Scaling the Vertebrate Embryo from the Ovocyte Upwards, via Hydrodynamic Flow: Consequence for Evolutionary Constraints

Presented in the Embryo Physics Course http://www.embryophysics.org

February 12, 2009

By

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Scaling the vertebrate embryo from the ovocyte upwards, with a hydrodynamic flow. Consequence for evolutionary constraints

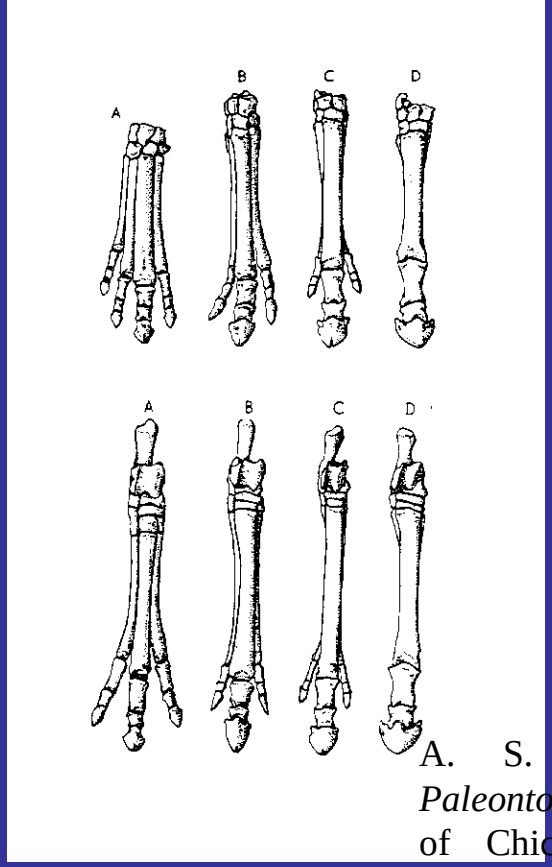
Embryo Physics Course, Silver Bog Research Inc., Second Life®

February 12, 2009.

Throughout whole classes various structures are formed on the same pattern, and at an embryonic age the species closely resemble each other…

… I believe that animals have descended from at most only four or five progenitors…
archetypes…
prototypes…

Charles Darwin



A. S. Romer, *Vertebrate Paleontology*, (The University of Chicago Press, Chicago 1966).

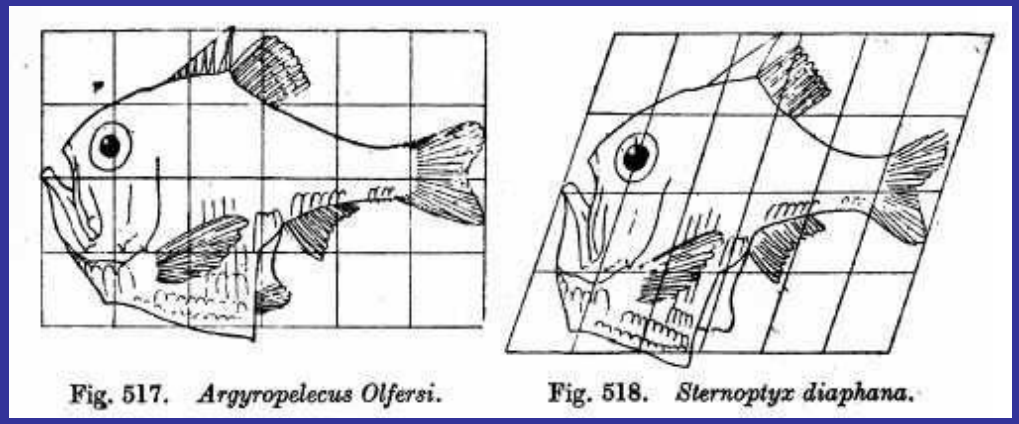
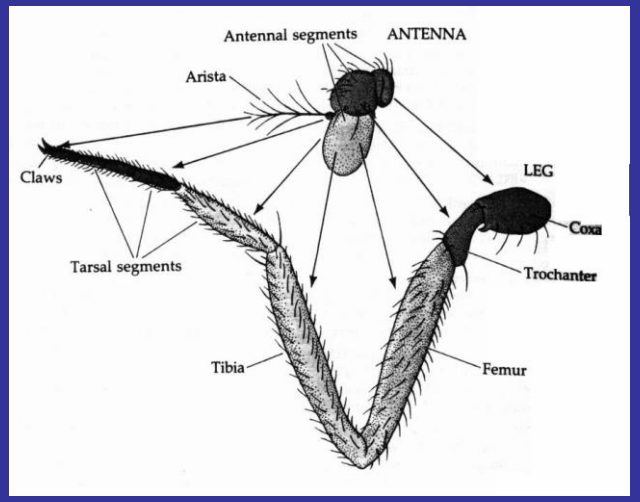


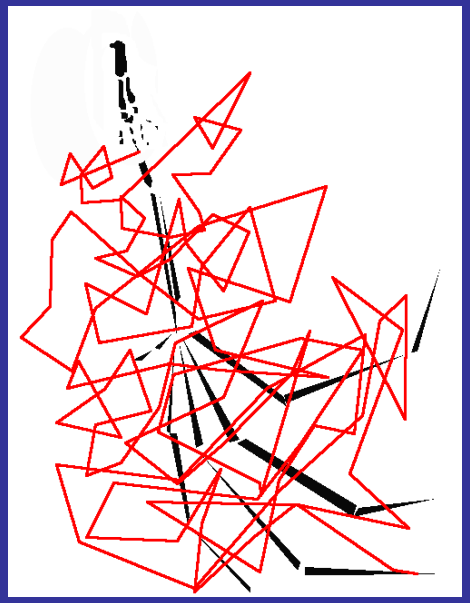
Fig. 517. *Argyropelecus Olfersi.* Fig. 518. *Sternoptyx diaphana.*

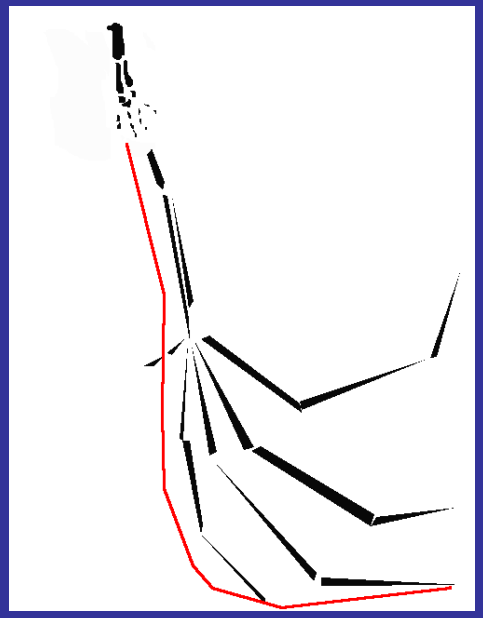
D'Arcy Thomson

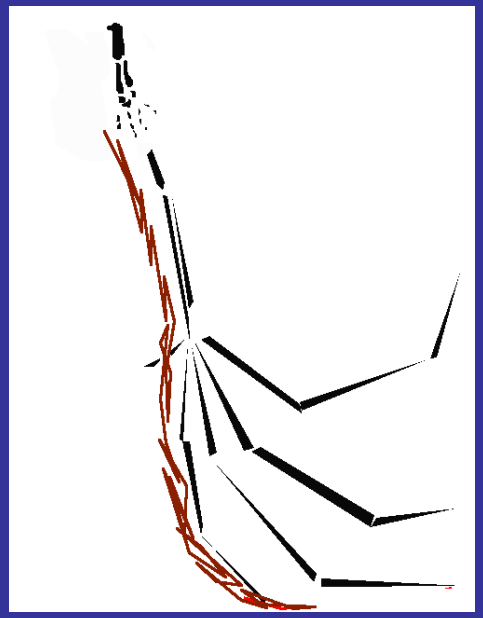


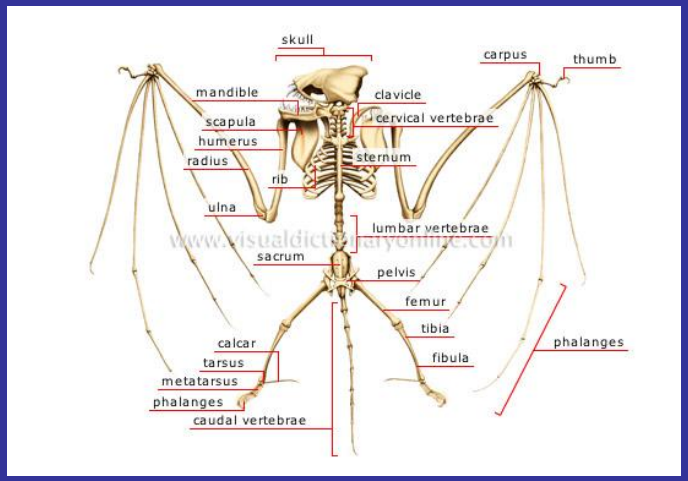
J. H. Poslethwait and H. Schneiderman, Dev. Biol., 25, 606 (1971)

…….the ancient progenitor, the archetype as it may be called, of all mammals, had its limbs constructed on the existing general pattern, for whatever purpose they served……







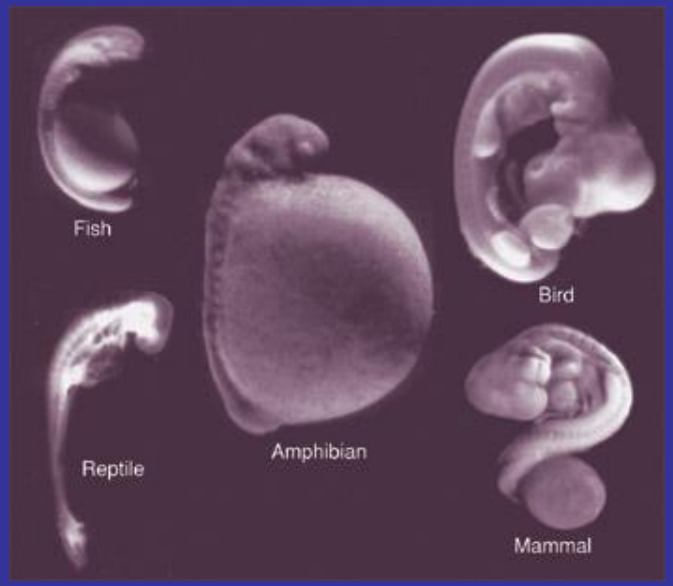


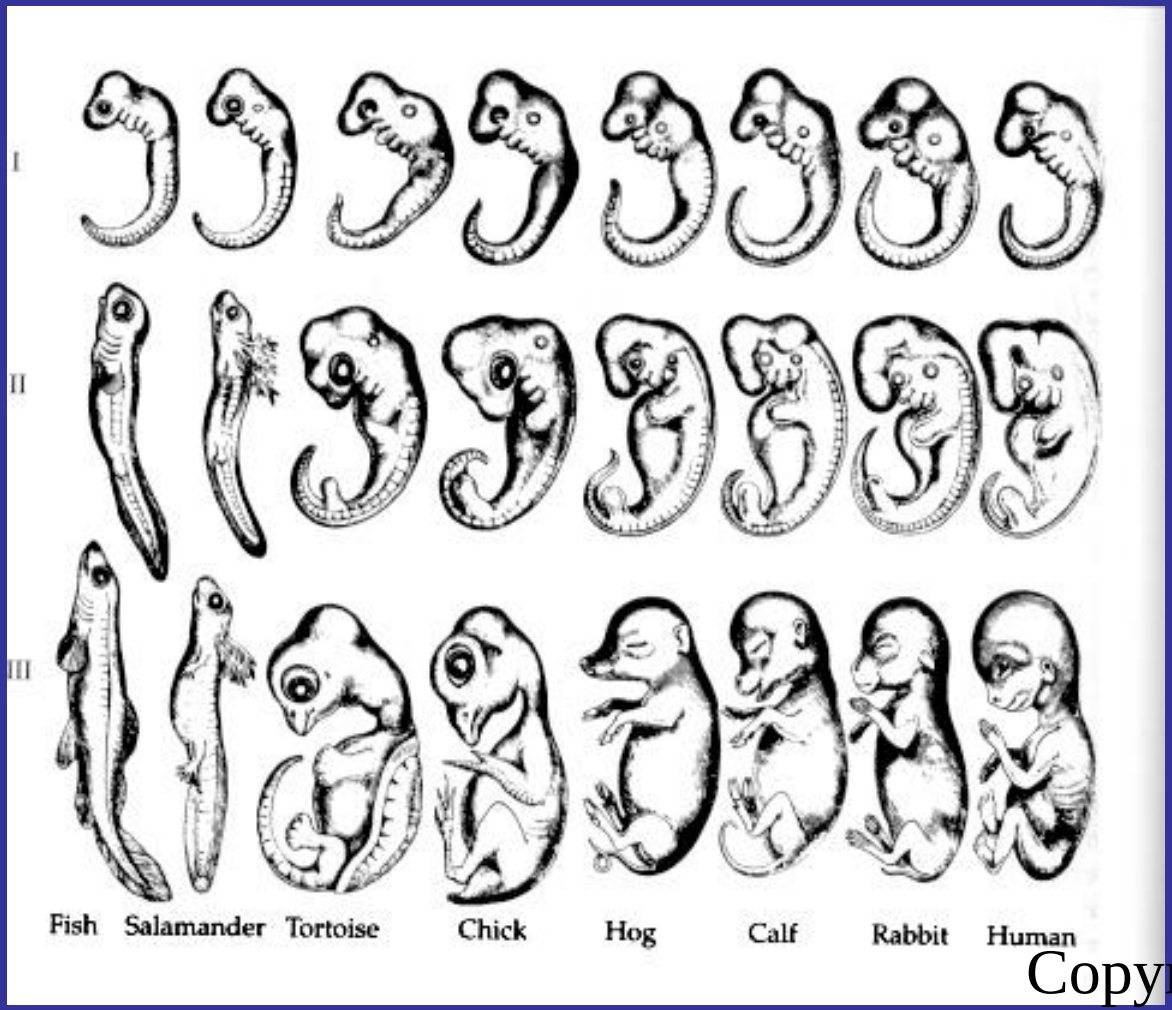
AFFINE TRANSFORMATION

In changes of this nature, there will be little or no tendency to modify the original pattern, or to transpose parts. The bones of a limb might be shortened and widened to any extent, … a foot might have all its bones… lengthened to any extent … so as to serve as a wing
yet in all this great amount of modification there will be no tendency to alter the framework of bones

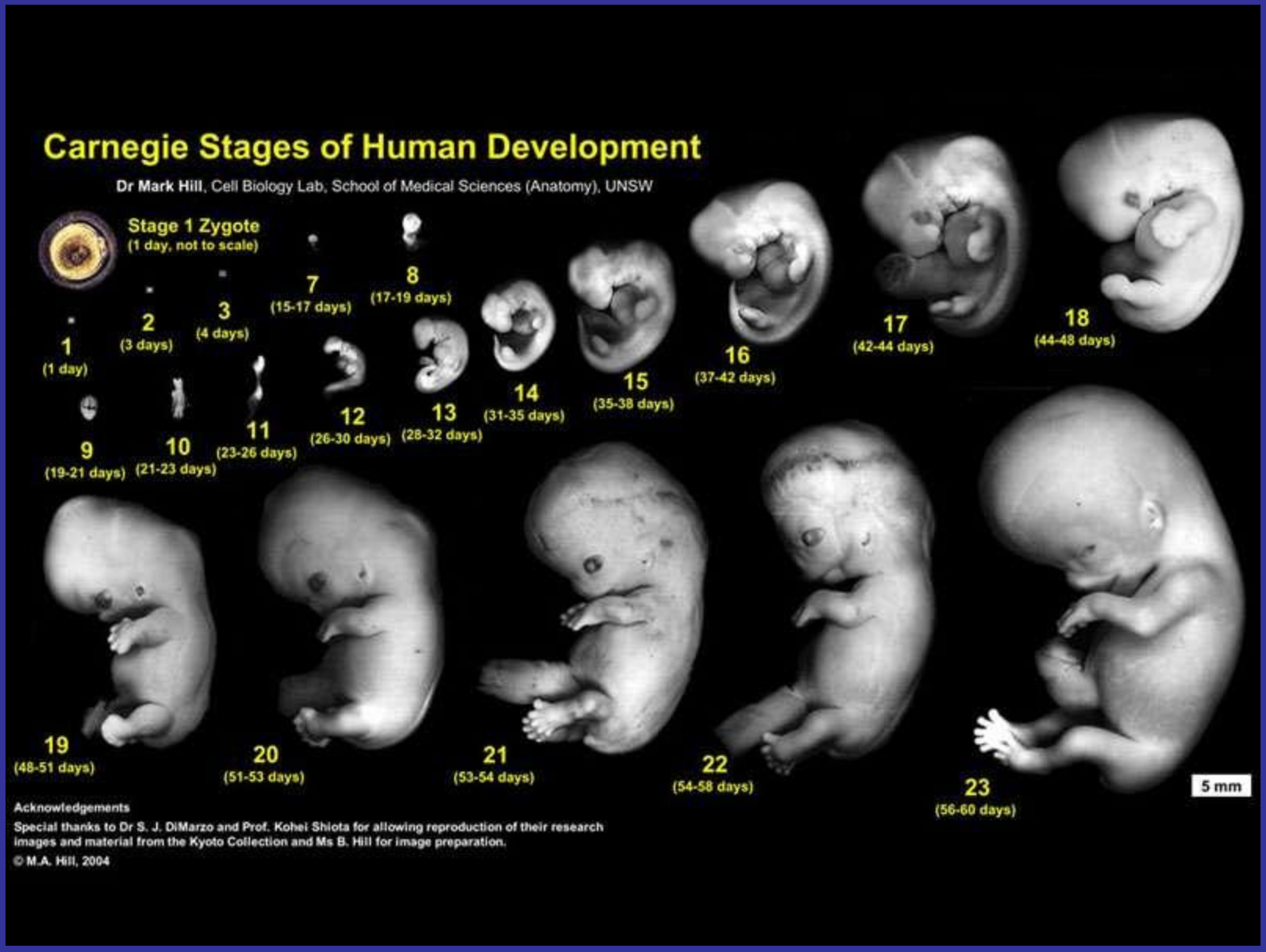
What is the « archetype »
The « general pattern »
« prototype »

Gabriela Loots





Haëckel


Carnegie Stages of Human Development
Dr Mark Hill, Cell Biology Lab, School of Medical Sciences (Anatomy), UNSW
Stage 1 Zygote
(1 day, not to scale)
1
(1 day)
2
(3 days)
3
(4 days)
7
(15-17 days)
8
(17-19 days)
9
(19-21 days)
10
(21-23 days)
11
(23-26 days)
12
(26-30 days)
13
(28-32 days)
14
(31-35 days)
15
(35-38 days)
16
(37-42 days)
17
(42-44 days)
18
(44-48 days)
19
(48-51 days)
20
(51-53 days)
21
(53-54 days)
22
(54-58 days)
23
(56-60 days)
5 mm
Acknowledgements
Special thanks to Dr S. J. DiMarzo and Prof. Kohei Shiota for allowing reproduction of their research images and material from the Kyoto Collection and Ms B. Hill for image preparation.
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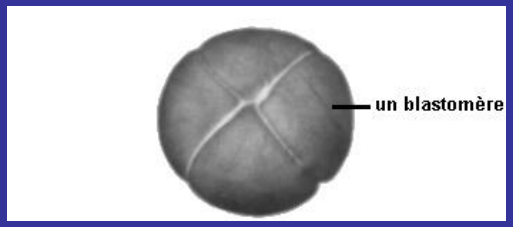
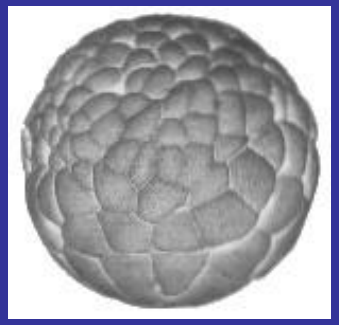
Living material : what kind of material

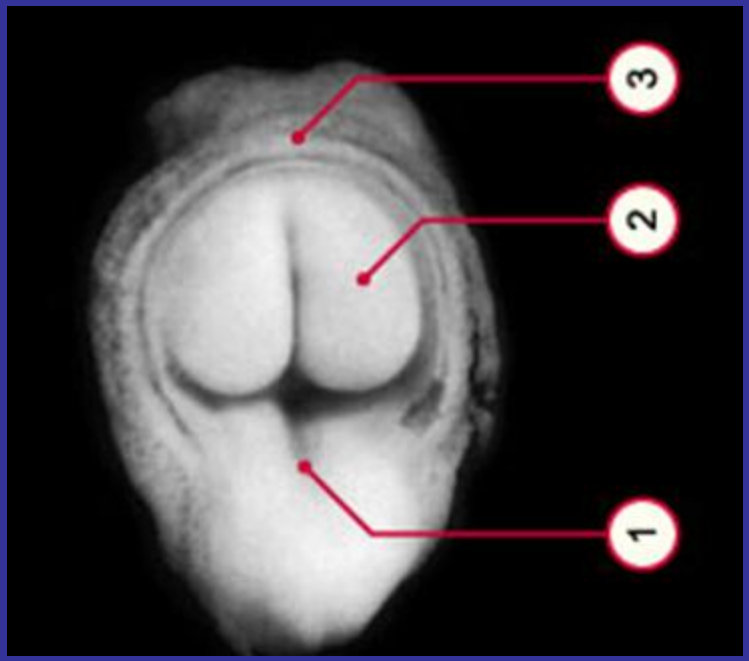
Elastic

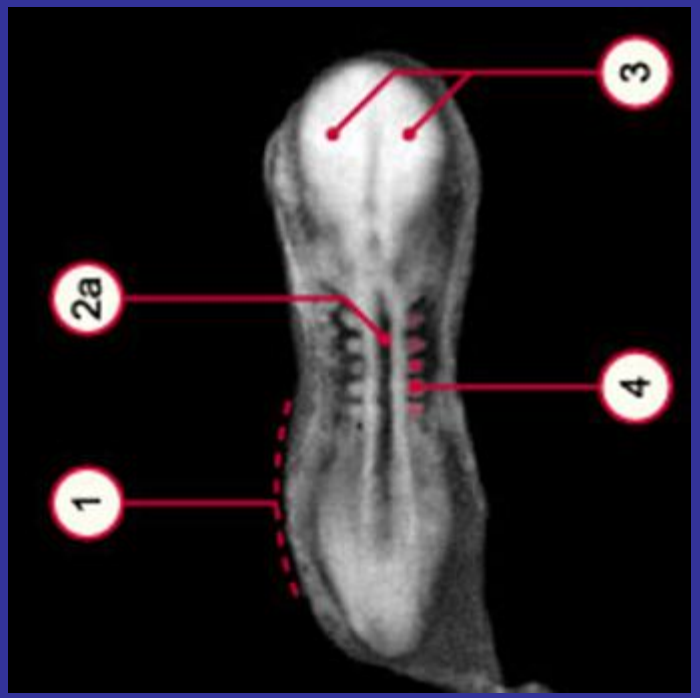
Viscous





FROG Morula

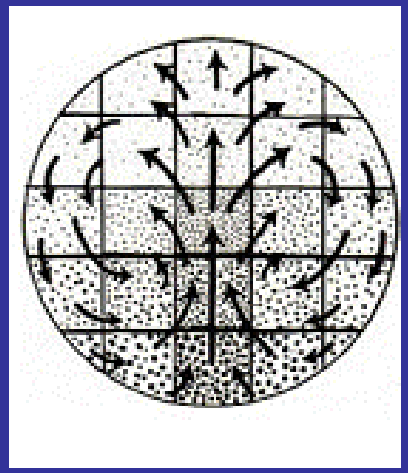




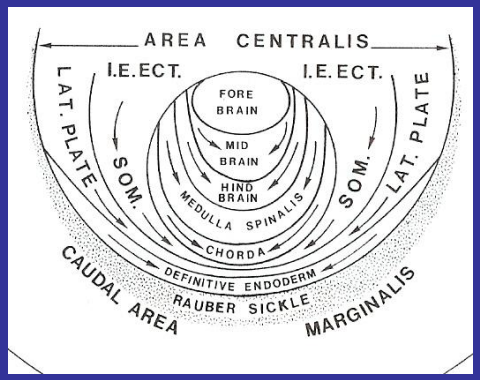
Plan establishment occurs here

HUMAN

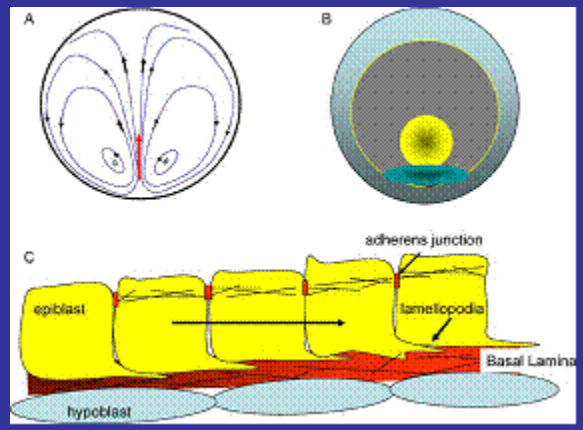
A flow occurs in a form-less embryo (blastula stage) towards a spot located caudally



1920's Wetzel

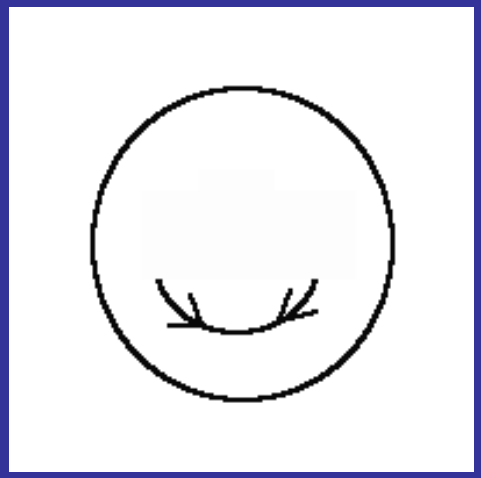


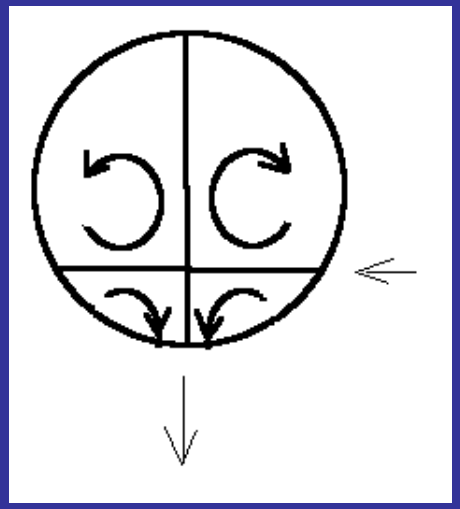
1990's Callebaut



2000's Weijer

Same description :
unfortunately, all wrong,
all *dipolar*





The flow is a quadrupolar flow
Two jets facing each-other

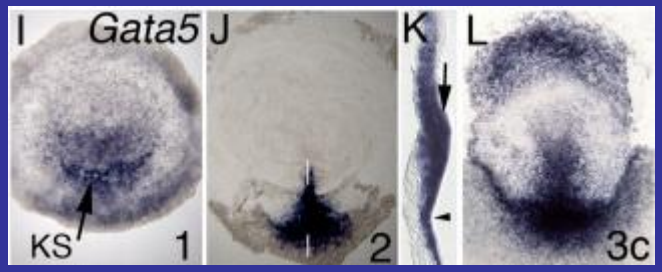
The result is a hyperbolic flow

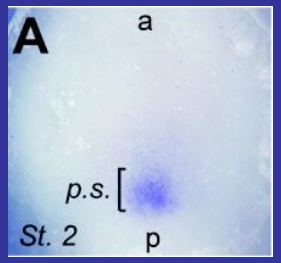
(well known in hydro)

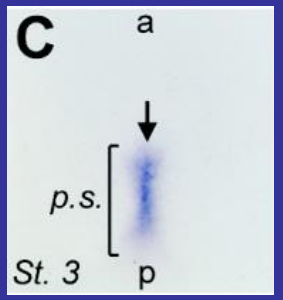
TWO JETS FACING EACH OTHER

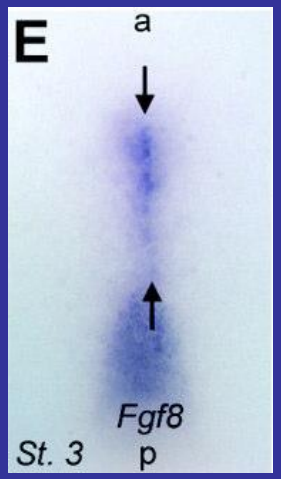
HEAD-ON COLLISION

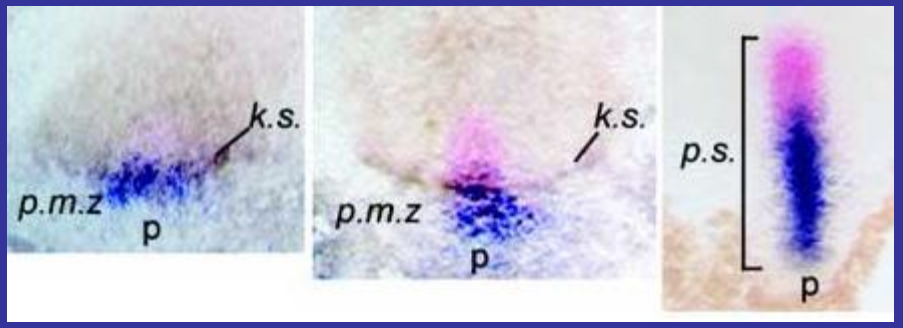
All genetic expressions follow passively the flow

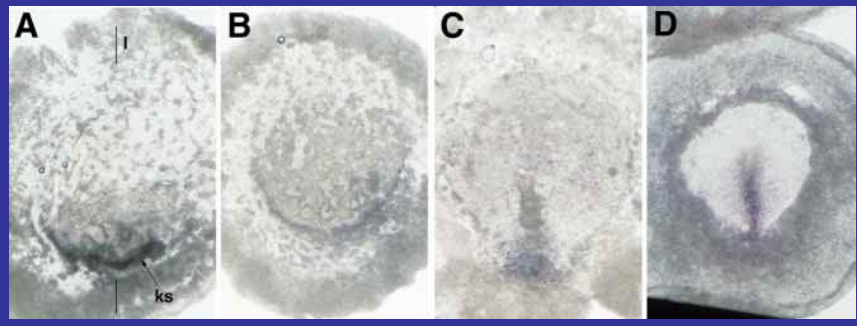






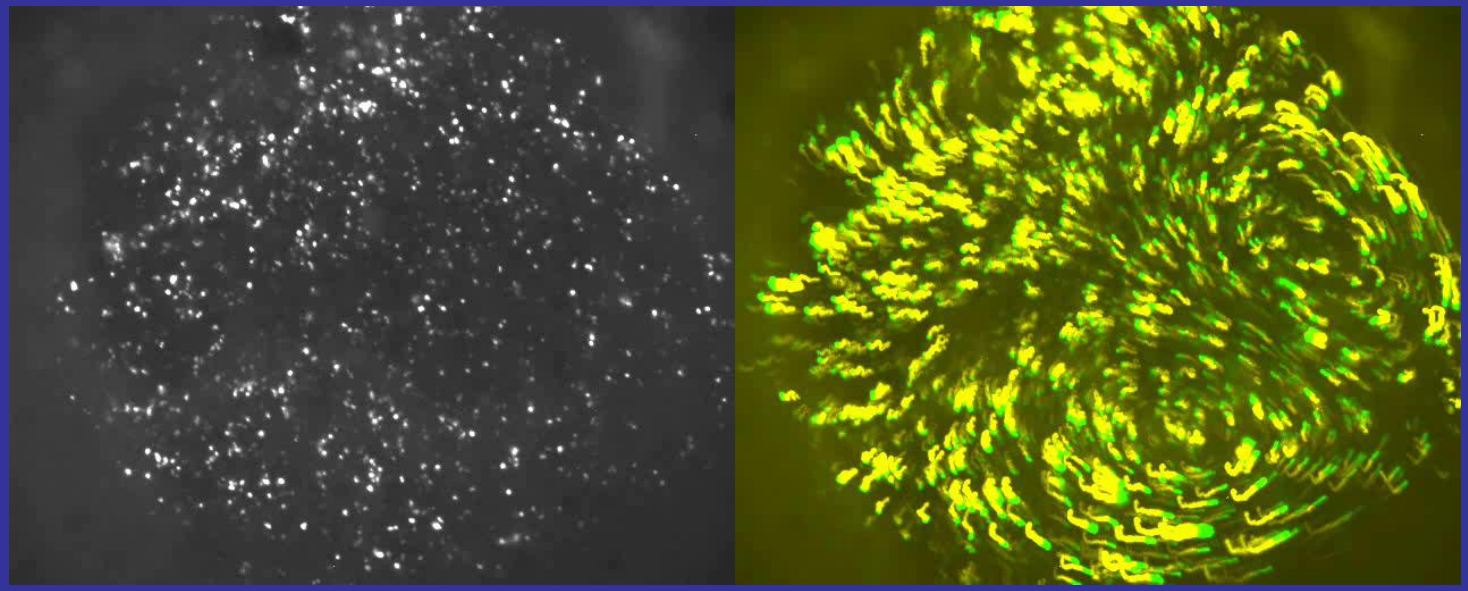


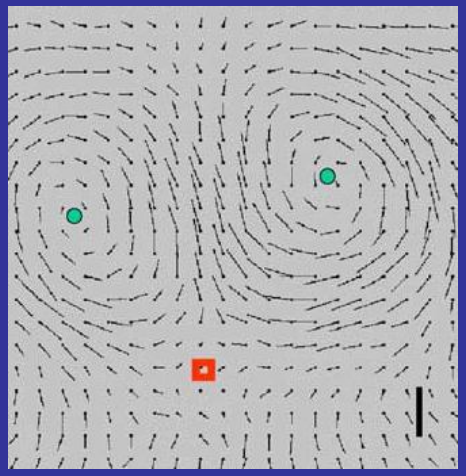




From database Geisha,Mikawa, I. Skromme, Stern , Chapman, et al.

Considerable number of recent confirmation





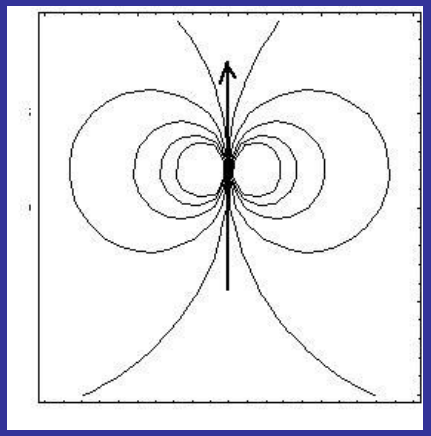
Cui, Chuai, Weijer et al.

All show a stagnation point

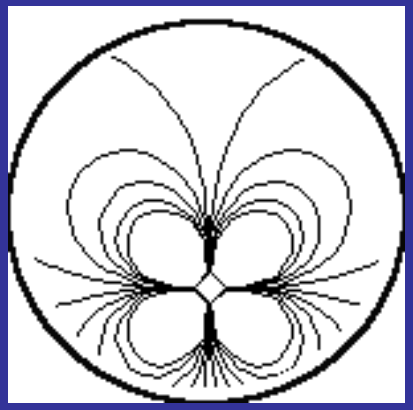
Zamir *et al* Plos biology 2008

Explanation of the flow

A single cell is a dipole (integrating friction terms)



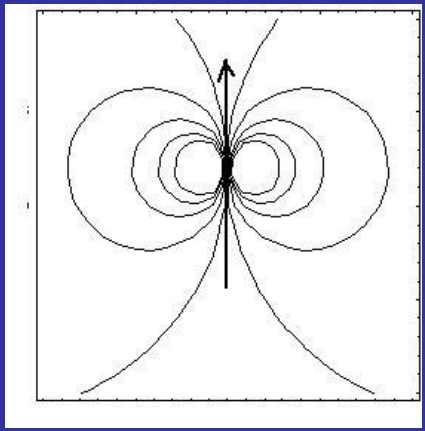
A single cell
(« quantum ») of force
tends to generate
vortices



Morula distribution
tends to generate
a quadrupole

VF Organogenesis 2,1 2005.

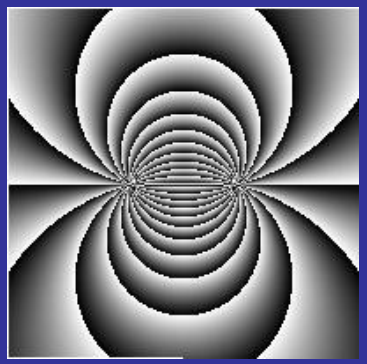
Explanation of the flow

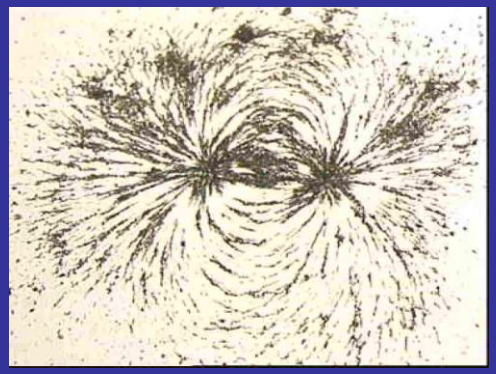


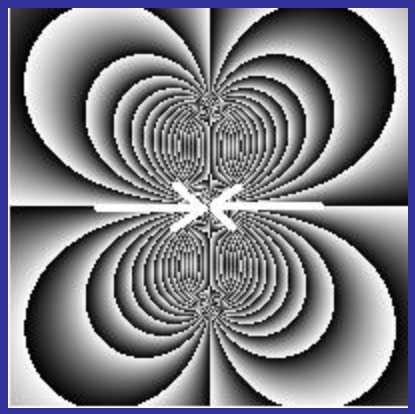
A single cell is a dipole

$$\Psi(x,y)=y/(x^2+y^2)$$

V=curl(Ψ)







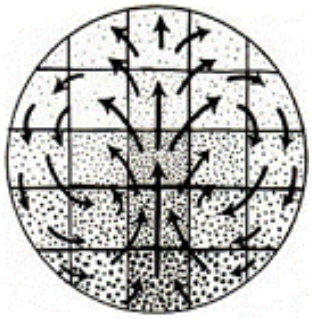
Solutions for a pulling segment

$$\Psi_A = \text{ArcTan}[(x-a)/(y-\beta)] - \text{ArcTan}[(x+a)/(y-\beta)]$$

For two segments pulling head on

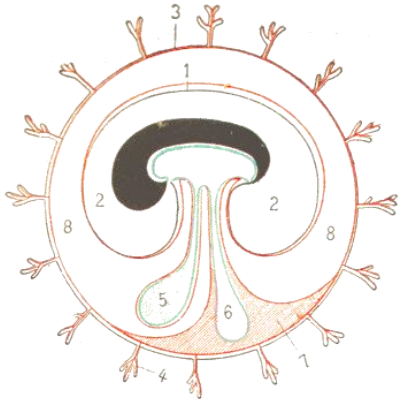
$$\Psi_A = \text{ArcTan}[(x-a)/(y-\beta)] - \text{ArcTan}[(x)/(y-\beta)] - \text{ArcTan}[(x)/(y-\beta)] - \text{ArcTan}[(x+a)/(y-\beta)]$$

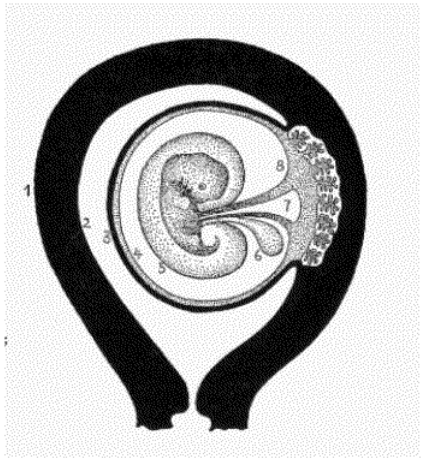
NOT THIS

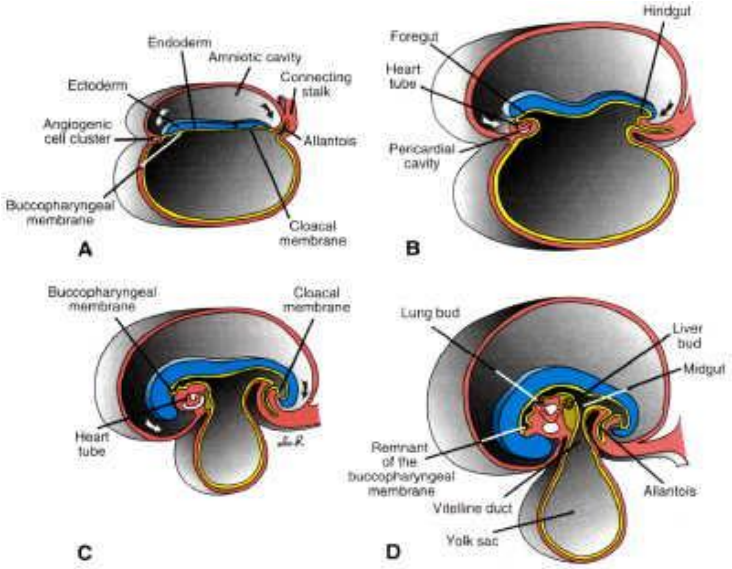


It is a collision of two vortex rings

THIS

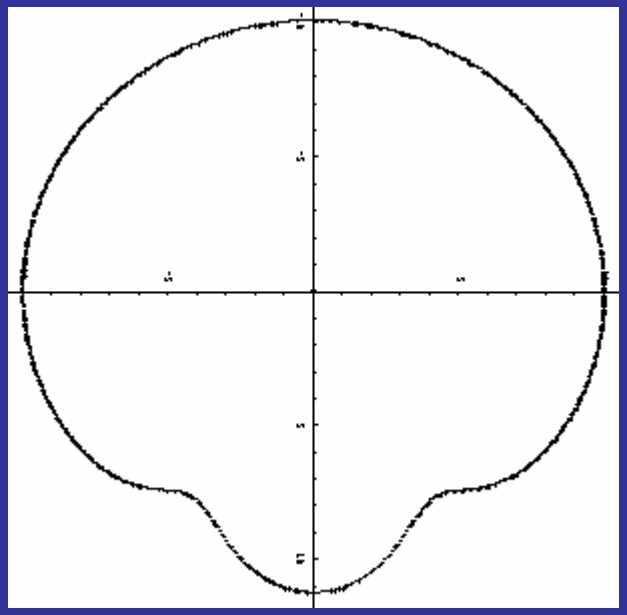






All drawings show actually vortex rings

One can calculate the deformation of the early embryo



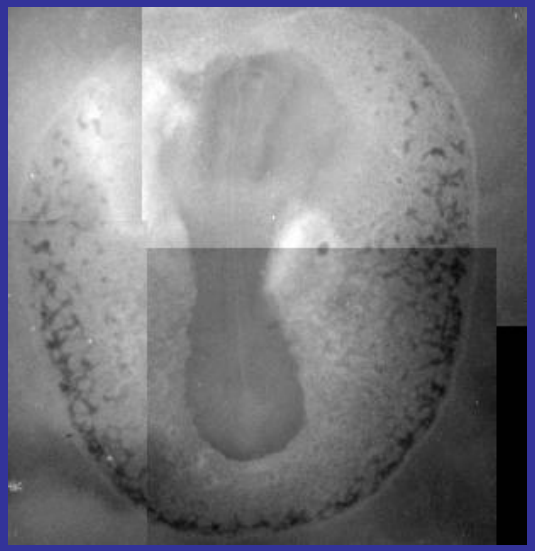
The blastodisc extends caudally.

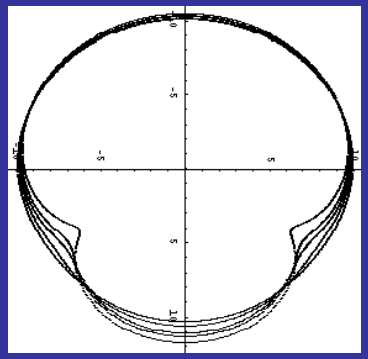
No gradient
No chimiotactisme
No diffusion

Cells just follow a flow wich they themselves generate

The « tadpole shape » is linked to conservation laws

The shape depends on the radius
Circles become slender « 8 »

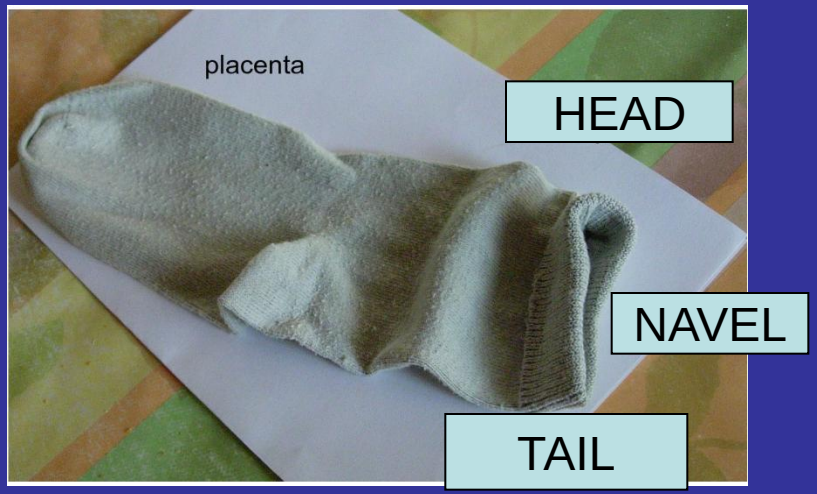


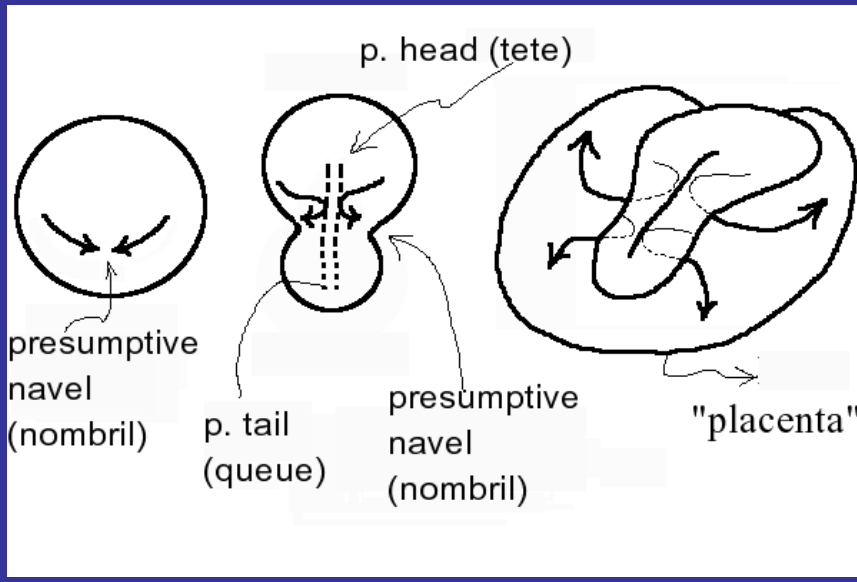


The shape depends on time

The shape depends on topology

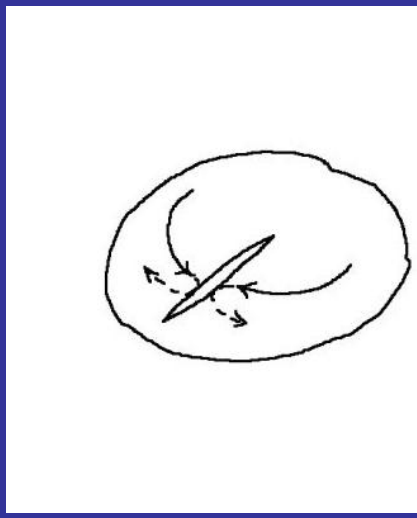
At stagnation point highest stress : nucleation of epiboly





Topology of embryo+placenta much like a sock

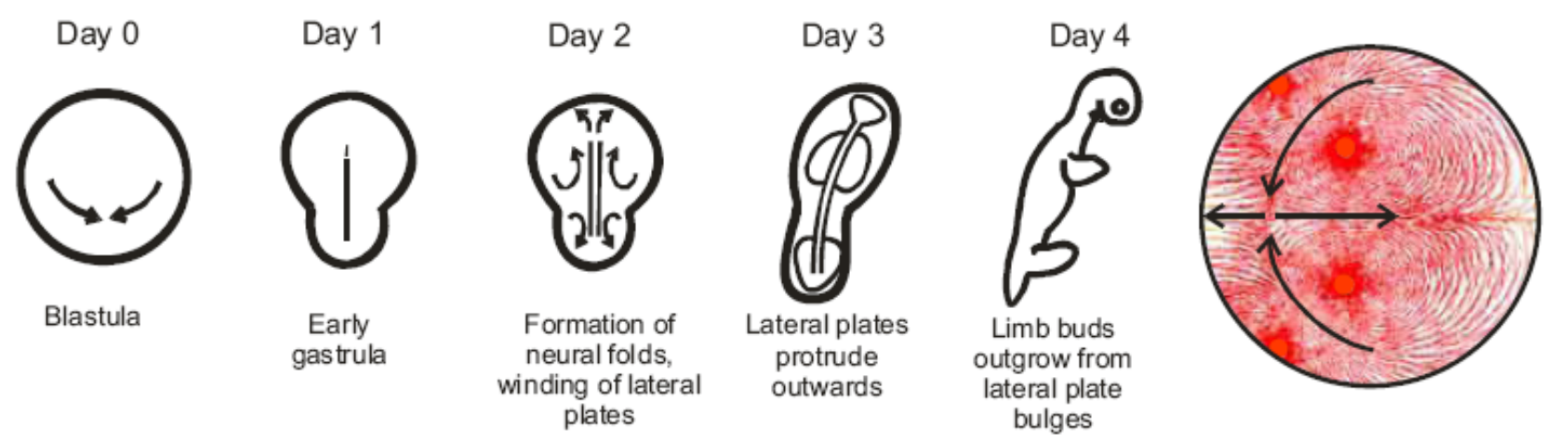
What converges becomes the embryo (8 shape)
What diverges becomes the placenta (circular)



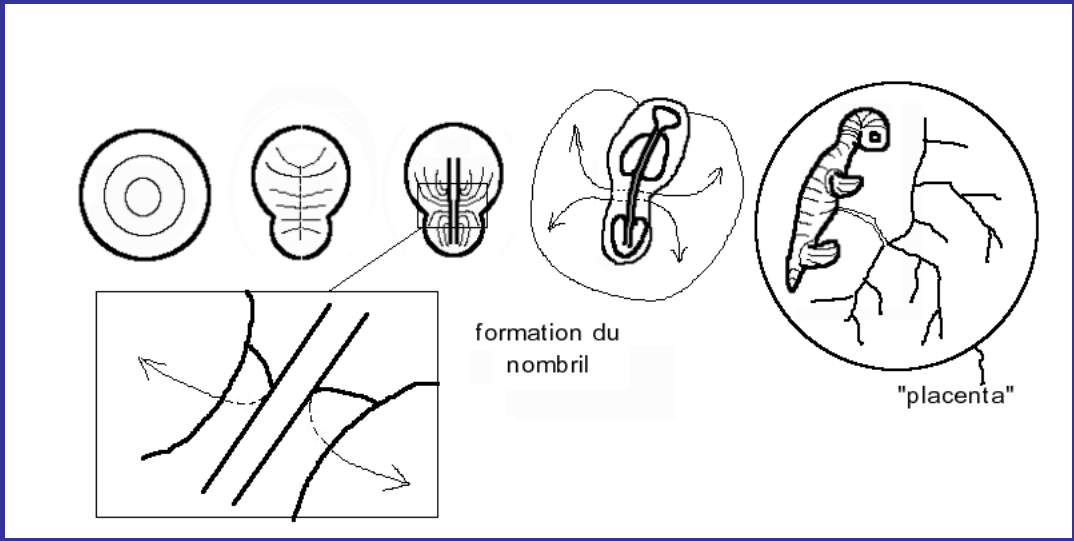
www.gastrulation.org movie15.1 Dr Cheng Cui in Professor C.J. Weijerâ€™s laboratory

Formation of a tetrapod goes like that : :

The embryo :



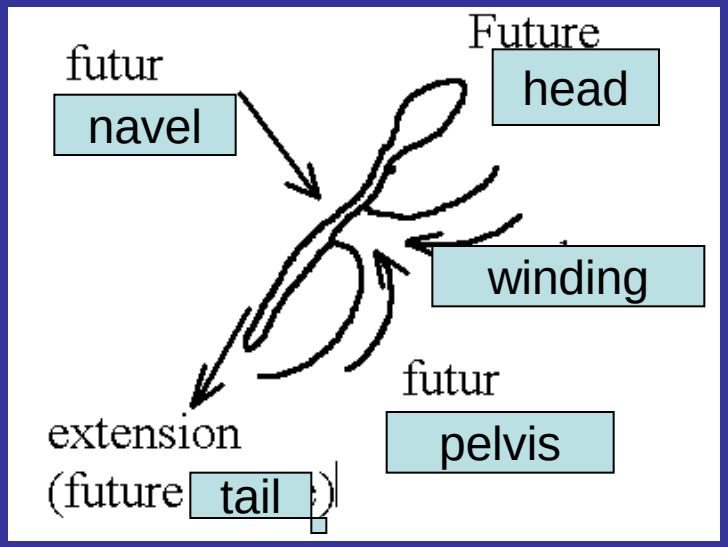
The extra-embryonic organs (placenta yolk-sac etc.)

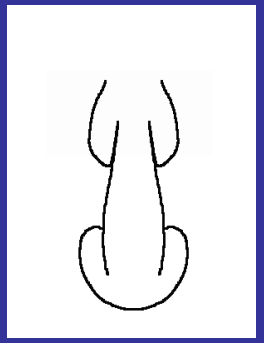


Physics of fruits
Monopole
Pure dilation

Quadrupole, hyperbolic
Convergent extension

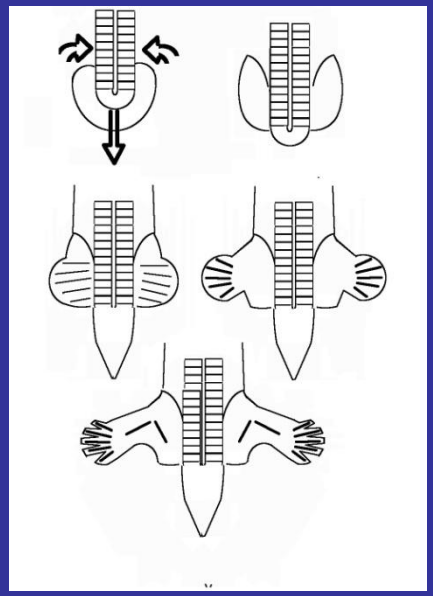
Detail of limb budding, outgrowth

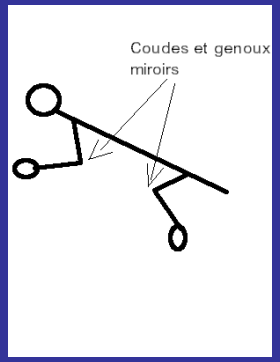




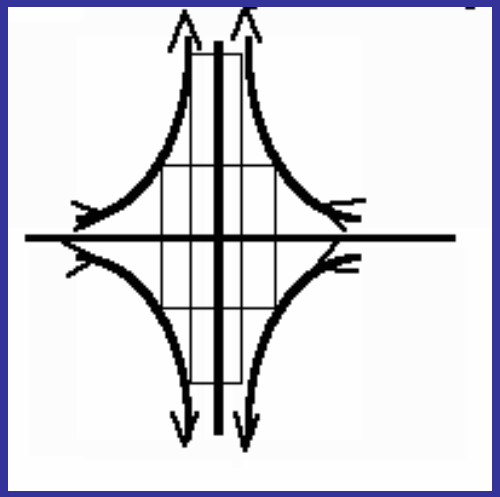
Richardson

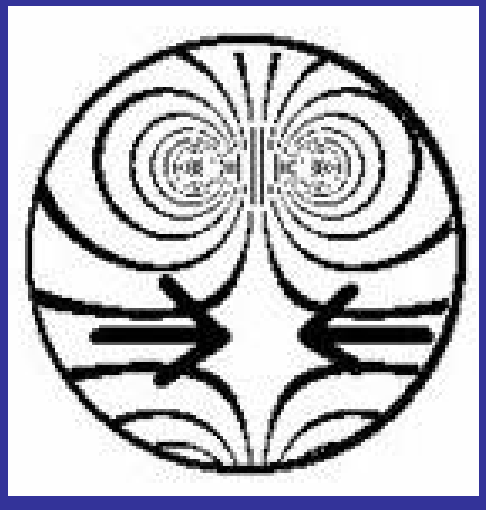
Direct frog





MATHEMATICAL MODELLING OF BODY FORM



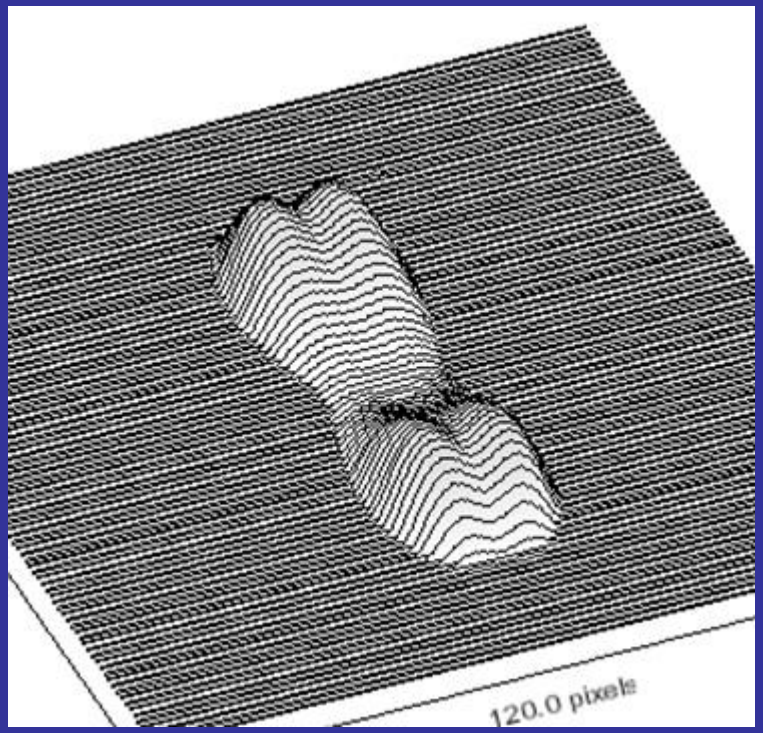


It is easy to form a body with the in-plane flow.

The hyperbolic flow exerts a pressure

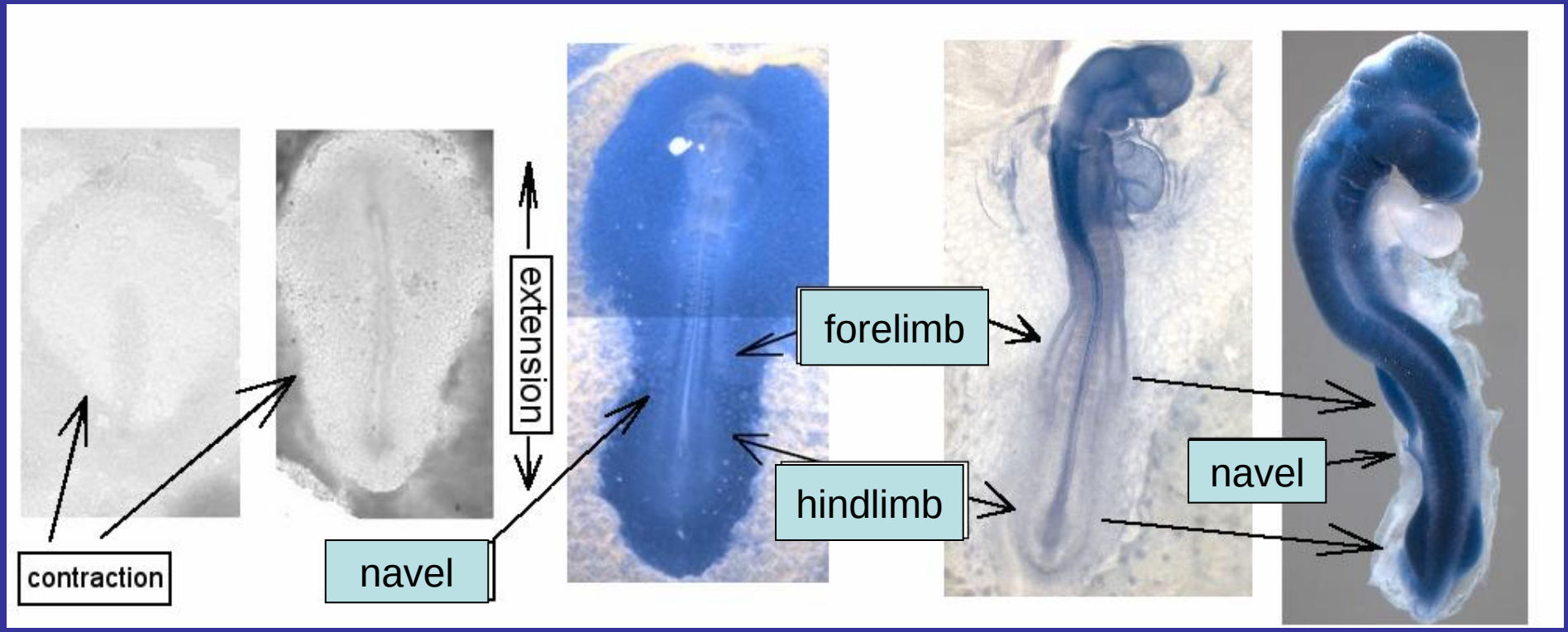
$P(x,y) \sim X^2 - Y^2$

Then the 3D shape can be calculated by von Karman equation

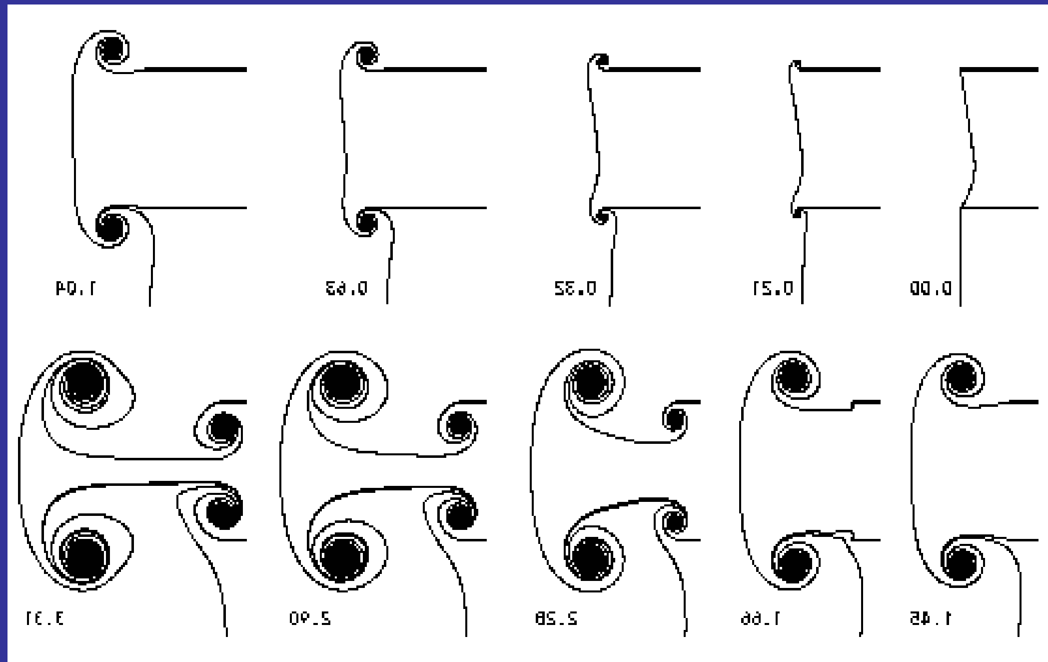


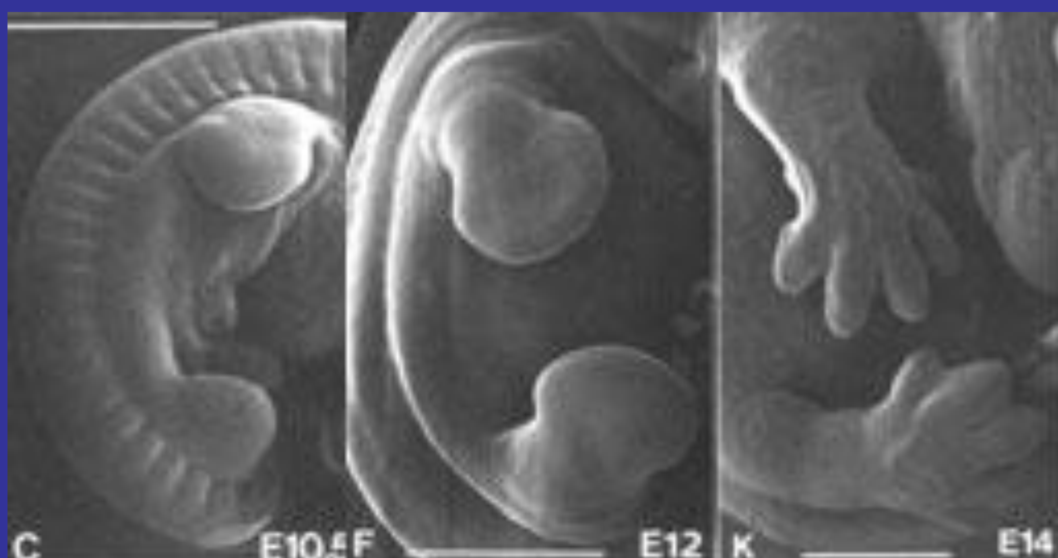
Body takes an « 8 » shape, with bumps at shoulders and hips

Mechanism of limb positioning in the hyperbolic flow (description)



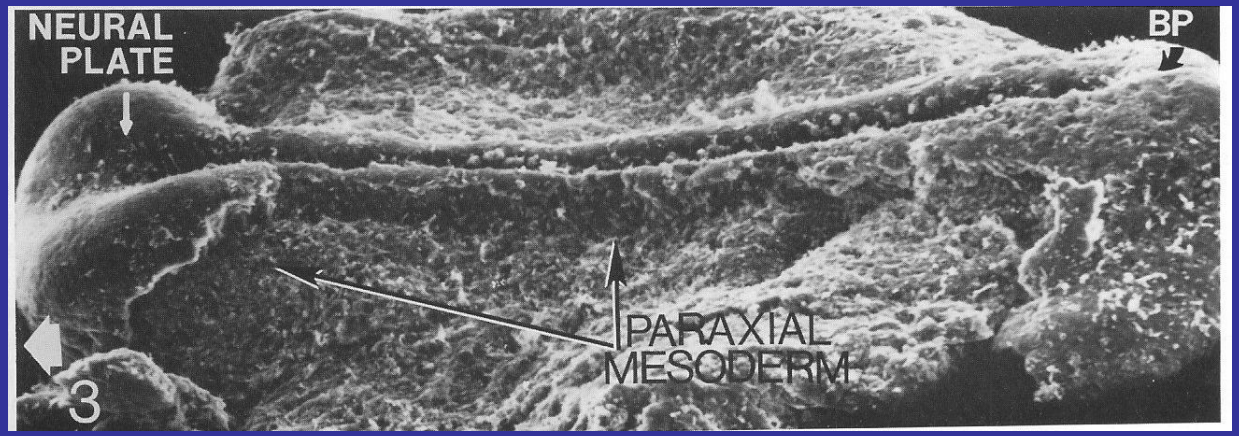
LIMBS positioned on either sides of the navel, by the hyperbolic flow, not an induction


1.04
0.63
0.32
0.21
0.00
3.31
2.90
2.58
1.66
1.45

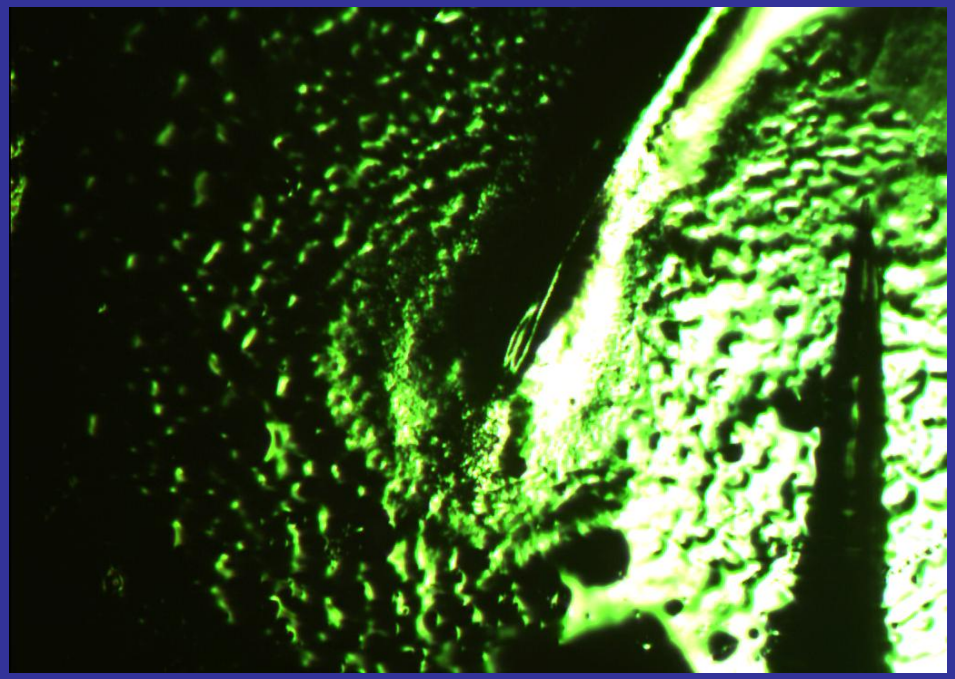

C
E10.5
F
E12
K
E14

Elastic fish

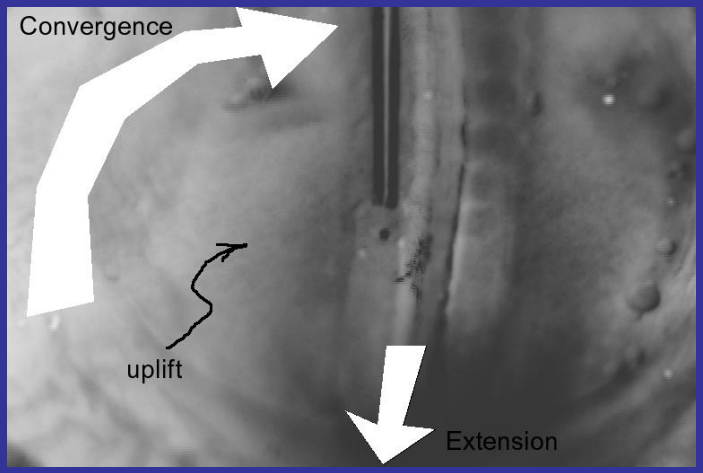
So simple!



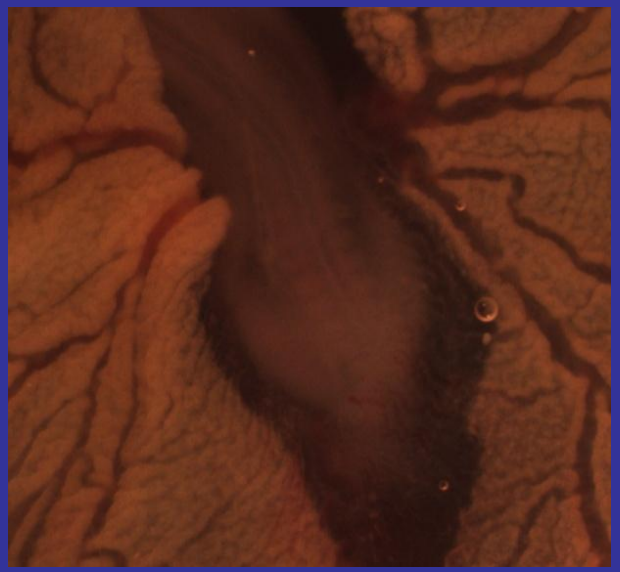
Meier and Packard (1984)



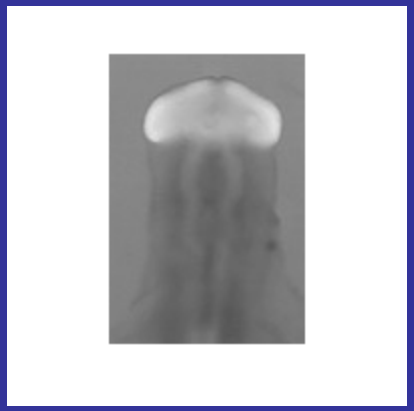
Shadowgraph imaging

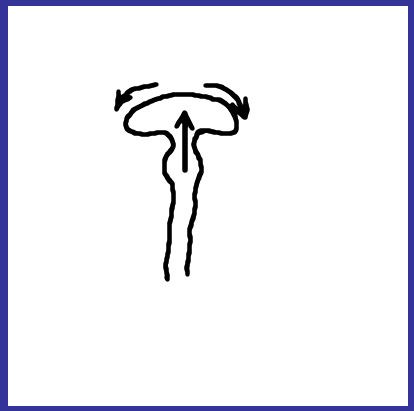


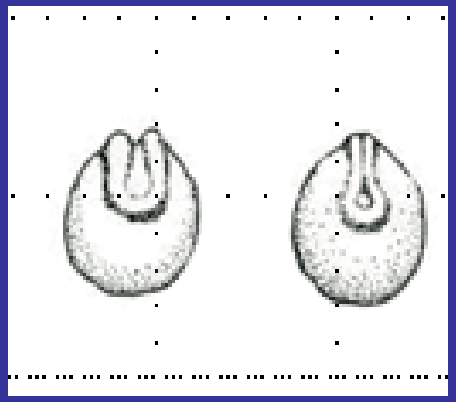
Scheme of the deformations

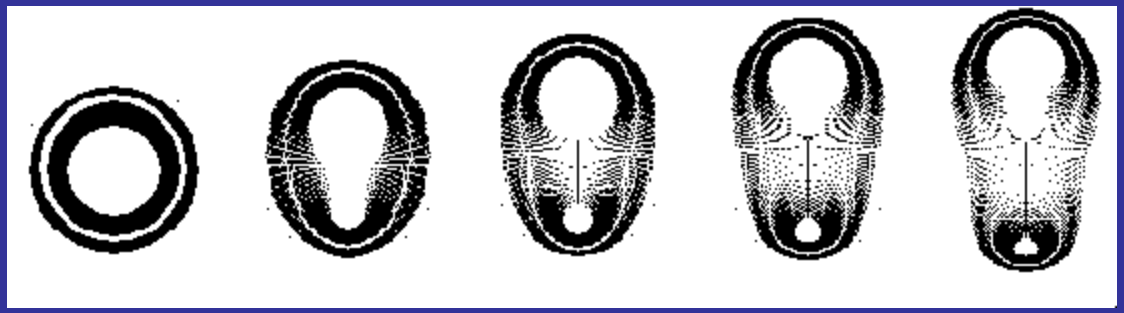


The body extends, flattens, and the caudal folds close, the cranial folds remain open

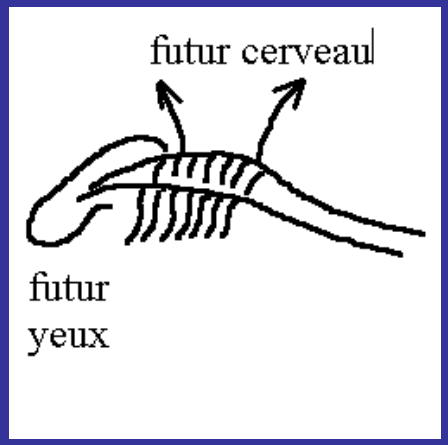


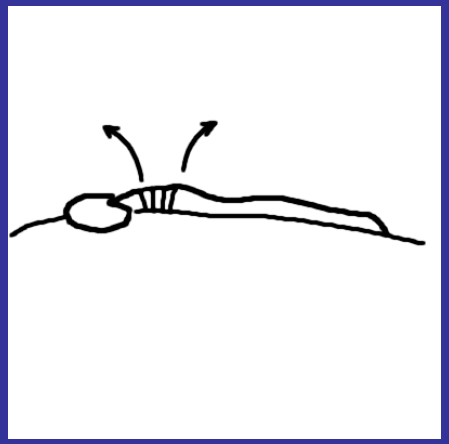


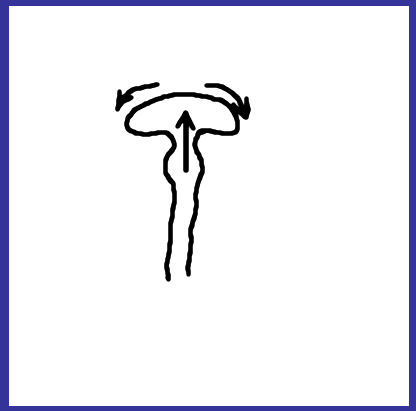


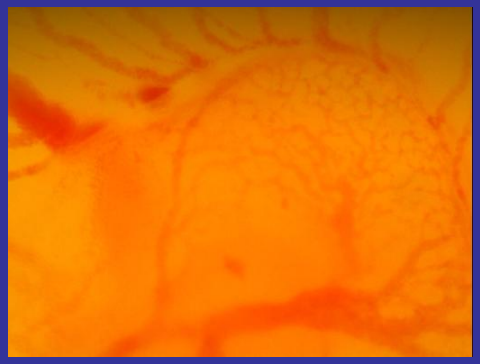


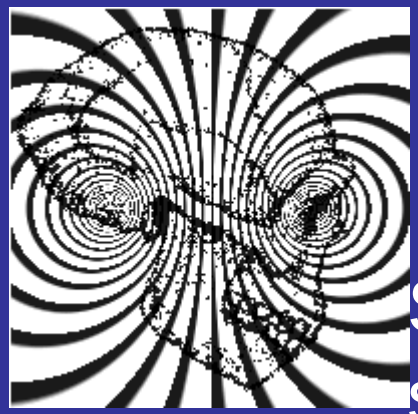
The neural crest fold winds upwards around the eye orbits and the ear duct





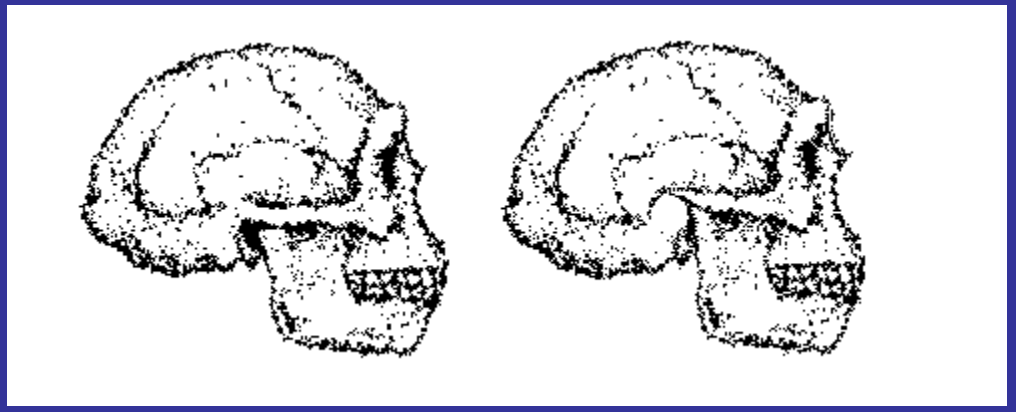


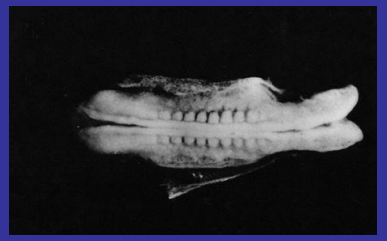




Simplified
mathematical model
(viscous flow)

Stroboscopes a dynamical system
from prehominians
towards humans





From Mark Hill, UNSW.