Image based modelling approaches for analysis of plant tissues morphology

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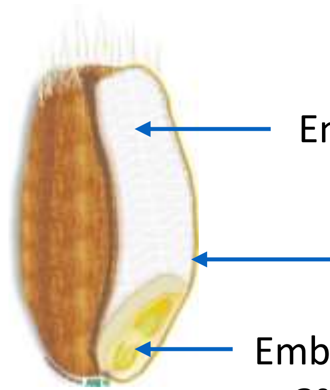
General context:
valorization and transformation of agro-resources

- Applications
  - Food
  - Bio based materials
  - Biofuels

Modelling growth of wheat grain - context

- Wheat: major crop resource worldwide
  - Yields for human and animal feeding
  - Impact of grain shape on milling process

Wheat grain



Endosperm
83%

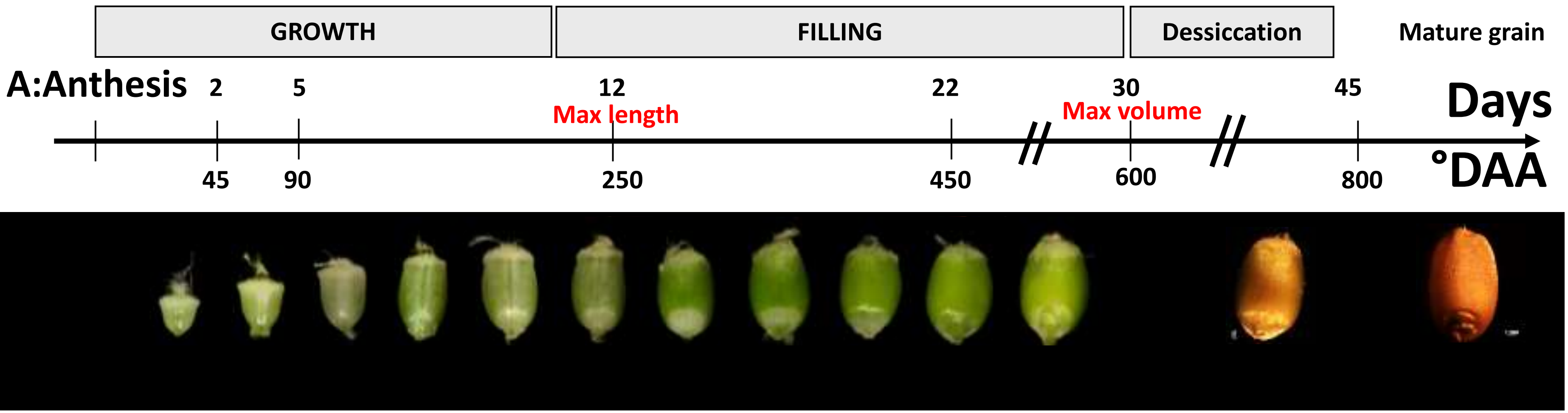
Outer layers
14%

Embryo
3%

- Decrease on global yields + global warming
  - What are the processes that govern **the size and the shape** of the mature wheat grain?

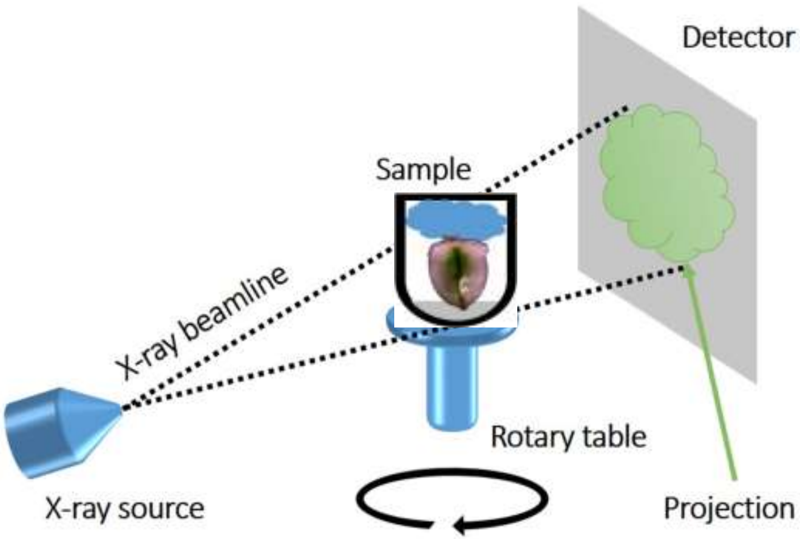
Objective: study of wheat grain growth

Changes of size and shape – towards morphogenesis

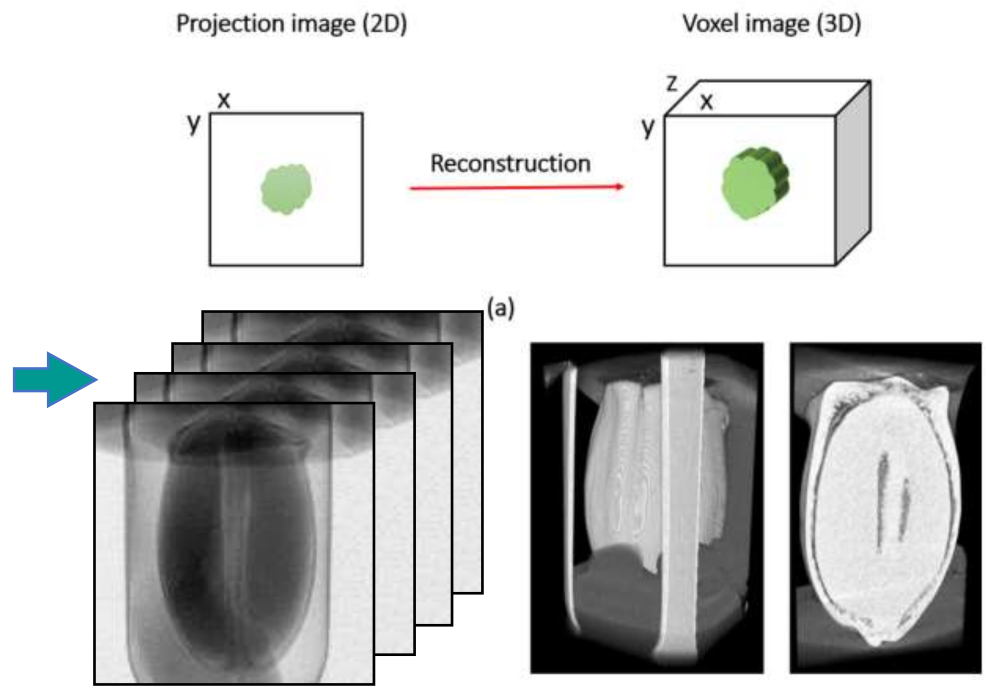


Need for whole-grain + 3D imaging

3D imaging using µ-tomography

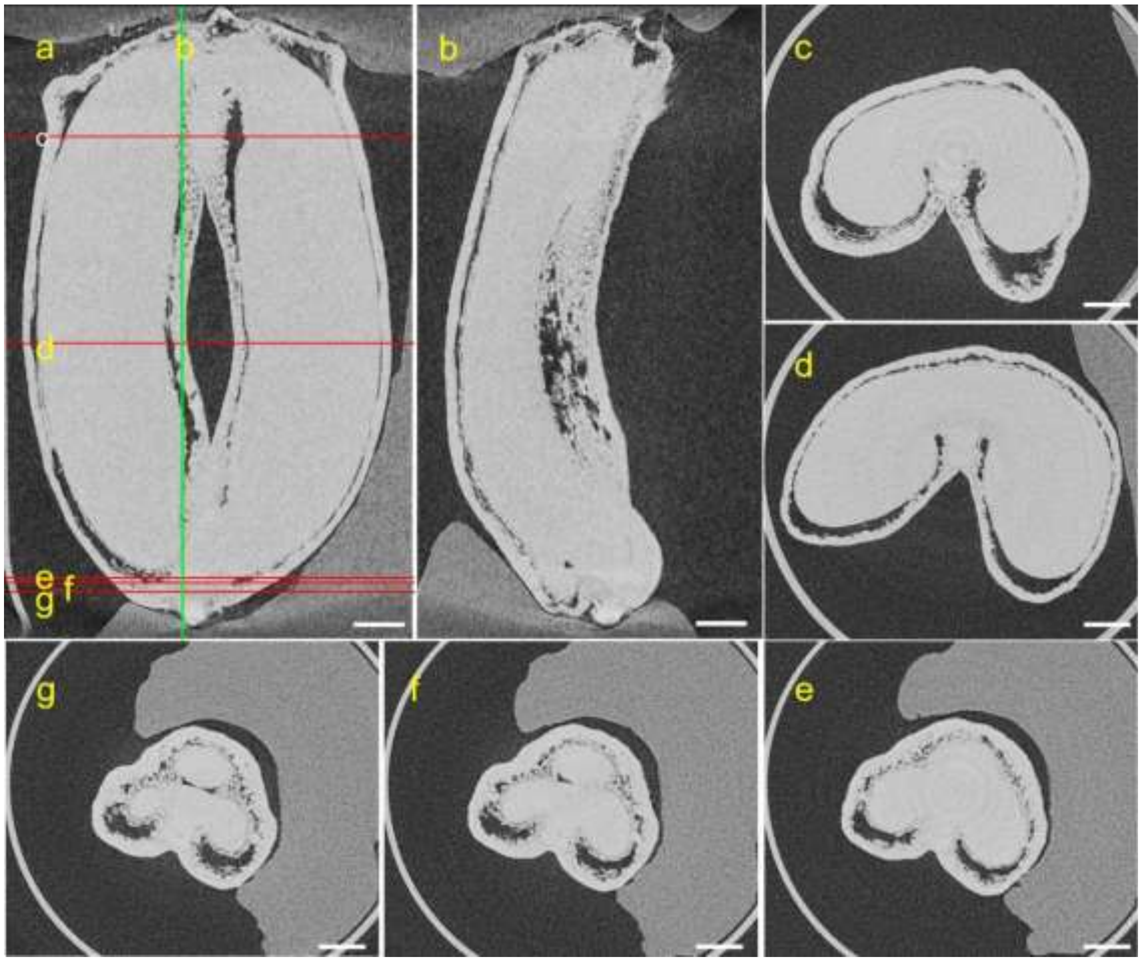


Nanotom 180 (G&E)



A stack of 2D CT slices

3D imaging by X-ray micro-tomography

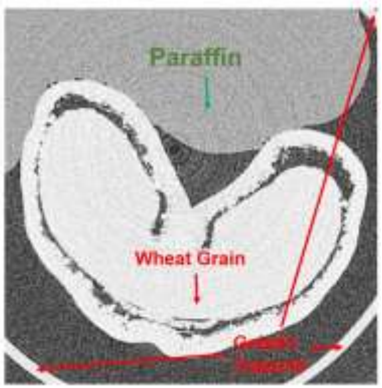


+ whole 3D imaging
+ tissue (and cells) determination
+ fast (5-10 min)

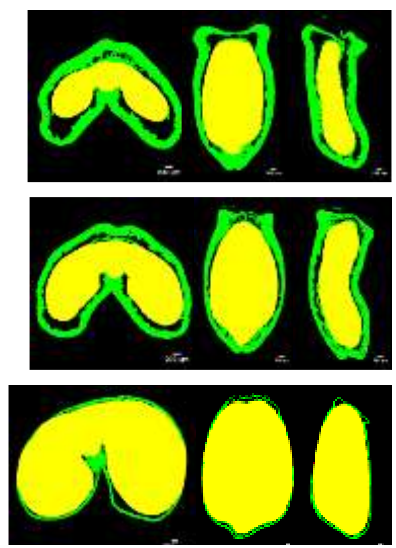
- Destructive sampling
  - No time-lapse imaging…
  - Use series of static images

Study of growth by 3D image analysis

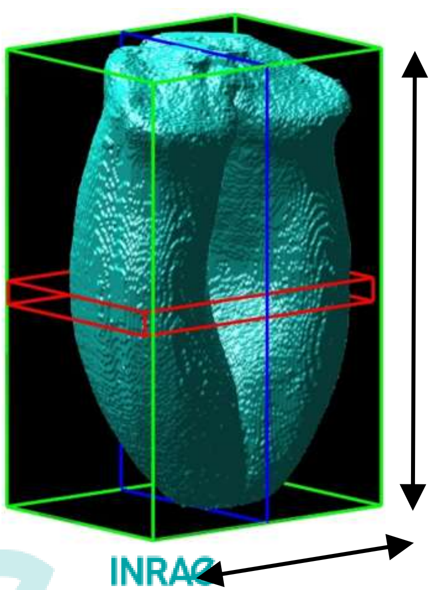
Quantification of global size & shape features for each stage



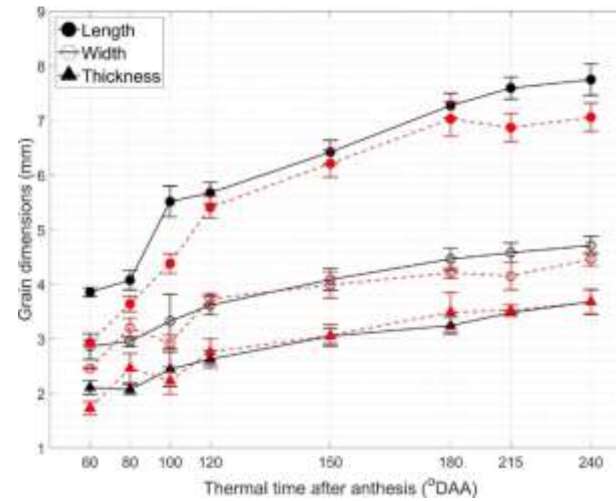
Grain segmentation



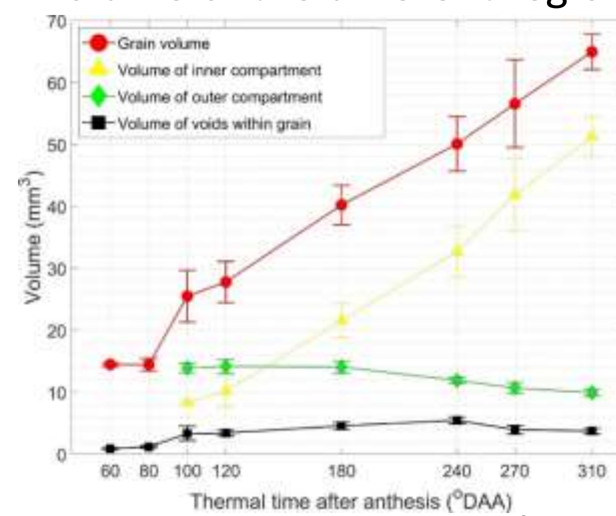
Segmentation of regions within grain



Grain dimensions



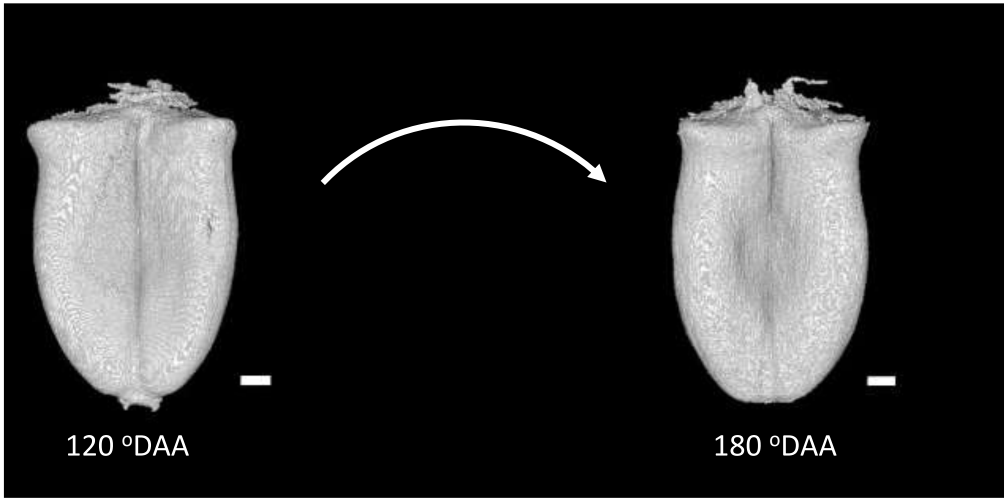
Volume of the different regions



Le et al, 2019

Study of growth changes

- How to better describe the **changes of morphology** between two successive stages?



Scale bar is 600 µm

- Seek for the **geometric deformation** between grains at two successive stages

Formalization of the problem

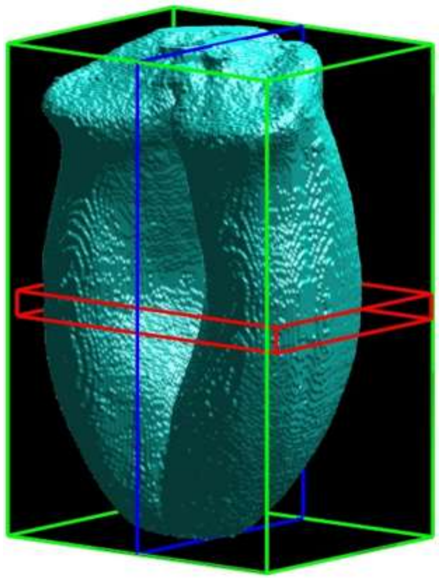
- Search for the optimal deformation by using **shape registration**:

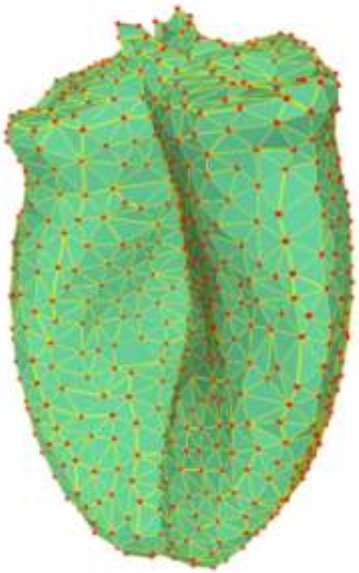
$$\boldsymbol{\phi}^* = \underset{\boldsymbol{\phi}}{\mathbf{argmin}}\, \boldsymbol{\mathcal{D}}(\boldsymbol{\phi}(\boldsymbol{S}), \boldsymbol{R}) + \boldsymbol{\mathcal{R}}(\boldsymbol{\phi})$$

- $\boldsymbol{\phi}$: deformation model
- $\boldsymbol{S}, \boldsymbol{R}$: individual (‘subject’) and reference shapes
- $\boldsymbol{\mathcal{D}}$: dissimilarity metric
- $\boldsymbol{\mathcal{R}}$: regularization function

Data pre-processing

- Transformation into 3D triangular meshes
  - (geometrization of images)
  - Reduction of computational complexity
  - Simplification of results interpretation

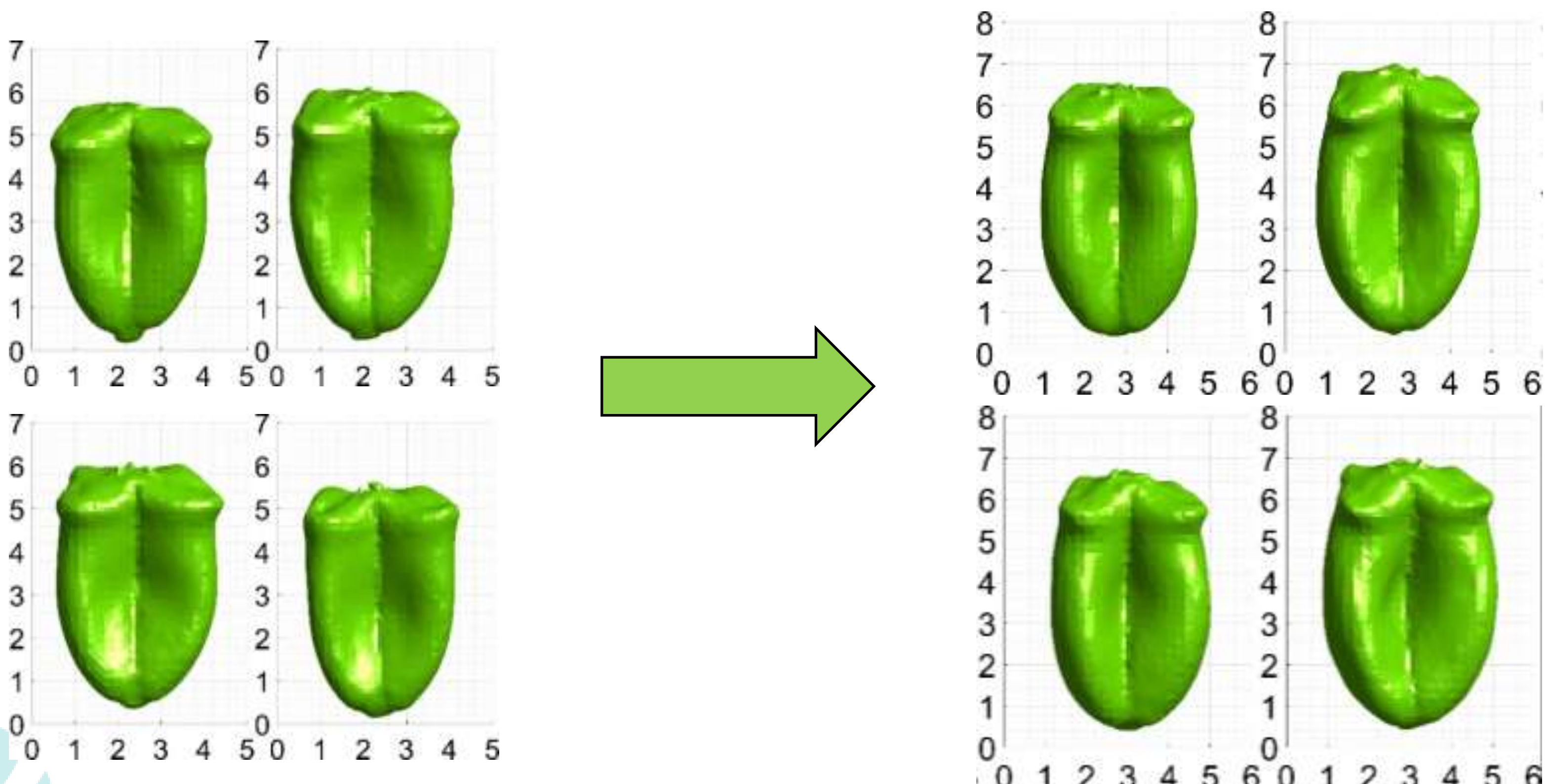




Taking into account the biological variability

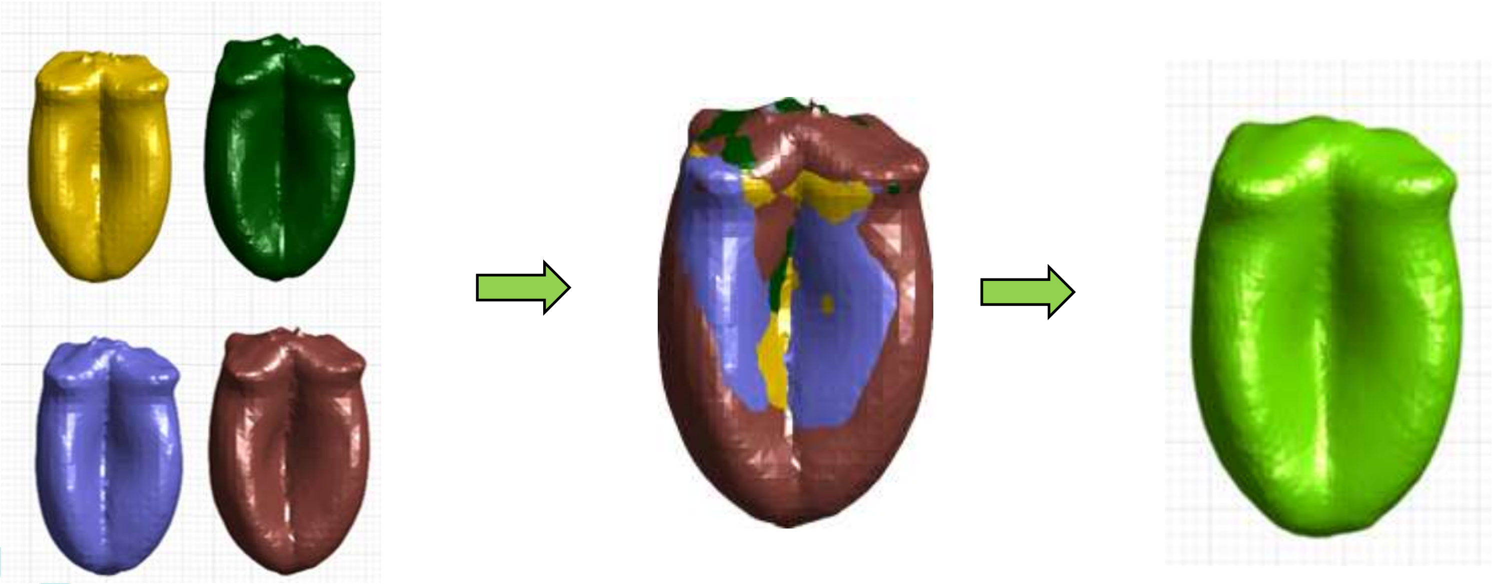
Group-wise registration

- Each stage is represented by several grains
- Need to register population of shapes…

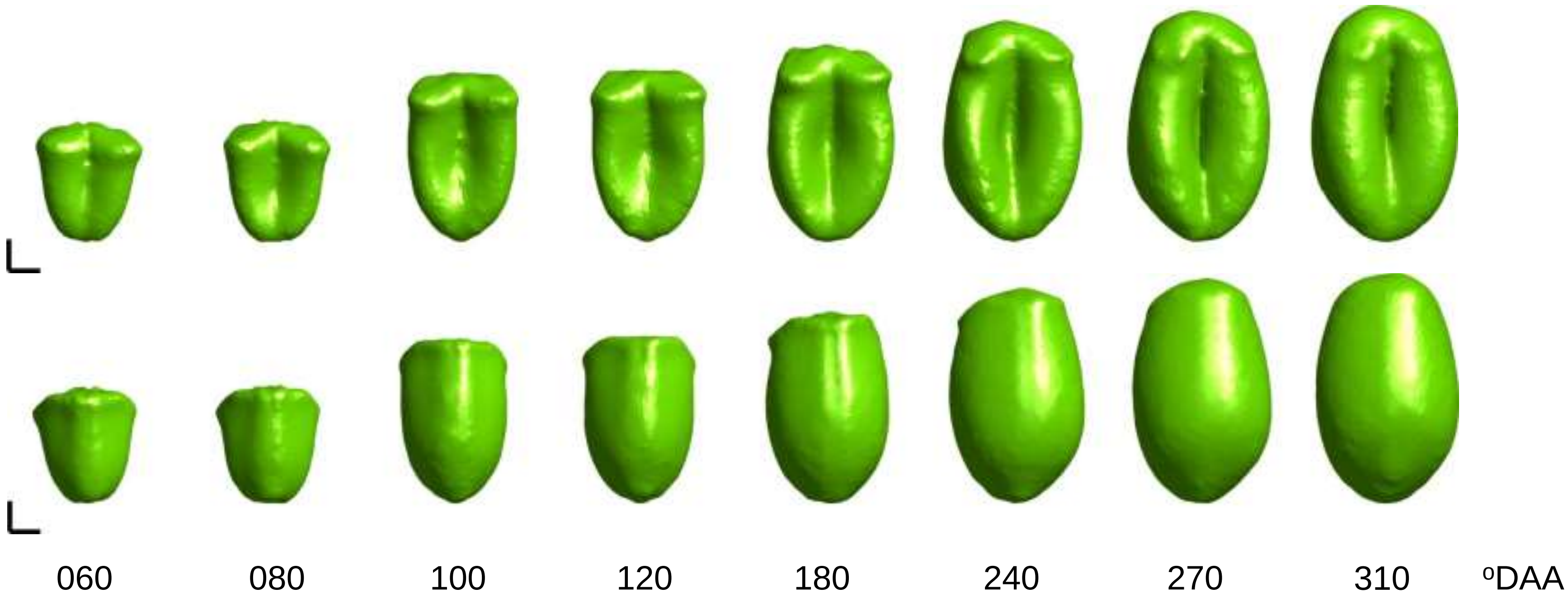


Representative shape for each stage

- Computation of average shapes
  - One shape per stage
  - Principle:
    - Global rigid alignment (ICP) + scaling
    - “Least square surface” computation



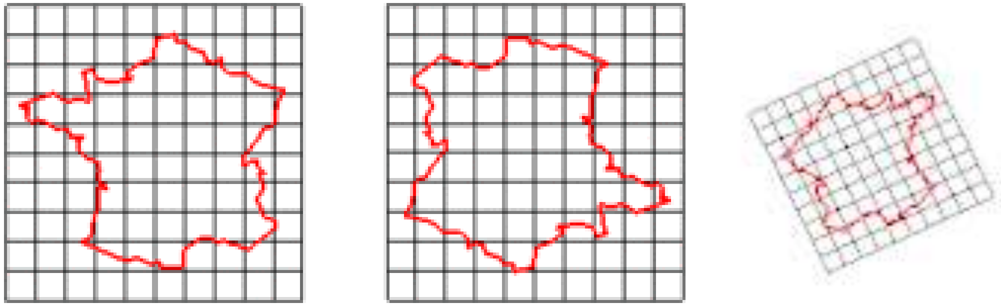
Time evolution of average shapes

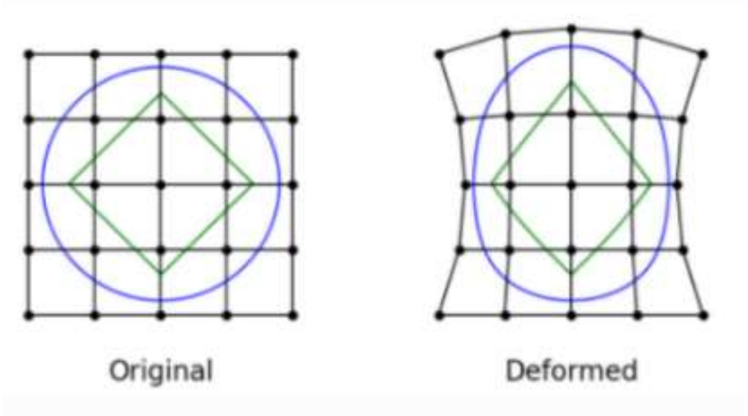


- Main shape variations are well preserved
- “smoothing” effect

Choice of transform model

- "Rigid" transforms
  - Translation
  - Rotation
  - (uniform) Scaling
  - => Similarity
- Elastic transforms
  - Polynomial
  - Displacement fields
  - Free-form deformation (Bsplines)
  - ...

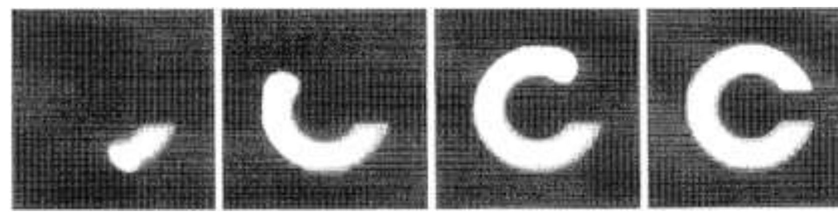




Rueckert et al., 1999
Sánchez Sorzano et al., 2005 (BUnwarpJ)

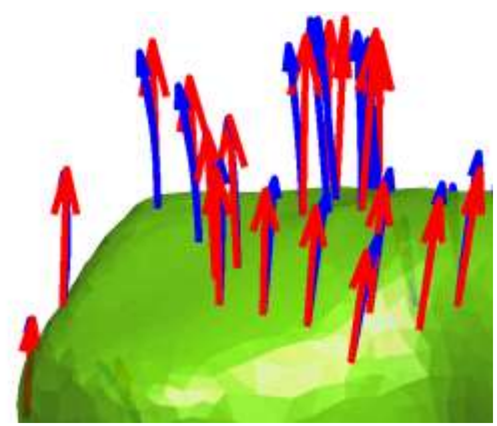
Choice of transform model

- "Large deformation diffeomorphism metric mapping" (LDDMM) framework
  - Diffeomorphism: smooth & invertible transform
  - Parameterization with "time"
    - t=0: stage *i*
    - t=1: stage *i*+1



$\phi_{t=0}(S) = S$

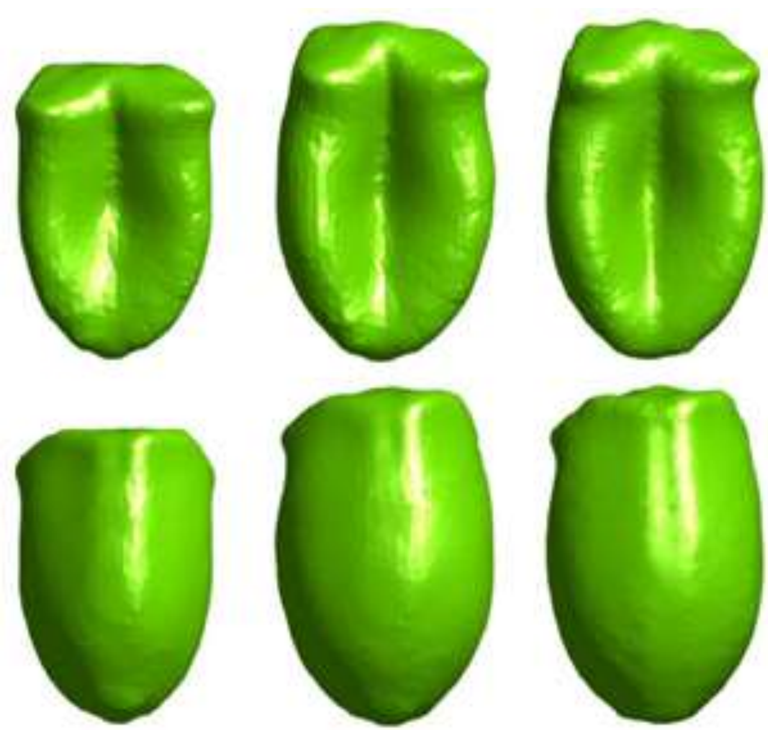
$\phi_{t=1}(S) \cong R$

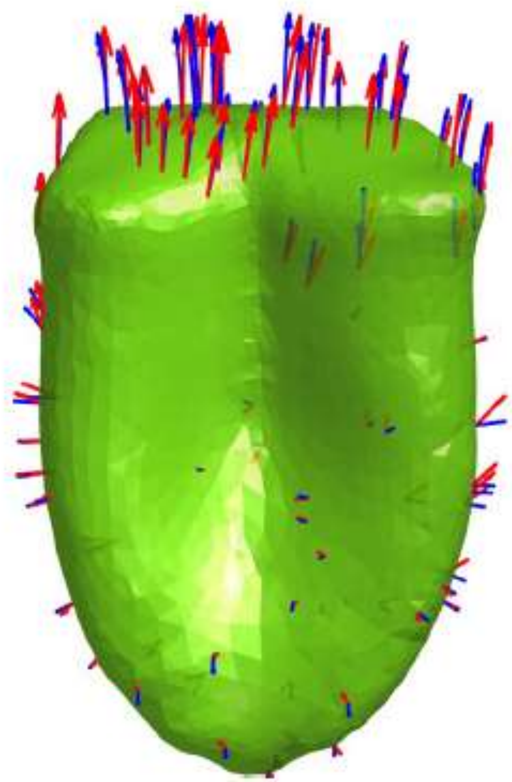


Christensen et al., 1996; Bône et al., 2018

Computation of deformations - results

source transformed target





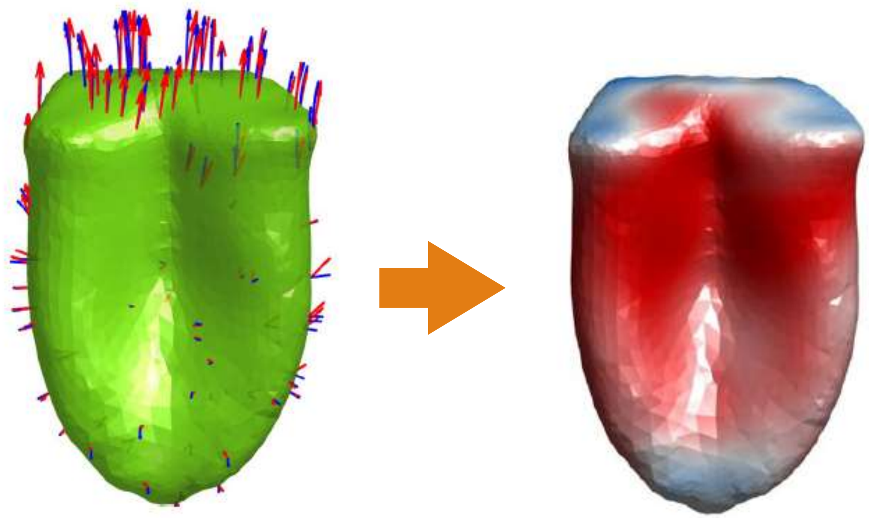
How to analyze a
3D deformation field?

Analysis of deformations

- Aim: relate local deformation to growth

- Several features
  - Local displacement
  - Local derivatives
  - …

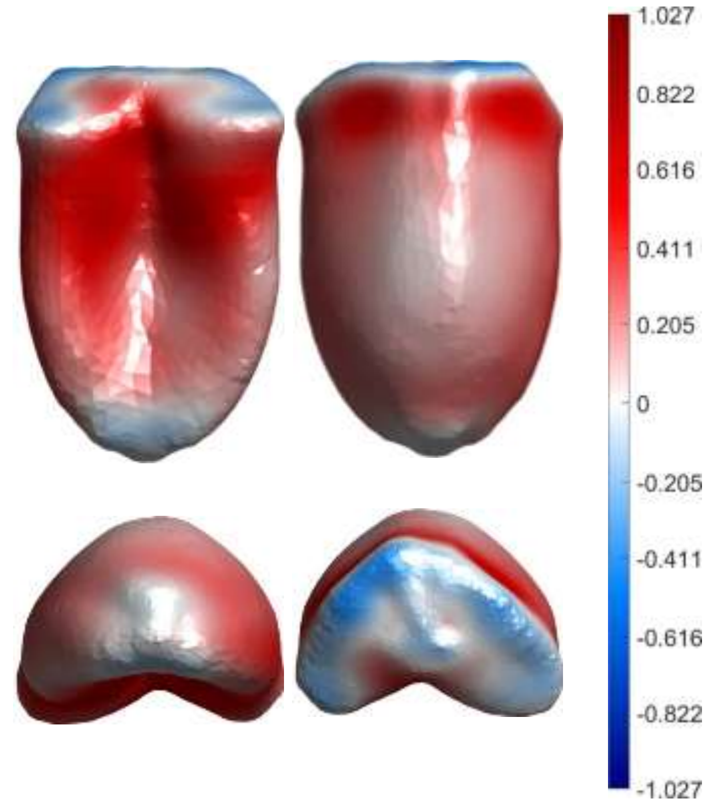
- Representation by means of parametric maps



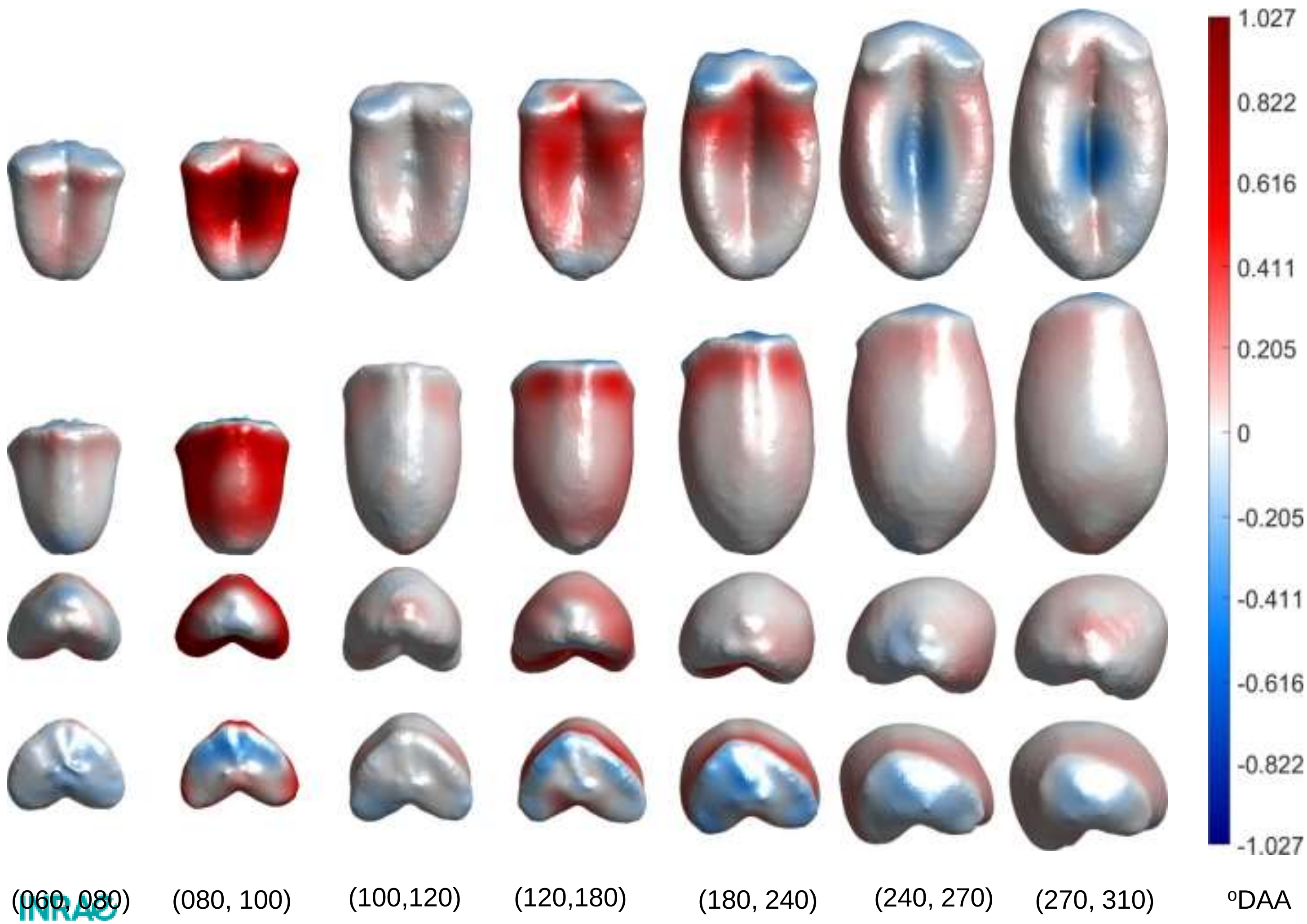
Rueckert et al., 2008

Local scaling

- Computed as the determinant of the Jacobian matrix
  - Logarithmic scale
- Depicts local variation of volume
- Localization mostly in the upper part of the grain

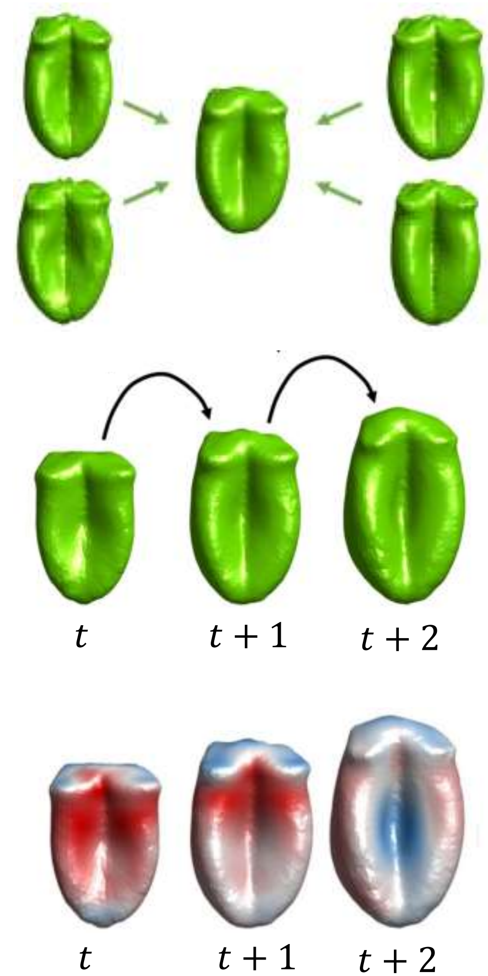


Note: can be used to check deformation obtained from expansion microscopy

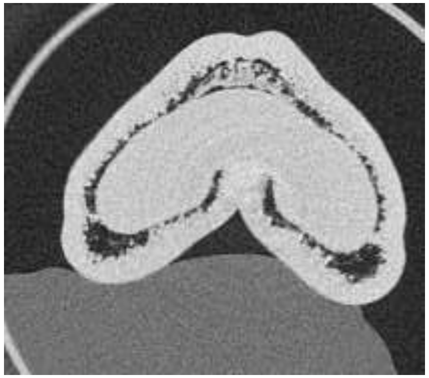

1.027
0.822
0.616
0.411
0.205
0
-0.205
-0.411
-0.616
-0.822
-1.027
(060, 080)
(080, 100)
(100,120)
(120,180)
(180, 240)
(240, 270)
(270, 310)
°DAA

Wheat grain – summary

- Computation of a representative "average grain" for each stage
- Computation of the geometric deformations between average grains
- Analysis of deformations
  - Local deformation maps
  - Relate to growth

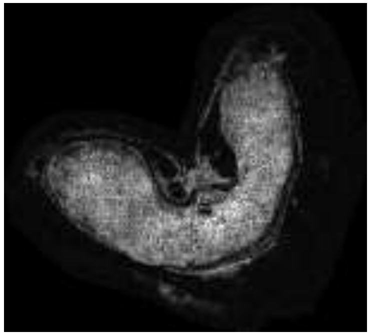


Wheat grain - perspectives

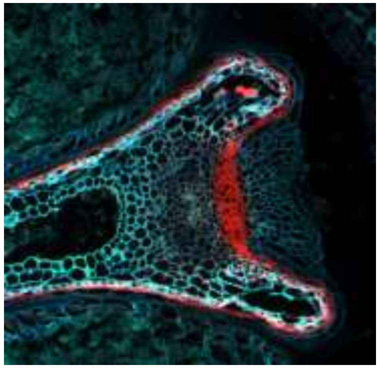


- Fusion of images from different modalities
  - Anatomy (tomography, microscopy…)
  - Composition (microscopy, MSI…)
  - Water mobility (MRI)
  - Mechanical properties (AFM)
  - …

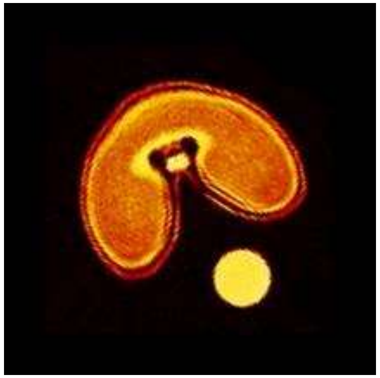
Microscopy



MALDI



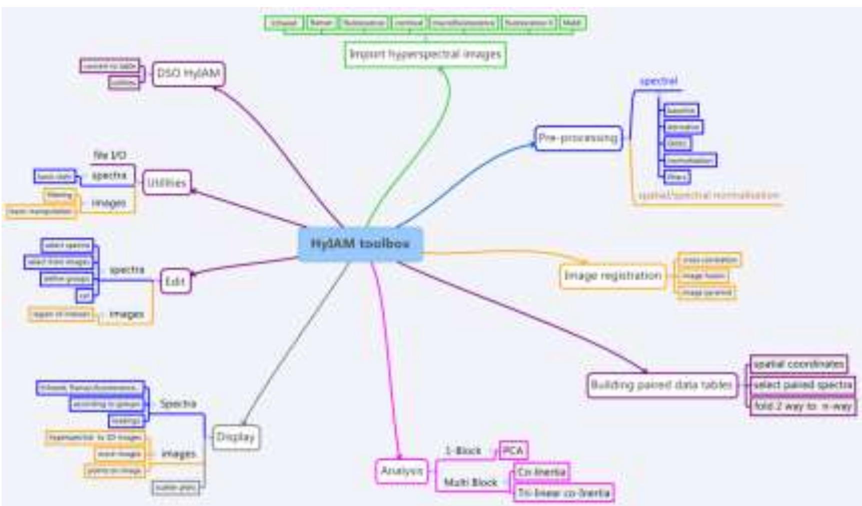
Macro-fluorescence



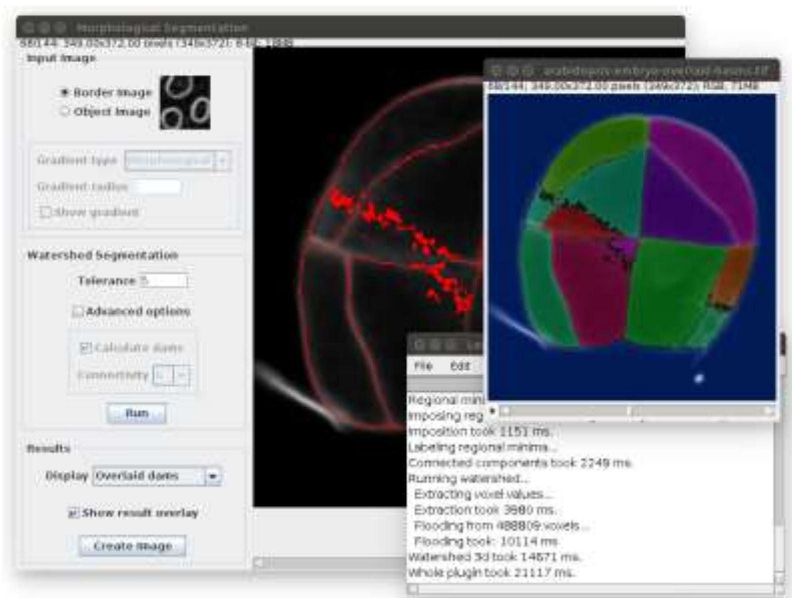
MRI

Diffusion / valorization of methodological developments

- Matlab
  - Shape / image registration
  - Granulometry
  - Multivariate image analysis
  - …



- ImageJ / Fiji
  - MorphoLibJ: Morphological image processing



Thanks

Cell Wall team

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- B. Novales
- A. D'Orlando
- …

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- M. Réfrégiers
- A. King
- C. Rivard
- …

ONIRIS

- M. Hanafi

IJPB

- P. Andrey
- J. Burguet
- E. Biot
- V. Méchin
- M. Reymond

PIAF team

- E. Badel

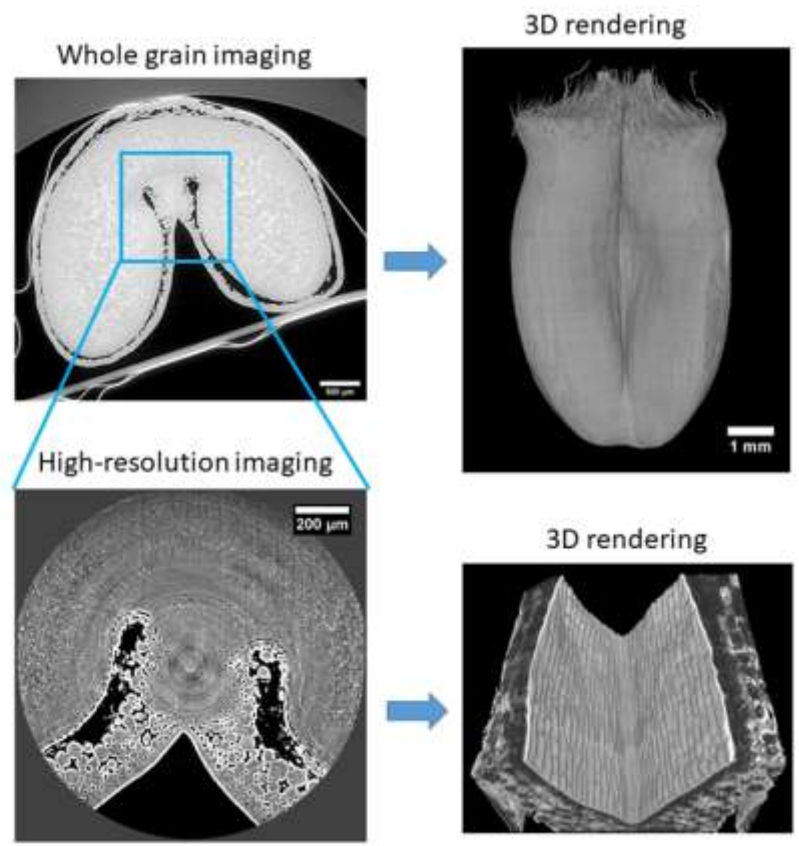
Any question?

X-ray imaging at SOLEIL synchrotron

Psiché beamline – Feb. 2018

- Objectives:
  - Imaging of thin tissues
  - Imaging at cellular scale
  - Explore space x time heterogeneity

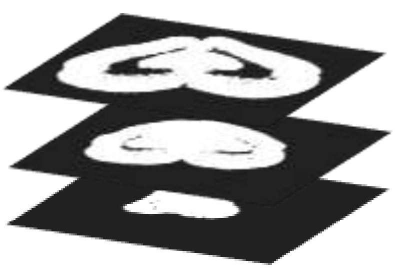
- Sampling design
  - Ten developmental stages
  - Two imaging scales
    - Full-grain imaging
    - High resolution imaging



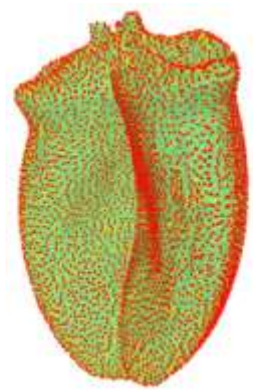
Conversion into polygonal meshes

- Reduction of computational complexity
- Simplification of results interpretation

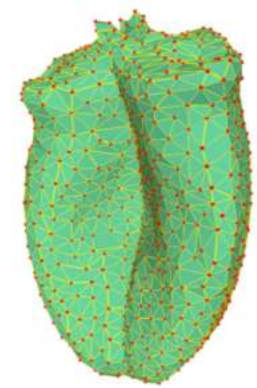
3D Binary Image → Generation of 3D Mesh → 3D Mesh → Mesh Simplification → 3D Mesh



- File size ~ 1 GB



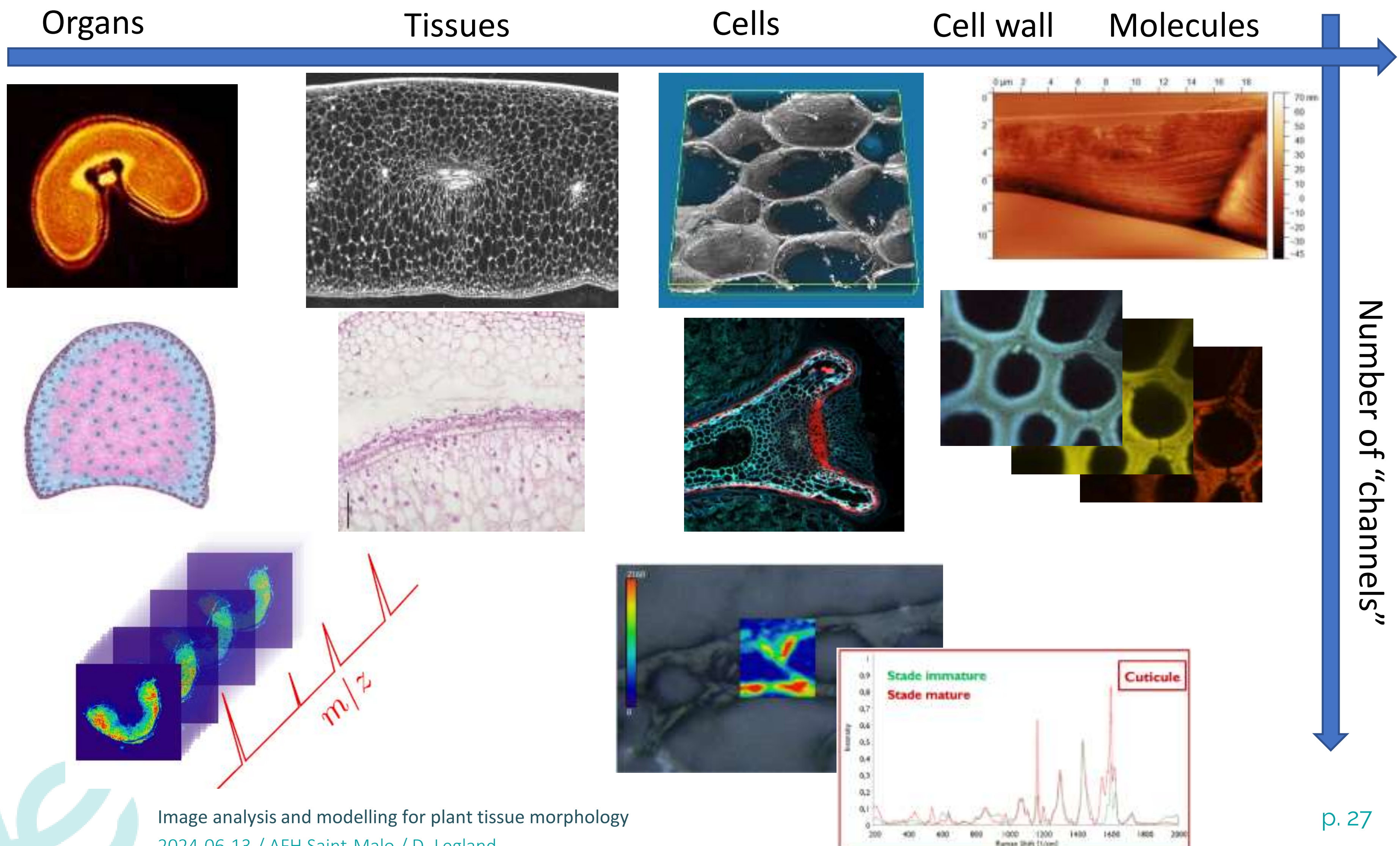
- Nº vertices = 10^6
- Nº faces = 2×10^6
- File size ~ 75 MB



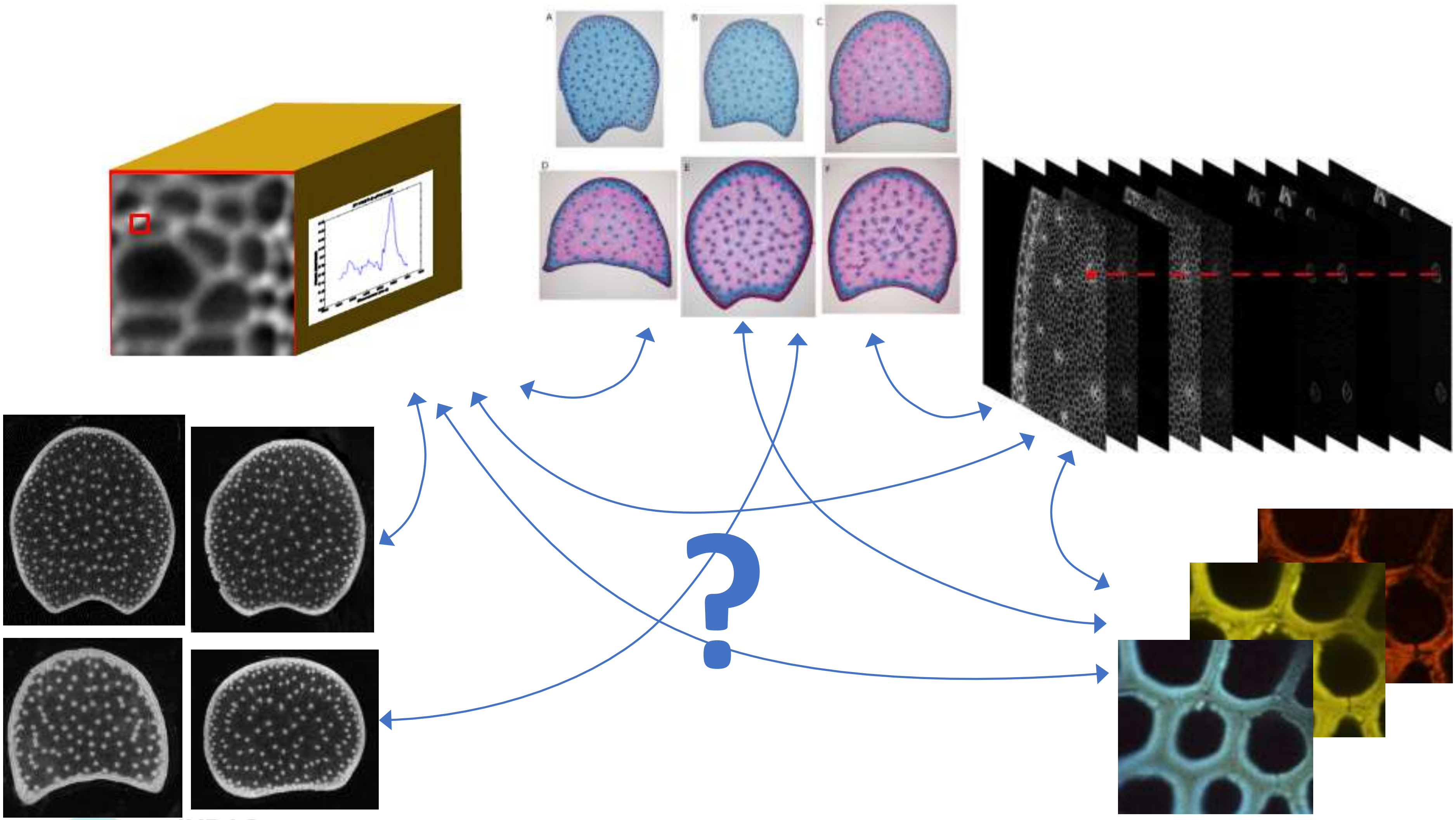
- Nº vertices ~ 10^3
- Nº faces =~ 2×10^3
- File size ~ 1 MB

Multi-scale imaging of plant tissues

Joint investigation of morphology and localized biochemistry



How to relate information obtained from different images / modalities

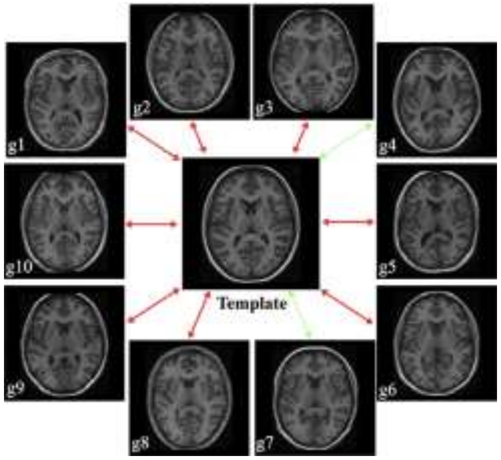


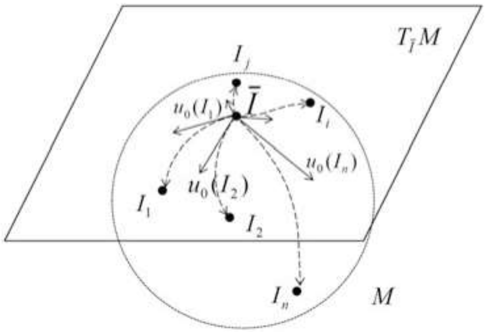
- Correlative imaging, image registration
- Different samples / different scales?

A "computational anatomy" approach

- Originally developed in a context of medical imaging

- Computation of a reference shape from a collection of individual shapes
  - Description of shape population ("shape space")
  - Comparison of different populations
  - Integration of localized quantitative data obtained on objects with different shapes

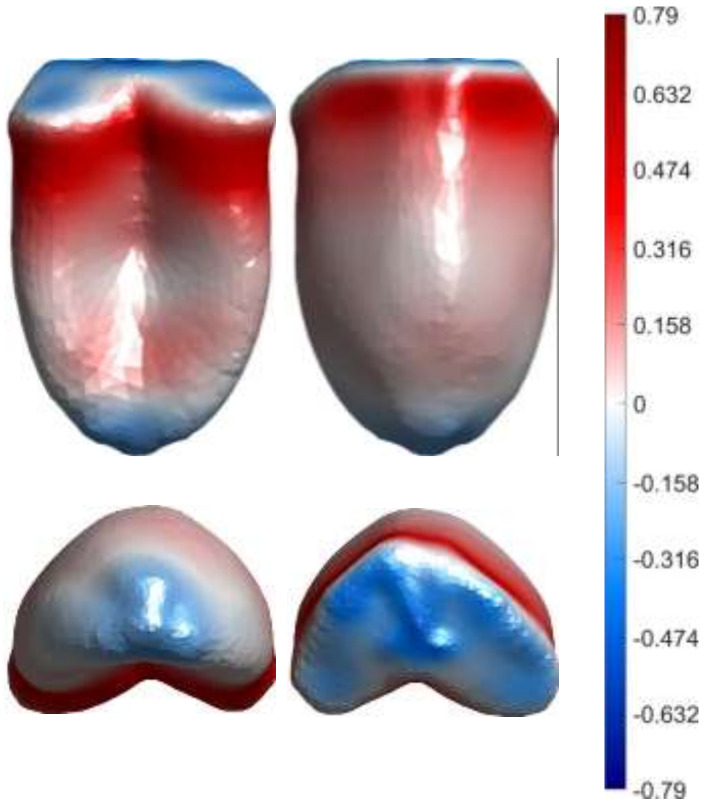




Grenander & Miller, 1998

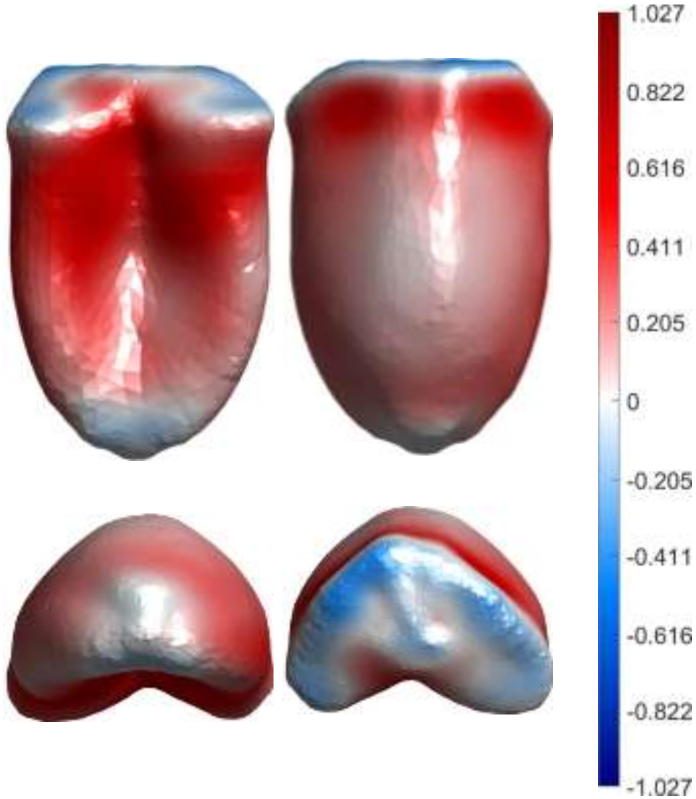
Vertical scaling

- Computed as the (3,3) coefficient of the Jacobian matrix
  - Logarithmic scale
- Depicts relative elongation in vertical direction
- Results seems similar to global scaling

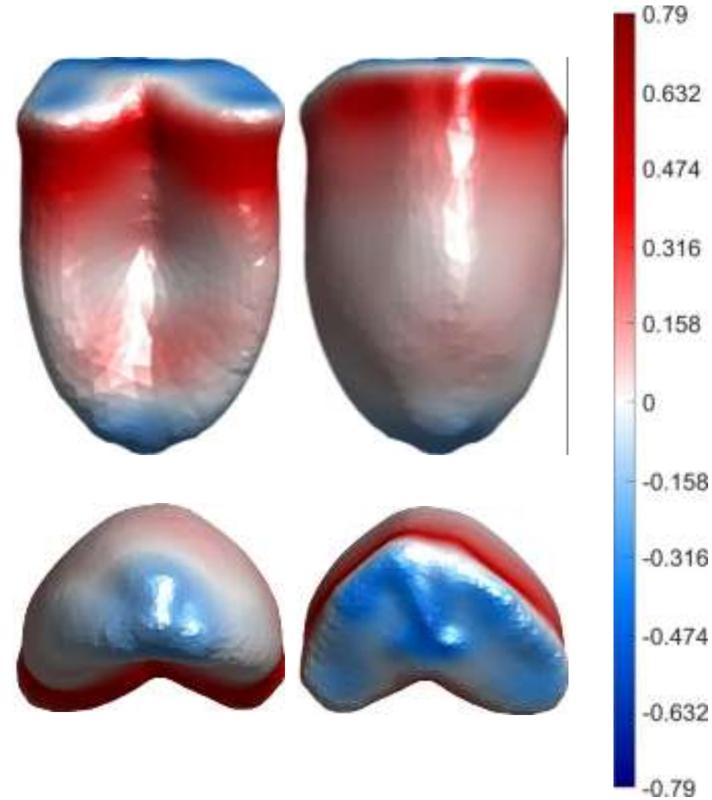


Global vs vertical growth

- Local scaling map $\boldsymbol{\Delta LD(x)}$
- Vertical growth map $\boldsymbol{\Delta VG(x)}$



$\boldsymbol{\Delta LD(x) > 0}$ = Increase in volume



$\boldsymbol{\Delta VG(x) > 0}$ = Vertical expansion in shape

- $\boldsymbol{\Delta LD(x) > 0, \Delta VG(x) > 0}$: Mostly elongation
- $\boldsymbol{\Delta LD(x) > 0, \Delta VG(x) \simeq 0}$: Mostly thickening