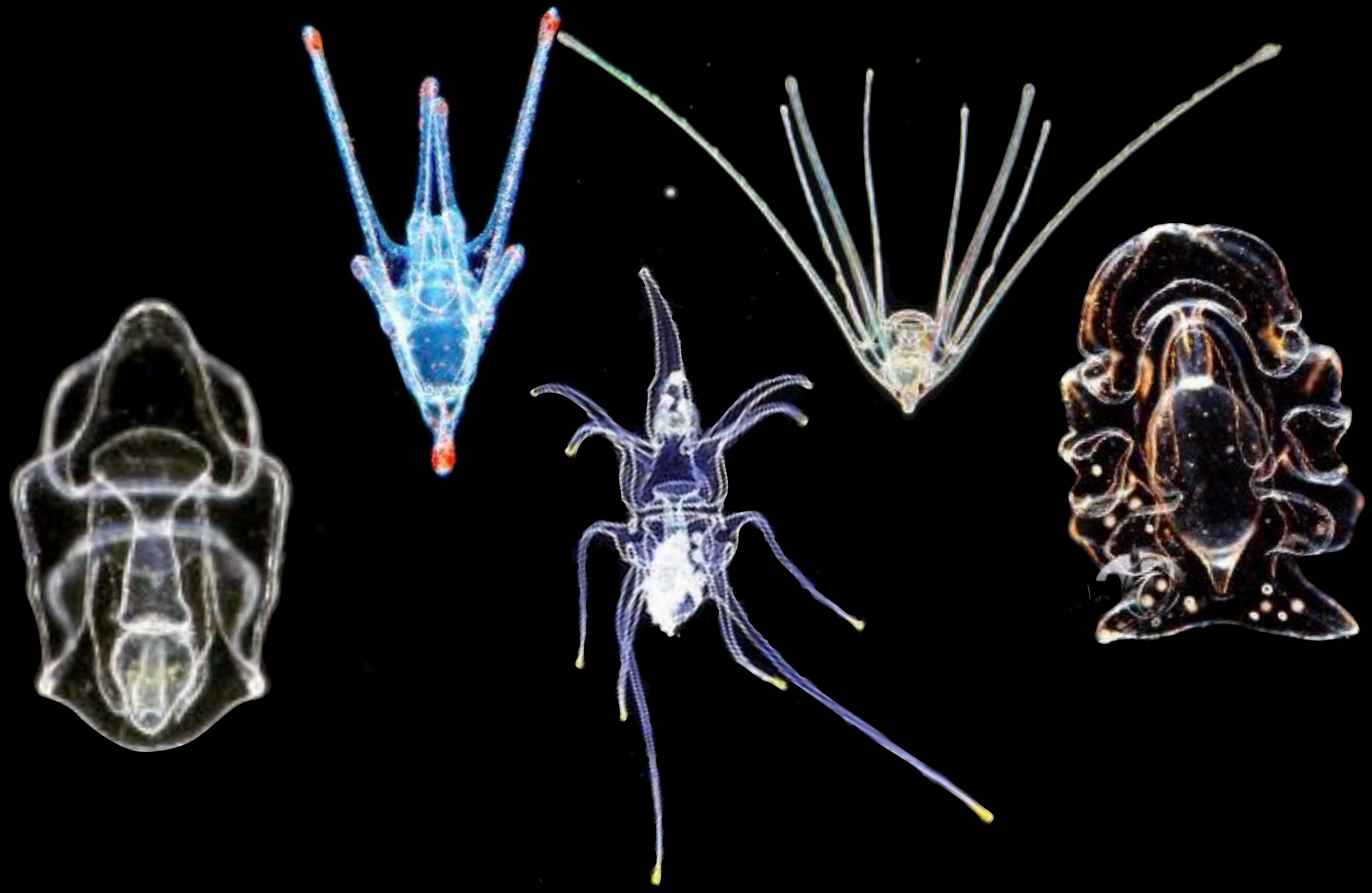
hemimetabolous insects



anurans

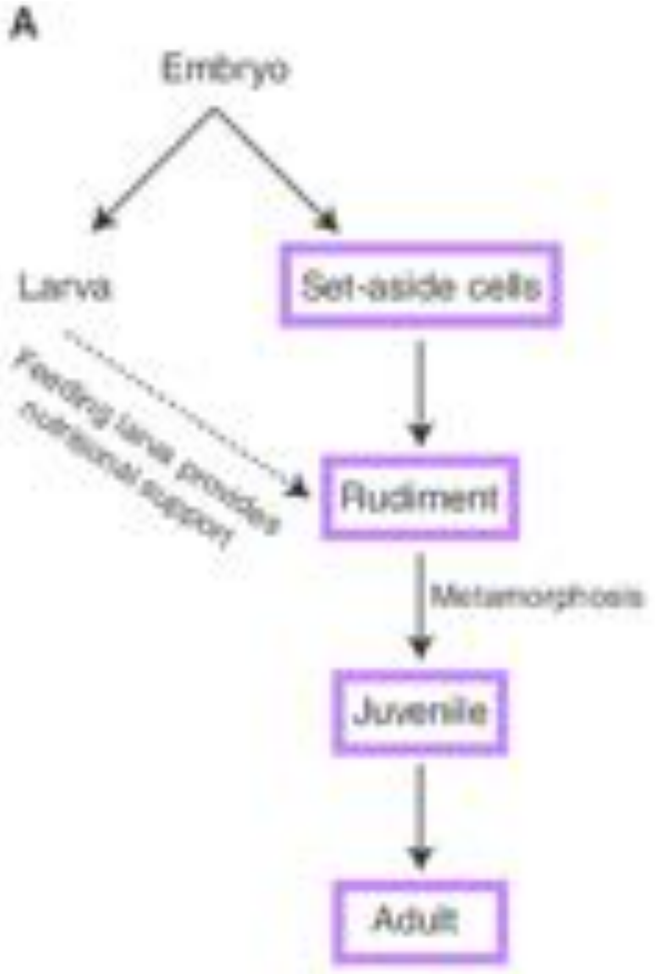
holometabolous insects

Many echinoderms have indirect development with a variety of larval forms



Images by: D. P. Wilson, Albert Calbet, and Image Quest 3D

Bruno C. Vellutini. A sea biscuit's life. Banco de imagens Cifonauta. Disponível em: http://cifonauta.cebimar.usp.br/video/282/ Acesso em: 2016-11-27.



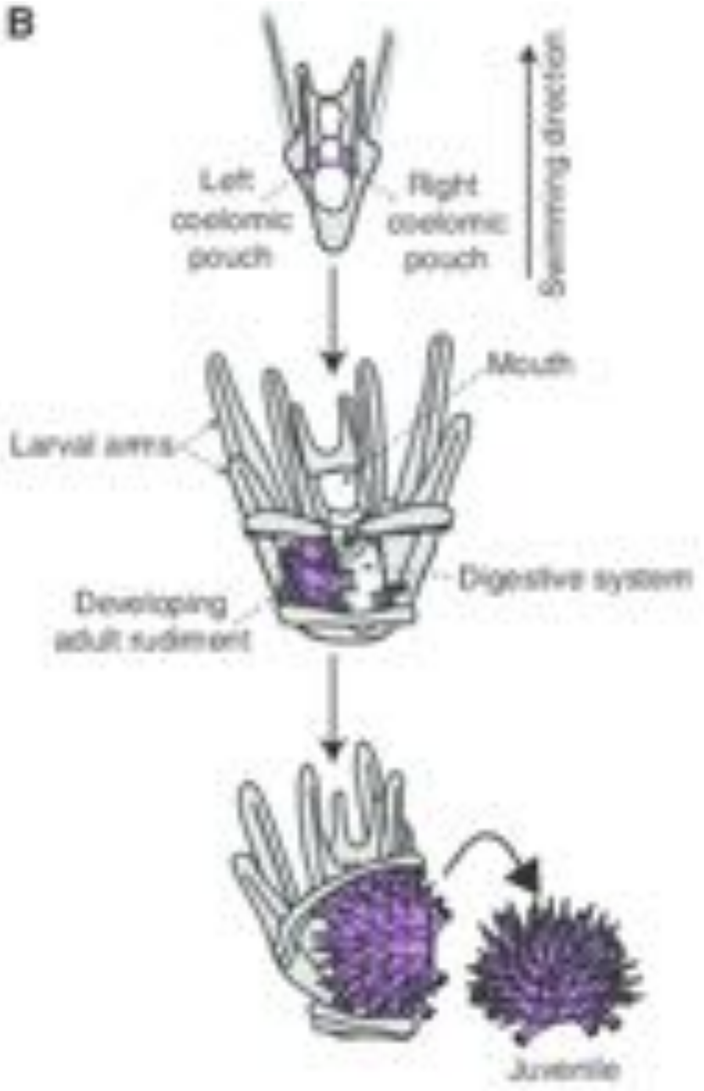


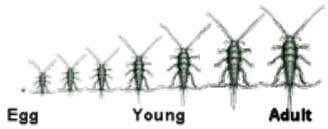
Fig. 3. The juvenile sea urchin develops from embryonic multipotent cells. (**A**) Schematic of indirect development in sea urchin. During embryogenesis, cells are set aside for constructing the adult (the rudiment, shown in purple). The larva swims and feeds, providing protection and nutritional support to the developing adult structures. A *S. purpuratus* larva is competent to undergo metamorphosis after ~6-8 weeks of feeding. (**B**) In the four-armed pluteus, the small micromere descendents are located in the left and right coelomic pouches (purple), where the adult rudiment will form. In the eight-armed pluteus, adult structures in the rudiment (purple) begin to form, such as the tube feet and spines. At metamorphosis, the juvenile emerges as an independent entity (purple) and larval tissues are lost.

The spectrum of metamorphic life cycles

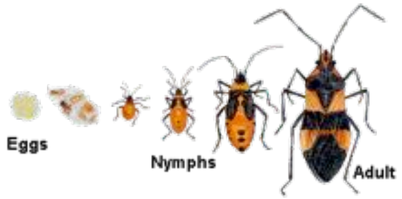
Direct developement

Indirect developement

ametabolous insects



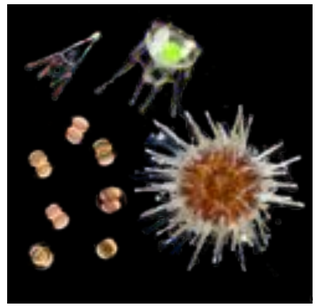
hemimetabolous insects



anurans

holometabolous insects

many echinoderms

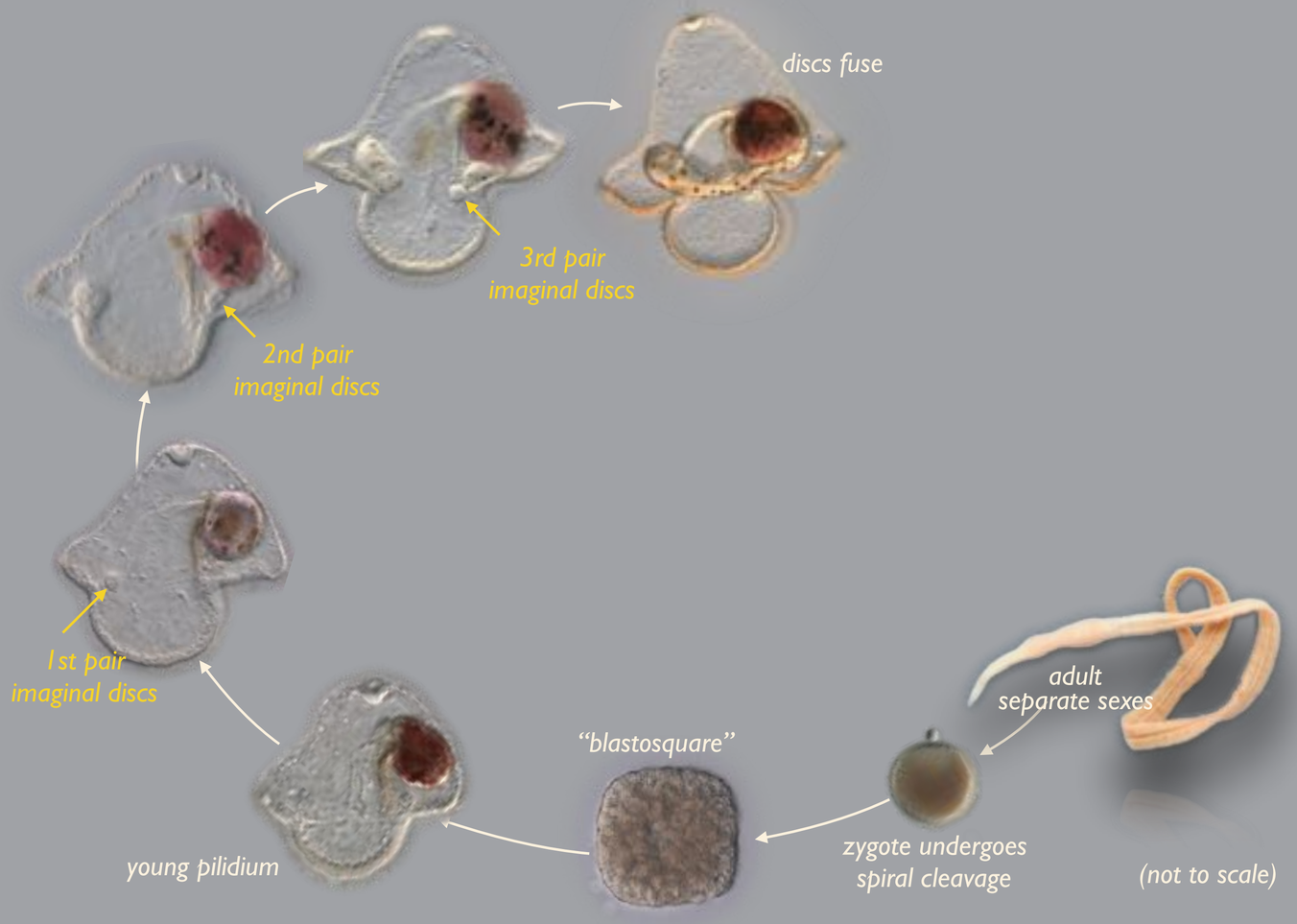


Nemerteans are a phylum of mostly marine predators
~ 1500 species

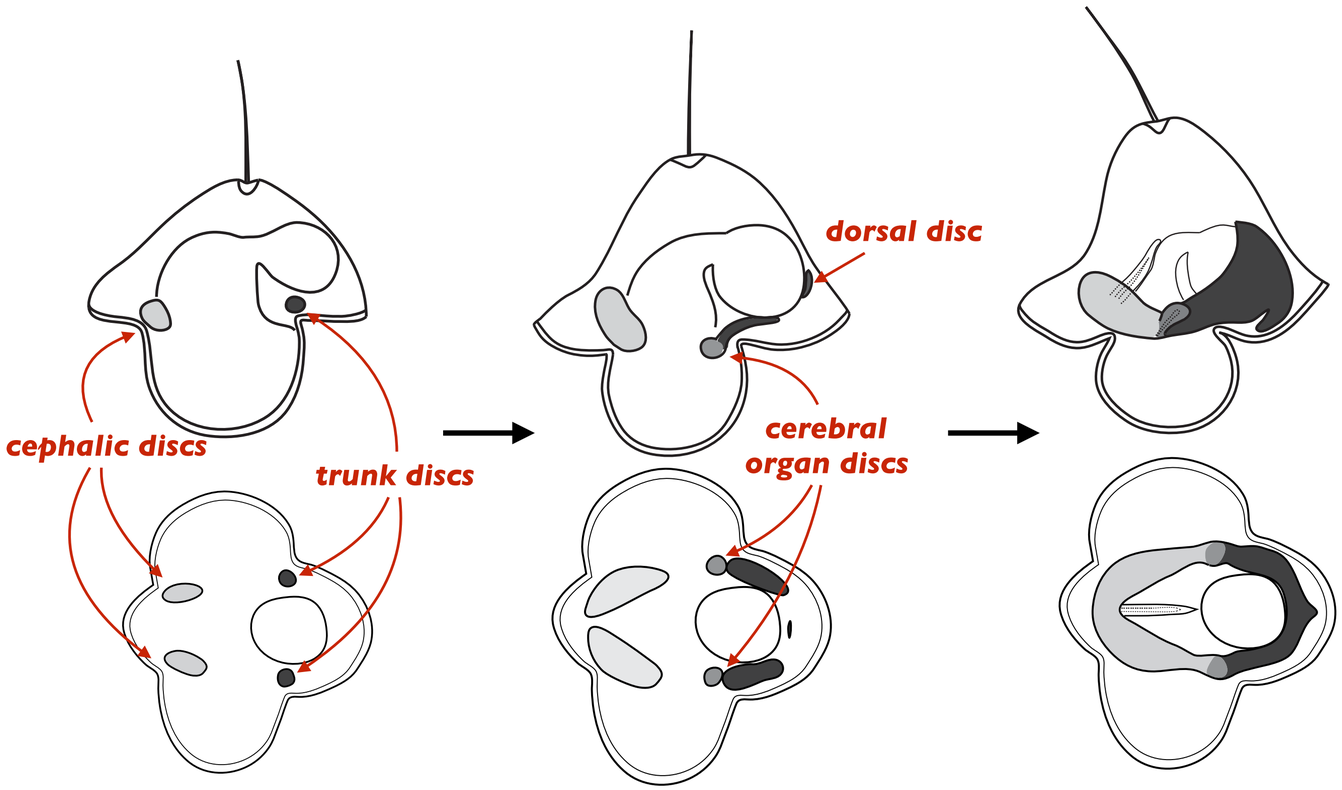
Coe, 1905

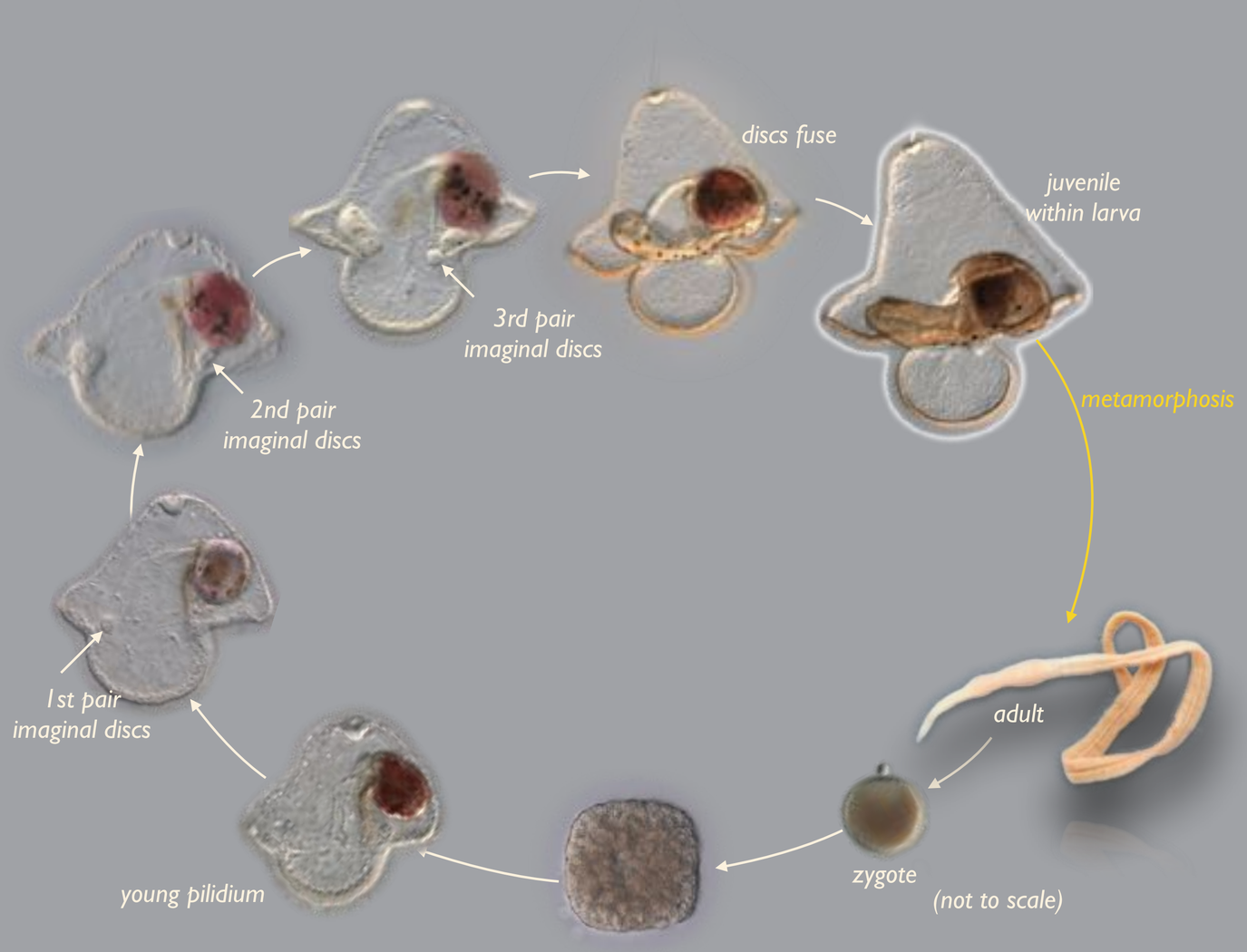
The pilidium larva

Pilidial development = indirect



The imaginal discs fuse around the larval gut to form the juvenile




discs fuse
juvenile within larva
3rd pair imaginal discs
2nd pair imaginal discs
metamorphosis
1st pair imaginal discs
adult
young pilidium
zygote
(not to scale)

Pilidial metamorphosis is rapid and catastrophic

movie by L. Hiebert and S. Maslakova

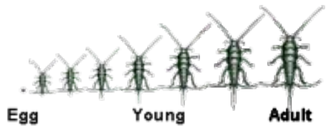
movie by L. Hiebert and S. Maslakova

The spectrum of metamorphic life cycles

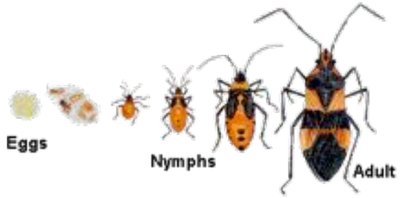
Direct developement

Indirect developement

ametabolous insects



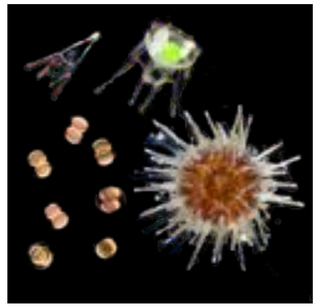
hemimetabolous insects



anurans

holometabolous insects

many echinoderms



Some nemerteans

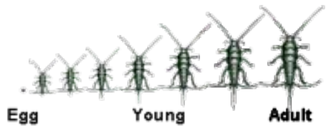
Veligers - larvae of marine mollusks

The spectrum of metamophic life cycles

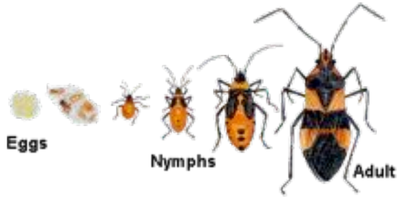
Direct developement

Indirect developement

ametabolous insects



hemimetabolous insects



anurans

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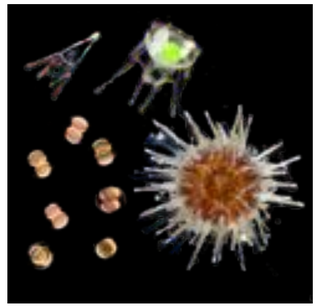
many echinoderms



Some nemerteans

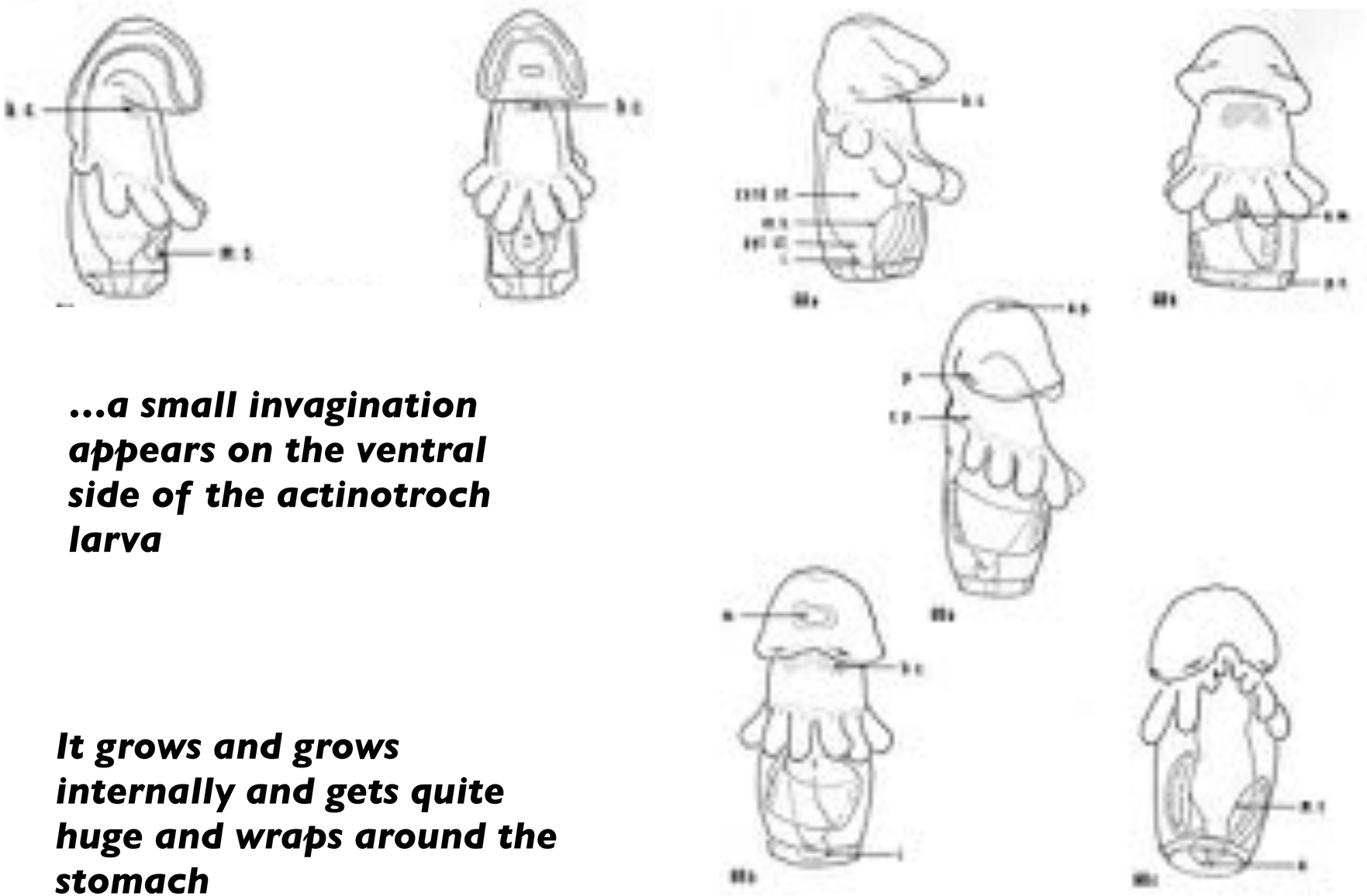
marine mollusks

The actinotroch larva of a phoronid worm

The tentacles produce a feeding current and particles are flicked into the mouth.

Telotroch for swimming

G. von Dassow



…a small invagination appears on the ventral side of the actinotroch larva

It grows and grows internally and gets quite huge and wraps around the stomach

Zimmer ‘64

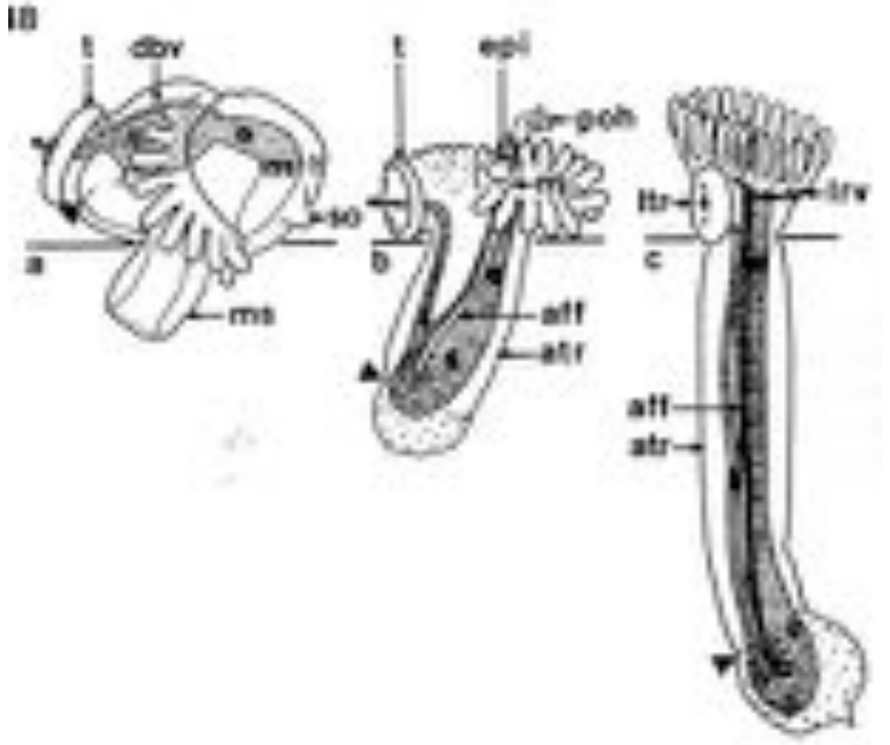
S. Maslakova

This invagination, called metasomal sack, has its own musculature.

Eventually, metasomal sack takes up most of the space inside larval trunk. What is this sack for???

When larva is ready to settle - metasomal sack is suddenly everted, and the gut and trunk coeloms are drawn into it

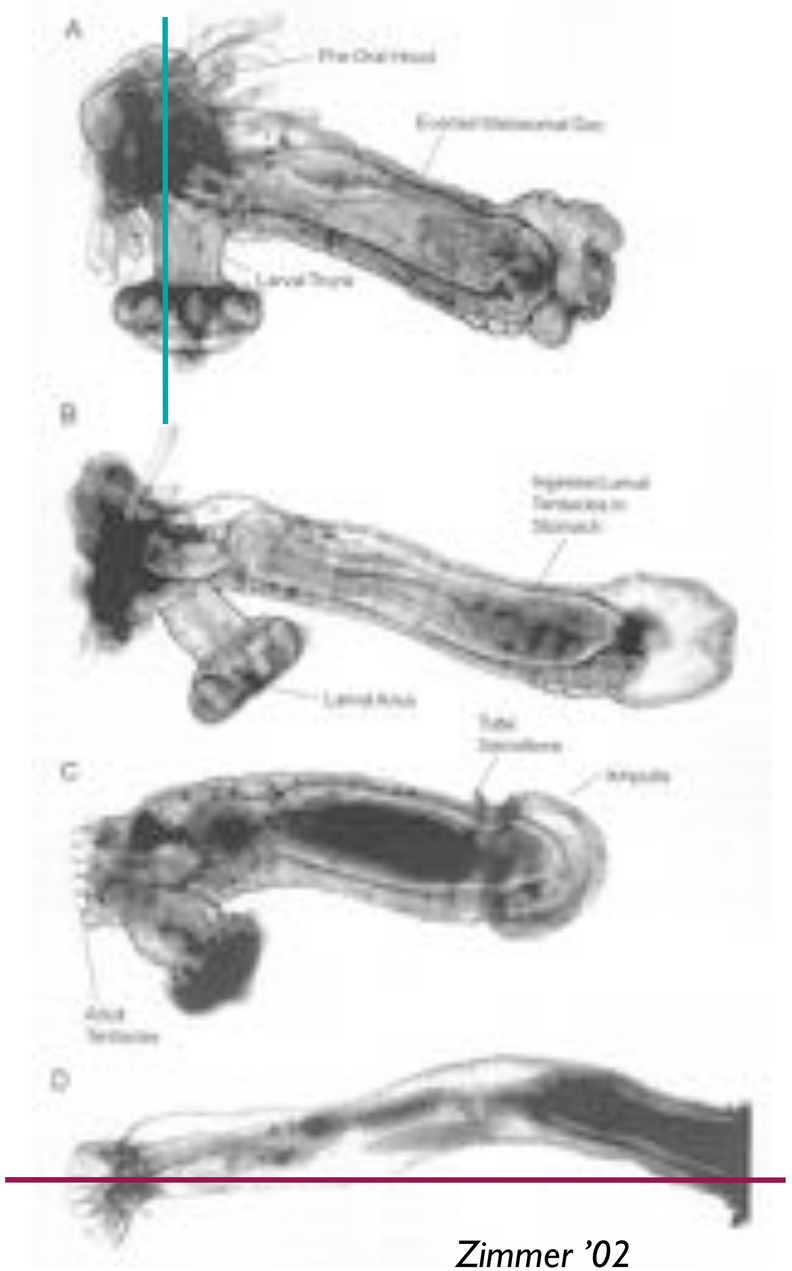
Zimmer '64



Zimmer '91

Everted metasomal sack becomes the body of the juvenile!

Metamorphosis is rapid (just minutes) and dramatic



Zimmer '02

the larval gut is pulled into the everting metasomal sac and becomes the U-shaped gut of the adult

larval tentacles eaten, oral hood resorbed, larval trunk contracted

(in some species, the larval tentacles turn into the adult lophophore)

rudiments of adult tentacles appear and young phoronid starts secreting a tube

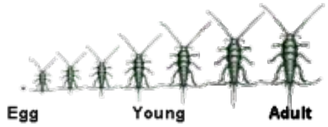
adult tentacles elongate, circulatory system established

The spectrum of metamophic life cycles

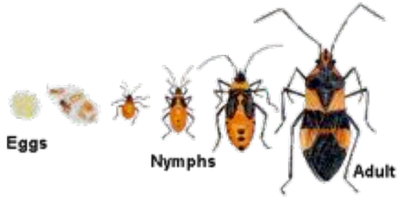
Direct developement

Indirect developement

ametabolous insects



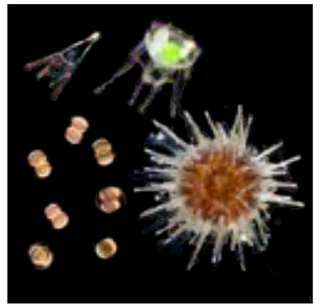
hemimetabolous insects



anurans

holometabolous insects

many echinoderms



Some nemerteans

marine mollusks

Phoronids

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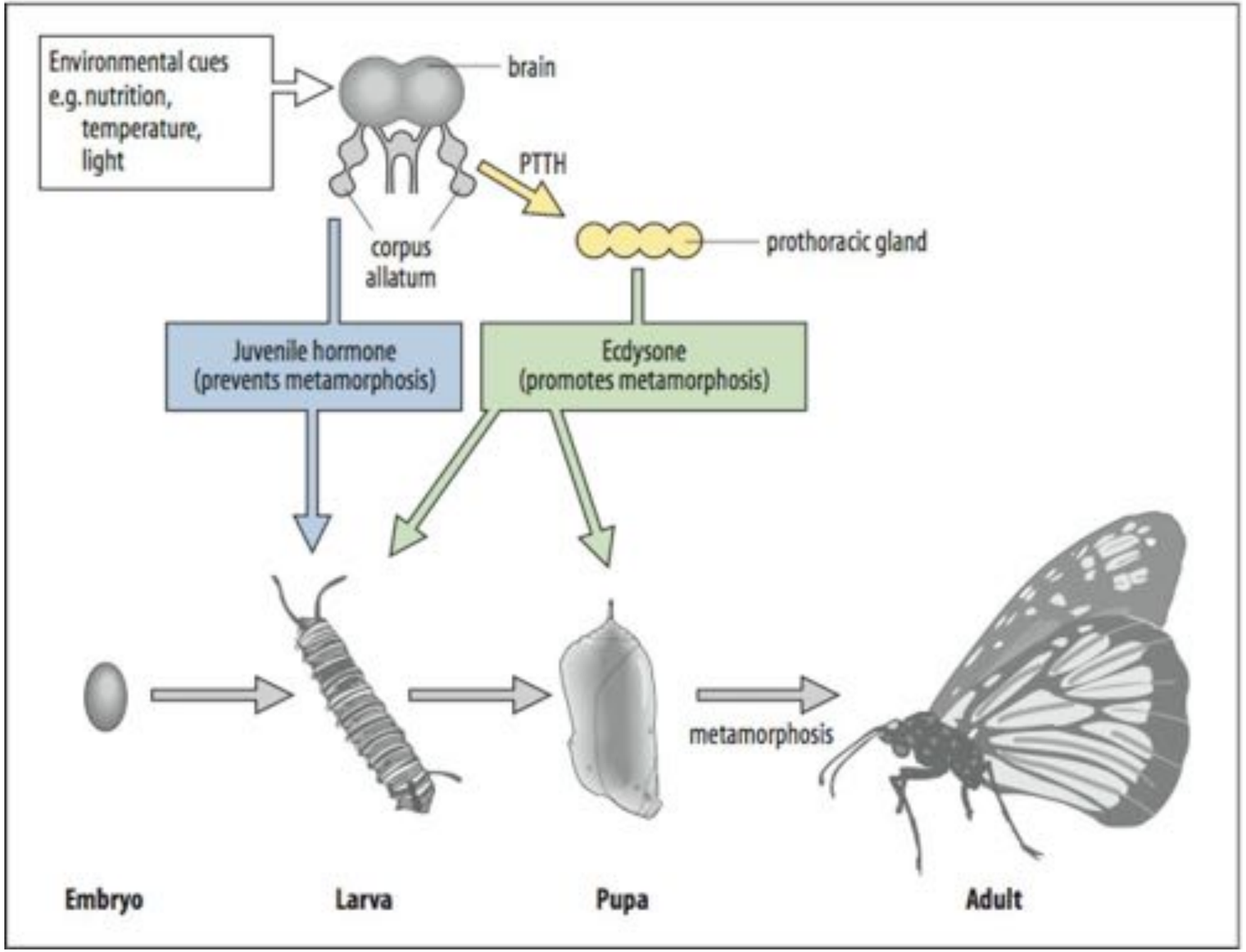
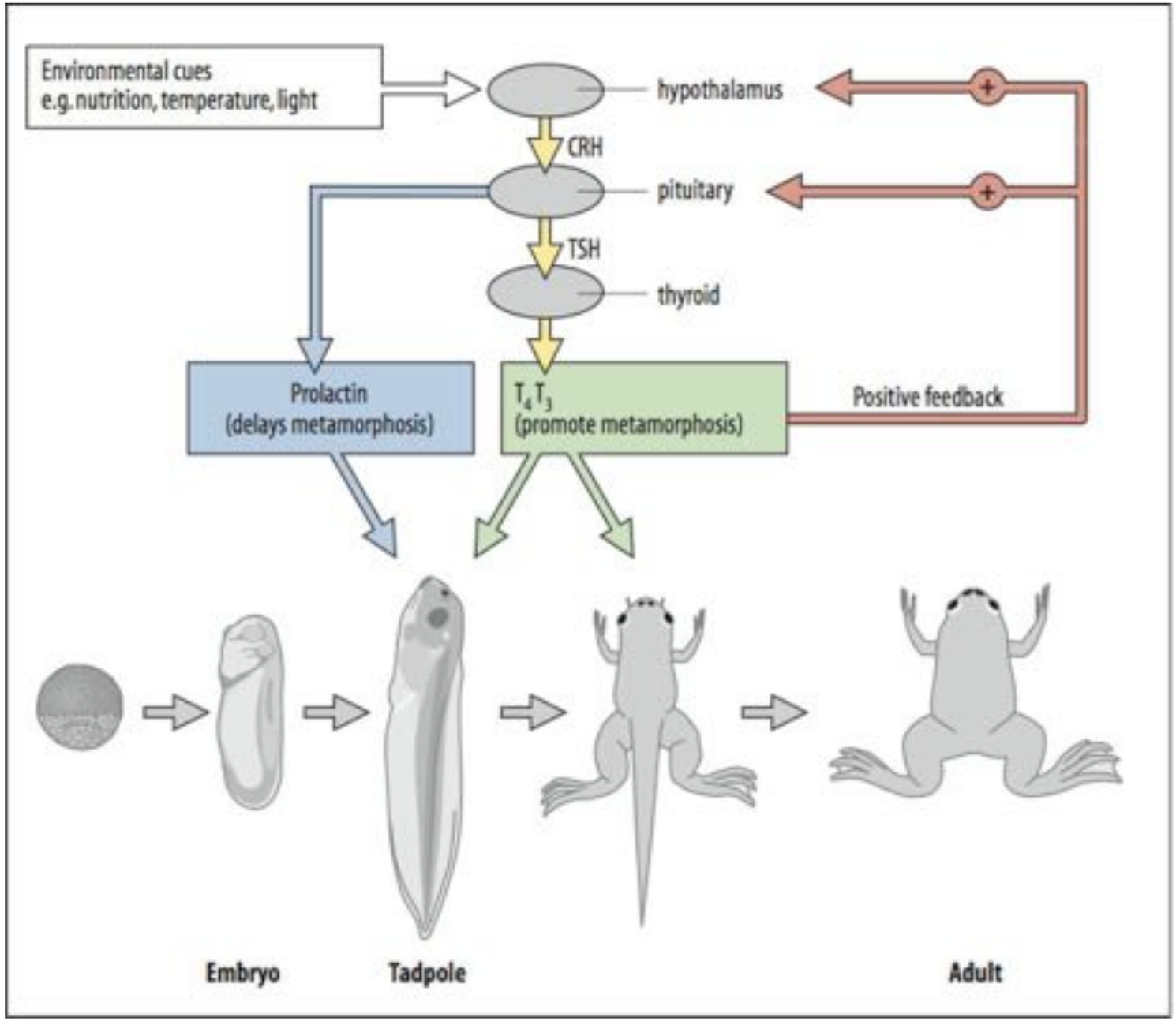
Is metamorphosis ancestral to all animals? Or has it evolved many times?

Metamorphosis is generally controlled by hormone signals: Insects



Metamorphosis is generally controlled by hormone signals: Anurans

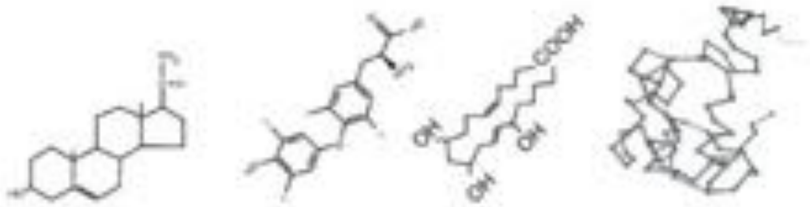


Most animals use hormones for life history transitions

Ecdysozoans

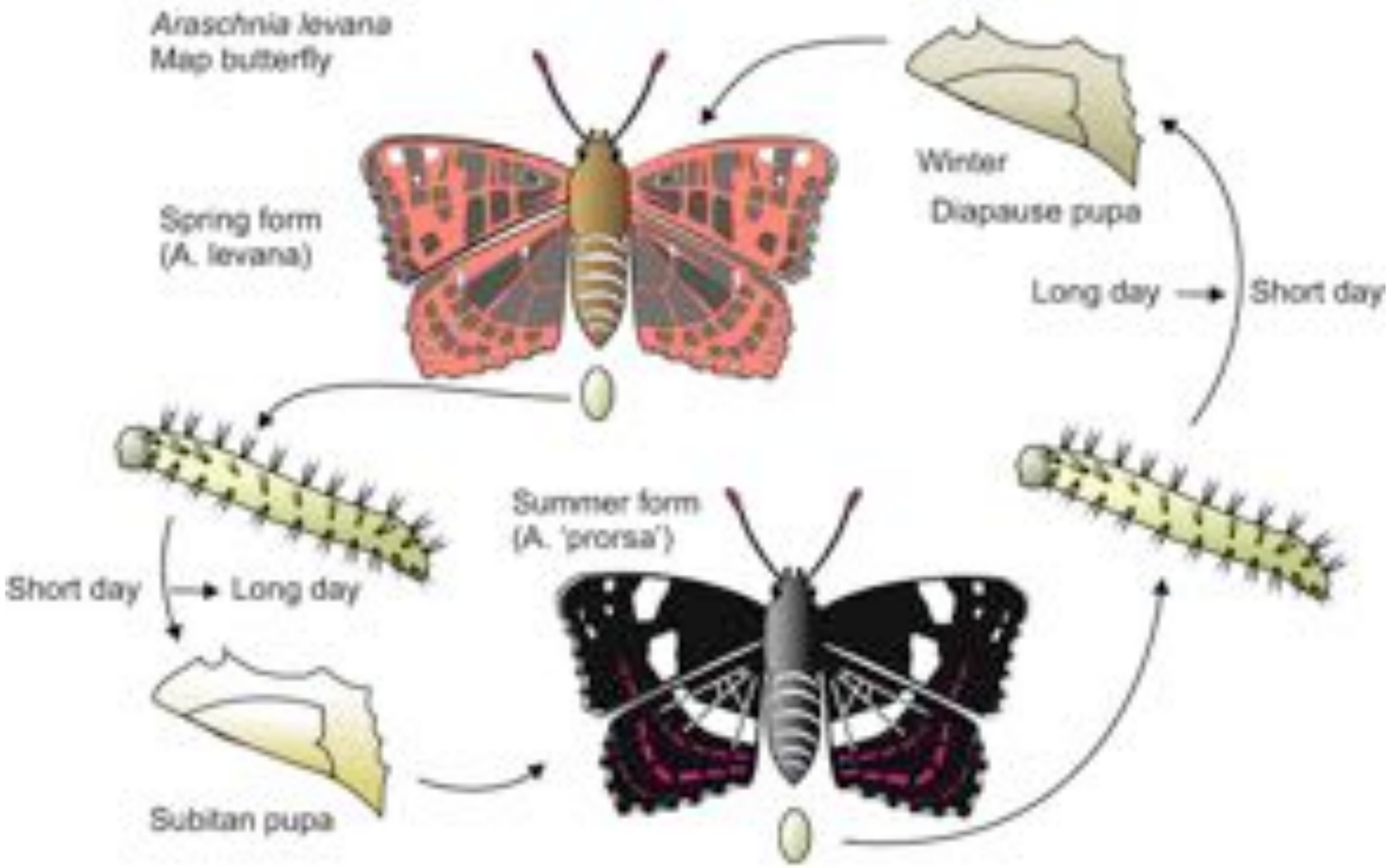
Lophotrochozoans

Deuterostomes



	Steroids	Amino Acid Derivatives	Eicosanoids	Peptides & Proteins
Porifera	?	?	?	?
Cnidaria	?	+(92)	?	+(40)
Ctenophora	?	?	?	?
Nematoda	+(94)	?	+(95)	+(96)
Arthropoda	+(41)	+(39)	+(97)	+(98)
Platyhelminthes	+(99)	?	+(93)	?
Nemertea	?	?	?	+(3)
Annelida	?	?	+(44)	+(100)
Echiura	?	?	?	?
Mollusca	+(101)	+?(38)	+(101)	+(101)
Bryozoa	?	?	?	?
Echinodermata	+(86)	+(37)	+(93)	+(86)
Hemichordata	?	?	?	?
Urochordata	+?(102)	+(102)	?	+(103)
Cephalochordata	?	?	?	+?(102)
Vertebrata	+(105)	+(32)	+(104)	+(32)

In Numerous Invertebrates External Cues Often Induce Metamorphosis; Hormones Synchronize the Internal Events



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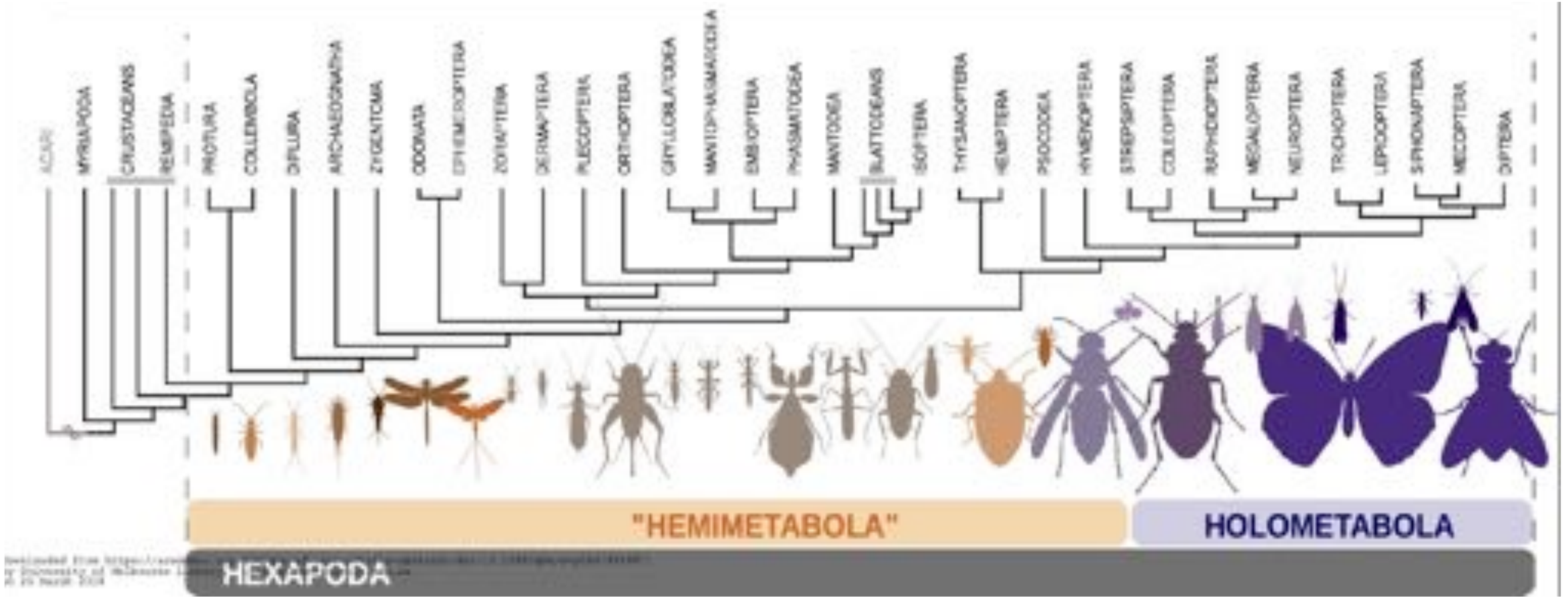
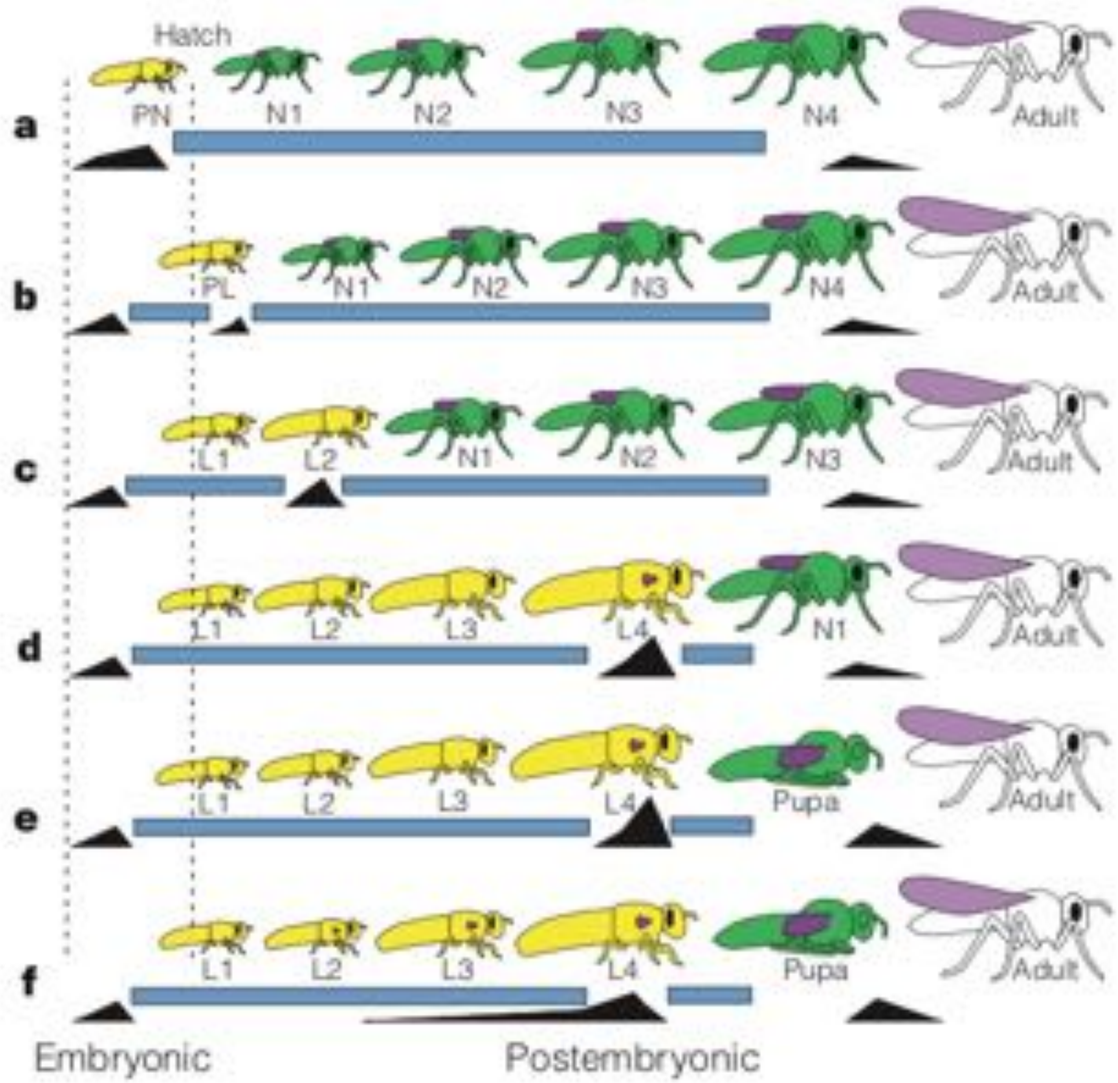
Is metamorphosis ancestral to all animals? Or has it evolved many times?

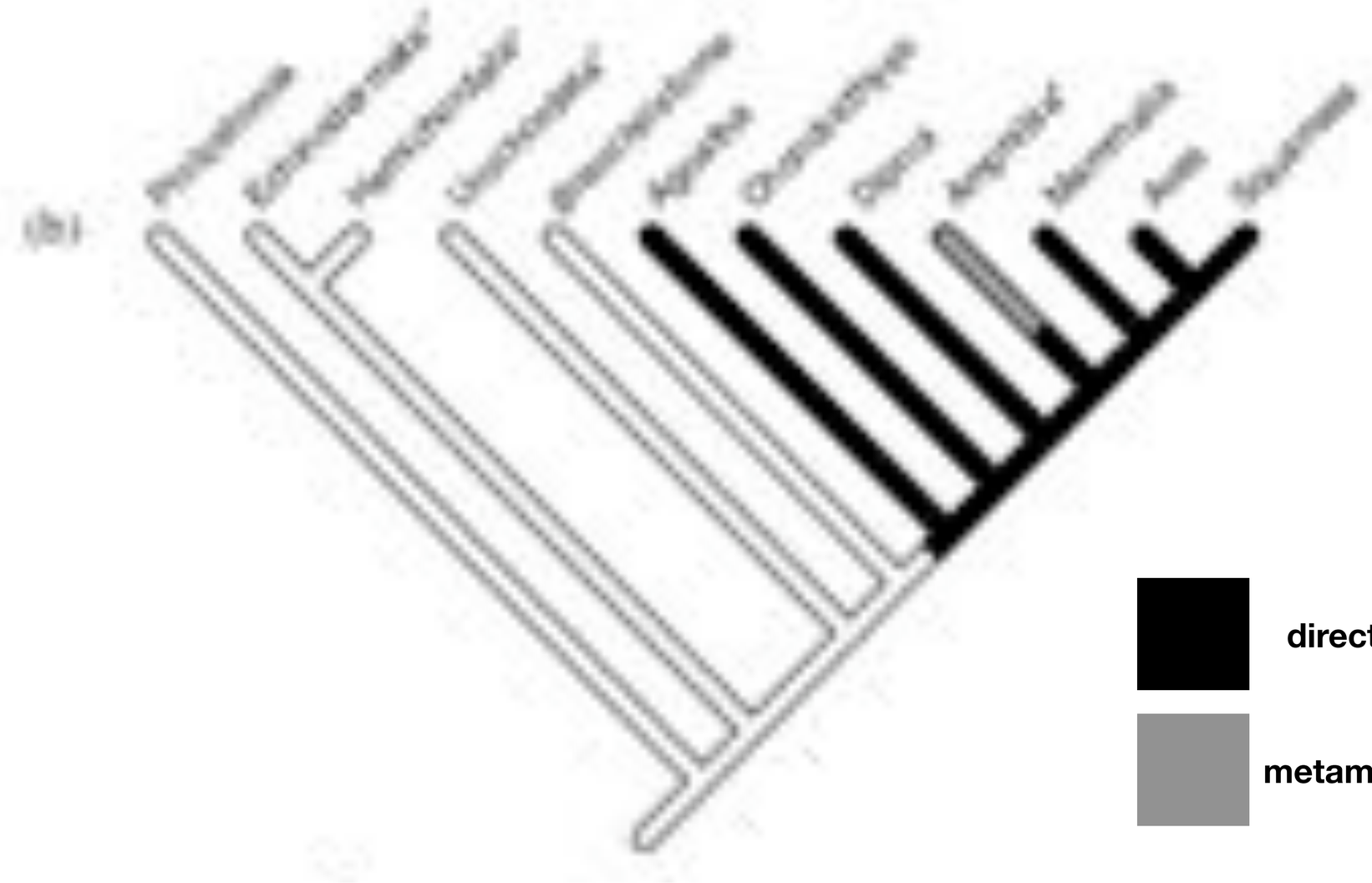
The evolution of metamorphosis in insects: ancestral insects were direct developers



Hypothesis: pronymph, nymph and adult may be equivalent to the larva, pupa and adult stages of insects with complete metamorphosis



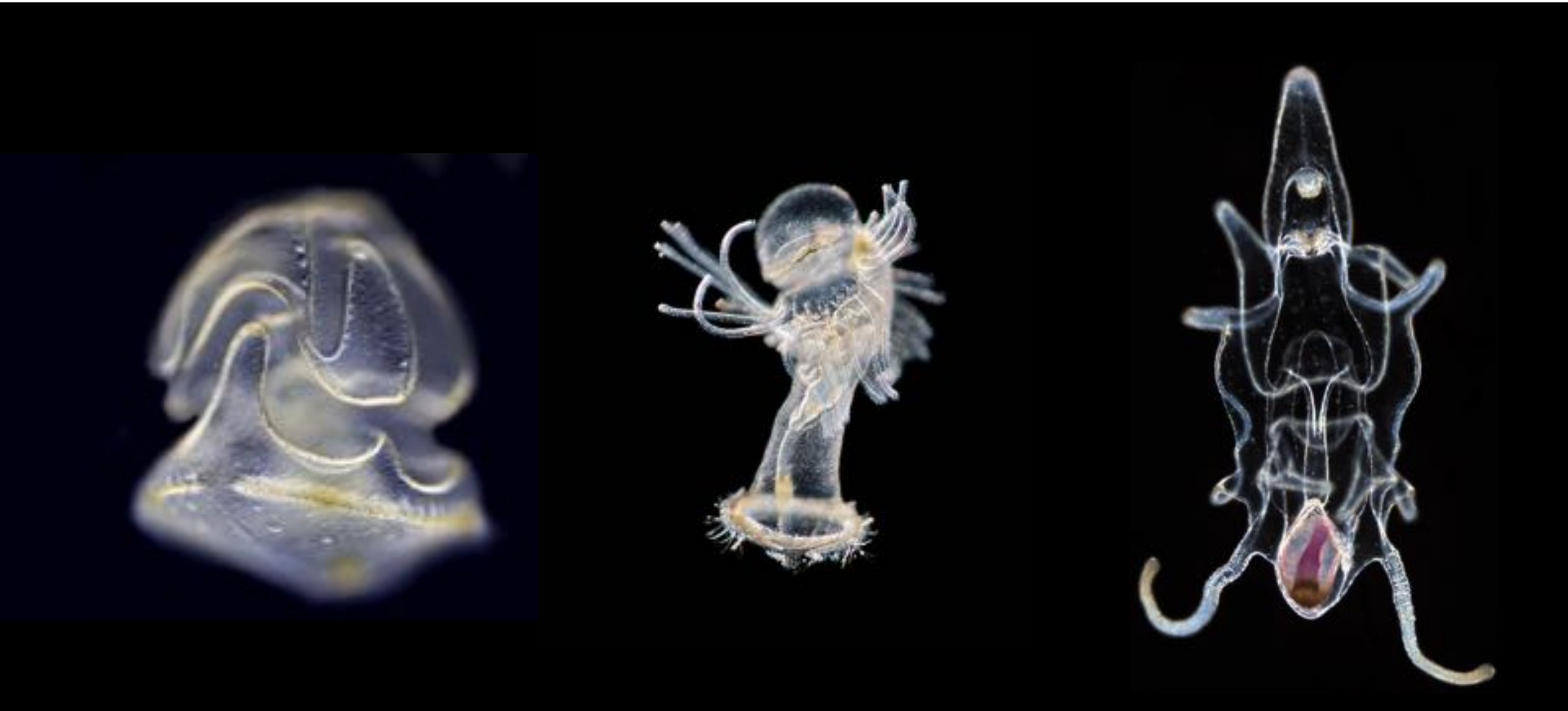
The evolution of metamorphosis in anurans: ancestral tetrapods were direct developers



direct development

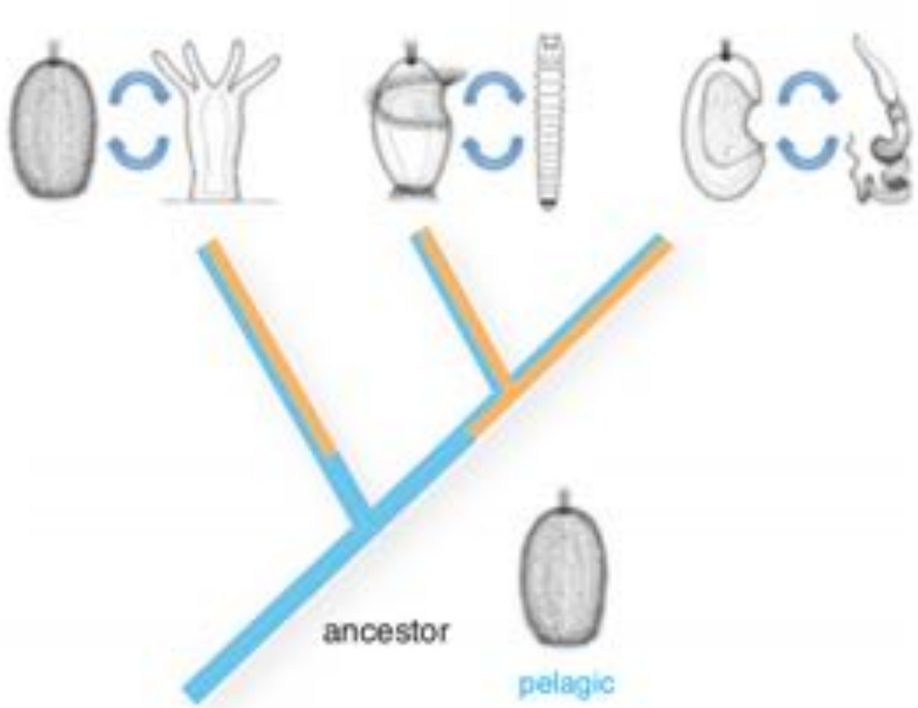
metamorphic development

What about all the marine invertebrate larvae? Did they all evolve metamorphosis independently too?



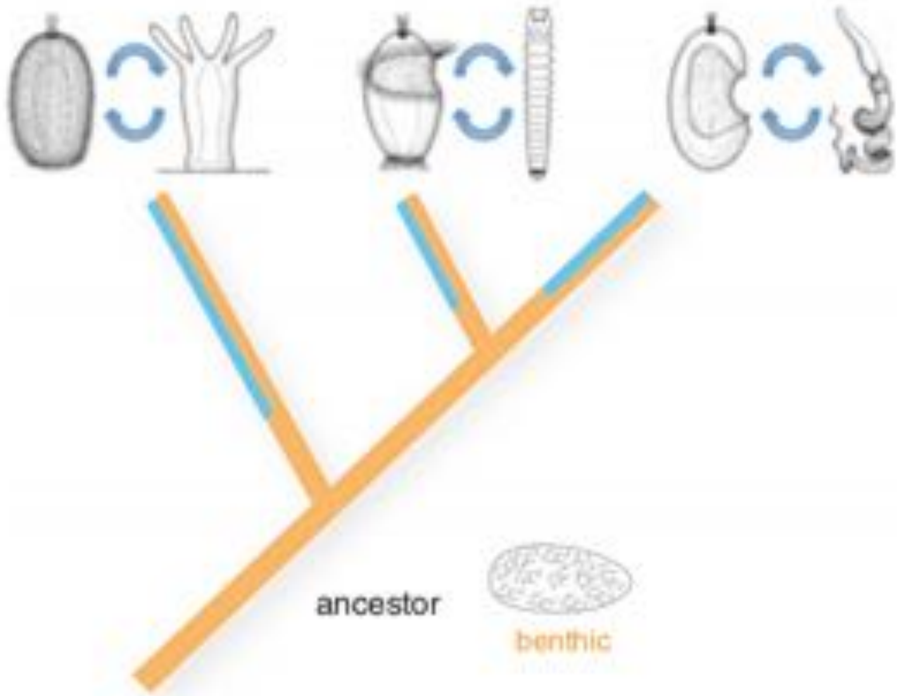
The debate on the origins of larvae and metamorphosis!

Larval first



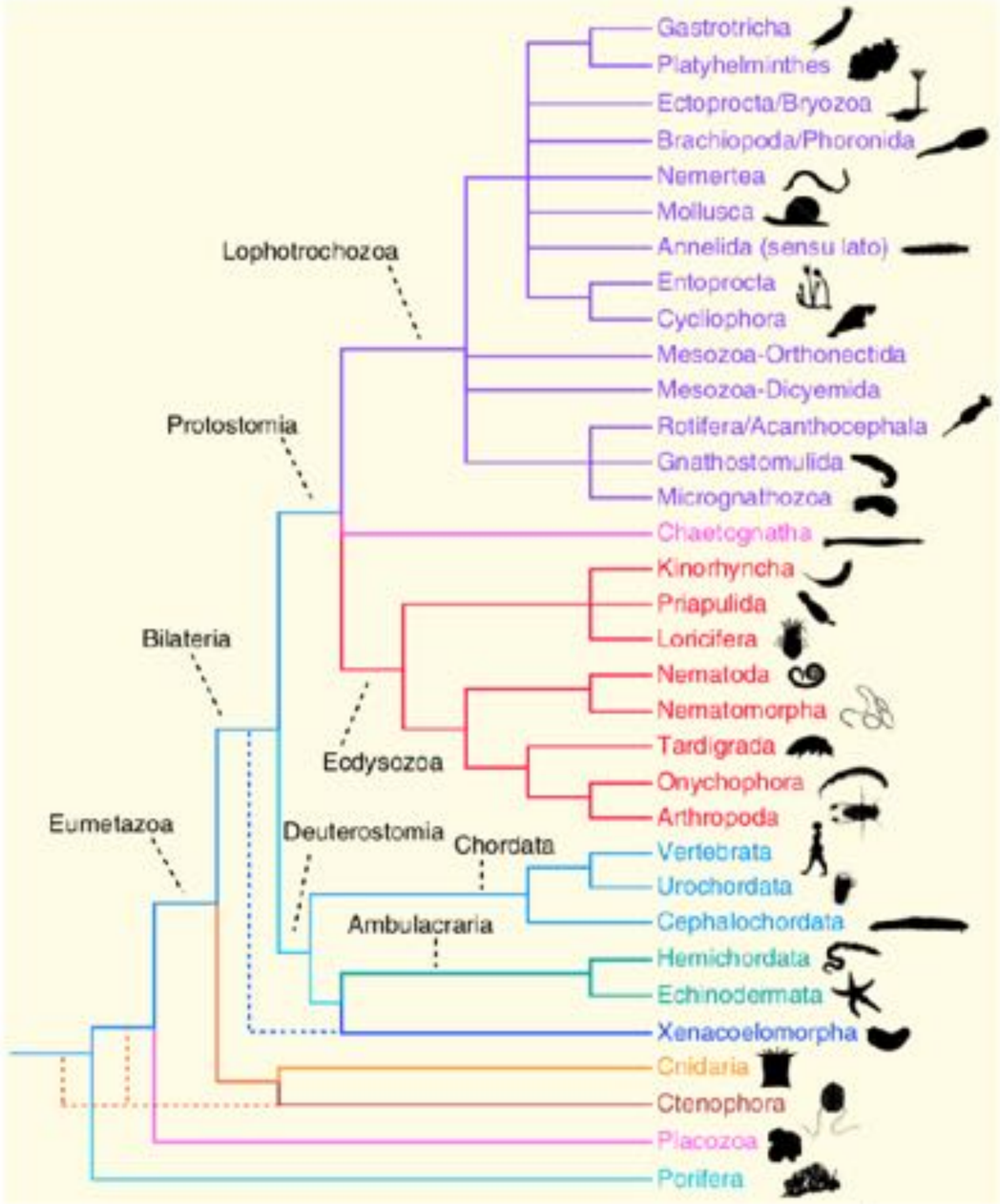
B Holopelagic neuralian ancestors.: Terminal addition of benthic adult benthic stages two (or three) times (Nielsen 2012)

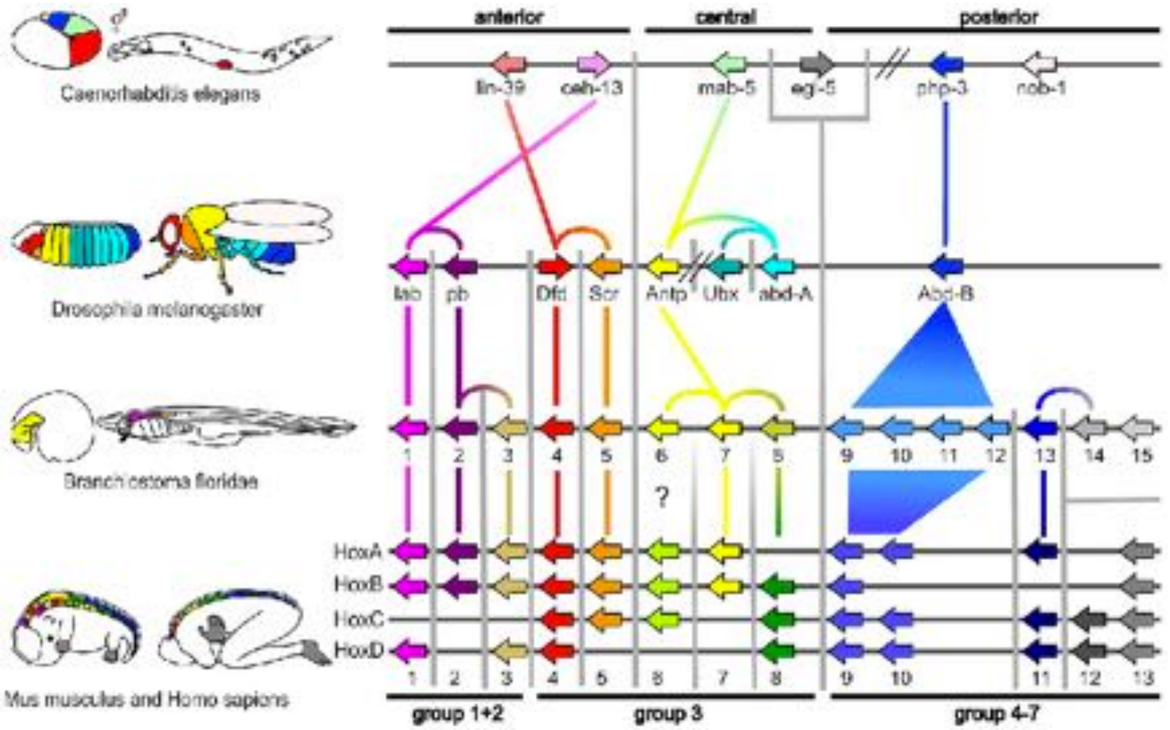
Adult first



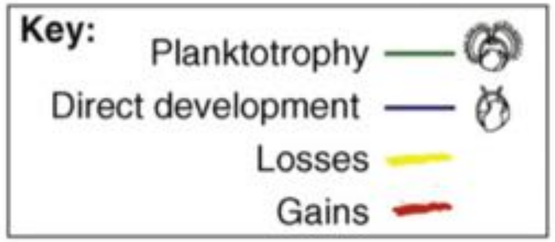
C Holobenthic neuralian ancestors: Repeated intercalation of swimming larval stages; many times in each lineage (Raff 2008)

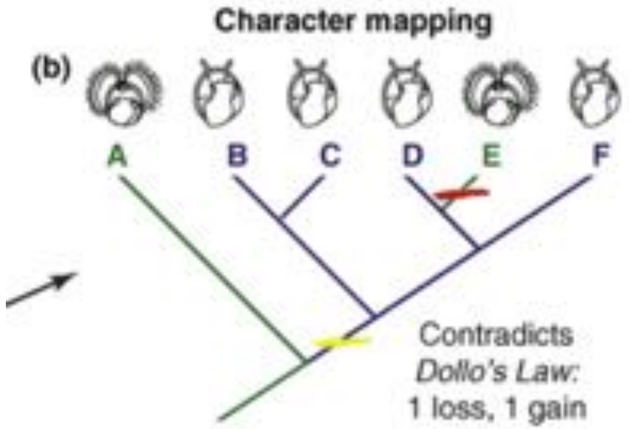
Argument in favor of the “adult-first” hypothesis: patterning genes highly conserved between adult forms

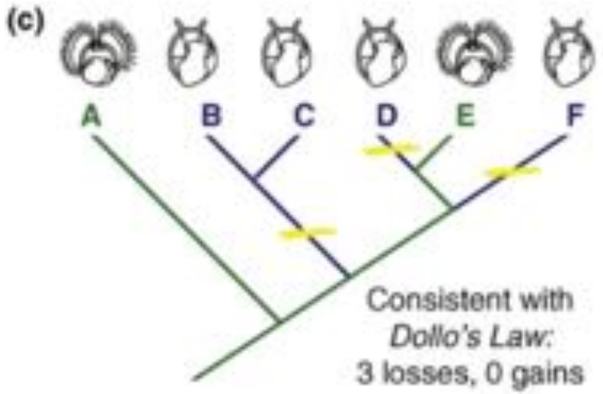




Argument in favor of the “adult-first” hypothesis: loss and gain of larval forms is common







Argument in favor of the “larva-first” hypothesis: expression patterns of many genes are shared across distant larval types

Table 2. Homology and homoplasy in protostome (trochophore) and deuterostome (dipleurula) indirect-developing larval gene expression.

gene	trochophore	dipleurula	reference
Brachyury	foregut	foregut	Arendt *et al.* (2001)
Gsc	foregut	foregut	Arendt *et al.* (2001)
Otx	oral ciliary bands	oral ciliary bands	Arendt *et al.* (2001)
NK2.1	*not* apical plate	apical plate	Dunn *et al.* (2007)
HNF6	*not* apical plate	apical plate	Dunn *et al.* (2007)
NK2.1	foregut	foregut	Dunn *et al.* (2007)
FoxA	foregut	foregut	Dunn *et al.* (2007)
Nodal	?	right ecto + coelom	Duboc & Lepage (2006)
Hox 2–5	early larval	adult rudiment	Arenas-Mena *et al.* (1998), Kulakova *et al.* (2007)
Hox 1	left–right	aboral (dorsal)	Ishii *et al.* (1999), Kulakova *et al.* (2007)
Hox 7	post-gut	oral (ventral)	Ishii *et al.* (1999), Kulakova *et al.* (2007)

More evidence in favor of the “larva-first” hypothesis: shared larval expression patterns

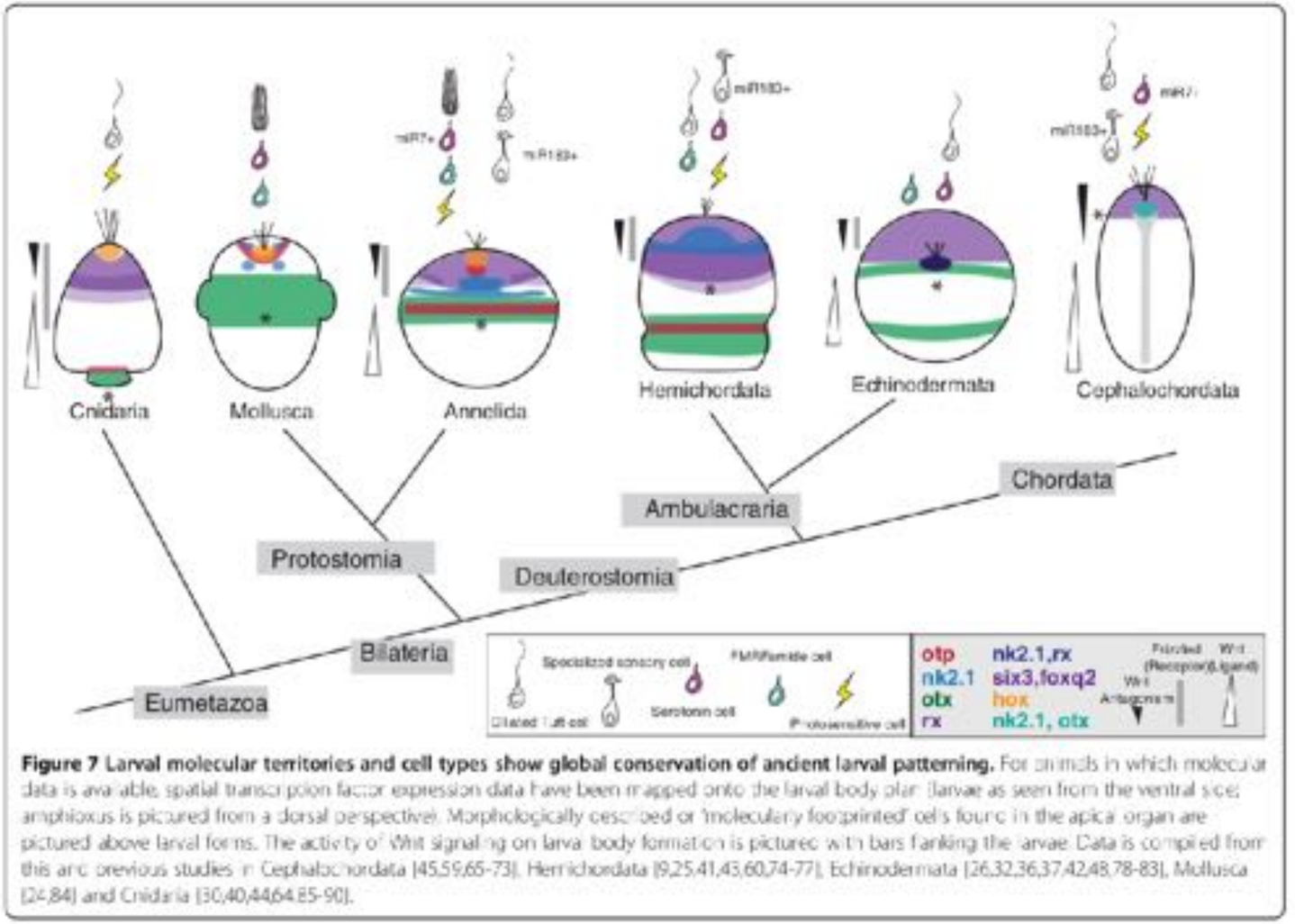
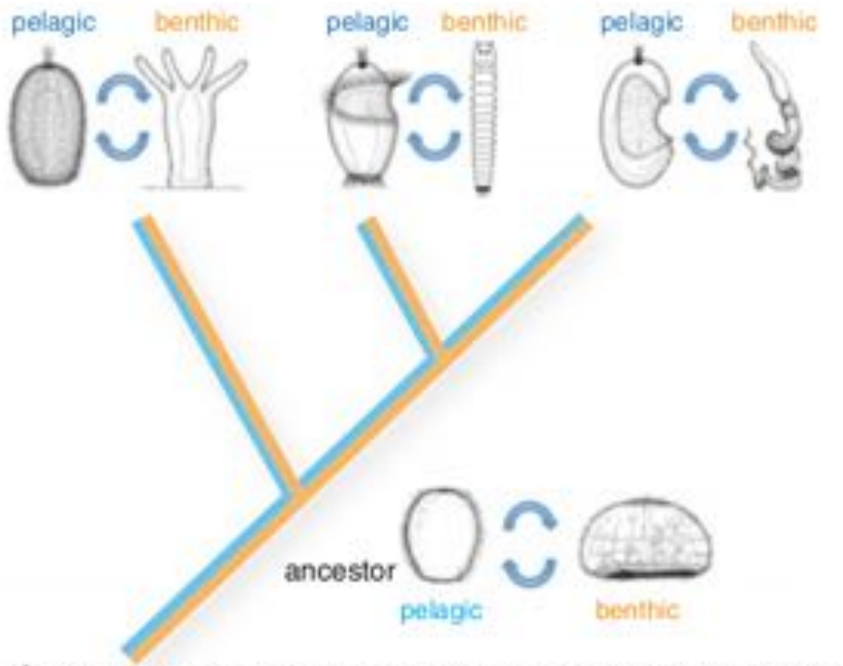


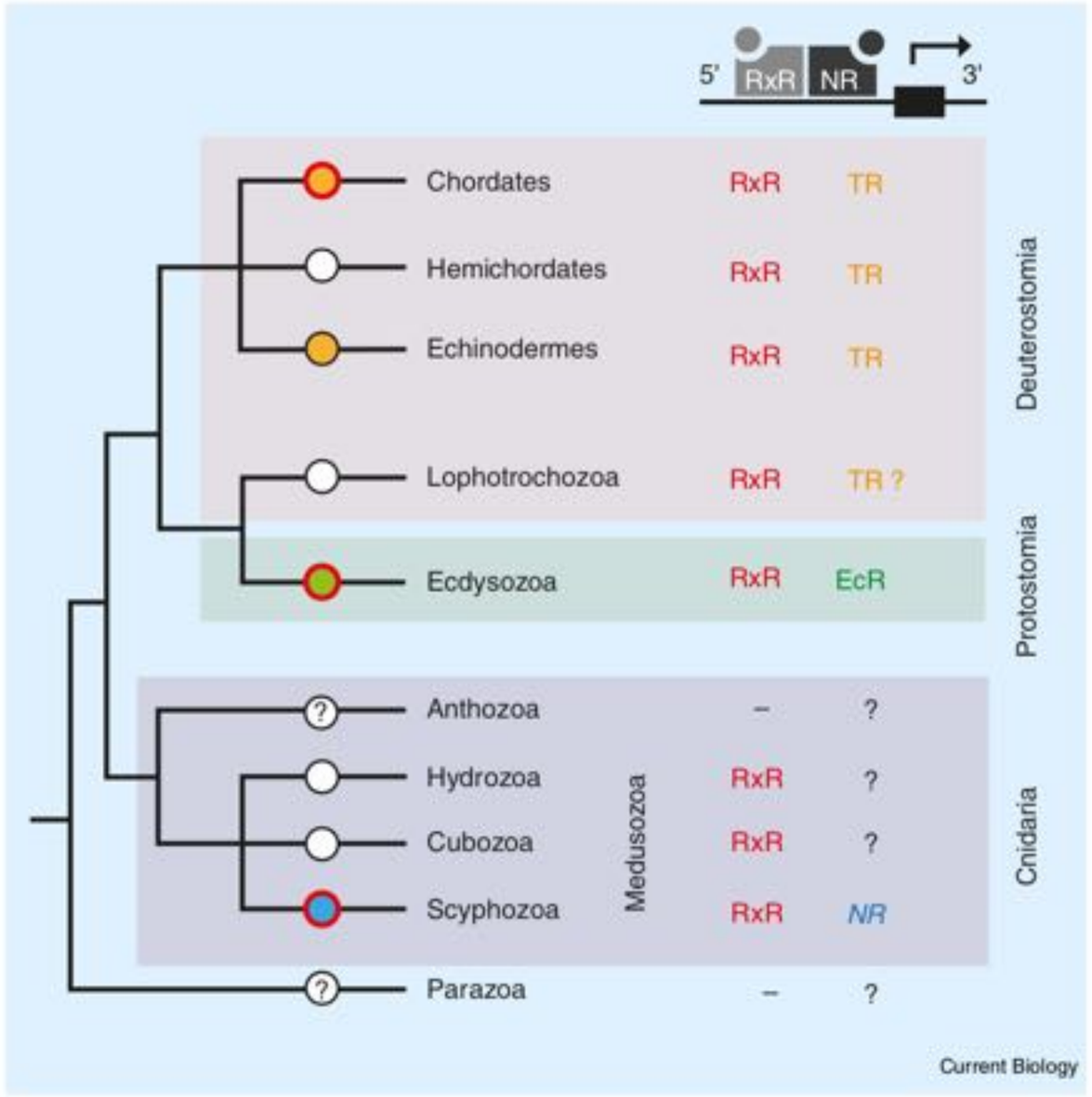
Figure 7 Larval molecular territories and cell types show global conservation of ancient larval patterning. For animals in which molecular data is available, spatial transcription factor expression data have been mapped onto the larval body plan (larvae as seen from the ventral side; amphioxus is pictured from a dorsal perspective). Morphologically described or 'molecularly footprinted' cells found in the apical organ are pictured above larval forms. The activity of Wnt signaling on larval body formation is pictured with bars flanking the larvae. Data is compiled from this and previous studies in Cephalochordata [45,59,65-73], Hemichordata [9,25,41,43,60,74-77], Echinodermata [26,32,36,37,42,48,78-83], Mollusca [24,84] and Cnidaria [30,40,44,64,85-90].

A third hypothesis: metamorphosis-first: all the data support this hypothesis



A Pelago-benthic neuralian ancestors: Single terminal addition of benthic adult stages (Jägersten 1972; Arendt et. al, 2013)

Support for metamorphosis-first hypothesis: shared hormonal-control of life history transitions

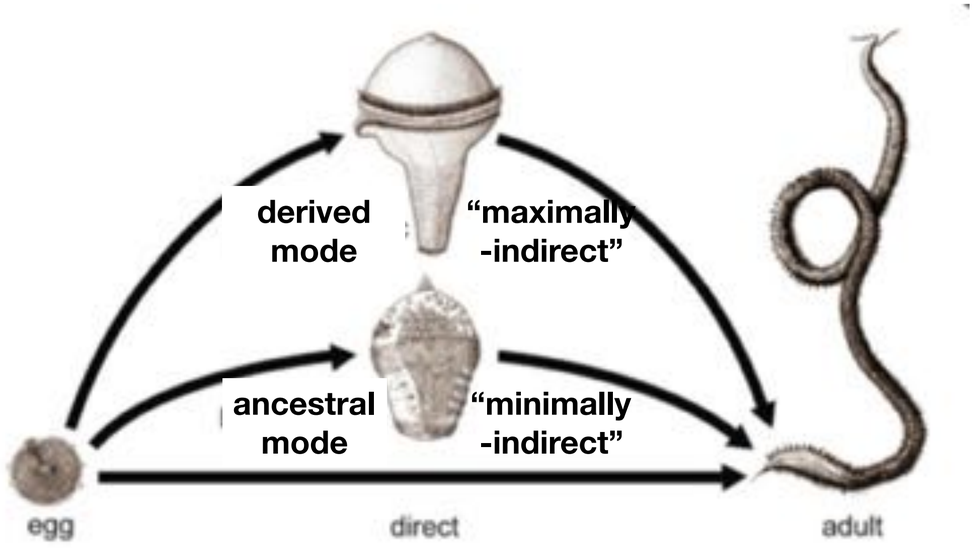


Nuclear Hormone Receptor (NR)

Nuclear Receptor (RxR)

Summary of Part 3:

- Most current hypothesis is that “minimally-indirect development” is ancestral



- Likely, some type of metamorphosis is an ancient trait among marine invertebrates!
- But a drastic metamorphosis (with feeding larva) is derived in many lineages