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Stéphane P. A. Bordas, 2017 XDMS Umeå - you can download the slides here: http://hdl.handle.net/10993/31487

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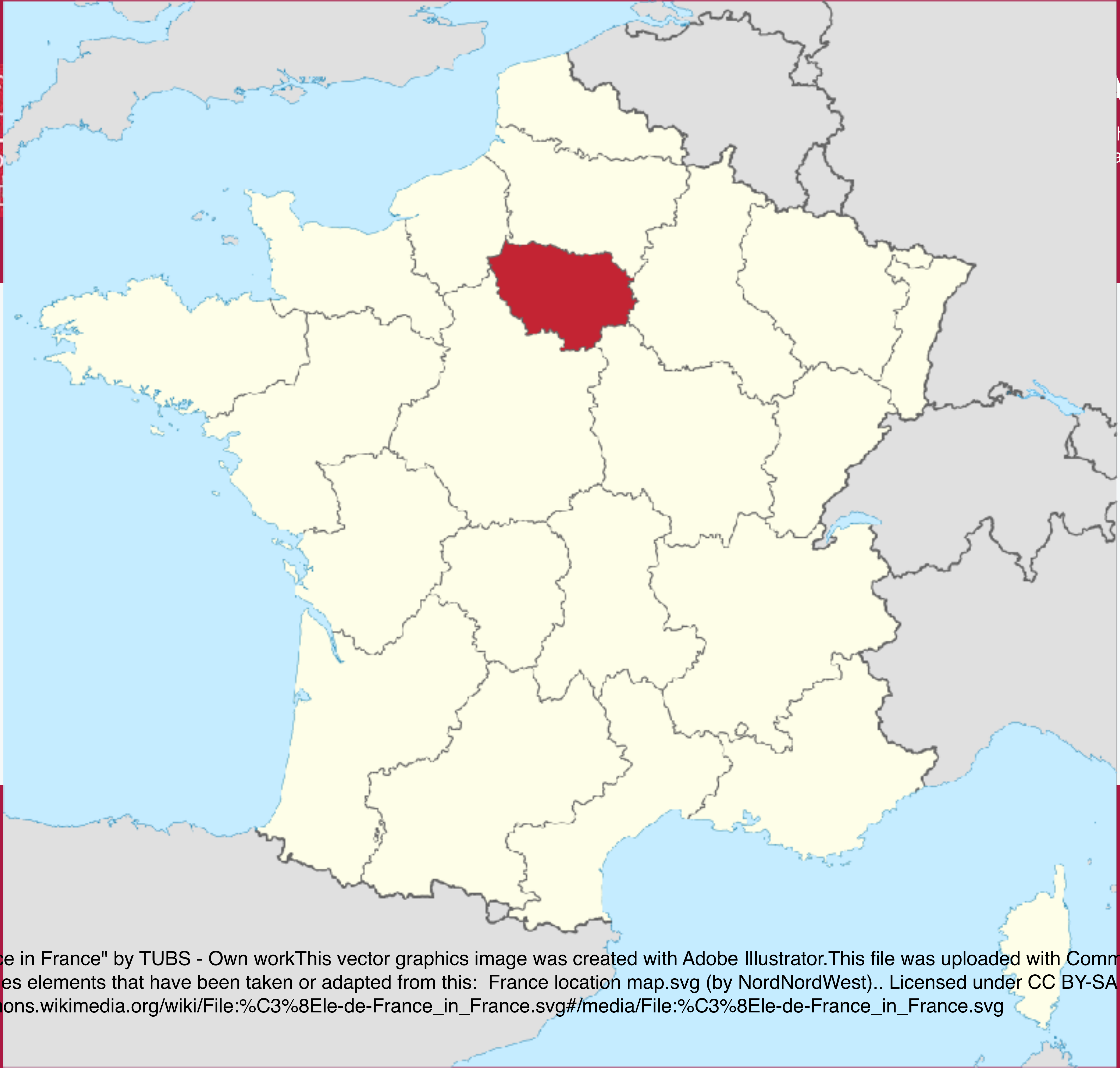
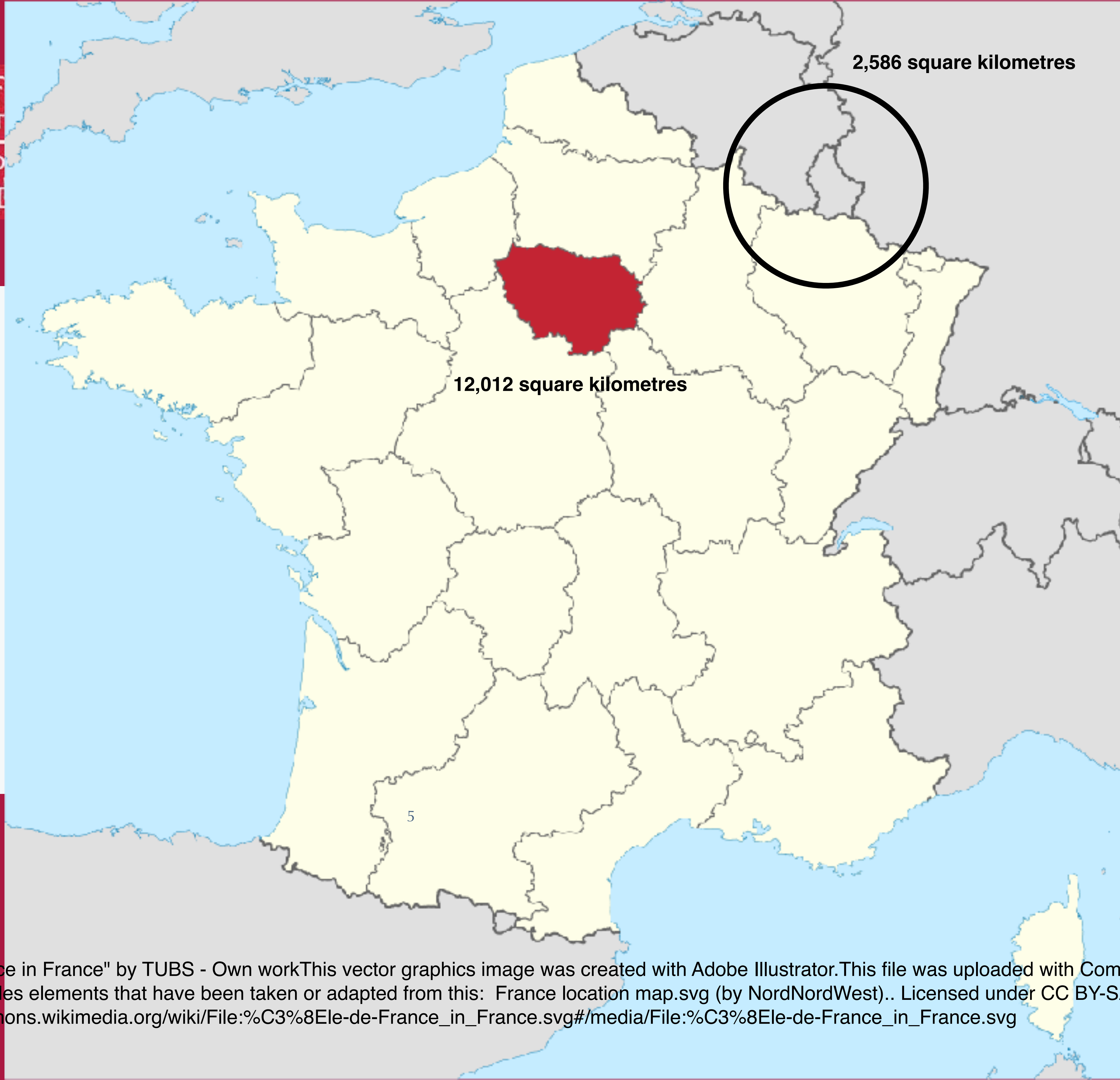


"Île-de-France in France" by TUBS - Own workThis vector graphics image was created with Adobe Illustrator.This file was uploaded with Commonist.This vector image includes elements that have been taken or adapted from this: France location map.svg (by NordNordWest).. Licensed under CC BY-SA 3.0 via Commons https://commons.wikimedia.org/wiki/File:%C3%8Ele-de-France_in_France.svg#/media/File:%C3%8Ele-de-France_in_France.svg



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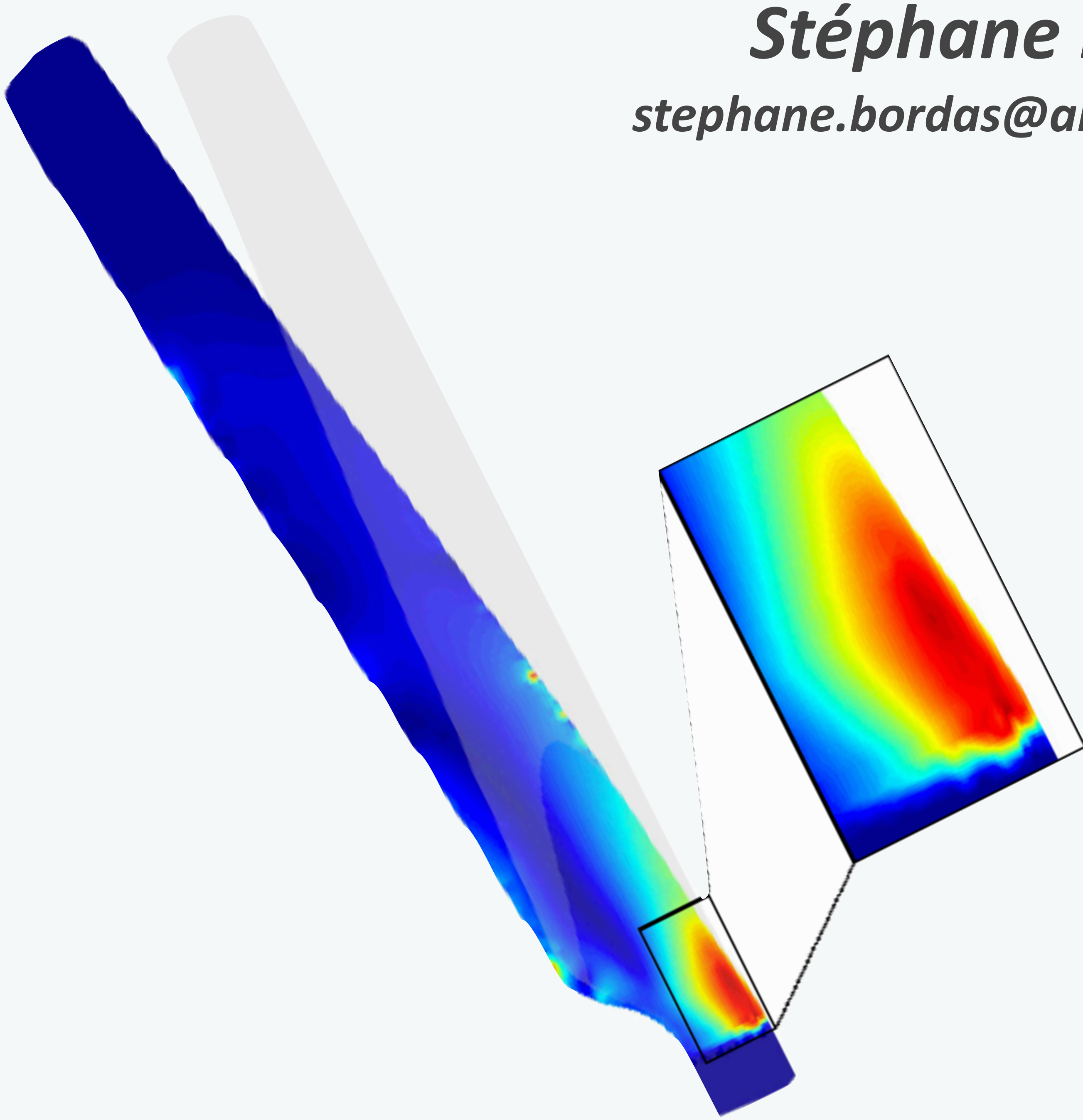
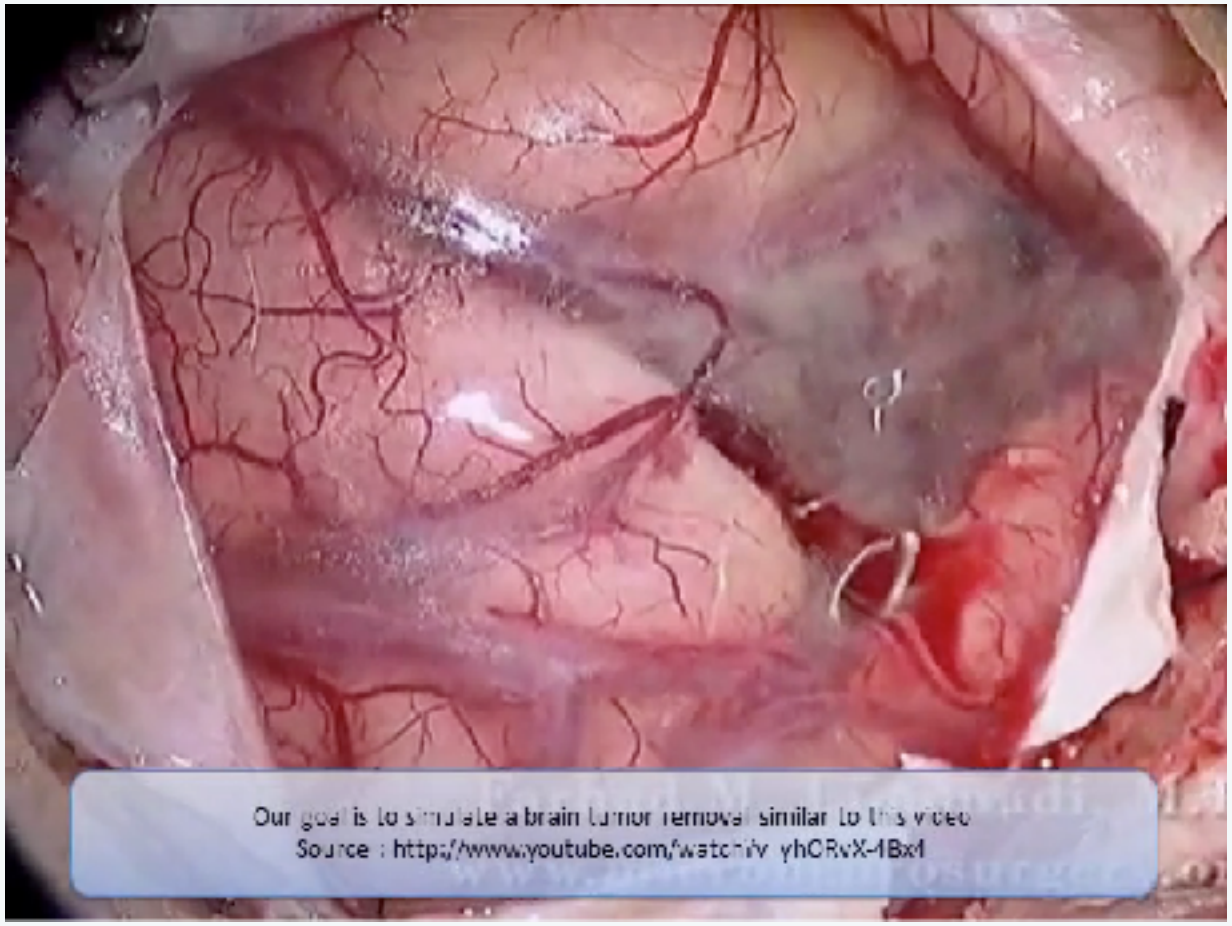
http://hdl.handle.net/10993/31487

Advances in enriched finite element formulations for fracture and cutting:
engineering and surgical simulation applications

Stéphane P.A. Bordas

stephane.bordas@alum.northwestern.edu



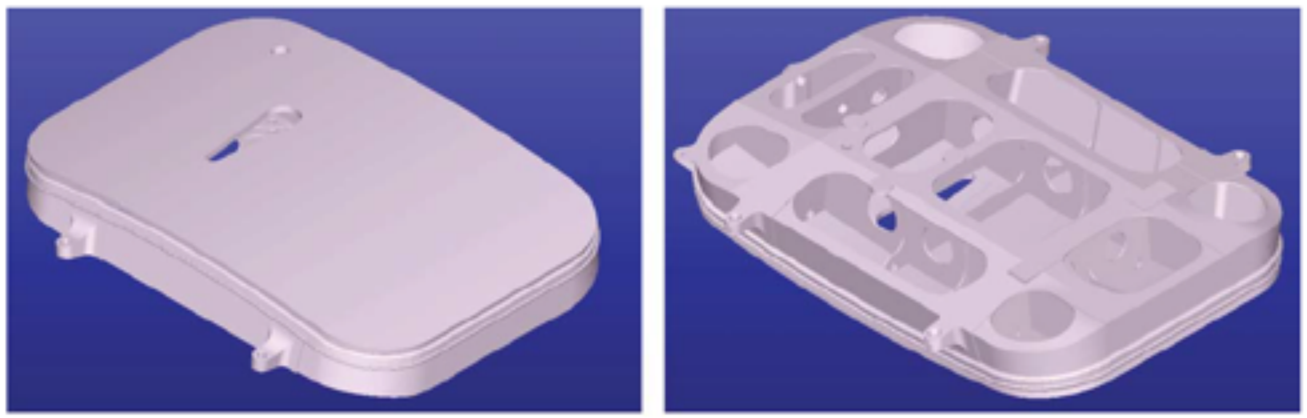


Motivation: fracture mechanics

Motivation

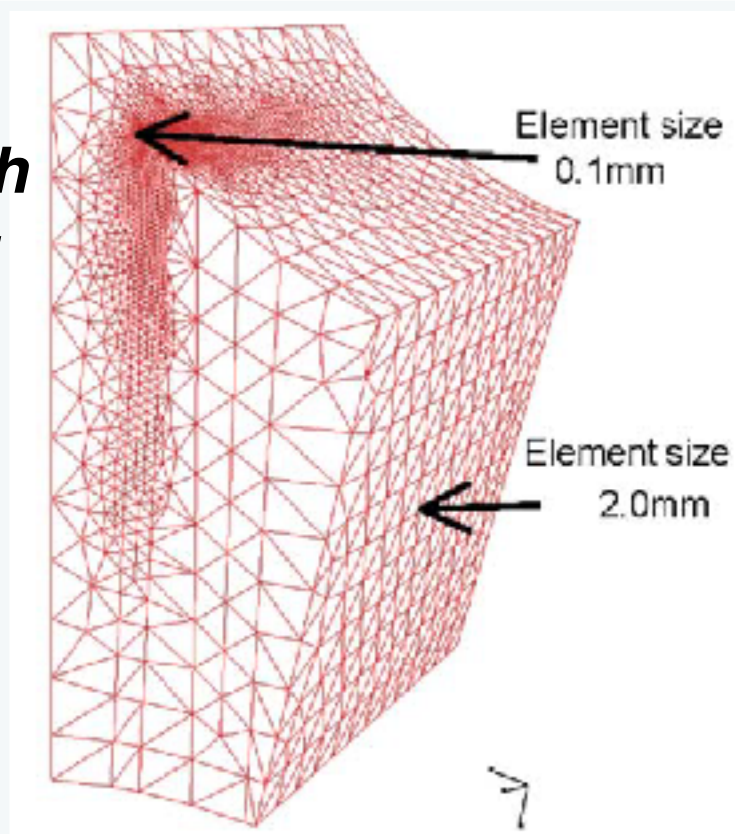
Fractured of homogeneous materials

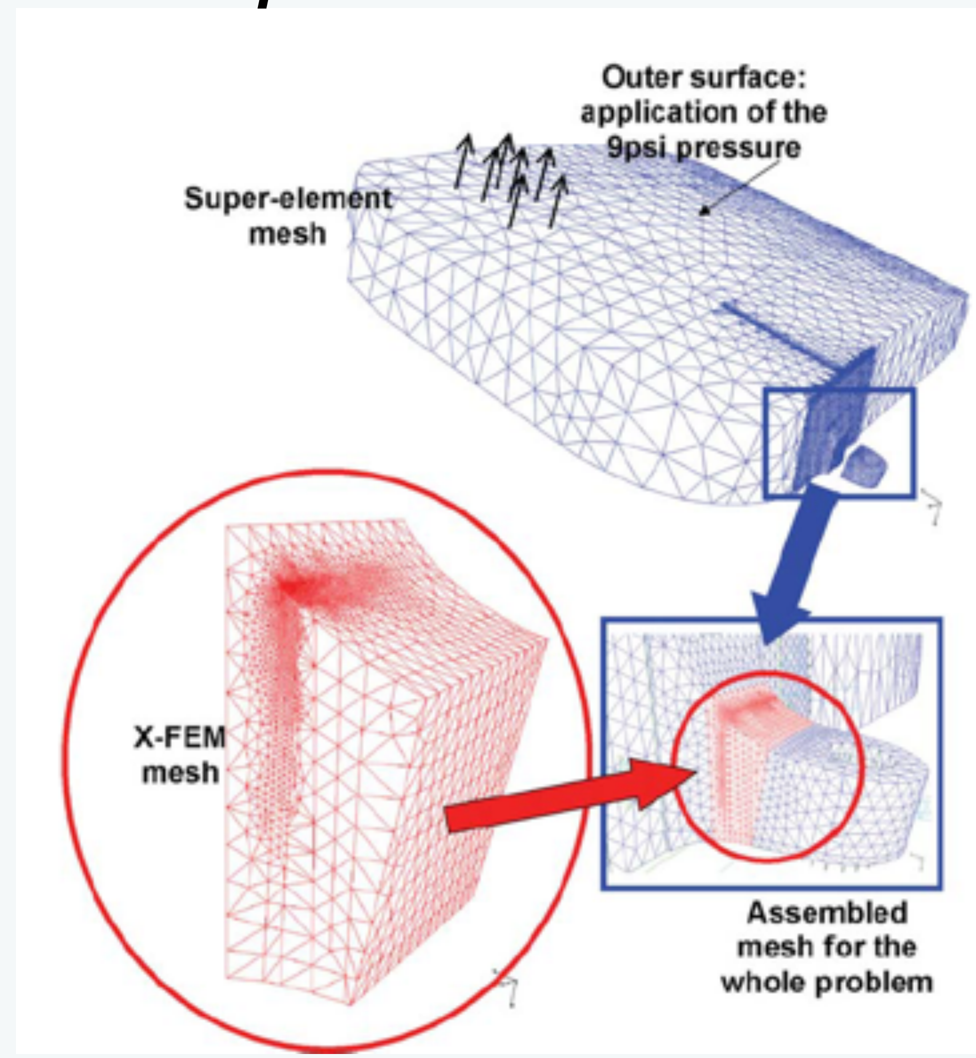
Question: when should a structure be inspected for flaws?



(a) Top view (b) Bottom view

ad hoc mesh refinement





SPAB and B. Moran, Engineering Fracture Mechanics, 2006
V.P. Nguyen et al. XFEM C++ Library IJNME, 2007
Industrial applications of extended finite element methods
See also E. Wyart et al, EFM, IJNME, 2008

Motivation

Fracture of homogeneous materials

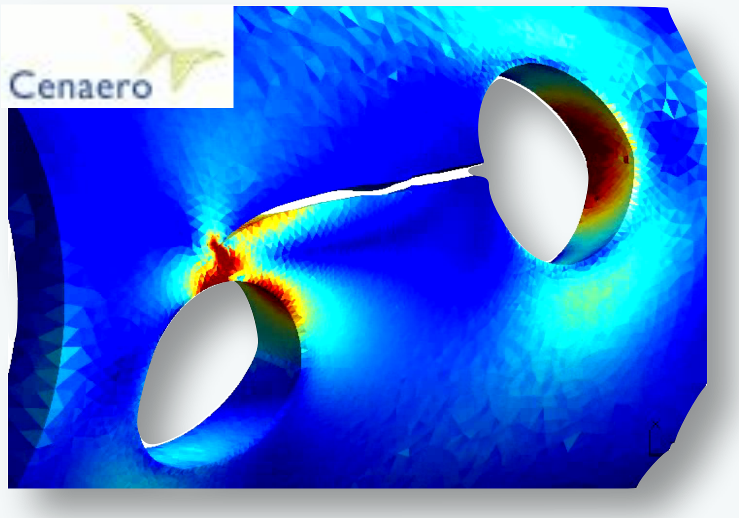
Question: How to control accuracy and simplify/avoid meshing?

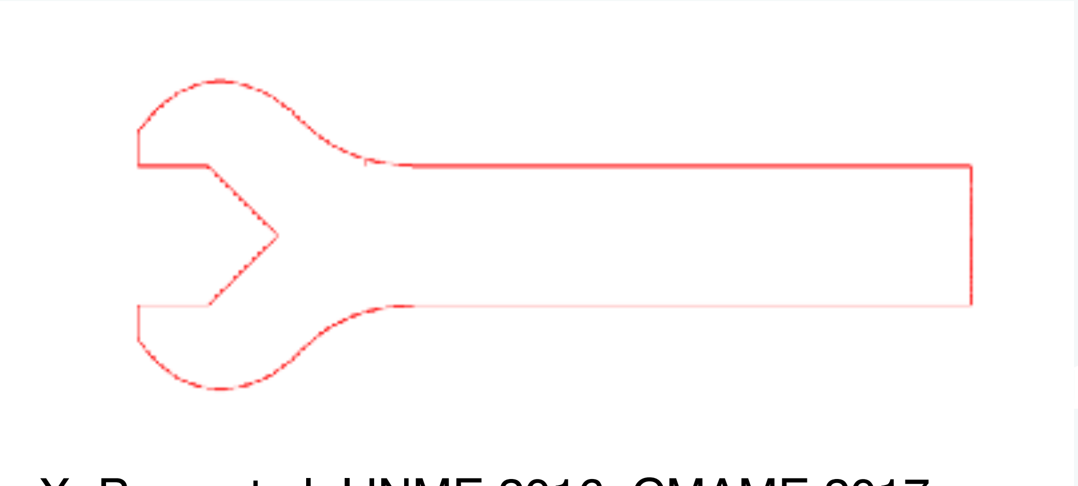
- Partition of Unity - eXtended/Generalized Finite Element Methods
  - ☑ Discretisation error governed by the worst approximant
  - ☑ Local enrichment of approximations
  - ☑ Requires enrichment volumes independent of the mesh
  - ☑ Conditioning issues for large enrichment zones or arbitrary enrichment (see stable GFEM, Banerjee, Babuška + Agathos)
- 3D fracture requires **accurate** stress intensity factors (SIFs)
  - ☐ Error at each step ~ (Error on SIF)^4
  - ☐ Standard enrichment => oscillations along the front

Motivation

Fracture of homogeneous materials

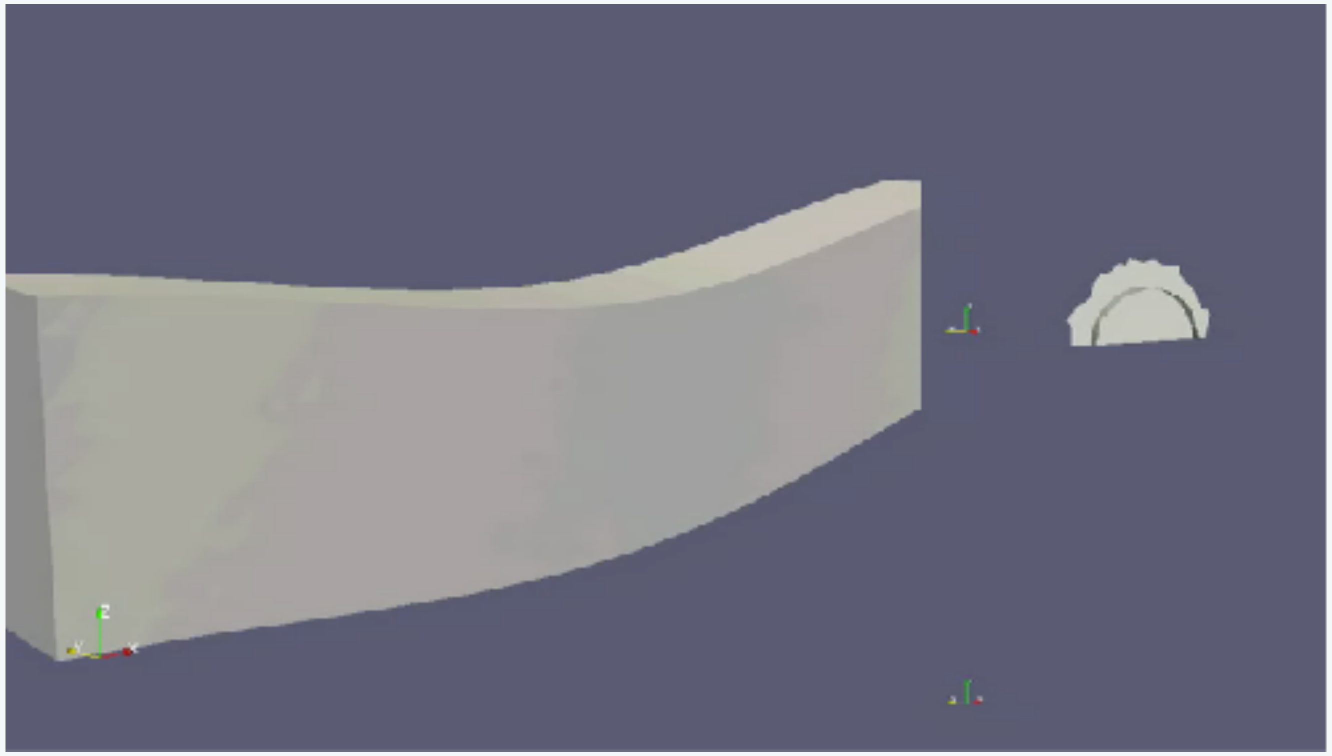
Question: How to control accuracy and simplify/avoid meshing?





X. Peng et al. IJNME 2016, CMAME 2017
Enriched Isogeometric Boundary Elements

How to avoid meshing completely for crack propagation simulations?



K. Agathos et al. IJNME 2016, CMAME 2016, IJNME 2017, CMAME 2017 with Eleni Chatzi and Giulio Ventura

How can we use large enrichment radii?
How can we control conditioning in large-scale enriched FEM?
How can we use higher order terms in the expansion?

More details…

Check out the talk by
Kostas Agathos (ETHZ)

16:20 - 17:20	BB	MS4: Enriched finite element methods - Simone
16:20 - 16:40		Generalized Finite Element Method: application to Interface Problems - Uday Banerjee
16:40 - 17:00		Improving conditioning of 3D XFEM for fracture mechanics - Konstantinos Agathos

More details…

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Sorry, it was yesterday…

More details…

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16:40 - 17:00		Improving conditioning of 3D XFEM for fracture mechanics - Konstantinos Agathos

Use your favourite time machine...

Or a more gradual introduction…

Agathos K, Ventura G, Chatzi E, Bordas S. Stable 3D XFEM/vector-level sets for non-planar 3D crack propagation and comparison of enrichment schemes. International Journal for Numerical Methods in Engineering. Computational Mechanics, 2017.

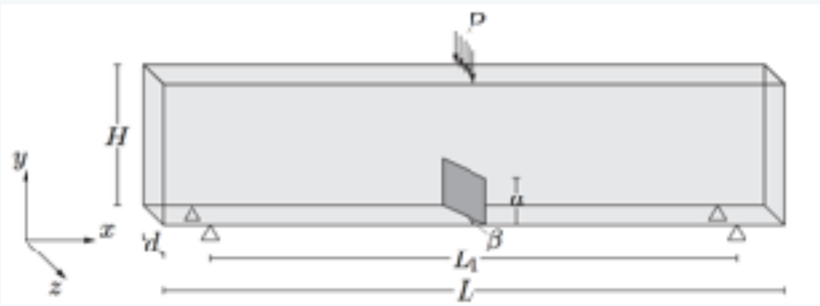
Agathos K, Chatzi E, Bordas S, Talaslidis D. A well−conditioned and optimally convergent XFEM for 3D linear elastic fracture. International Journal for Numerical Methods in Engineering. 2016 Mar 2;105(9):643-77.

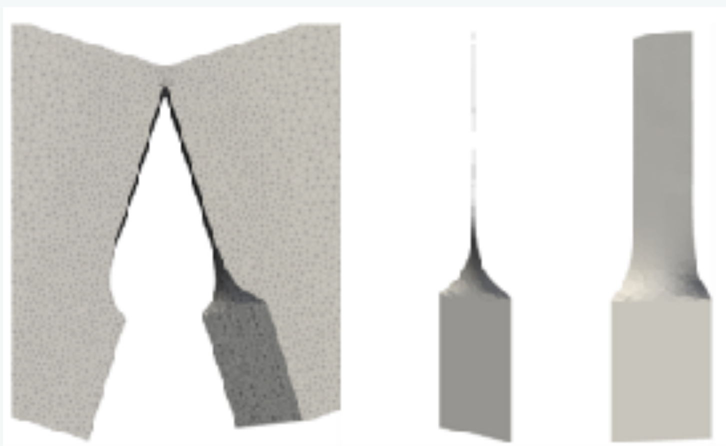
Agathos, K., E. Chatzi, and SPA Bordas. "Stable 3D extended finite elements with higher order enrichment for accurate non planar fracture." *Computer Methods in Applied Mechanics and Engineering* 306 (2016): 19-46.

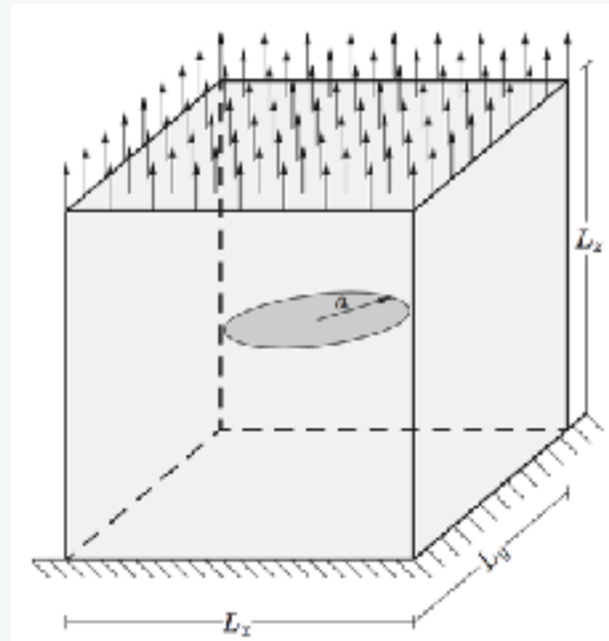
https://orbilu.uni.lu/bitstream/10993/22331/2/paper.pdf

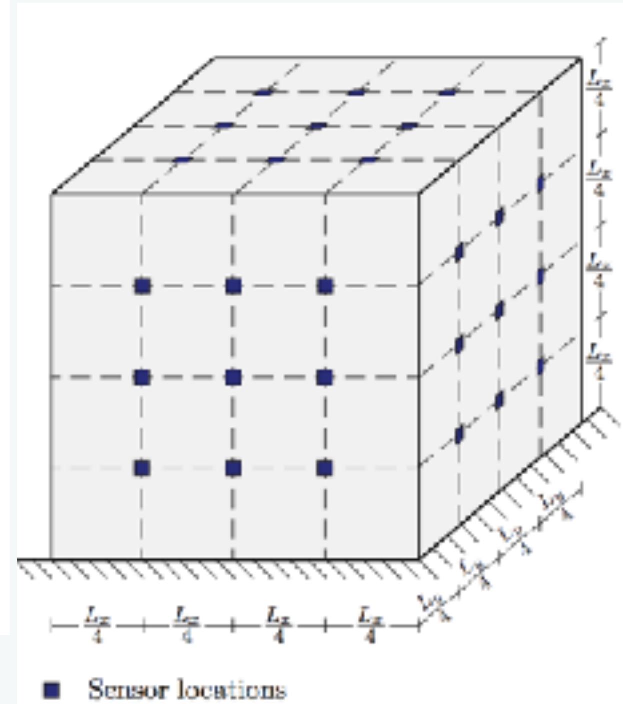
http://orbilu.uni.lu/bitstream/10993/22420/1/presentation.pdf

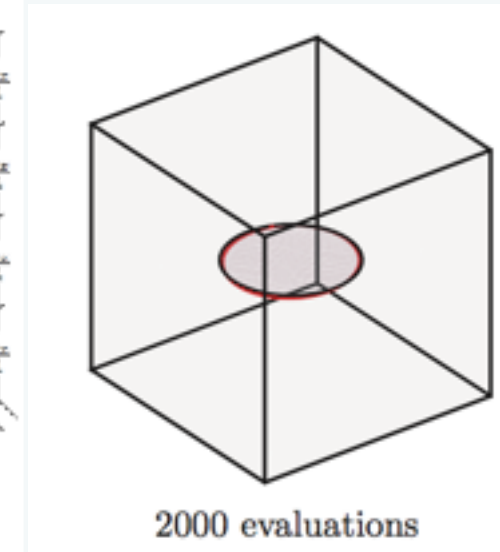
Conclusions from Kostas Agathos' talk









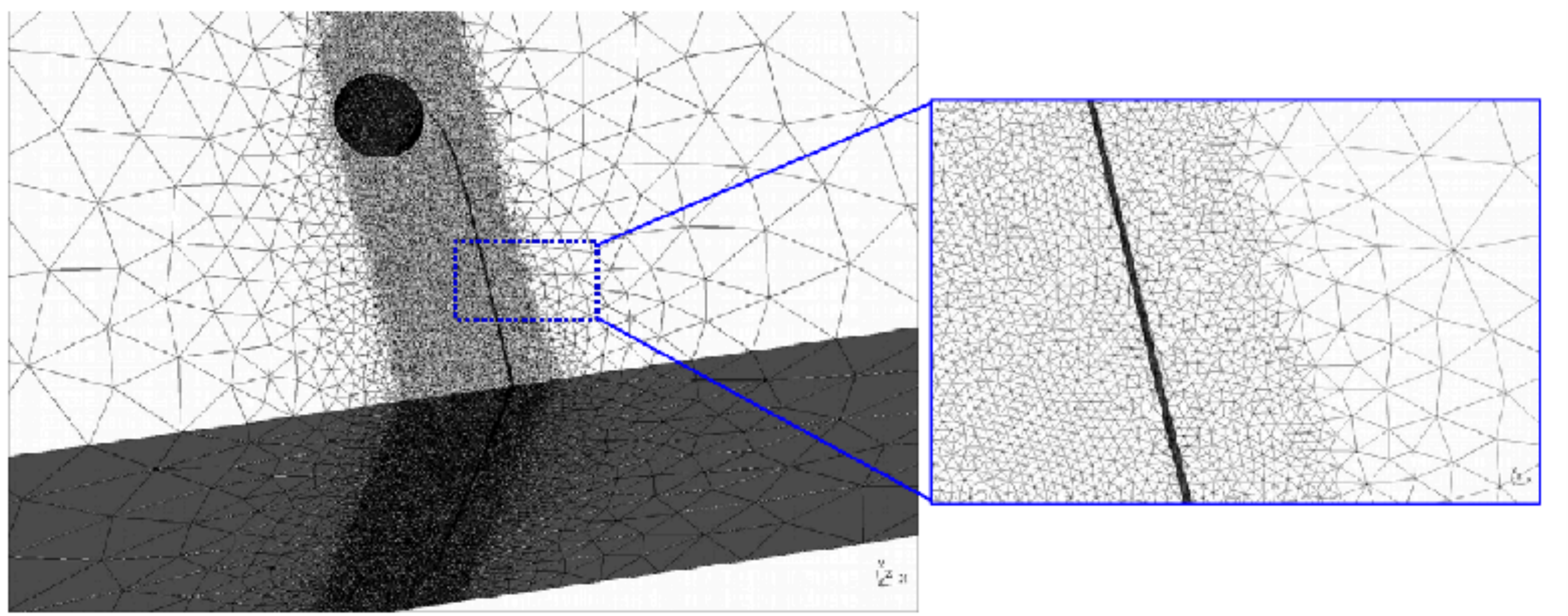


- Introduces a novel form of enrichment.
- Provides improved conditioning.
- Enables the use of geometrical enrichment.
- Enables the use of higher order terms in fracture mechanics
- Was combined to vector level sets to solve crack propagation problems.
- Was applied to inverse problems.
- Provides high accuracy and optimal convergence.

What if you can't add new functions or you don't want to increase the enrichment radius?

Motivation

(Goal oriented) adaptive computational fracture use h-refinement

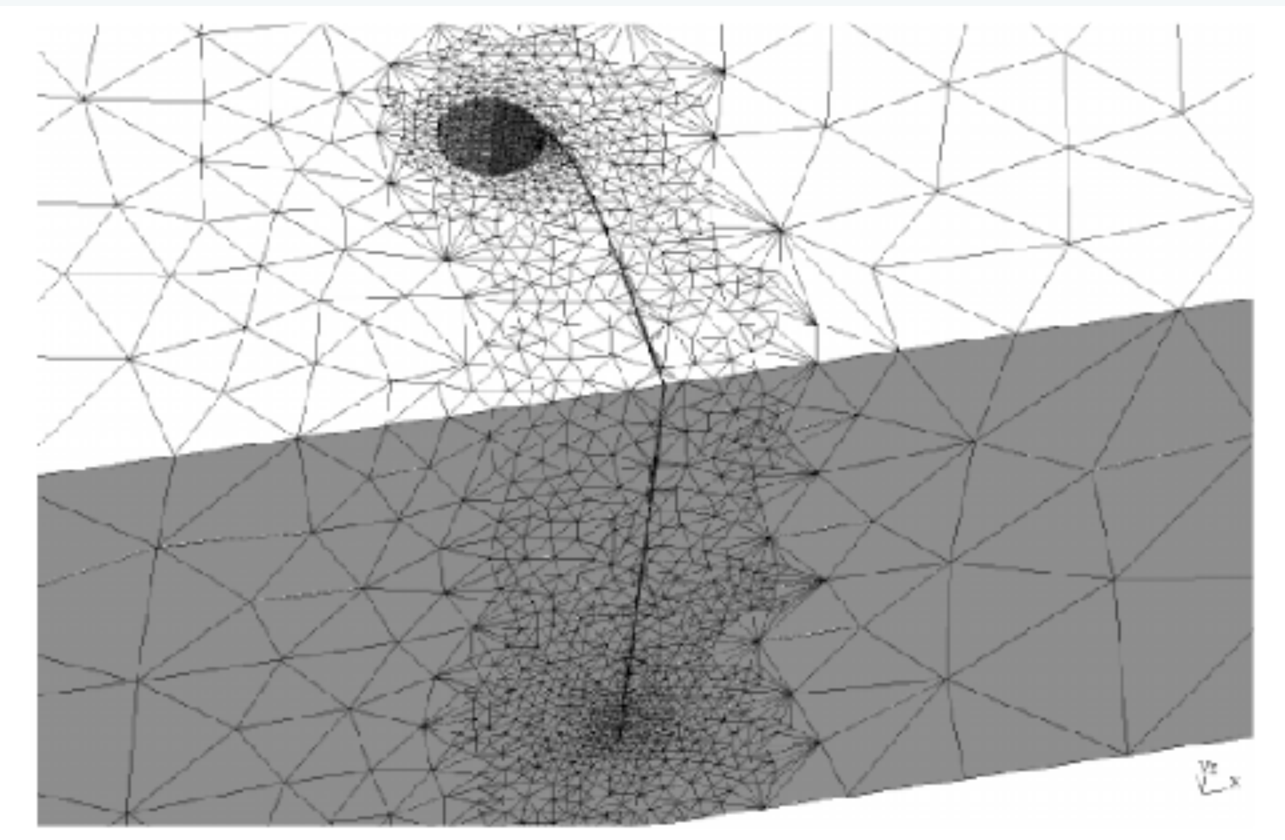


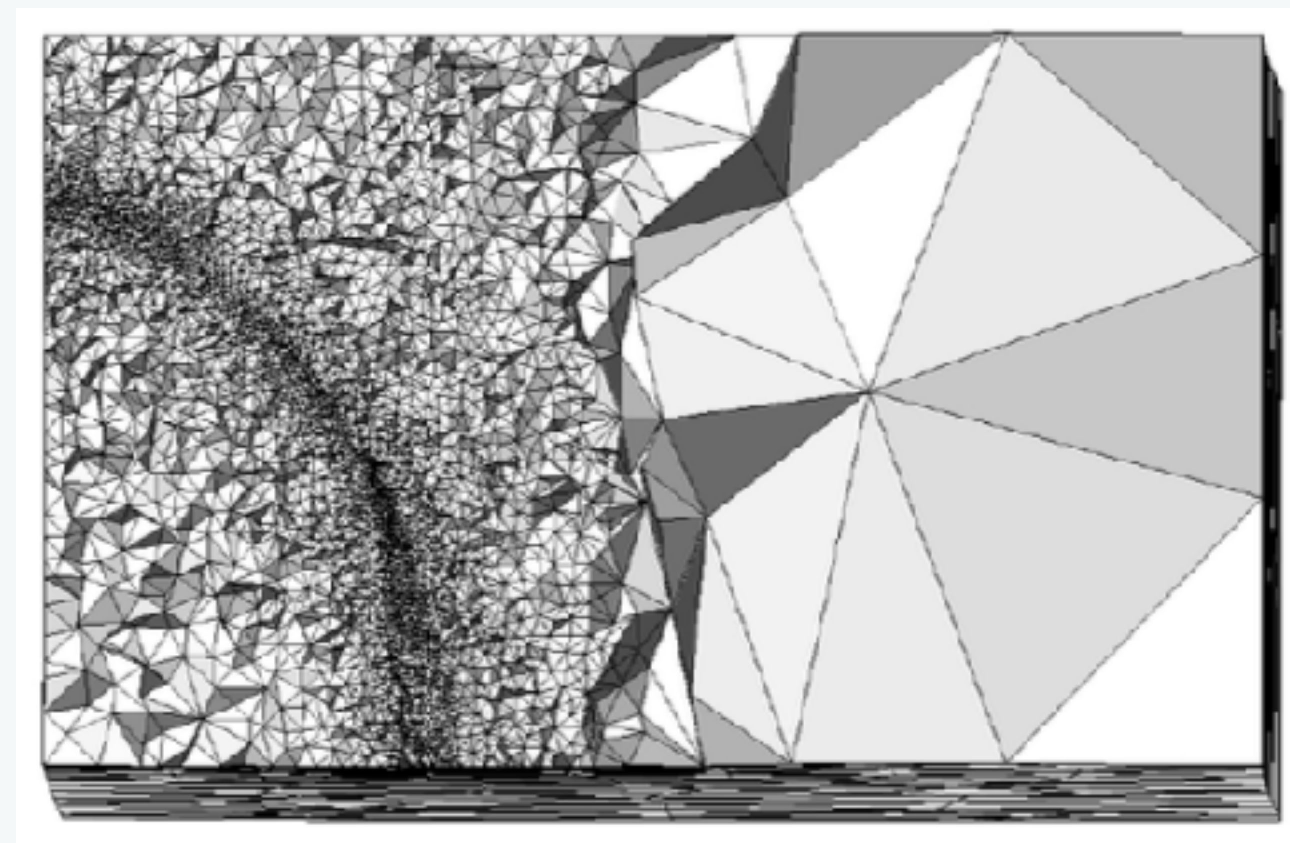
Before: mesh "finely" in the region where the crack is "expected" to propagate

Y. Jin, O. Pierard, et al. Comput. Methods Appl. Mech. Engrg. 318 (2017) 319–348
O.A. González-Estrada et al. Computers and Structures 152 (2015) 1–10
O.A. González-Estrada et al. Comput Mech (2014) 53:957–976
C. Prange et al. IJNME 91.13 (2012): 1459-1474.
M. Duflot, SPAB, IJNME 2007, CNME 2007, IJNME 2008.
J-J. Ródenas Garcia, IJNME 2007
F.B. Barros, et alIJNME 60.14 (2004): 2373-2398.
M. Rüter CMECH (2013) 1;52(2):361-76.
J. Panetier IJNME 81.6 (2010): 671-700.
P. Hild, CMECH (2010): 1-28.

Motivation

Fracture of homogeneous materials: error estimation and adaptivity





After: determine mesh refinement adaptively using a (goal-oriented) error estimate

Y. Jin, O. Pierard, et al. Error-controlled adaptive extended finite element method for 3D linear elastic crack propagation Comput. Methods Appl. Mech. Engrg. 318 (2017) 319–348
M. Duflot, SPAB, IJNME 2007, CNME 2007, IJNME 2008.

More details…

Check out the talk by Olivier Pierard (Cenaero) later this morning MS4 at 11:00

11:00 - 12:20	**BB**	**MS4: Enriched finite element methods - Aragón**
11:00 - 11:20		Error-based mesh adaptation during crack propagation simulation with X-FEM - Olivier Pierard

More cracks?...

Extended Finite Element Method (XFEM)

Fracture of “XFEM” using XFEM

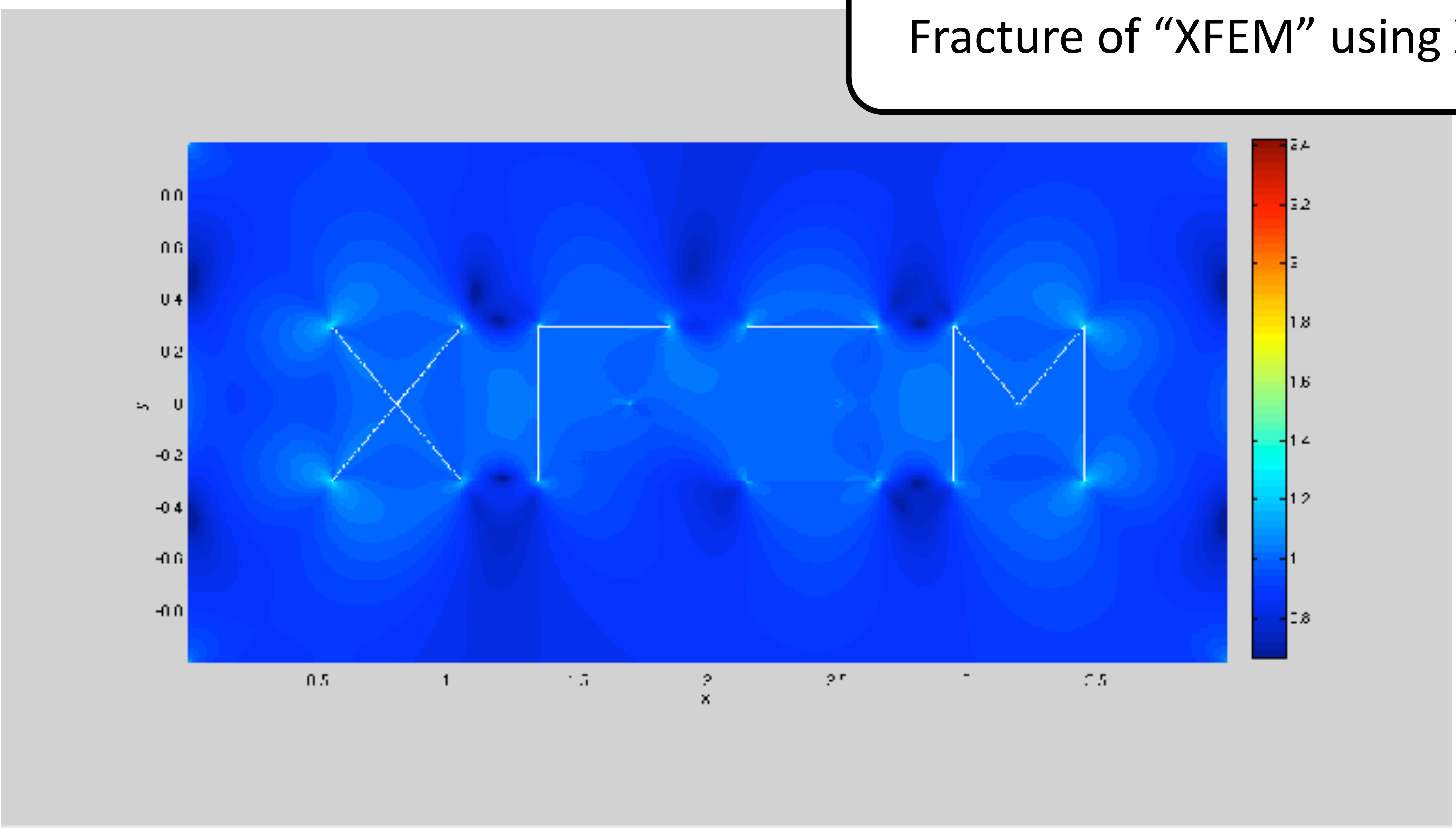
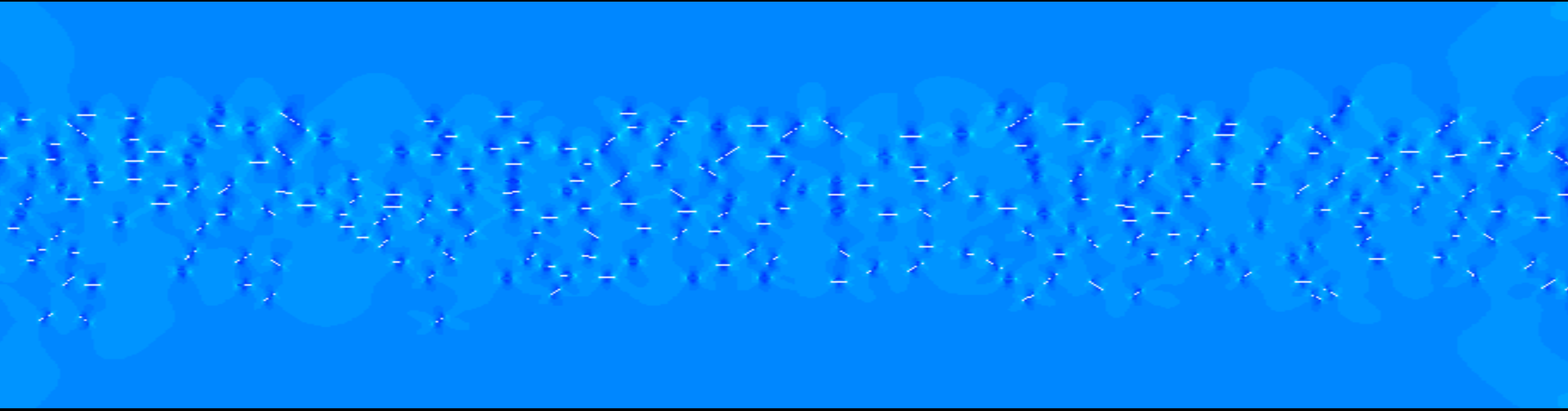


Plate with 300 cracks - vertical extension BCs

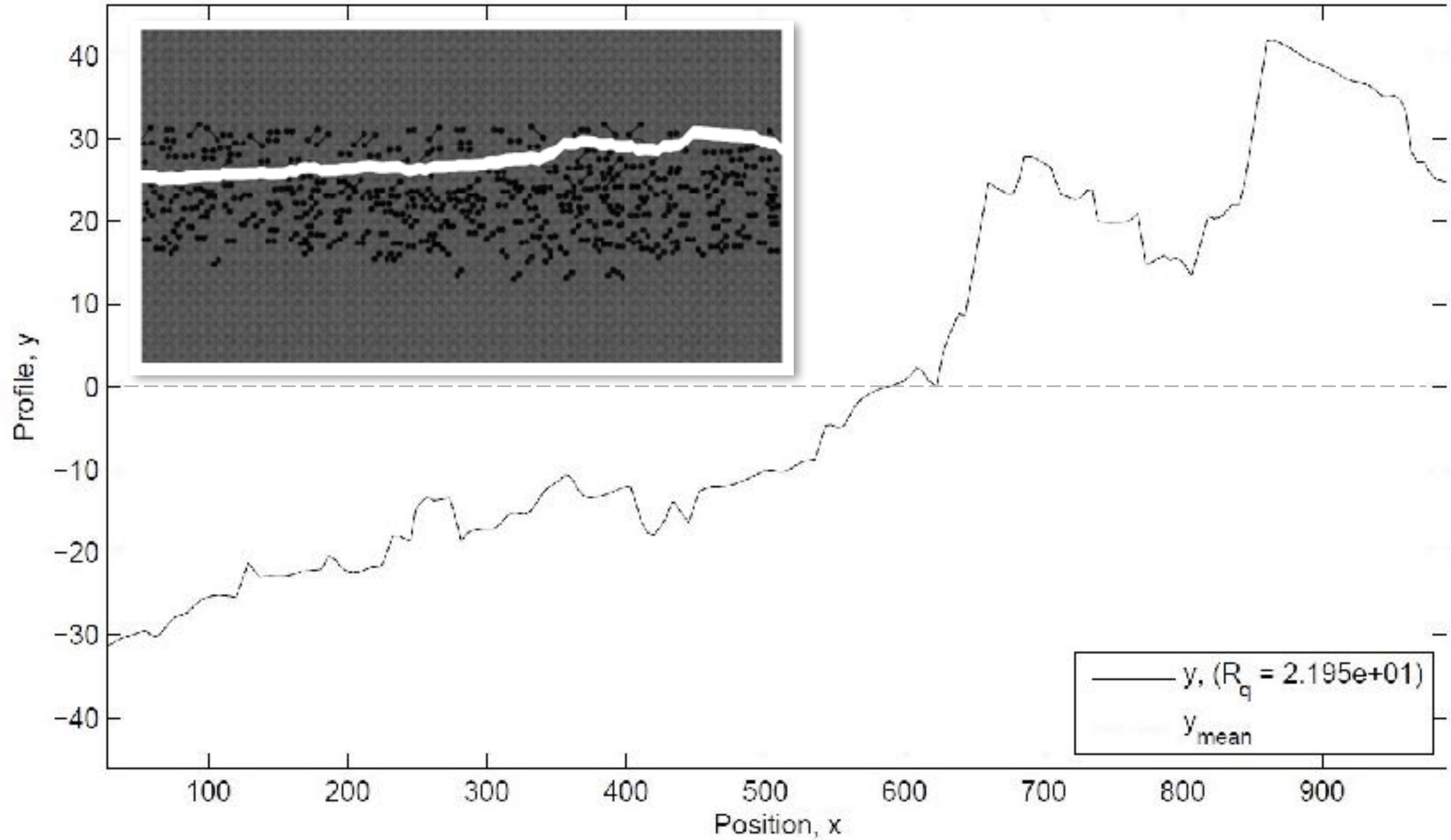
Energy-minimal crack growth using XFEM



Sutula et al. Preprint of three part EFM paper at
http://hdl.handle.net/10993/29414

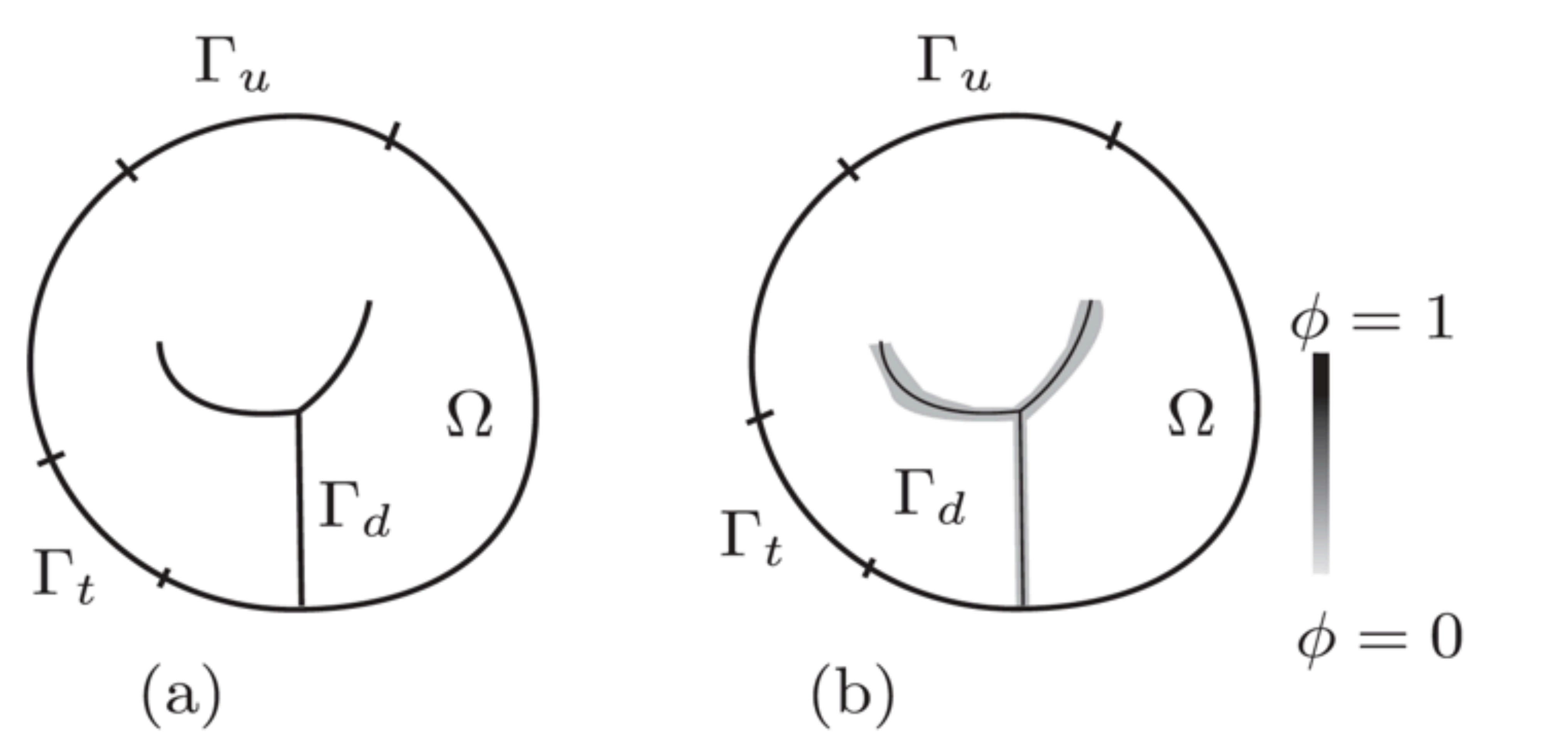
Vertical extension of a plate with 300 cracks

Post-split roughness



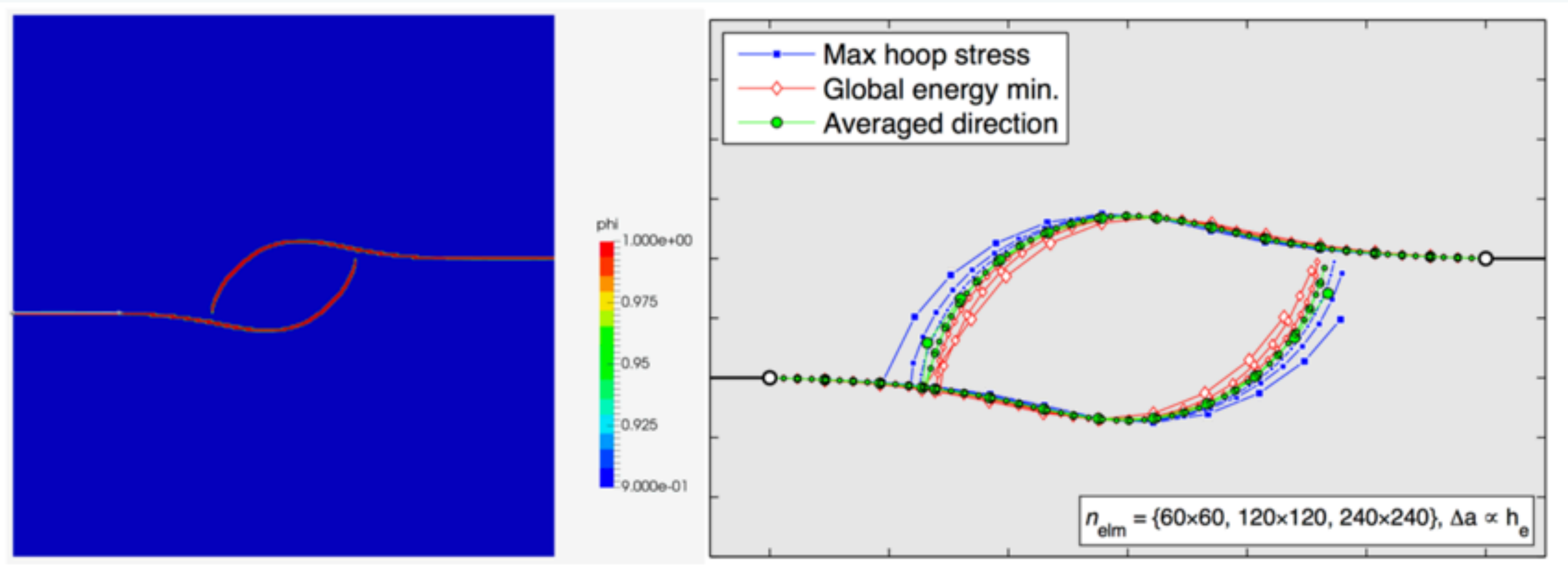
More cracks?… 3D? …

Phase field/thick level sets



With Danas Sutula and Nguyen Vinh Phu (Monash)
9TH Australasian Congress on Applied Mechanics (ACAM9)
27 - 29 November 2017
phu.nguyen@monash.edu

Energy minimal XFEM vs. Phase field



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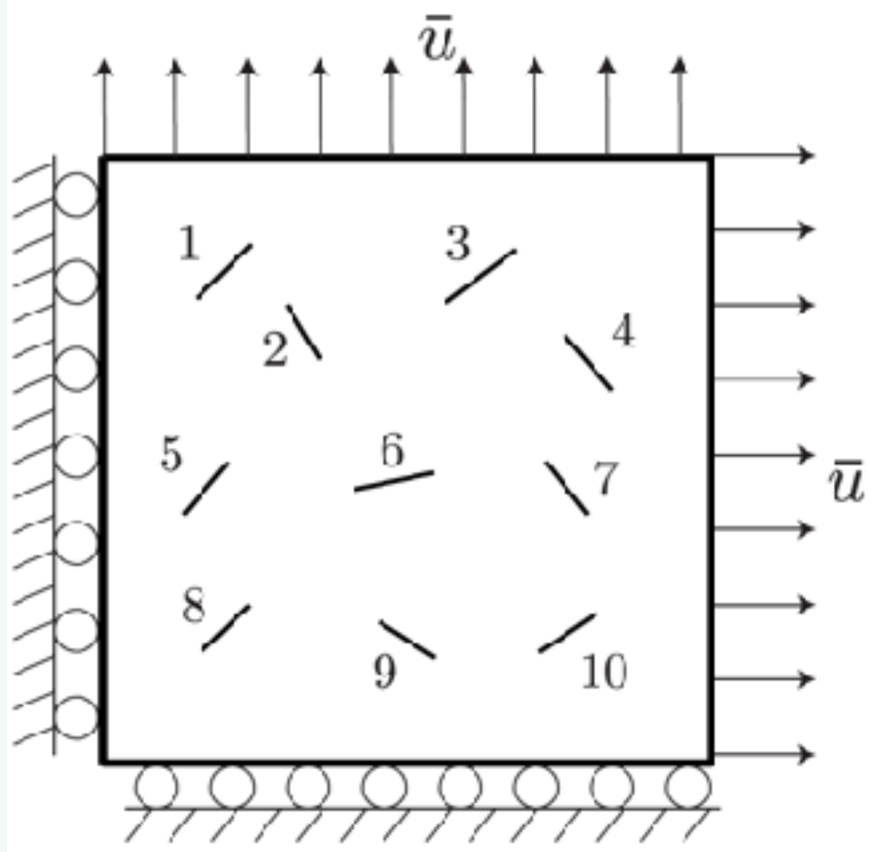

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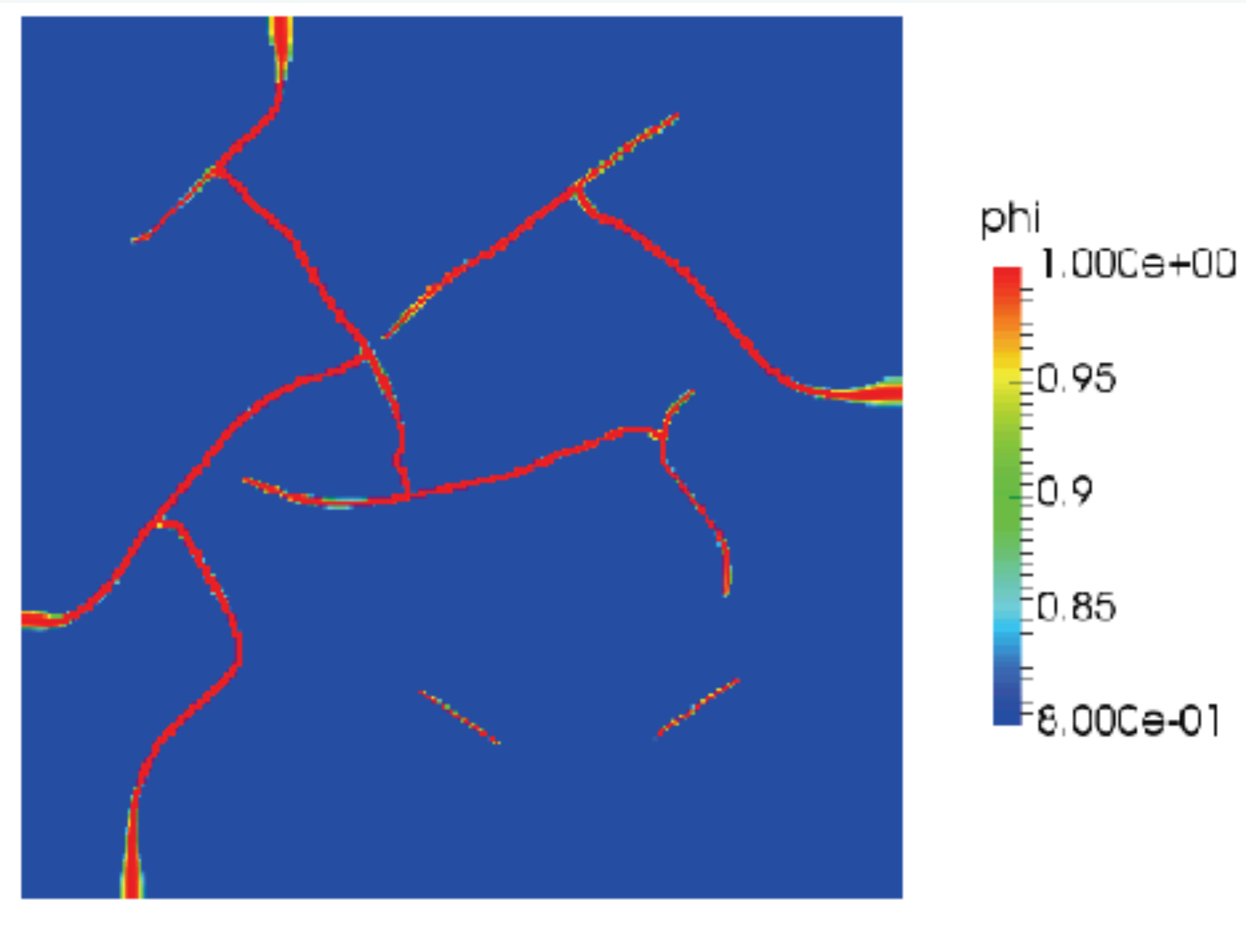

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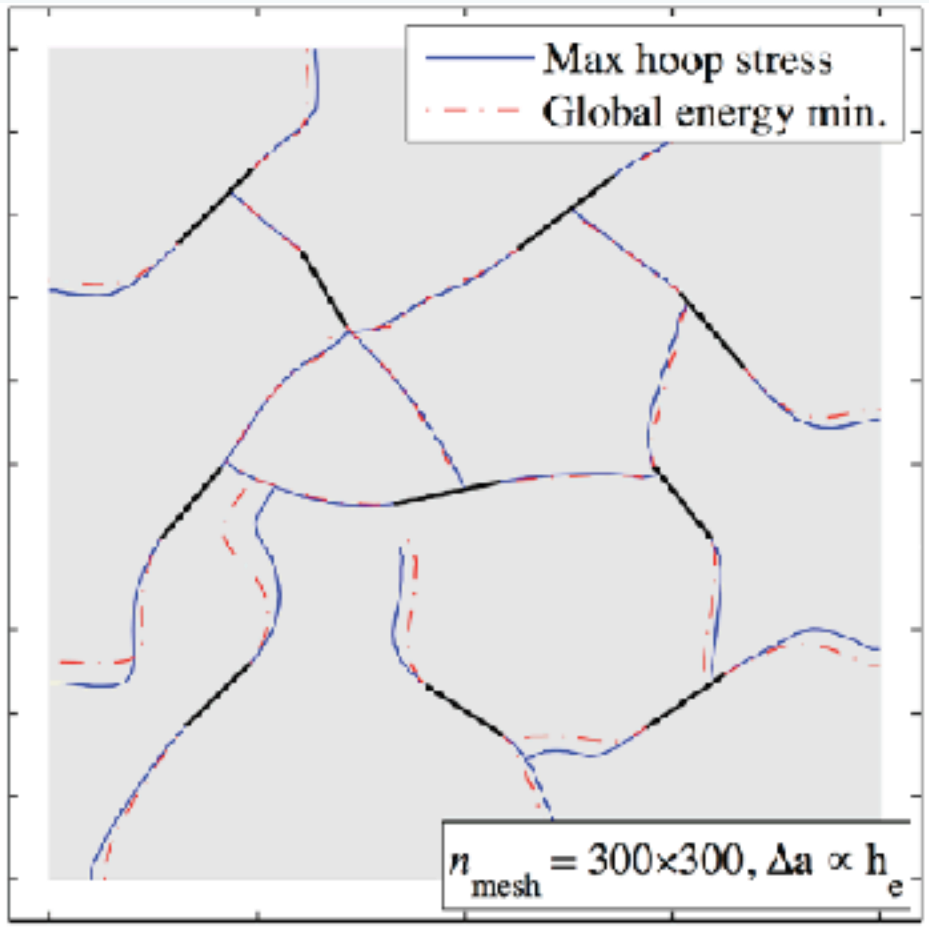
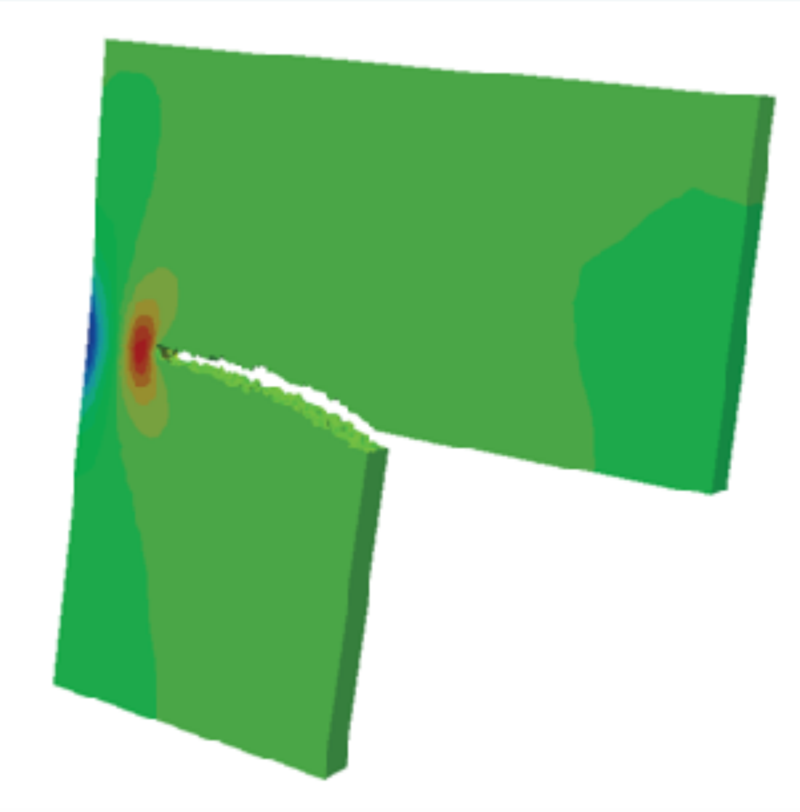
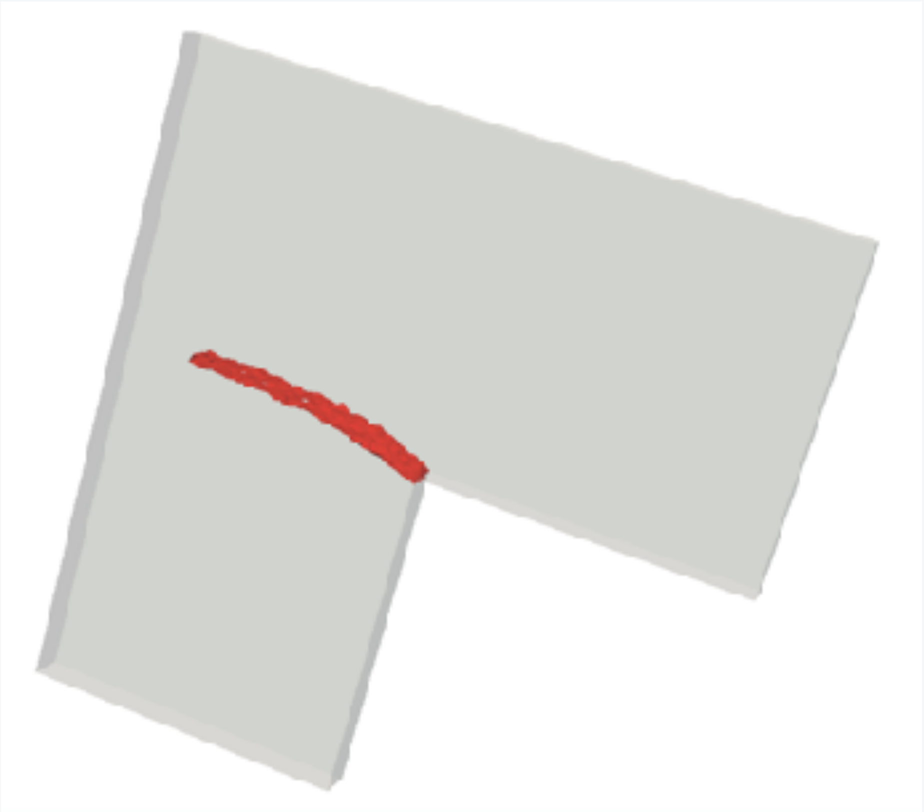
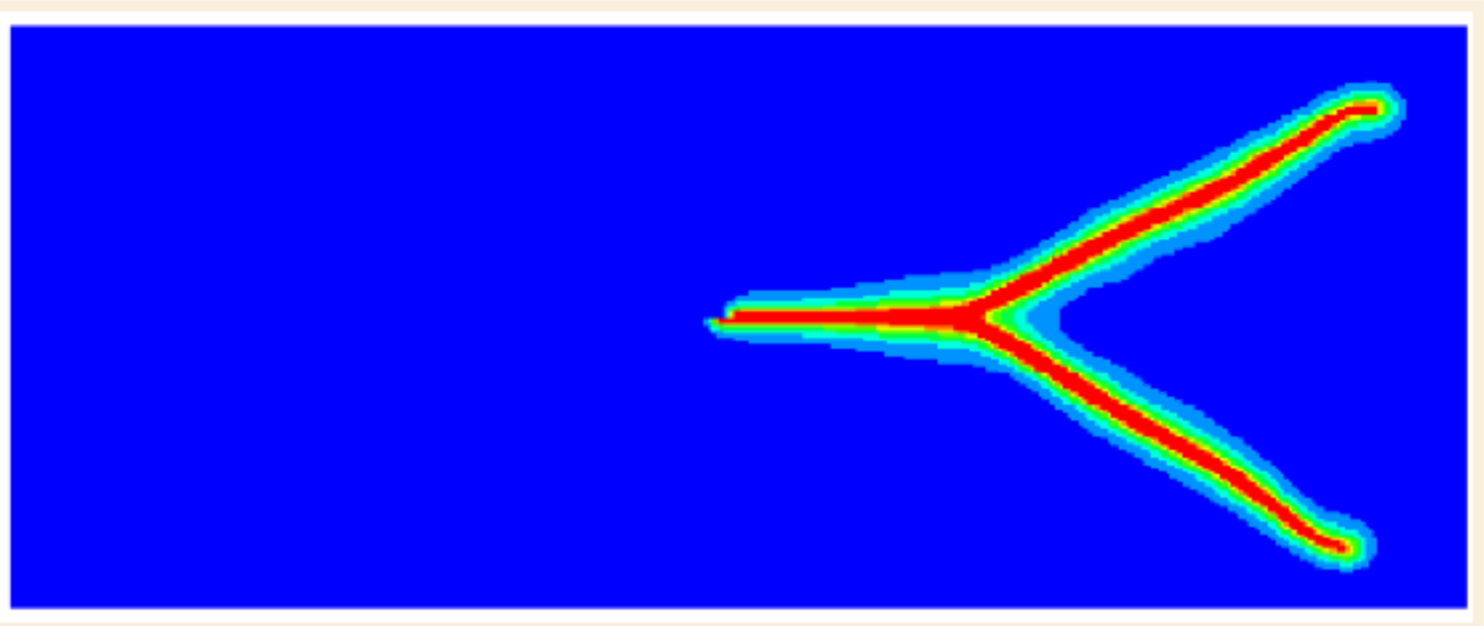
8.000e-01



Max hoop stress
Global energy min.
n_{mesh} = 300×300, Δa ∝ h_e







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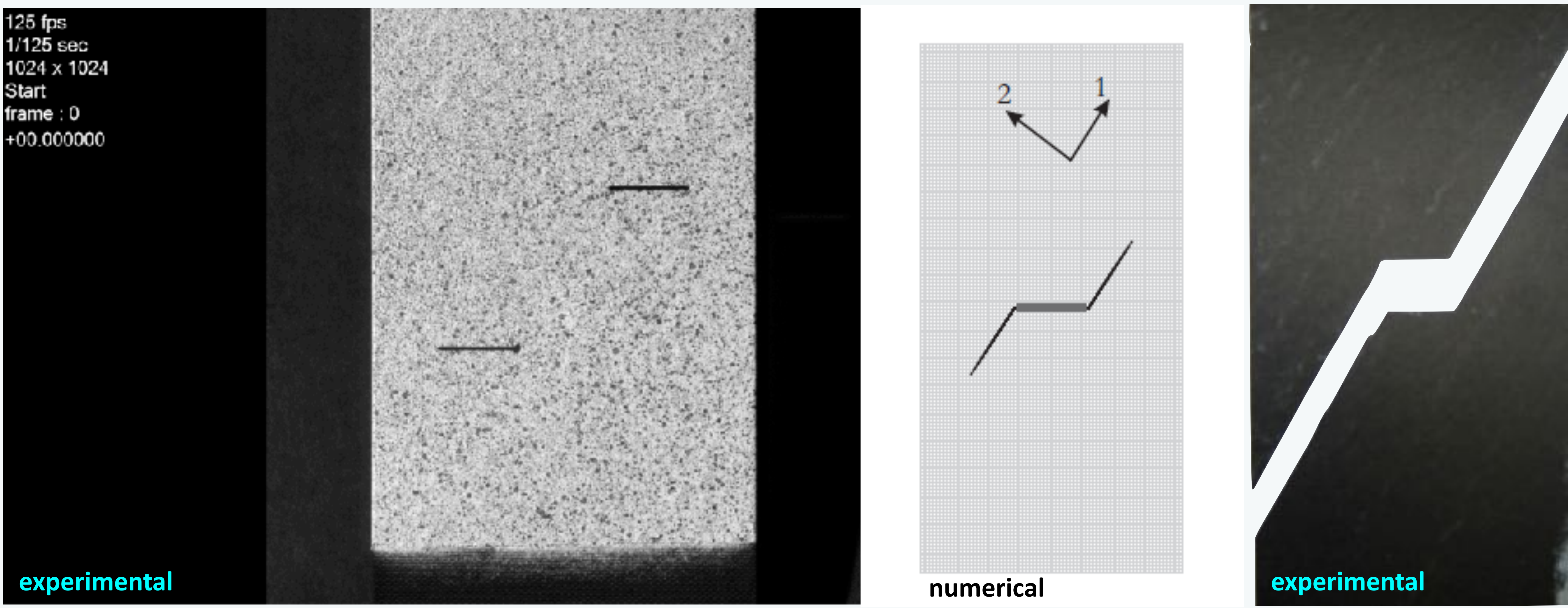
Partial conclusions on fracture of homogeneous materials using enriched FEM

- Adaptivity for enriched approximations using error estimates
  - Adapt enrichment radius
  - Adapt the choice of enrichment
  - Locally h-adapt the mesh
- More than a few cracks in 3D may warrant using phase fields models as opposed to discrete cracks
- Meshfree methods are possible alternatives (See the work of Rabczuk, Belytschko, Zi, SPAB)
- Next step: heterogeneities

Fracture of composites

Question: what main factors govern crack growth in composite laminates?

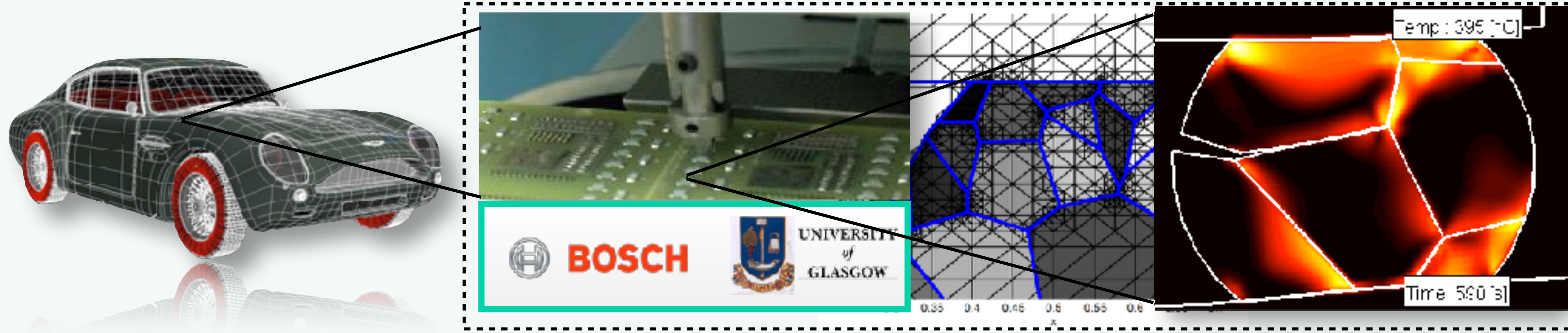


L. Cahill et al. Composite Structures, 2014

Experimental/Numerical approach to determining the driving force for fracture in composites

Fracture over the scales

Solder joint durability (microelectronics), Bosch GmbH

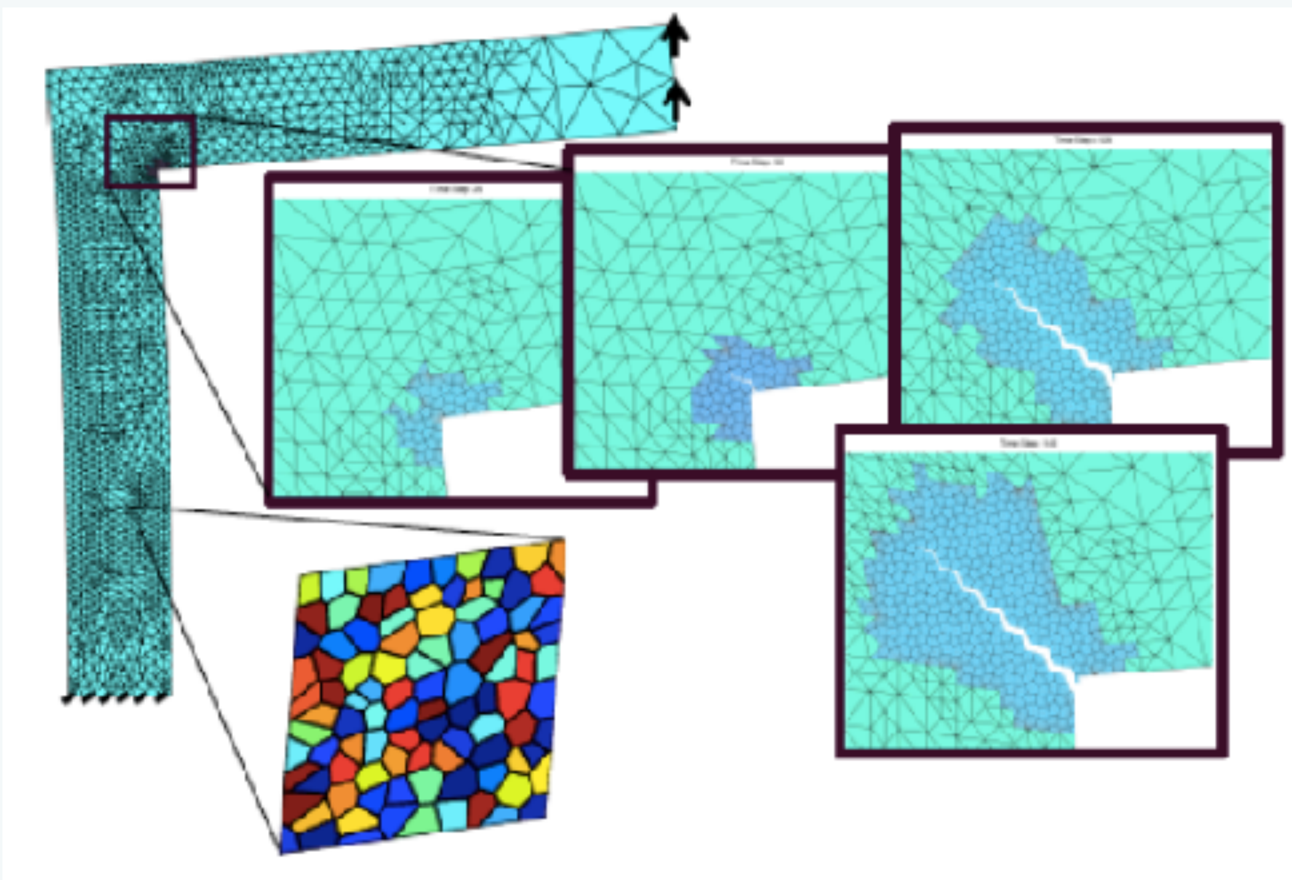


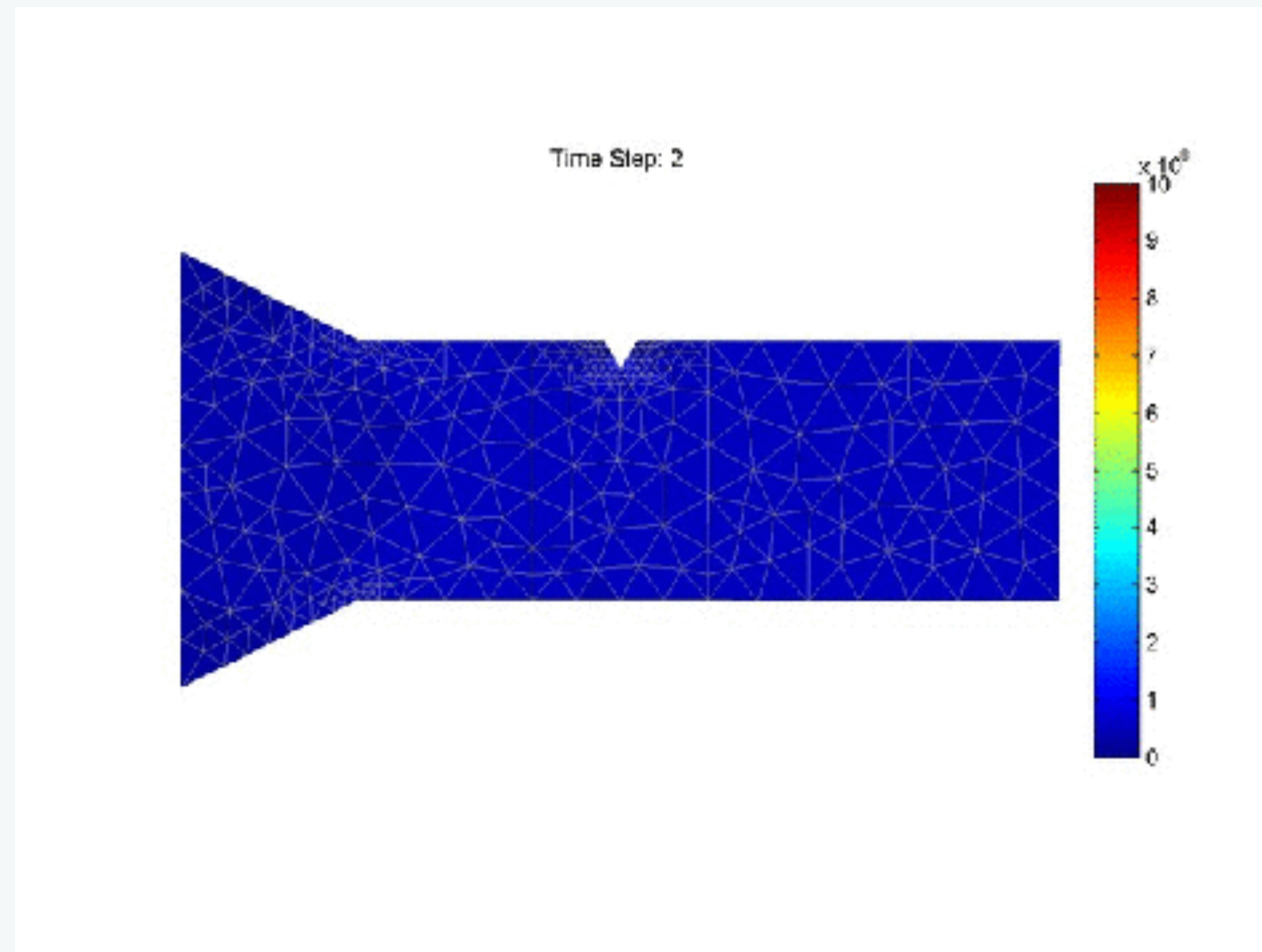
Question: what is the role of Pb in thermo-mechanical reliability of solder joints?

A. Menk and SPAB, IJNME 2011, Comp. Mat. Sci. 2012
XFEM Preconditioning and application to polycrystalline fracture

D. A. Paladim et al. Int. J. Numer. Meth. Engng 2017; 110:103–132
P. Kerfriden et al. Int. J. Numer. Meth. Engng 2014; 97:395–422
P. Kerfriden et al. Int. J. Numer. Meth. Engng 2012; 89:154–179
P. Kerfriden et al. Comput. Methods Appl. Mech. Engrg. 200 (2011) 850–866
K. C. Hoang et al. Num Meth PDEs DOI 10.1002/num.21932

Fracture over the scales, adaptivity model reduction and selection





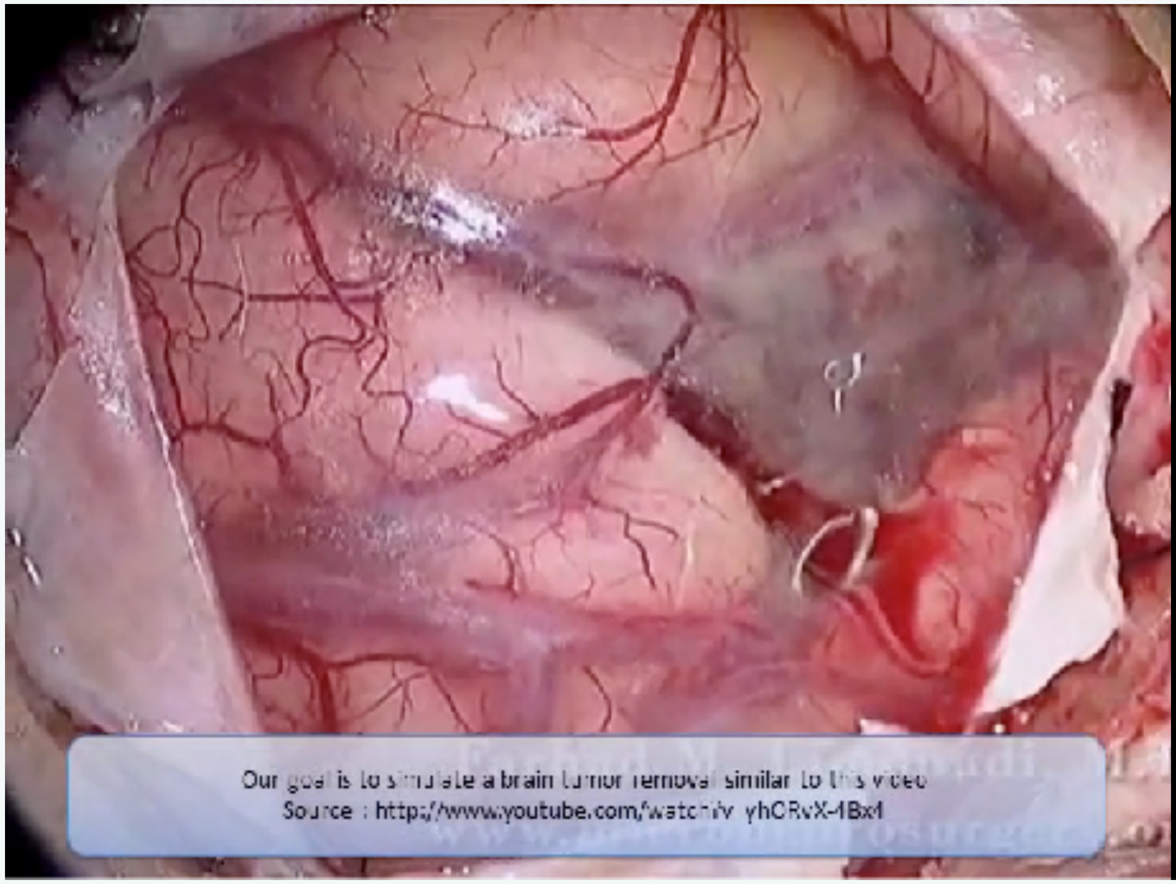
Question: how can we account for microstructures in a computationally tractable way?

O. Goury, P. Kerfriden et al. CMAME, 2016, CMECH (**2017**) DOI 10.1007/s00466-016-1290-2 - Model reduction for fracture
C. Hoang et al. Comput. Methods Appl. Mech. Engrg. 298 (**2016**) 121–158 - Model reduction for elastodynamics
A. Akbari, P. Kerfriden and SPAB, Philosophical Magazine, (**2015**) http://dx.doi.org/10.1080/14786435.2015.1061716
P. Kerfriden et al. Comput. Methods Appl. Mech. Engrg. 256 (**2013**) 169–188 - Model reduction methods for fracture

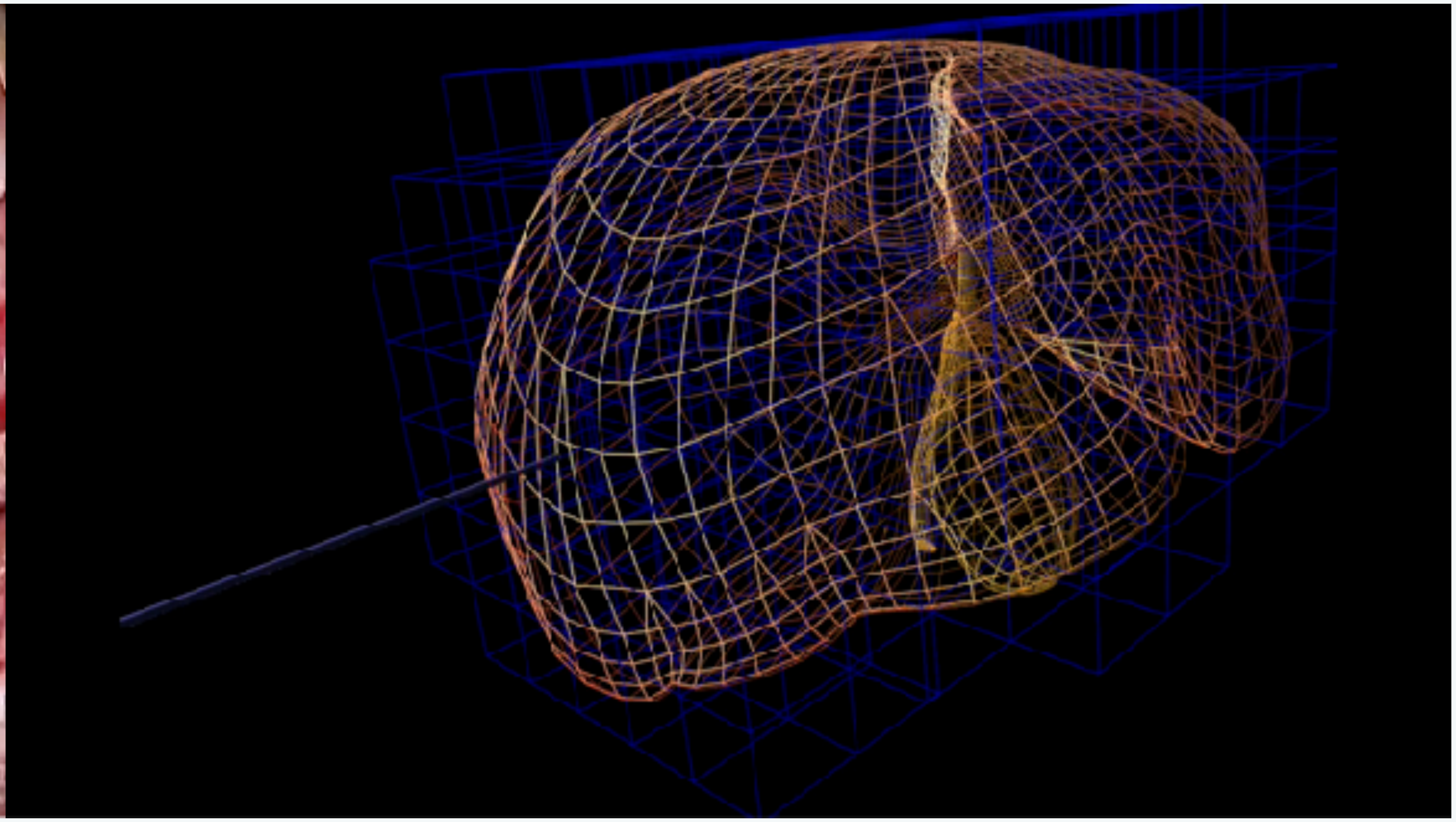
Partial conclusions on fracture of heterogeneous materials

- Simple methods can deal with fracture in unidirectional composites
- Model + mesh adaptivity for adaptive fracture mechanics simulations: expensive + implementation must be done carefully
- Model order reduction is ineffective for problems lacking separation of scales
    - Domain-wise model selection
    - Adaptive model selection
    - Machine learning…
- Next step: biomechanics/real-time

Cutting and Needle Insertion



H. Courtecuisse et al. Medical Image Analysis, 2014

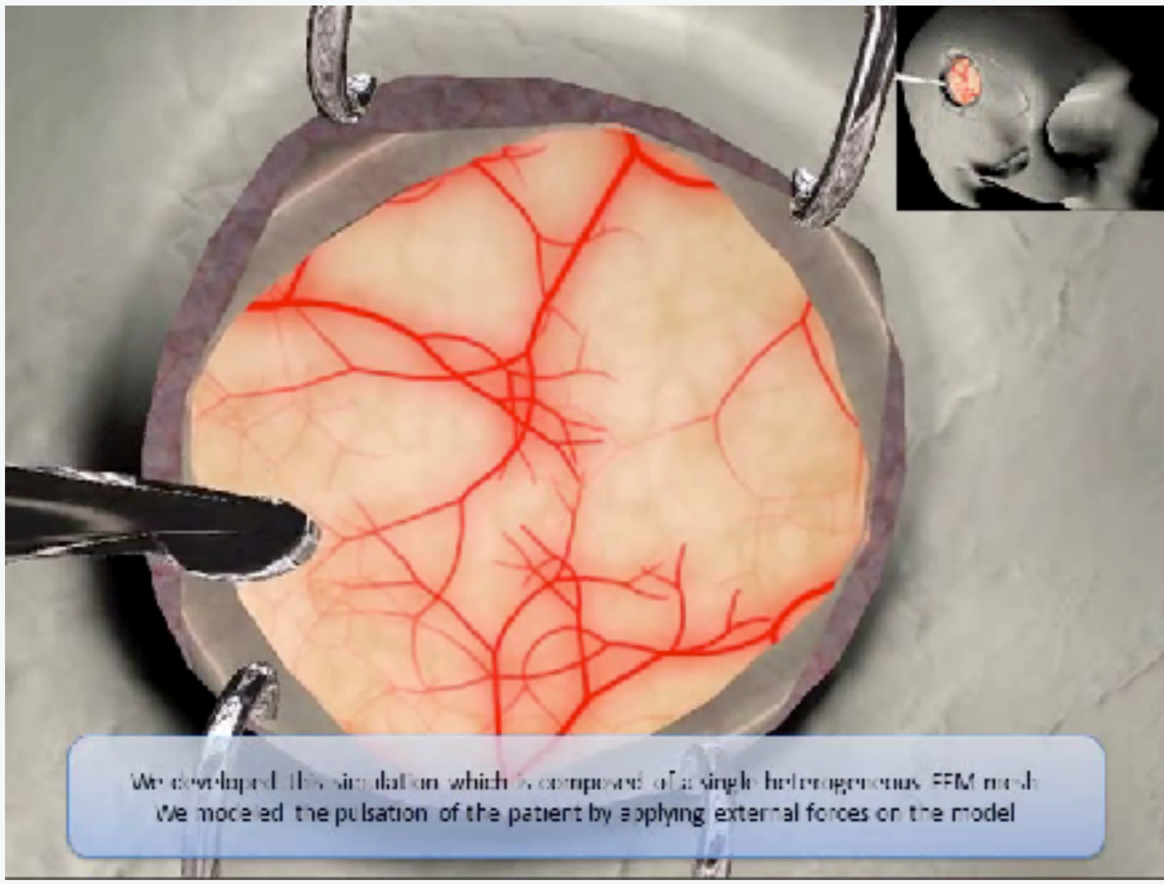


P.H. Bui et al. IEEE T. Biomed Eng. 2017 & Frontiers in Surgery, 2017

http://orbilu.uni.lu/handle/10993/30937 http://orbilu.uni.lu/handle/10993/29846

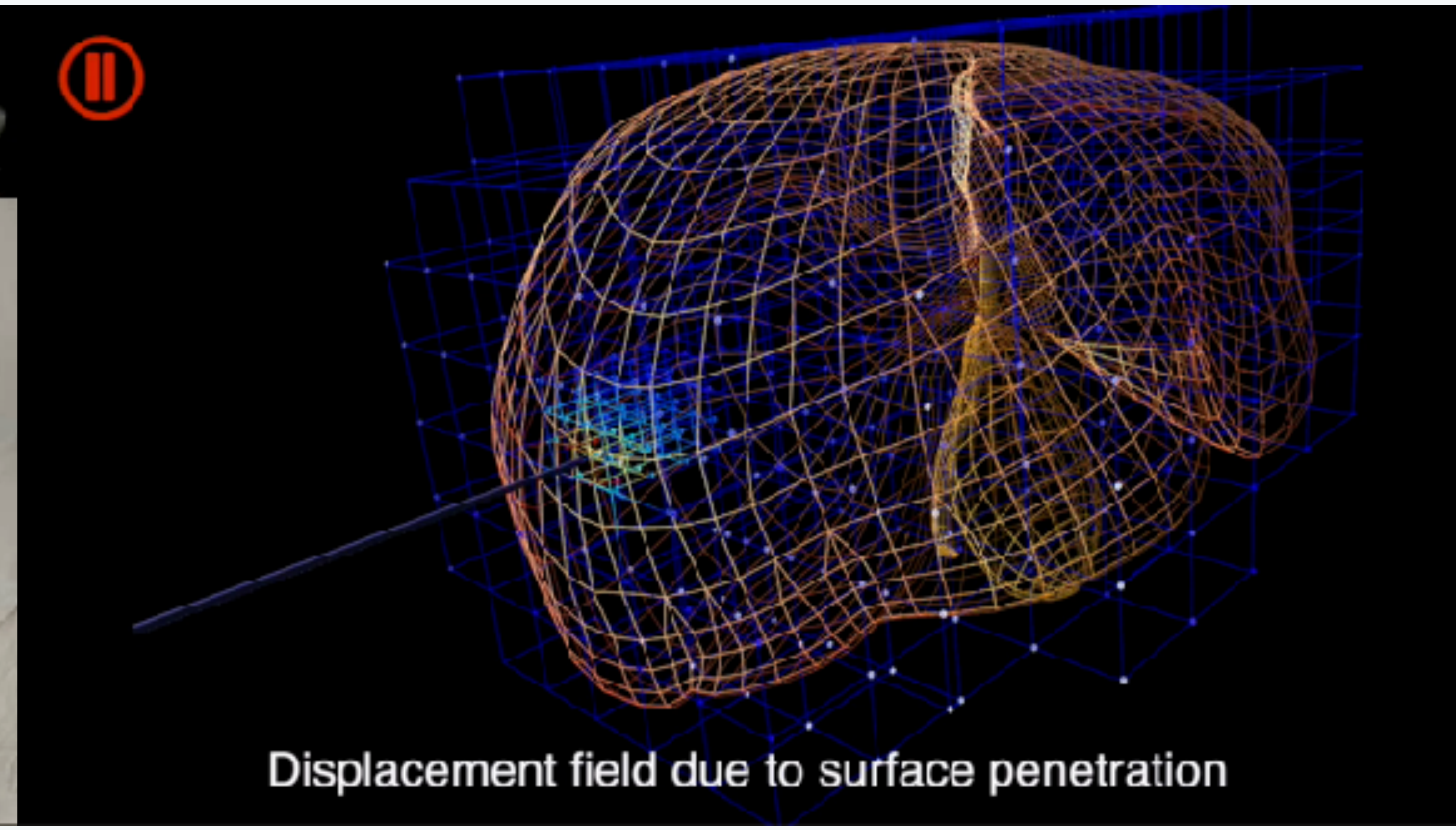
Topological changes in surgical simulation

Cutting and Needle Insertion



H. Courtecuisse et al. Medical Image Analysis, 2014

Question: how can we simulate cutting/fracture in real time using implicit time stepping?



P.H. Bui et al. IEEE T. Biomed Eng. 2017 & Frontiers in Surgery, 2017

Question: how can we adapt the mesh in real time using a posteriori error estimates?

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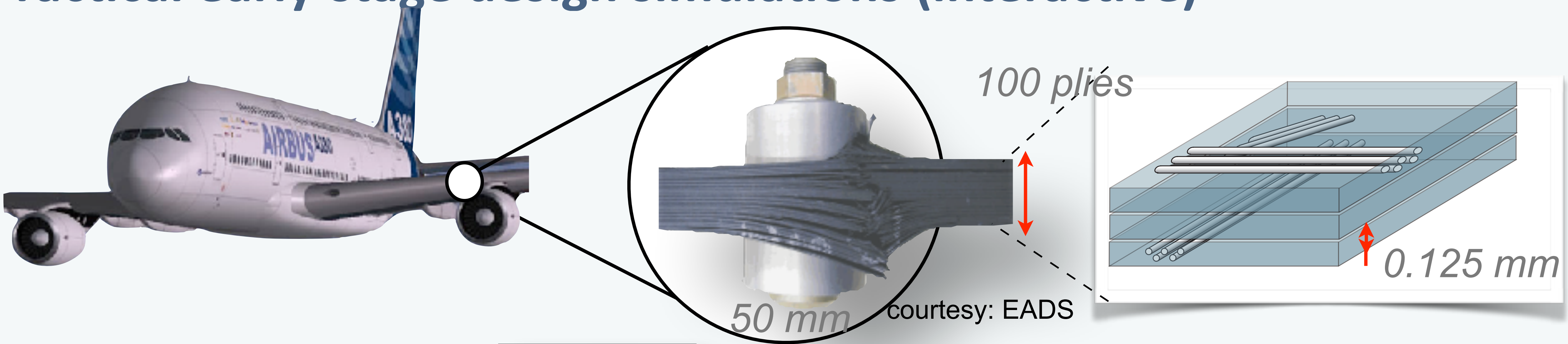
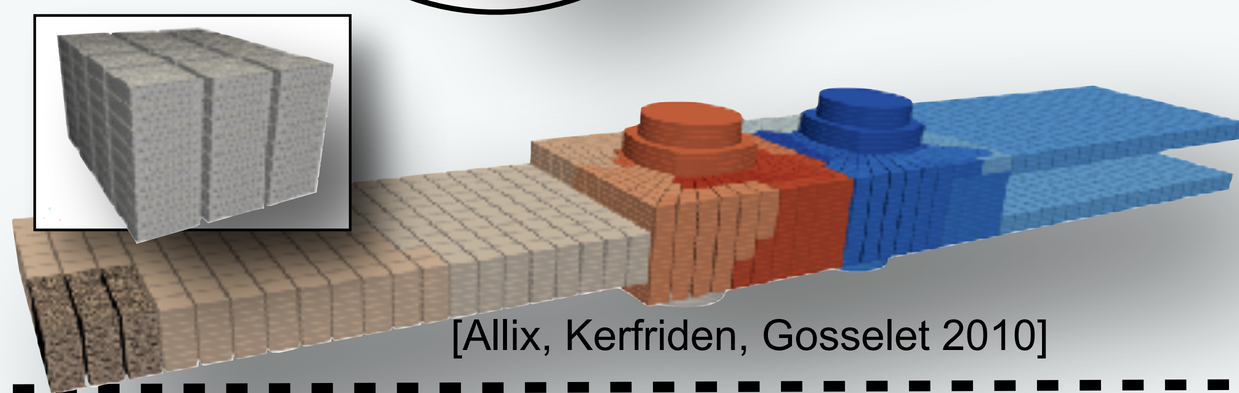
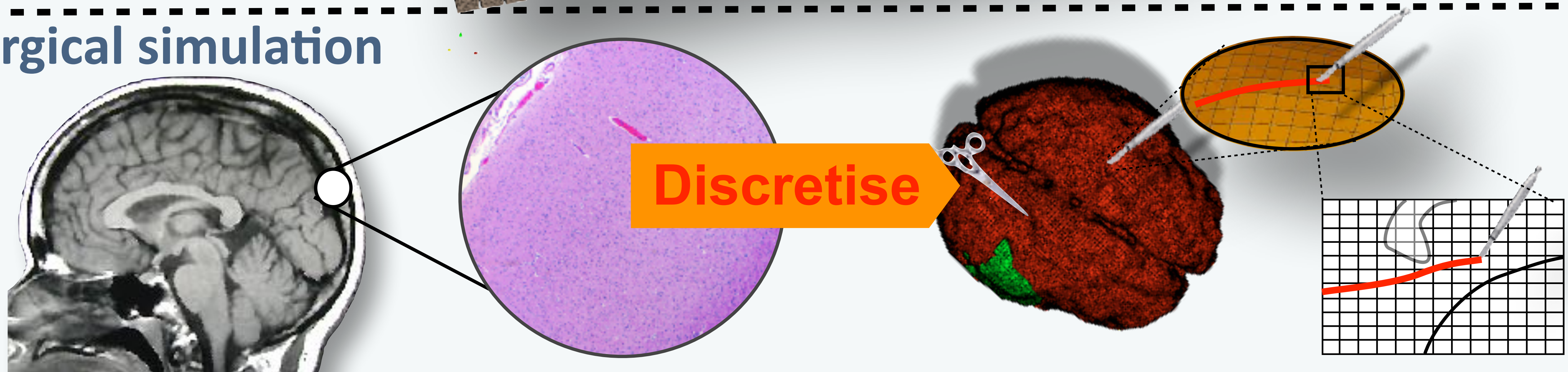
Practical early-stage design simulations (interactive)



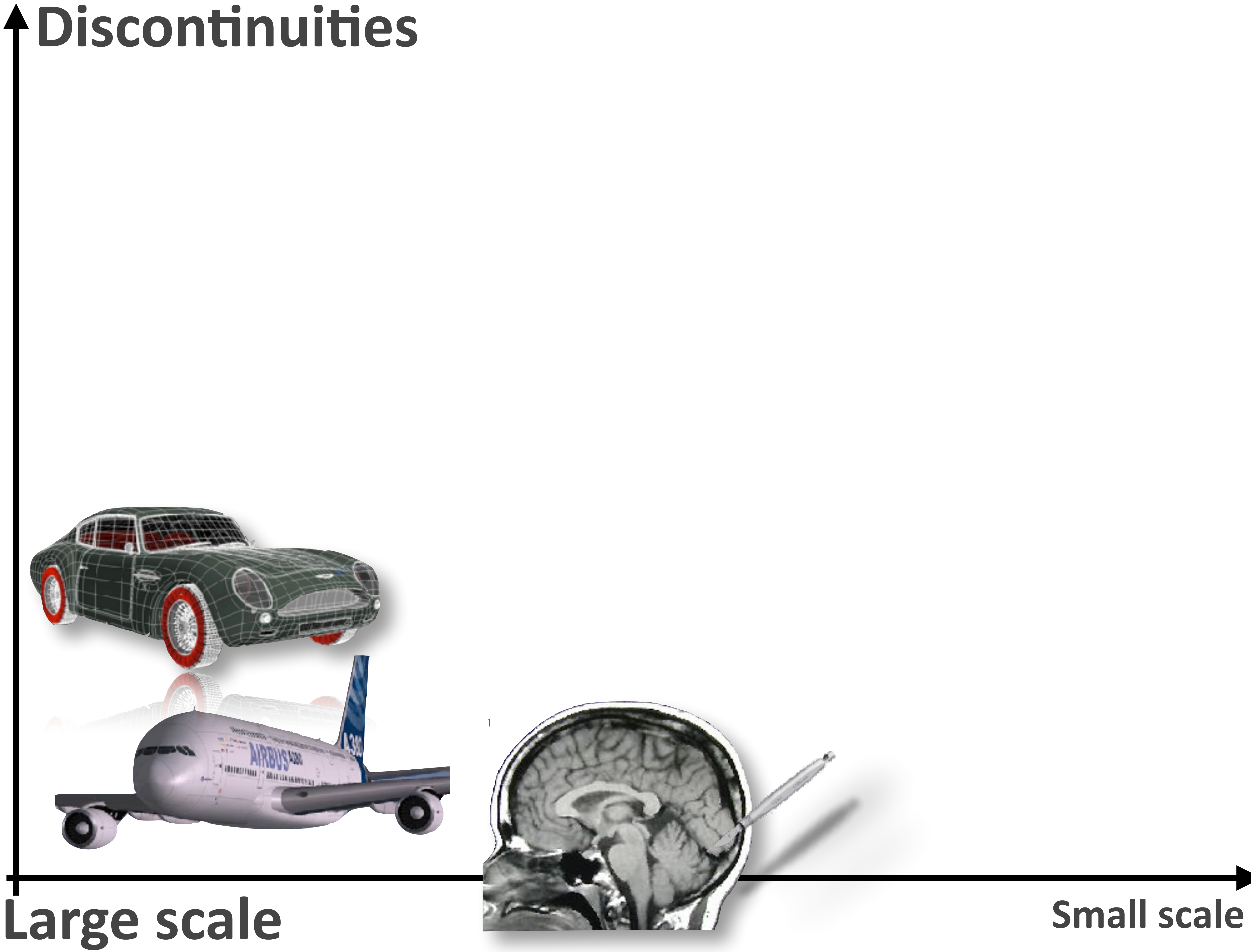
Discretise

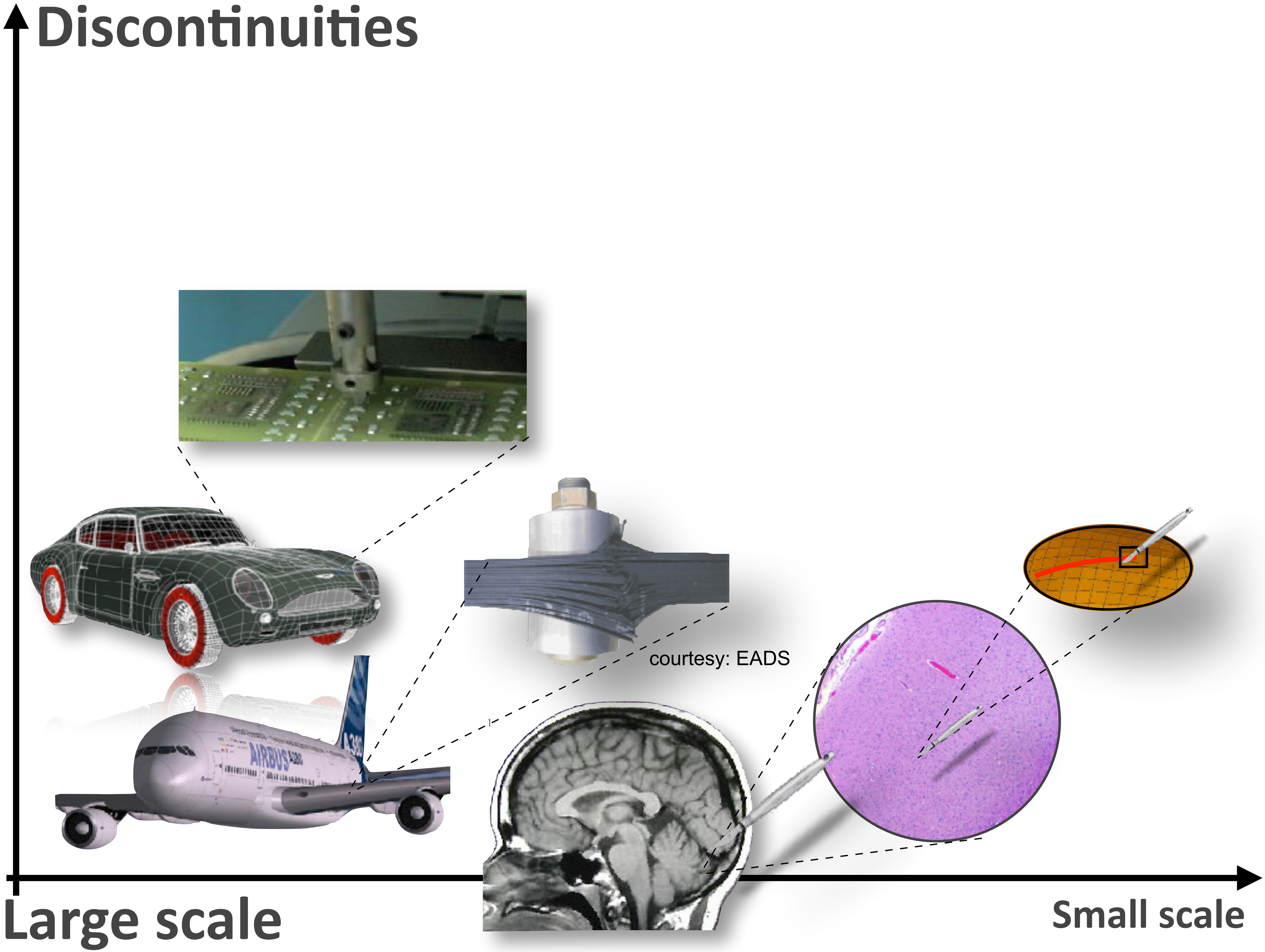


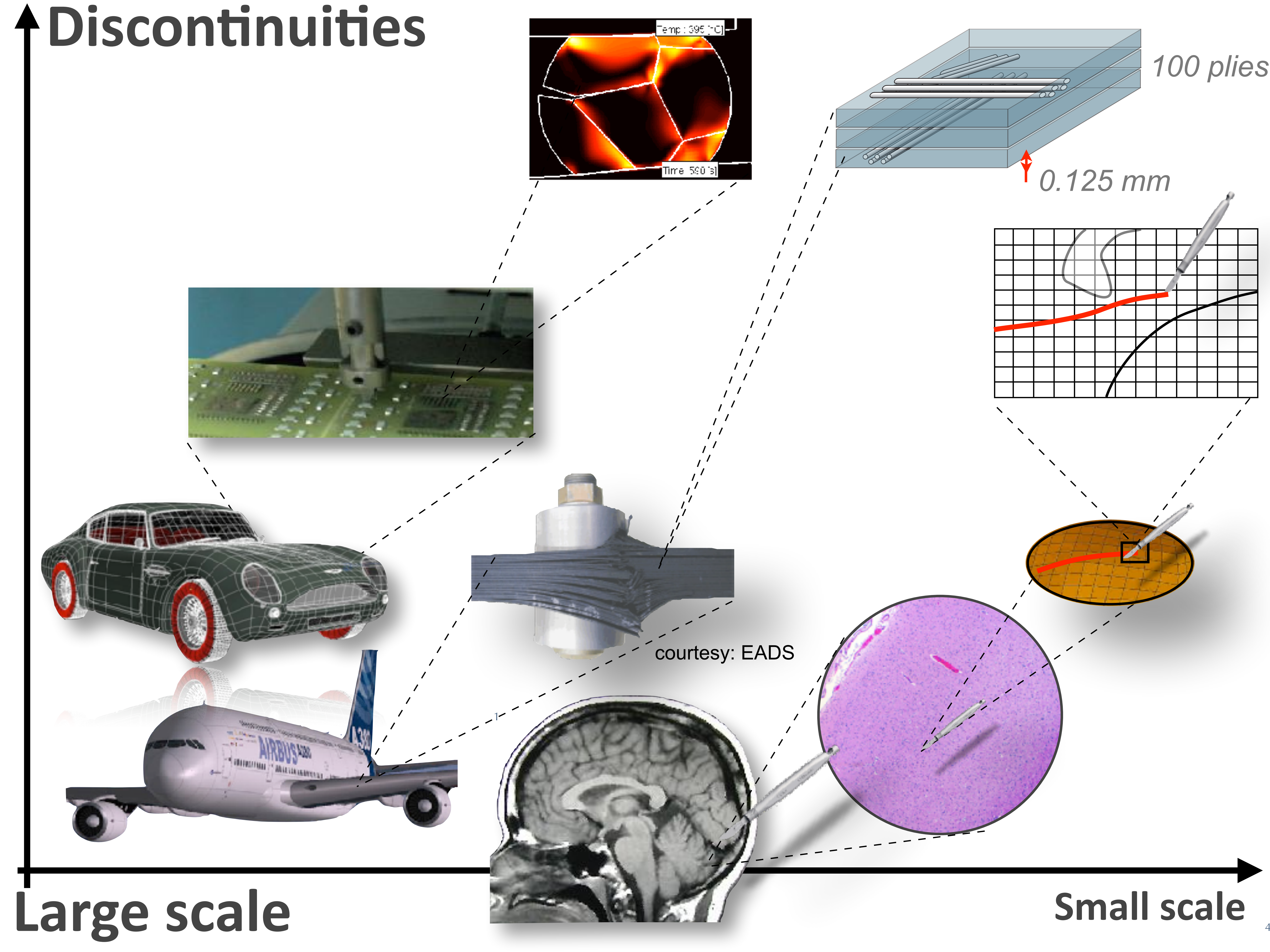
Surgical simulation



- Reduce the problem size while controlling the error (in QoI) when solving very large (multiscale) mechanics problems


Discontinuities
Large scale
Small scale


Discontinuities
courtesy: EADS
Large scale
Small scale


Discontinuities
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courtesy: EADS
Large scale
Small scale

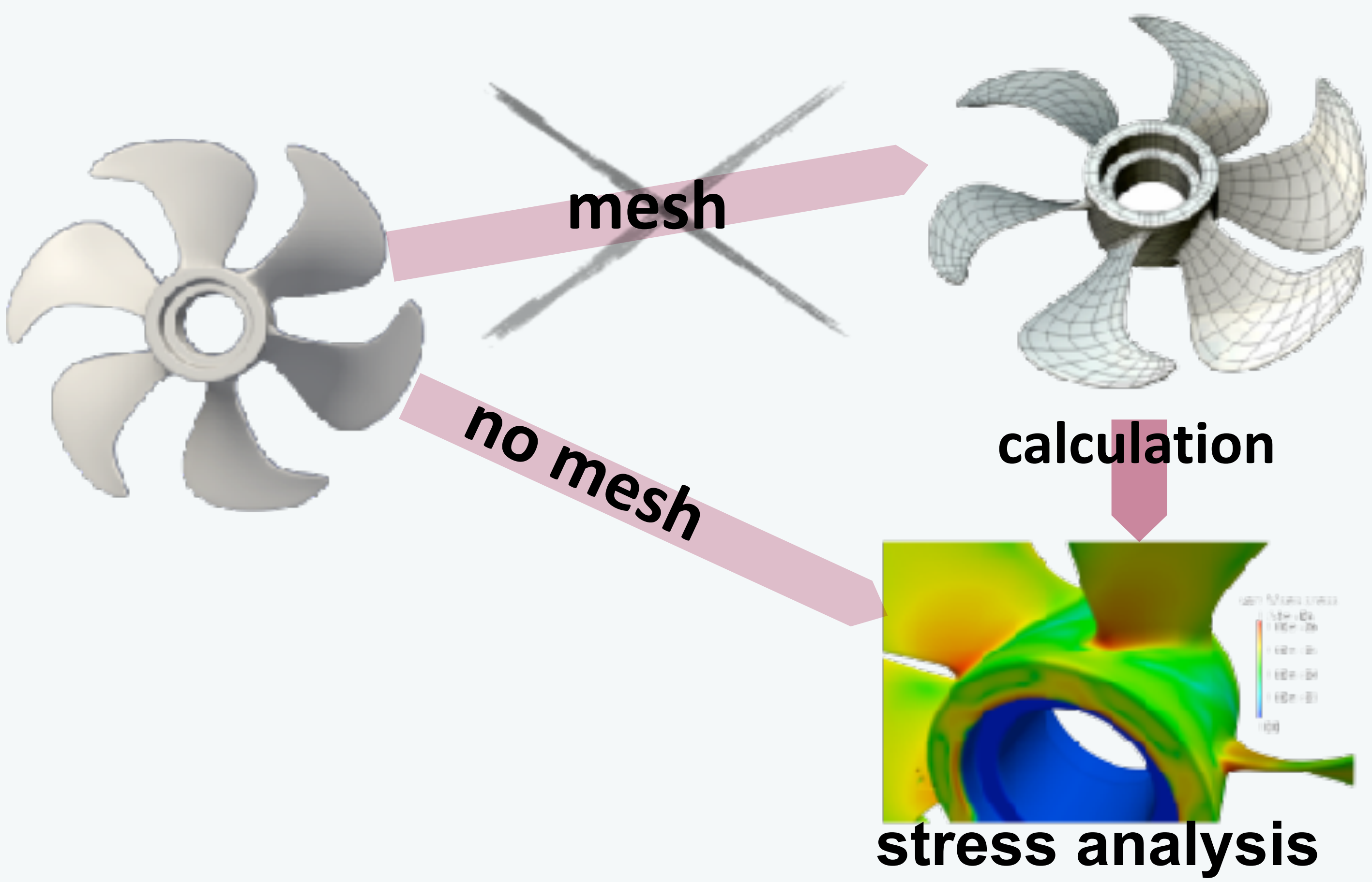
Partial conclusions

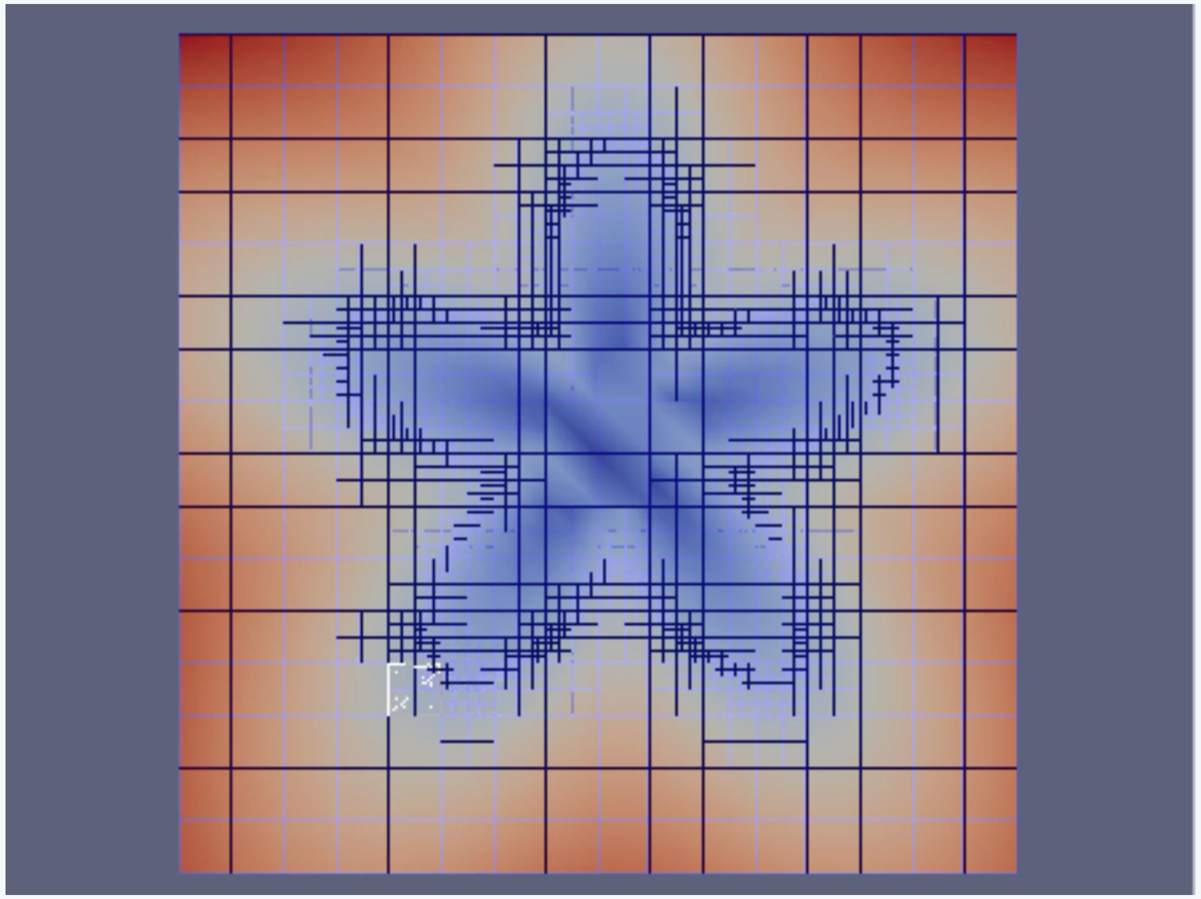
- Zooming into materials/structures reveals discontinuities with complex shapes
- Geometries of domains are complex, even at the continuum level

Next: a few methods to deal with this complexity

Handling (complex) interfaces numerically

Coupling, or decoupling?





Question: When are we better off coupling/decoupling the geometry from the field approximation?

Handling (complex) interfaces numerically

Coupling geo and field: Isogeometric Analysis

Question:
What is the performance of Isogeometric Analysis in Reducing the Mesh Burden?

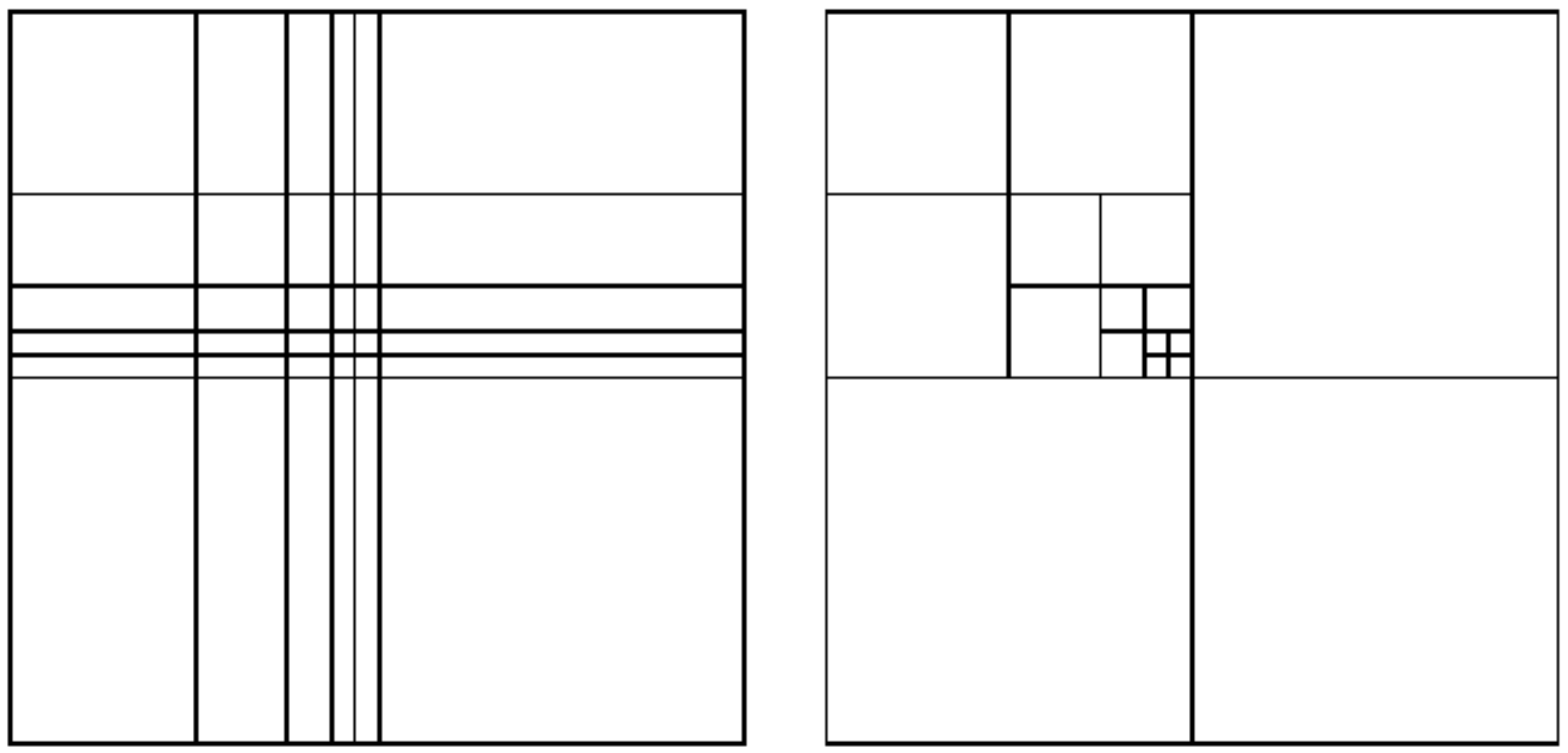
Isogeometric Finite Element Analysis

- [x] For shell-like domains
- [ ] For volumes (needs volume parameterisation)
- [ ] Coupling between multiple patches (Nitsche, Mortar…)

Adaptivity

- [x] Global refinement - cannot refine field without refining geo…
- [ ] Local refinement (not with NURBS)… (PH)T-splines…
- [ ] Geometry independent refinement for the field variables?

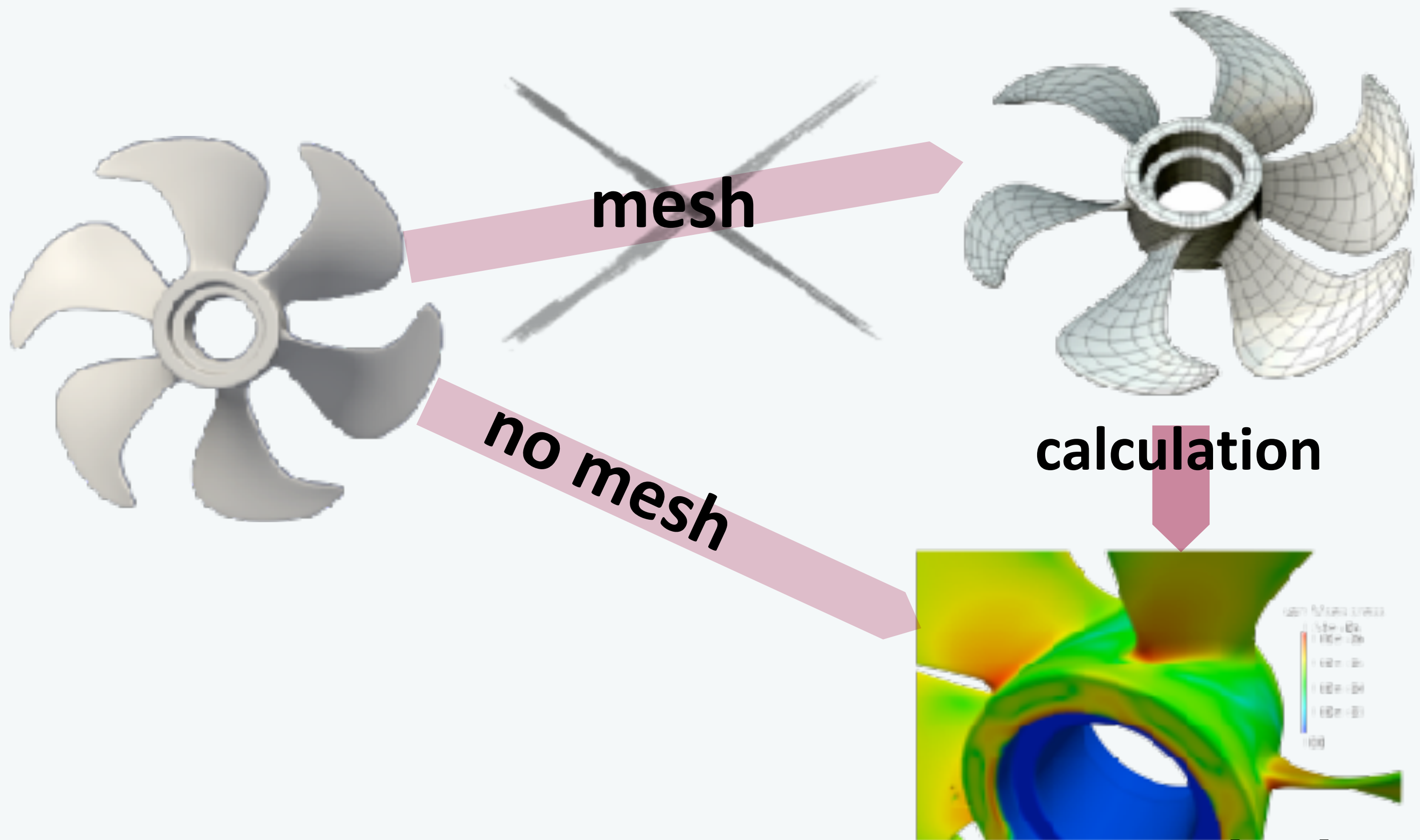
Mesh refinement in IGA



Global refinement (tensor-product mesh) vs local refinement (T-mesh)

Handling (complex) interfaces numerically

Coupling



Question: How can we fully benefit from the "IGA" concept?

☑ Refine the field independently from the geometry

☑ Suppress the mesh generation and regeneration completely

Handling (complex) interfaces numerically

Coupling geometry and field approximation

Question: How can we fully benefit from the "IGA" concept?
☑ Refine the field independently from the geometry

Isogeometric Finite Elements

☑ For shell-like domains
☐ For volumes (needs volume parameterisation)

Geometry Independent Field approximaTion (GIFT)

☑ Super/Sub-geometric

[REF] Weakening the tight coupling between geometry and simulation in isogeometric analysis: from sub- and super- geometric analysis to Geometry Independent Field approximaTion (GIFT), IJNME, 2017, submitted [preprint available on arXiv]

Permalink: http://hdl.handle.net/10993/31469

Geometry Independent Field approximaTion (GIFT)

Conclusions

- ☑ Tight link between CAD and analysis
- ☑ The same basis functions, which are used in CAD to represent the geometry, are used in the IGA as shape functions to approximation the unknown solution
- ☑ Geometry is exact at any stage of the solution refinement process
- ☑ Better accuracy per DOF in comparison with standard FEM but higher computational cost (bandwidth…)

Geometry Independent Field approximaTion (GIFT) *Conclusions*

- ☑ Retain the advantages of IGA but decouple the geometry and the field approximation

- ☑ Standard patch tests may not always pass, yet the convergence rates are optimal as long as the geometry is exactly represented by the geometry basis

- ☑ With geometry exactly represented by NURBS, using same degree B-splines or NURBS for the approximation of the solution field yields almost identical results

- ☑ With geometry exactly represented by NURBS, using PHT splines for the approximation of the solution gives additional advantage of local adaptive refinement

- ☑ Any other approximation field can be used for the field variables

Handling (complex) interfaces numerically

Coupling

Question: How can we fully benefit from the "IGA" concept?

☑ Suppress the mesh generation and regeneration completely

Isogeometric Finite Elements

☑ For shell-like domains
☐ For volumes (needs volume parameterisation)

Stress analysis and shape optimisation directly from CAD

H. Lian et al. (2017). CMAME*:* 317 (2017): 1-41.
H. Lian et al. (2015). IJNME
H. Lian et al. (2013). EACM:166(2):88-99.
M. Scott et al. (2013) CMAME 254: 197-221.
R. N. Simpson et al. (2013) CAS 118: 2-12.
R. N. Simpson et al. (2012) CMAME Feb 1;209:87-100.

Isogeometric Boundary Element Analysis

☑ For shell-like domains
☑ For volumes

Fracture mechanics directly from CAD

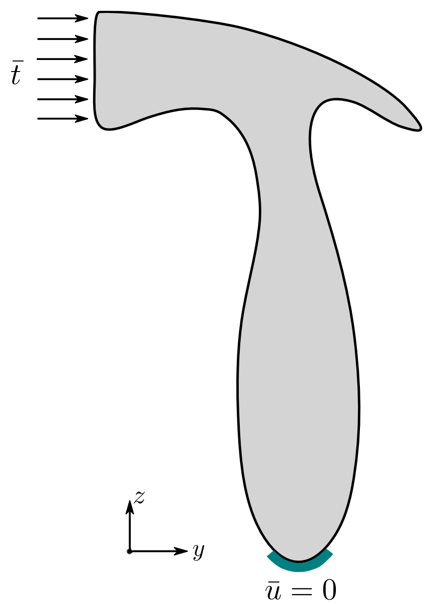
X. Peng, et al. (2017). *IJF*, 204(1), 55–78.
X. Peng, et al. (2017). *CMAME*, 316, 151–185.

Handling (complex) interfaces numerically

Example applications

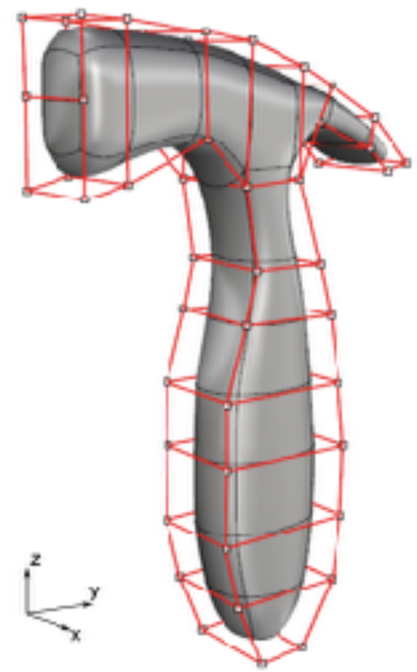
Isogeometric Boundary Element Analysis (IGABEM)

Shape optimisation



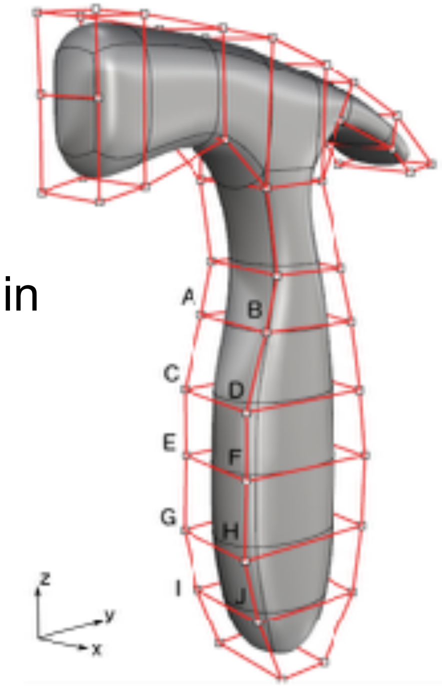
Problem definition

Model construction with CAD



Control points

Design points selection in control points



Design points

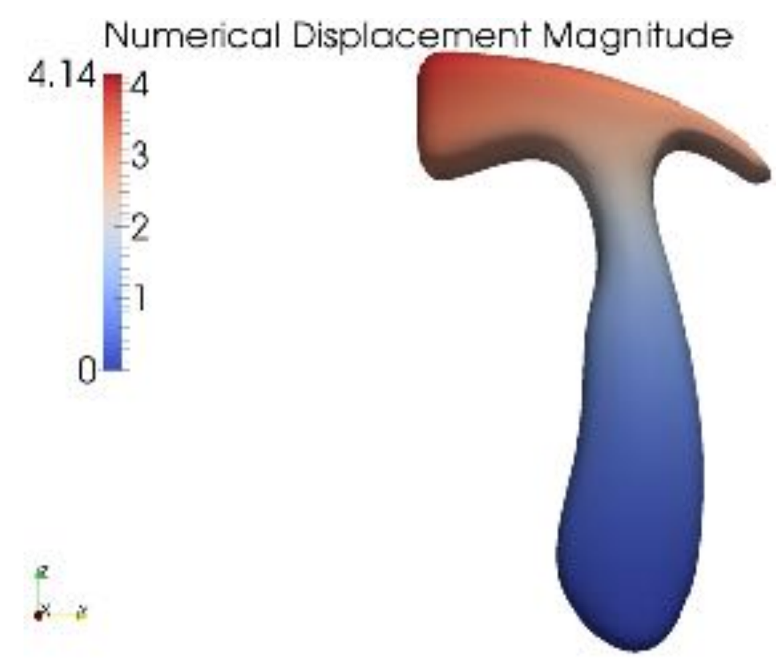
Objective function: $$\int_S t_i u_i \mathrm{d}S$$

Volume constraint: $$V - V_0 \leq 1$$

Side constraints:

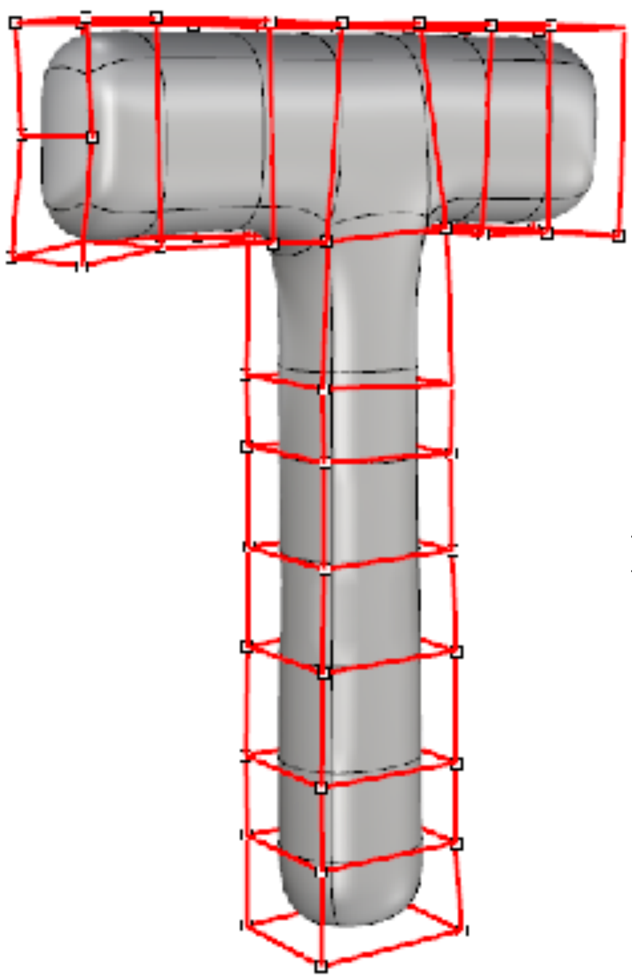
Design variable	Lower bound	Upper bound	Initial value
t_1	0	4	2.45
t_2	0	4	1.25
t_3	0	4	1.33
t_4	0	4	1.28
t_5	0	4	2.30

Structural analysis;
Sensitivity analysis;
gradient-based optimizer

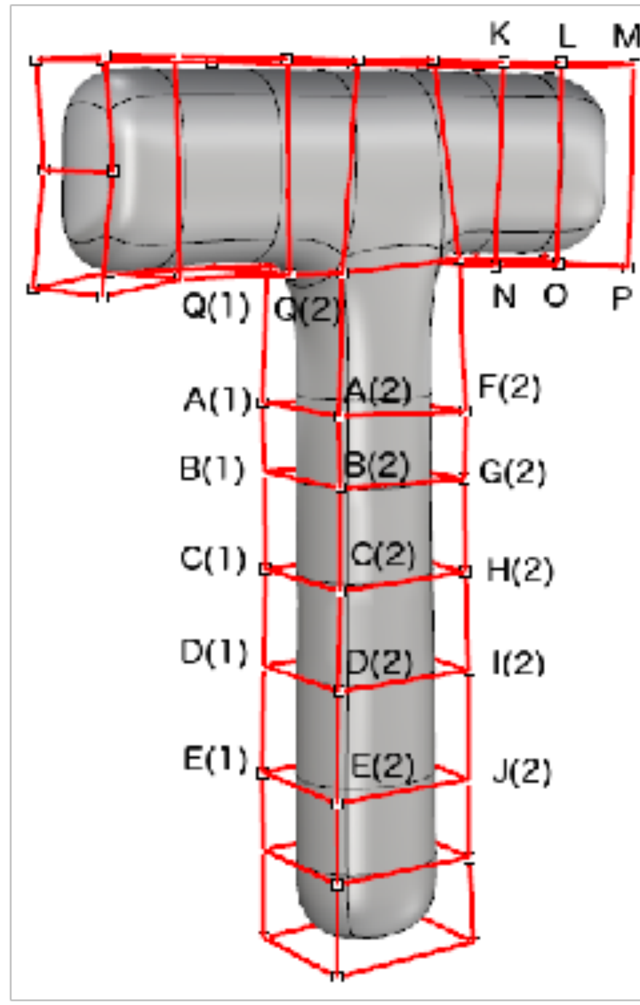


Optimized solution

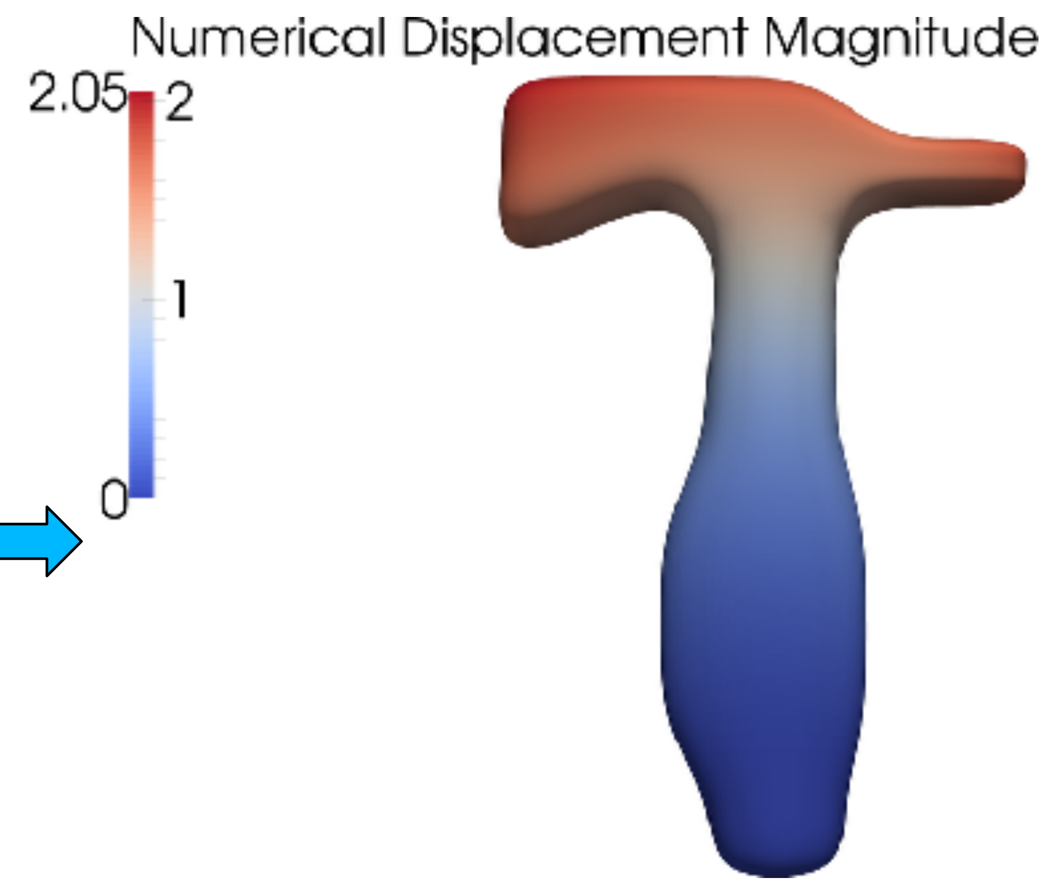
Shape optimisation



Construct the geometric model



Choose design points from the control points



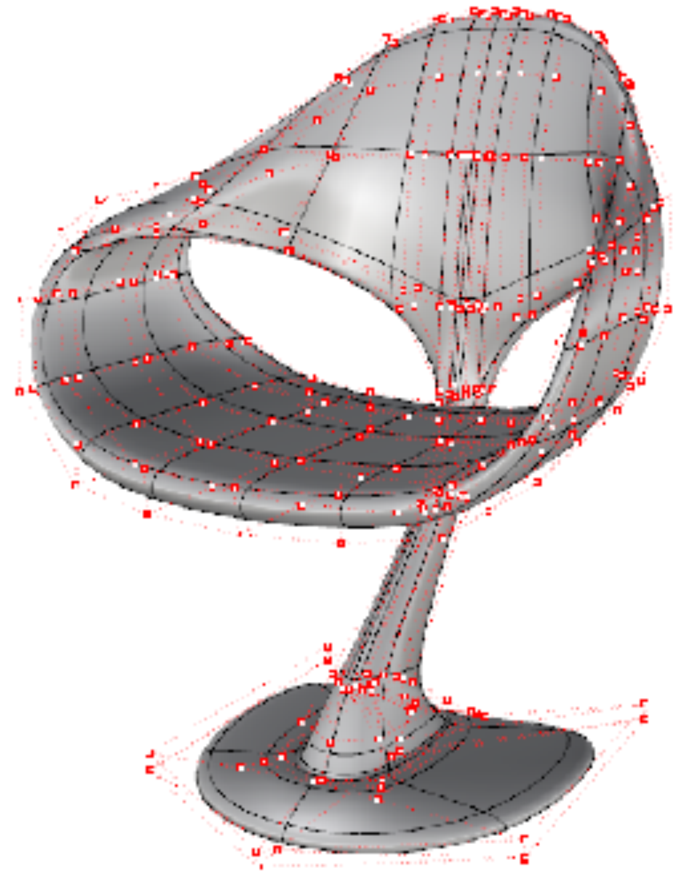
Conduct sensitivity analysis to converge to the optimized solution

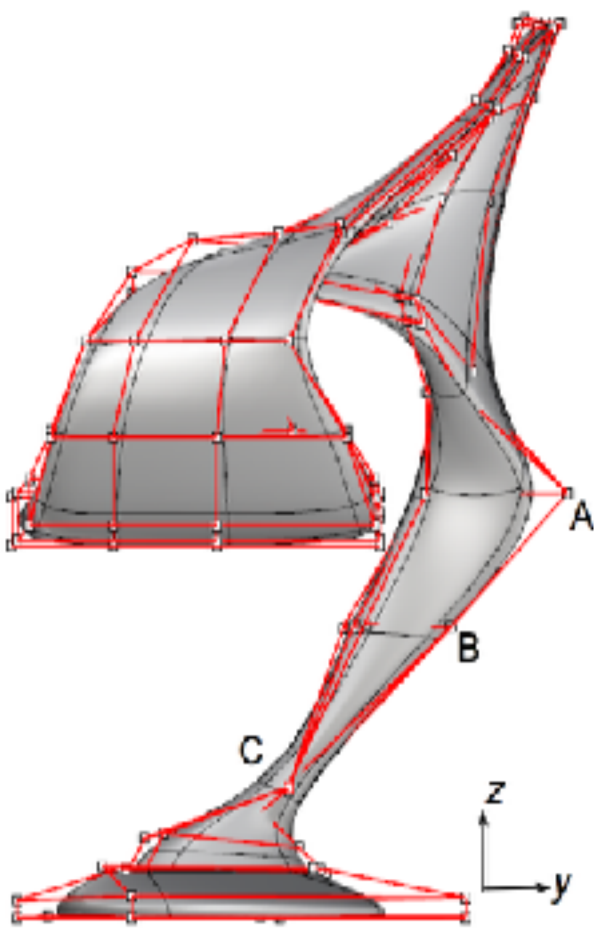
Stress analysis and shape optimisation directly from CAD
H. Lian et al. (2017). CMAME: 317 (2017): 1-41.
H. Lian et al. (2015). IJNME
H. Lian et al. (2013). EACM:166(2):88-99.
M. Scott et al. (2013) CMAME 254: 197-221.
R. N. Simpson et al. (2013) CAS 118: 2-12.
R. N. Simpson et al. (2012) CMAME Feb 1;209:87-100.

Shape optimisation

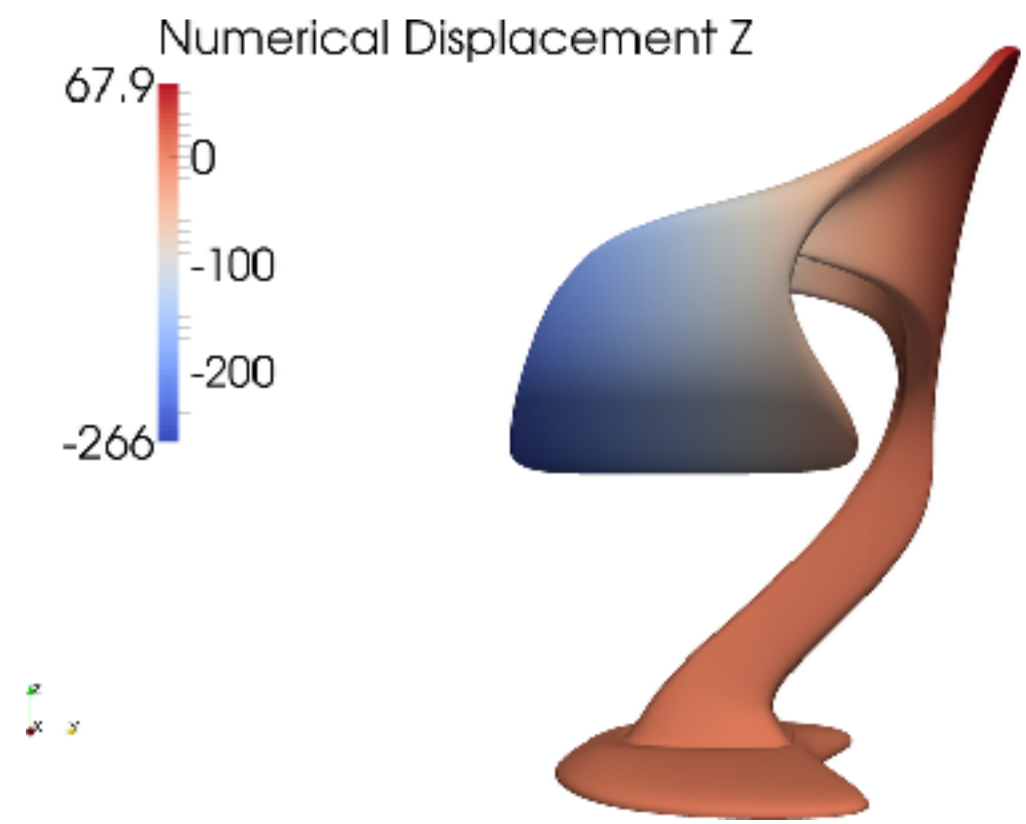
UNIVERSITÉ DU LUXEMBOURG

Construct the geometric model
(imported from Rhino)



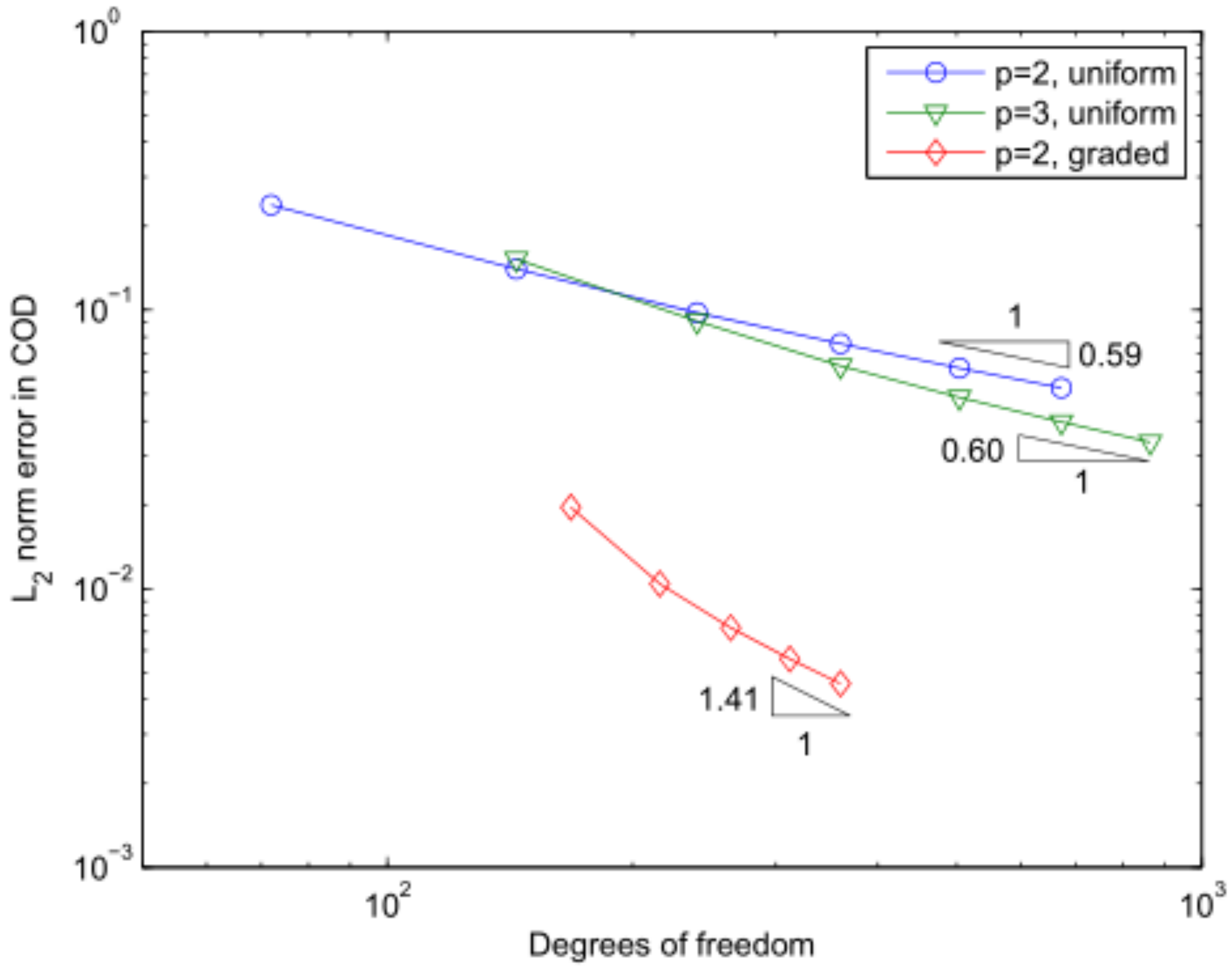


Select design points from control points

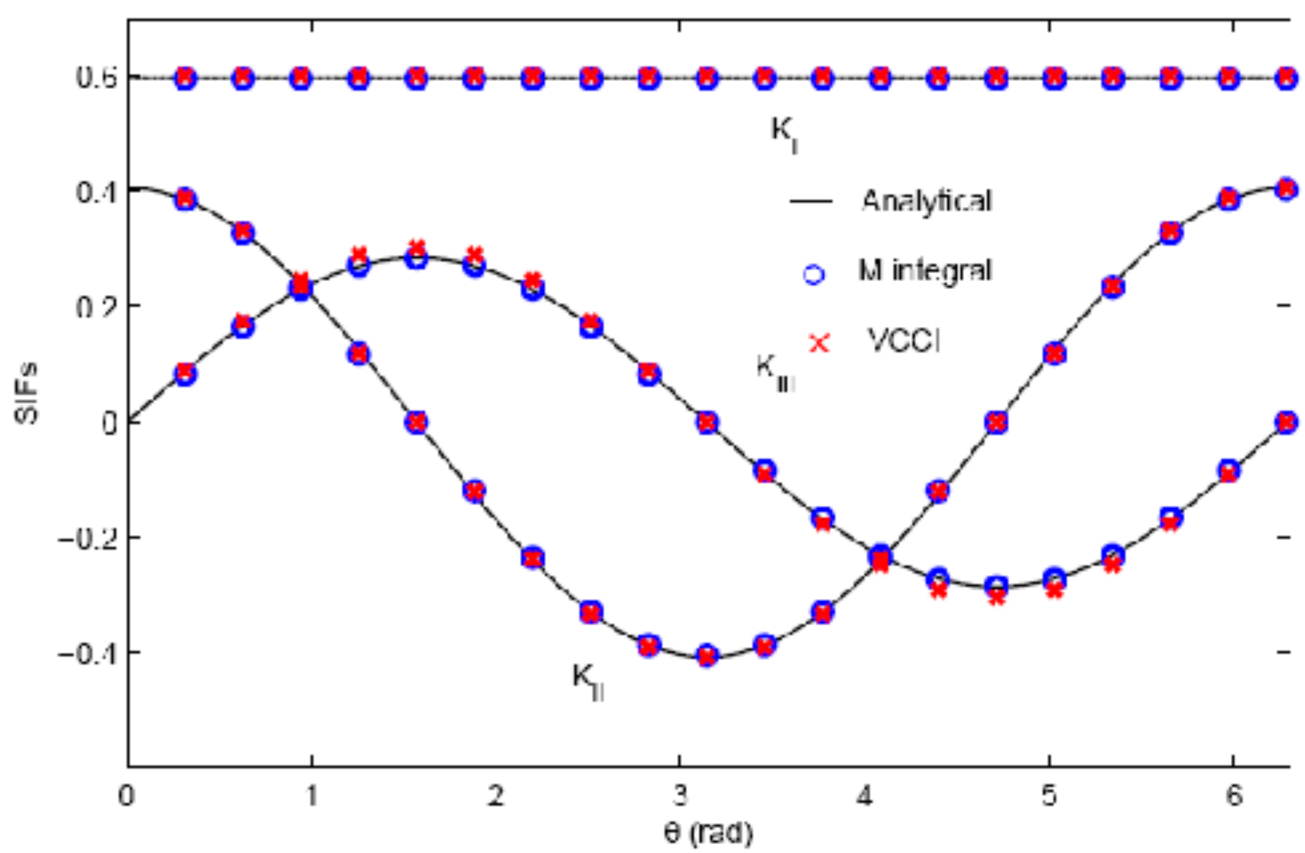


Find optimized solution

Penny-shaped crack under remote tension



L_2 norm error of COD for penny-shaped crack



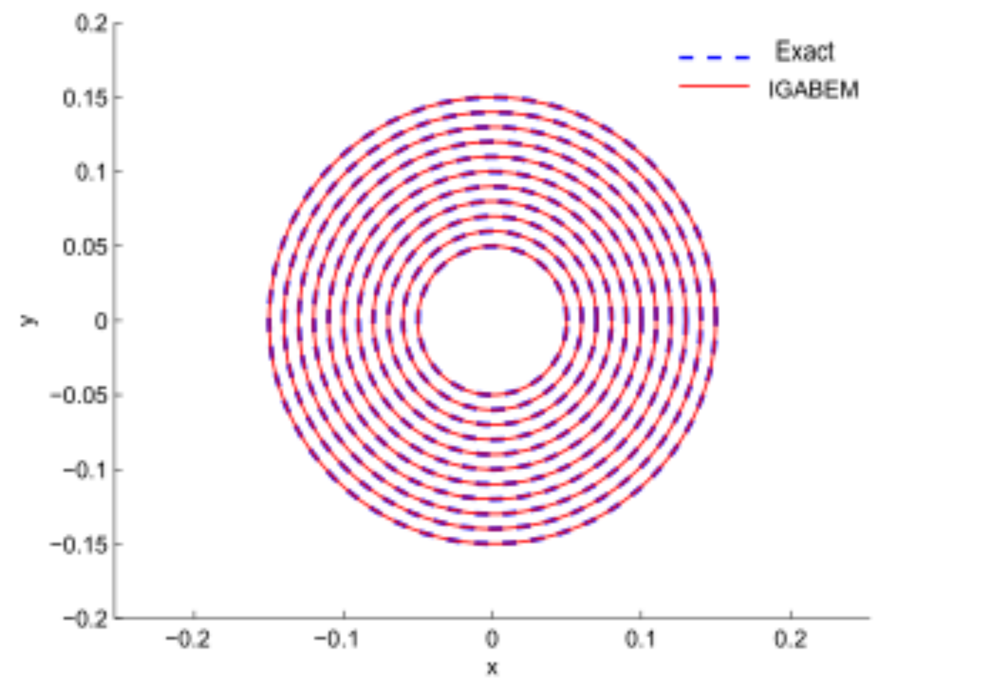
stress intensity factors for penny crack with $\varphi = \pi/6$

Fracture mechanics directly from CAD

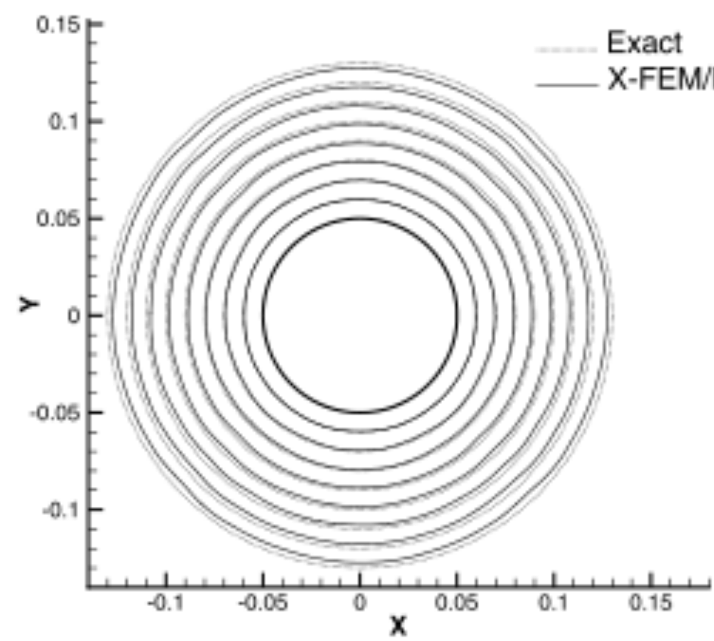
X. Peng, et al. (2017). *IJF*, 204(1), 55–78.

X. Peng, et al. (2017). *CMAME*, 316, 151–185.

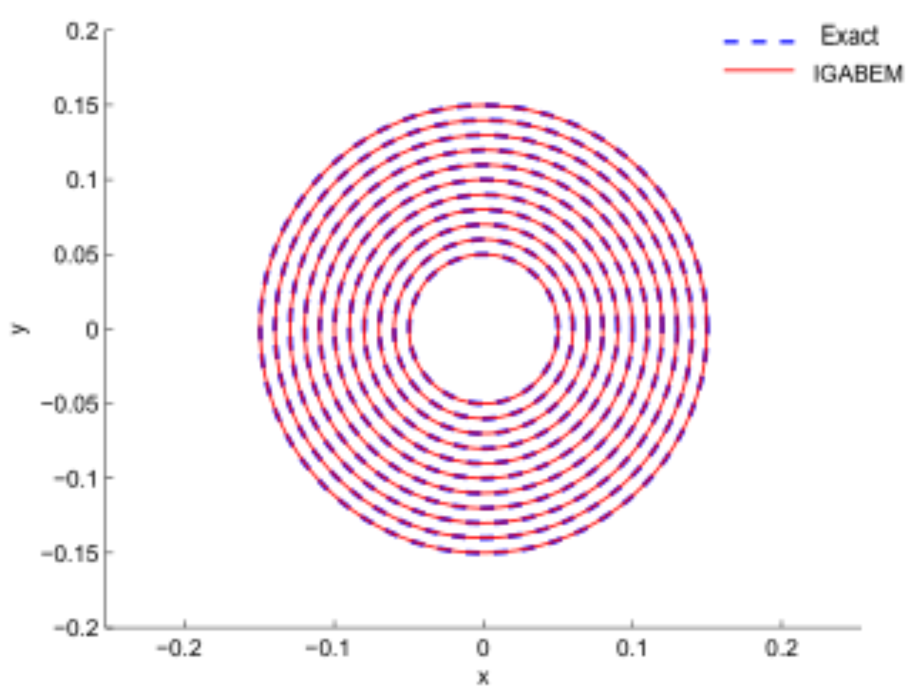
Numerical example of horizontal penny crack growth (first 10 steps)



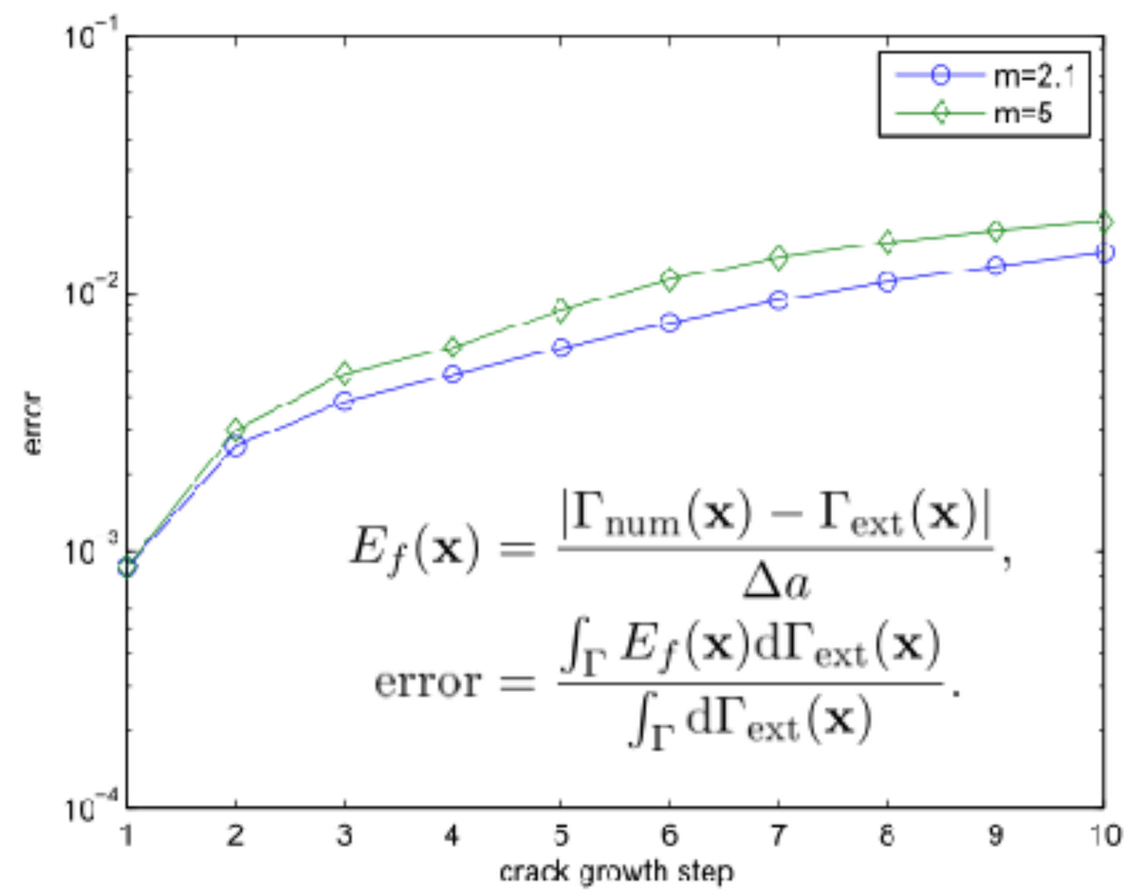
(a) IGABEM, $m = 2.1$



(b) XFEM/FMM, $m = 2.1$, Sukumar *et al* 2003

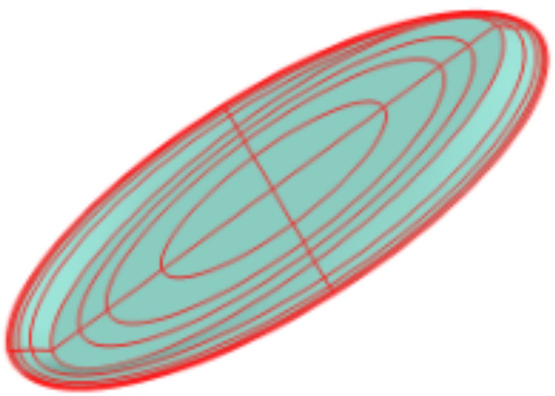


(c) IGABEM, $m = 5$

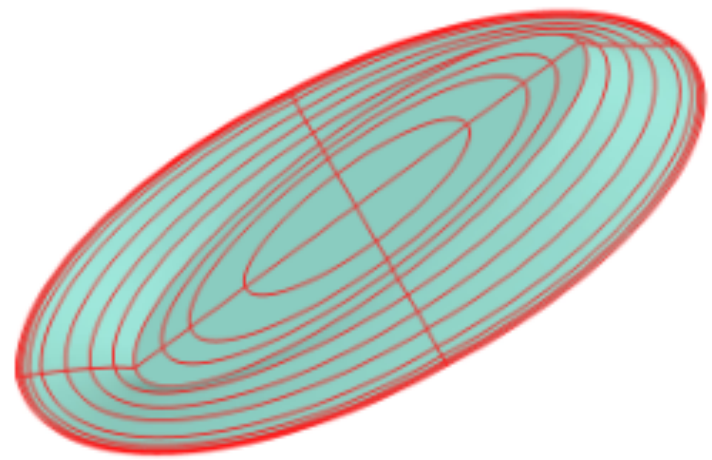


Relative error of the crack front for in each crack growth step by IGABEM

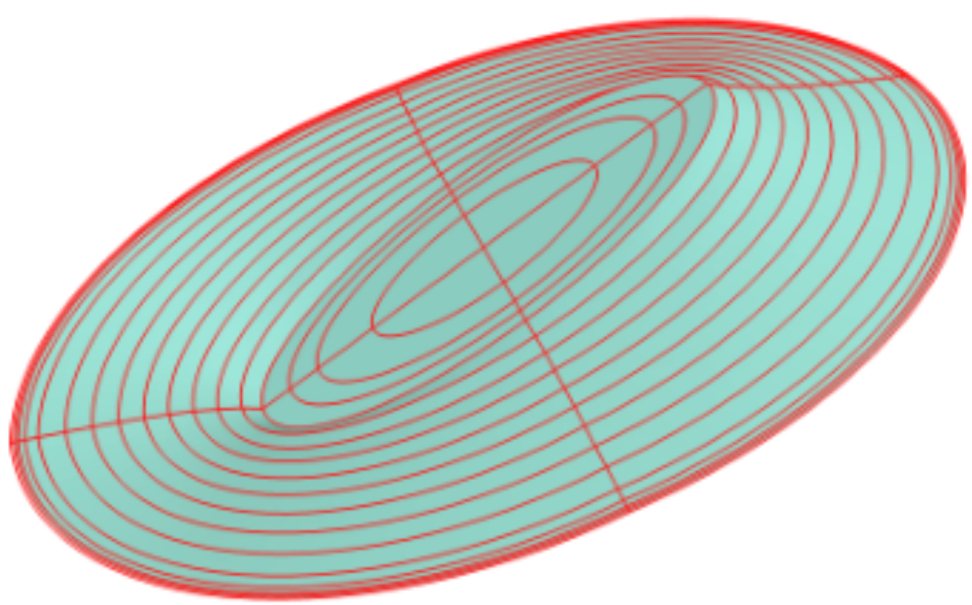
Numerical example of inclined elliptical crack growth (first 10 steps)



(a) Step 2



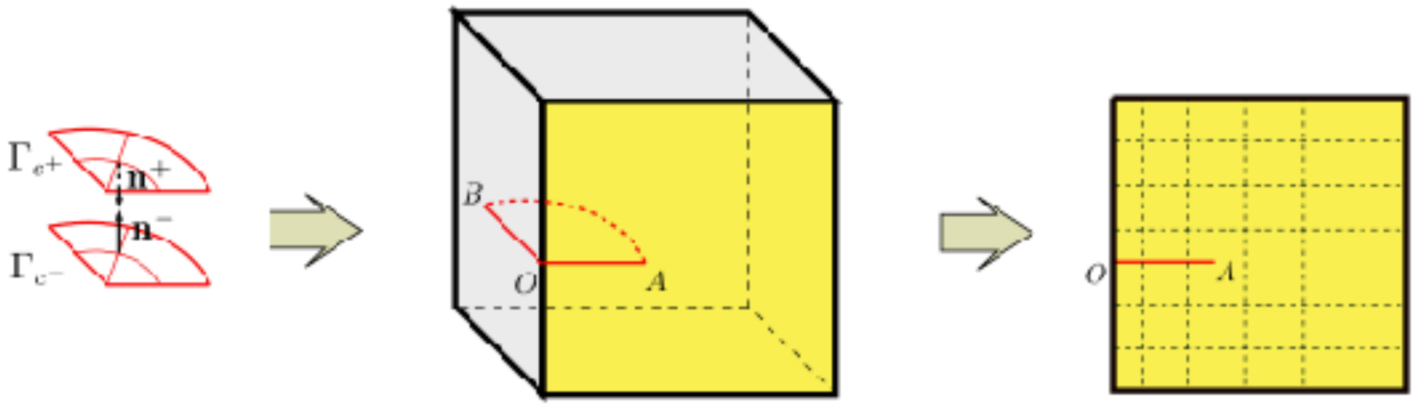
(b) Step 5



(c) Step 10

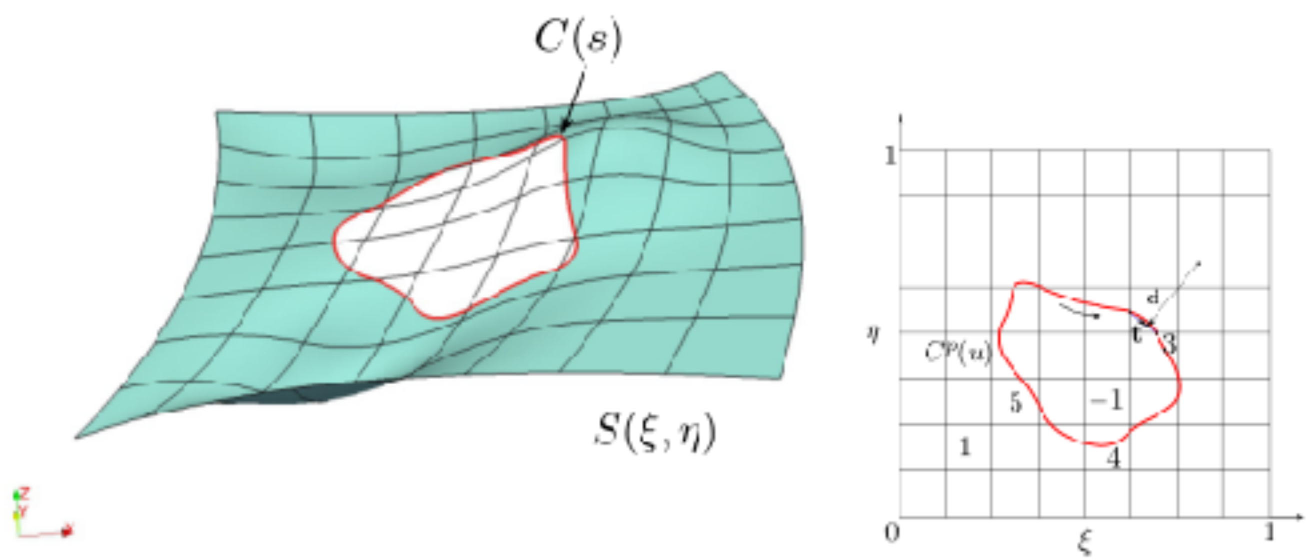
Fracture mechanics directly from CAD
X. Peng, et al. (2017). *IJF*, 204(1), 55–78.
X. Peng, et al. (2017). *CMAME*, 316, 151–185.

Modeling techniques for surface cracks? Trimmed curves…



(a) (b) (c)

Surface discontinuity is introduced



(a) (b)

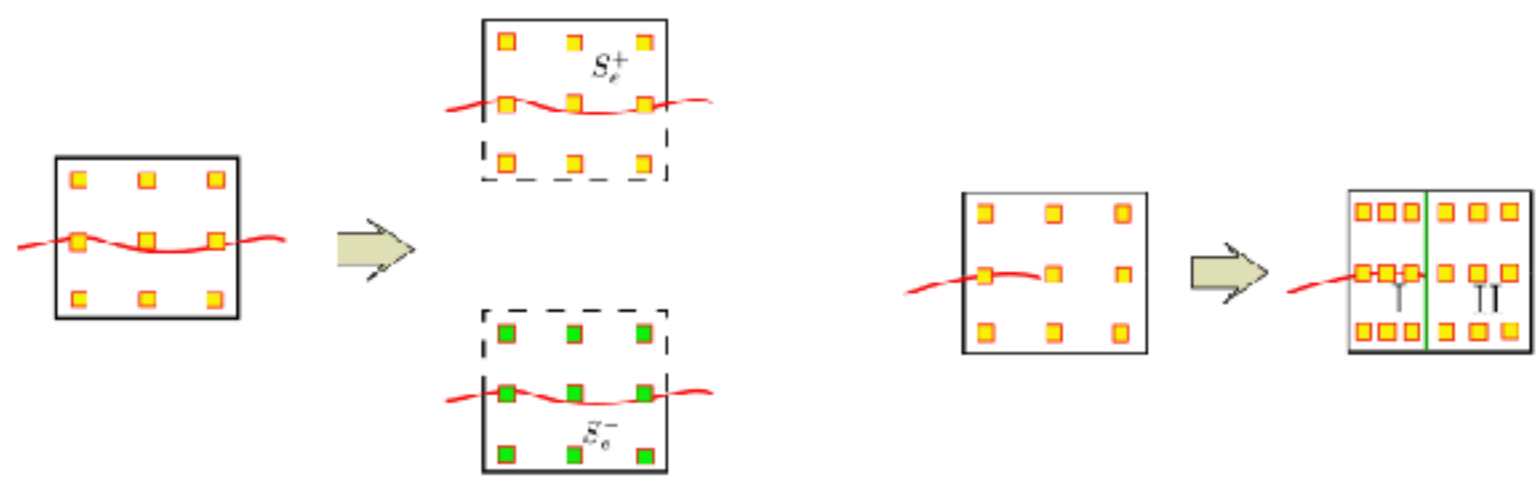
Trimmed NURBS technique

Crack = trimming curve

Phantom node method

$$\mathbf{u}^+(\mathbf{x}) = \sum_{j}^{N^e} \mathbf{R}_j(\mathbf{x})\mathbf{d}_j, \quad \mathbf{x} \in S_e^+,$$

$$\mathbf{u}^-(\mathbf{x}) = \sum_{k}^{N^e} \mathbf{R}_k(\mathbf{x})\mathbf{d}_k, \quad \mathbf{x} \in S_e^-$$



(a) (b)

References

Peng, X., Atroshchenko, E., Kerfriden, P., & Bordas, S. P. A. (2017). Linear elastic fracture simulation directly from CAD: 2D NURBS-based implementation and role of tip enrichment. *International Journal of Fracture*, 204(1), 55–78.

Peng, X., Atroshchenko, E., Kerfriden, P., & Bordas, S. P. A. (2017). Isogeometric boundary element methods for three dimensional static fracture and fatigue crack growth. *Computer Methods in Applied Mechanics and Engineering*, 316, 151–185.

Simpson, R. N., Bordas, S. P. A., Trevelyan, J., & Rabczuk, T. (2012). A two-dimensional Isogeometric Boundary Element Method for elastostatic analysis. *Computer Methods in Applied Mechanics and Engineering*, *209–212*(0), 87–100.

Guiggiani, M., Krishnasamy, G., Rudolphi, T. J., & Rizzo, F. J. (1992). A General Algorithm for the Numerical Solution of Hypersingular Boundary Integral Equations. *Journal of Applied Mechanics*, *59*(3), 604–614.

Rong, J., Wen, L., & Xiao, J. (2014). Efficiency improvement of the polar coordinate transformation for evaluating BEM singular integrals on curved elements. *Engineering Analysis With Boundary Elements*, *38*, 83–93.

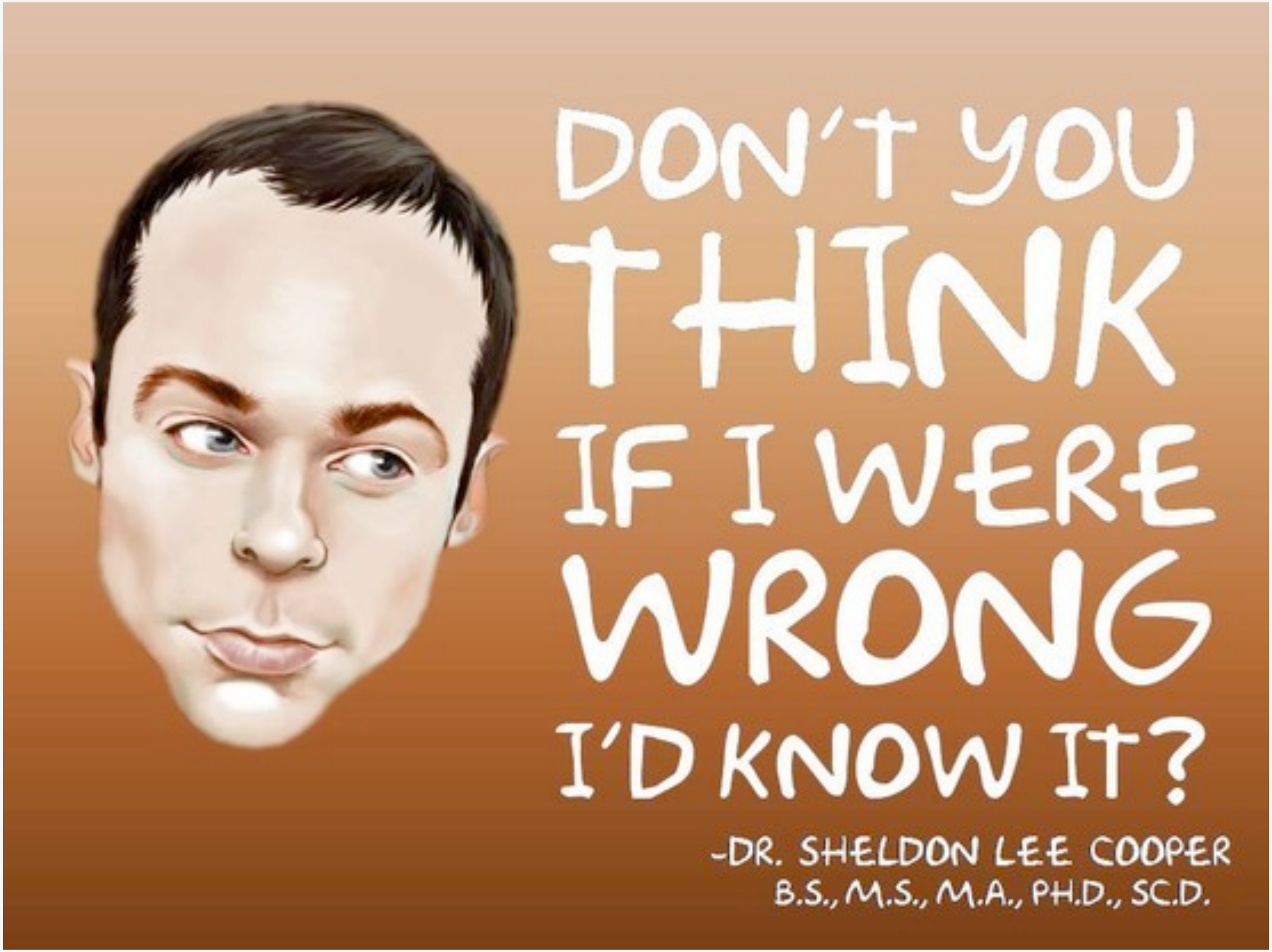
Mi, Y., & Aliabadi, M. H. (1992). Dual boundary element method for three-dimensional fracture mechanics analysis. *Engineering Analysis with Boundary Elements*, *10*(2), 161–171.

Becker, A. (1992). The Boundary Element Methods in Engineering. *McGraw-Hill Book Company*.

Partial conclusions on methods coupling geometry and field approximations

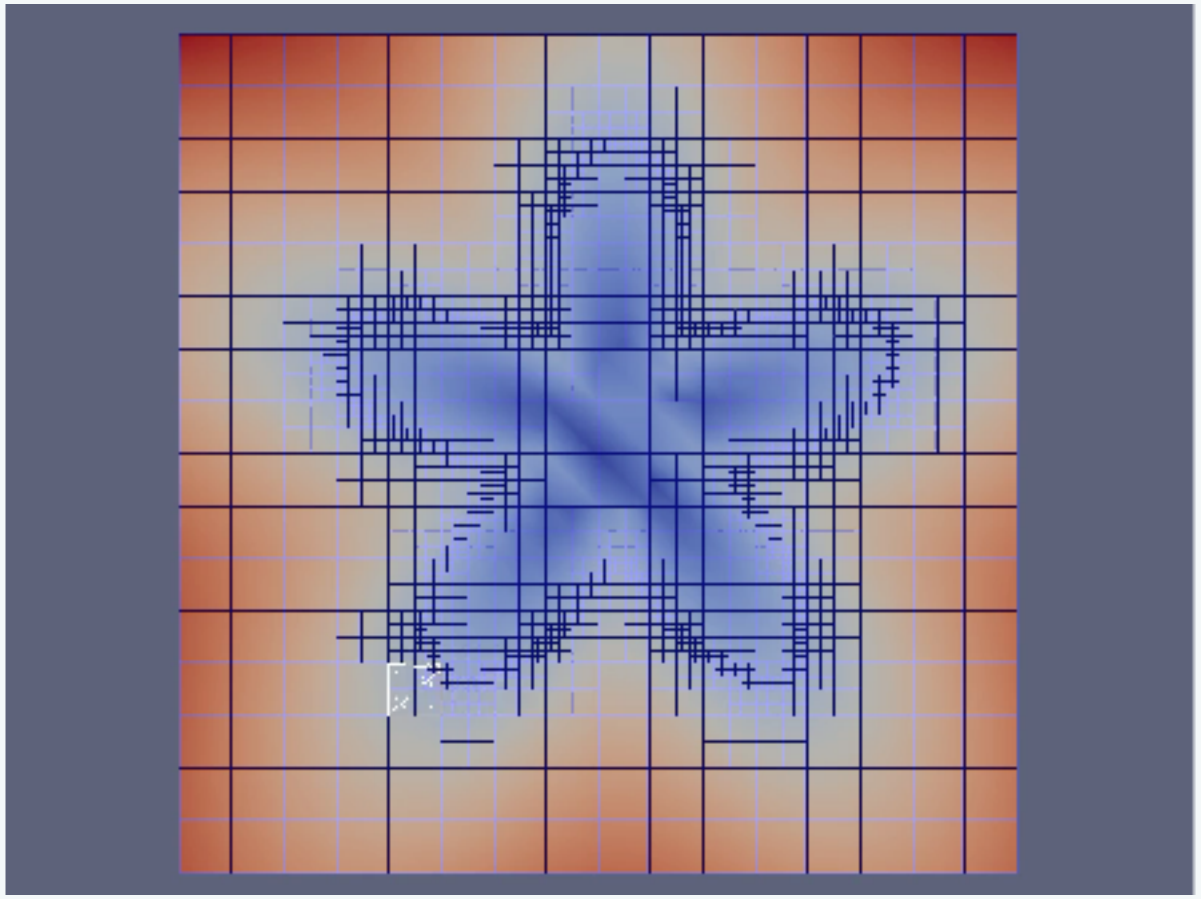
- There are numerous alternatives (subdivision surfaces, IGA, NEFEM, NIGFEM)
- IGA can offer simulations directly from CAD when used with boundary elements
- GIFT generalizes this approach by decoupling geometry and field approximations

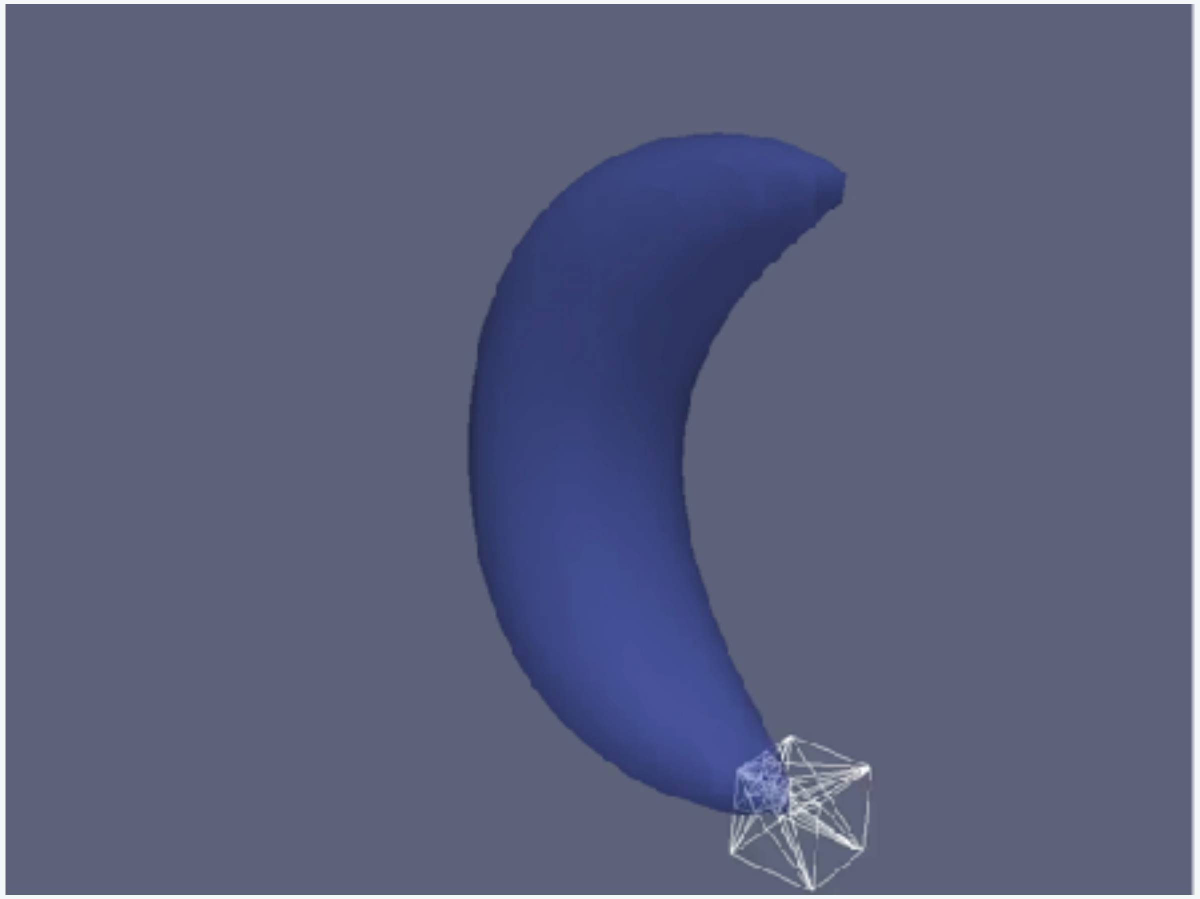
Next: methods which decouple geometry and field approximation


DON'T YOU THINK IF I WERE WRONG I'D KNOW IT?
-DR. SHELDON LEE COOPER
B.S., M.S., M.A., PH.D., SC.D.

Handling (complex) interfaces numerically

Decoupling - Unfitted FEM?





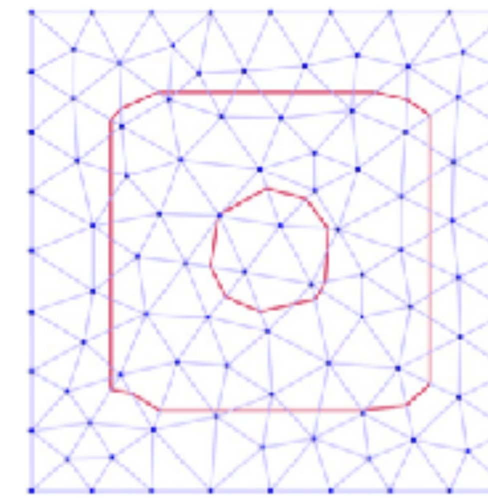
Question: for which problems are we better off coupling/decoupling the geometry from the field approximation?

Implicit surfaces

T. Rüberg (2016) Advanced Modeling and Simulation in Engineering Sciences 3 (1), 22
M. Moumnassi (2011) CMAME *200*(5): 774-796. (CSG and multiple level sets)
N. Moës (2003) CMAME192.28 (2003): 3163-3177. (Single level set)
T. Belytschko IJNME 56.4 (2003): 609-635. (Structured XFEM)
…

Separate field and boundary discretisation

- Immersed boundary method (Mittal, *et al.* 2005)
- Fictitious domain (Glowinski, *et al.* 1994)
- Embedded boundary method (Johansen, *et al.* 1998)
- Virtual boundary method (Saiki, *et al.* 1996)
- Cartesian grid method (Ye, *et al.* 1999, Nadal, 2013)

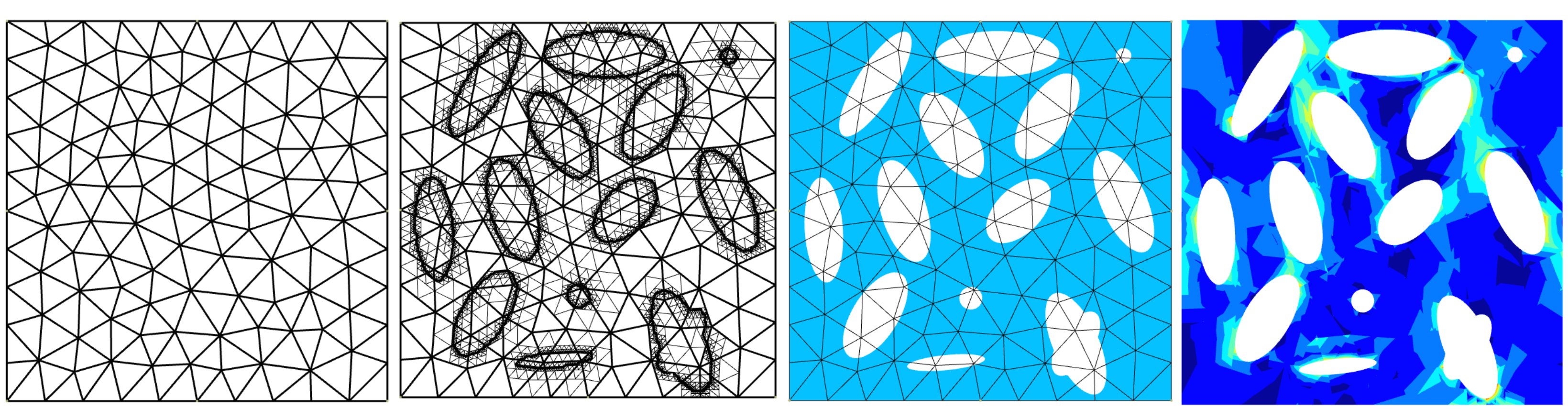


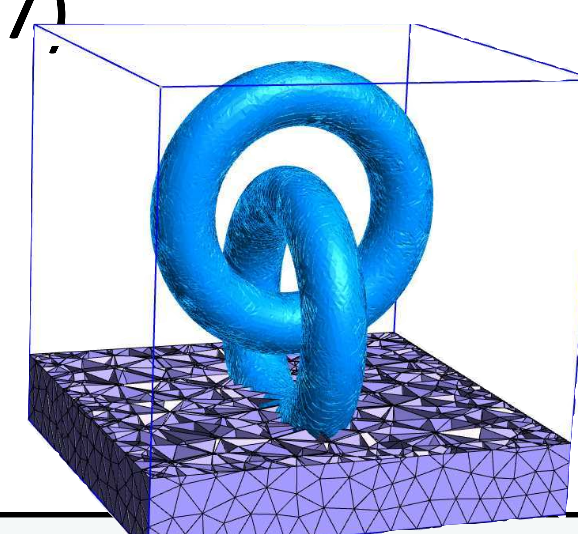
✓ Easy adaptive refinement + error estimation (Nadal, 2013)

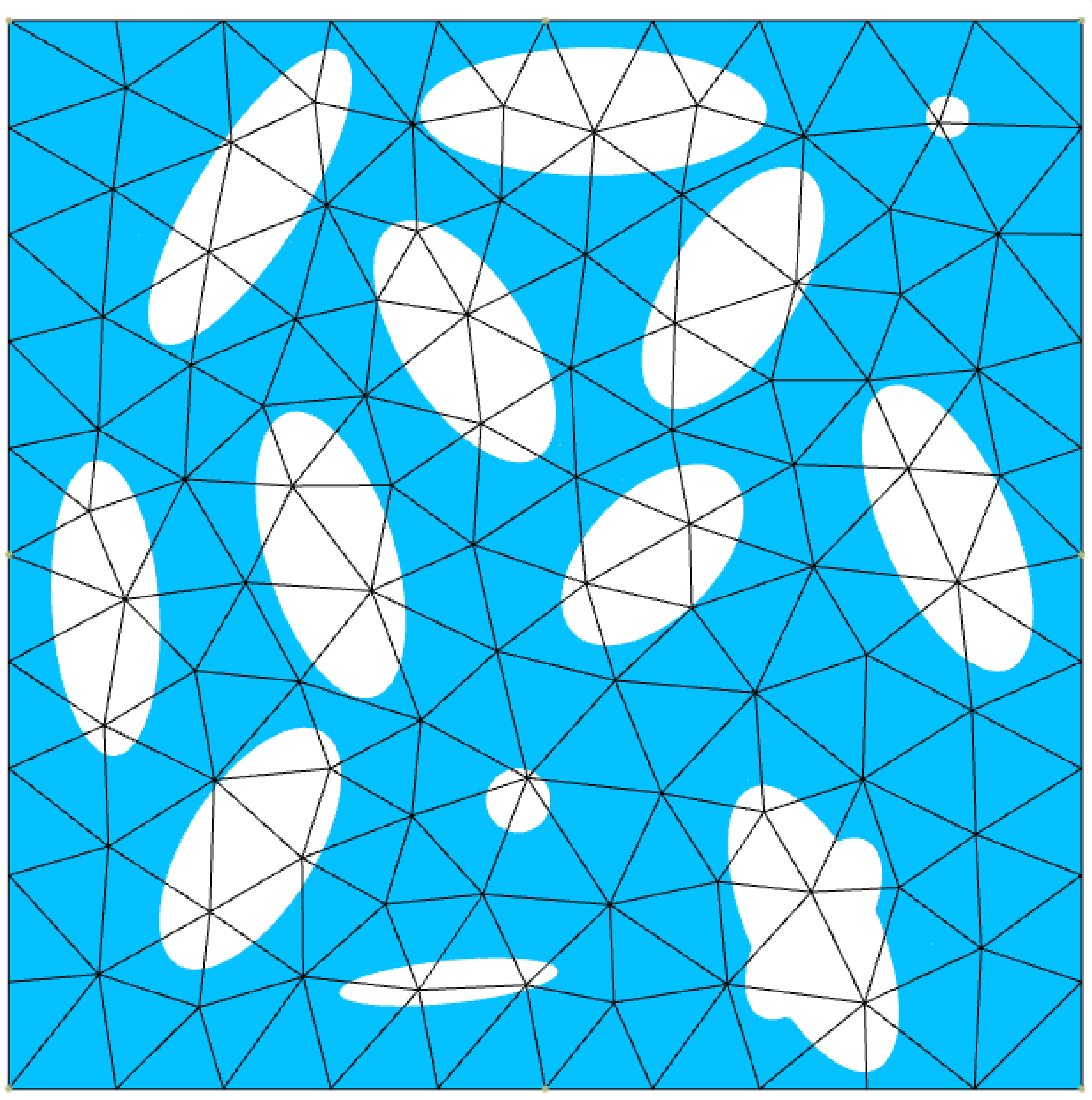
✓ Flexibility of choosing basis functions

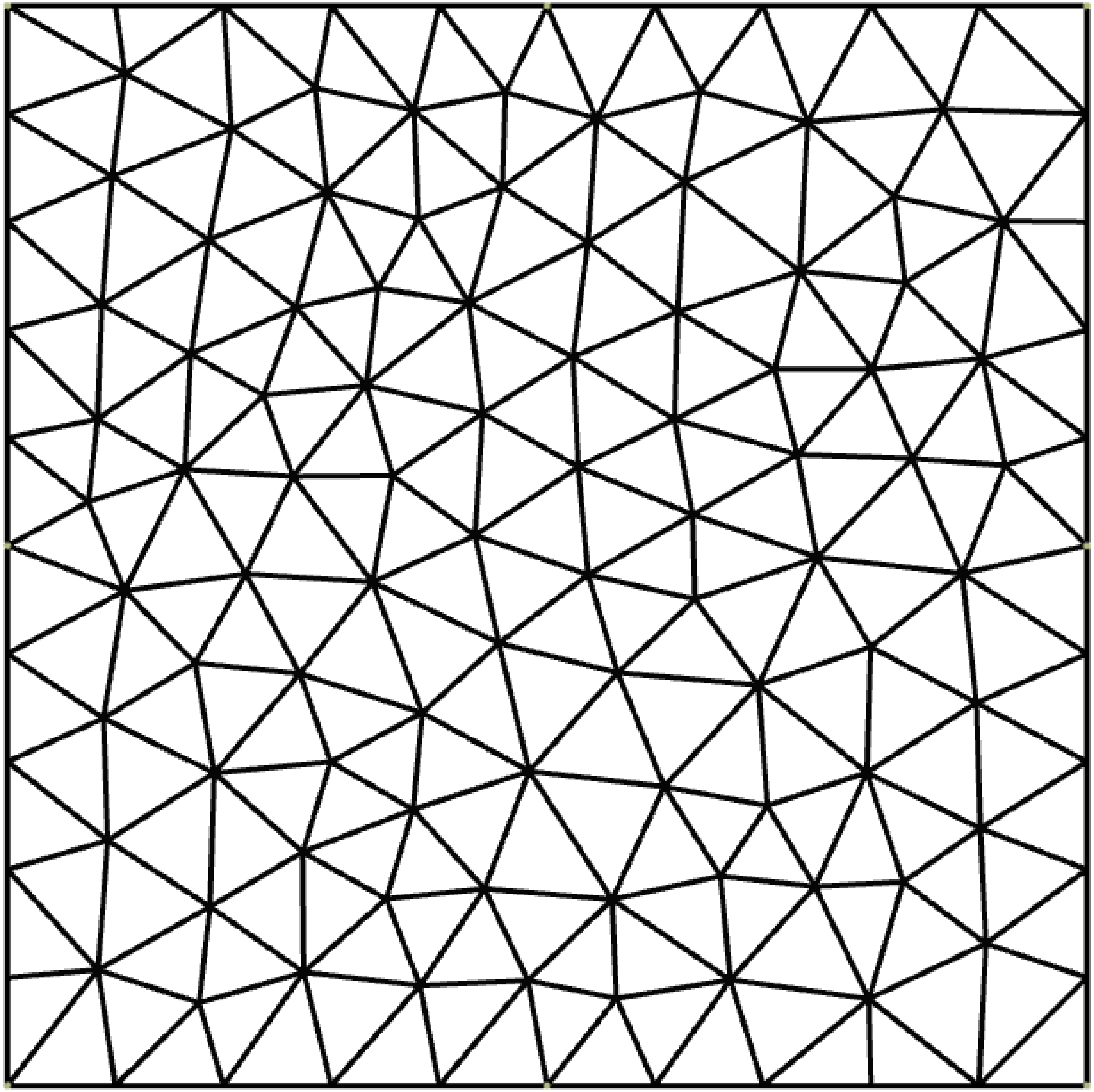
- Accuracy for complicated geometries? BCs on implicit surfaces?

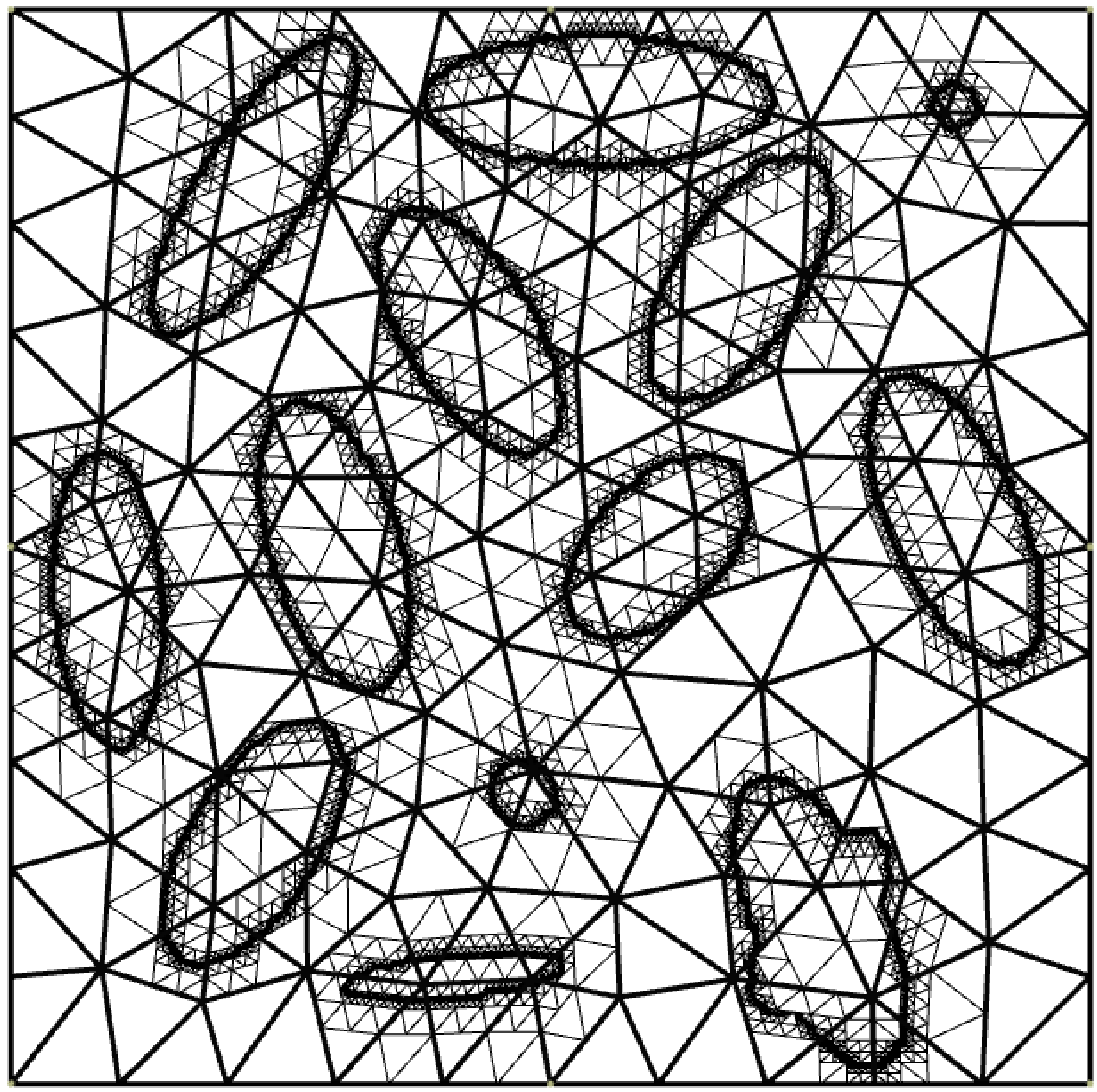
➡ An accurate and implicitly-defined geometry from arbitrary parametric surfaces including corners and sharp edges (Moumnassi 2011; Ródenas Garcia 2016; Fries 2017)

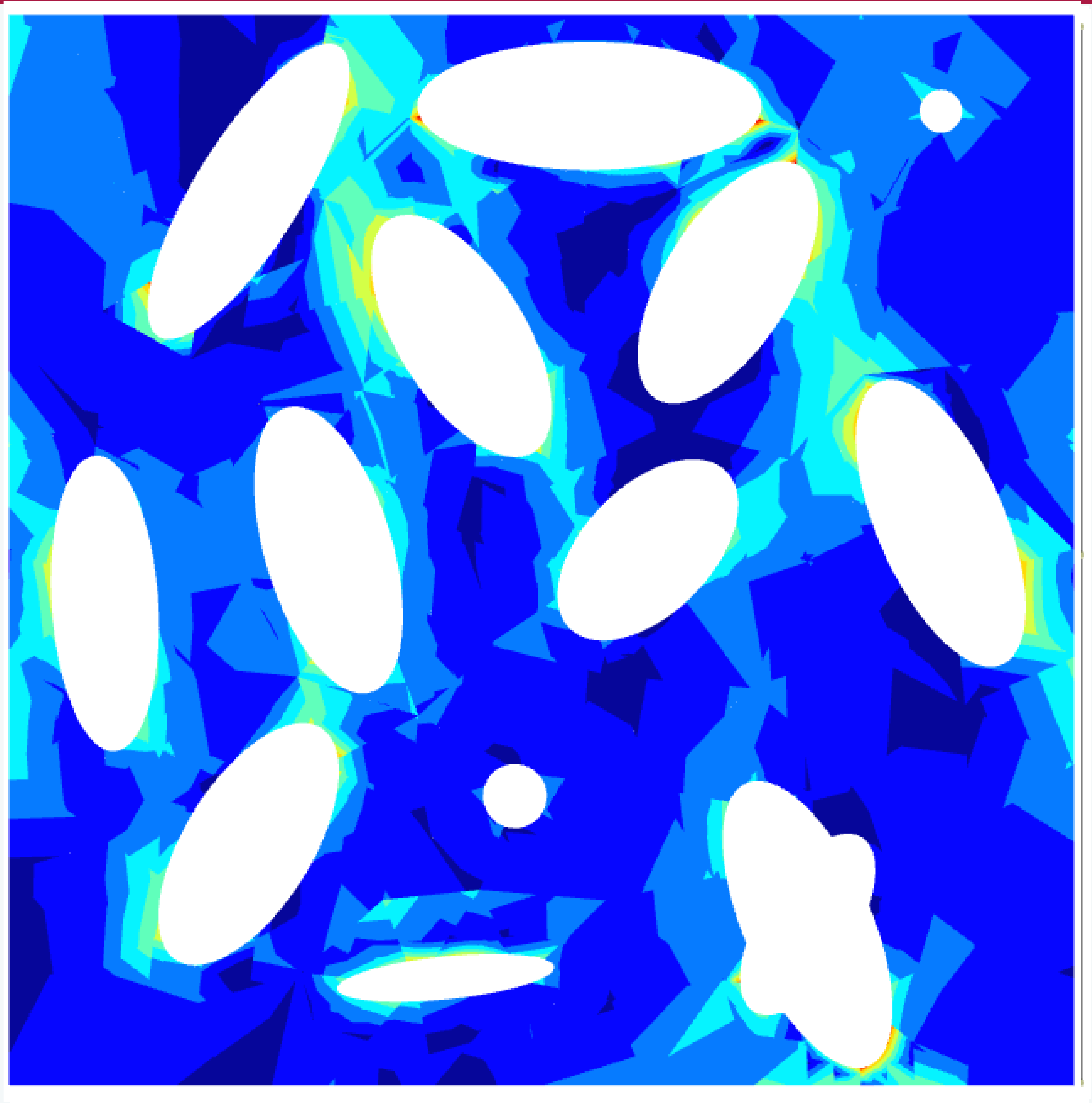




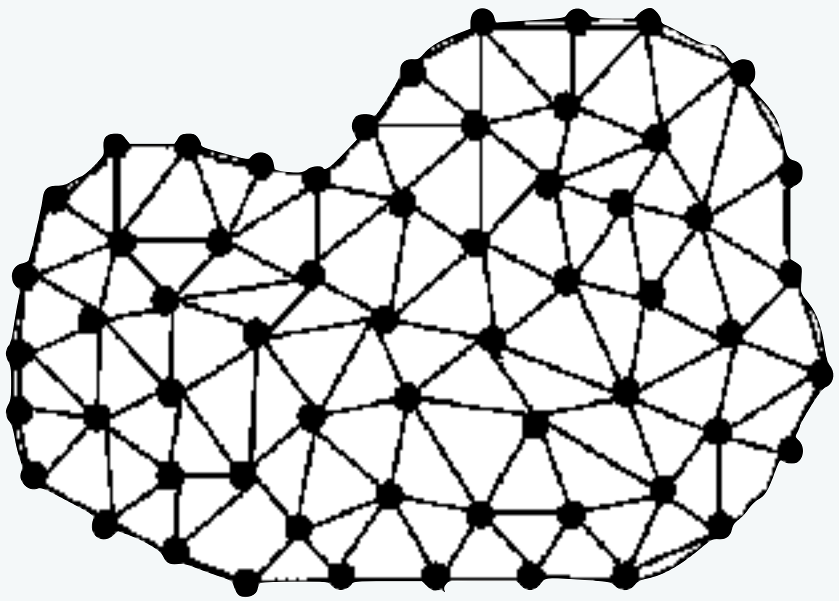


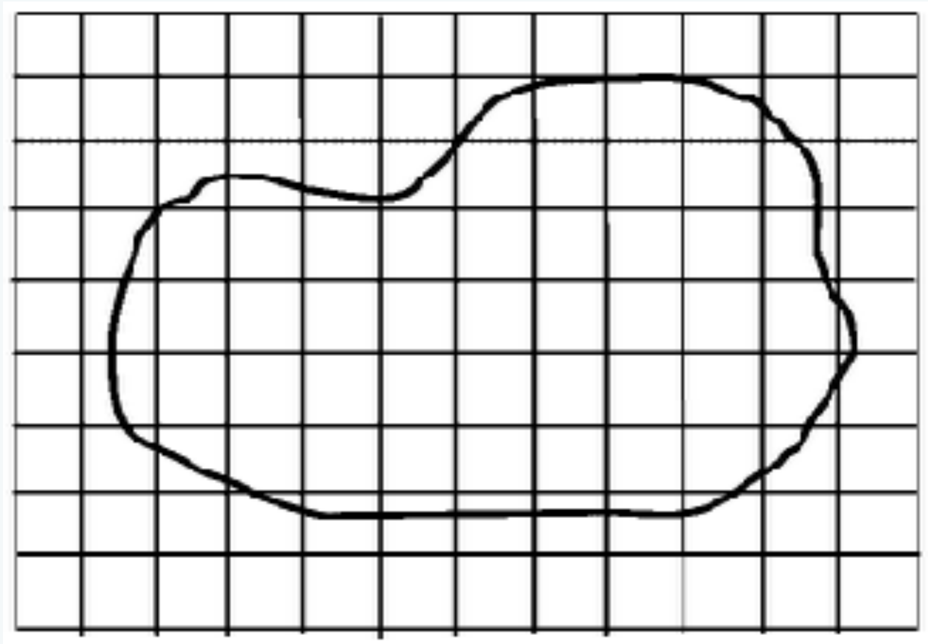




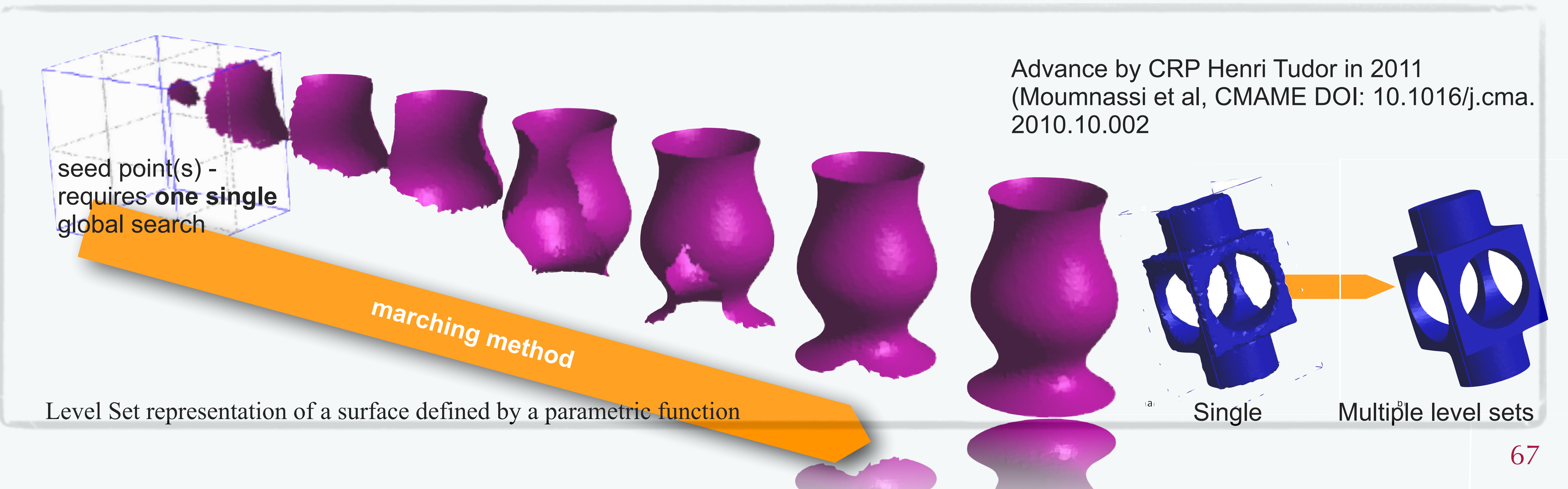


Moumnassi et al, CMAME DOI:10.1016/j.cma.2010.10.002

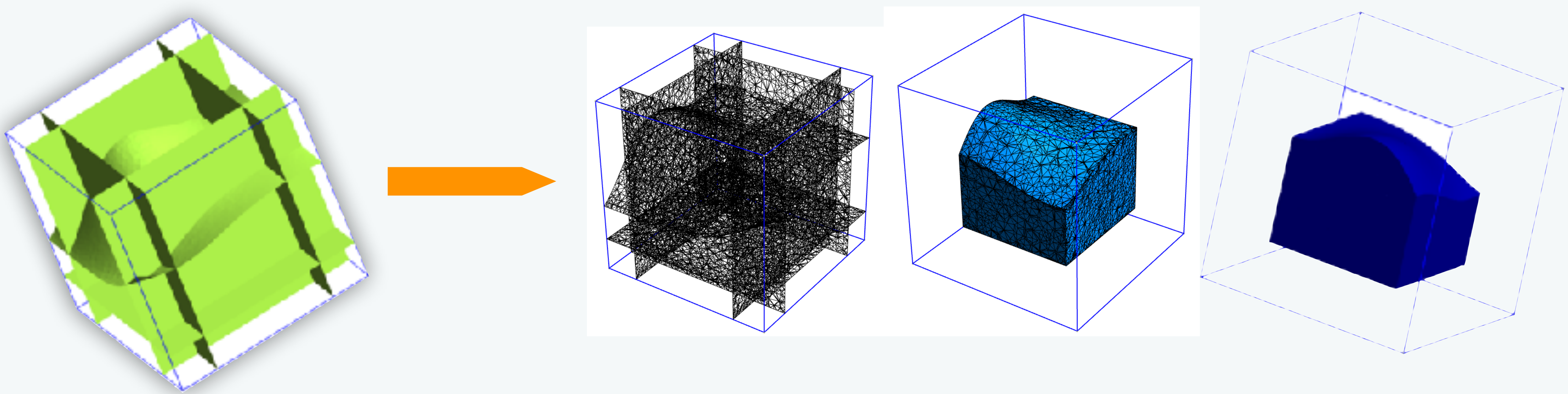


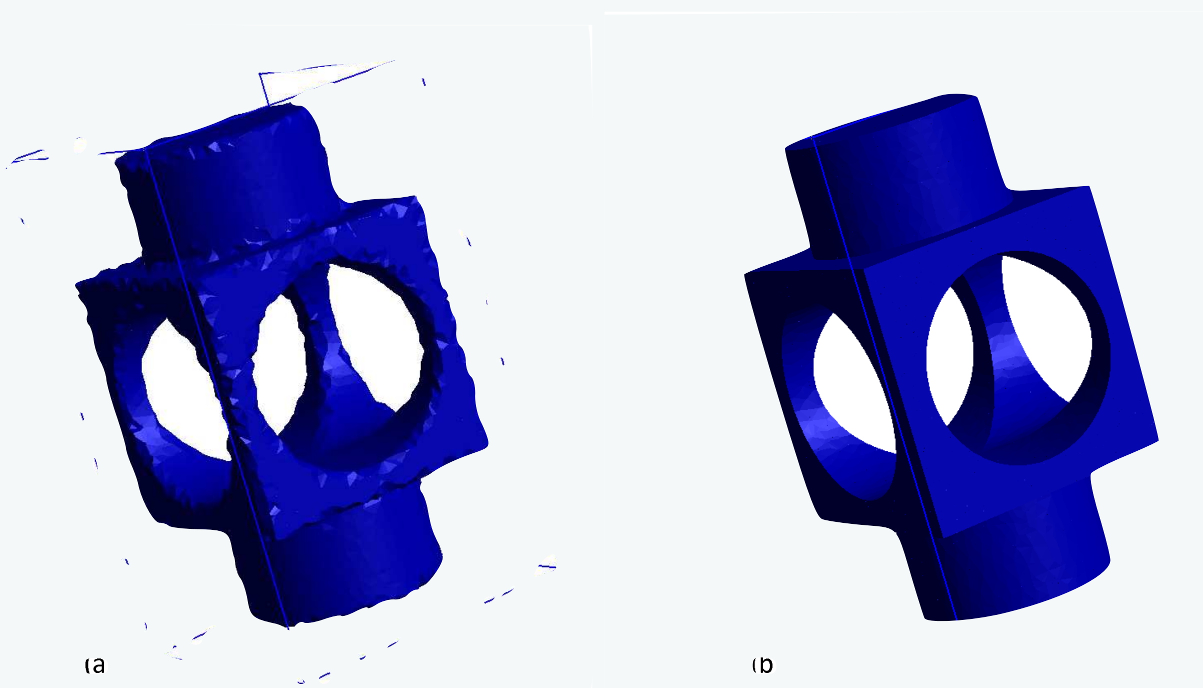


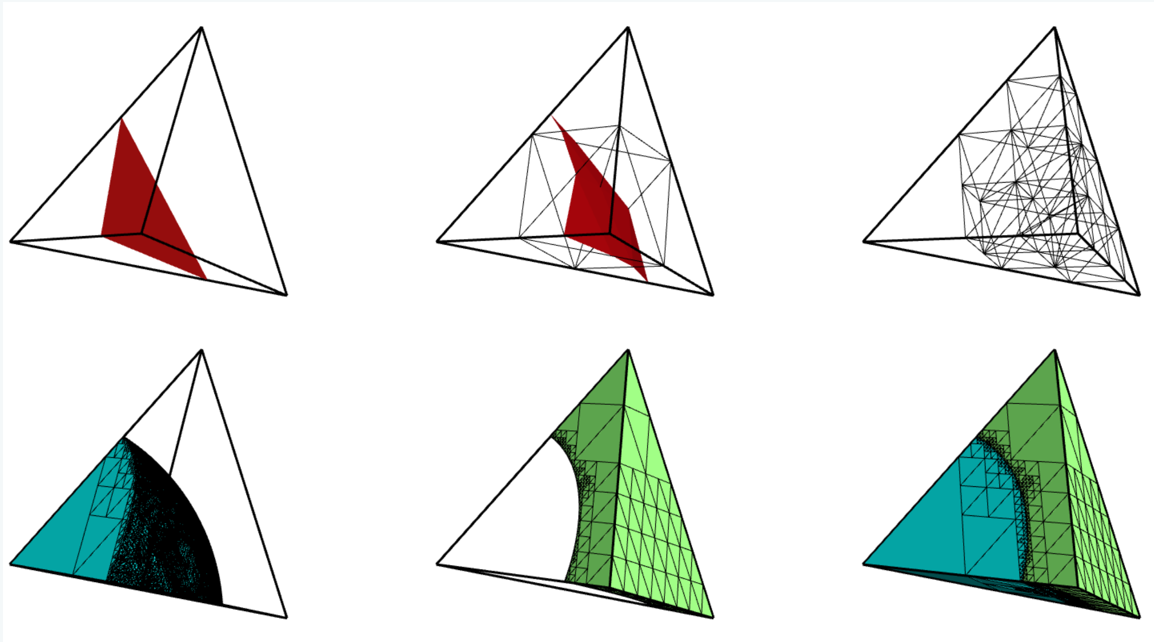
Question: How can we generate level set functions from CAD descriptions (including corners/vertices)?



Examples





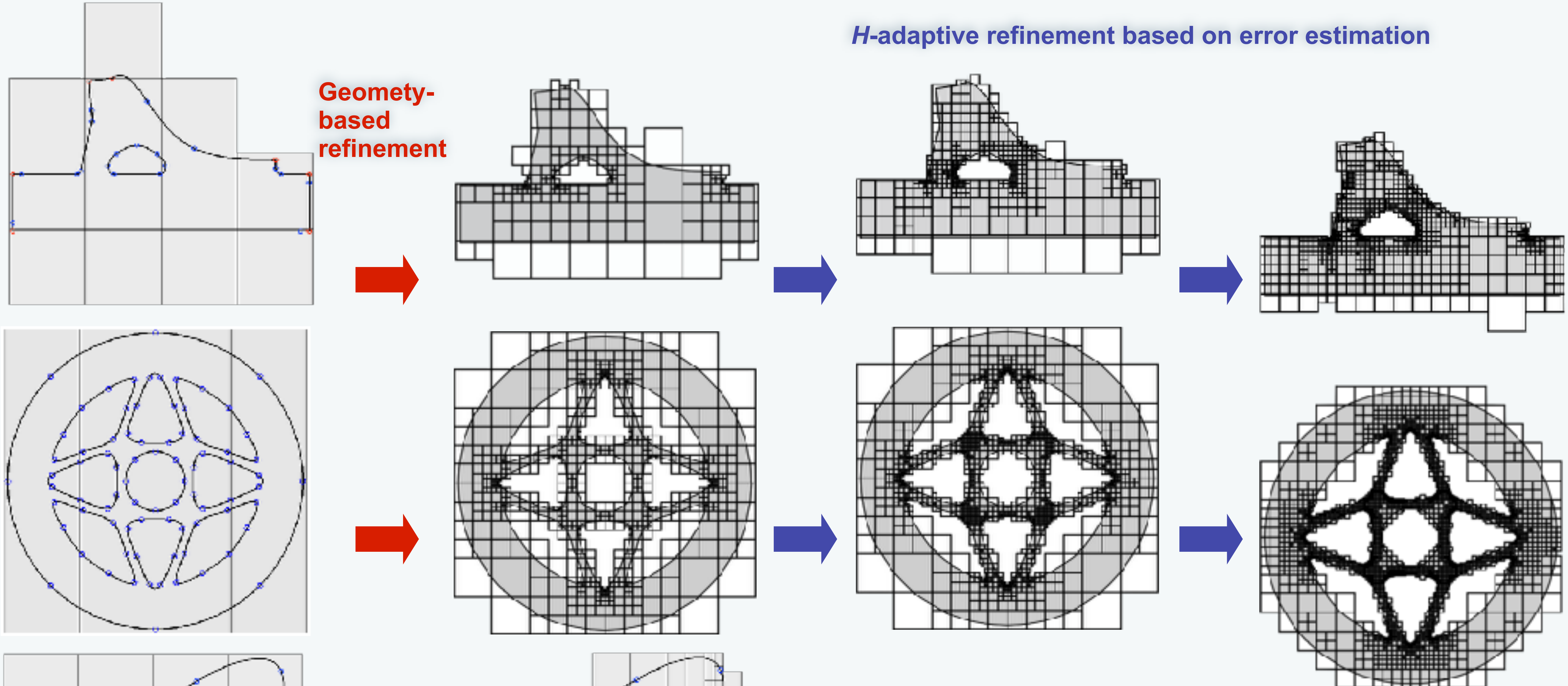


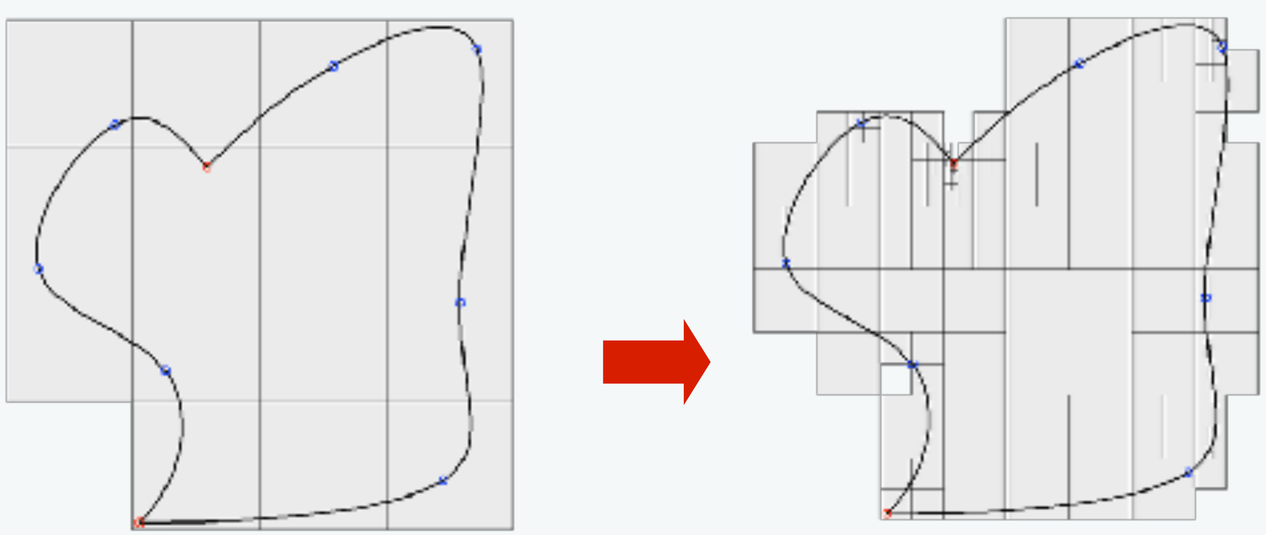
Single level set **Multi level sets**

Examples

***H*-adaptive refinement based on error estimation**

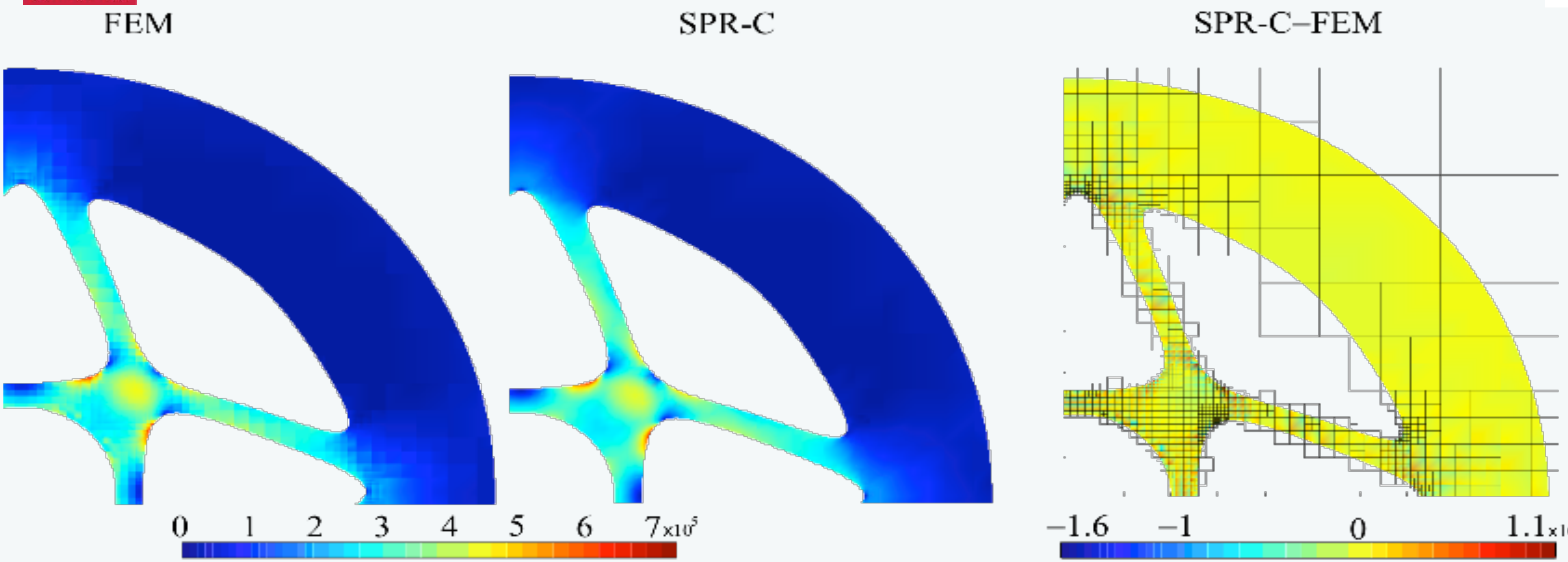
Geomety-based refinement



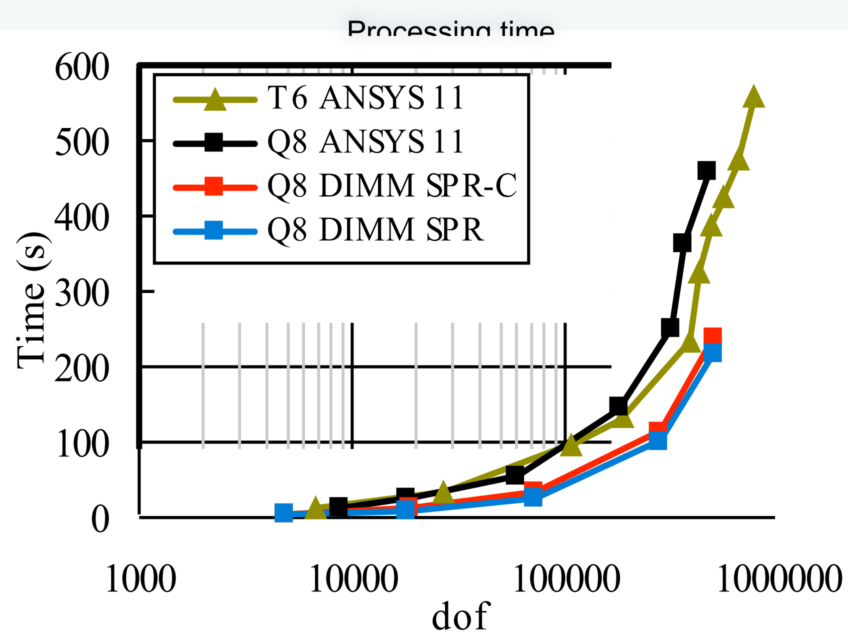


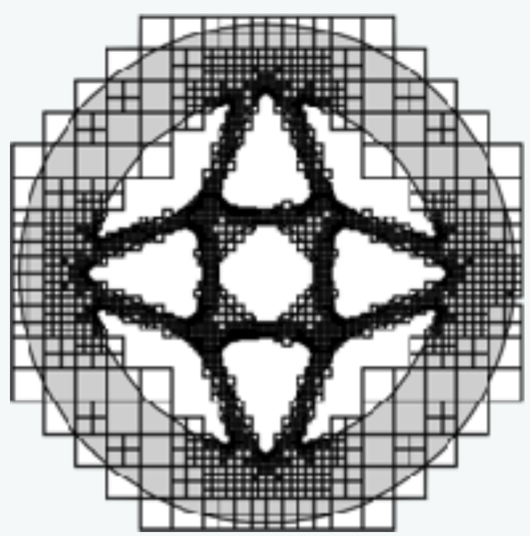
See recent work of Ródenas Garcia (UP Valencia) on Cartesian meshes

Examples



Quad8 uniform refinement

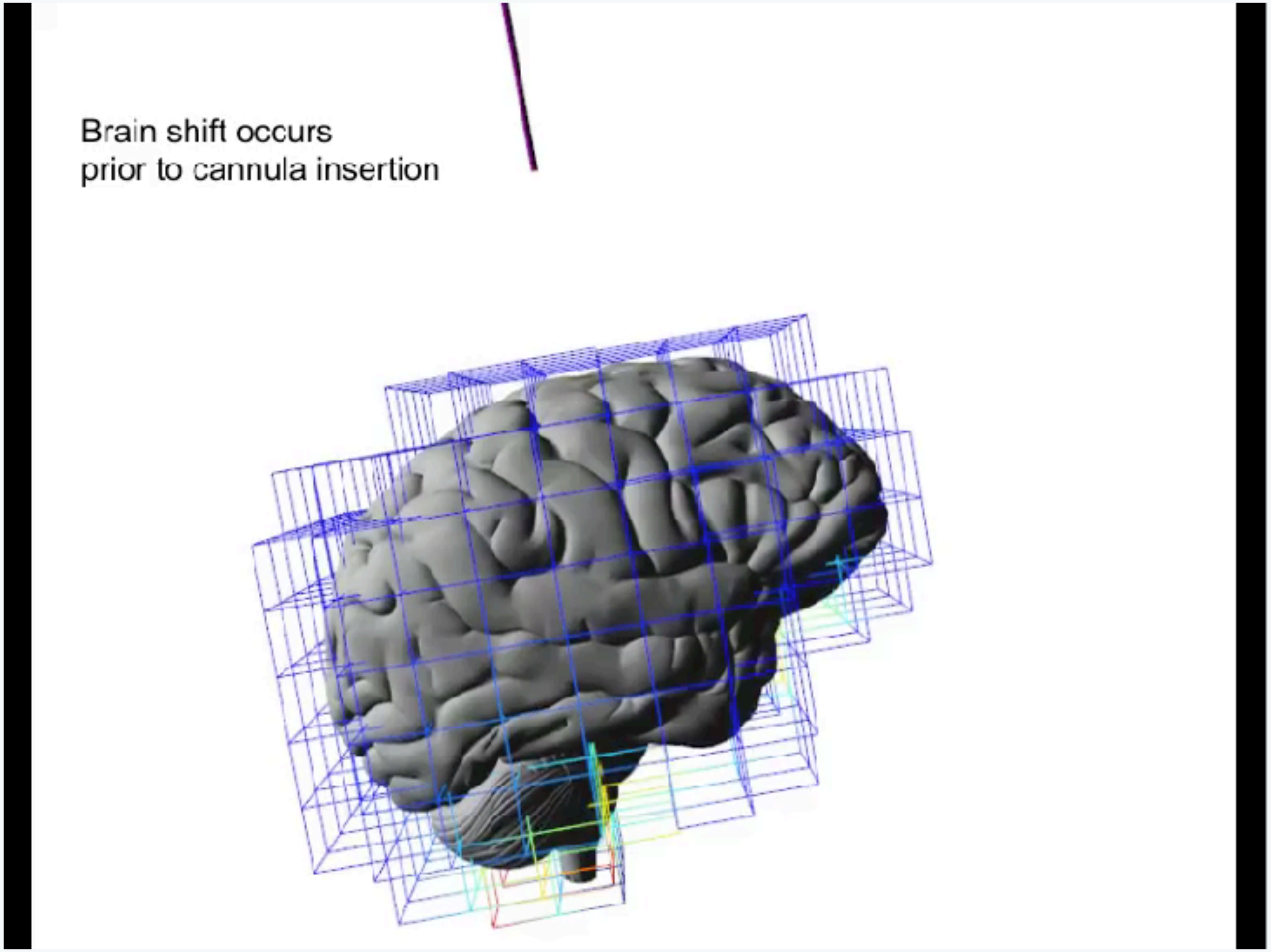




See recent work of Ródenas Garcia (UP Valencia) on Cartesian meshes

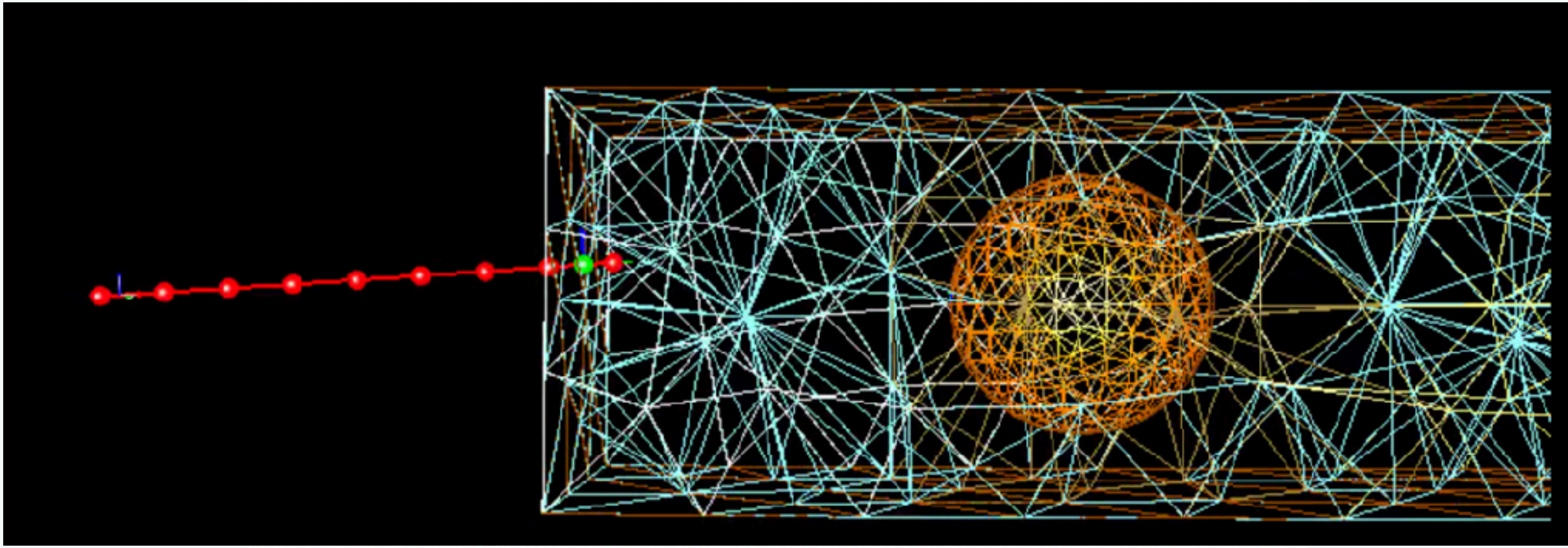
Real-time needle insertion simulation

With implicit boundaries



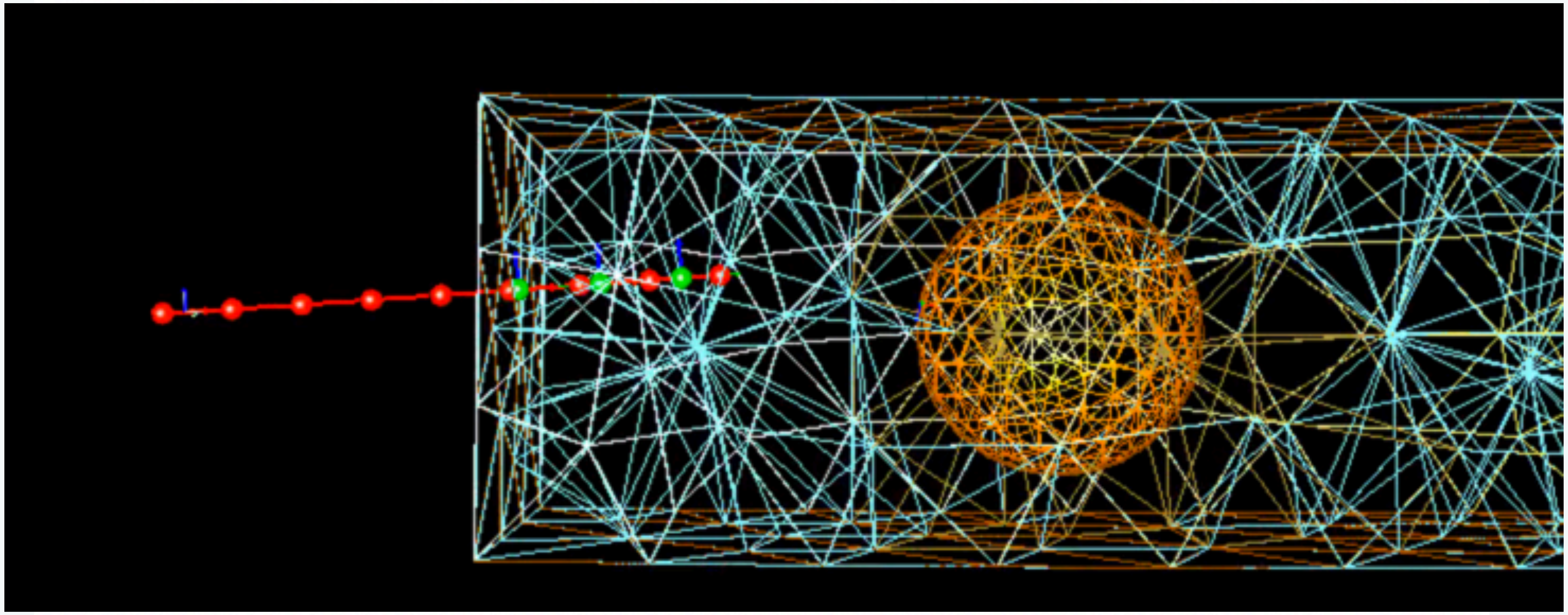
Real-time needle insertion simulation

With implicit boundaries



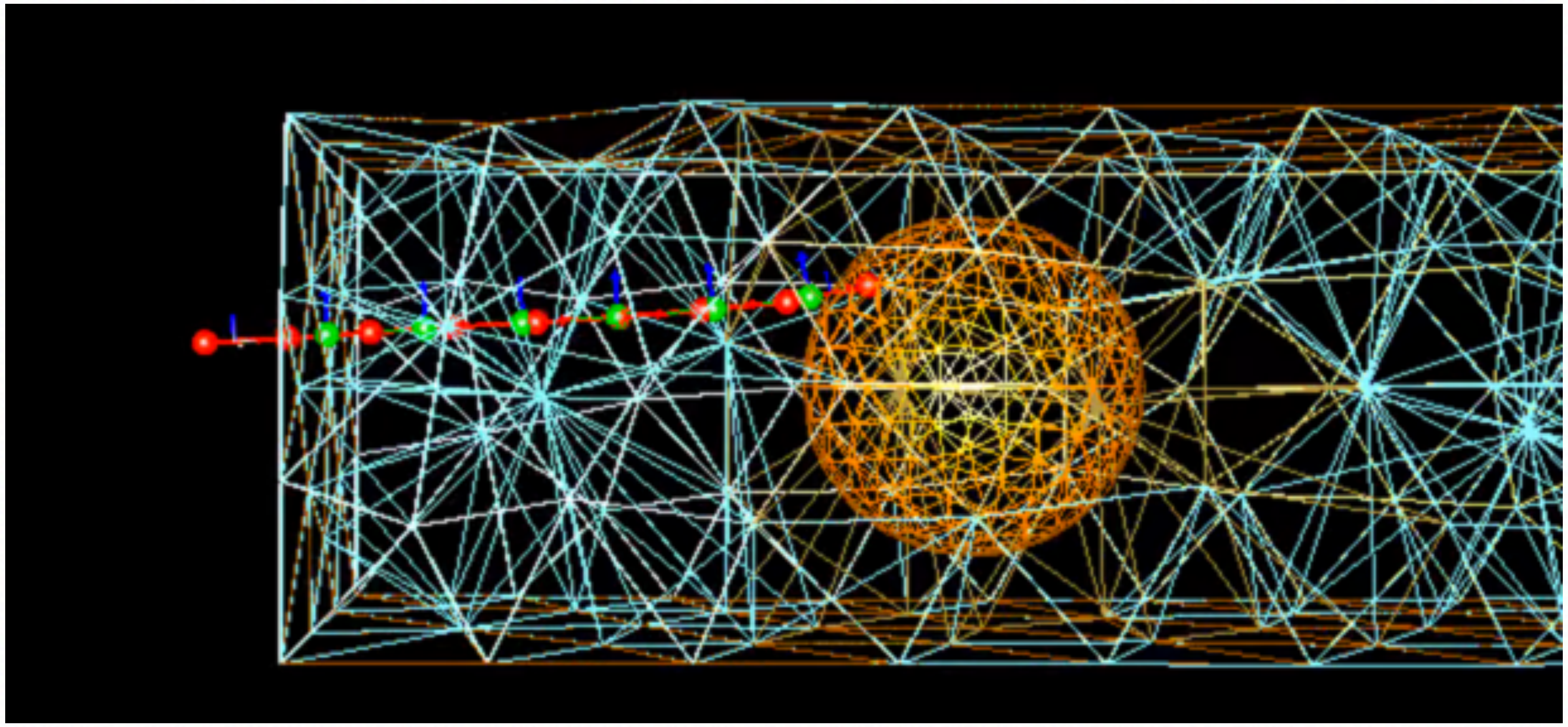
Real-time needle insertion simulation

With implicit boundaries

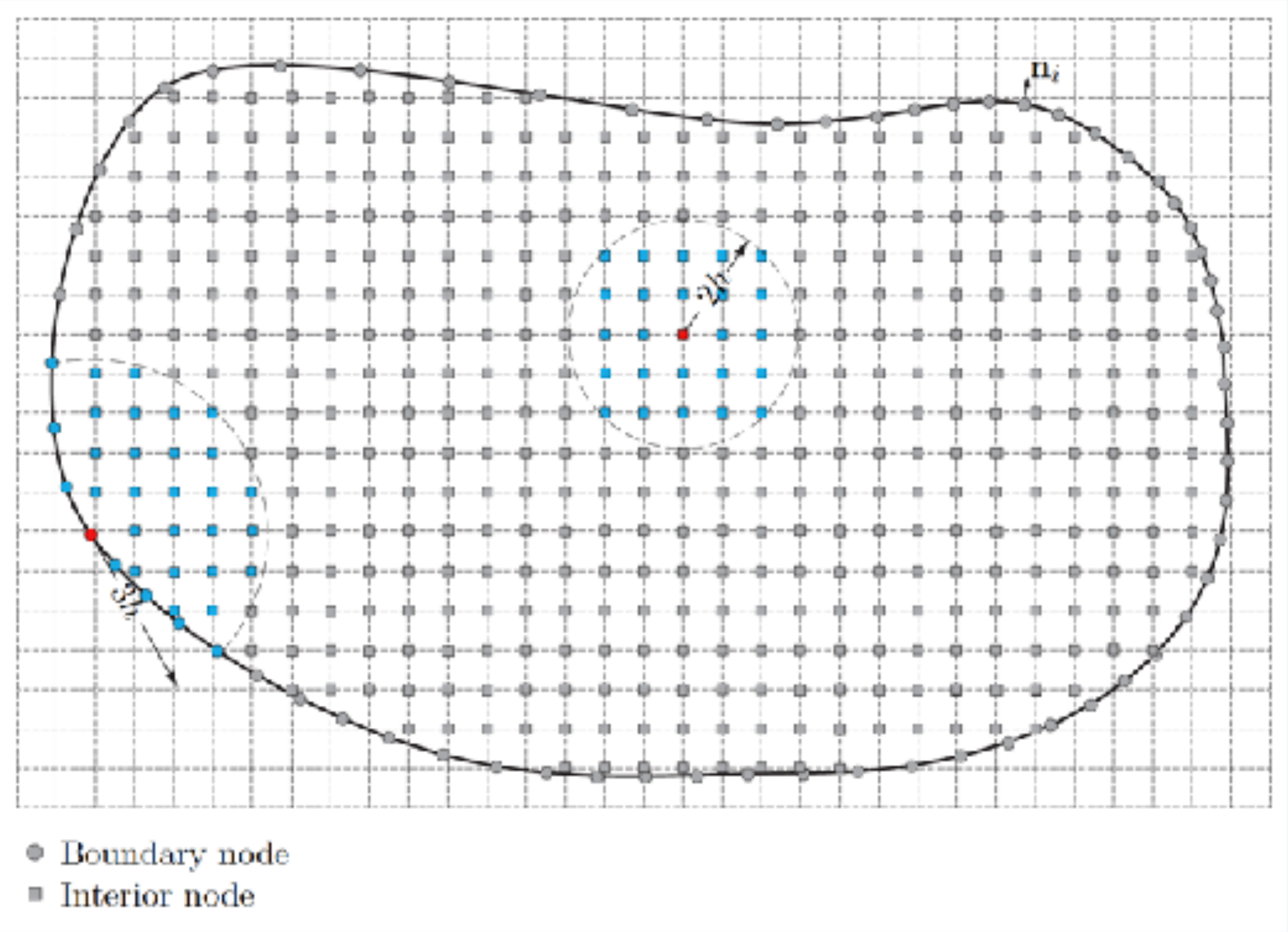


Real-time needle insertion simulation

With implicit boundaries



Discretisation Correction of Particle Strength Exchange Collocation

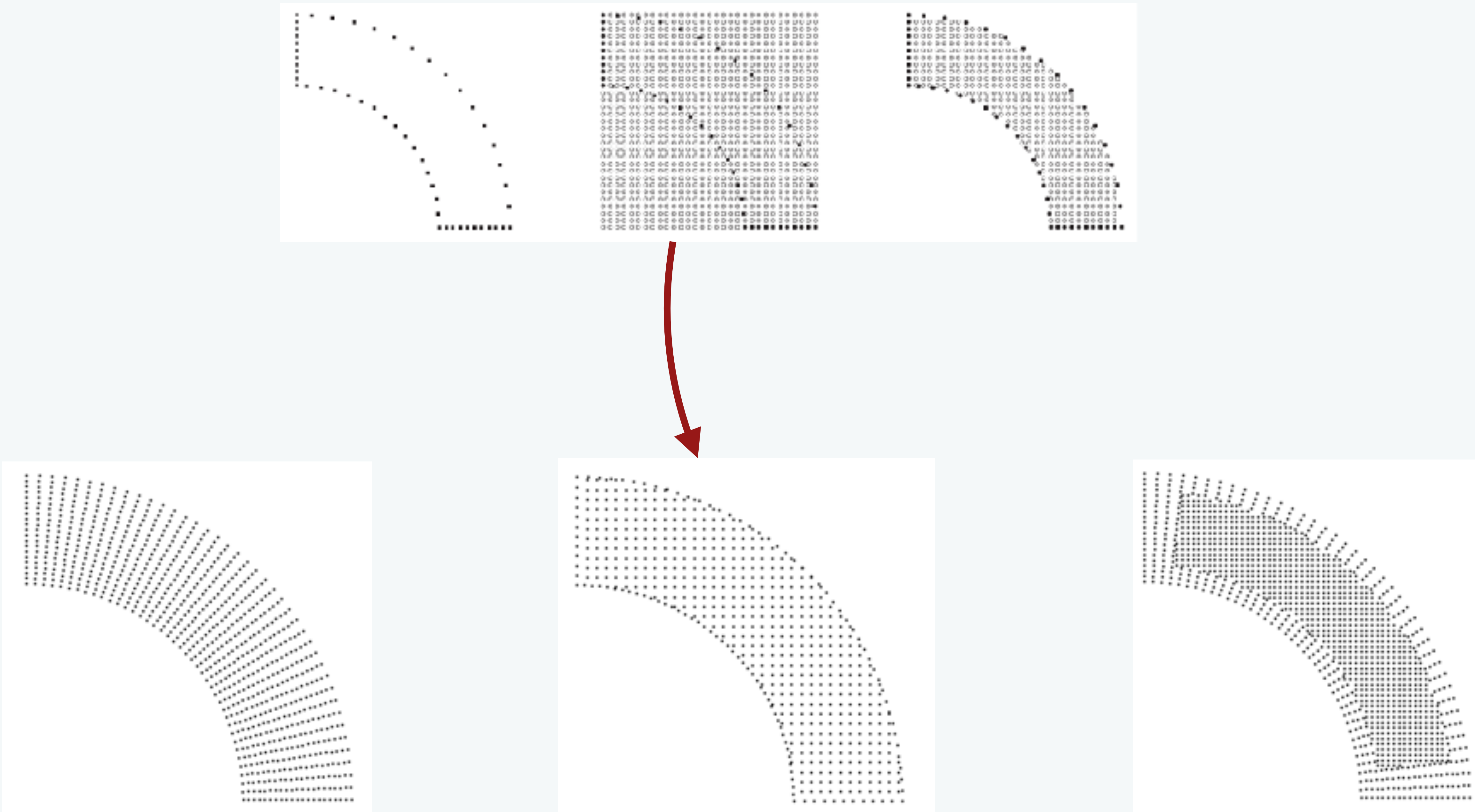


Key idea: use "generalized" finite differences

Key difficulty: stability and complex boundaries

Birte Schrader, Sylvain Reboux, and Ivo F Sbalzarini. Discretization correction of general integral PSE operators for particle methods. Journal of Computational Physics, 229(11):4159–4182, 2010.

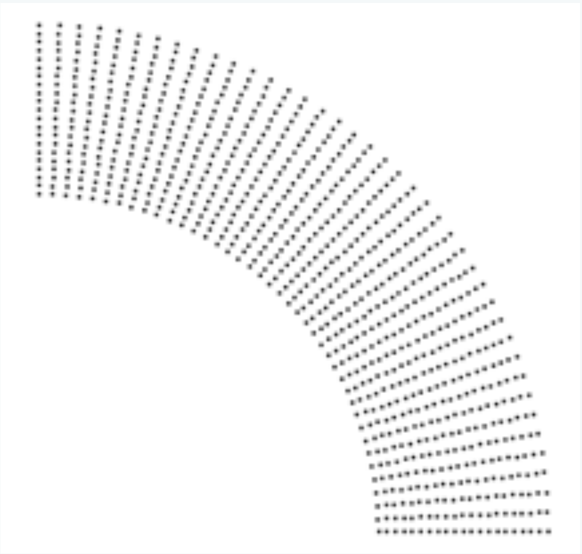
K. Agathos et al. Stable immersed collocation method for elasto-static analysis directly from CAD [preprint available on orbi.uni.lu]



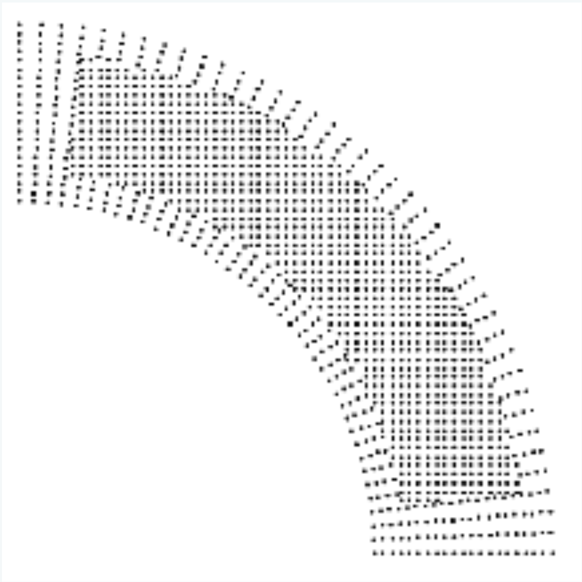
Symmetric

Cartesian

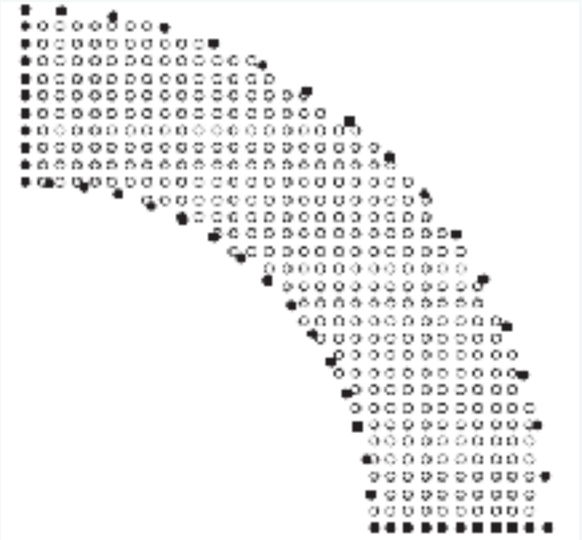
Hybrid



Symmetric



Hybrid



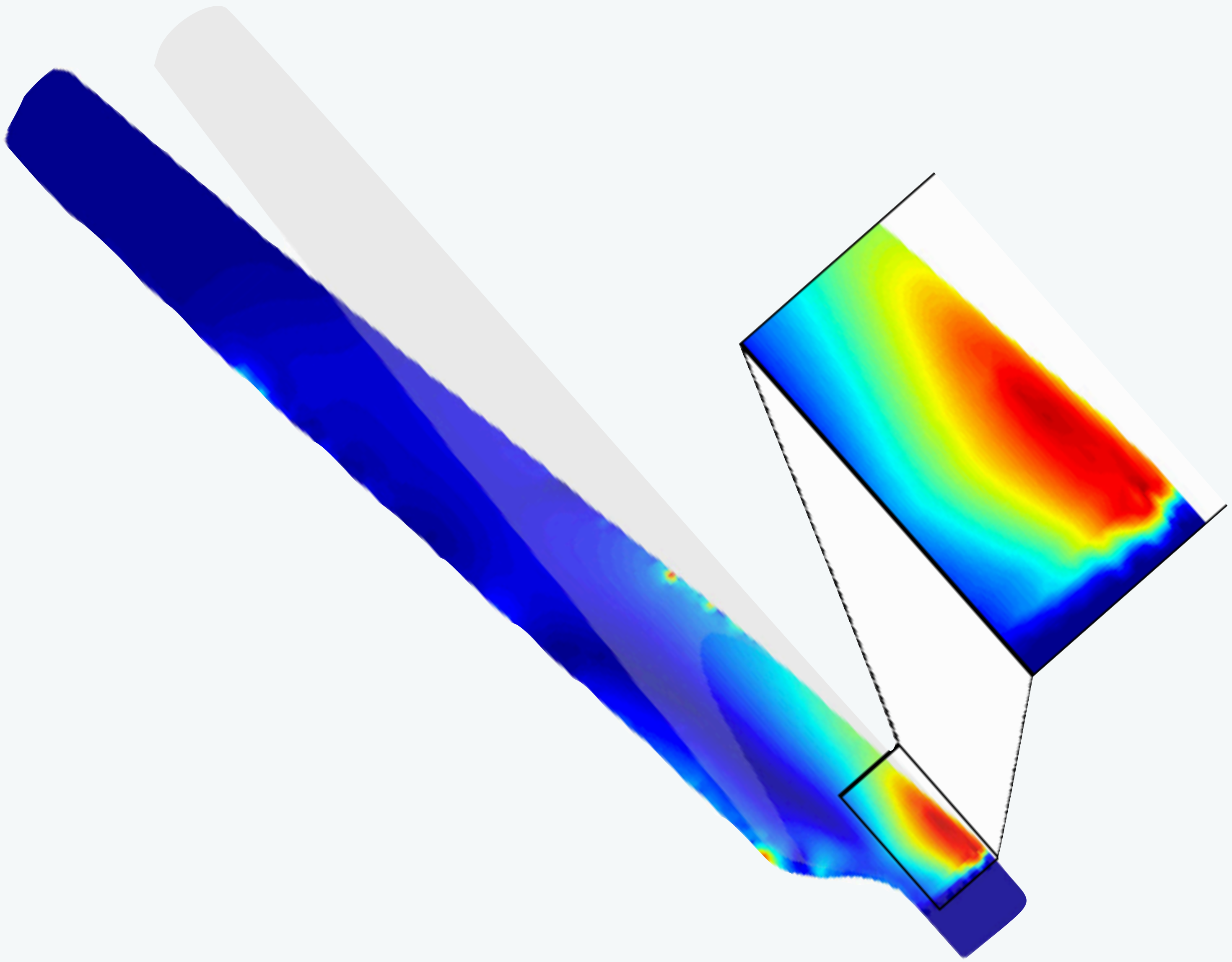
Cartesian

The symmetric node distribution is the most accurate whilst the Cartesian distribution is the worst, the Cartesian-symmetric distribution is intermediate.

Convergence rates of the collocation approach is similar to that of the P1 FEM we compared to whilst the error level is slightly higher. This corroborates results of the isogeometric point collocation method.

Applications

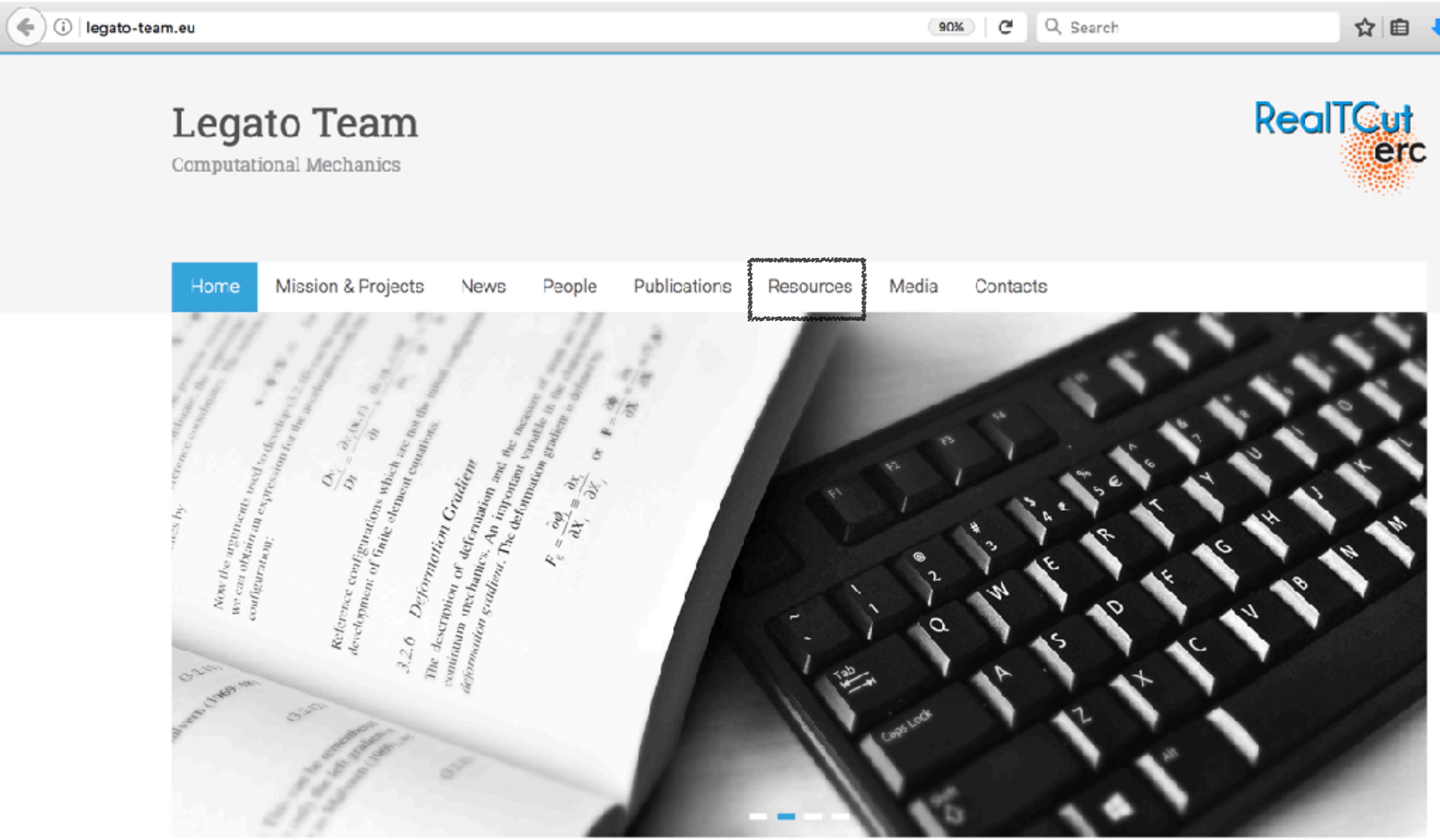
Wind turbine blade & aorta



Partial conclusions on methods decoupling geometry and field approximations

- There are numerous alternatives (immersed, CutFEM, structured XFEM, collocation…)
- Discussions on higher order boundaries (see XDMS2017 book of abstracts!)
- Using CAD geometries within a structured mesh/grid is a versatile approach

Next: beyond discretisations…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Username: cmechanicsos
Joined: 2012-04-13 14:29:25

Projects

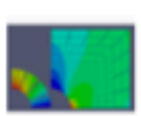
ElemFreGalerkin
A tutorial Galerkin meshfree code
Last Updated: 2017-01-29

OpenXfem++
OpenXfem++ is an XFEM (eXtended Finite Element Method) written in C++.
Last Updated: 2017-01-28

XFEM
XFEM implementation in MATLAB
Last Updated: 2017-02-08

ciGen
ciGen is a short C++ code to generate cohesive interface elements.
Last Updated: 2017-01-25

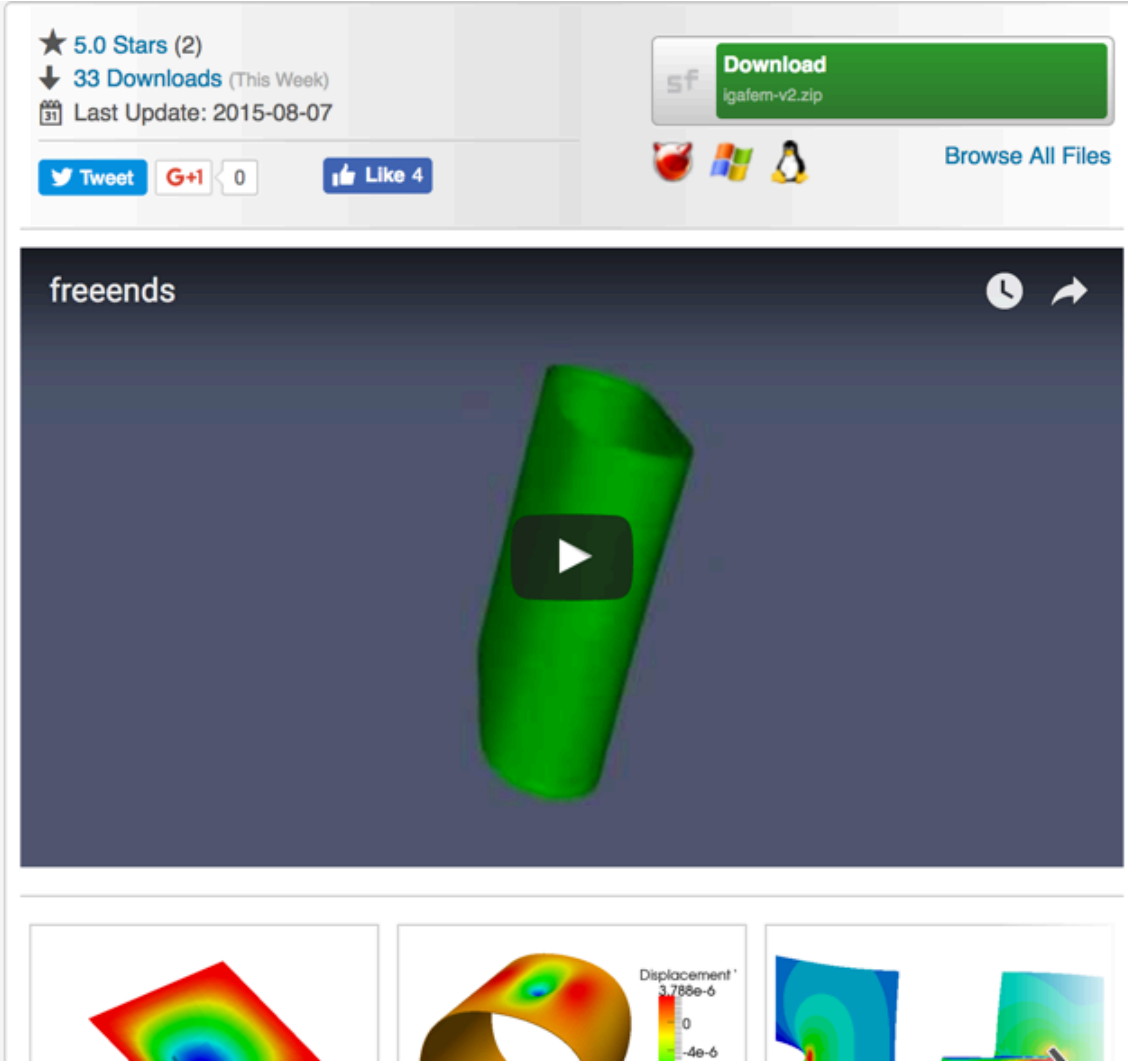
igabem
Isogeometric boundary element analysis with matlab
Last Updated: 2017-03-02



igafem
Open source 3D Matlab Isogeometric Analysis Code
Last Updated: 2017-02-05

igafemgui
Last Updated: 2017-05-10

.net/p/cmcodes/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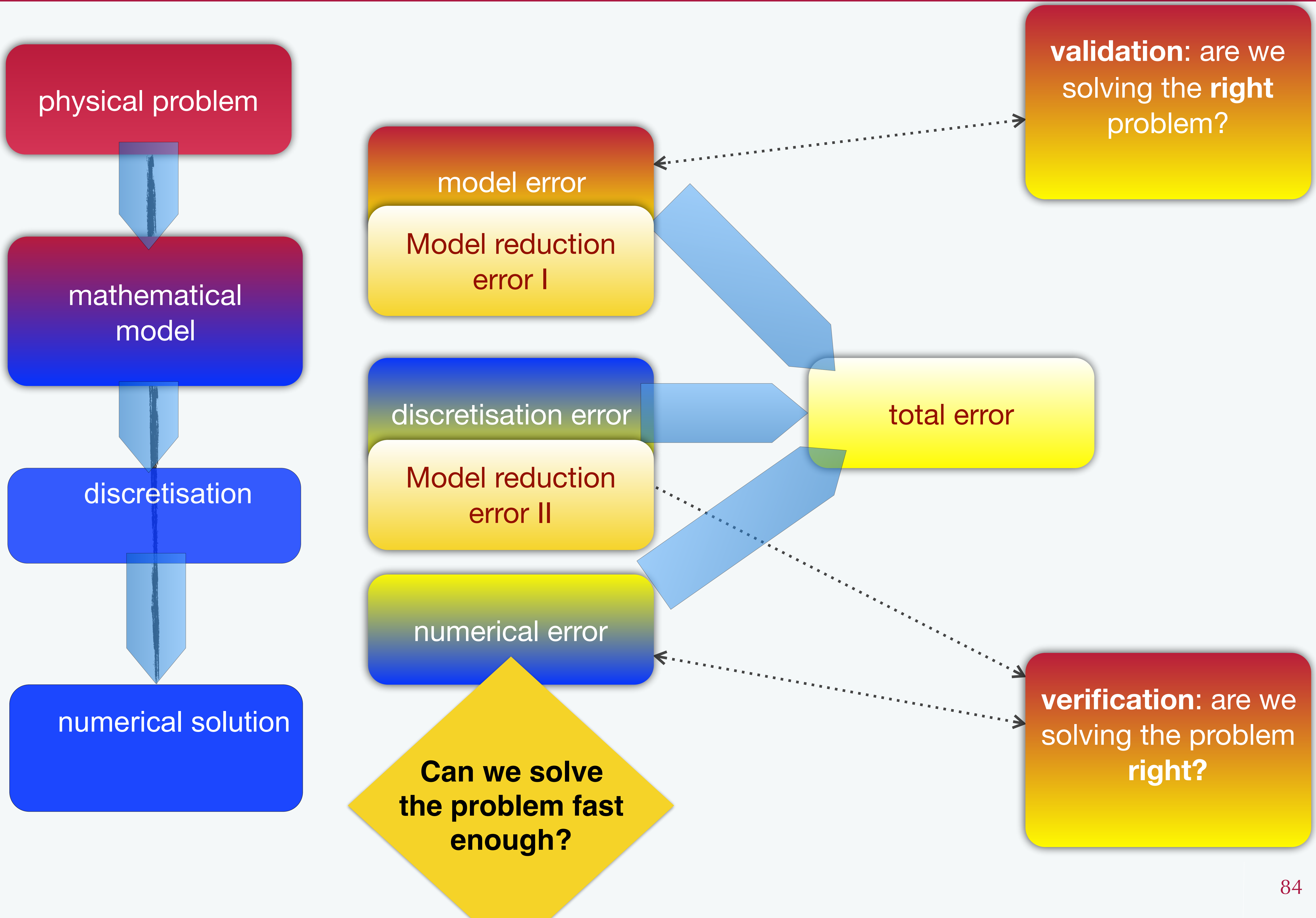
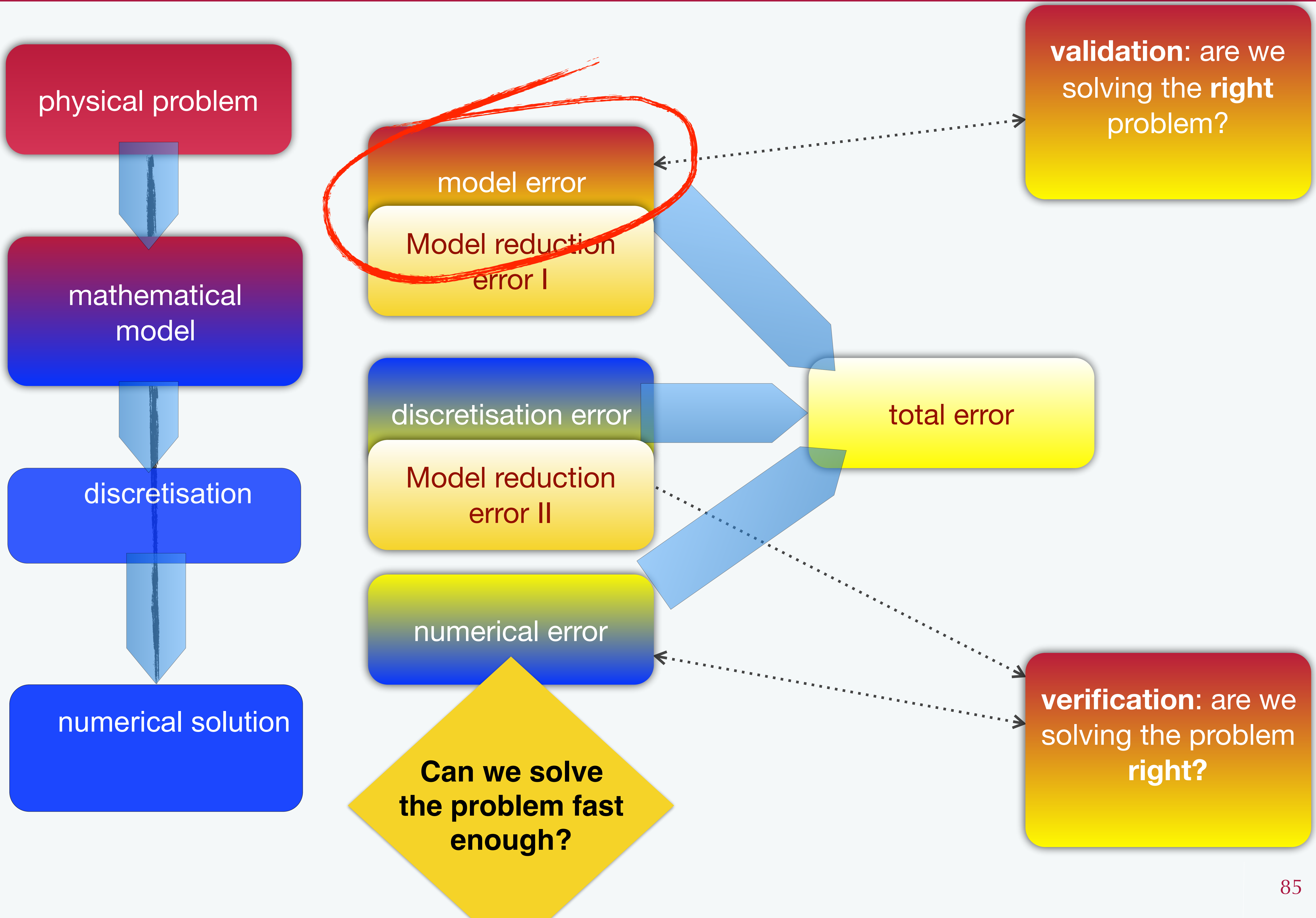
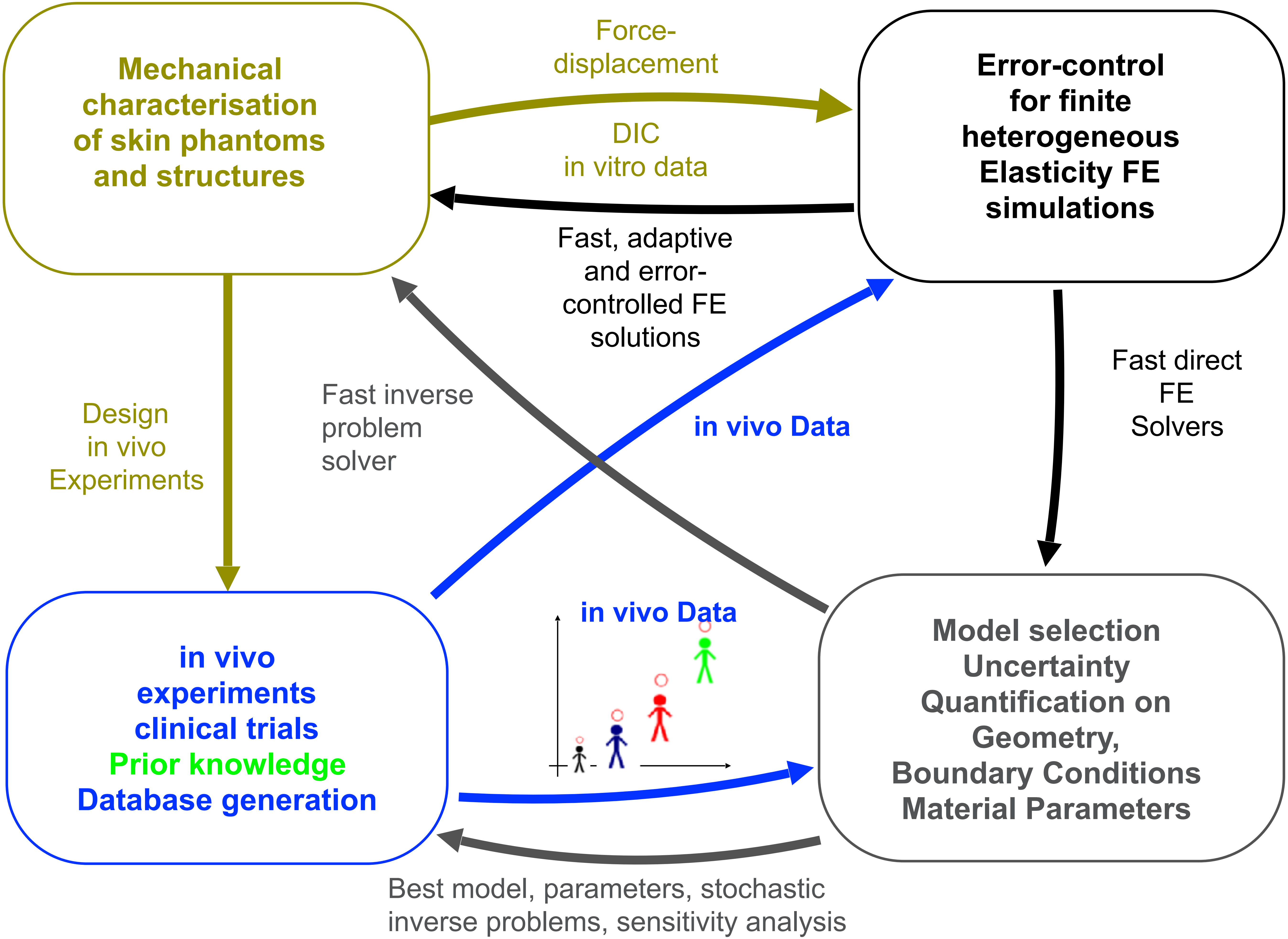
Modelling and simulation



Modelling and simulation




Mechanical characterisation of skin phantoms and structures
Force-displacement
DIC in vitro data
Error-control for finite heterogeneous Elasticity FE simulations
Fast, adaptive and error-controlled FE solutions
Design in vivo Experiments
Fast inverse problem solver
in vivo Data
Fast direct FE Solvers
in vivo Data
in vivo experiments clinical trials
Prior knowledge
Database generation
Model selection Uncertainty Quantification on Geometry, Boundary Conditions Material Parameters
Best model, parameters, stochastic inverse problems, sensitivity analysis

Ingredient #1 - Error control

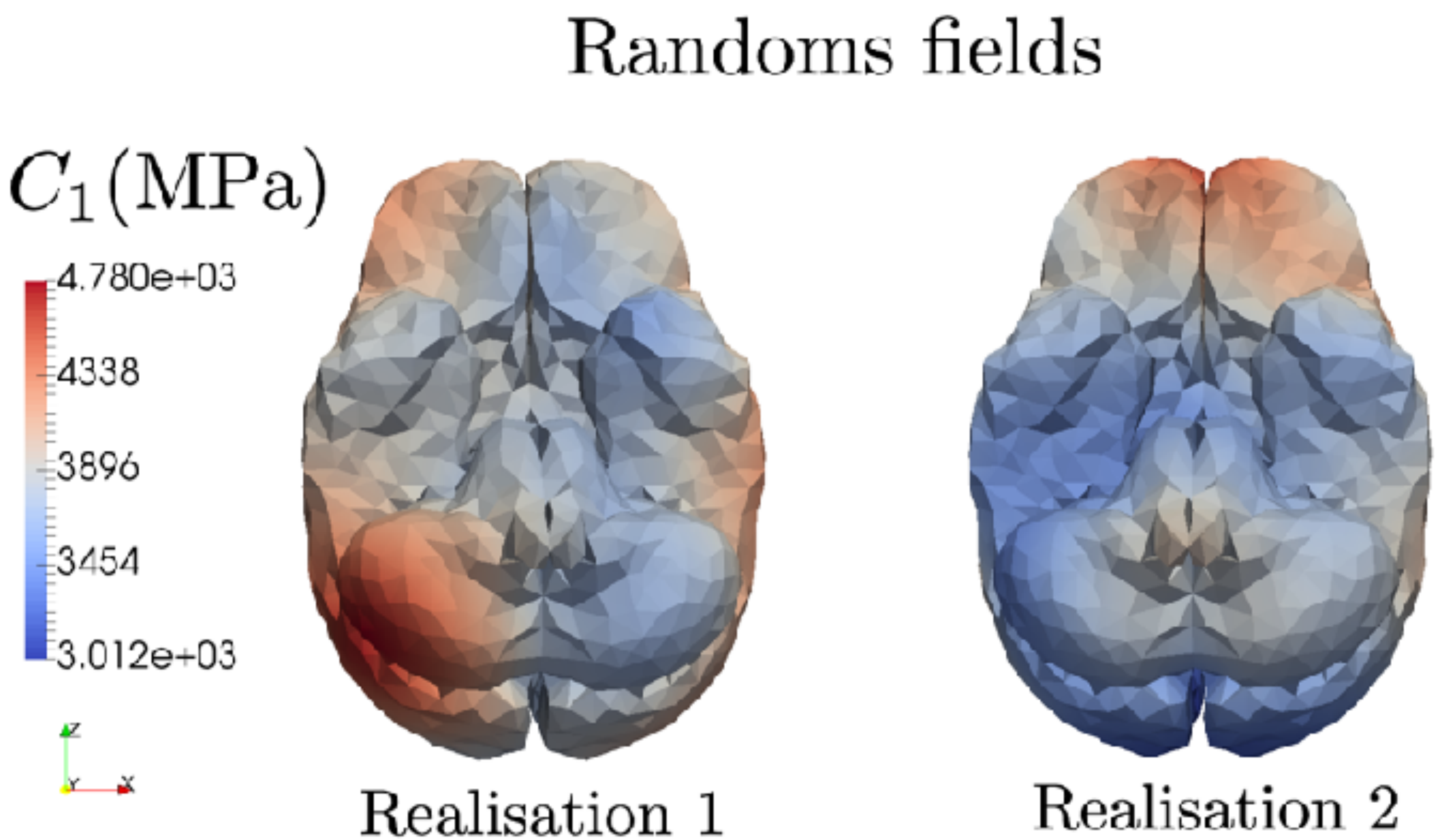
Error-control
for finite
heterogeneous
Elasticity FE
simulations

Ingredient #2 - Uncertainty quantification

Model selection
Uncertainty
Quantification on
Geometry,
Boundary Conditions
Material Parameters

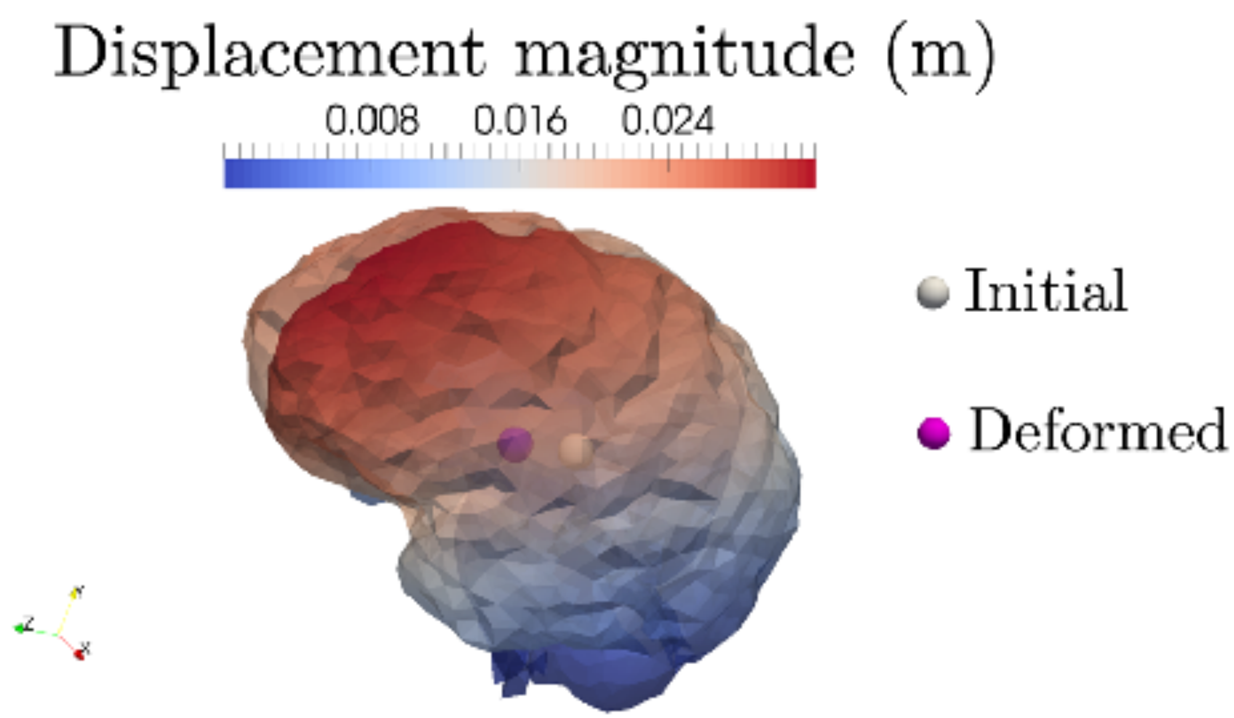
Random Fields

- Different methods: Karhunen–Loève expansion [Adler 2007], Fast Fourier transform [Nowak 2004].

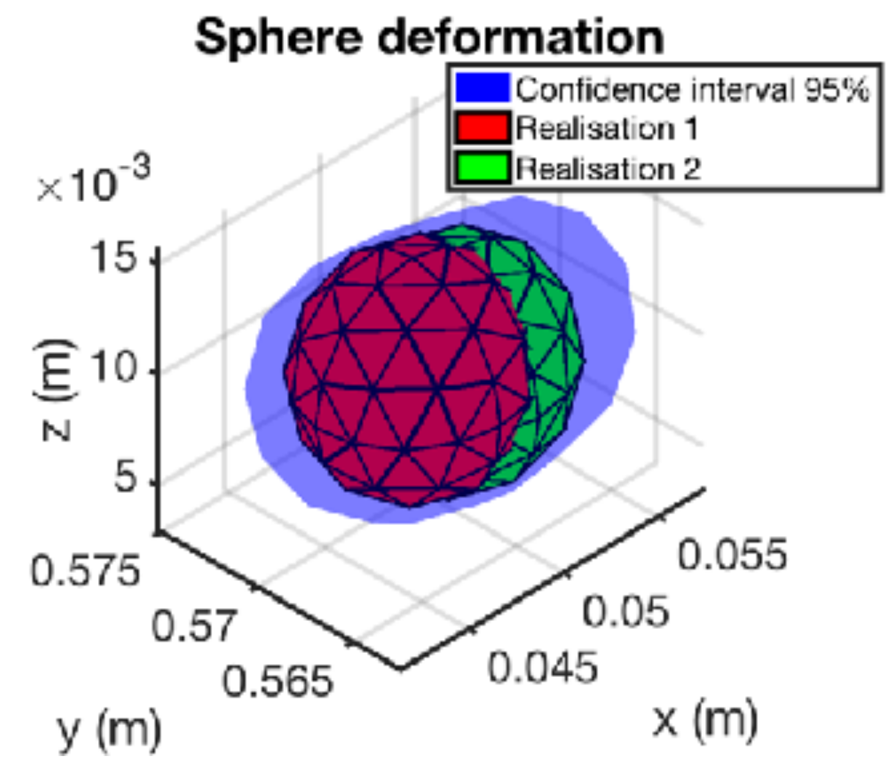


Two realisations of RF, with a log-normal distribution, for the parameter C_1 (in MPa).

Stochastic FE analysis of brain deformation
Numerical results (8 RV, Holzapfel model)



Brain deformation with random parameters
1 MC realisation.



Confidence interval 95%
MC simulations.

Numerical results: convergence

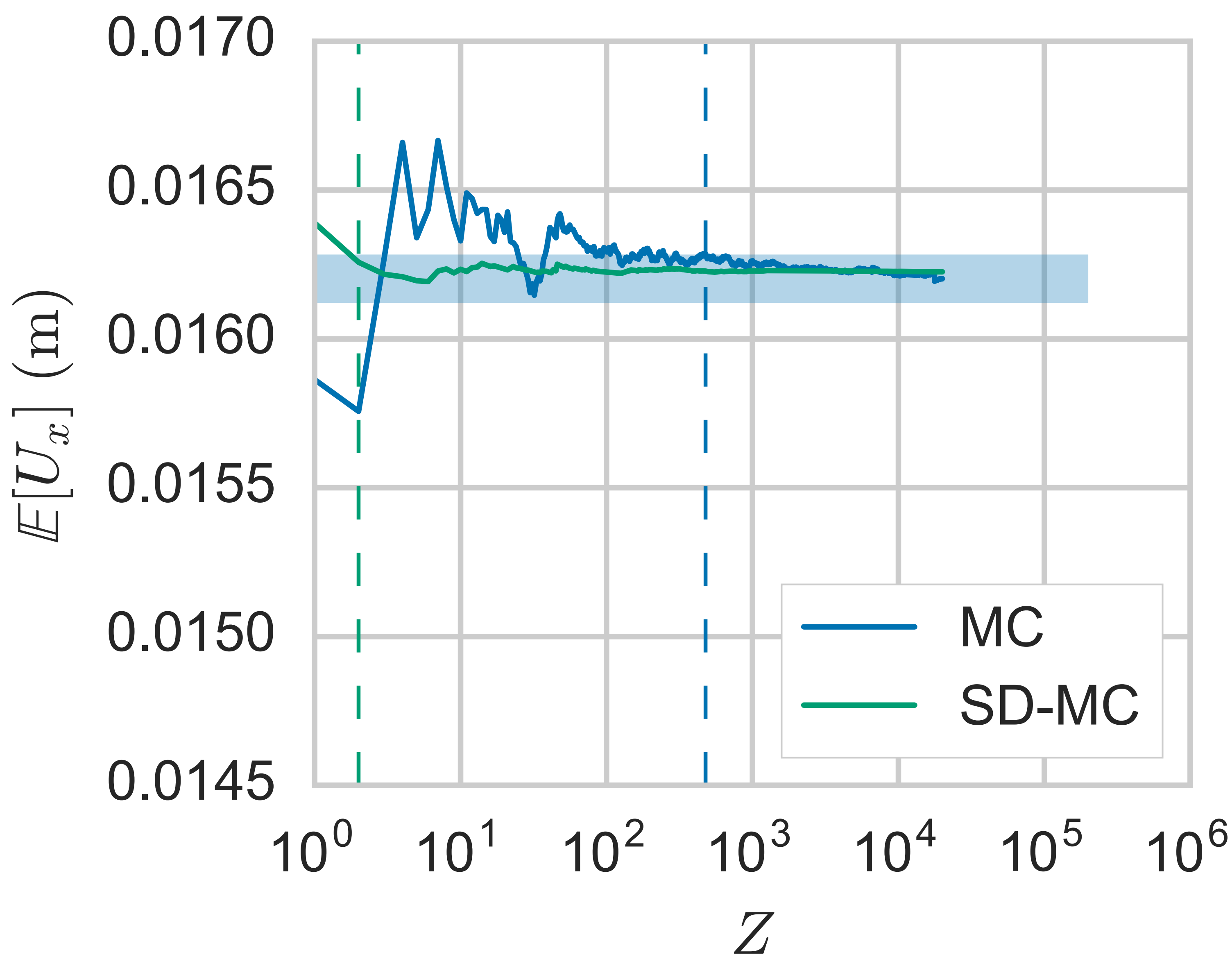
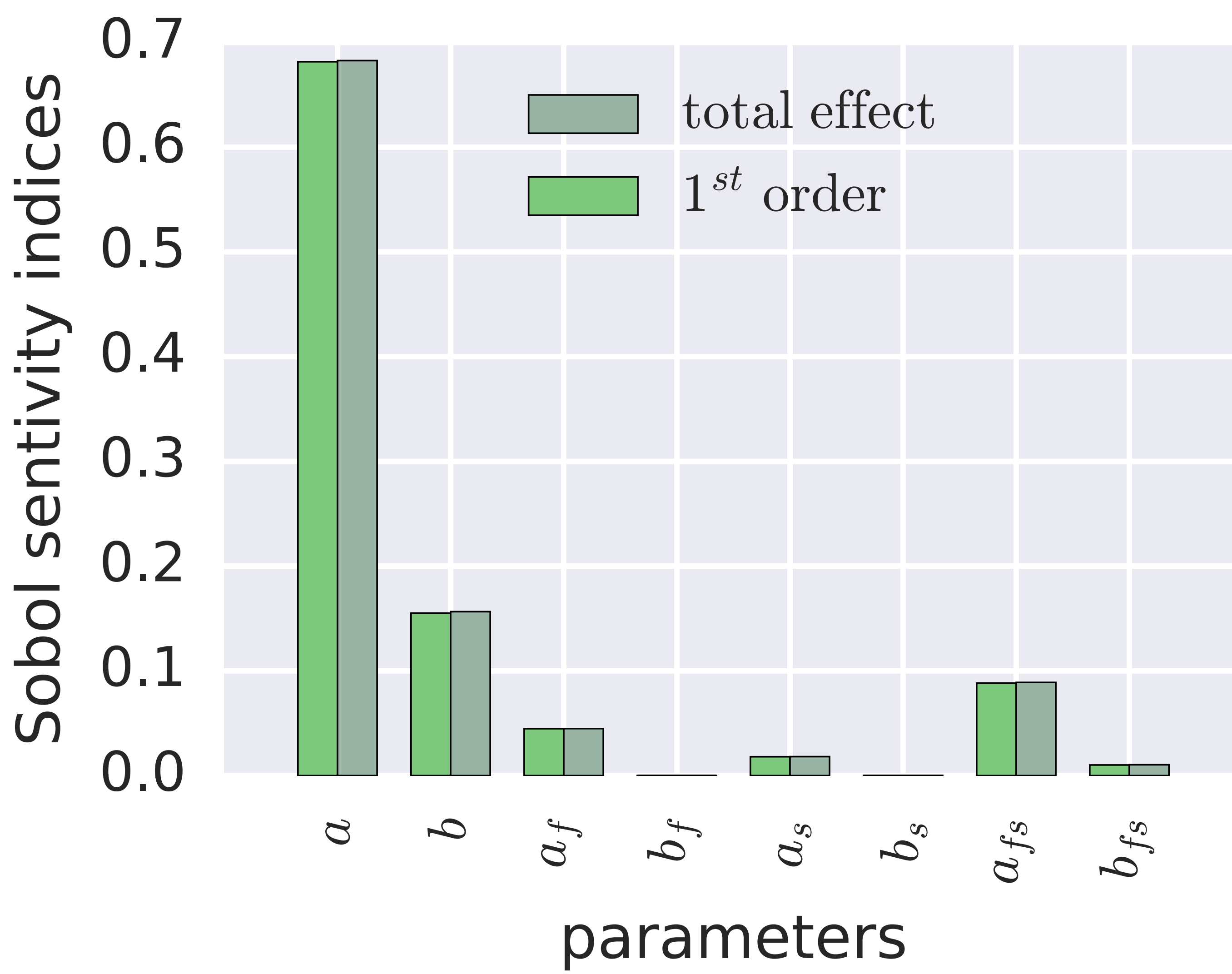


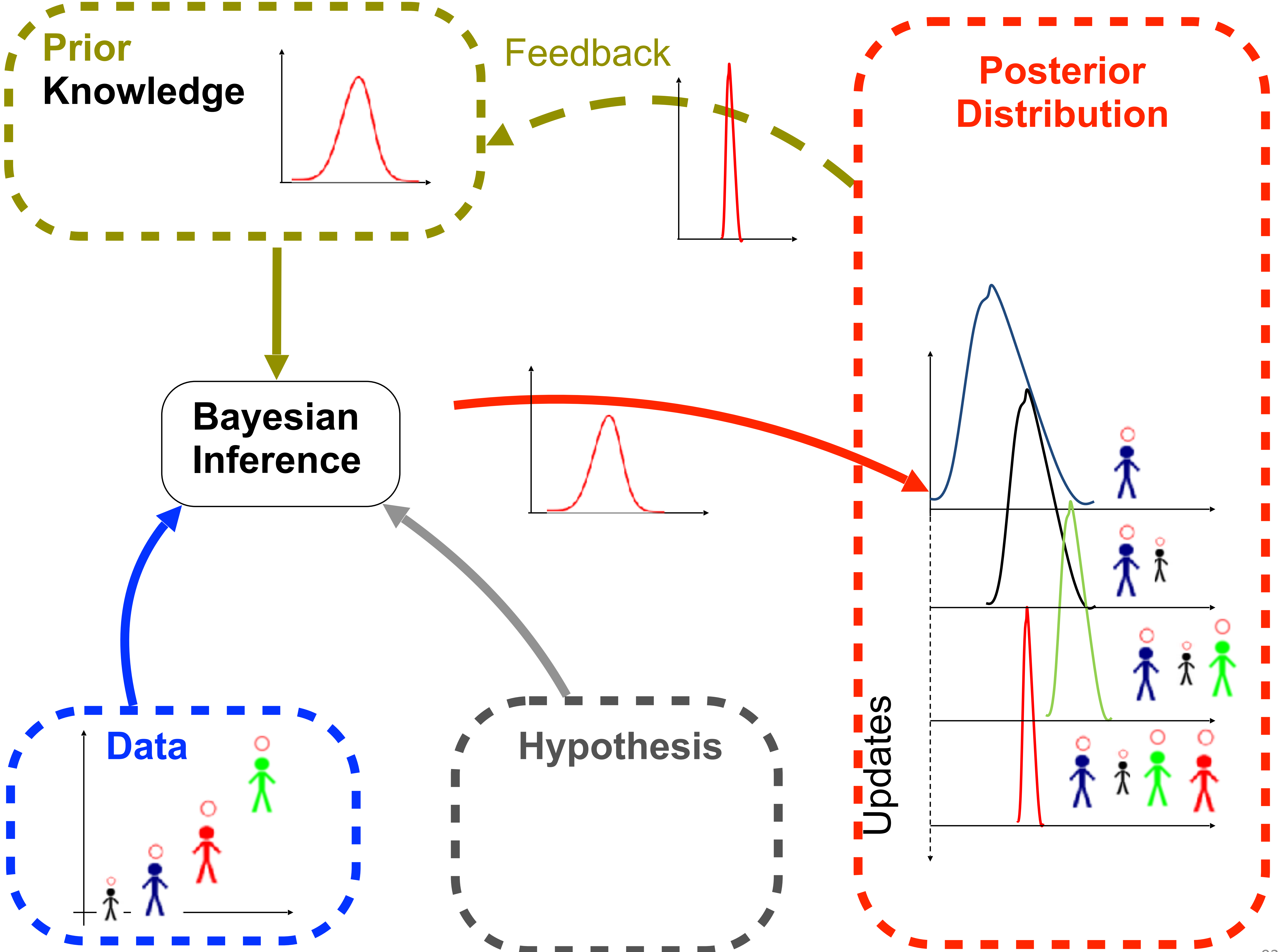
Fig. Center of the sphere: expected value of the displacement in the x direction as a function of Z.

Global sensitivity analysis

- Sobol sensitivity indices [Sobol 2015, Saltelli 2002]



Quantity of interest: displacement magnitude of the target.


Prior
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Distribution
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Updates
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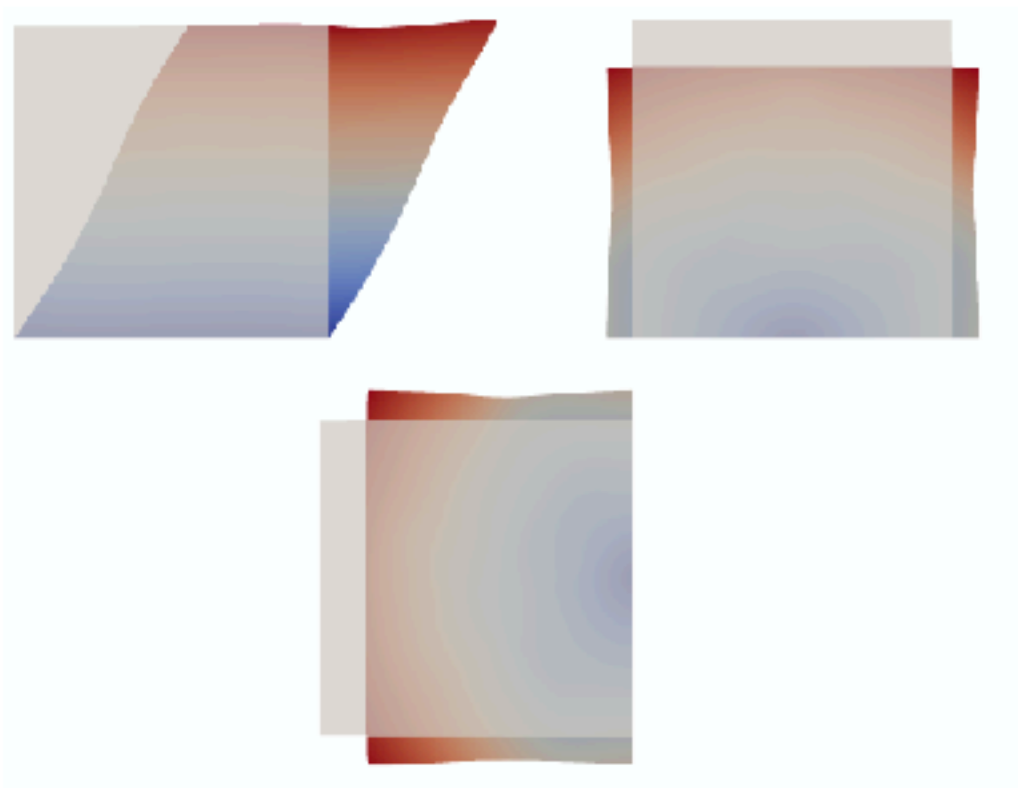
MODEL PROBLEM

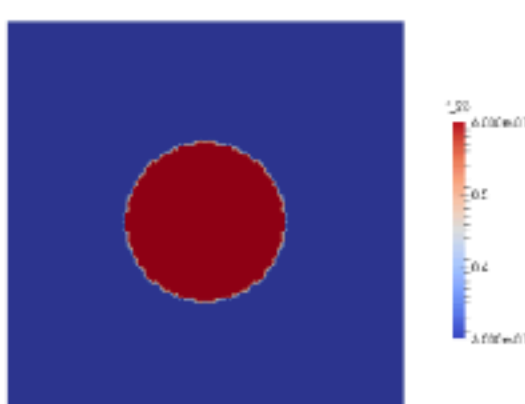
Given displacement observations on the surface of a block of soft tissue, possibly containing a stiff tumor, what can we infer about the material parameters of the tissue inside? How sure are we about what we infer?

FIGURE 1



Left: Three virtual experimental results from applying three different loads to the same non-homogeneous block of soft tissue. We are only given the observations on the exterior surface, and they are corrupted by random white noise.

FIGURE 2



Left: The true material parameter field used to generate the experimental data in Figure 1. A stiff circular tumour is surrounded by softer healthy tissue.

Elastography under uncertainty

METHODOLOGY

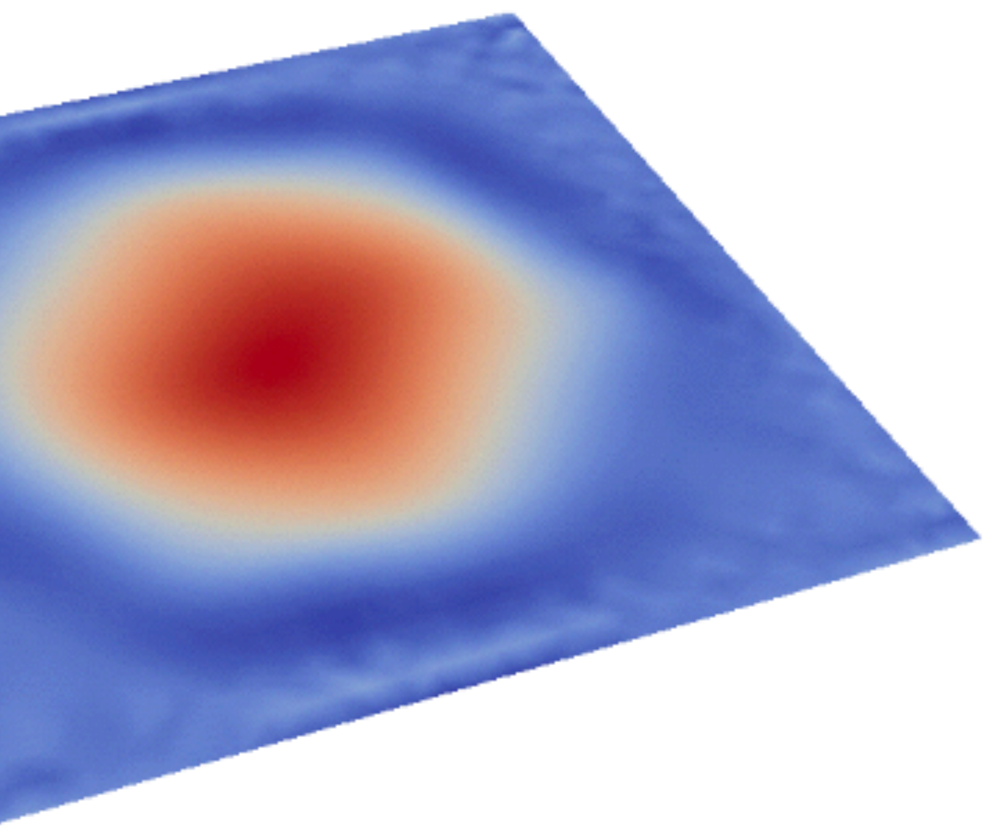
- We use the Bayesian framework for statistical inference (Stuart, 2010).
- Allows for rigorous statistical quantification of uncertainty arising from:
  - Partial observations.
  - Noisy instruments.
  - Model inadequacy.
- Soft tissue modelled by a fully non-linear hyperelastic PDE.
- Flexible Gaussian noise and prior modelling.
- We use derivatives of the finite element model to find the most likely material parameters and approximate the covariance structure.

Elastography under uncertainty

COMPUTATIONAL TECHNIQUES

- Automatic construction of forward and adjoint models with `dolfin-adjoint` (Farrell et al., 2013). *Easy to change physical model.*
- Efficient algebraic multigrid preconditioning of forward and adjoint models. *Forward runs dominate overall cost, reduce as much as possible.*
- Gauss-Newton Conjugate-Gradient method to find maximum a posteriori point. *Scales well on mesh refinement.*
- Matrix-free Krylov-Schur algorithm for principal component analysis of prior pre-and-post-conditioned Hessian of likelihood. *Fixed cost for given observations/model.*
- Optimal low-rank update from prior to posterior covariance (Spantini et al., 2014). *Reduces Hessian actions/forward model runs.*

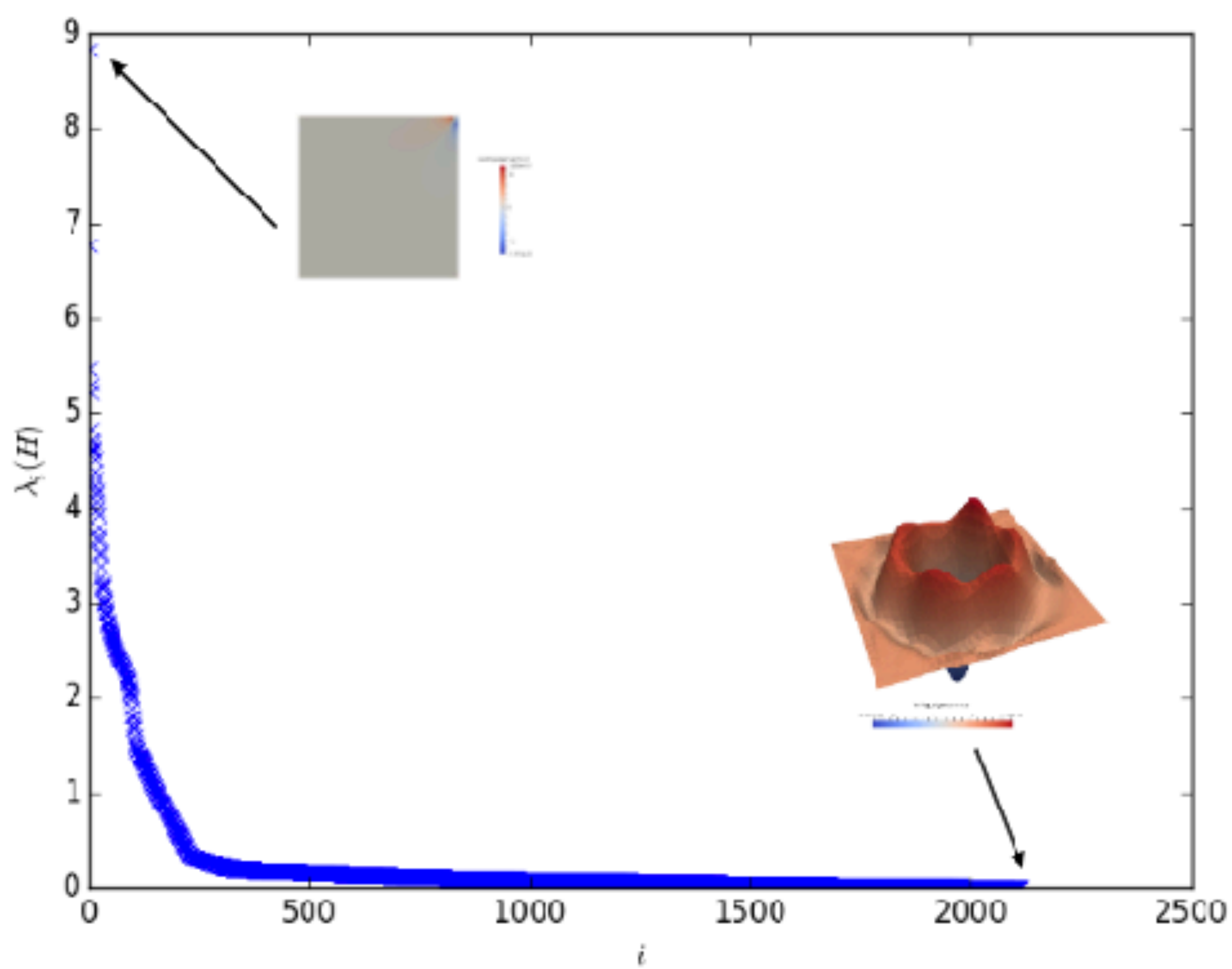
Elastography under uncertainty



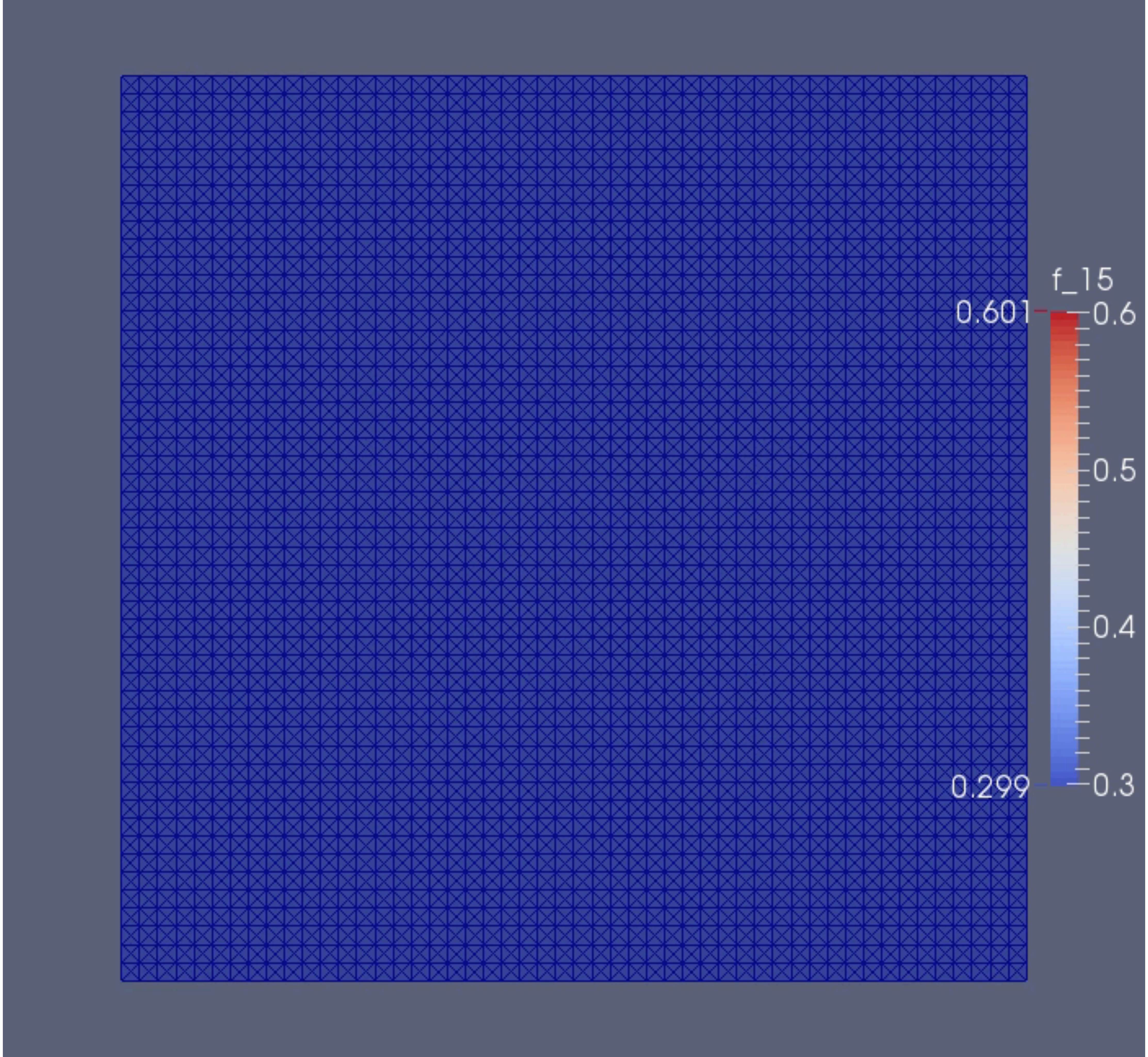
Left: Recovered MAP point, cf. Figure 1. We *can* detect the stiff inclusion inside the object just from the noisy surface observations.

Elastography under uncertainty

FIGURE 5



Left: Low-rank structure of spectrum of posterior covariance. Data is only informative on low-rank subspace of original parameter space. Top left eigenvector points towards direction in parameter space most-constrained by the observations, bottom right towards least-constrained.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Eye surgery
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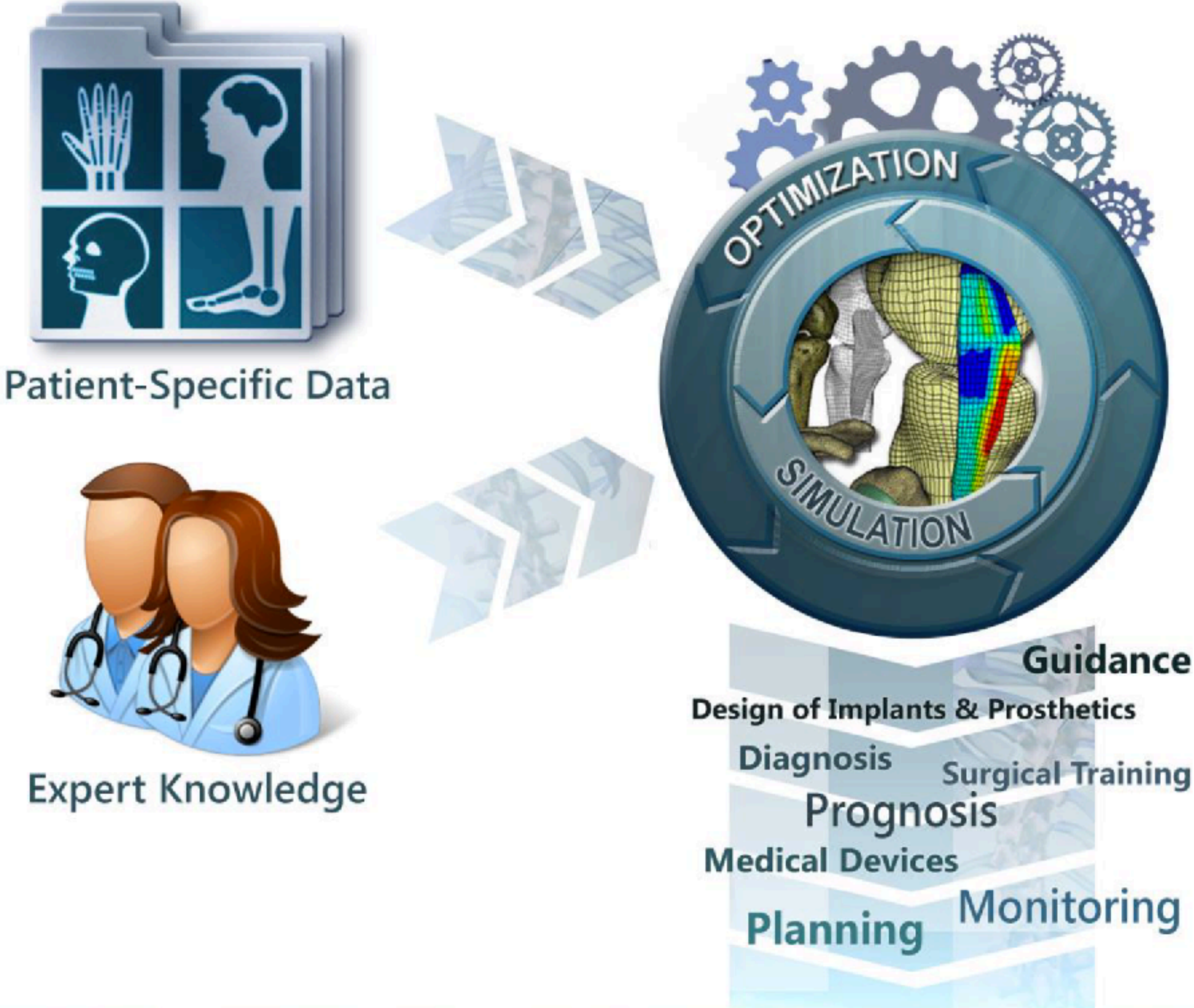
Breast Cancer
Surgical navigation
Surgical planning
Apps



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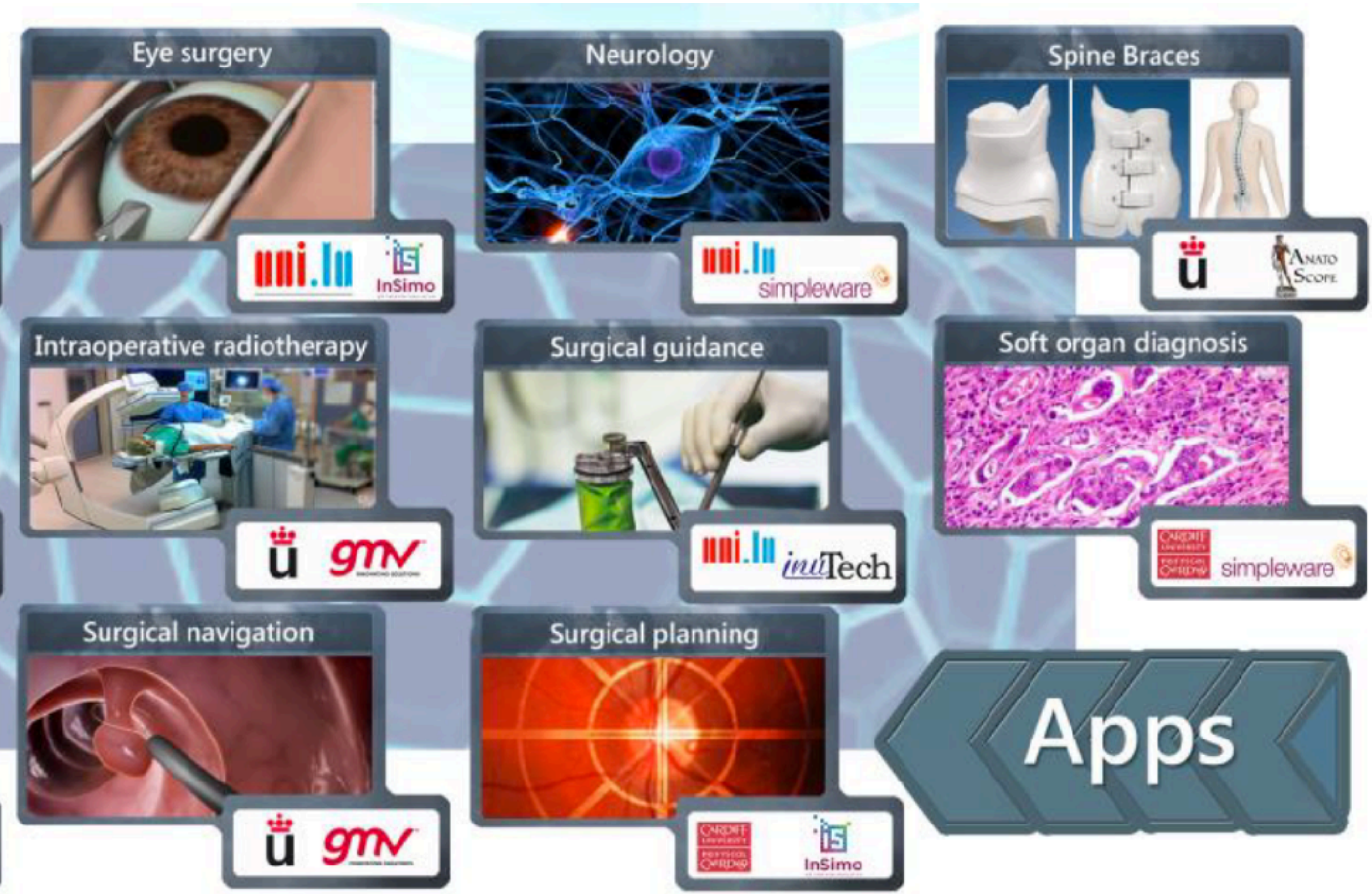
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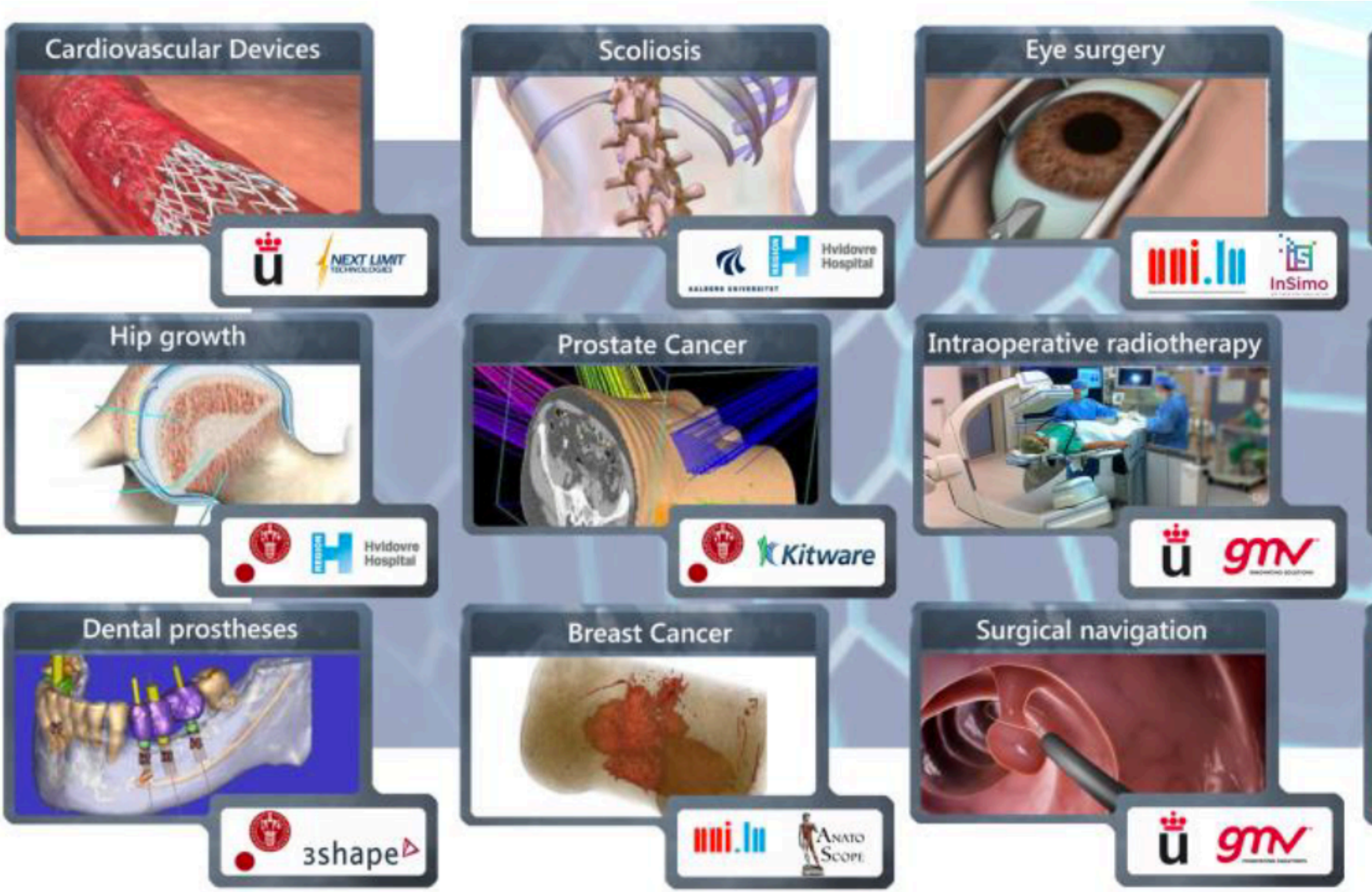
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