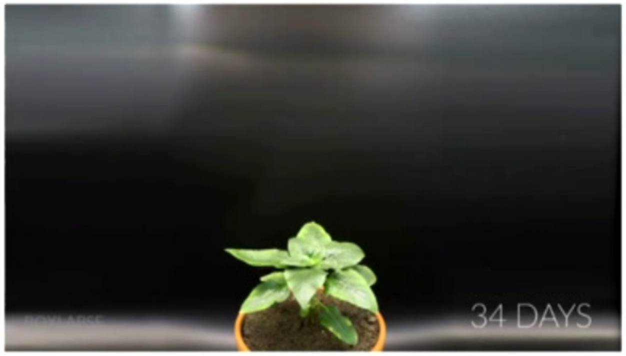
Title: Morphogenesis: Geometry, Physics, and Biology

Speakers:
Date: May 05, 2021 - 7:00 PM

URL: https://pirsa.org/21050028

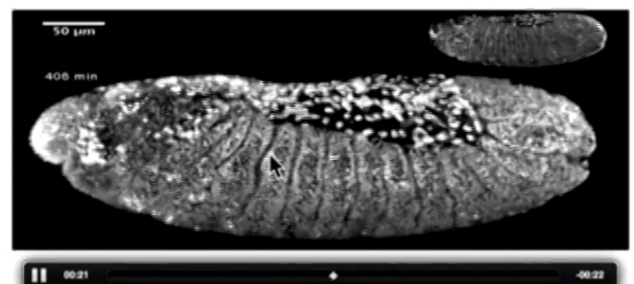
Abstract: In his May 5 Perimeter Public Lecture webcast, Harvard professor L. Mahadevan will take viewers on a journey into the mathematical, physical, and biological workings of morphogenesis to demonstrate how scientists are beginning to unlock many of the secrets that have vexed scientists since Darwin.

Morphogenesis



μορφη γεννtση

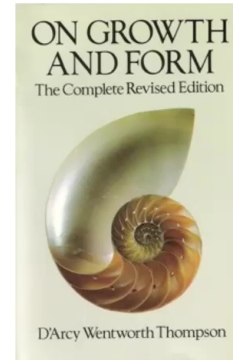
form emergence



Morphogenesis

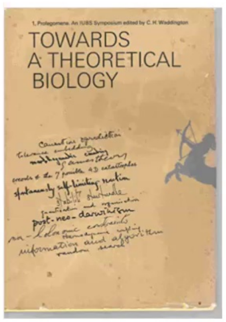
μορφη γεννтση

form emergence



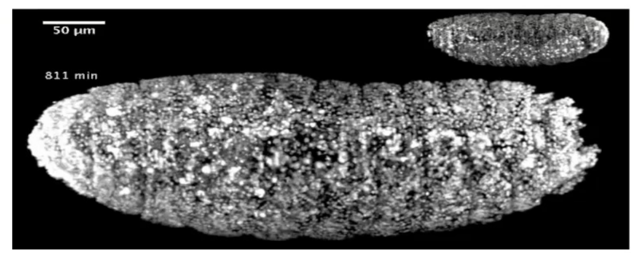
An organism is so complex a thing, and growth so complex a phenomenon, that for growth to be so uniform and constant is unlikely and unusual… rates vary, proportions change, … the whole configuration alters accordingly.

D. Thompson



“form ever follows function” L. Sullivan, architect

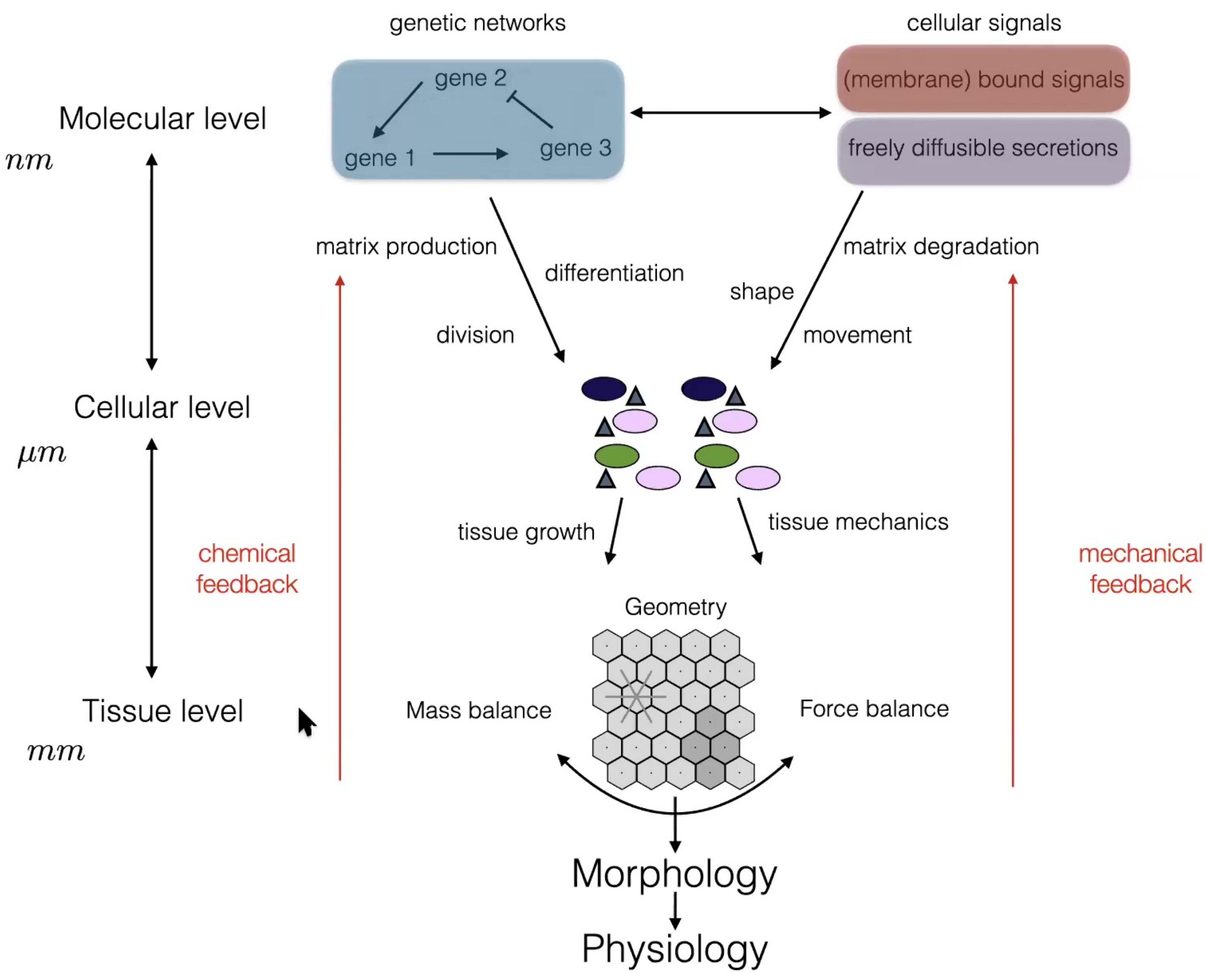
In biology and engineering, function ever follows form …



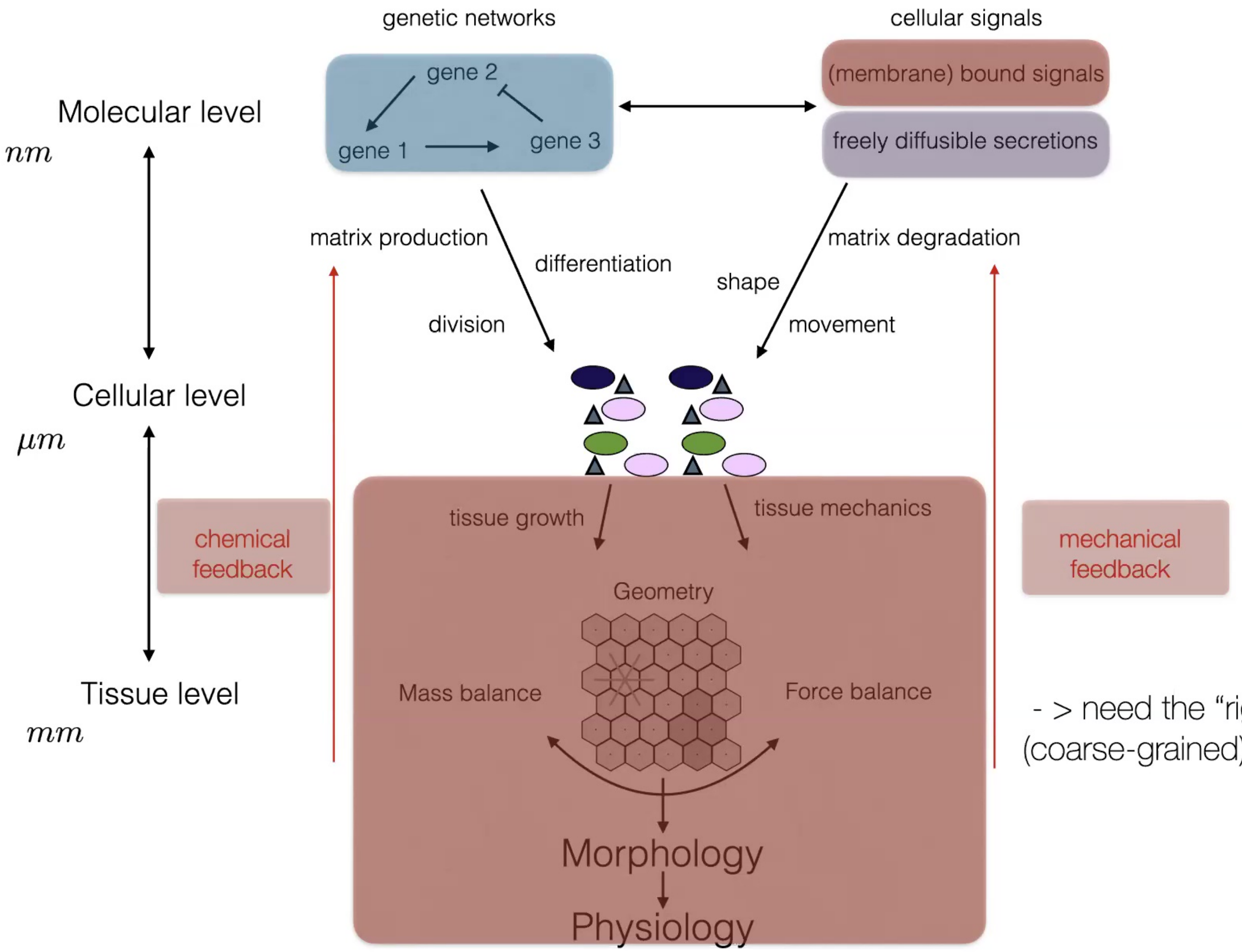
“No conceptualization of a living system is adequate unless it includes at least four importantly different time scales, those of metabolism, development, heredity and evolution”

C. Waddington

Where to start ?



Where to start ?



- > need the "right" (coarse-grained) description

Comparative studies

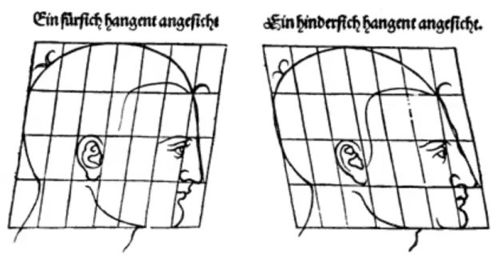
- Principles (development)
- Morphospaces (evolution)

Theoretical description

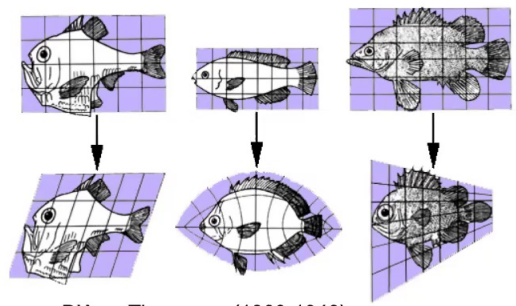
- Models (physics)
- Metaphors (mathematics)

Description: Mathematics (geometry)

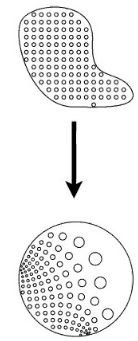
"Their problems of form are in the first instance mathematical problems" DWT

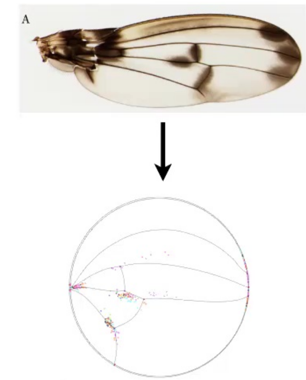


A. Durer (1471-1528)



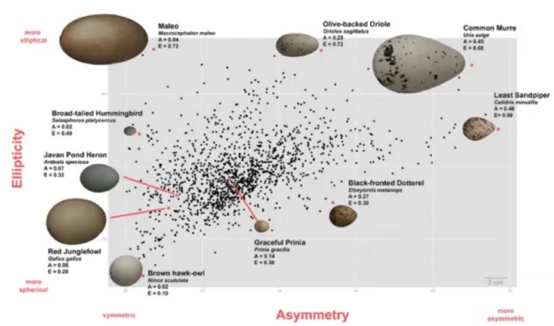
D'Arcy Thompson (1860-1948)





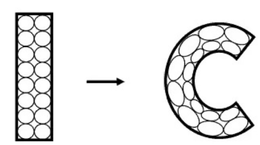
conformal

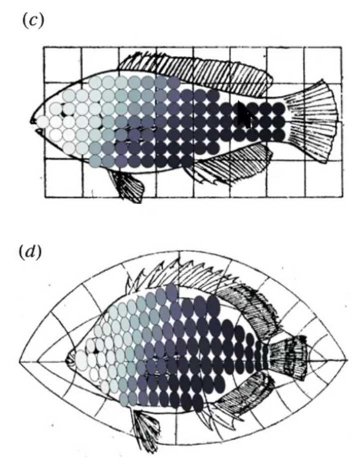
non-Euclidean



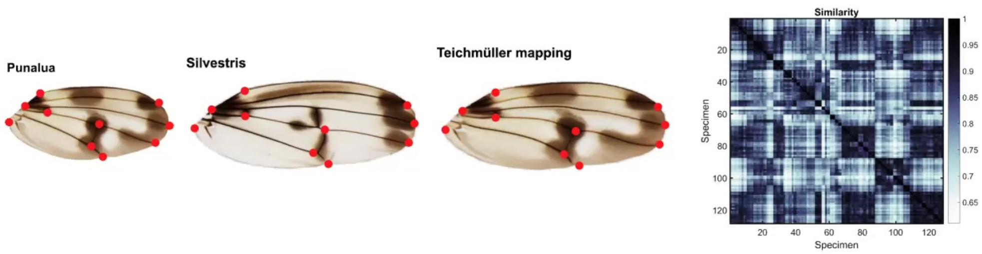
projective

quasi-conformal

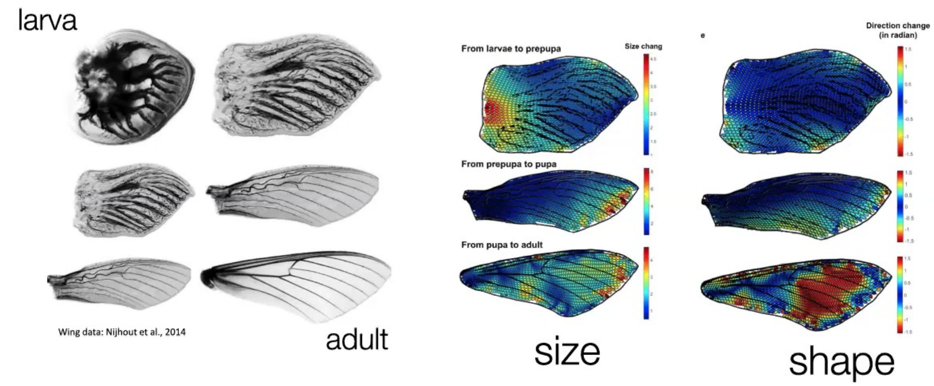




Allows for comparison across species

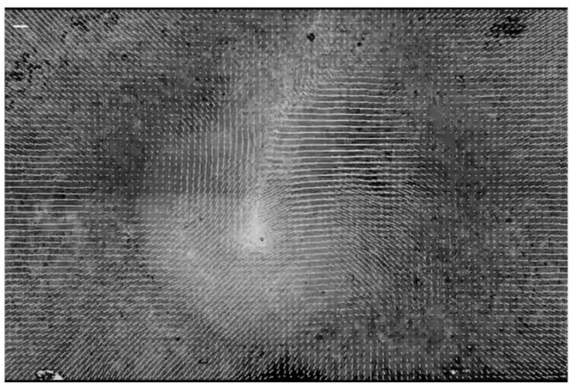


Allows for comparison across developmental time



Dynamics

Morphodynamic descriptors from 4D cell trajectories?

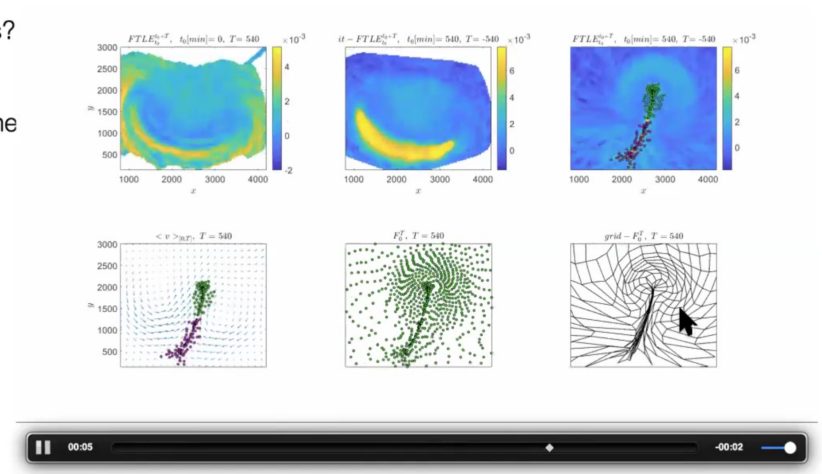


Invariant: to rigid translations, time-dependent rotations?

Predictive: capable of determining (coarse-grained) organizers of cellular trajectories in space-time

Intuitive: understandable, implementable?

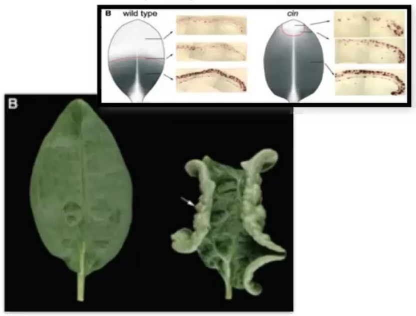
Follow neighborhoods of cells in (forward/ backward) time



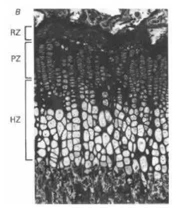
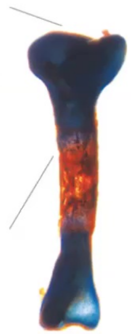
Prediction: (Bio)physics ?

"Cell and tissue … are so many portions of matter, and it is in obedience to the laws of physics that their particles have been moved, moulded and conformed….." DWT

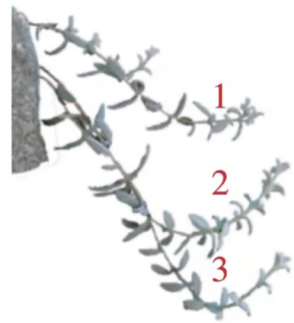
Nath et al. (2003)

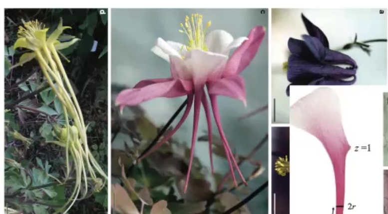
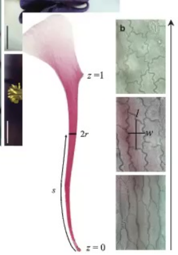


cell number change

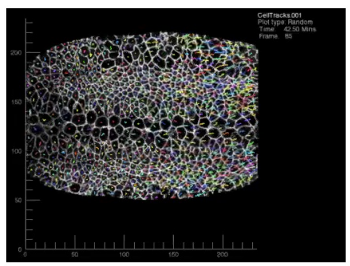



cell size change

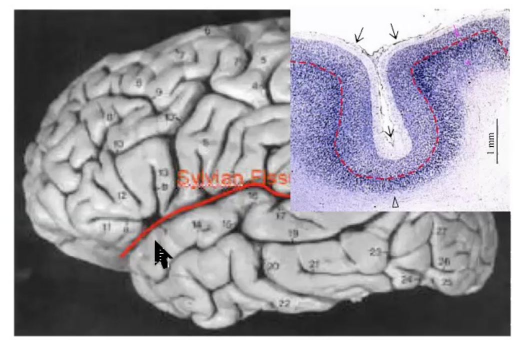


cell shape change

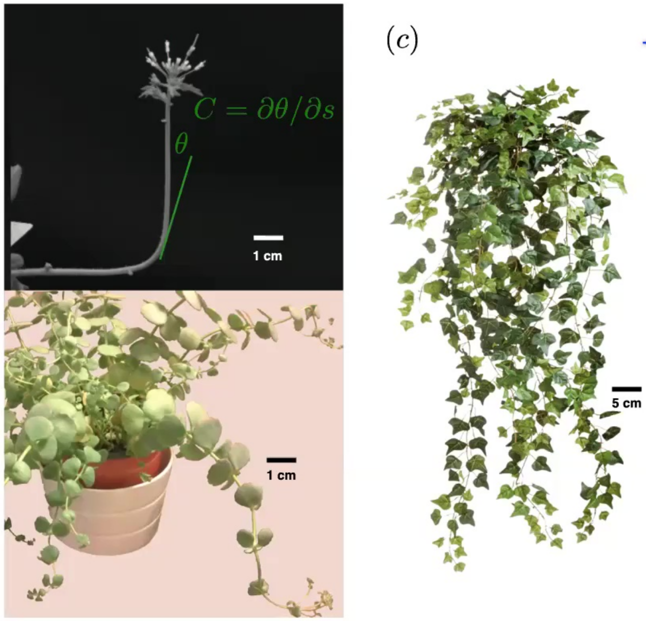


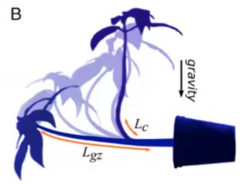
cell position change



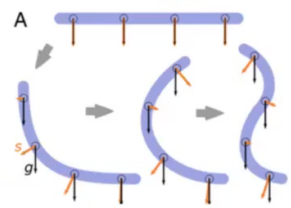
Growth and form of shoots ?

- diffuse growth zone (near tip)
- gravitropic - sensing gravity non-locally





sunlight



How to eliminate:

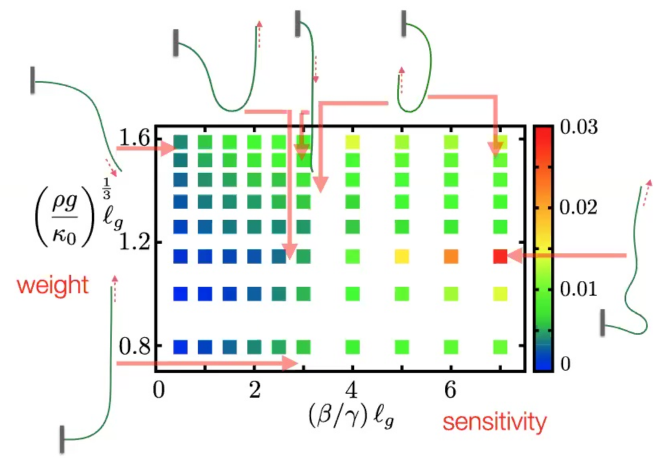
noise ? oscillations ?

gravitropism + postural sensing

↓

postural correction

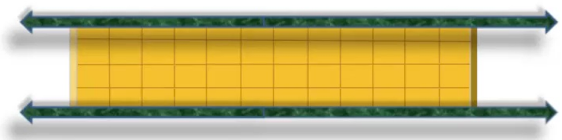
Morphospace ?

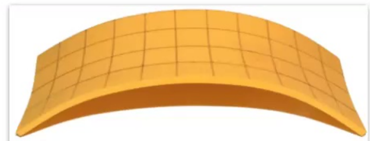


How leaves ripple ?

Surgery -- relaxation of internal strains !

Physical model

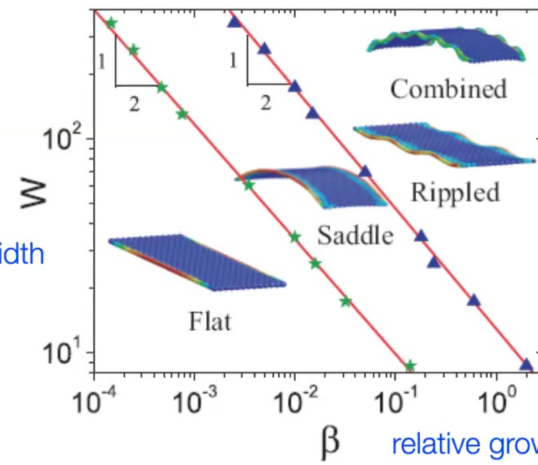




Saddle

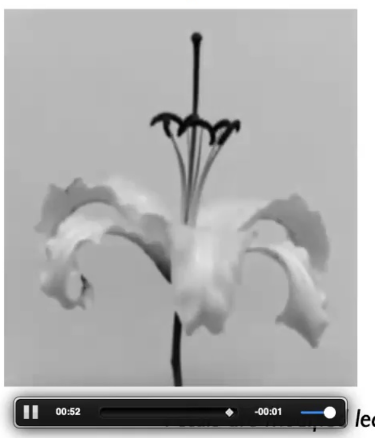
Ripple

Morphospace ?

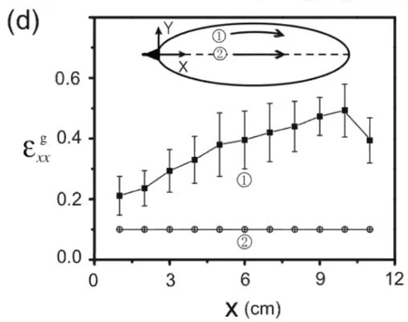


SHAPE = frustration induced by embedding

How the lily blooms ?



experiment -> driven by edge growth!

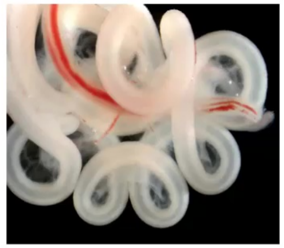


leaves" *Metamorphosen, W. von Goethe*

Similar principles elsewhere ?   gut looping !

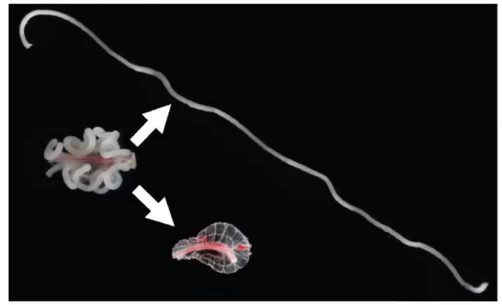
7 mm long

?



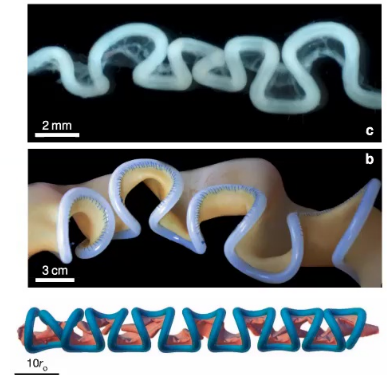
170 mm long

surgical separation of tissues



i.e. differential growth -> looping

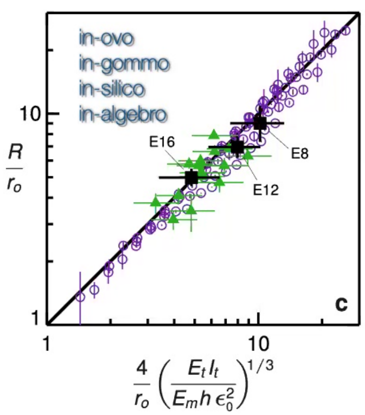
Model



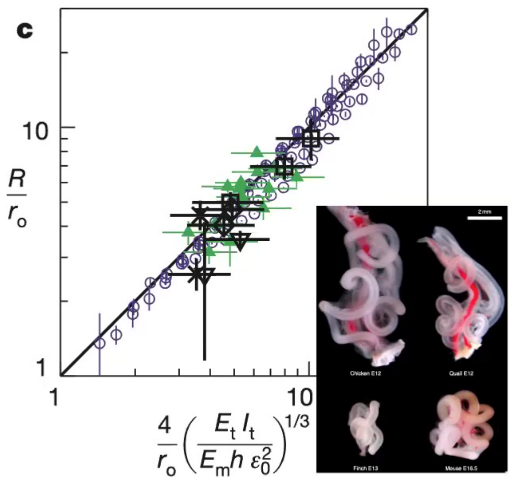
Model !

+ Topology: Lk = Tw + Wr =0 !

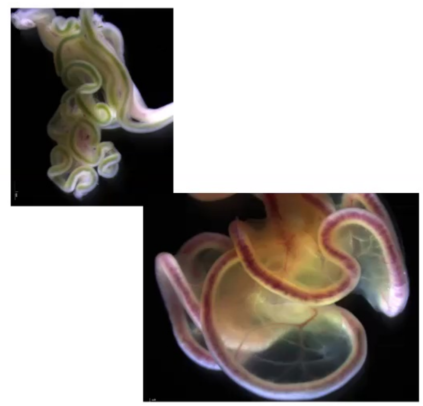
Over time



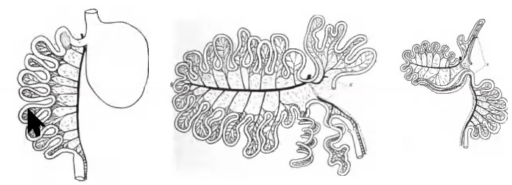
Across species



(Molecular) control of growth



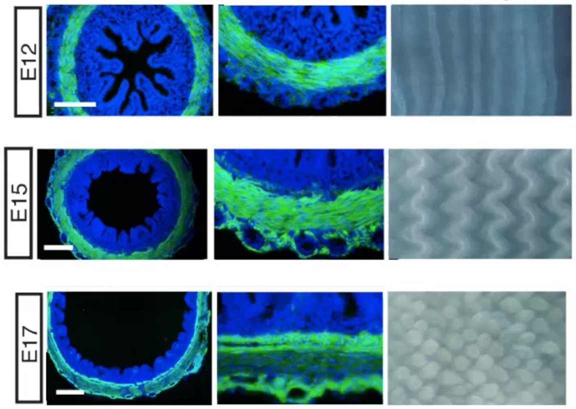
Evolution ?



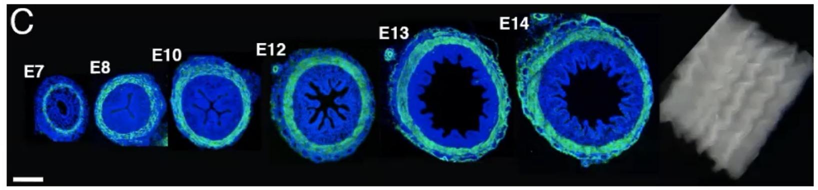
Mitchell, 1896

Meanwhile - Inside the gut ?

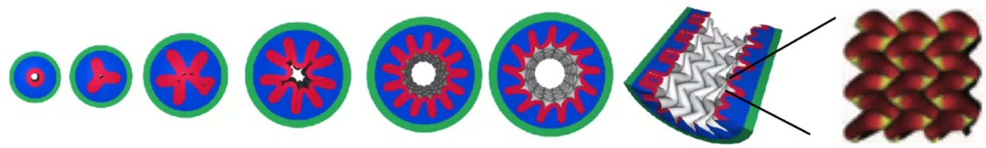
Local shape ? differential growth



Over time ?



T. Tallinen



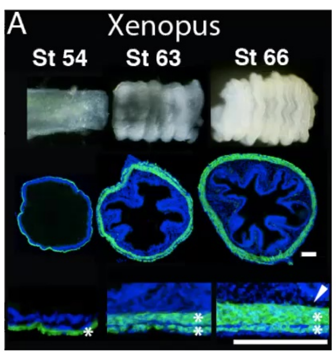
3 timed muscle layers

3 broken symmetries ....

- ridges,
- zigzags,
- villi

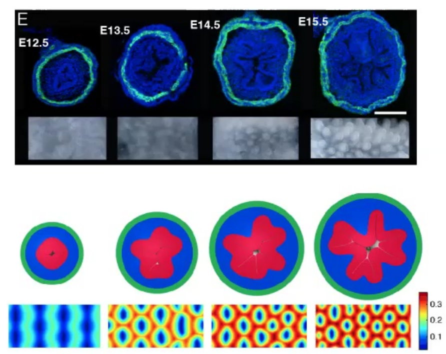
Across organisms ?

Frog



- only two stages !

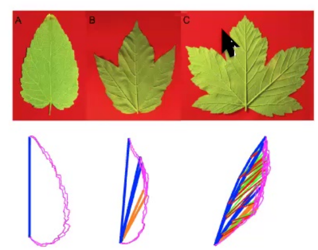
Mouse



- relatively rapid development !

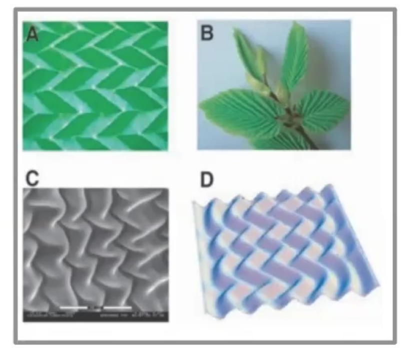
Elsewhere ?

How the maple leaf forms?

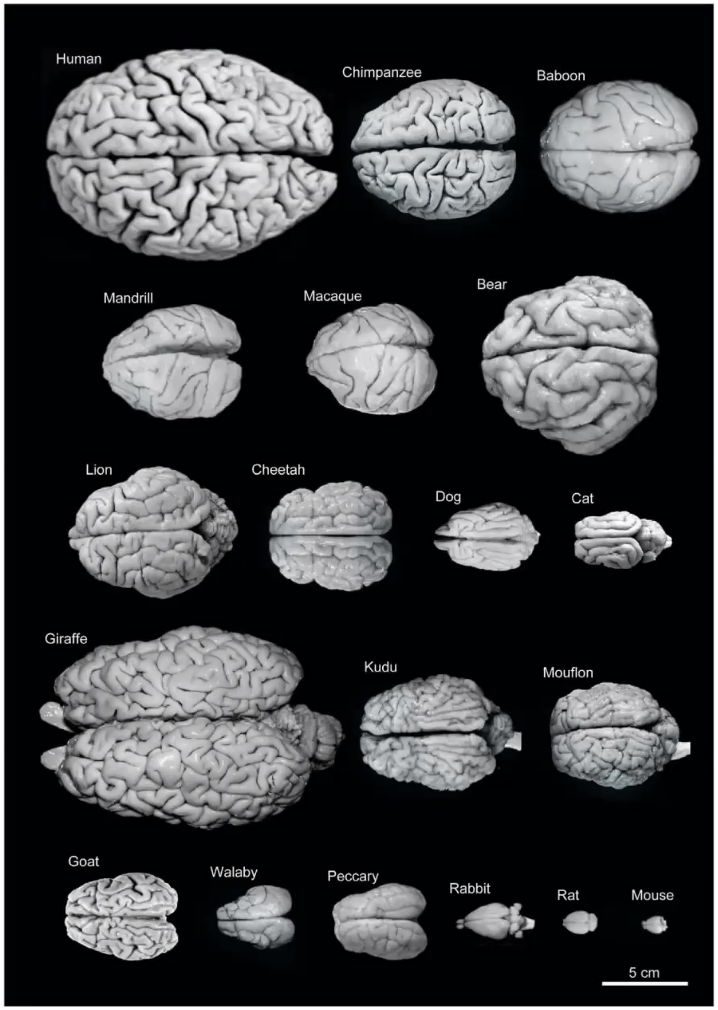


Coutourier et al. (2009)

self-organized origami

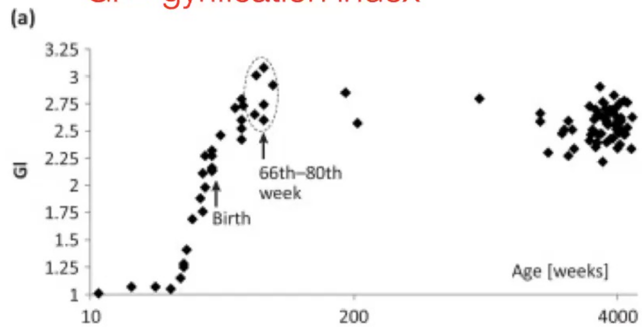


Cortical convolutions

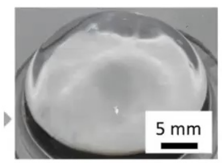


deFelipe (2011)

GI = gyrification index



Gel swelling in solvent



Functional consequence ?

Folded cortex -
maximizes cortical connectivity
and minimizes wiring length

Origin (distal) ?

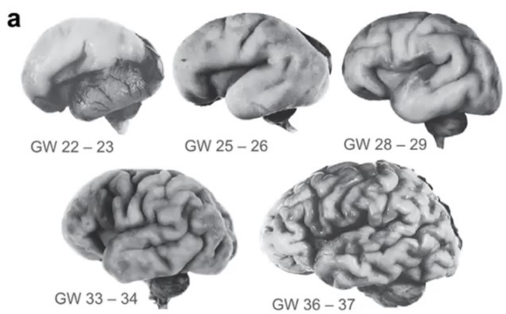
External constraints (packing) ? No .

Internal constraints (forces) ? Yes ..

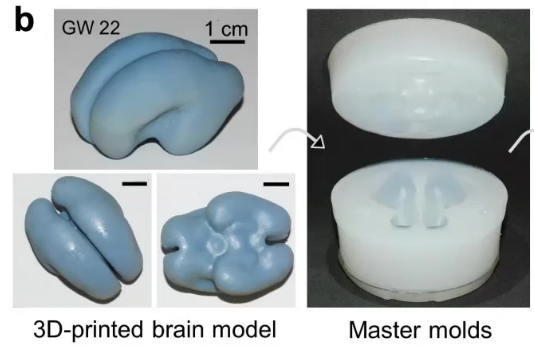
Origin (proximal) ?

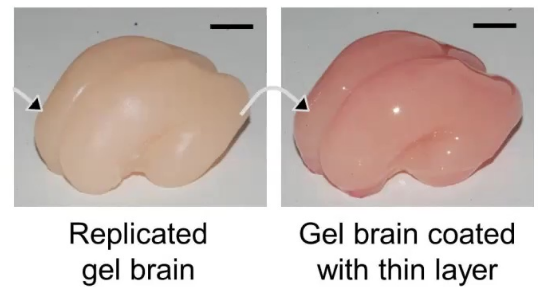
Increased surface expansion of cortex

Human fetal brain development?

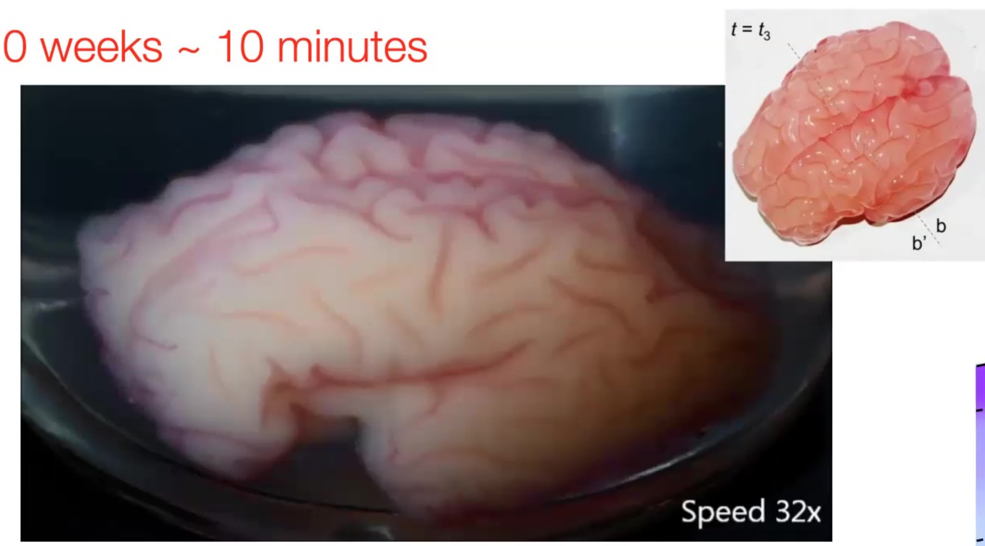


Physical mimic using 3d printing ?

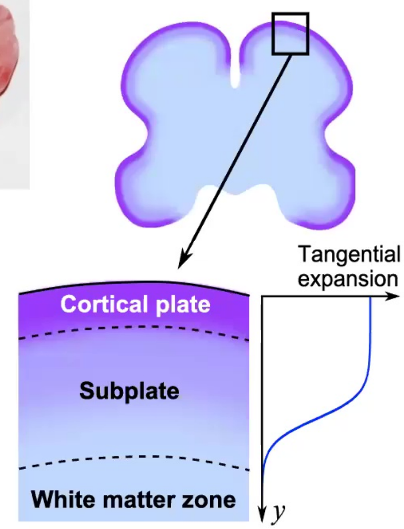


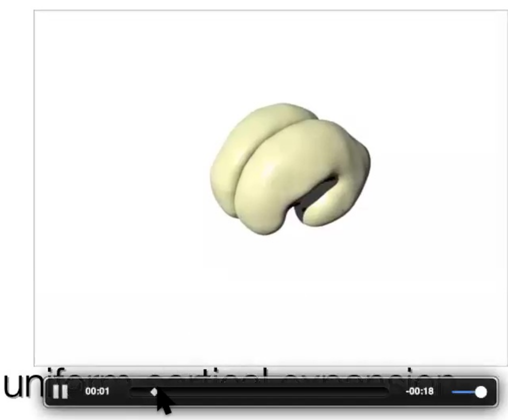


10 weeks ~ 10 minutes



Computational mimic using elastic growth ?

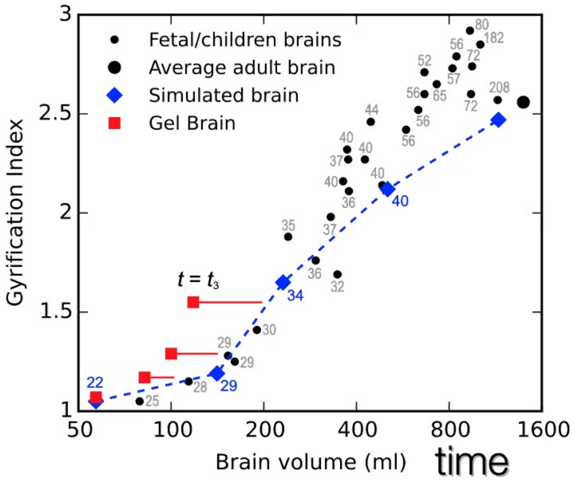




+ elastic energy minimization

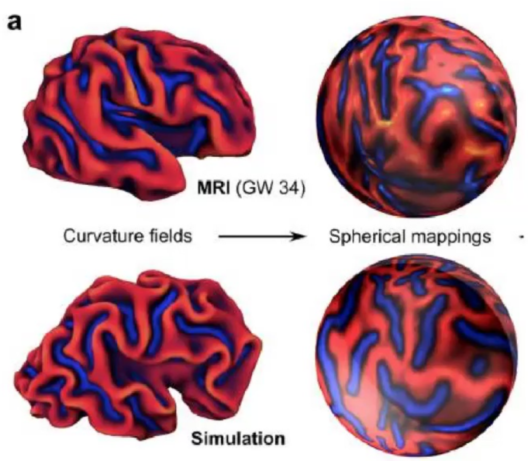
Evolution - “space” of shapes ?

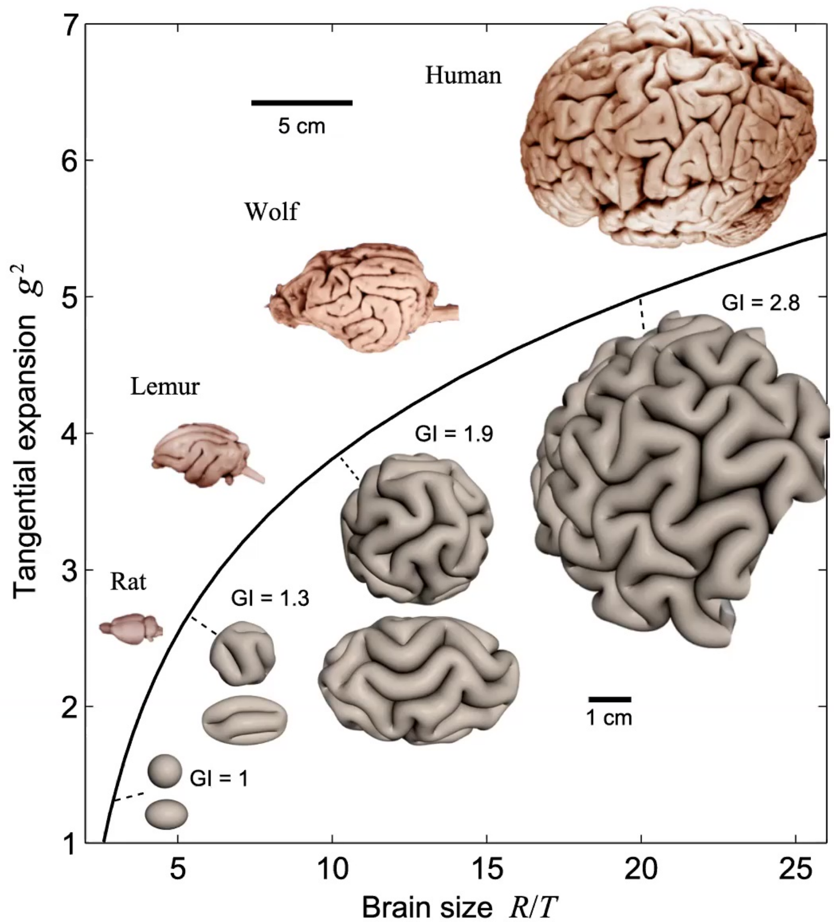
cortical area



time

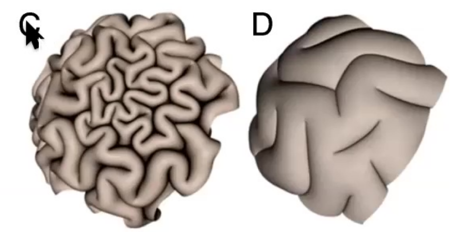
conformal map comparison





Pathologies

polymicrogyria



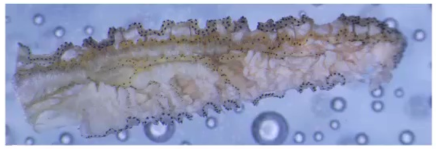
pachygyria

Elsewhere ?

Gibson

(Nematostella) anemone mesentery

Salcedo



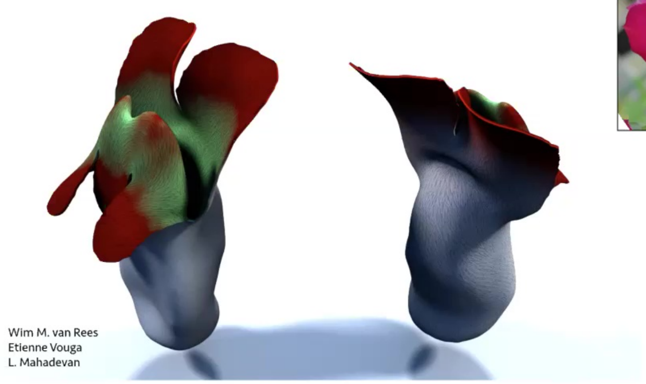
(Libellulida) dragonfly nymph wing

Differential Geometry

Global *embedding problem Riemannian manifold* (M^m, g) *immersion in Euclidean* R^n *?*

(Nash, Kuipers 1960s; Gromov) $n \geq m + 1$ $C^1,\ g_{ij}$ preserved

Elastic regularization - gives a constructive approach to biophysical realization !

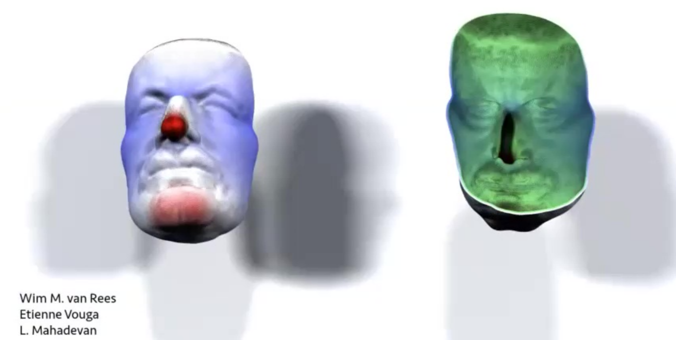


Forward problem: Given growth patterns, predict morphology ?

Feedback from morphology to growth ?

Inverse problem : Can one "design" growth patterns, given desired morphology ?

Development / Evolution ? Engineering ?



So what? Where to?

Geometries allow for pattern quantification in space and time

Layered “understanding” - phenomenological, predictive, but not molecular …

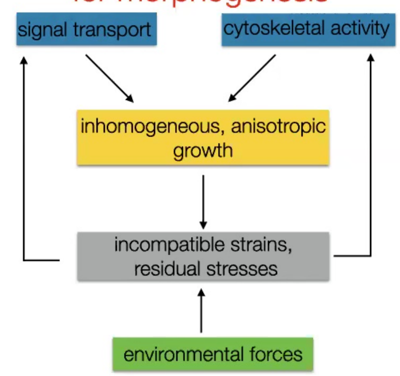
Parameters under molecular control <—> environment (mechanical stress)

Simple physics associated with differential growth -> instability -> spatial patterns

Layered “understanding” - phenomenological, predictive, but not molecular …

Parameters under molecular control <—> environment (mechanical stress)

Towards a geometrical + physical basis for morphogenesis



complementing A. Turing’s (1952)

“The chemical basis for morphogenesis”

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