Computed in Luxembourg

Computational Sciences Luxembourg

Data-driven modelling and simulation: fracture and medical simulations

Computed in Luxembourg

Computational Sciences Luxembourg

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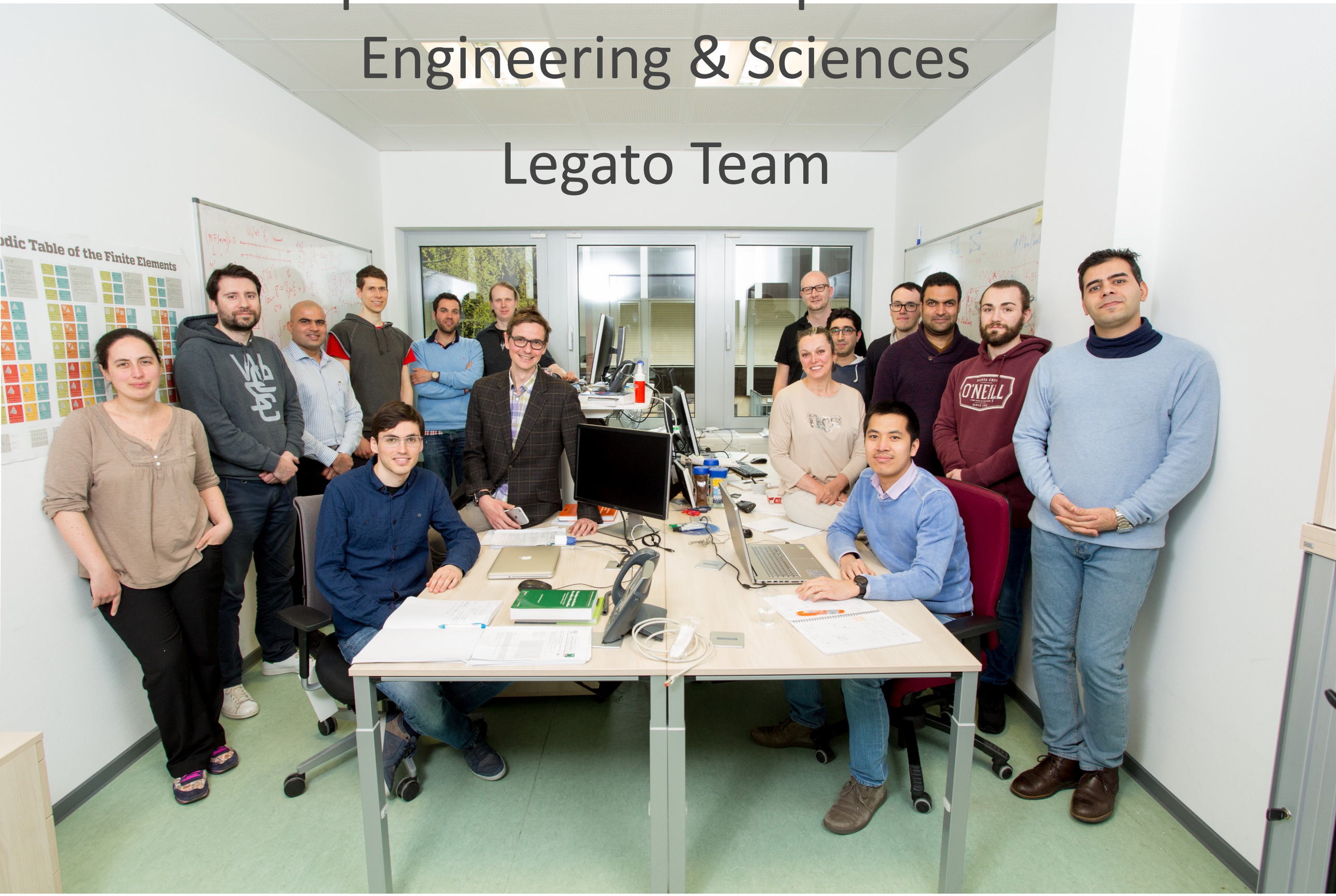
Vanessa Lleras
Claudio Lobos
Alexei Lozinski
Pierre-Yves Rohan
Satyendra Tomar

Department of Computational Engineering & Sciences

Legato Team



Detailed presentation: IGA, Fracture, Errors, Free Boundaries http://hdl.handle.net/10993/31487


10 km
10 miles
ARDENNES
Clervaux
BELGIUM
Wiltz
Vianden
GERMANY
Diekirch
MULLERTHAL
Echternach
LUXEMBOURG
Grevenmacher
LUXEMBOURG
MOSELLE
VALLEY
Moselle
Petange
Differdange
Modorf-les-Bains
Esch
Budelange
FRANCE
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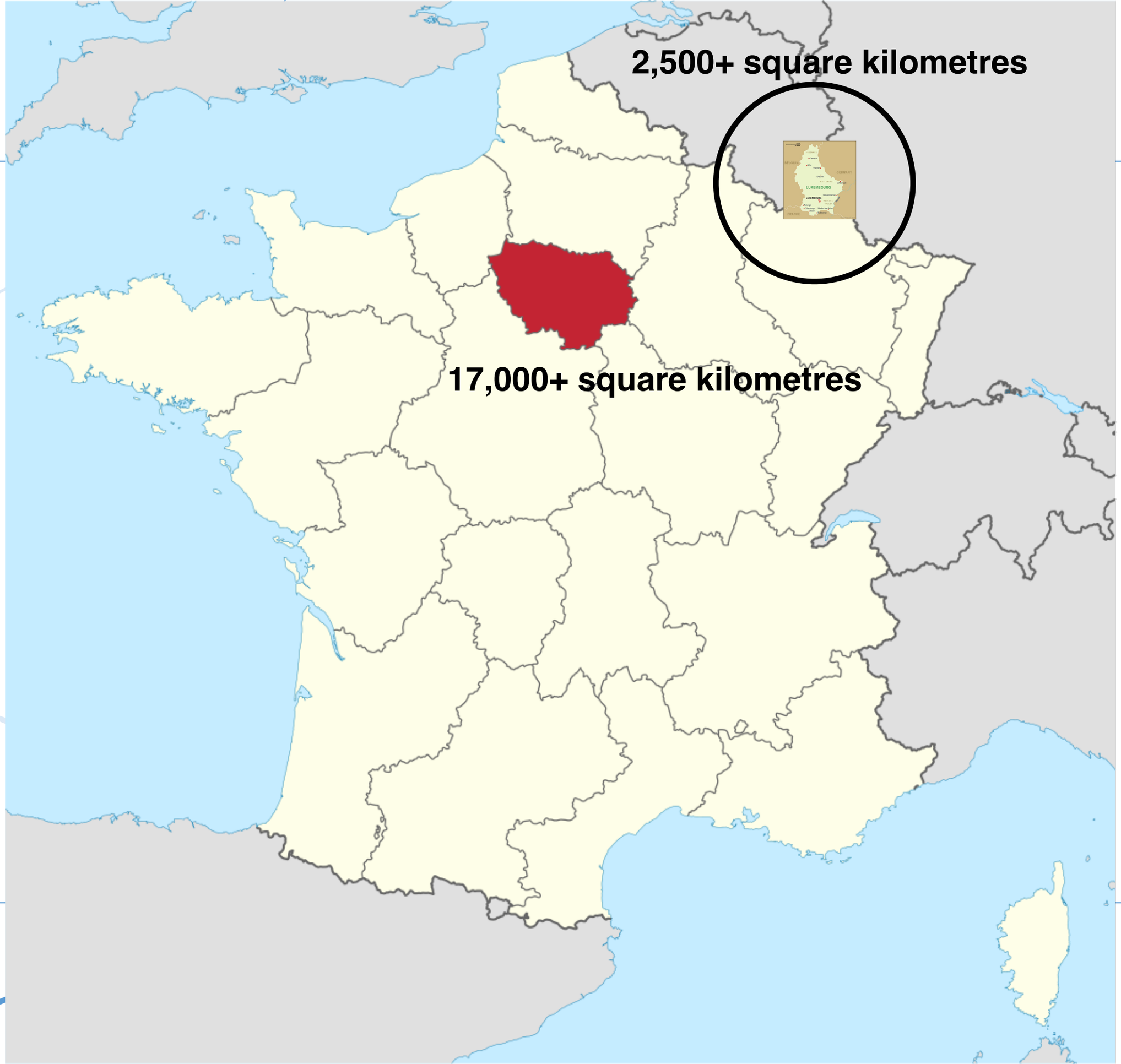
BELGIUM
GERMANY
LUXEMBOURG
FRANCE


2,500+ square kilometres
17,000+ square kilometres
LUXEMBOURG
BELGIUM
GERMANY
FRANCE


10 km
10 miles
ARDENNES
Clervaux
BELGIUM
Wiltz
Vianden
GERMANY
Diekirch
MULLERTHAL
Echternach
LUXEMBOURG
Grevenmacher
LUXEMBOURG
MOSELLE
VALLEY
Moselle
Petange
Differdange
Modorf-les-Bains
Budelange
FRANCE
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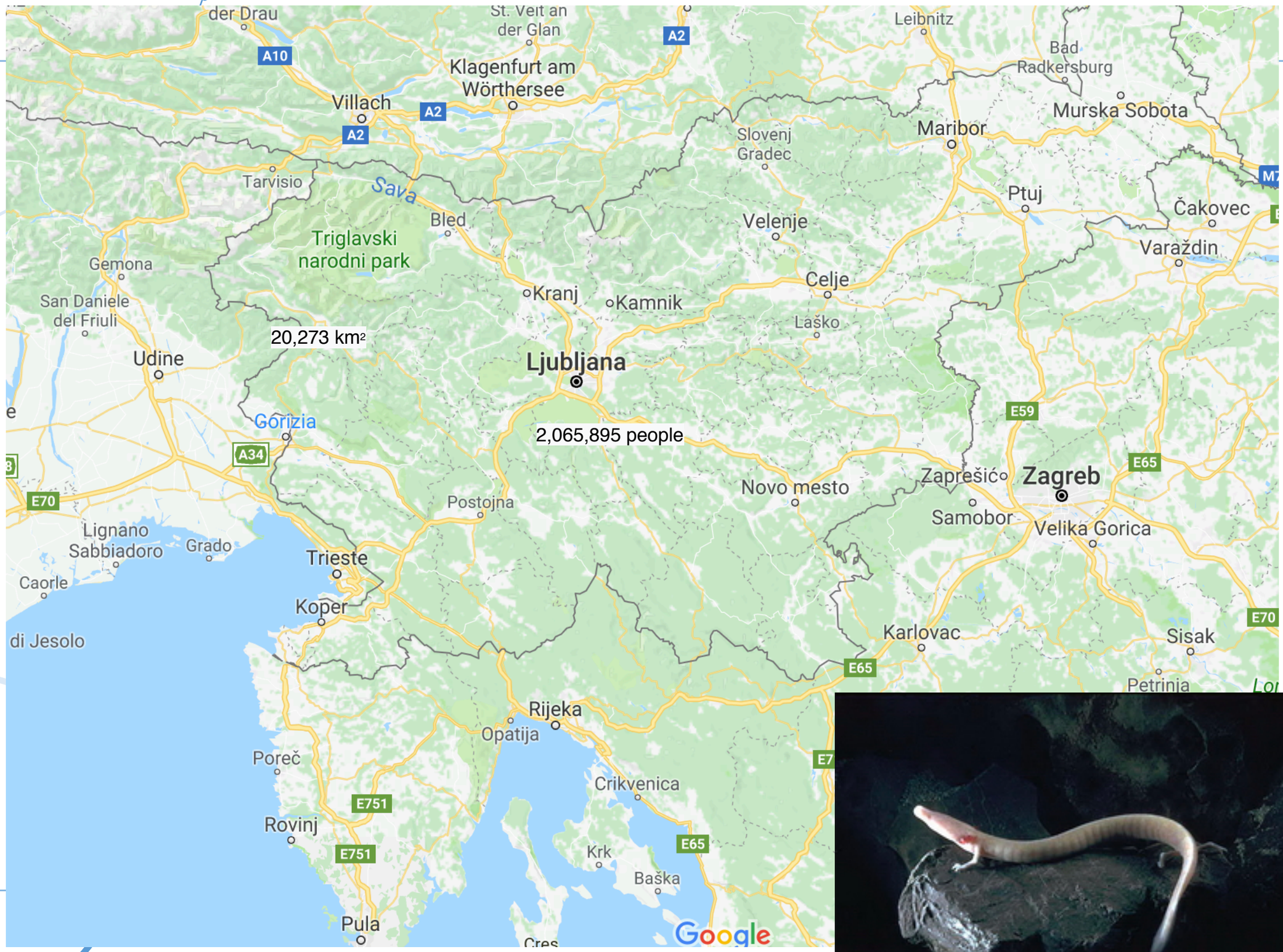
20,273 km²
2,065,895 people
Ljubljana
Kranj
Kamnik
Velenje
Celje
Ptuj
Maravar
Murska Sobota
Bad Radkersburg
Leibnitz
Slovenj Gradec
Maribor
Čakovec
Varaždin
Laško
Triglavski narodni park
Sava
Bled
Tarvisio
Gemona
San Daniele del Friuli
Udine
Gorizia
Villach
Klagenfurt am Wörthersee
St. Veit an der Glan
der Drau
Postojna
Novo mesto
Zaprešić
Zagreb
Samobor
Velika Gorica
Lignano Sabbiadoro
Grado
Caorle
di Jesolo
Trieste
Koper
Rijeka
Opatija
Poreč
Rovinj
Pula
Crikvenica
Krk
Baška
Karlovac
Sisak
Petrinja
Velika Kladuša
Cazin
Plitvička Jezera
A10
A2
A34
E70
E65
E751
E71
E59
Google



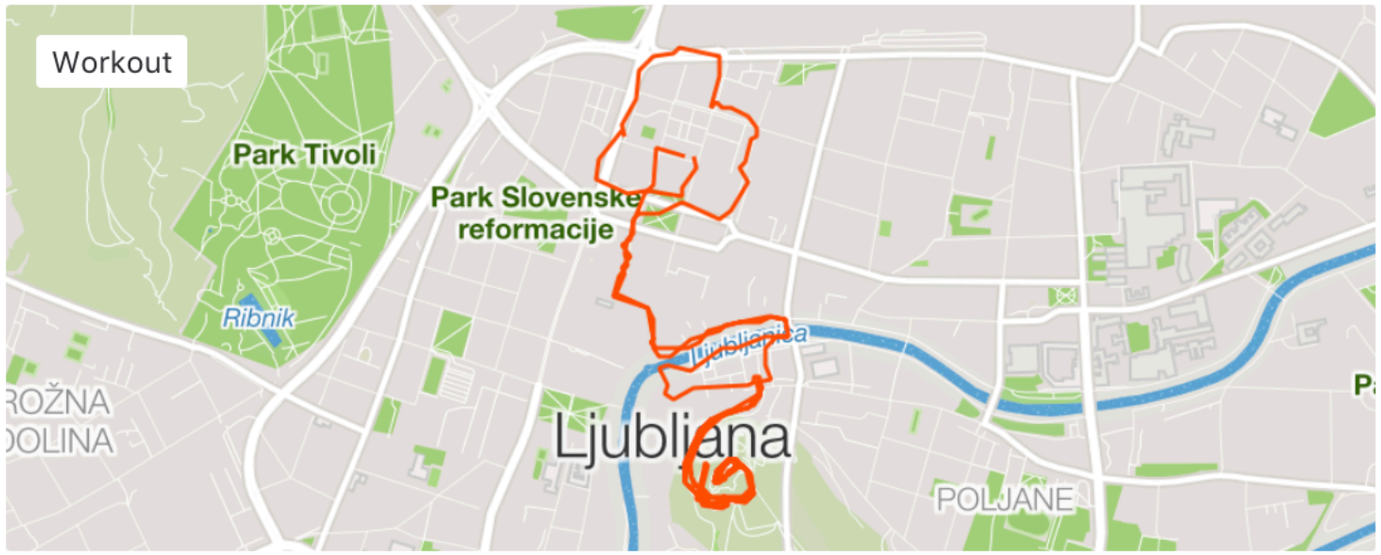
Olm can be found in Postojna caveand other caves in the country.

Stéphane BORDAS
Today at 5:53 PM

Climb to Ljubljana castle x 2. D+450m

Distance	Elevation Gain	Average Pace	Achievements
8.02km	446m	6:52/km	6

Na Stolbi 8 Climb **7th overall** (3:35)
This ain't easy. **PR** (3:39)



February Climbing Challenge

Nice work, Stéphane!

2,050 m	16	1,127 / 53,321
Total Elevation	Total Runs	Current Rank

Overall Leaderboard

1	Igor Sa	57,415 m
2	Evanio Valentini	35,298 m
3	Juanjo Cabrera Martinez	33,656 m
4	Chris Norris	31,810 m
5	Lucilene Damiani	31,046 m
	...	
1,125	Andy Ford	2,050 m
1,126	Jan Salke	2,050 m
1,127	Stéphane BORDAS	2,050 m
1,127	Damien Lane	2,050 m
1,127	Ricardo C	2,050 m

Computed in Luxembourg

Computational Sciences Luxembourg

UNIVERSITÉ DU LUXEMBOURG

20180207 Jožef Stefan Institute Colloquium, Ljubljiana, Slovenia

Medicine

The average drug developed by a major pharmaceutical company costs at least $4 billion, and it can be as much as $11 billion.

Mechanics

The development cost of the A380

11 billion euros…

of the dreamliner…

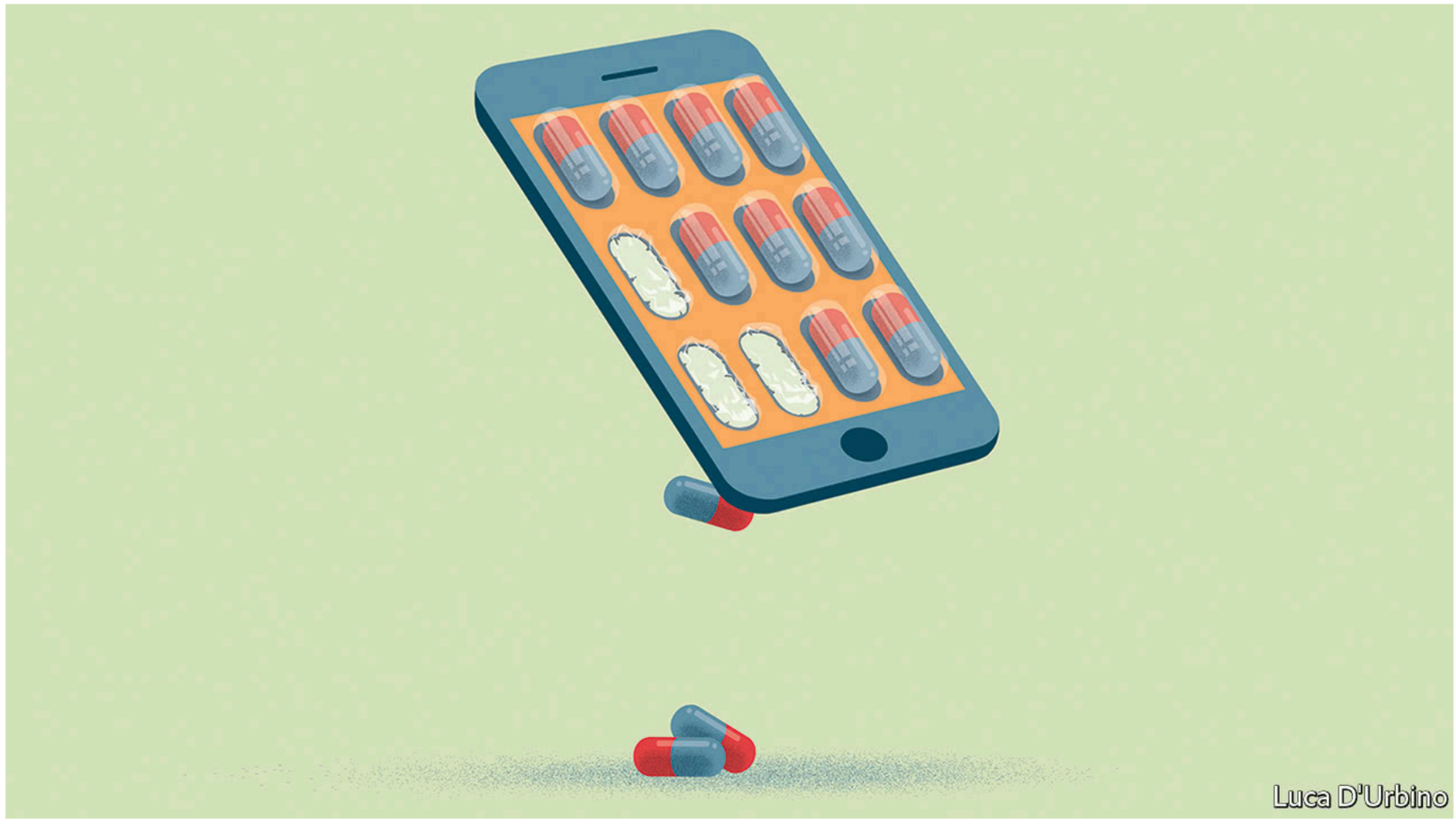
$32 billion


The Economist
FEBRUARY 3RD–9TH 2018
Theresa May: dead woman standing still
Ponzi schemes in China
Higher education, lower returns
Pity the pangolin
Doctor You
How data will transform health care

Tech giants go to med school

Apple and Amazon's moves in health signal a coming transformation

The world's biggest tech firms see a rich opportunity in health care, which could mean empowered patients, better diagnosis of disease and sharply lower costs



Print edition | Business ›

Feb 3rd 2018


GARMIN
AUTHORISED DEALERS SINCE 2005
GARMIN
IQ
Run
SUSTUU ON EBAY SINCE 2005


GARMIN
AUTHORISED DEALERS SINCE 2005
GARMIN


GARMIN
AUTHORISED DEALERS SINCE 2005
GARMIN
TIMEX
Connecting to fitness app...
wahoo
Bluetooth
TIMEX

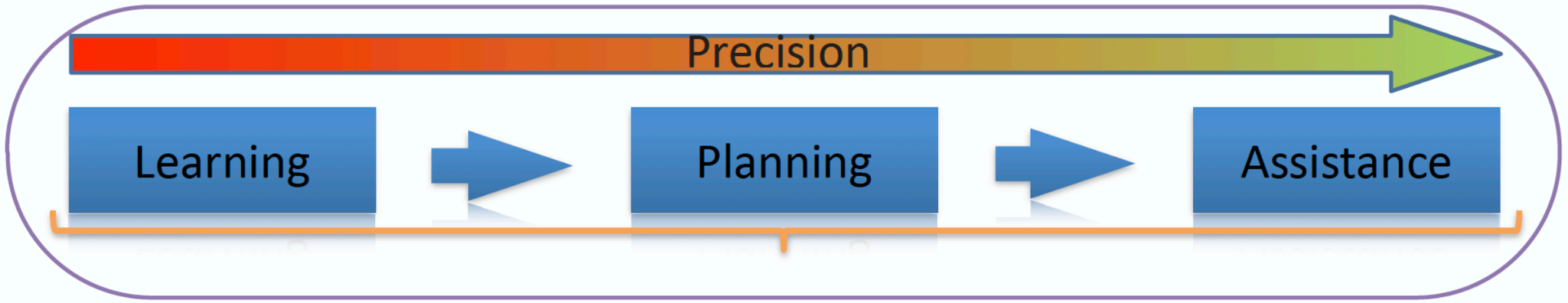

Measuring...
For best results, keep Apple Watch still and snug on top of your wrist.
65 BPM, 8m ago
68 BPM
65 BPM, 8m ago

DIGITAL TWIN OF…

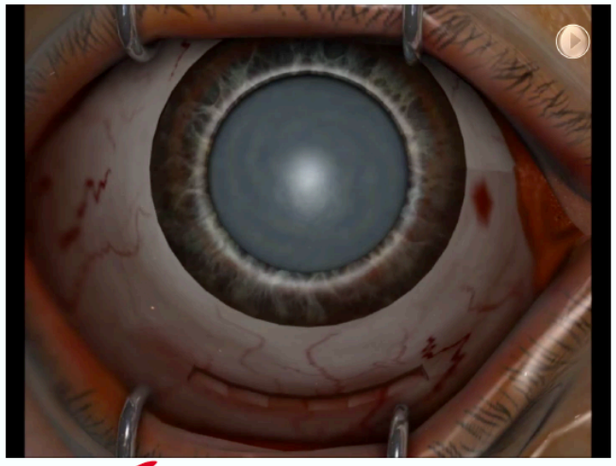
Alex Garland, *Ex Machina*, 2015

Surgical simulation

RealTcut

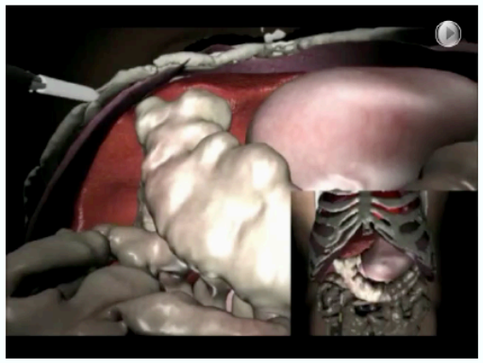


Cataract Surgery



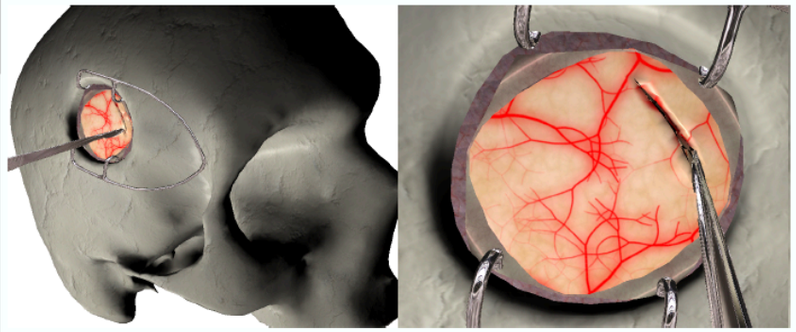
Inria

Abdominal minimally invasive surgery simulation (Inria, Shacra)



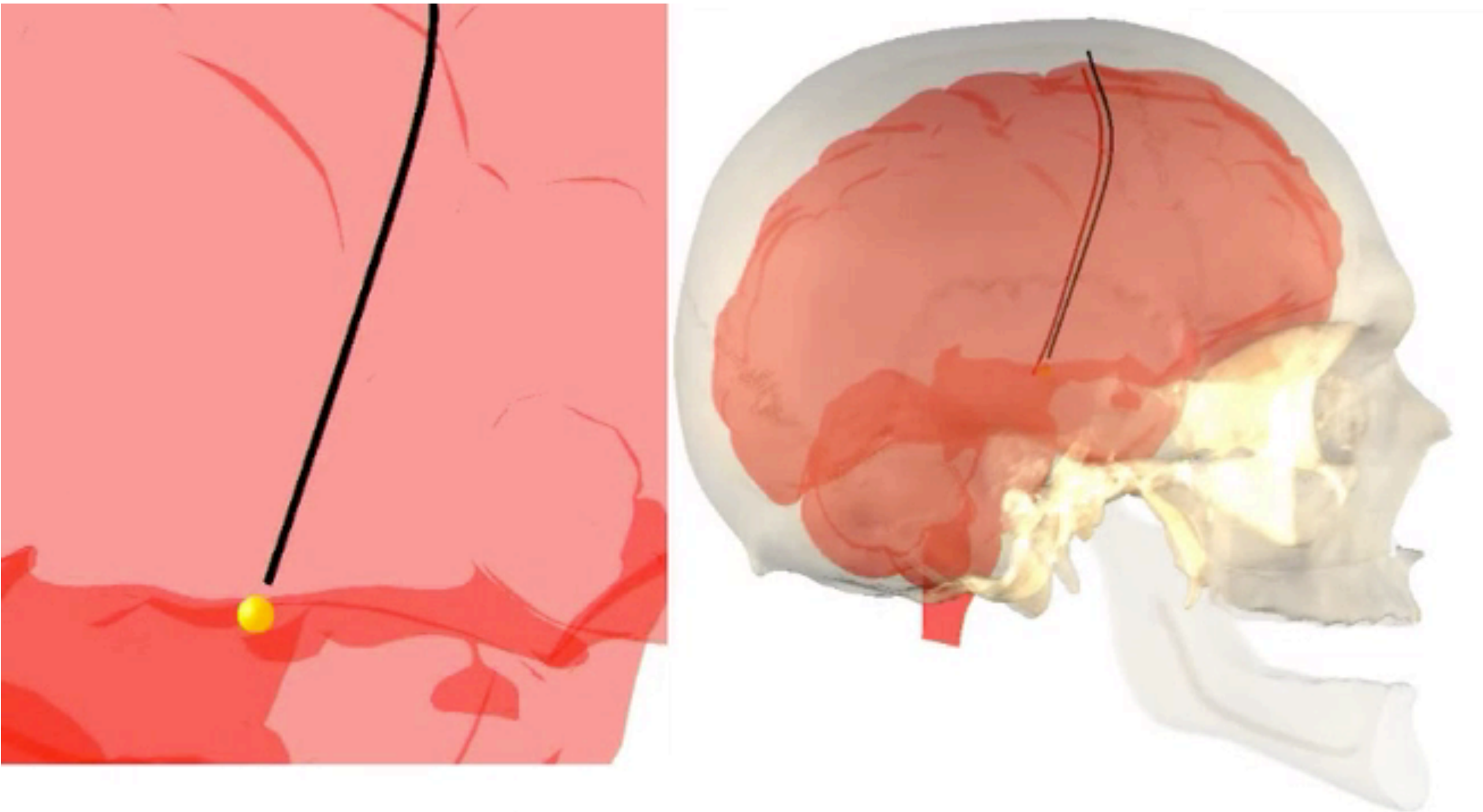
Inria

First implicit, interactive method for cutting with contact



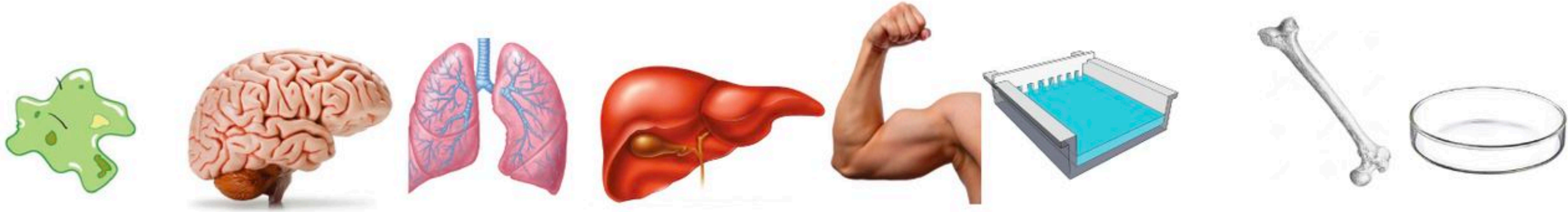
[Courtecuisse et al., MICCAI, 2013 and Medical Image Analysis, 2014]

YOU!



Deep-brain stimulation

Courtesy Alexandre Bilger, post-doc in the Legato team, PhD thesis, Inria, 2014

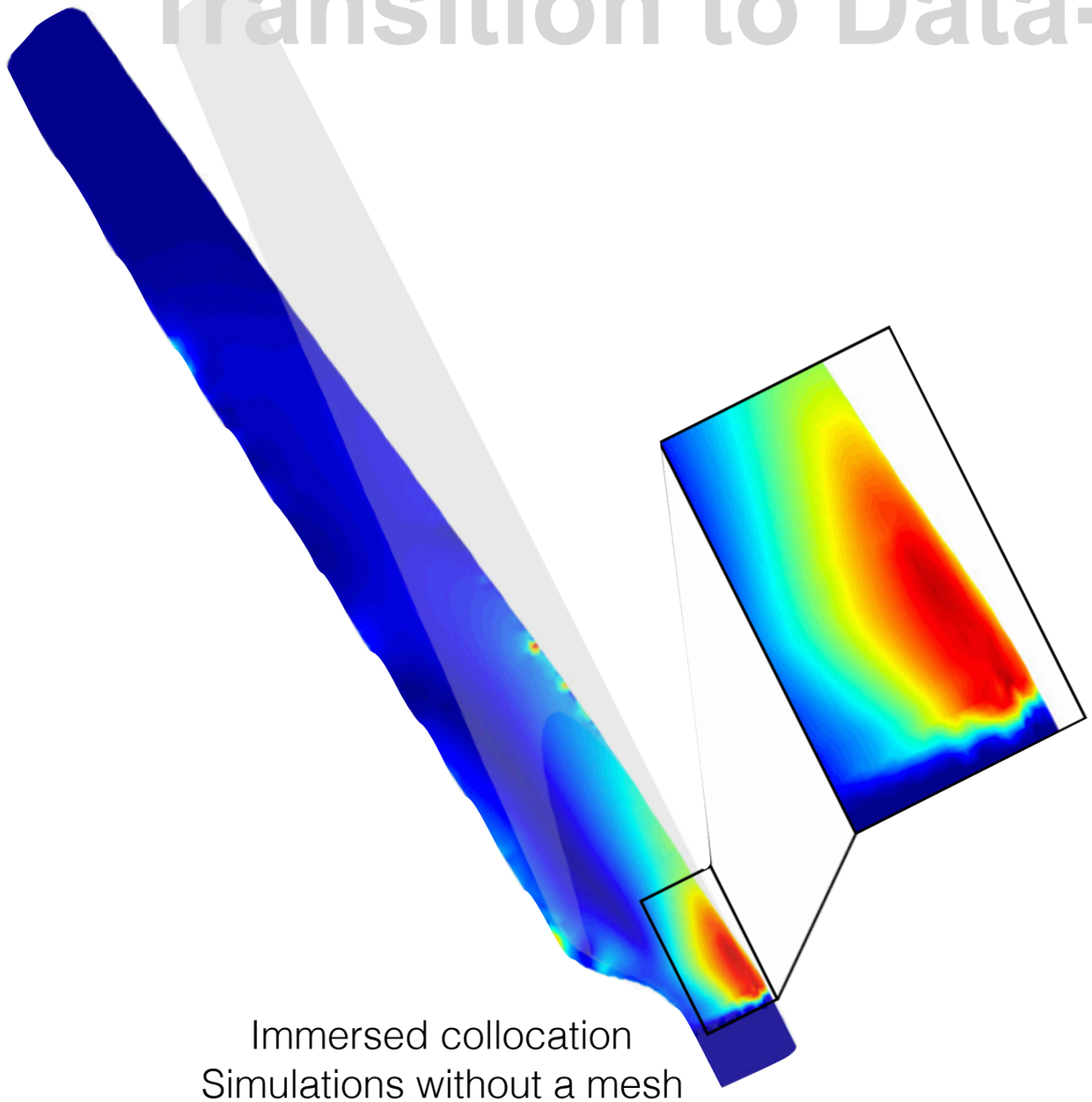


Tissue mechanics regulate brain development, homeostasis and disease

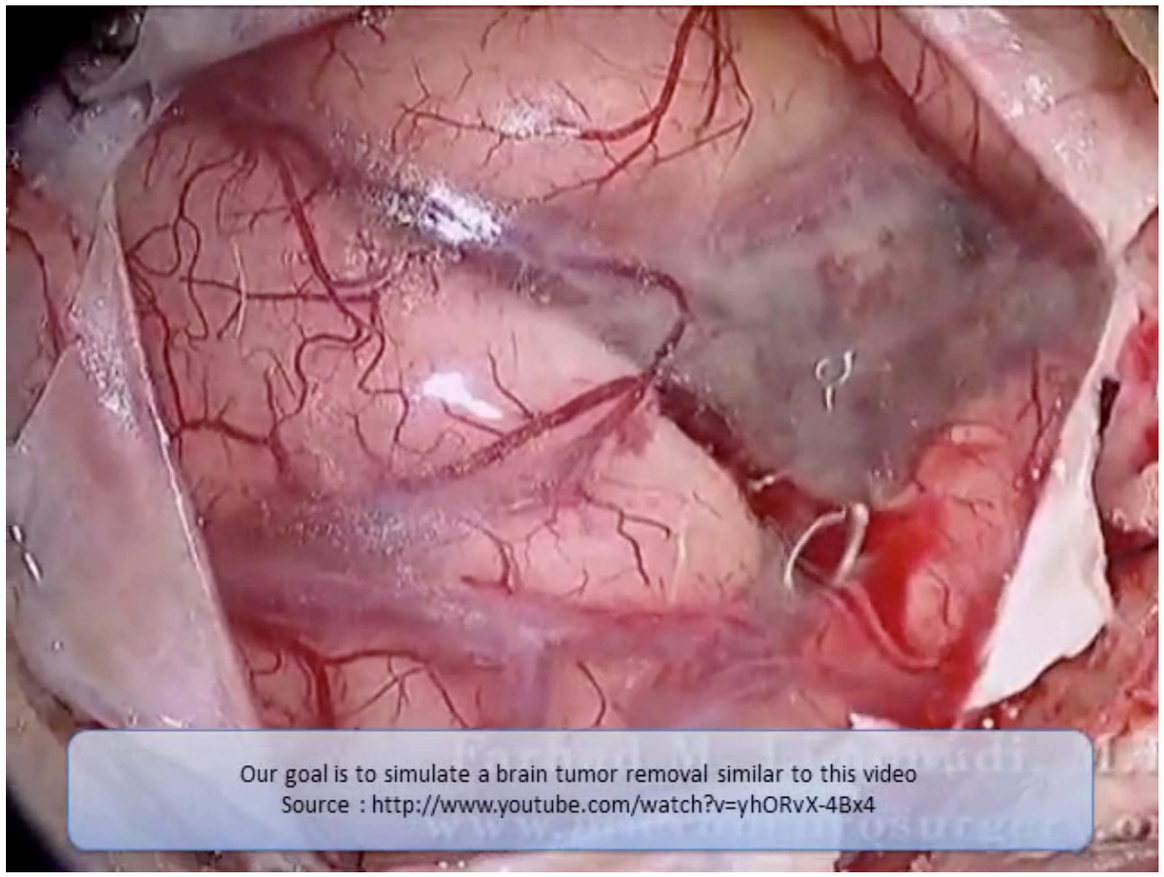
J. Matthew Barnes, Laralynne Przybyla, Valerie M. Weaver

J Cell Sci 2017 130: 71-82; doi: 10.1242/jcs.191742

Computational Sciences & Transition to Data-Driven Modelling



Immersed collocation
Simulations without a mesh



Real-time cutting, MEDIA2014, IEEE2017

Engineering

Personalised medicine

erc

RealTCut

Stéphane Pierre Alain BORDAS, Department of Computational Engineering & Sciences University of Luxembourg

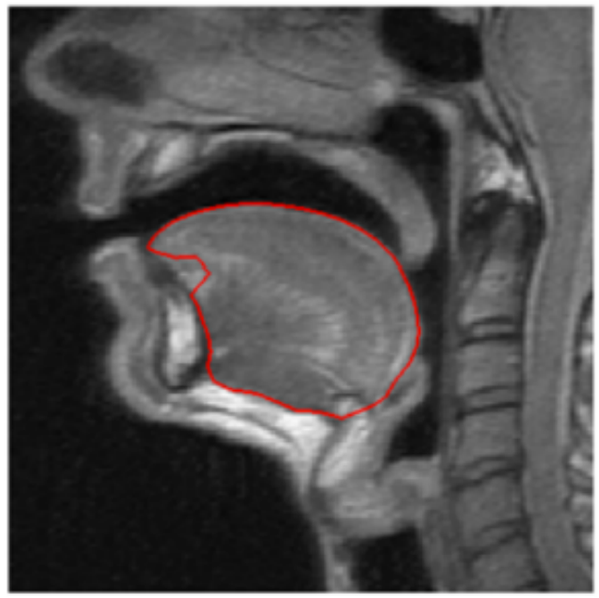
Quantify the quality of the simulation

physical problem

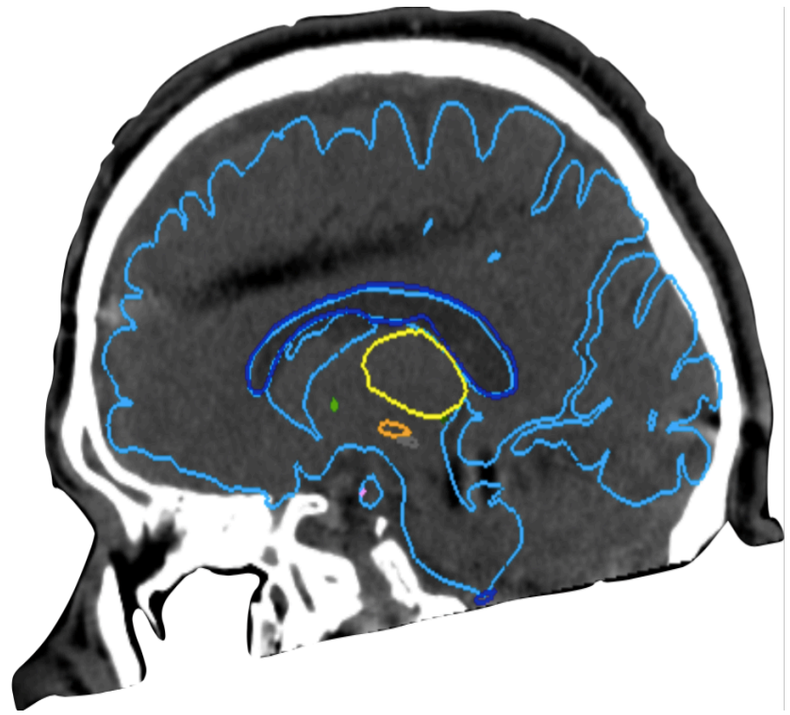
Stéphane Pierre Alain BORDAS, Department of Computational Engineering & Sciences University of Luxembourg

Quantify the quality of the simulation

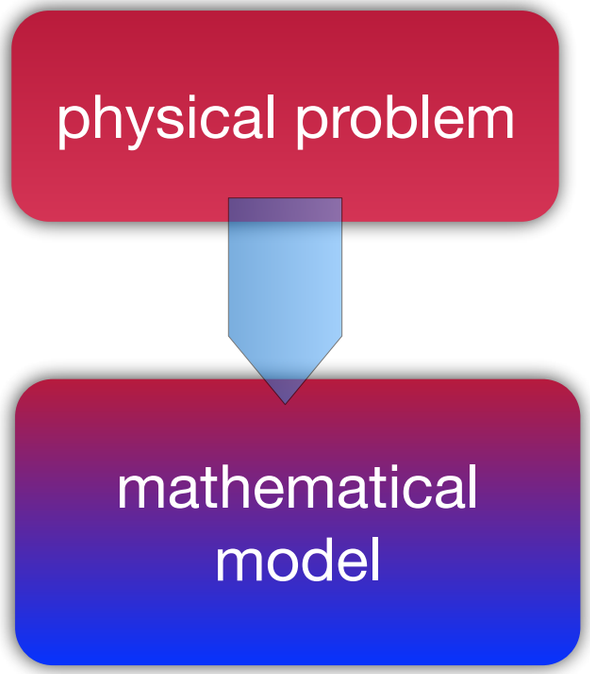
physical problem



Bijar, Rohan, Perrier & Payan 2015



Quantify the quality of the simulation



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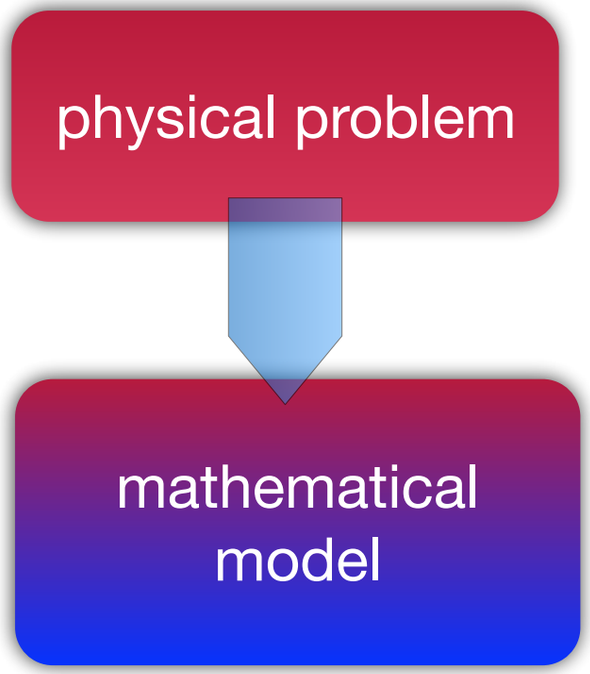


$$\min_{\mathbf{u}\in\mathbf{V}} \frac{1}{2}\int_\Omega \boldsymbol{\sigma}(\mathbf{u},\beta) : \boldsymbol{\varepsilon}(\mathbf{u})\, d\mathbf{x} - \int_\Omega \mathbf{g}\cdot\mathbf{u}\, d\mathbf{x}$$

with $\boldsymbol{\sigma}(\mathbf{u},\beta) = \underbrace{\boldsymbol{\sigma}_P(\mathbf{u})}_{\text{passive material}} + \underbrace{\boldsymbol{\sigma}_A(\beta)}_{\text{muscular activation}}$

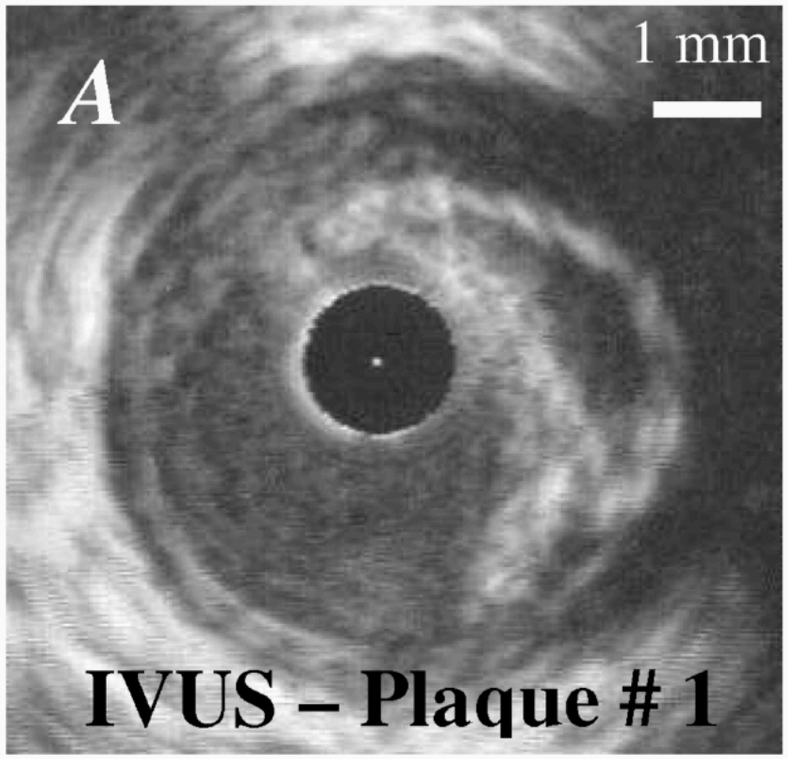
$$\begin{cases} \boldsymbol{\sigma}_A(\beta) = \beta T e_A \otimes e_A \\ e_A : \text{ fiber direction} \\ T : \text{ tension} \\ \beta : \text{ activation} \end{cases}$$

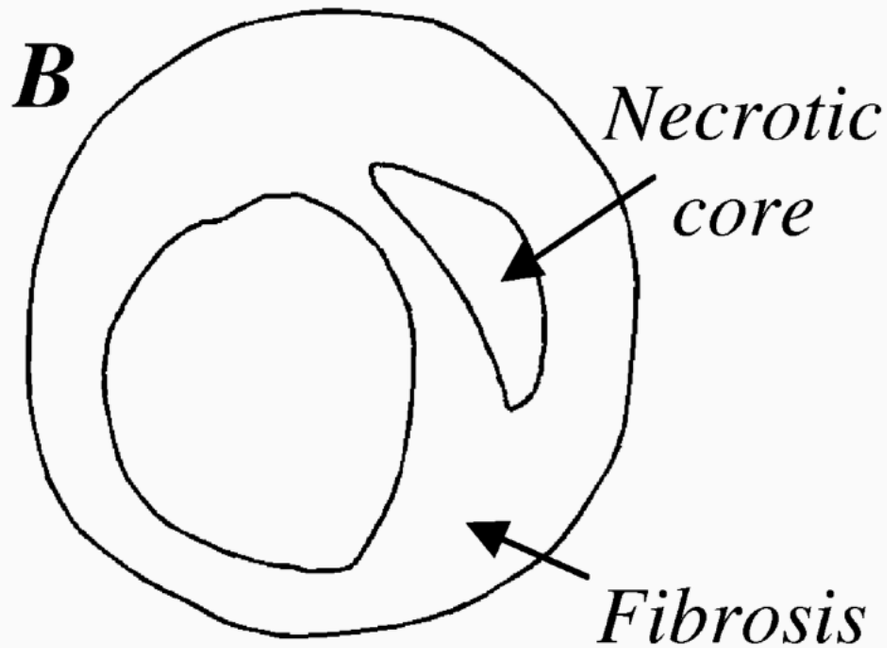
Material model and governing equations

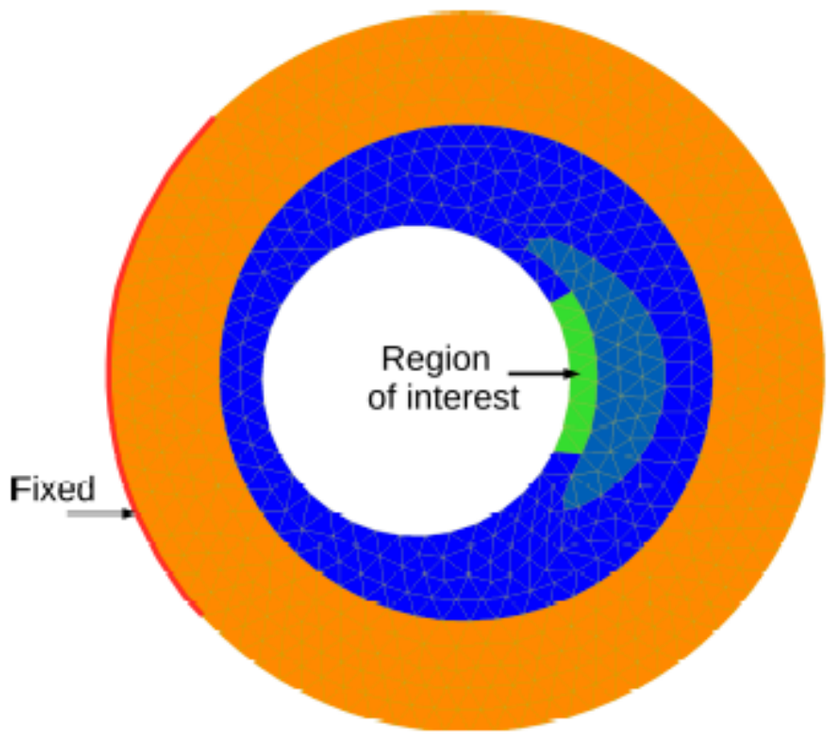
Quantify the quality of the simulation

physical problem

mathematical model

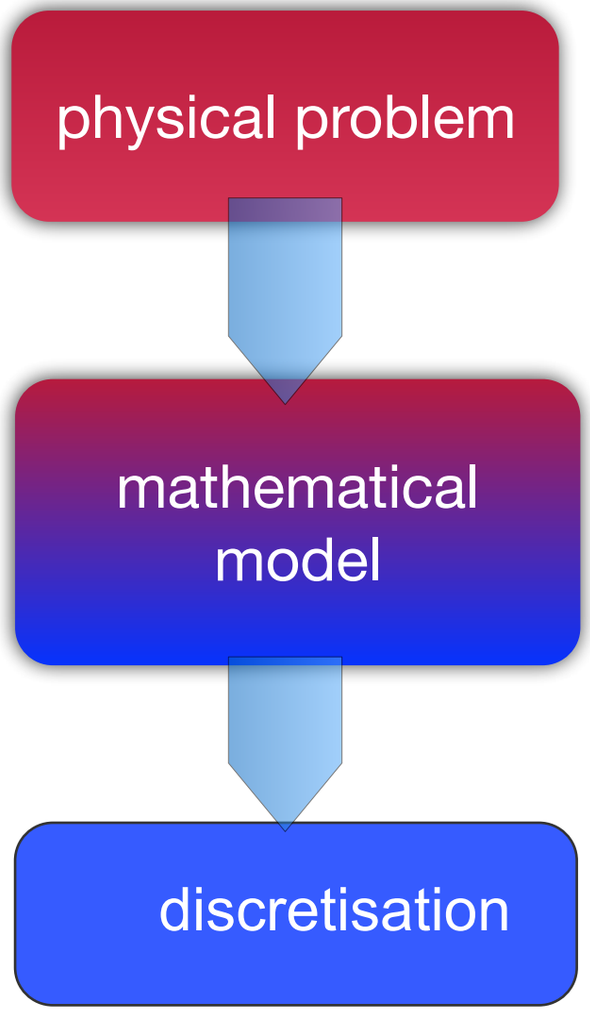






Geometry and Boundary Conditions

Quantify the quality of the simulation

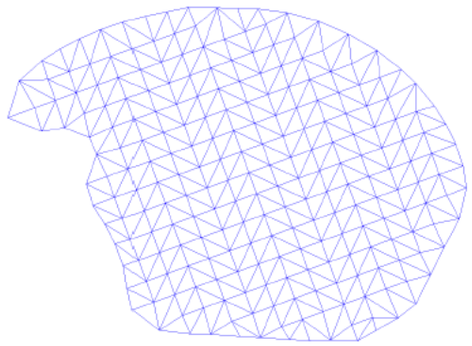


Quantify the quality of the simulation

physical problem

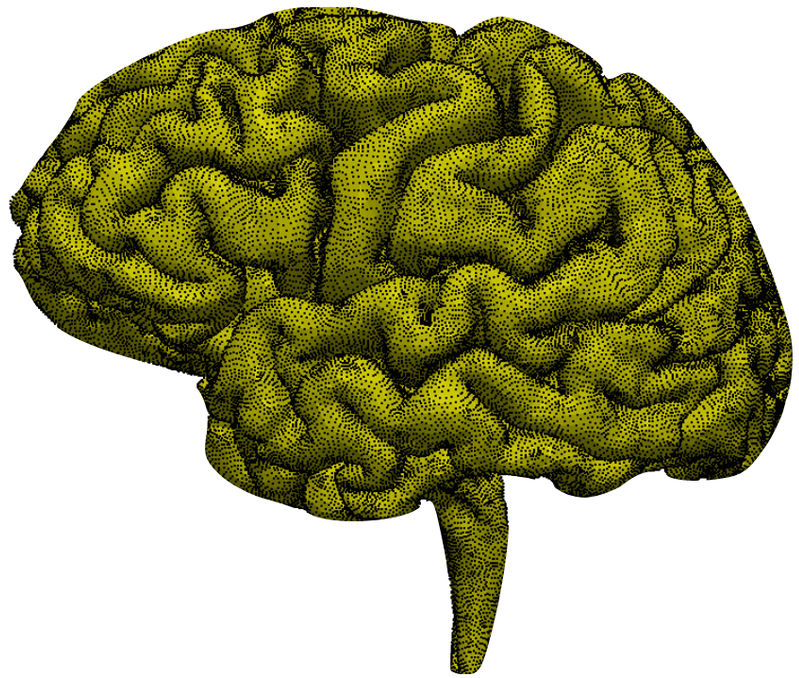
mathematical model

discretisation



Finite element mesh
of a tongue with F. Chouly et al.

Hexahedral mesh of a brain
with Bruno Lévy, Inria



Meshless brain discretization
with Bruno Lévy, Inria

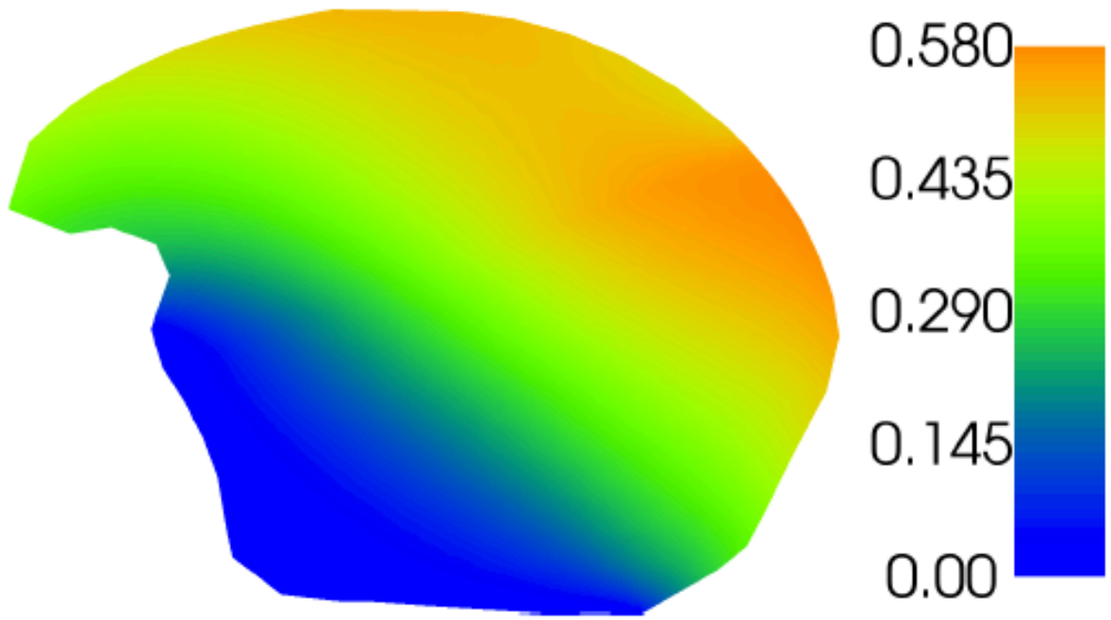
Quantify the quality of the simulation

physical problem

mathematical model

discretisation

numerical solution



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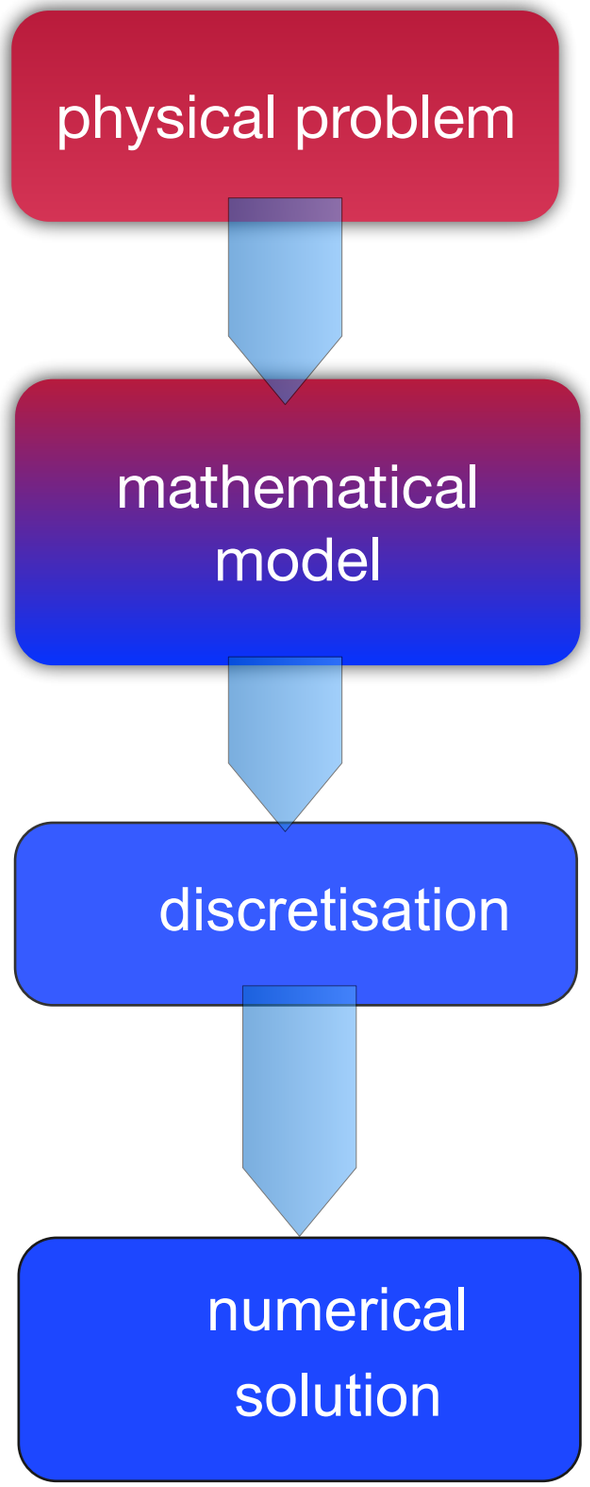
Quantify the quality of the simulation



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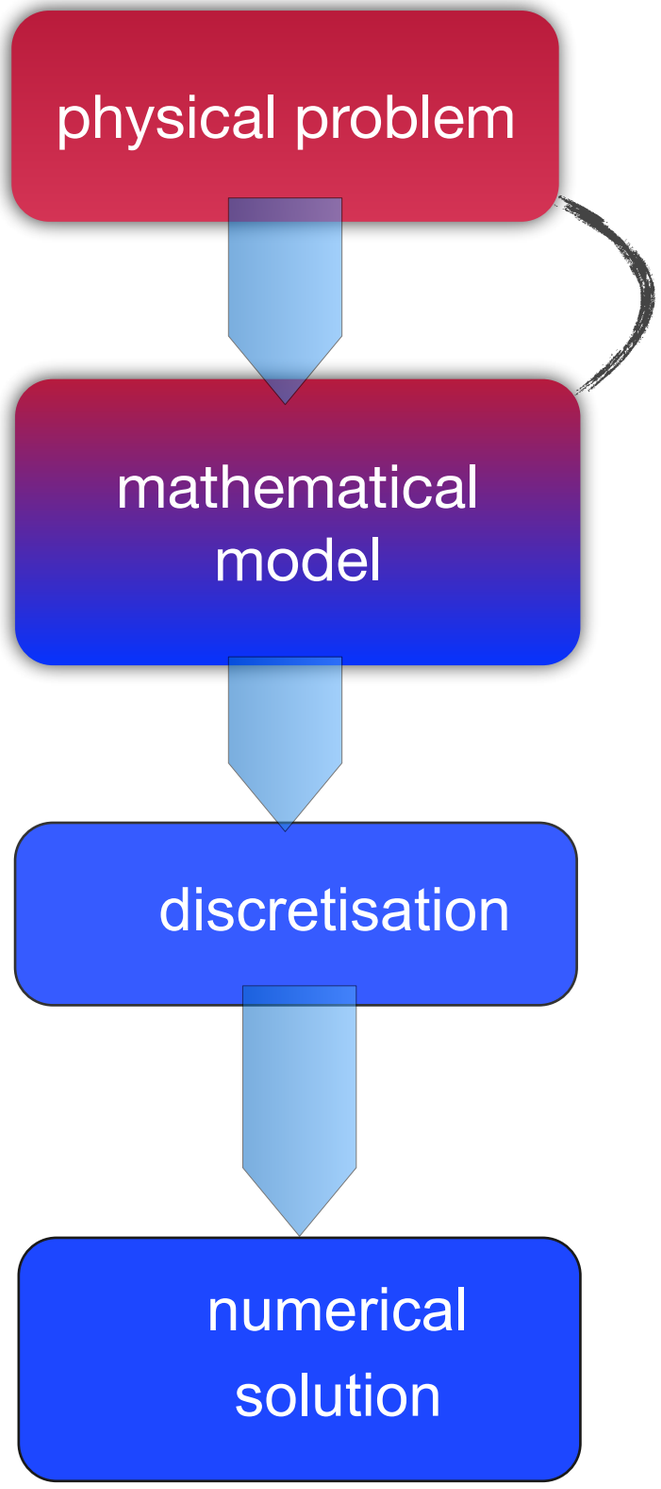
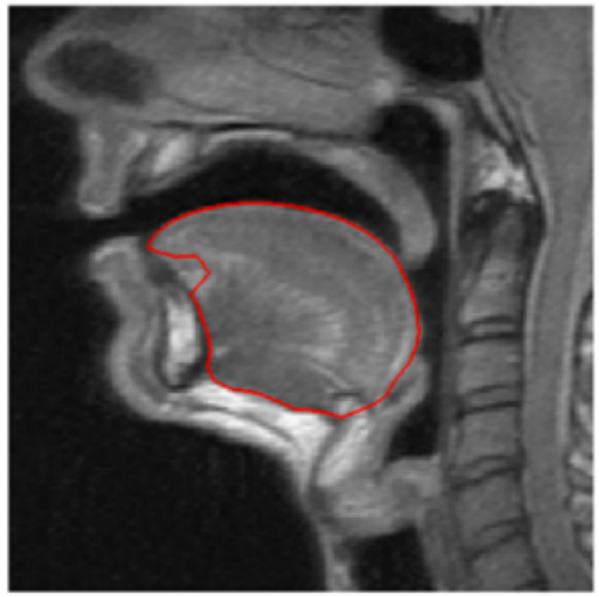


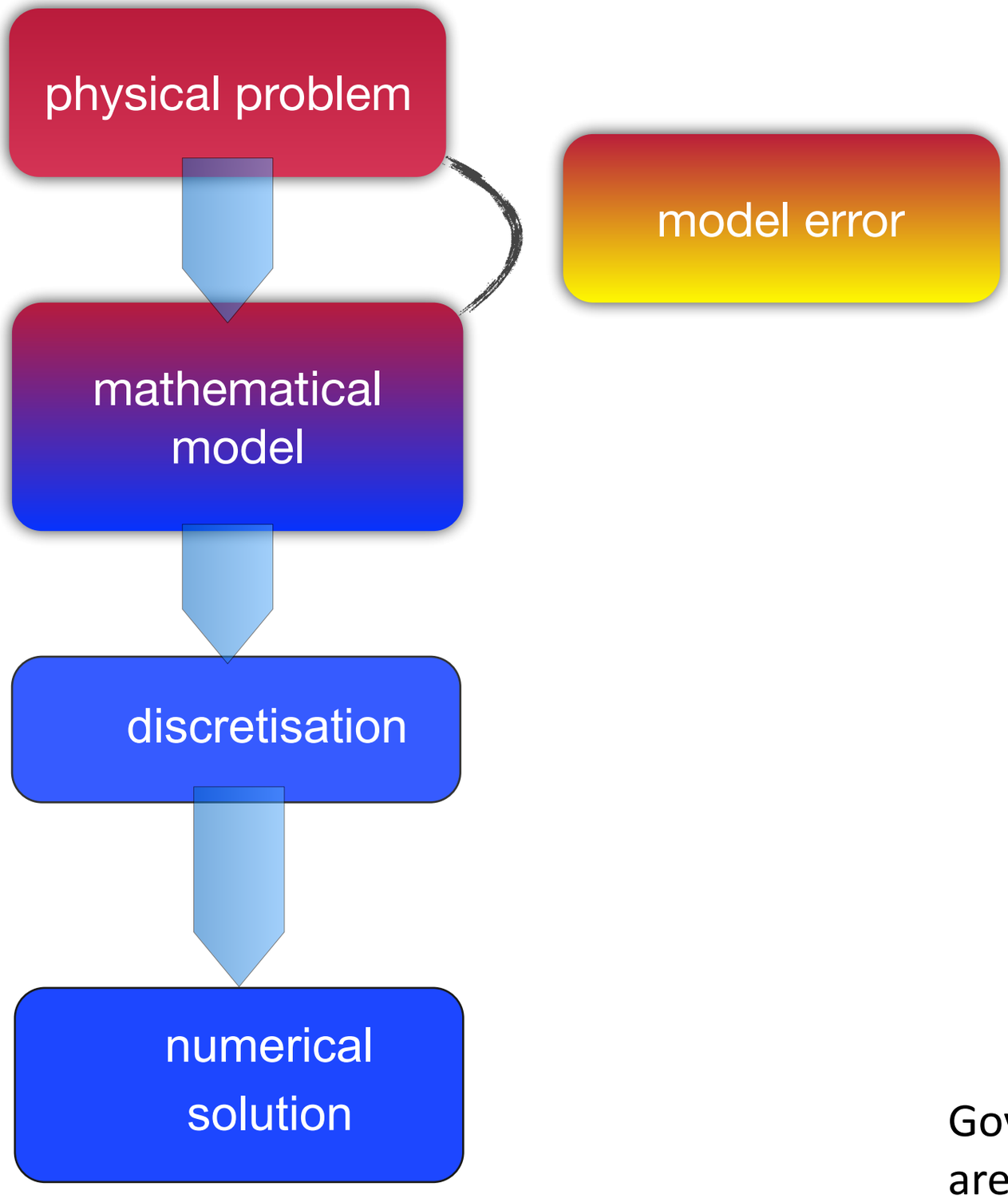


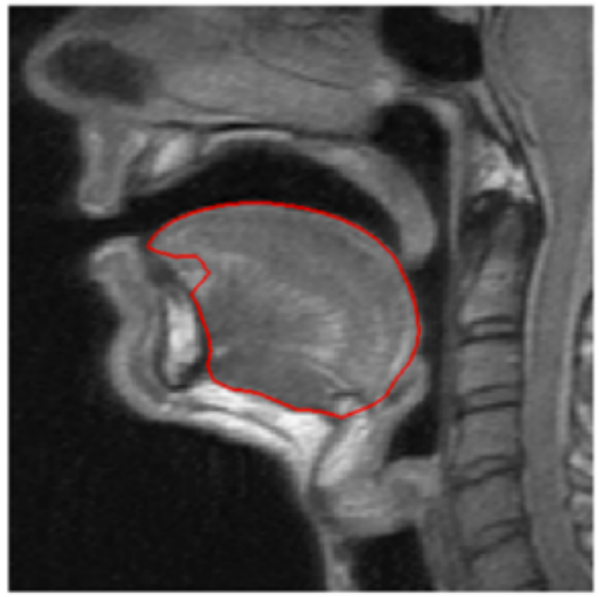
Bijar, Rohan, Perrier & Payan 2015

$$\neq$$

$$\min_{\mathbf{u}\in\mathbf{V}} \frac{1}{2}\int_\Omega \boldsymbol{\sigma}(\mathbf{u},\beta) : \boldsymbol{\varepsilon}(\mathbf{u})\, d\mathbf{x} - \int_\Omega \mathbf{g}\cdot\mathbf{u}\, d\mathbf{x}$$

Quantify the quality of the simulation





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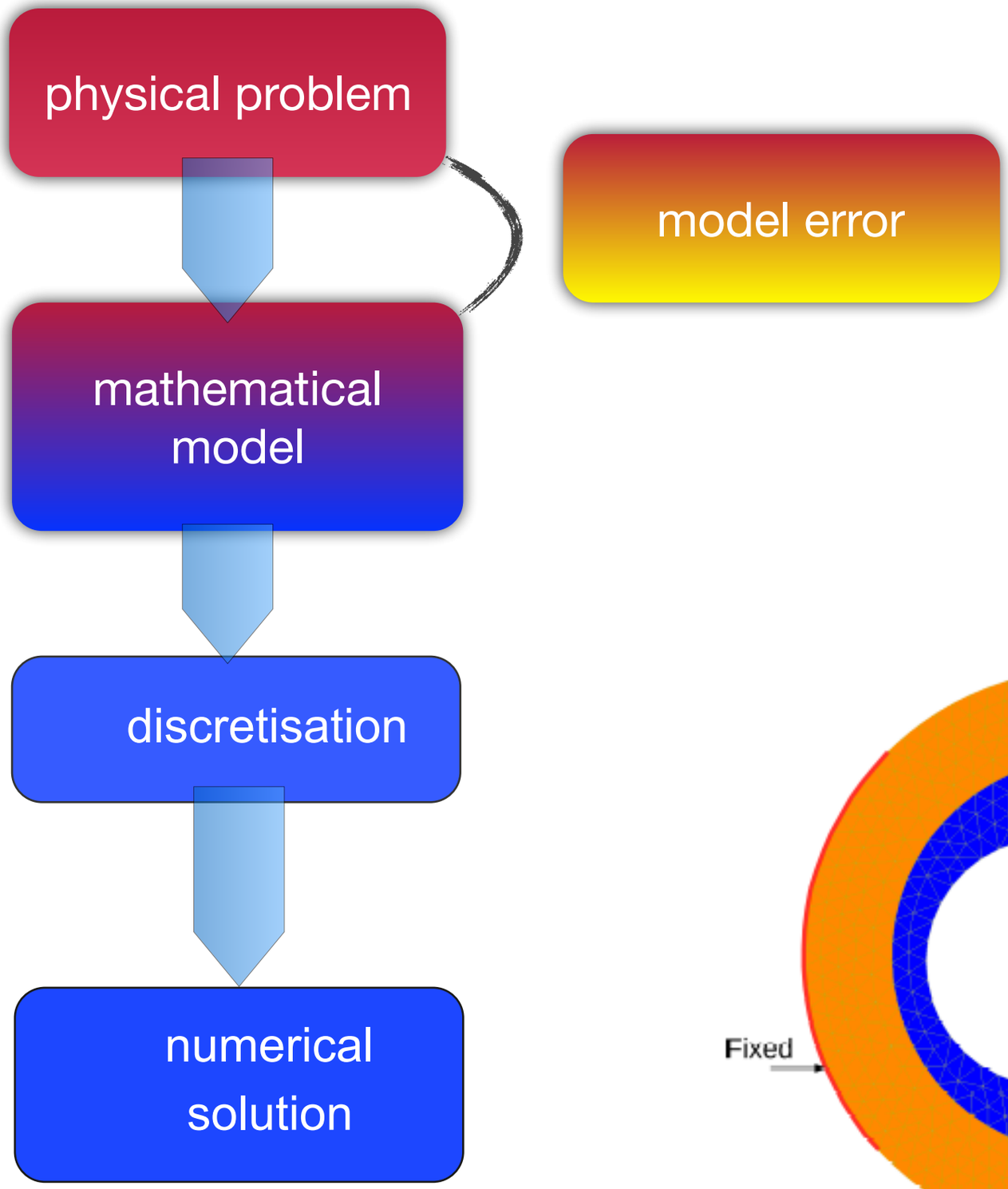
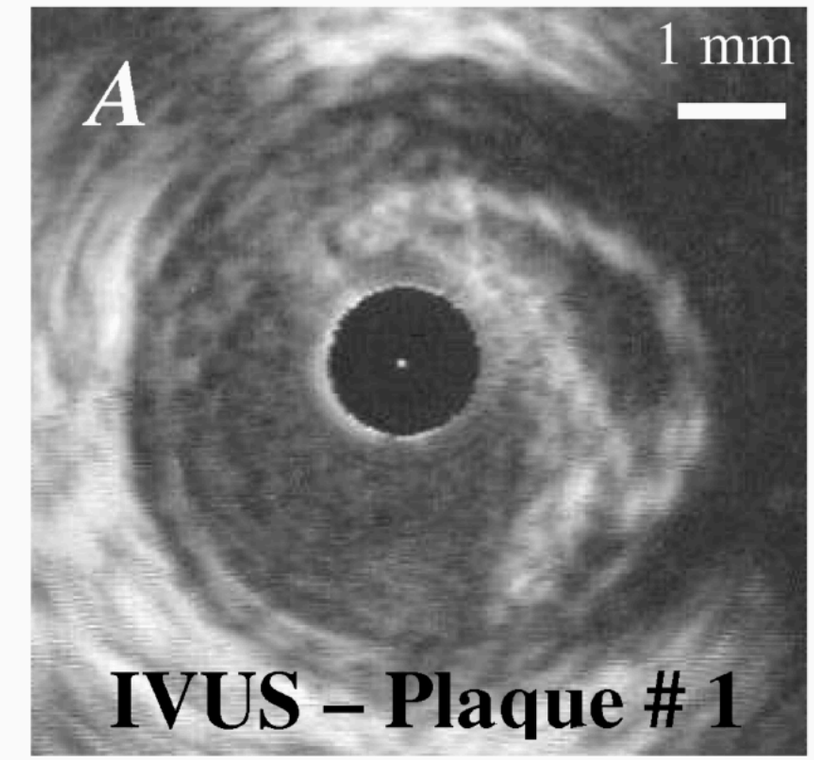
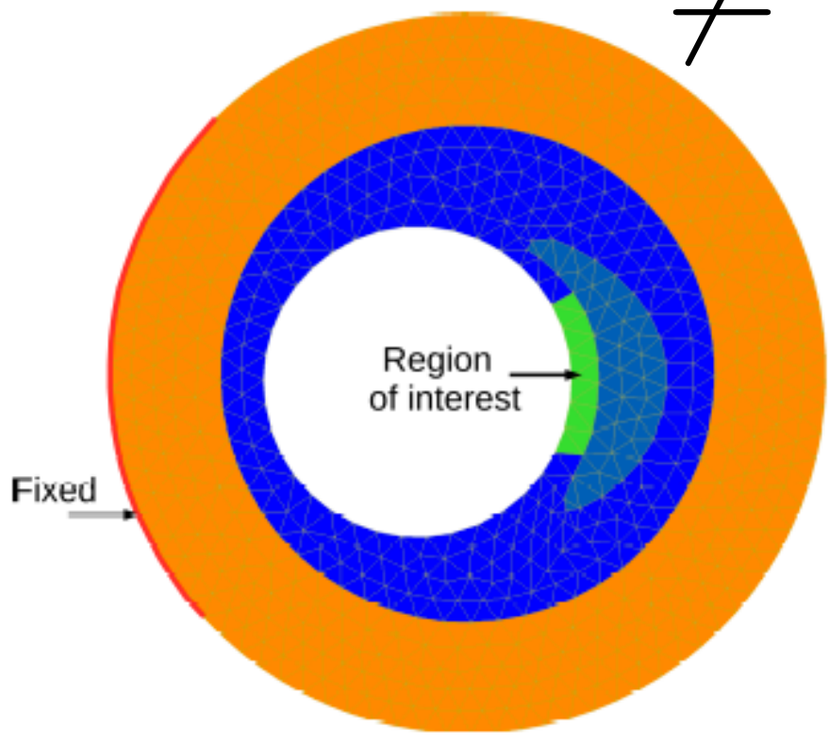
Governing equations and material models are erroneous

Quantify the quality of the simulation



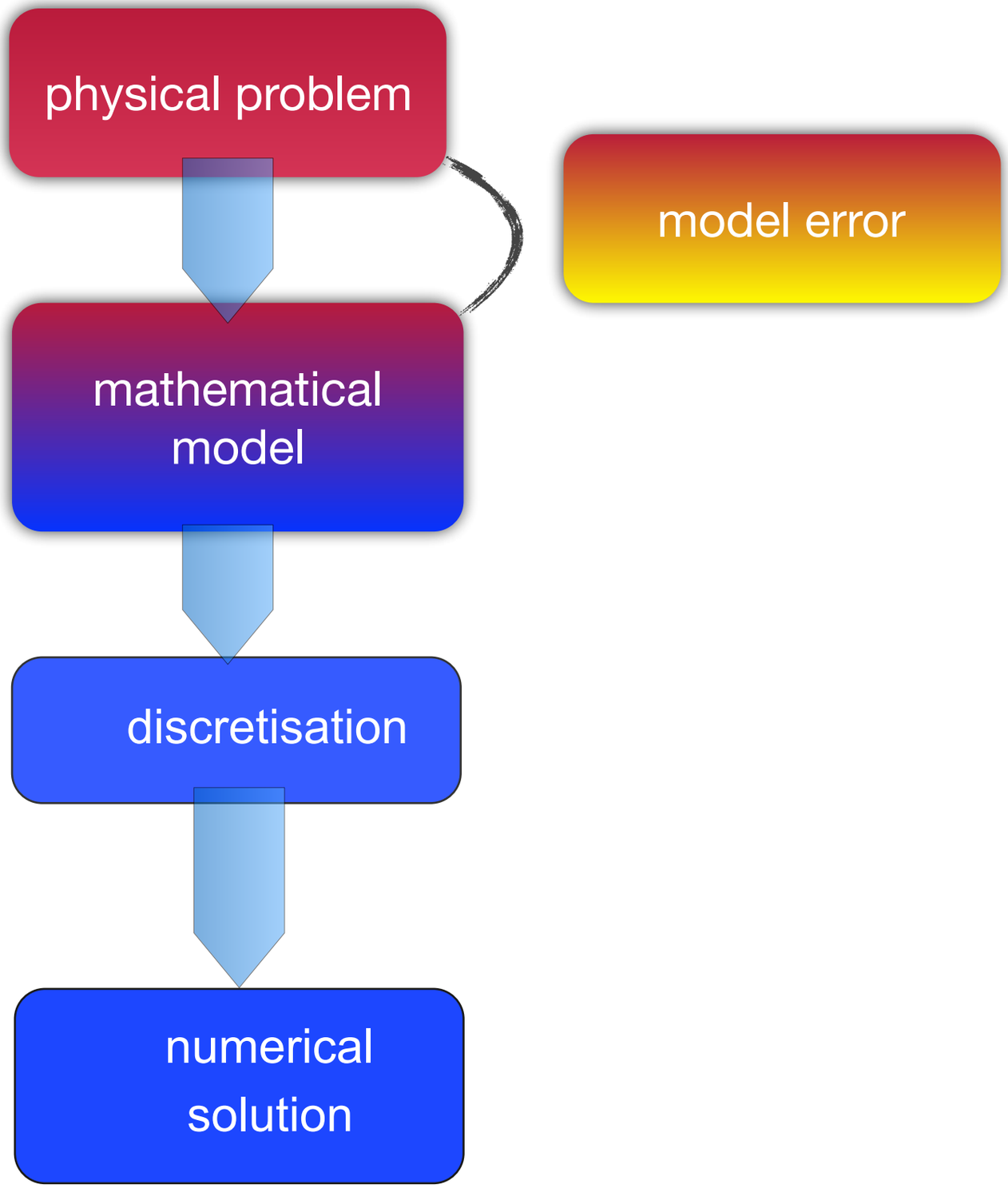


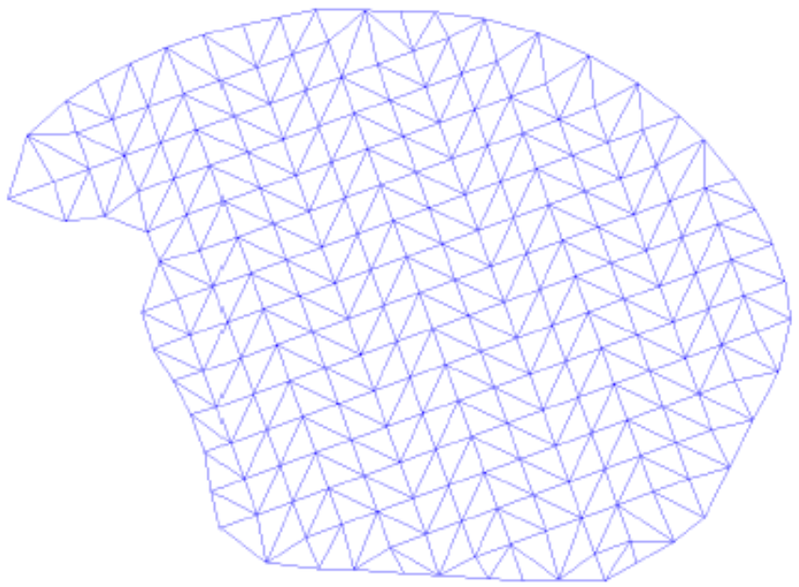
$\neq$



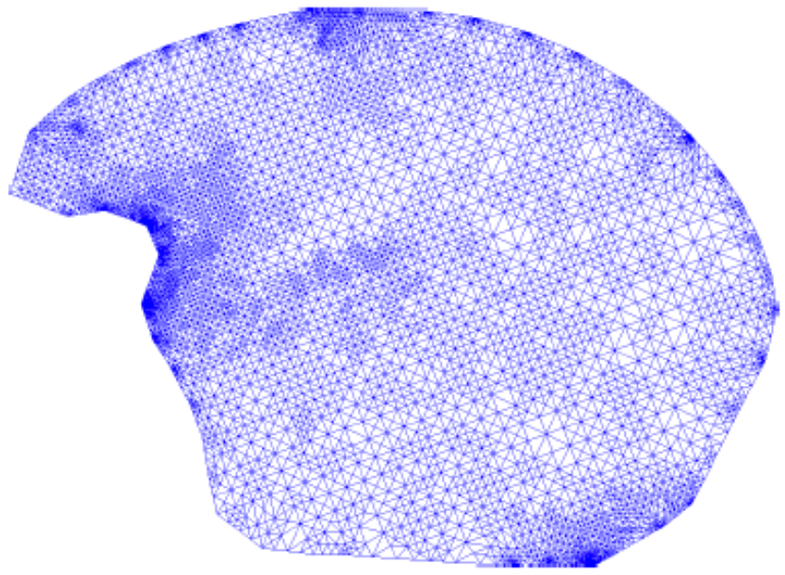
Geometry and boundary conditions are not known exactly

Quantify the quality of the simulation





vs.



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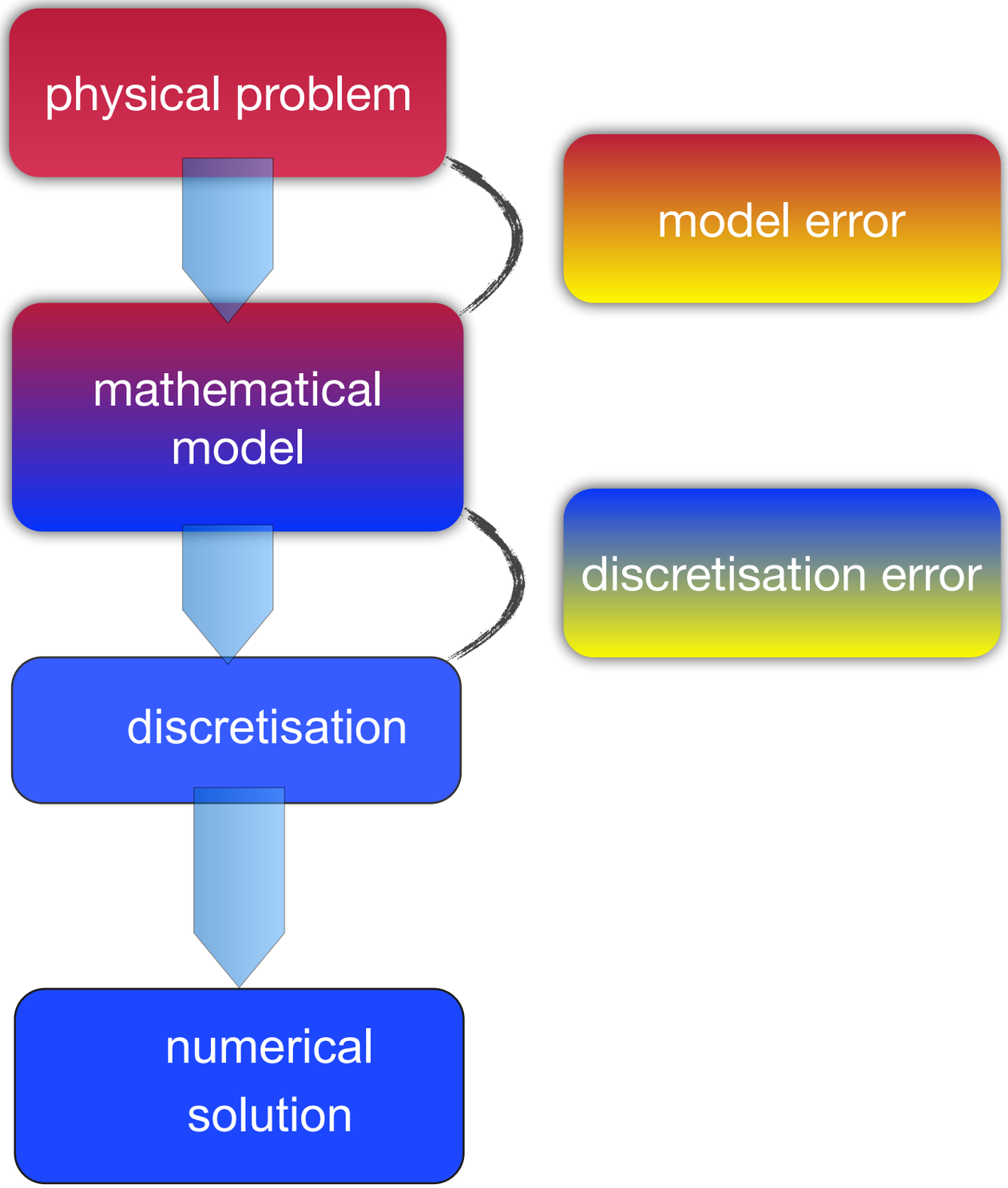
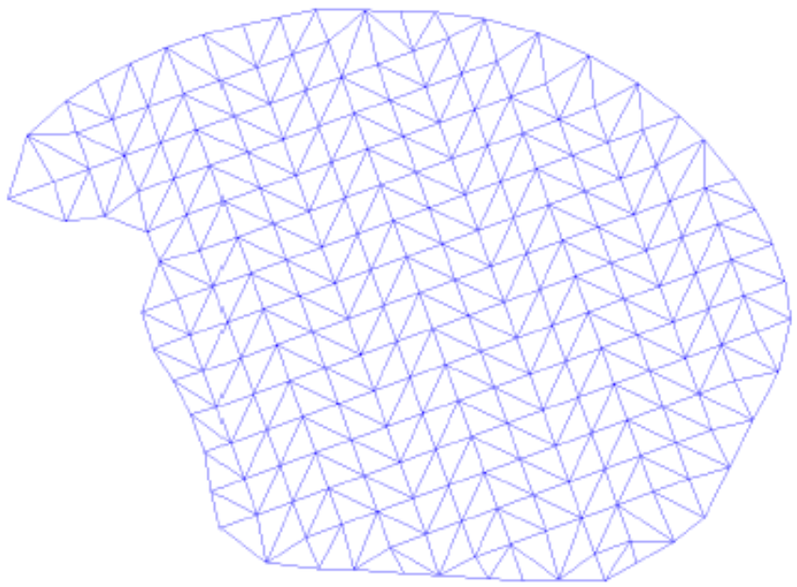
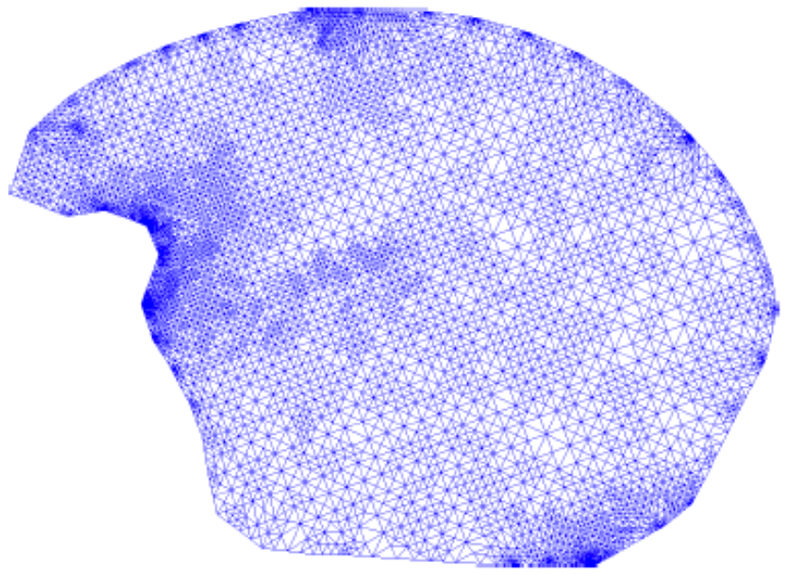




vs.



Quantify the quality of the simulation

physical problem

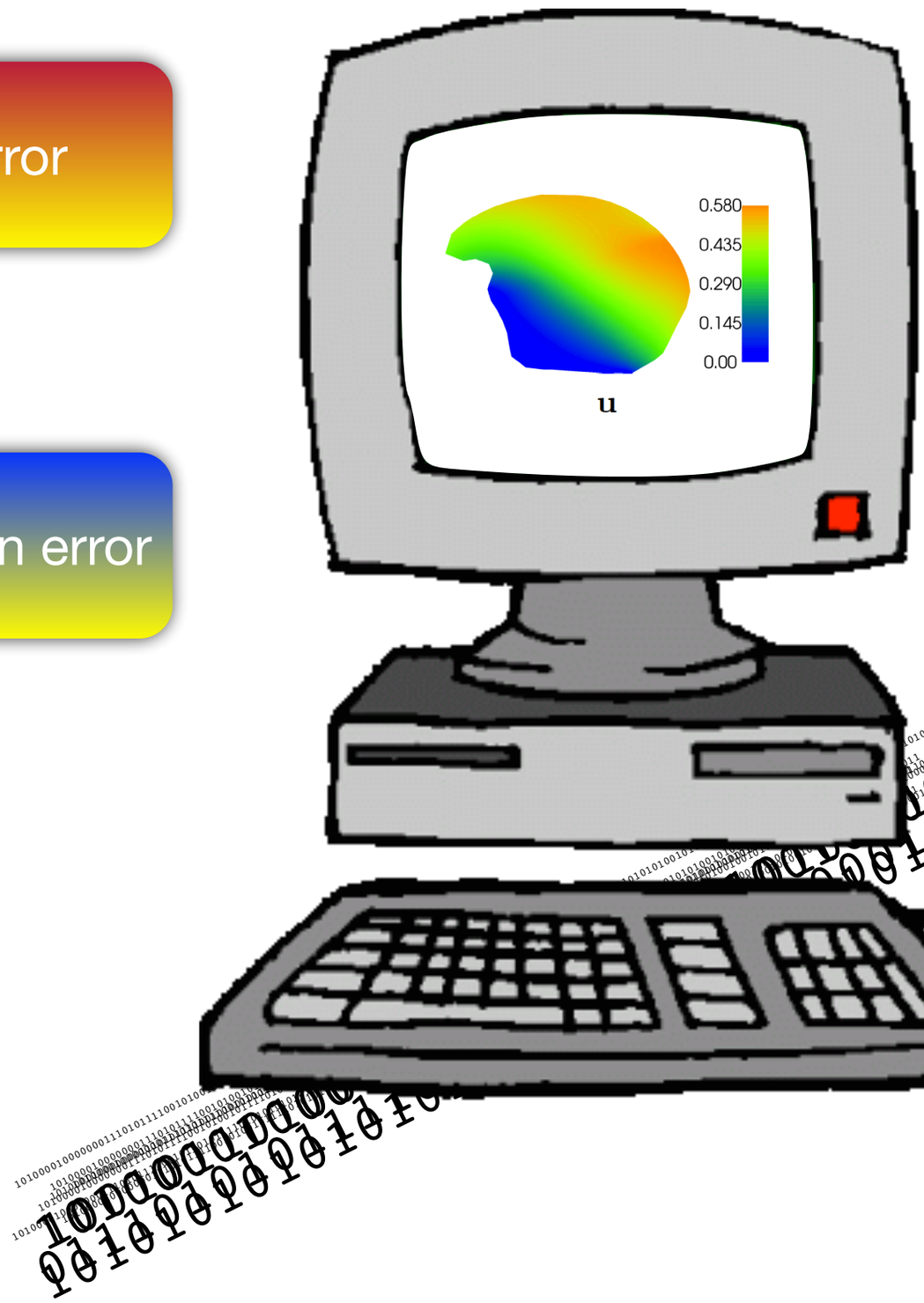
model error

mathematical model

discretisation error

discretisation

numerical solution



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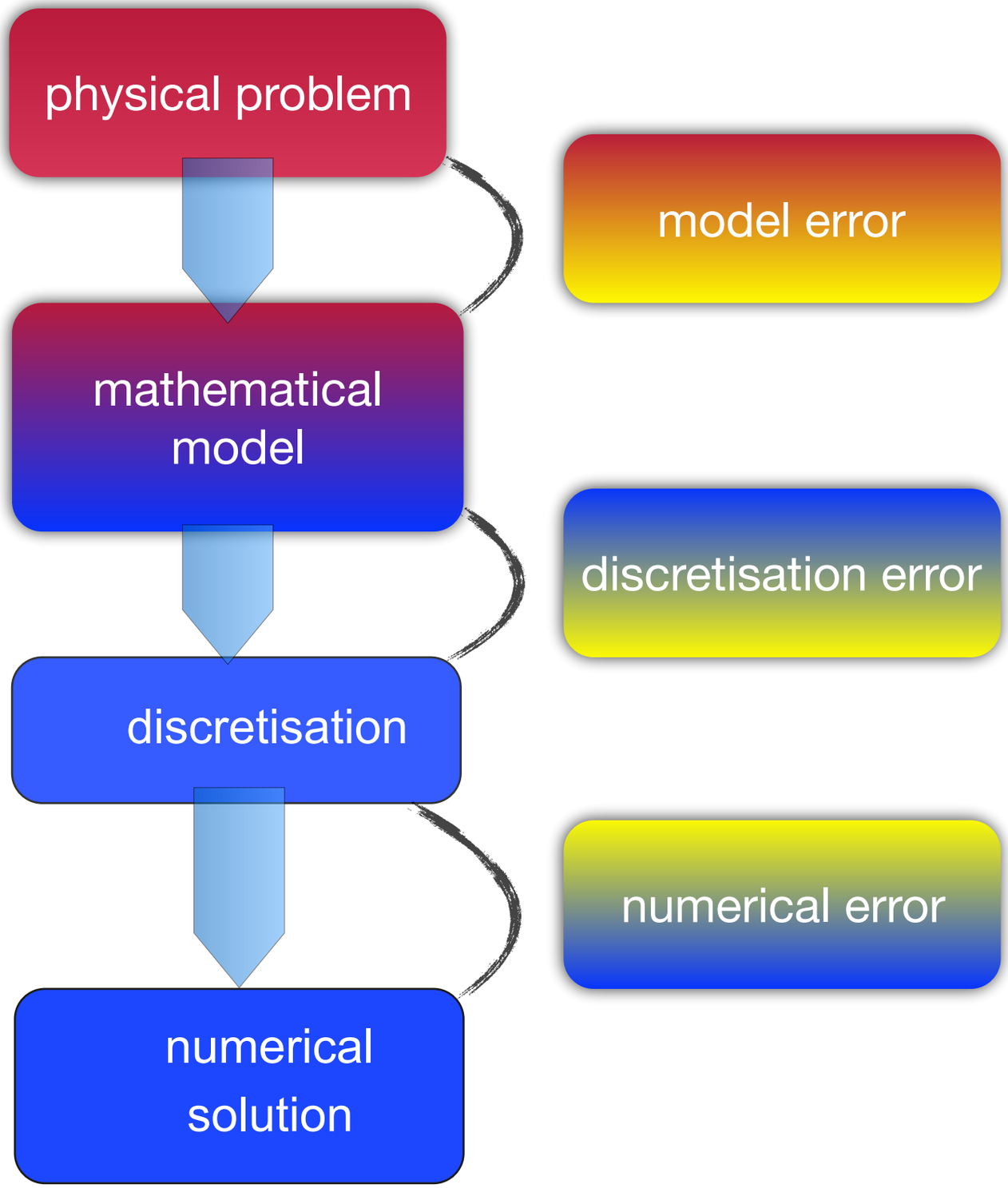


Quantify the quality of the simulation

physical problem

mathematical model

discretisation

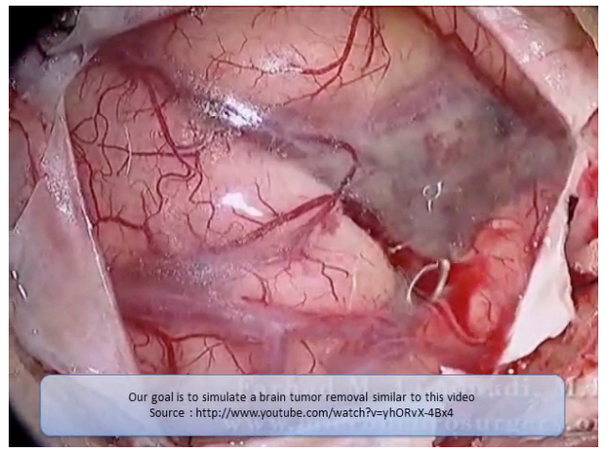
numerical solution

model error

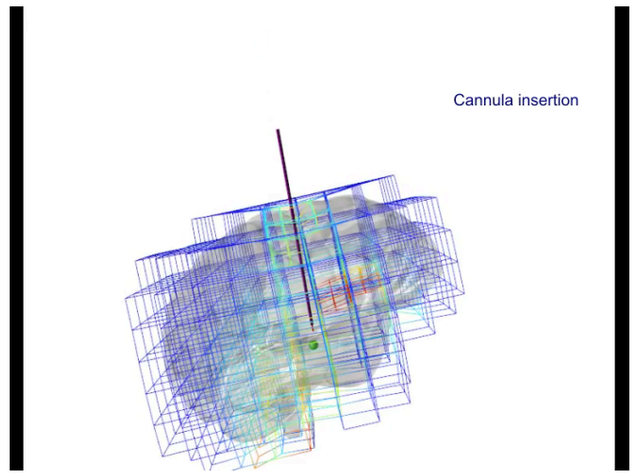
discretisation error

numerical error

total error



vs.



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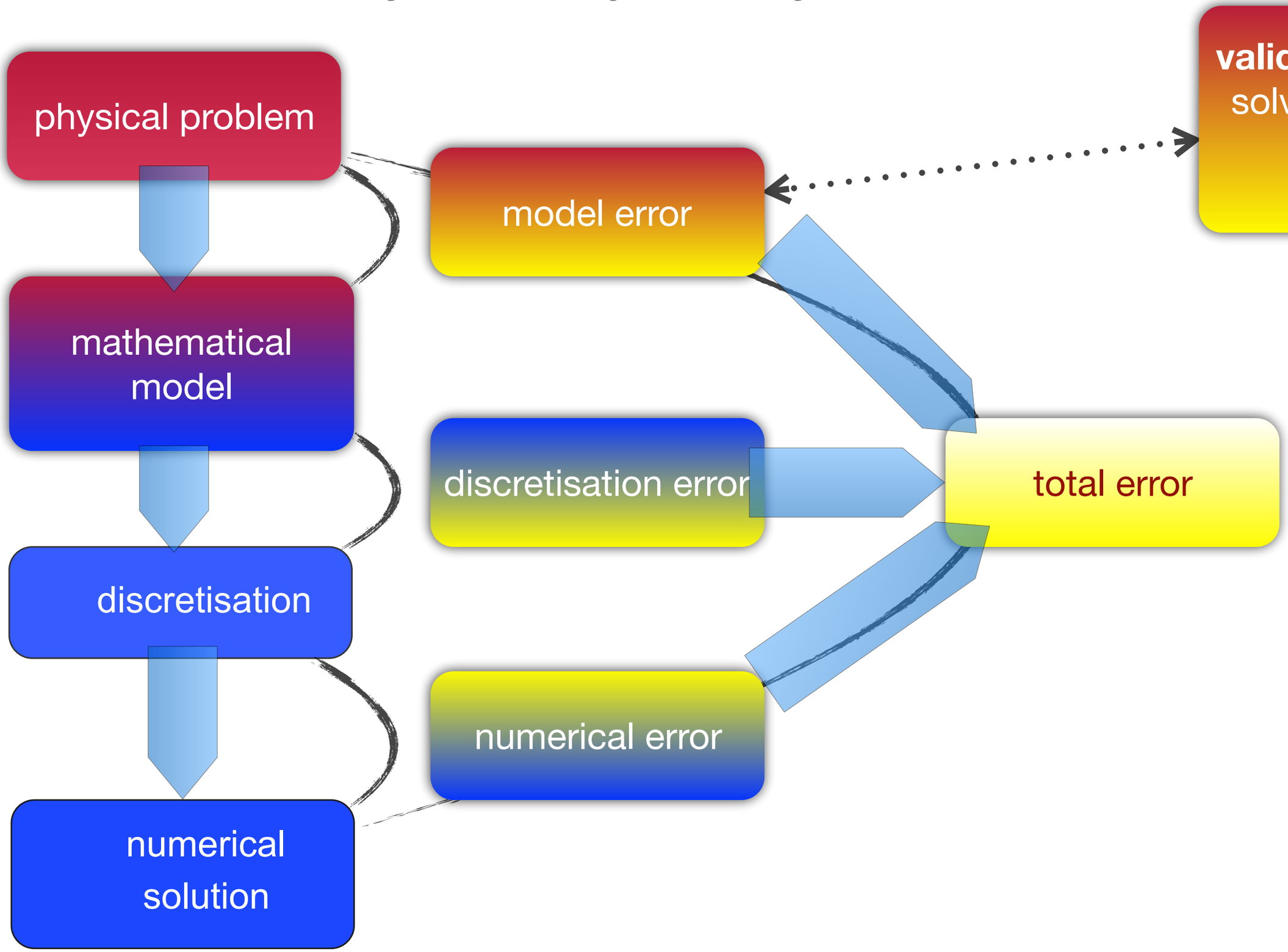
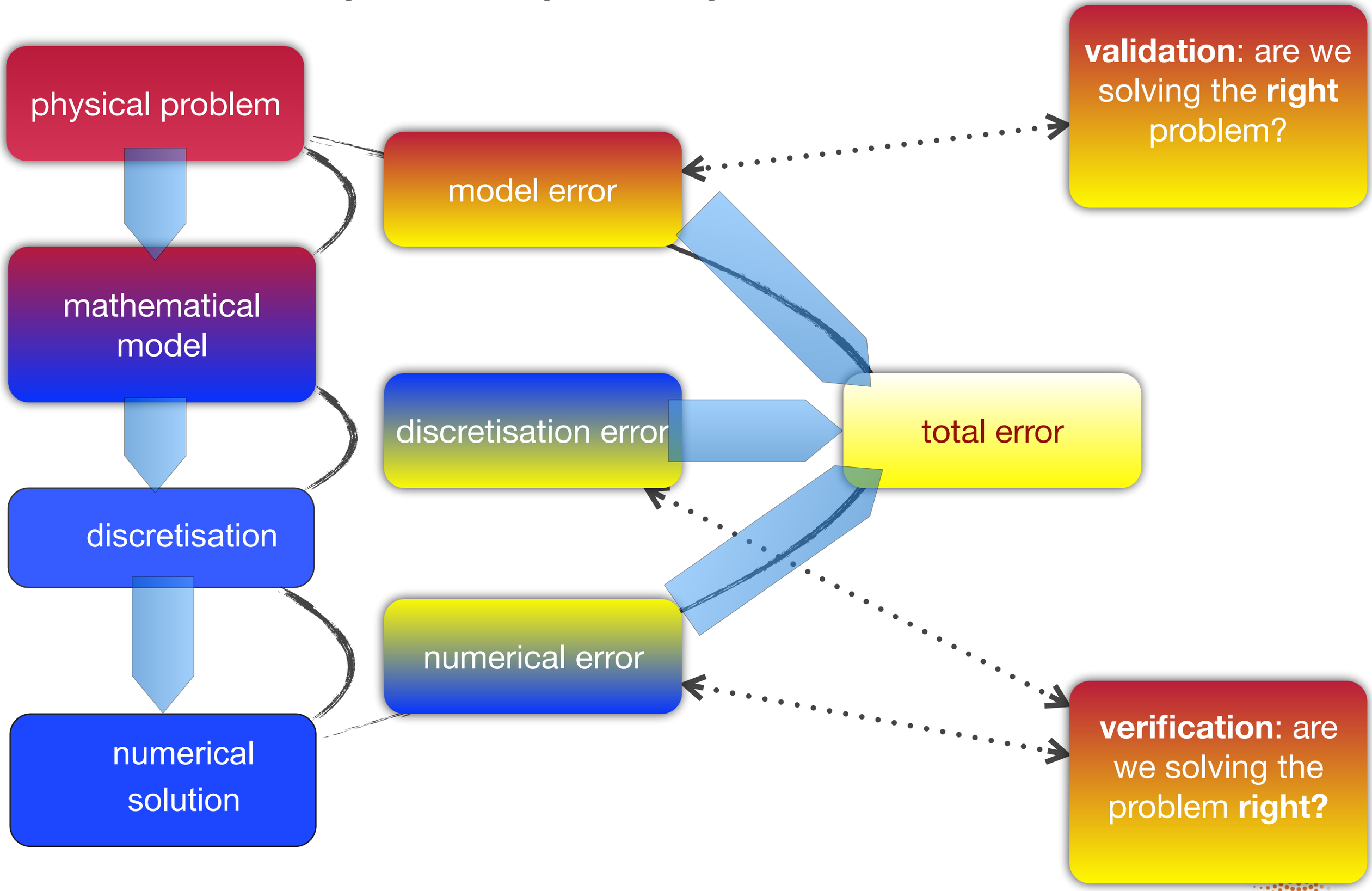
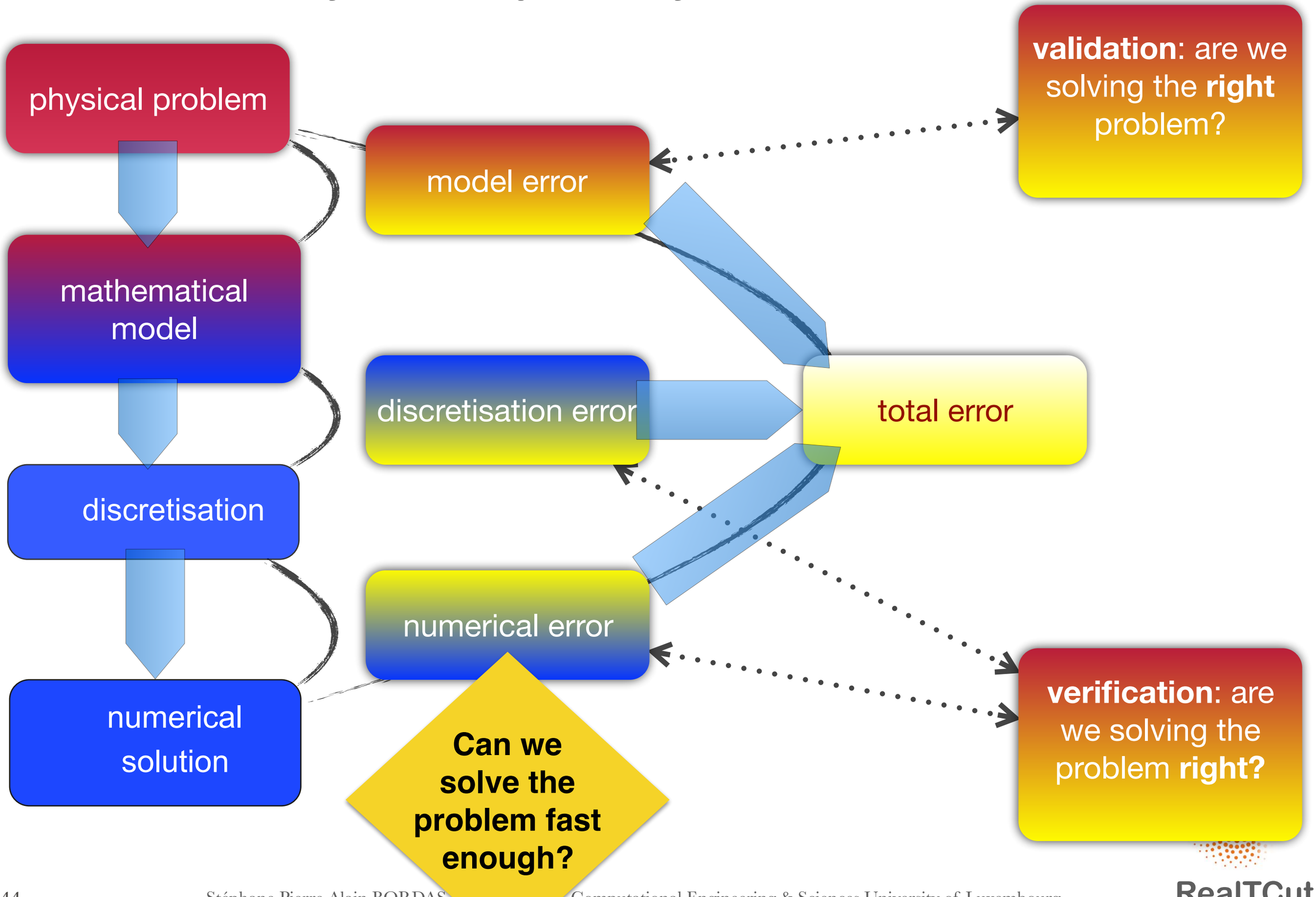


Stéphane Pierre Alain BORDAS, Department of Computational Engineering & Sciences University of Luxembourg

Quantify the quality of the simulation



Quantify the quality of the simulation



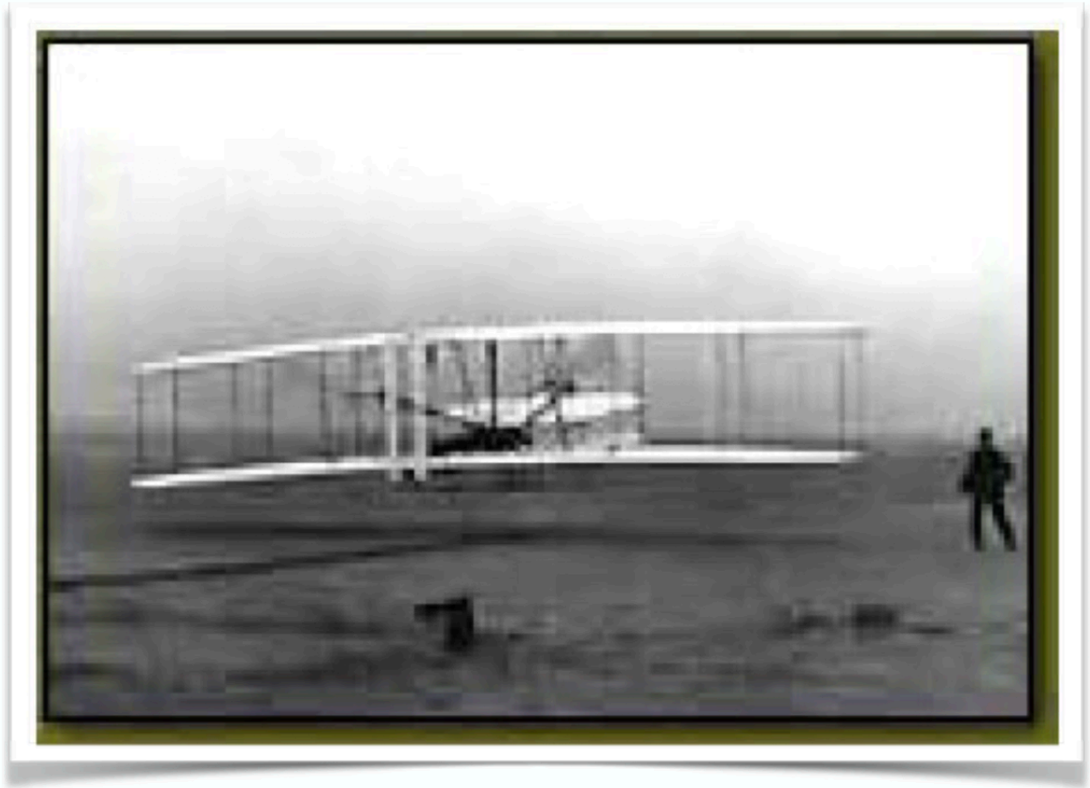
ERC: first love

ERC: first love

Wilbur and Orville Wright, 1903

Wright Flyer

10:35am Dec 17, 1903

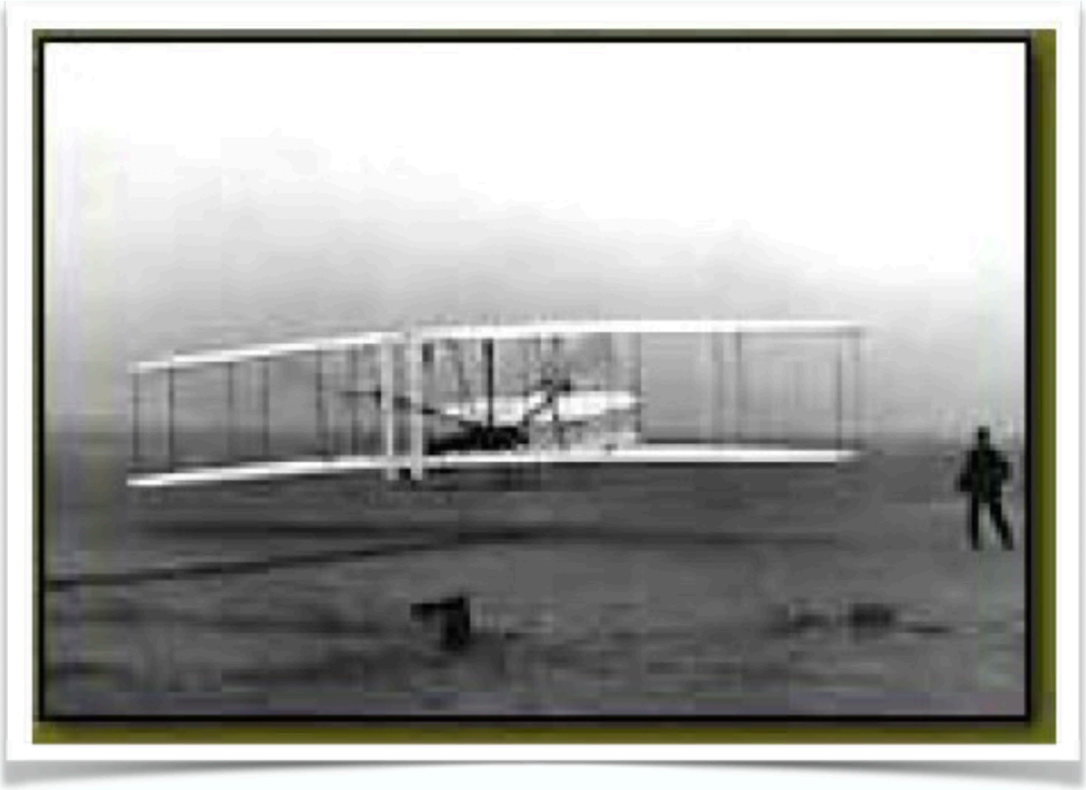


Wilbur and Orville Wright, 1903

On Dec 14 Wilbur won the coin toss, made the first attempt and stalled

Orville made the first flight on Dec. 17

12 seconds & 120 ft



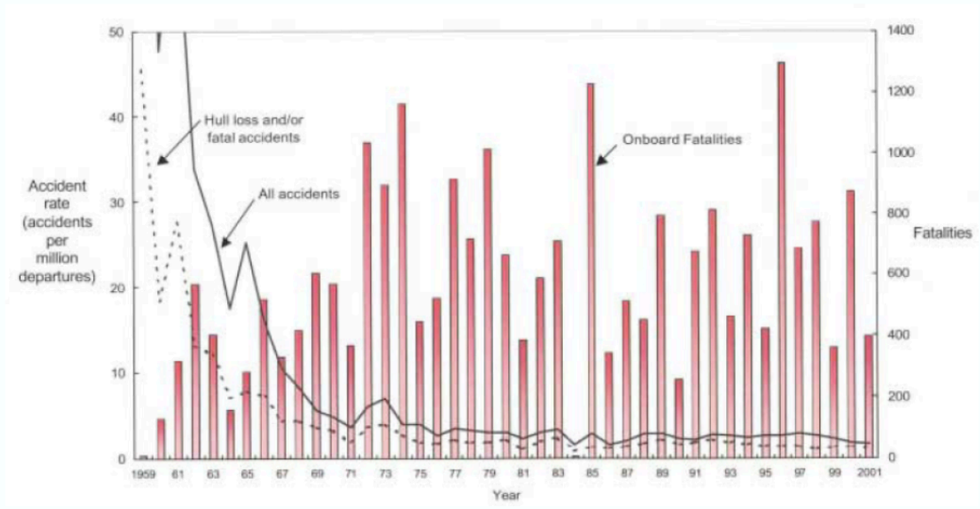
Stéphane Pierre Alain BORDAS, Department of Computational Engineering & Sciences University of Luxembourg

Aircraft safety

20,000 years

Worldwide statistics

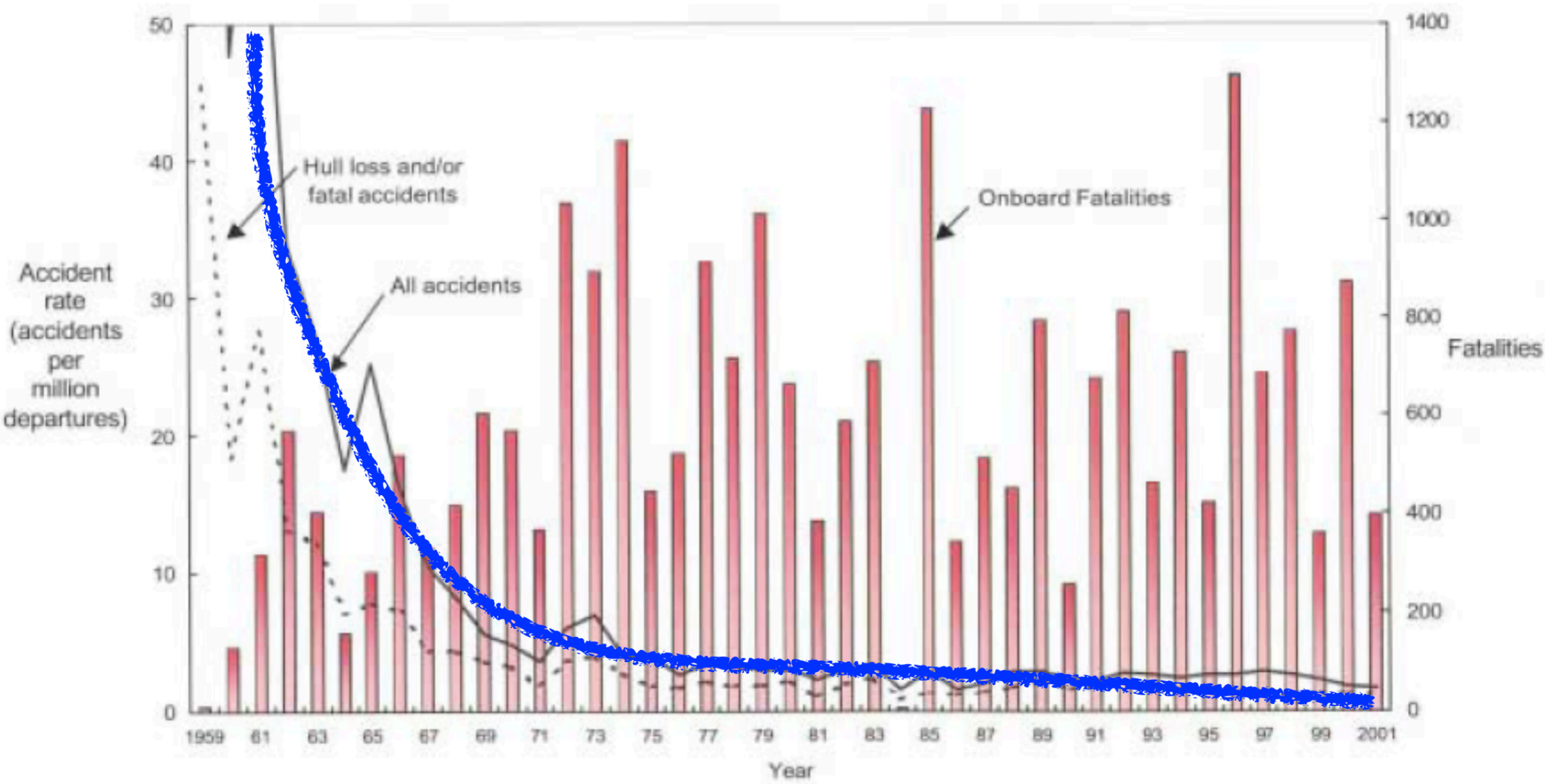
[1959-2001] 1,307 commercial jet aircraft losses



Today:

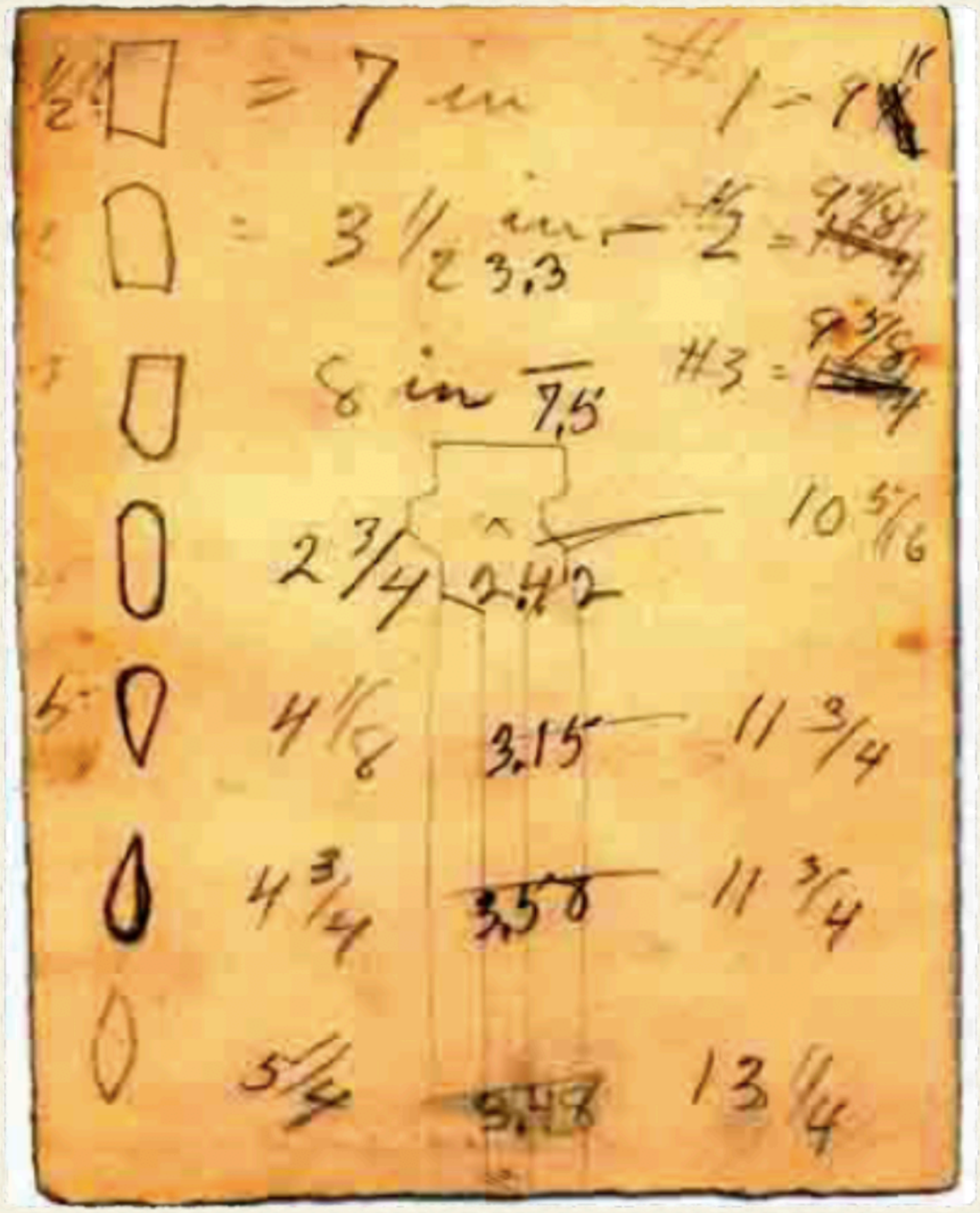
1 accident per 1,000,000 departures

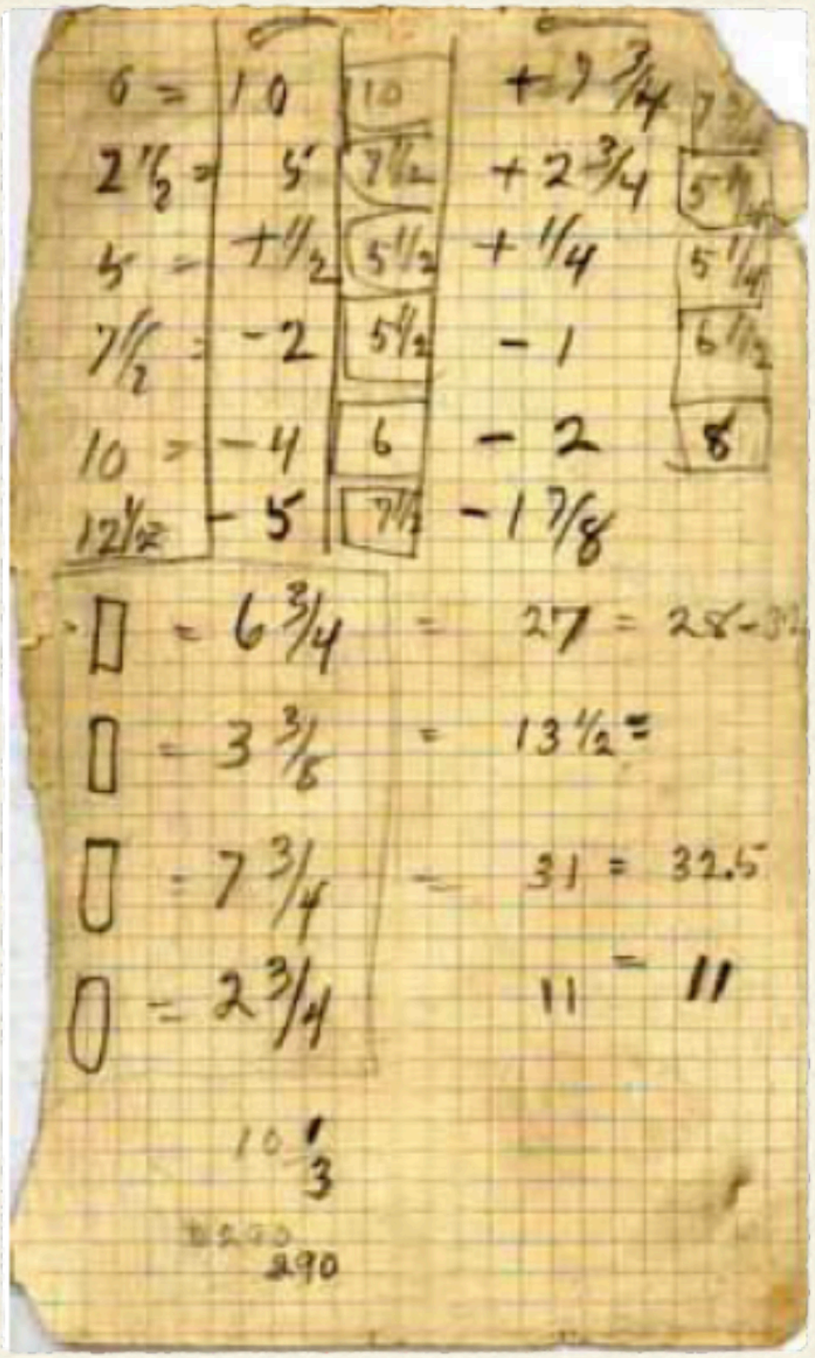
Accident rates and fatalities/year



Source: Flight Safety Foundation/Boeing Commercial Airplane Group

Learning from intuition & theory

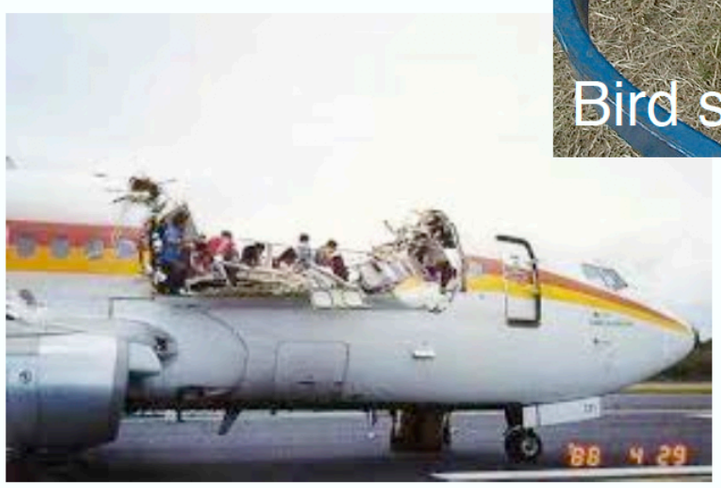


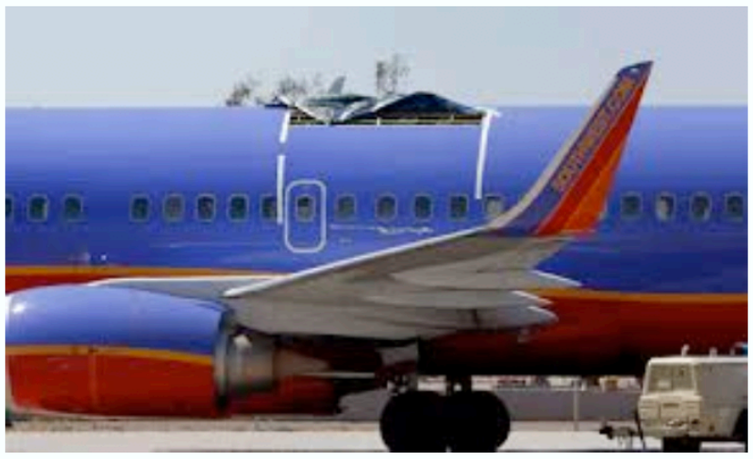


Franklin Institute Science Museum. Wilbur Wright's handwriting

Learning from experience

Increased practical understanding of mechanics — in particular fracture and fatigue





Aloha airlines accident - fatigue cracks at corners

Novel convertible aircraft

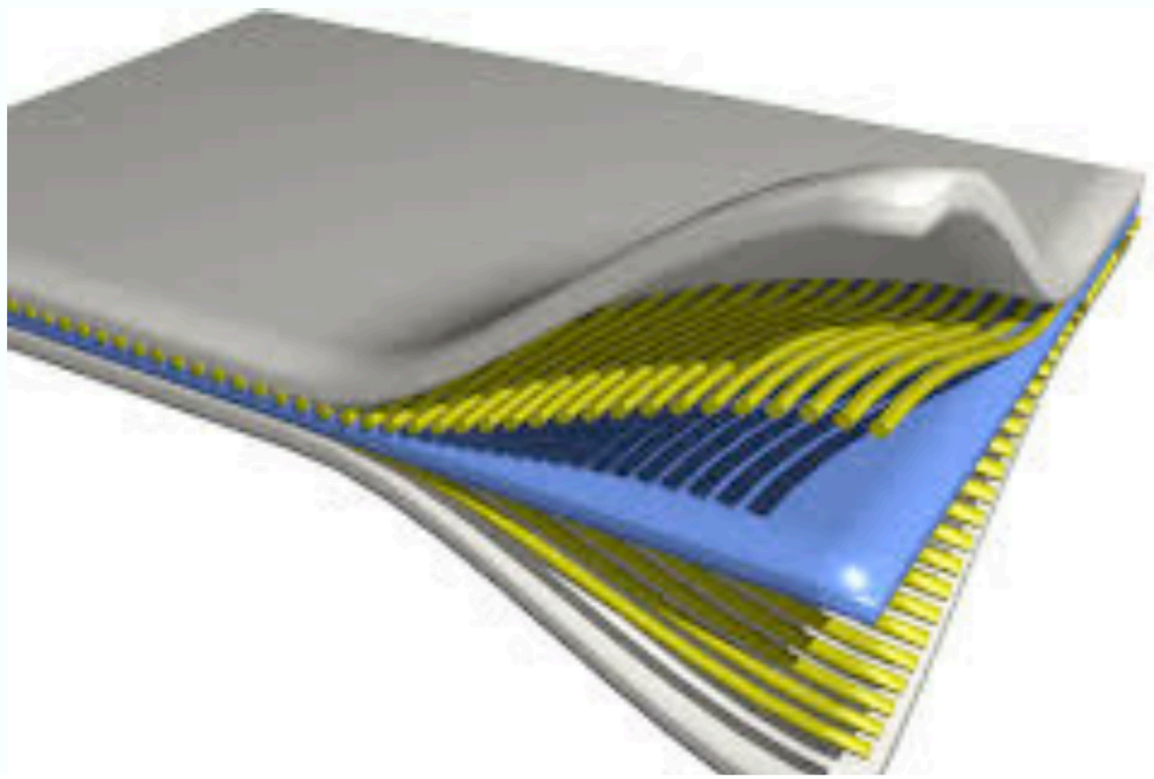
Learning from experi**ments**

World's largest wind tunnel (2014)

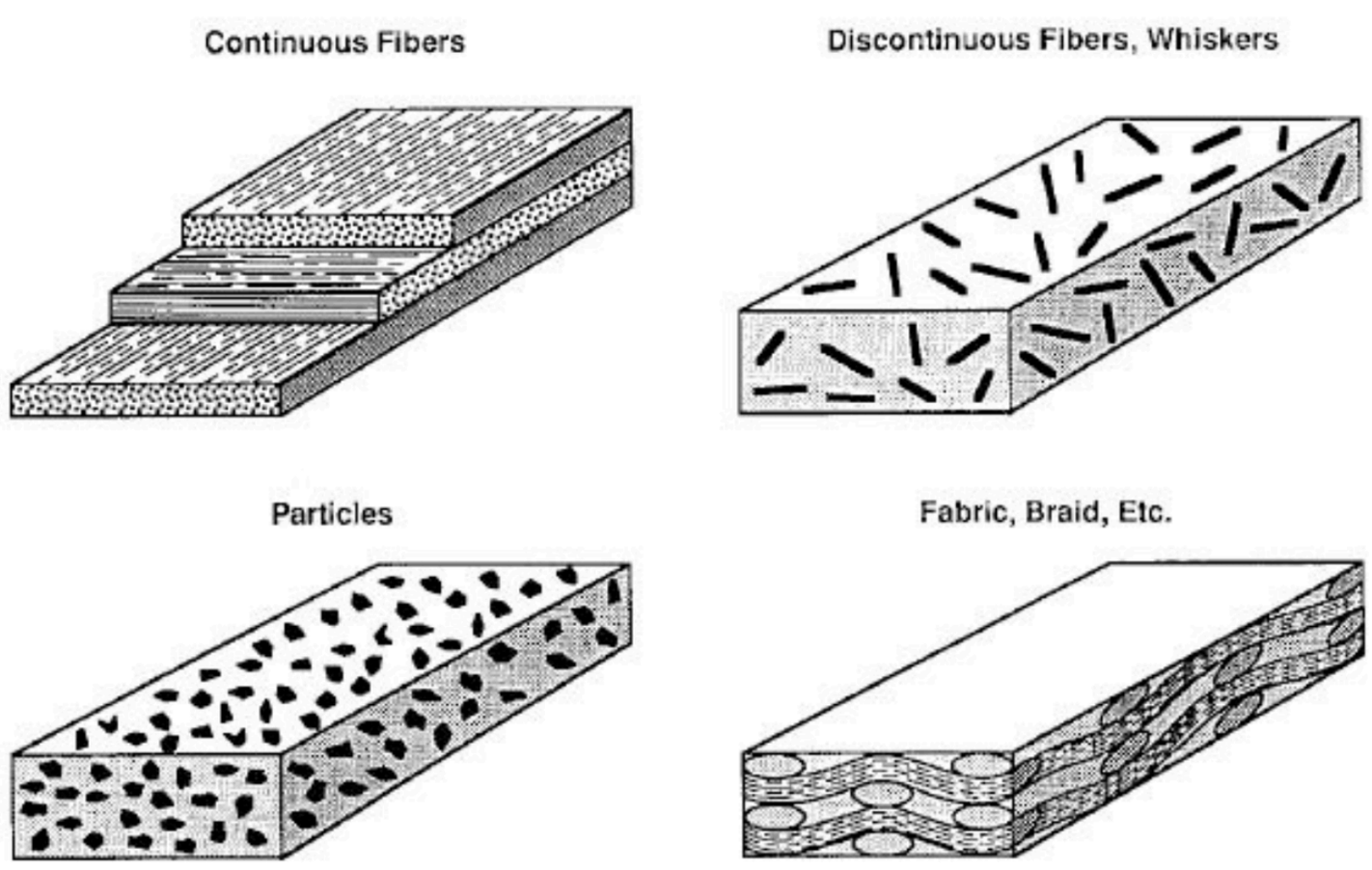
Replica of the 1901 Wright Wind Tunnel (constructed with assistance from Orville Wright)

New materials for more payload

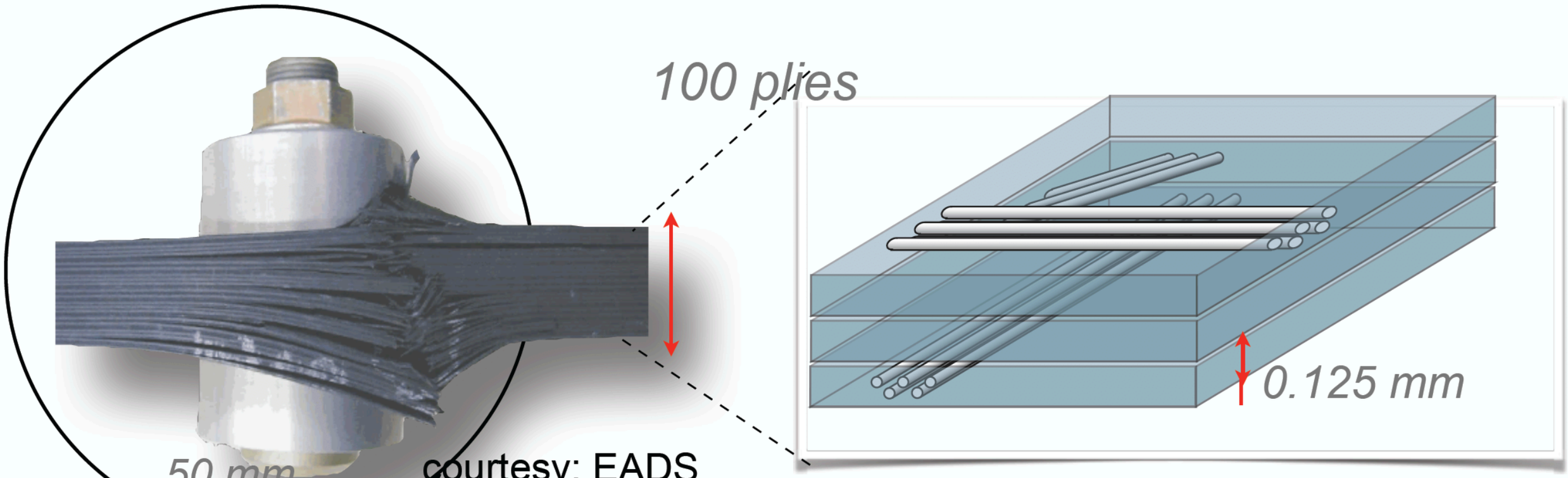
Introduction of composite materials have reduced the weight of structures by 20%



Over 1,000km saving of 8,660kg of fuel [A340-300]



A bolted joint



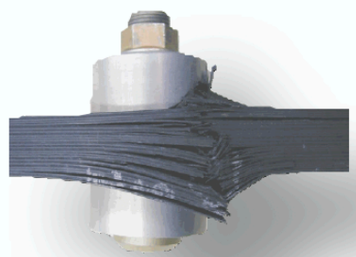
- 5 elements through the thickness of a ply => 0.025mm/element
- 50mm bolted joint area => 2,000 elements
- 50mm x 50mm x 100 plies => 2,000 x 2,000 x (100 x 5)

  => **2 billion elements**

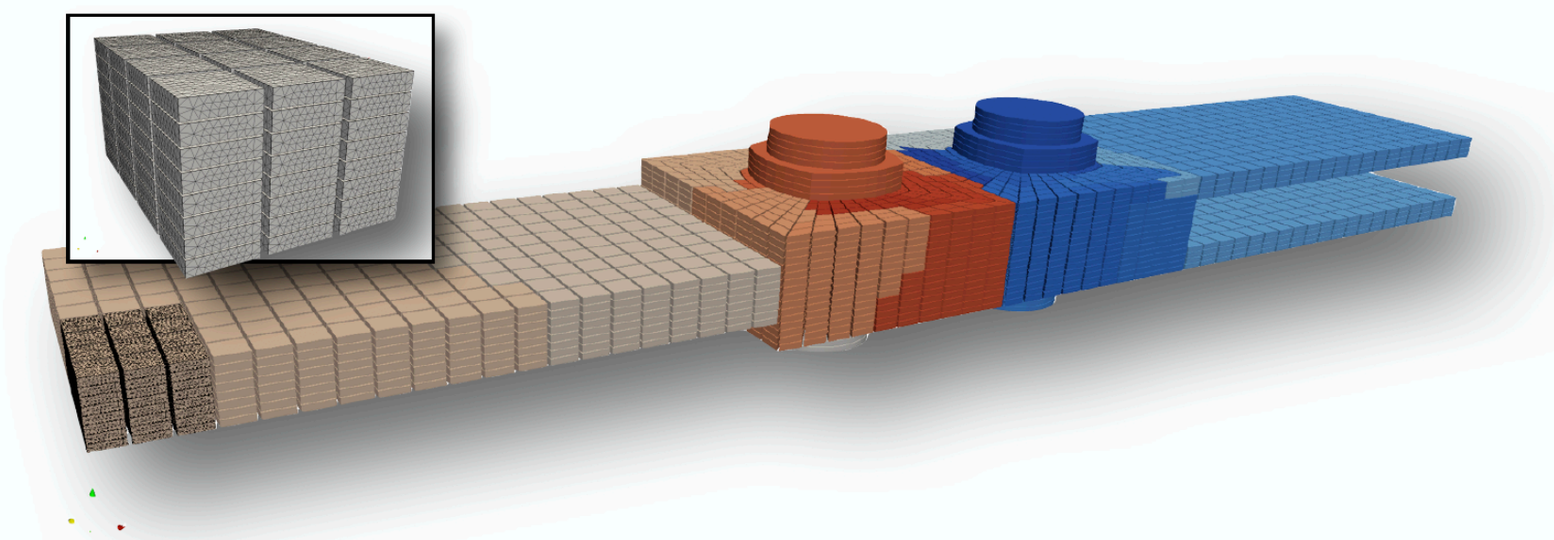
A380 giant

Large structures

whose behaviour is governed by small-scale effects



=> intractable problem size



Challenge

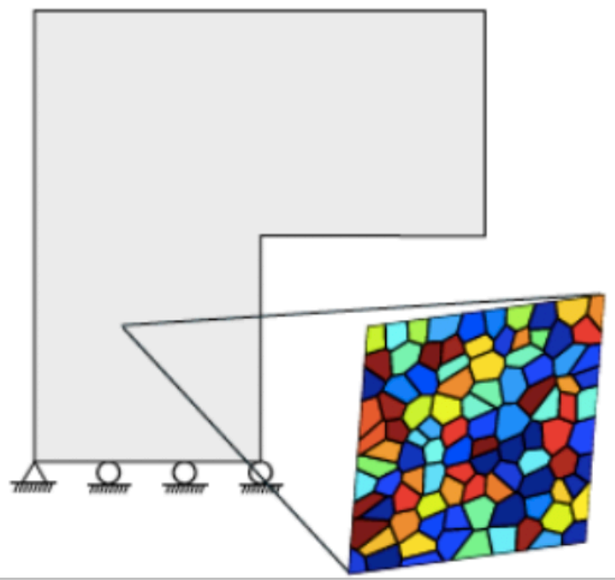
- Reduce the problem size
- Preserve essential features

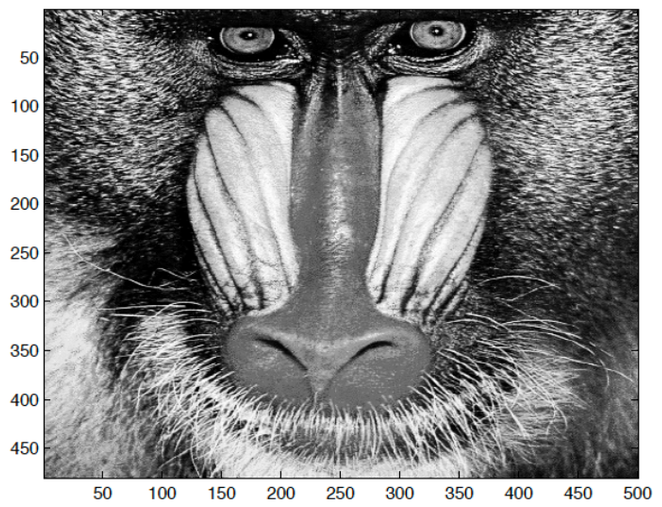
Reduce computational expense

Control the error

Physics based model reduction a.k.a. **Multiscale Methods**

Algebraic based model reduction a.k.a. **Machine Learning**



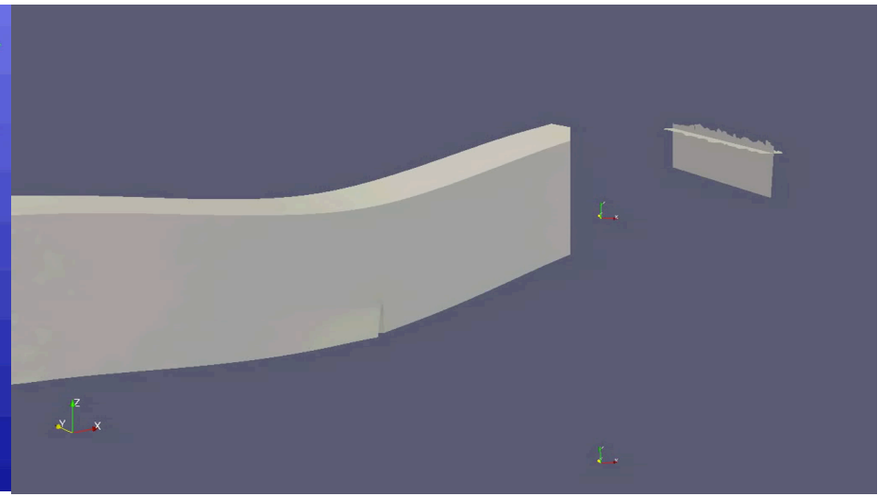


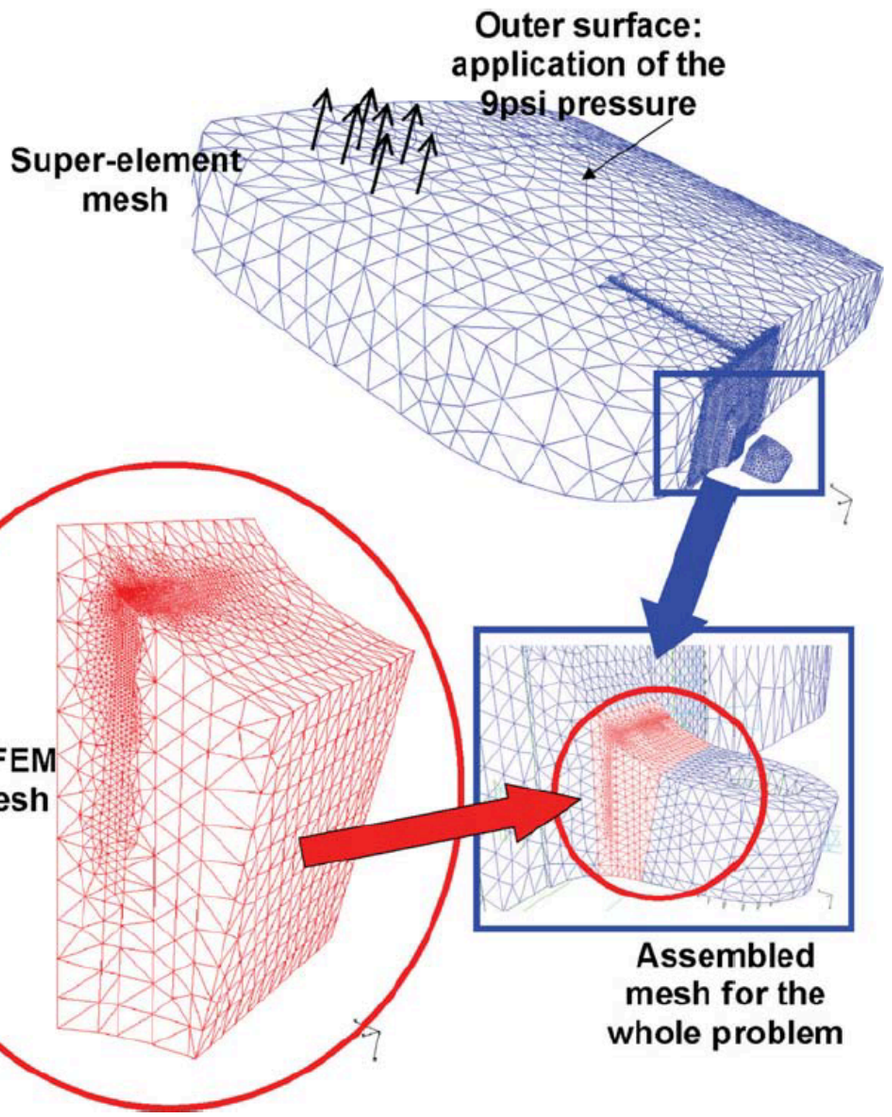
A simple approach to reducing problem size

Adaptivity driven by error estimators

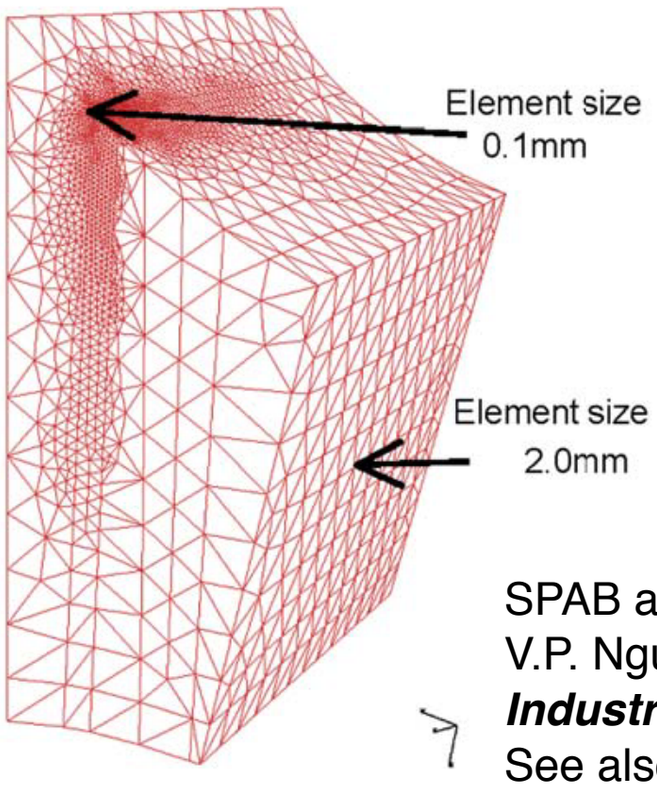
1999-2003 Damage Tolerance Assessment of Aerospace Structures PhD

How often should we inspect a structure for flaws?



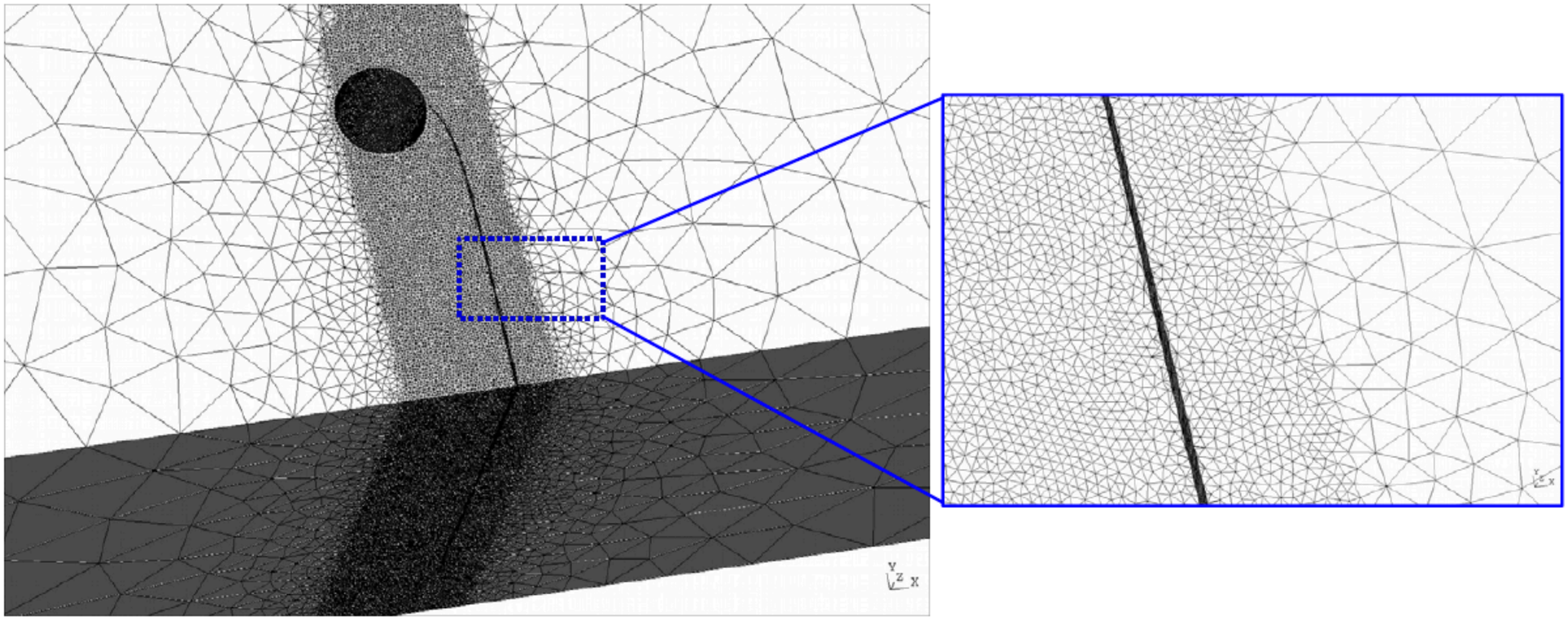


ad hoc mesh refinement



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

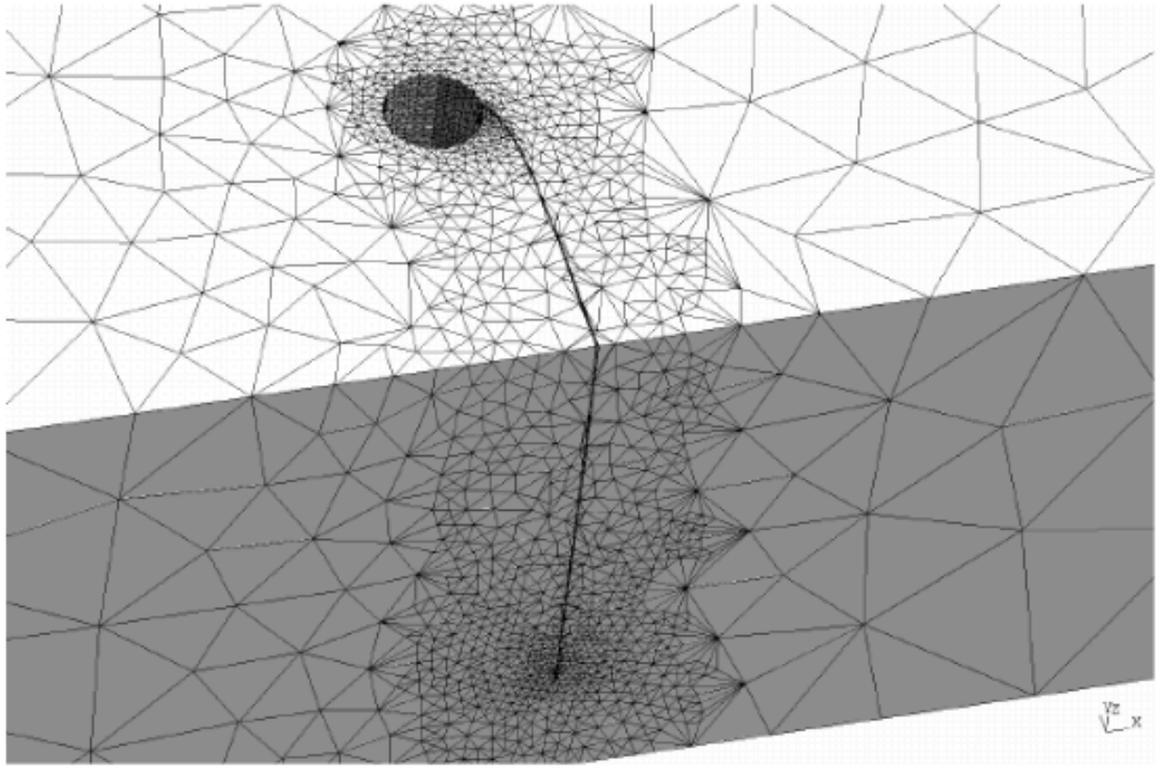
Refine along the “expected” crack path…

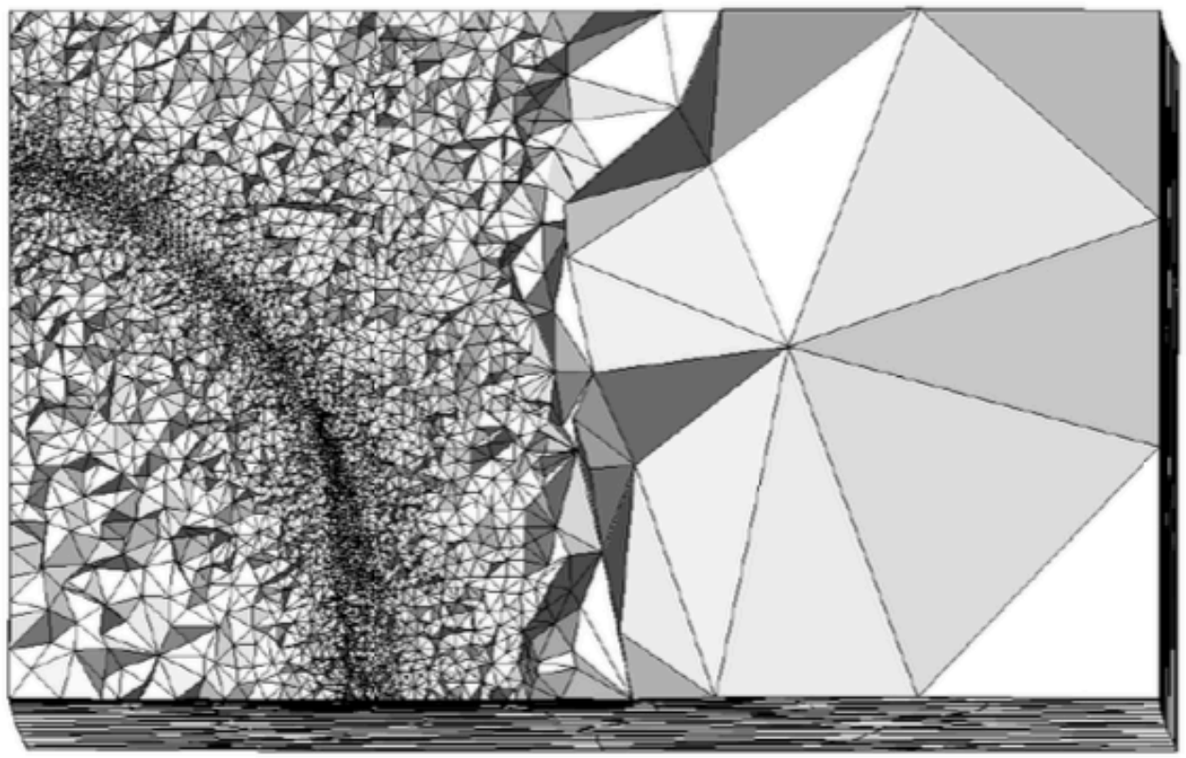


Before: mesh “finely” in the region where the crack is “expected” to propagate

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.

Much better… adapt the discretisation locally

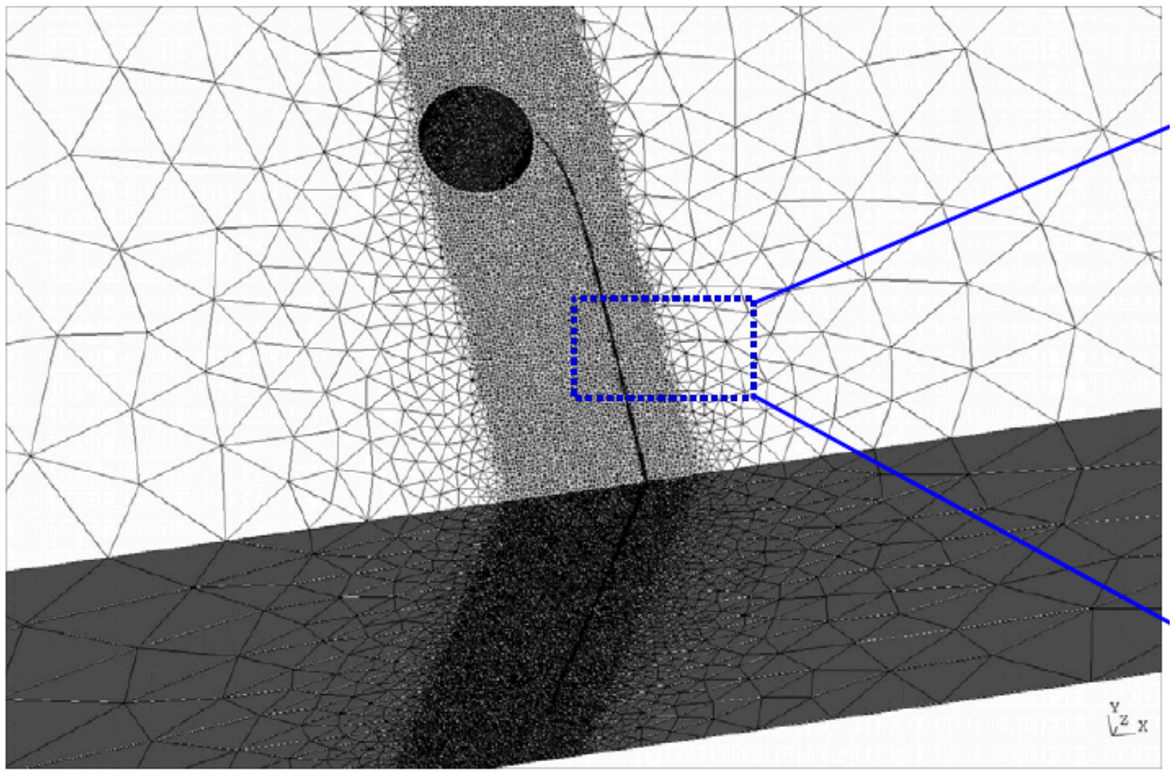


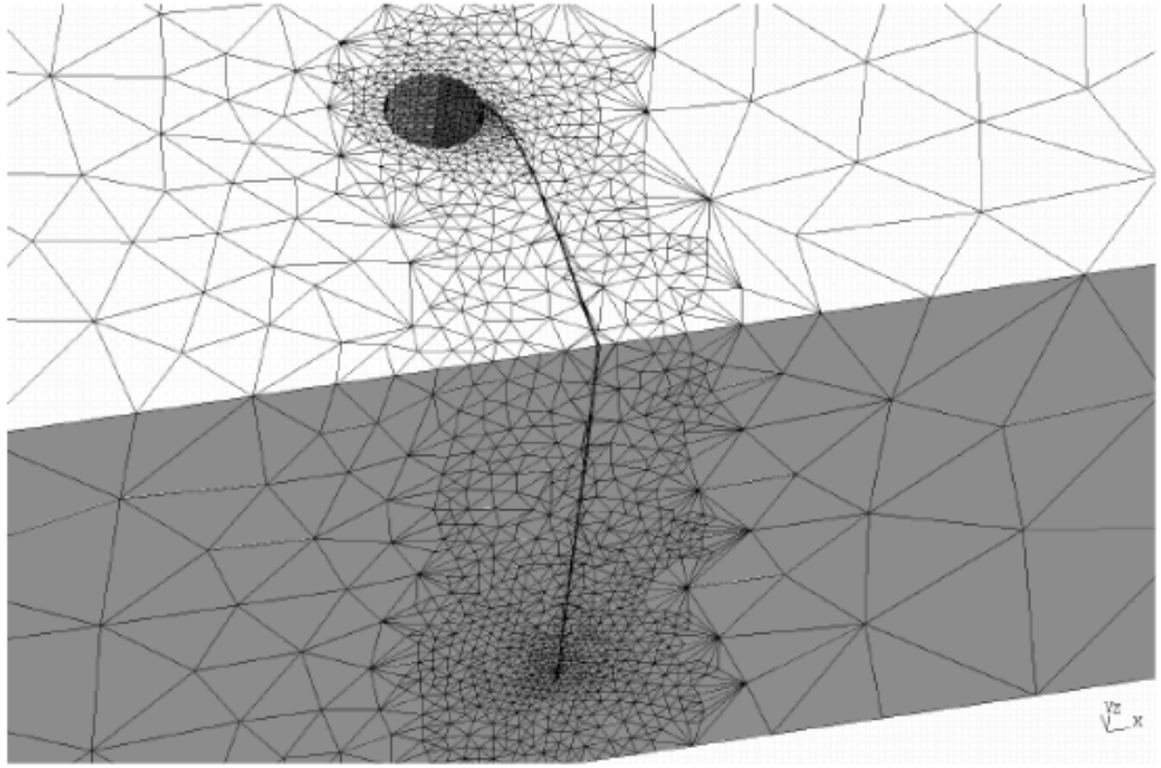


After: determine mesh refinement adaptively using a (goal-oriented) error estimate

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.

Much better… adapt the discretisation locally



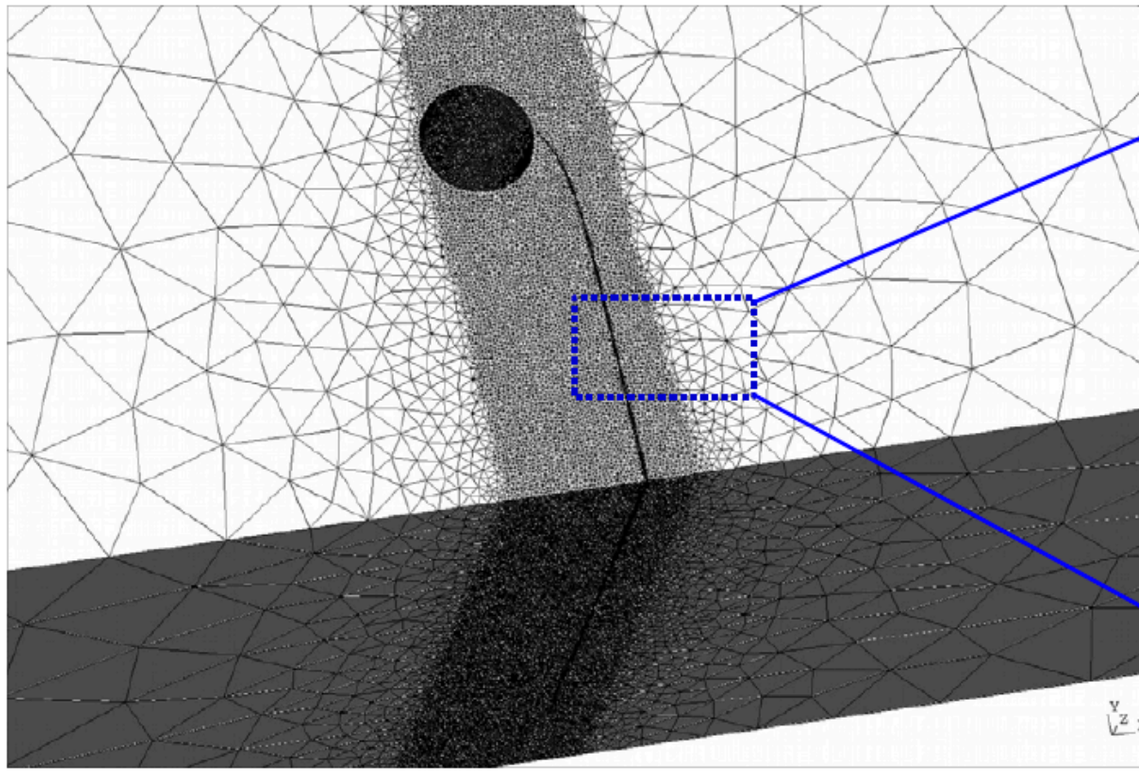


Orders of magnitude fewer elements

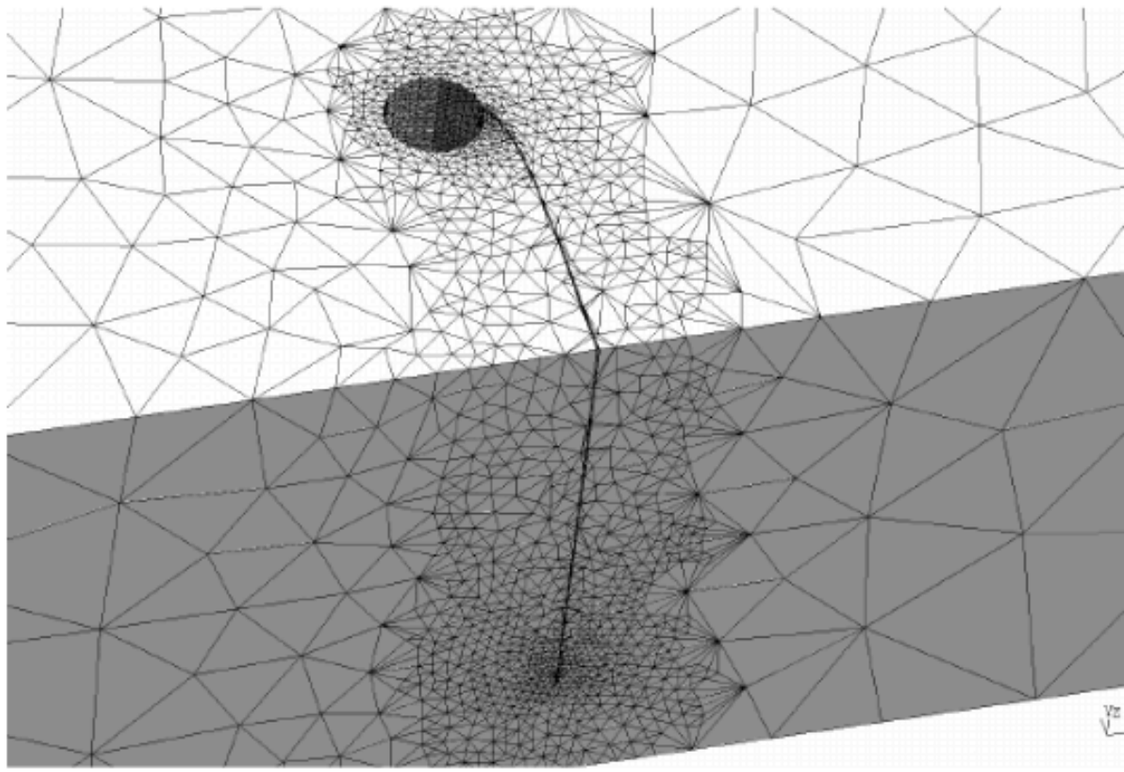
Y. Jin, O. Pierard, et al. Error-controlled adaptive extended finite element method for 3D linear elastic crack propagation Comput. Methods Appl. Mech. Engrg. 318 (2017) 319–348
M. Duflot, SPAB, IJNME 2007, CNME 2007, IJNME 2008.

TAKE HOME MESSAGE

UNIFORM MESH



REFINEMENT IS NOT AN OPTION



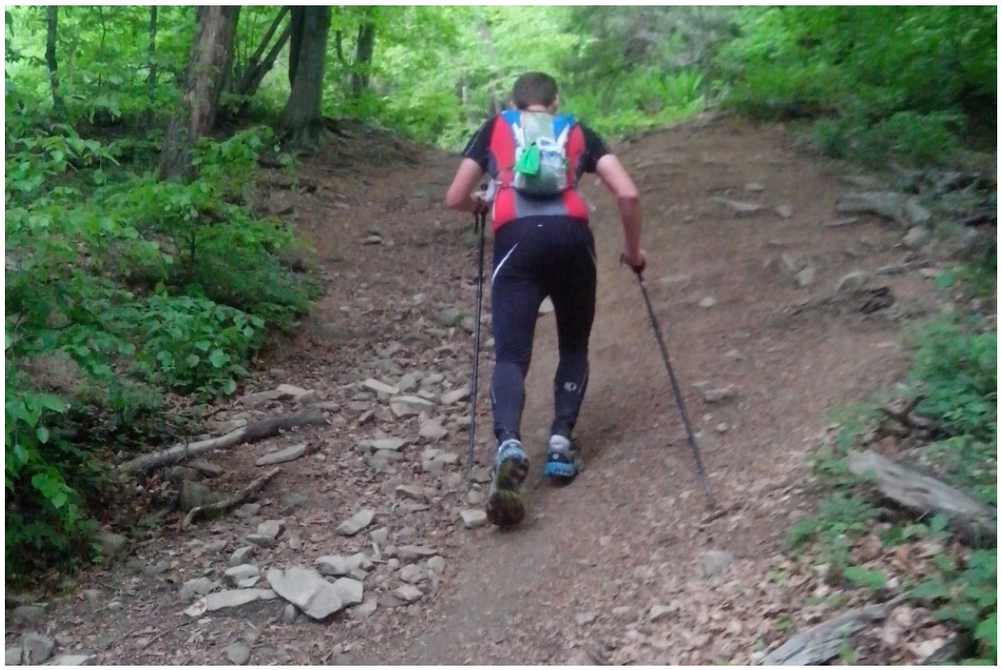
LIMITATIONS

No material is homogeneous… nor linear elastic…

Multi-scale methods…

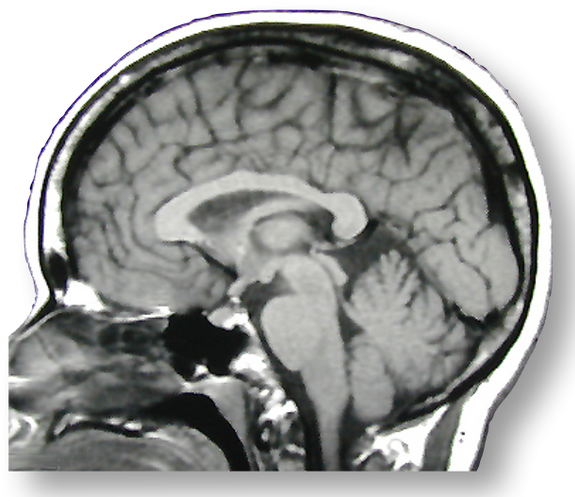
From your first love to the ERC

hiking - 20km D+500m



ultra-marathon 52km D+2500m

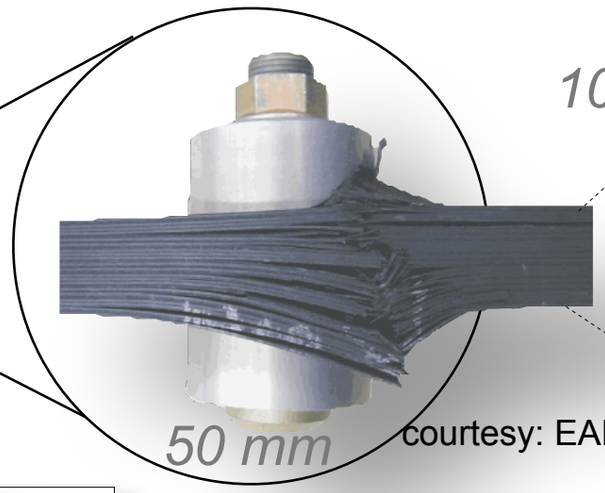
aerospace



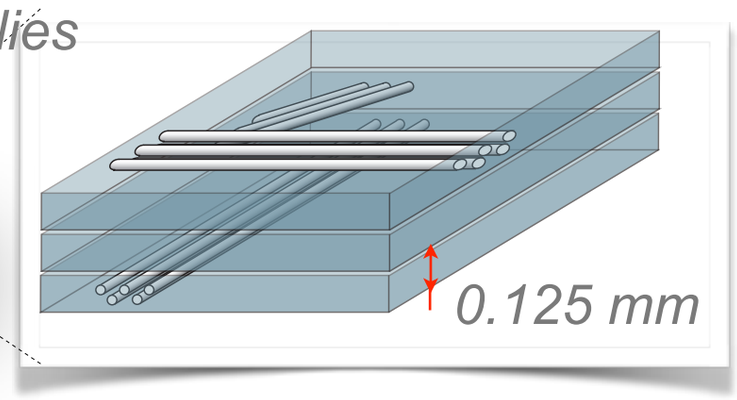
biomechanics

Motivation: multiscale fracture of engineering structures and materials

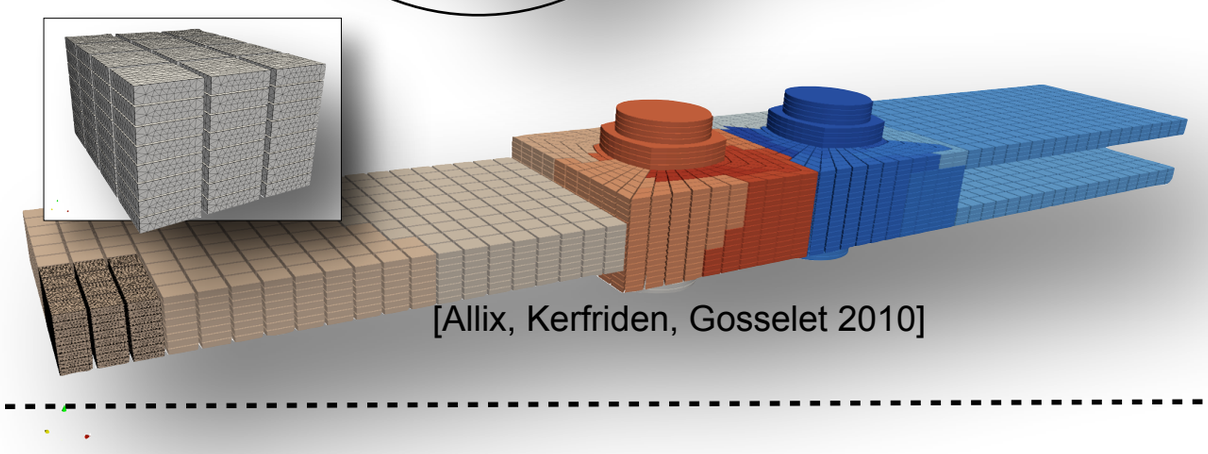
Aerospace



courtesy: EADS



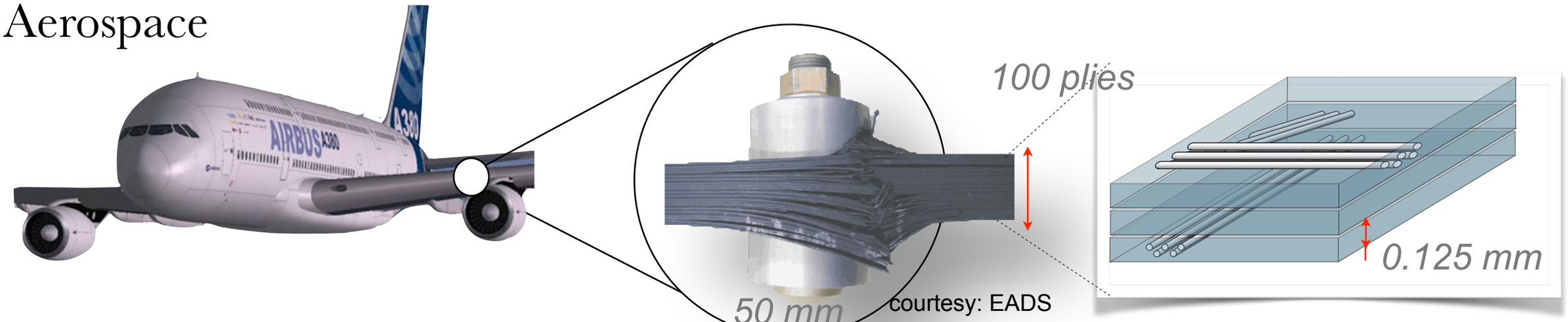
Discretise



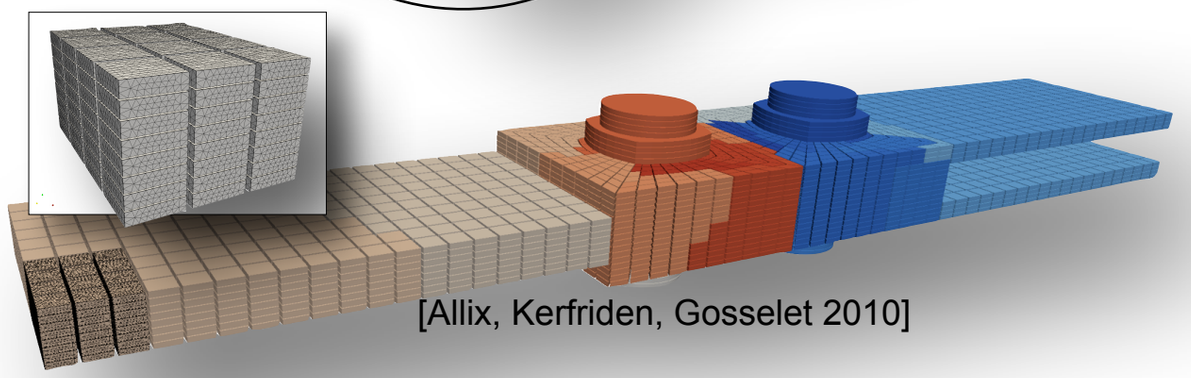
[Allix, Kerfriden, Gosselet 2010]

Motivation: multiscale fracture of engineering structures and materials

Aerospace

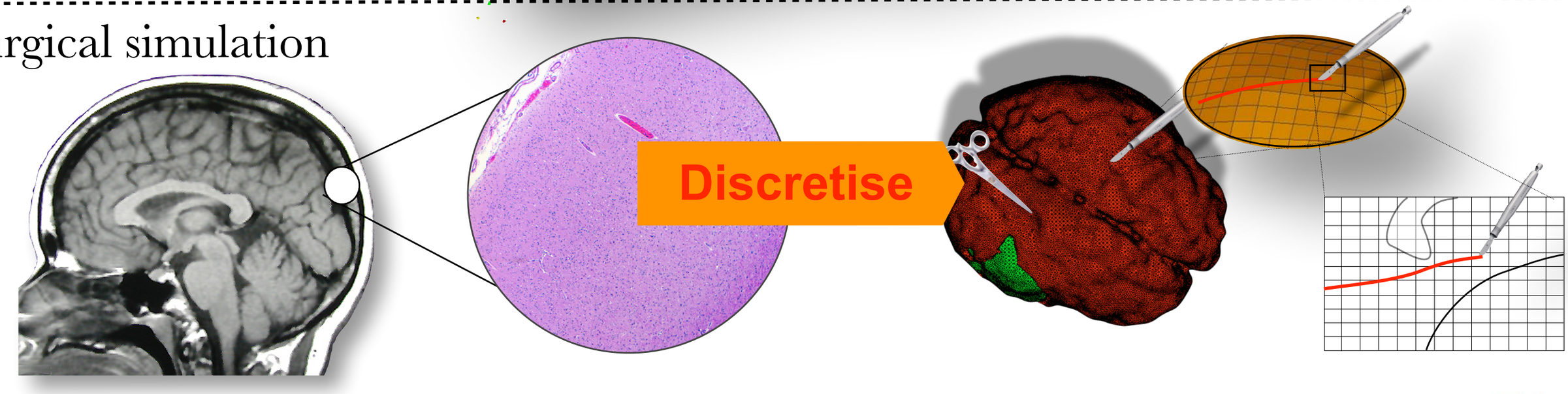


Discretise



[Allix, Kerfriden, Gosselet 2010]

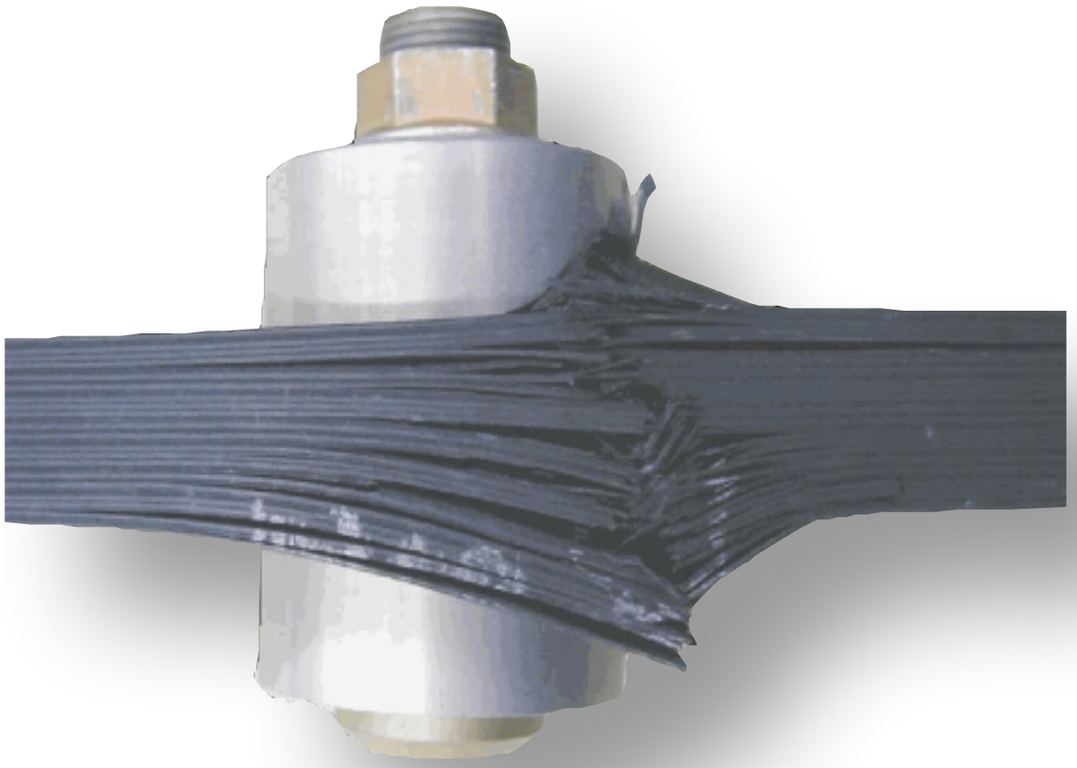
Surgical simulation



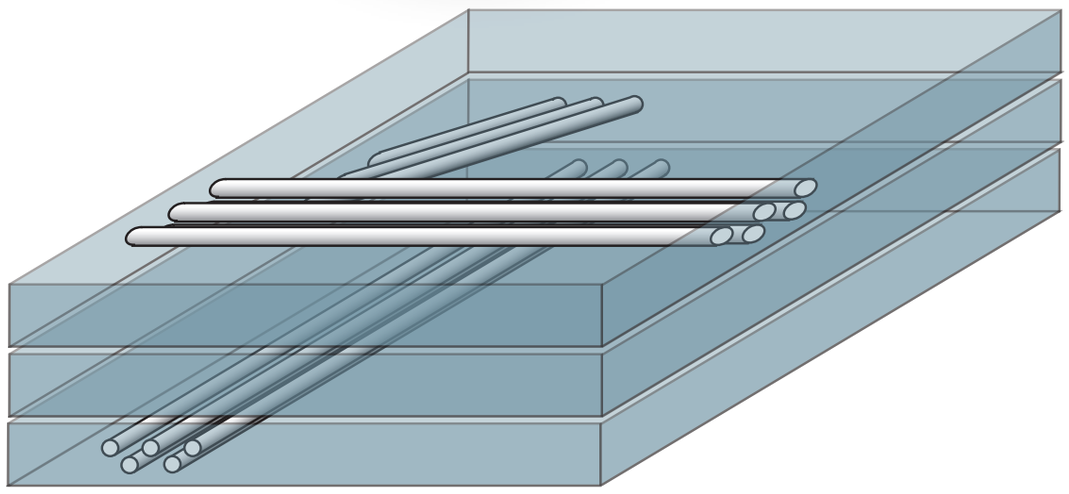
- Reduce the problem size while controlling the quality for problems involving (free) interfaces

RealTCut

Aero

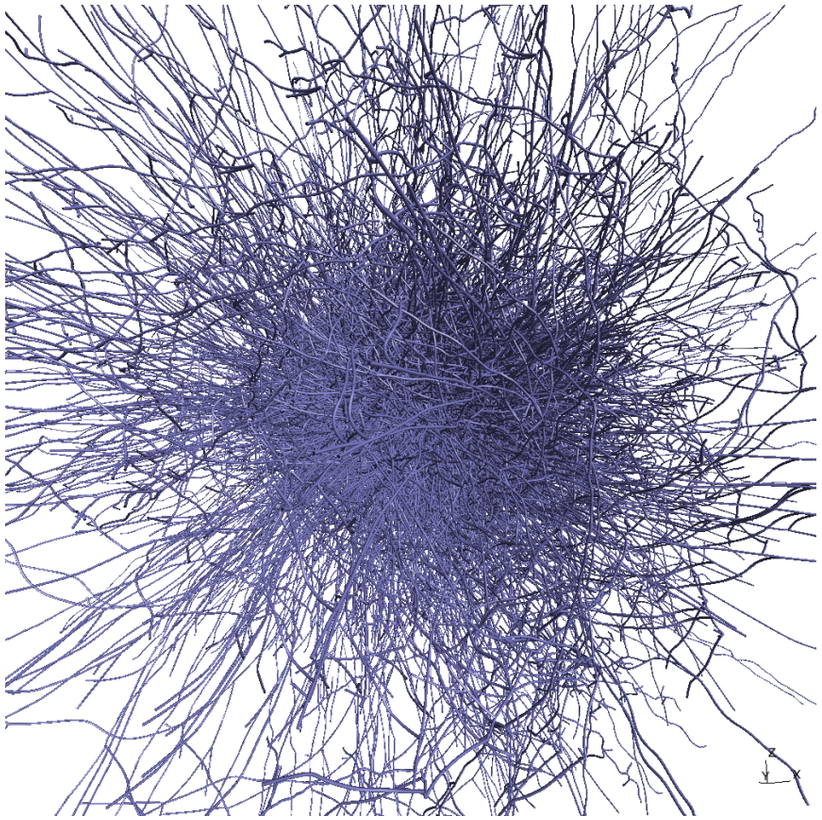


Bolted joint Courtesy EADS

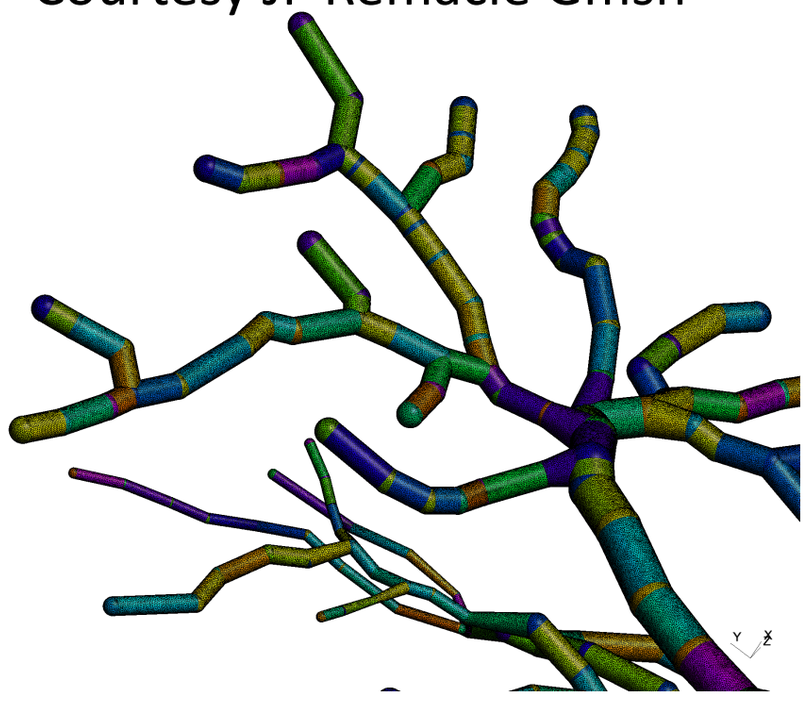


Multi-scale fibre lay-up Courtesy EADS

Bio



Courtesy JF Remacle Gmsh



Courtesy JF Remacle Gmsh

Speed

ms

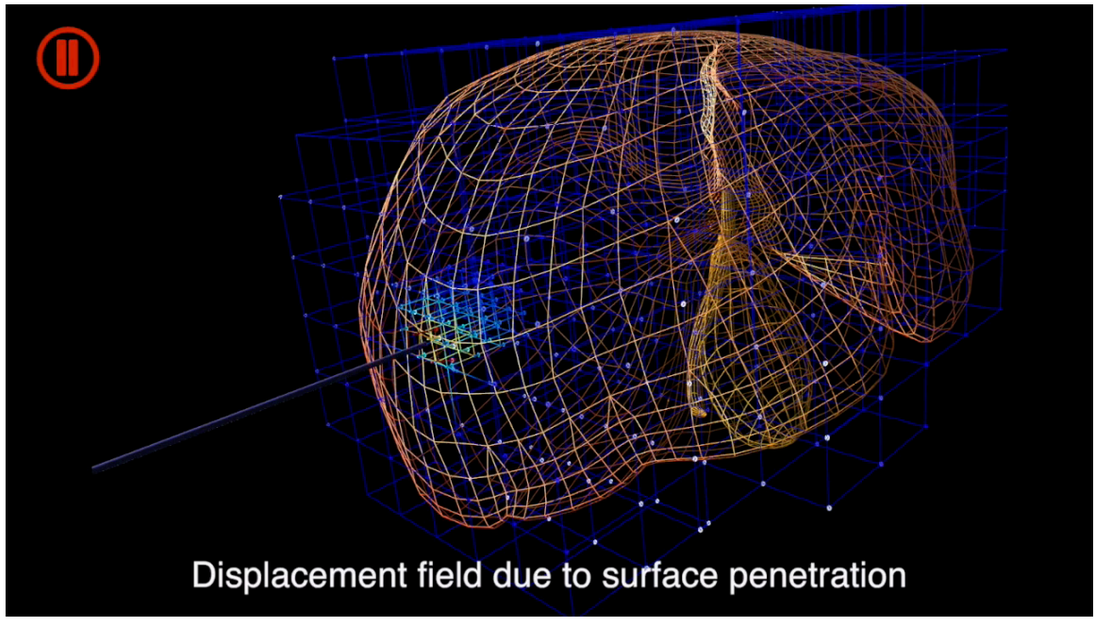
sec

min

hours

days

Surgical guidance

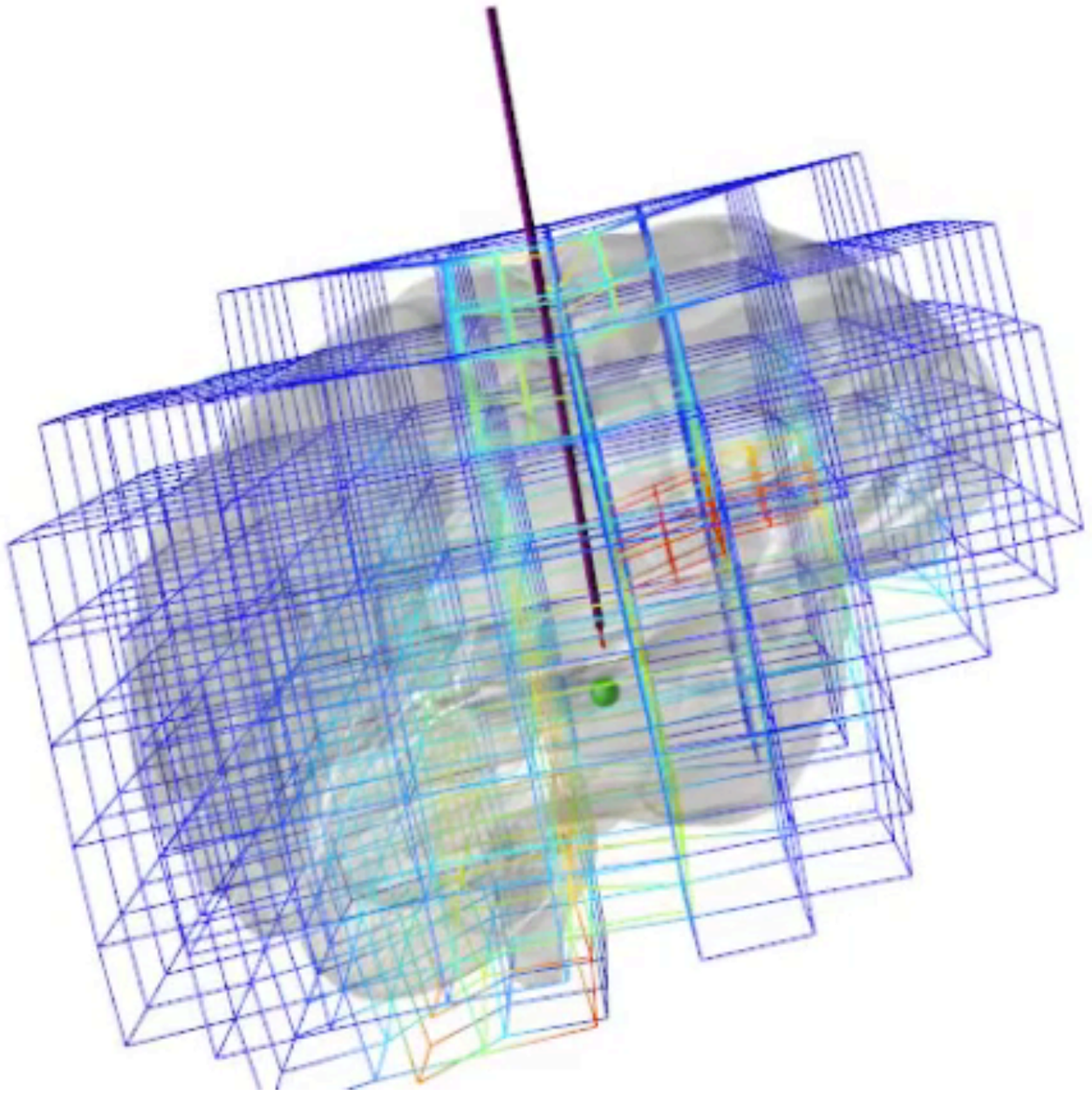


User Expertise & Accuracy of the Simulation

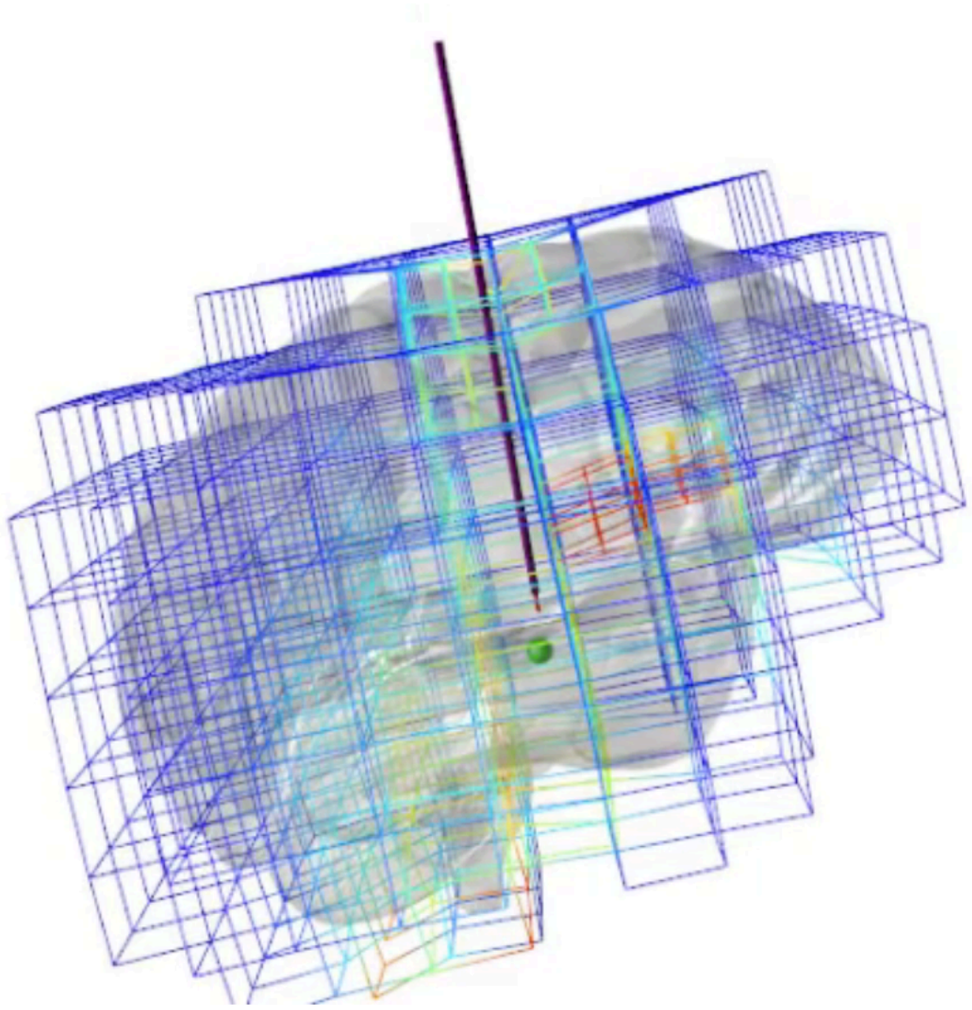
erc

RealTCut

Cannula insertion



CHALLENGE: everything happens close to the needle… focus the computational expense



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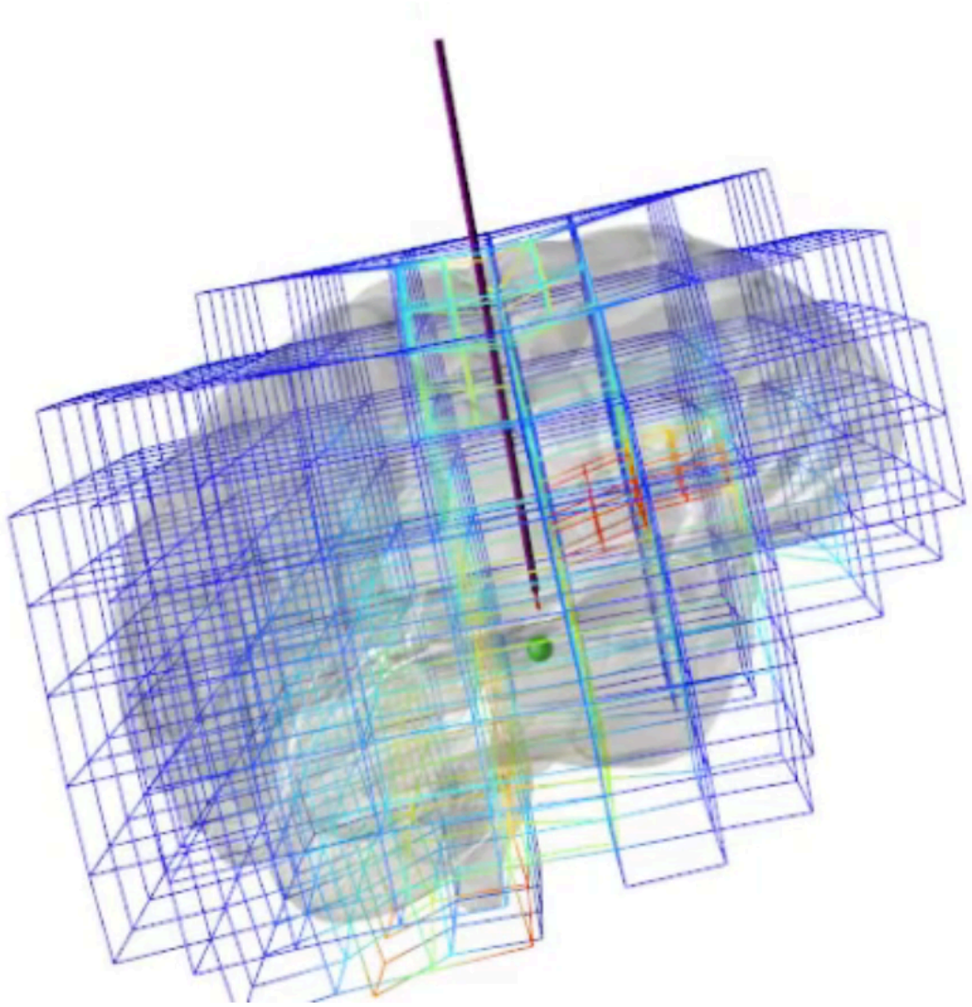


But HOW can we decide where and what the element size should be?

QUESTIONS

Local mesh refinement is necessary, but where? how?

We do not know the exact solution. How can we find out where the mesh should be refined?

Engineers are interested in specific quantities of interest, not in the “energy” norm, which is what mathematics uses most naturally.

What else is missing?

Model of contractile tissue

$$\min_{\mathbf{u}\in\mathbf{V}} \frac{1}{2}\int_\Omega \boldsymbol{\sigma}(\mathbf{u},\beta) : \boldsymbol{\varepsilon}(\mathbf{u})\, d\mathbf{x} - \int_\Omega \mathbf{g}\cdot\mathbf{u}\, d\mathbf{x}$$

with $\boldsymbol{\sigma}(\mathbf{u},\beta) = \underbrace{\boldsymbol{\sigma}_P(\mathbf{u})}_{\text{passive material}} + \underbrace{\boldsymbol{\sigma}_A(\beta)}_{\text{muscular activation}}$

$$\begin{cases} \boldsymbol{\sigma}_A(\beta) = \beta T e_A \otimes e_A \\ e_A : \text{ fiber direction} \\ T : \text{ tension} \\ \beta : \text{ activation} \end{cases}$$

where

Cowin & Humphrey 2001
Payan & Ohayon 2017
Biomechanics of Living Organs : Hyperelastic Constitutive Laws for Finite Element Modeling.

a posteriori error estimates

$$\mathbf{u} \in \mathbf{V} \; : \; a(\mathbf{u}, \mathbf{v}) = l(\beta, \mathbf{v}) \quad \forall \, \mathbf{v} \in \mathbf{V}$$

$$a(\mathbf{u}, \mathbf{v}) = \int_\Omega \boldsymbol{\sigma}_P(\mathbf{u}) : \boldsymbol{\varepsilon}(\mathbf{v}) \, d\mathbf{x} \qquad l(\beta, \mathbf{v}) = \int_\Omega \boldsymbol{\sigma}_A(\beta) : \boldsymbol{\varepsilon}(\mathbf{v}) \, d\mathbf{x} + \int_\Omega \mathbf{g} \cdot \mathbf{v} \, d\mathbf{x}$$

Prediction of a quantity of interest (e.g., local strain or stress) :

$$J : \mathbf{V} \ni \mathbf{u} \mapsto J(\mathbf{u}) \in \mathbb{R}.$$

(Goal-oriented) discretization error : $|J(\mathbf{u}) - J(\mathbf{u}_h)|$?

Exact solution : $\mathbf{u} \in \mathbf{V}$
MEF approximation : $\mathbf{u}_h \in \mathbf{V}_h$

Dual Weighted Residuals (DWR)

$$J(\mathbf{u}) - J(\mathbf{u}_h) = a(\mathbf{u}, \mathbf{z}) - a(\mathbf{u}_h, \mathbf{z}) = \underbrace{l(\mathbf{z}) - a(\mathbf{u}_h, \mathbf{z})}_{\text{residual}} =: \eta_h(\mathbf{z})$$

where $\mathbf{z} \in \mathbf{V}$ s.t. $a(\mathbf{v}, \mathbf{z}) = J(\mathbf{v}) \qquad \forall\, \mathbf{v} \in \mathbf{V}$ (dual problem)

➥ **global estimator** : η_h

Local representation

$$\begin{aligned} J(\mathbf{u}) - J(\mathbf{u}_h) &= \sum_{K \in \mathcal{K}_h} \langle R_K, \mathbf{z} - \pi_h \mathbf{z} \rangle_K + \langle R_{\partial K}, \mathbf{z} - \pi_h \mathbf{z} \rangle_{\partial K} \\ &=: \sum_{K \in \mathcal{K}_h} \eta_K (z - \pi_h z) \end{aligned}$$ **local estimator**

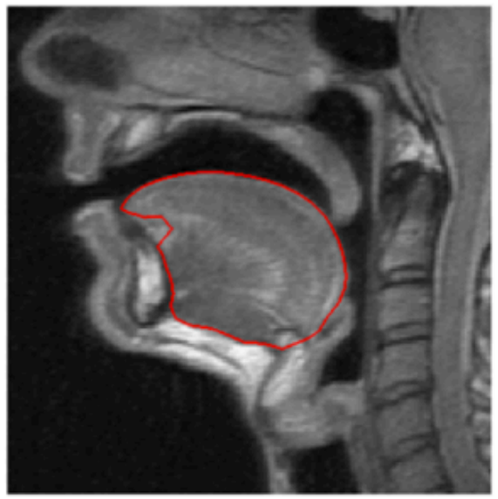
$\pi_h \mathbf{z}$: interpolant of dual solution

R_K / $R_{\partial K}$: residual contributions on K / ∂K

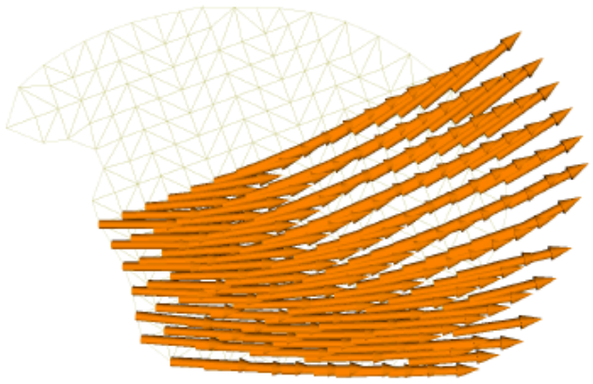
➥ **local estimators** : η_K

Becker & Rannacher 1997, 2001
Rognes & Logg 2013 (FEniCS)

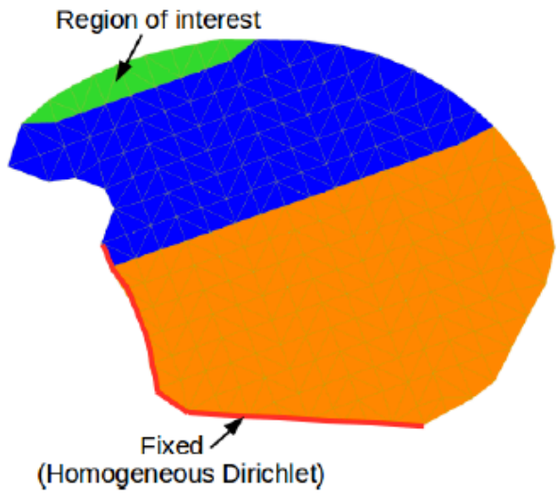
Genioglossus activation



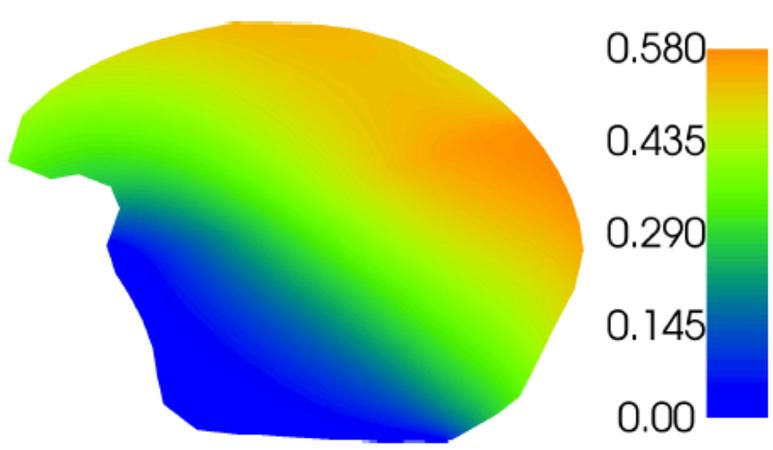
Bijar, Rohan, Perrier & Payan 2015



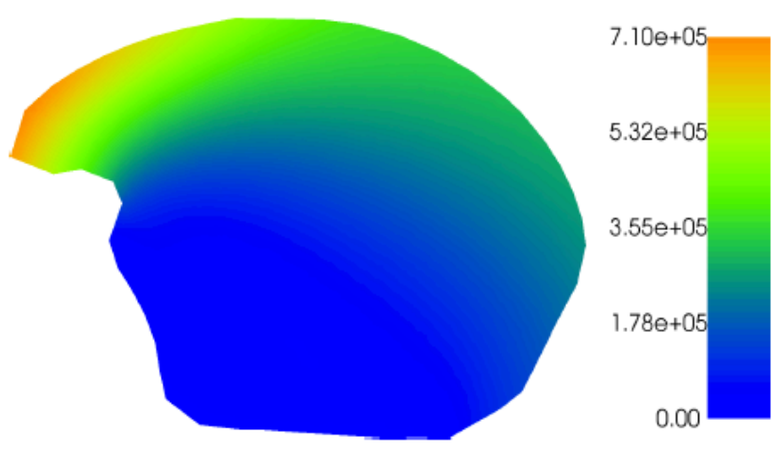
fibers (genioglossus)



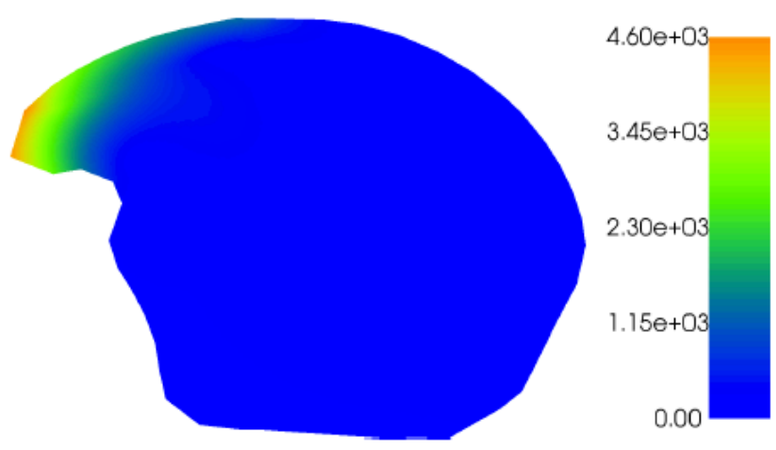
region of interest ω (green)



$\mathbf{u}$



$\mathbf{z}$ / J_1

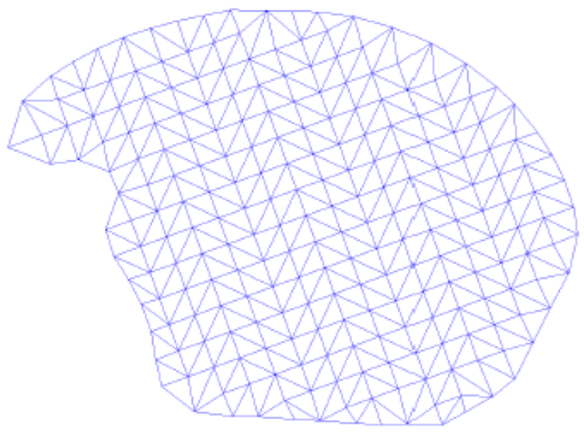


$\mathbf{z}$ / J_2

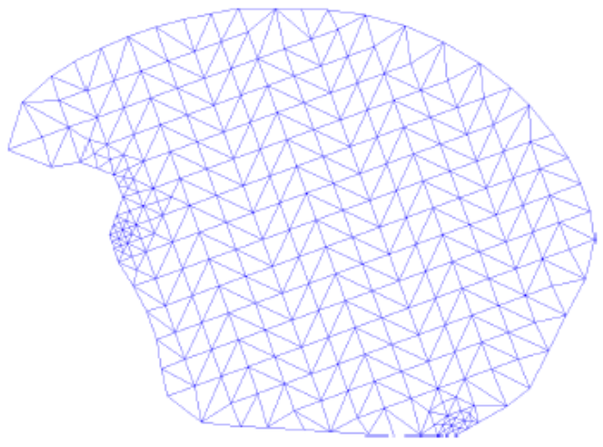
$$J_1(\mathbf{u}) := \int_\omega (u_x + u_y)\, d\mathbf{x} \qquad J_2(\mathbf{u}) := \int_\omega \text{div}\, \mathbf{u}\; d\mathbf{x}$$

Genioglossus activation

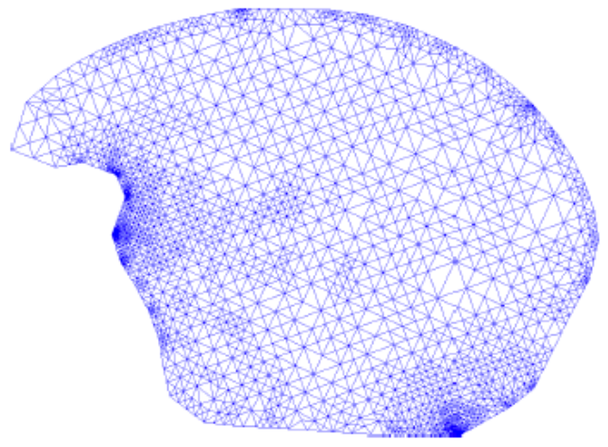
J_1 :



init
(N=426, $\varepsilon = 1.10^{-2}$)

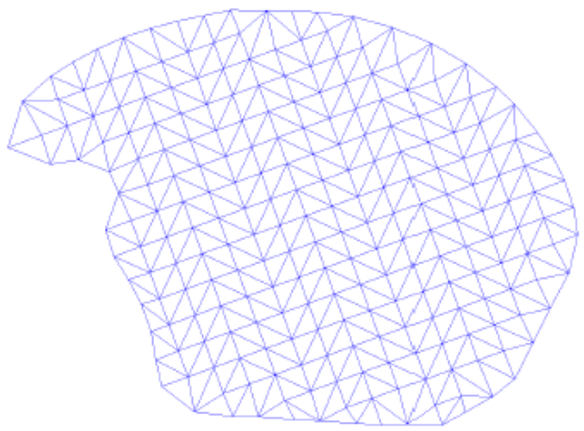


2nd iteration
(N=523, $\varepsilon = 3.10^{-3}$)

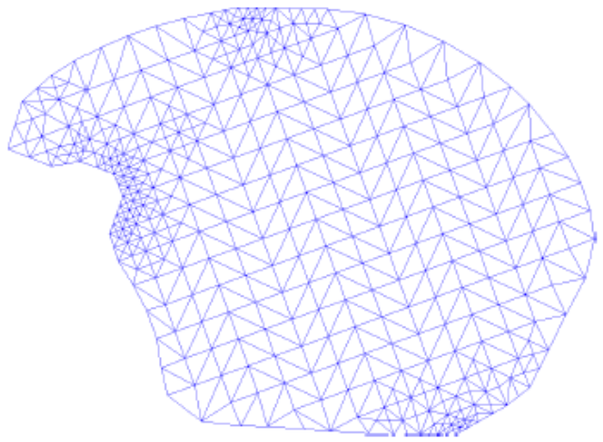


8th iteration
(N=5143, $\varepsilon = 4.10^{-5}$)

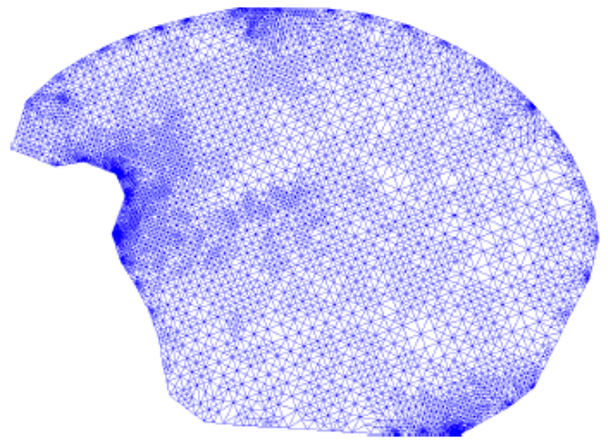
J_2 :



init
(N=426, $\varepsilon = 3.10^{-2}$)

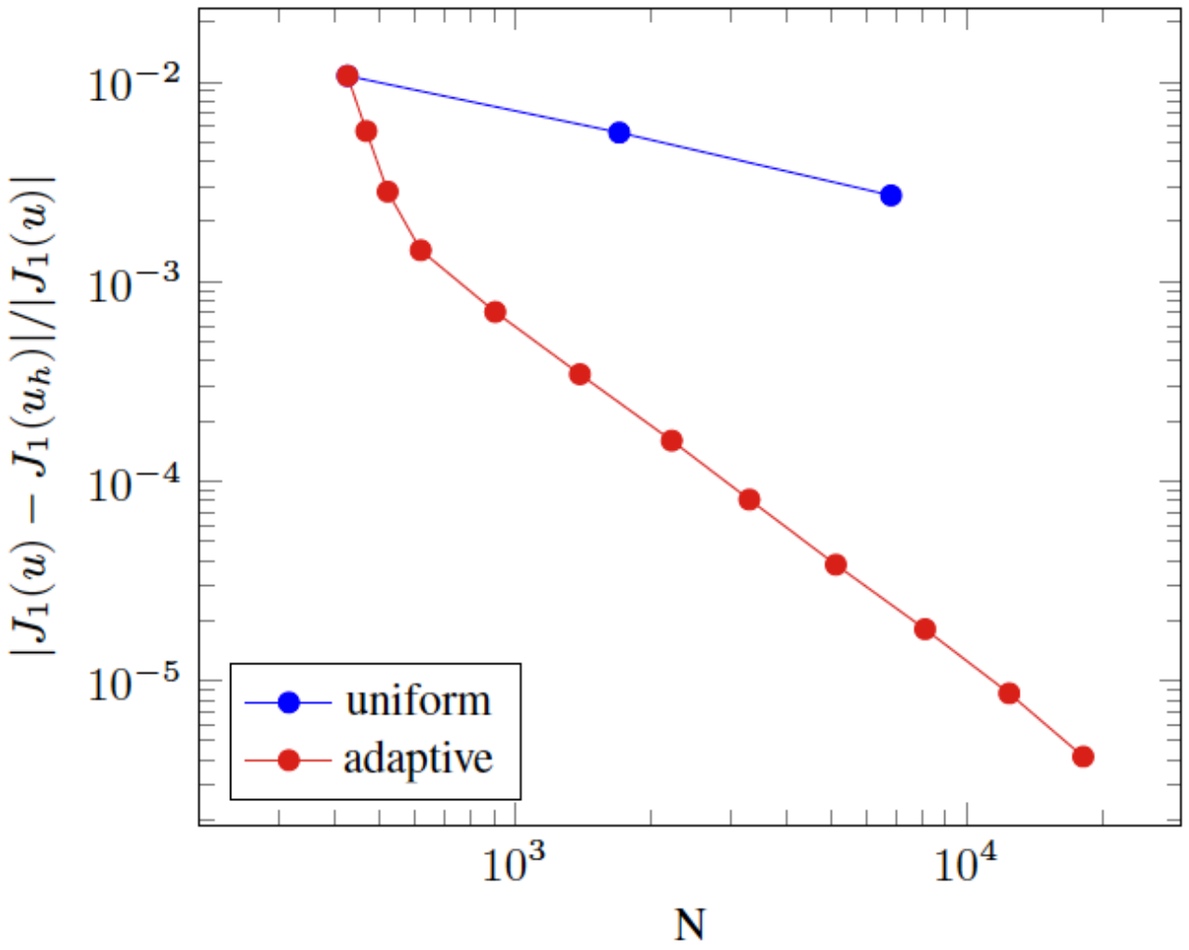


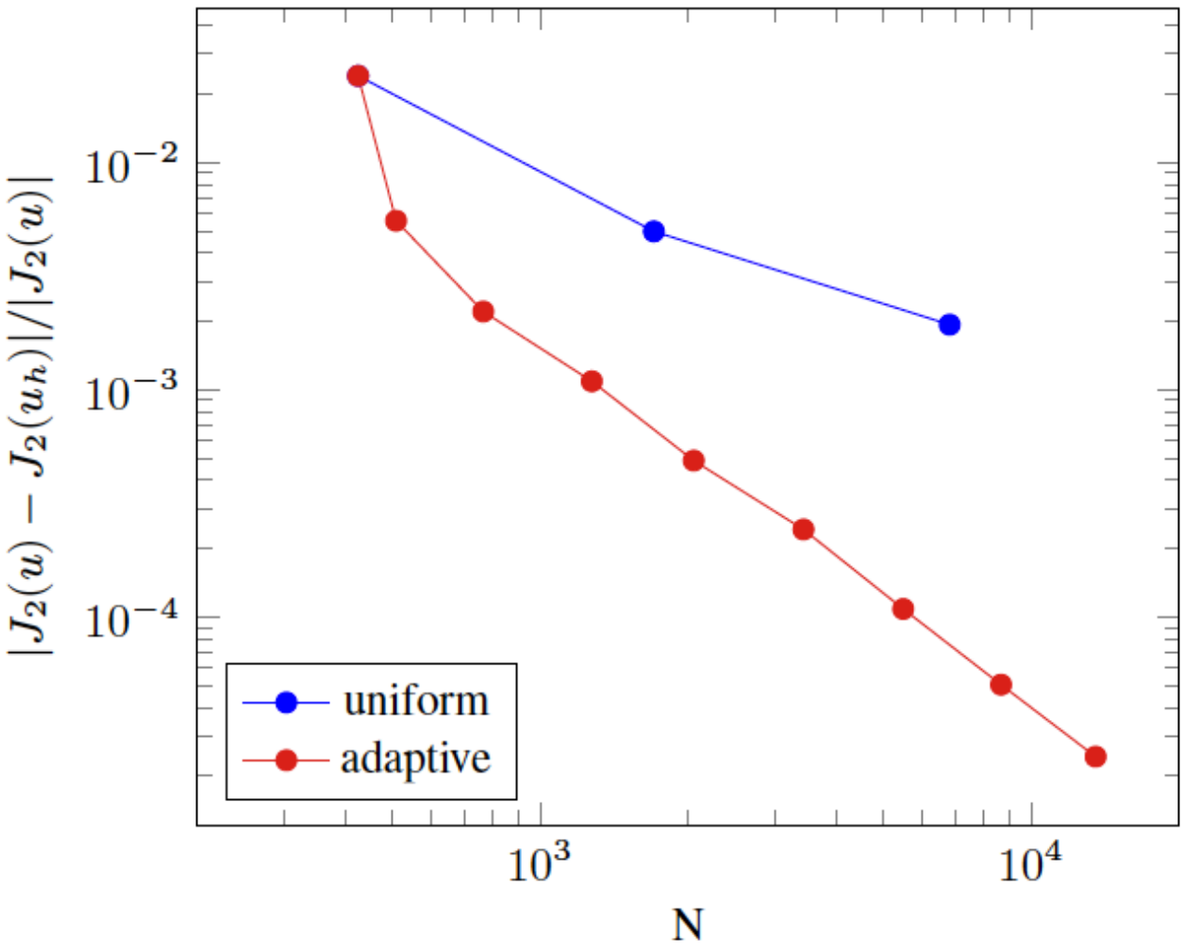
2nd iteration
(N=766, $\varepsilon = 2.10^{-3}$)



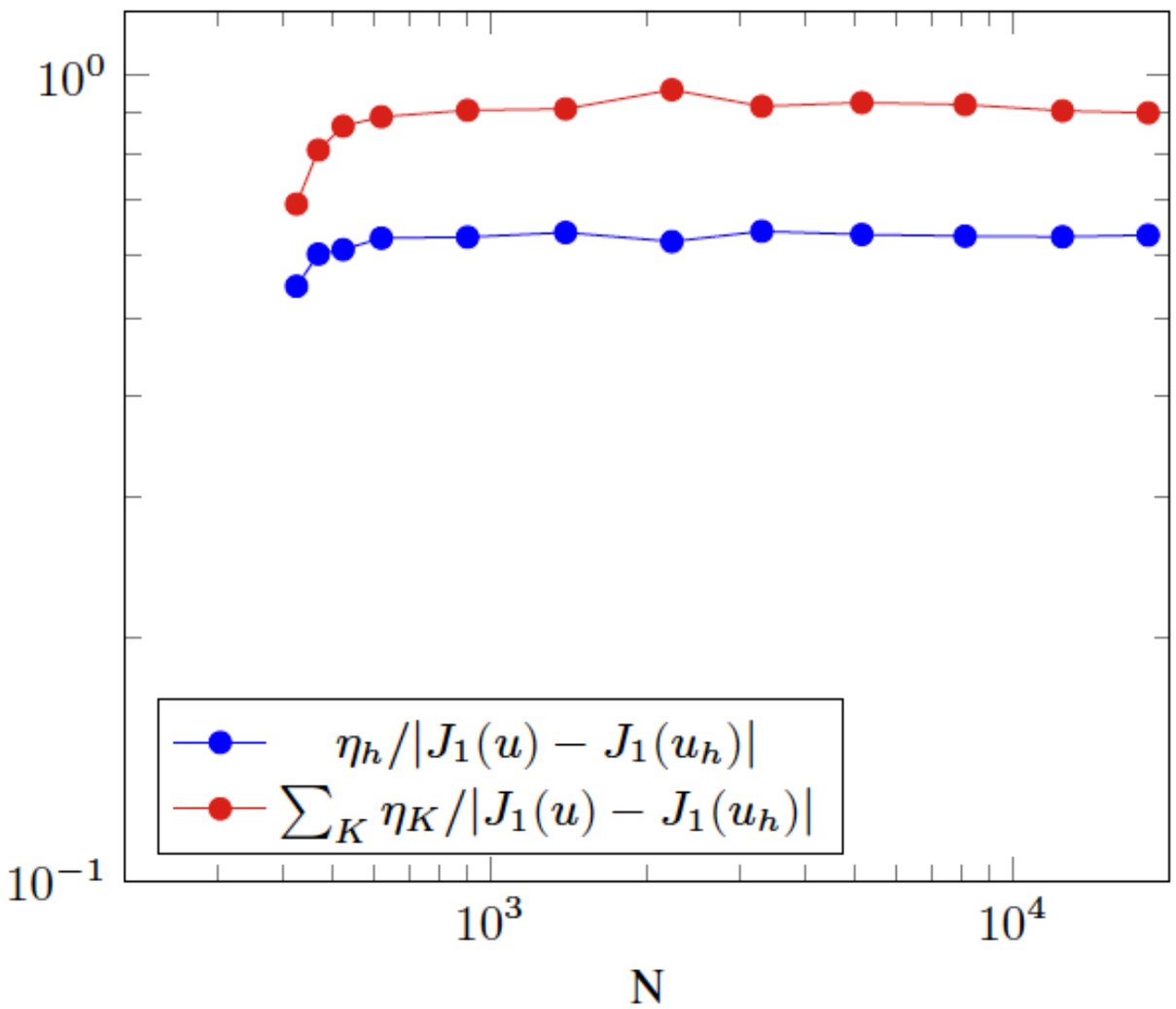
8th iteration
(N=13513, $\varepsilon = 2.10^{-5}$)

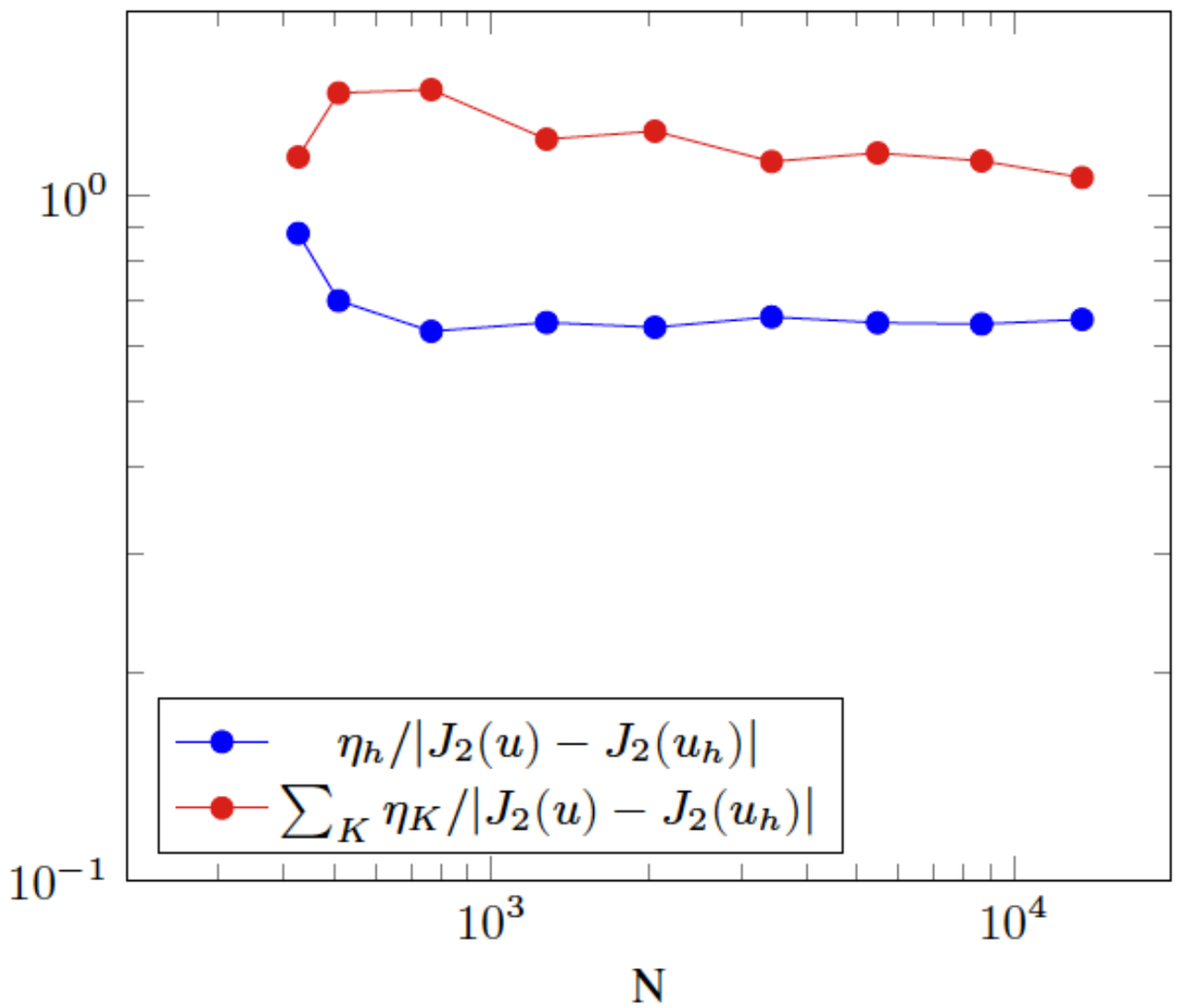
Effect of adaptive refinement



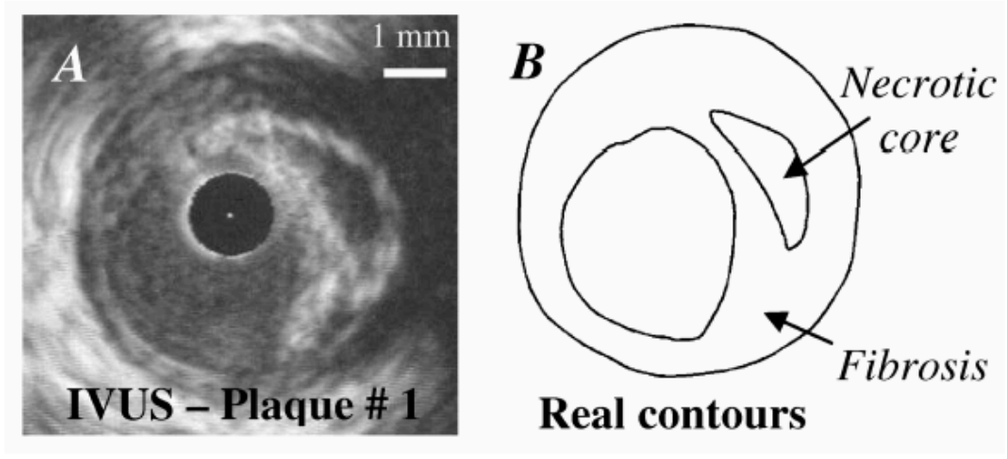


Effectivity of the error indicator

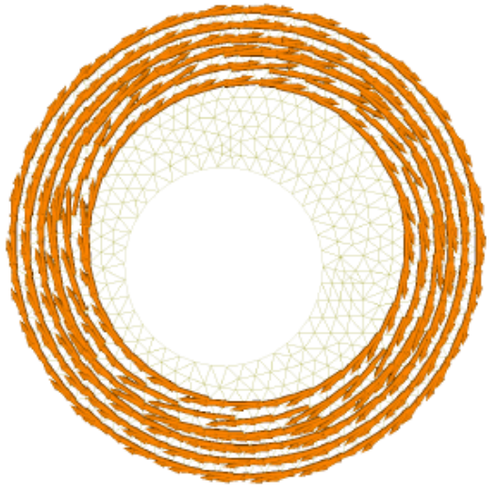




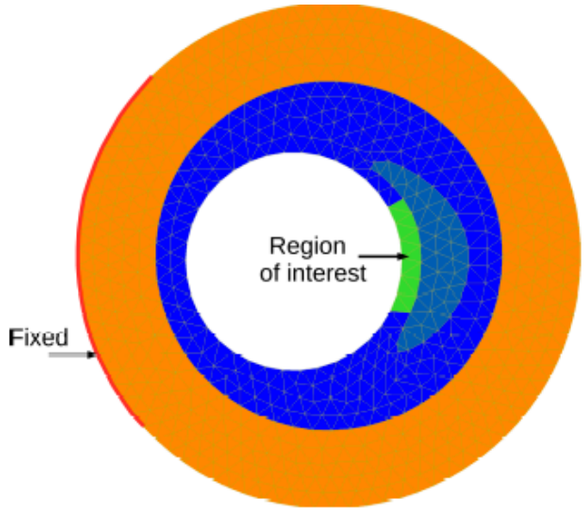
Arterial wall activation



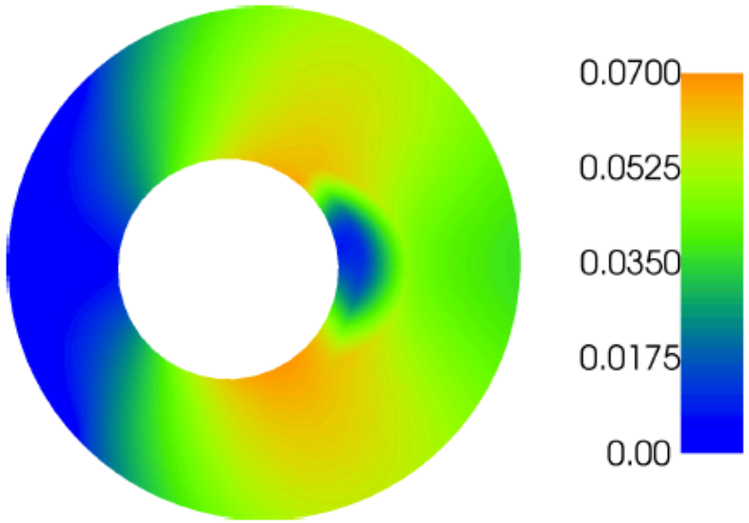
Le Floc'h et.al 2008



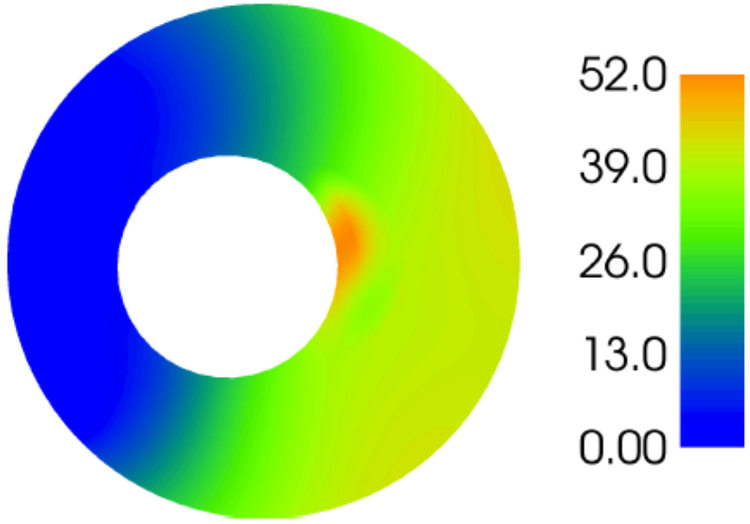
media



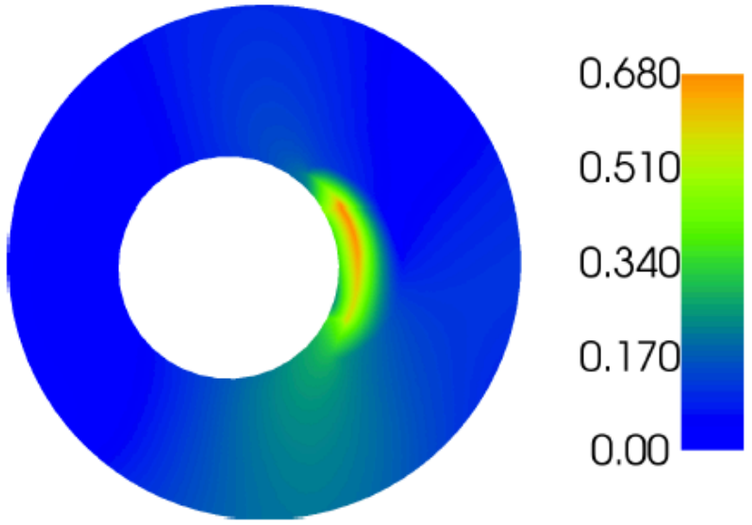
region of interest ω (green)



$\mathbf{u}$



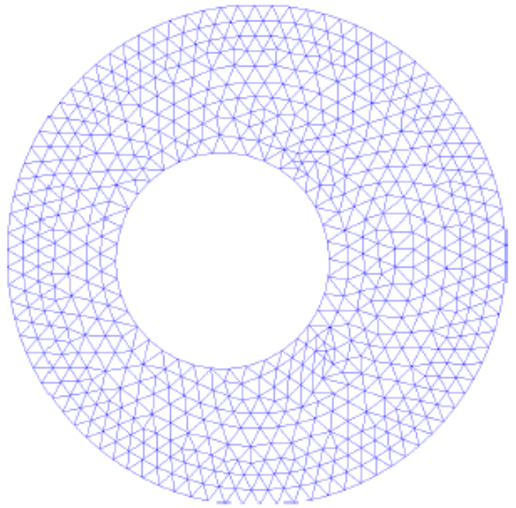
$\mathbf{z}$ / J_1



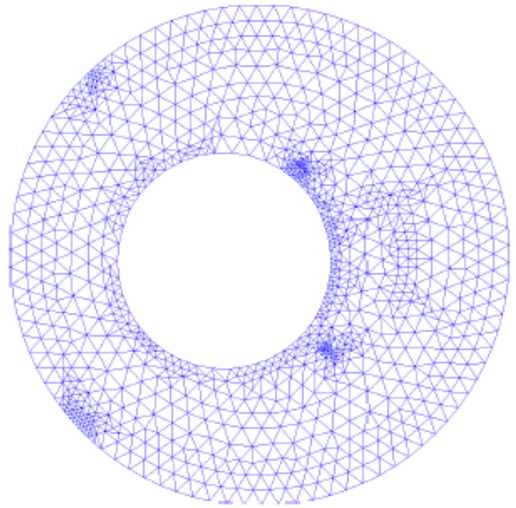
$\mathbf{z}$ / J_2

$$J_1(\mathbf{u}) := \int_\omega (u_x + u_y)\, d\mathbf{x} \qquad J_2(\mathbf{u}) := \int_\omega \text{div}\, \mathbf{u}\, d\mathbf{x}$$

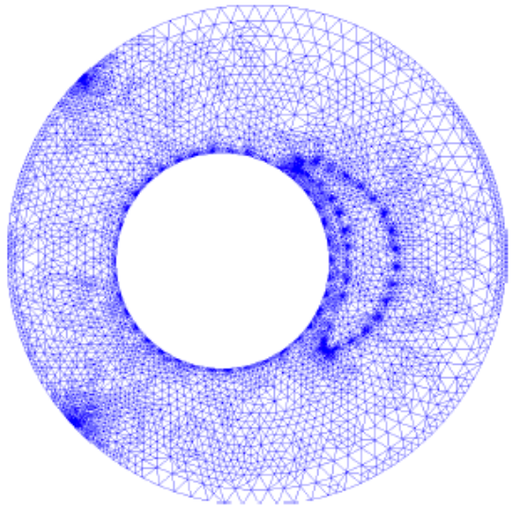
J_1 :



init
(N=1242, $\varepsilon = 0.4$)

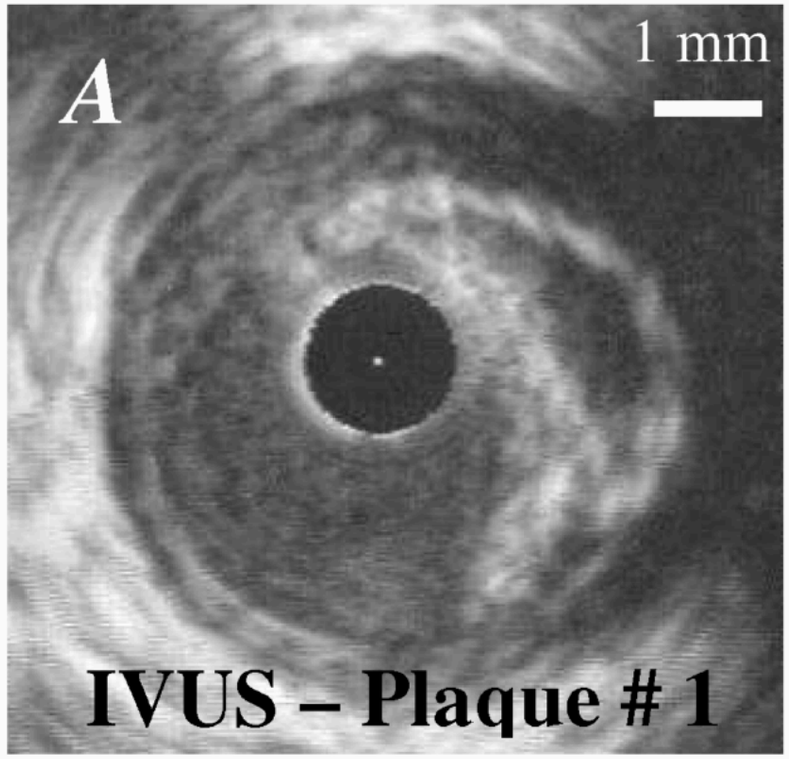


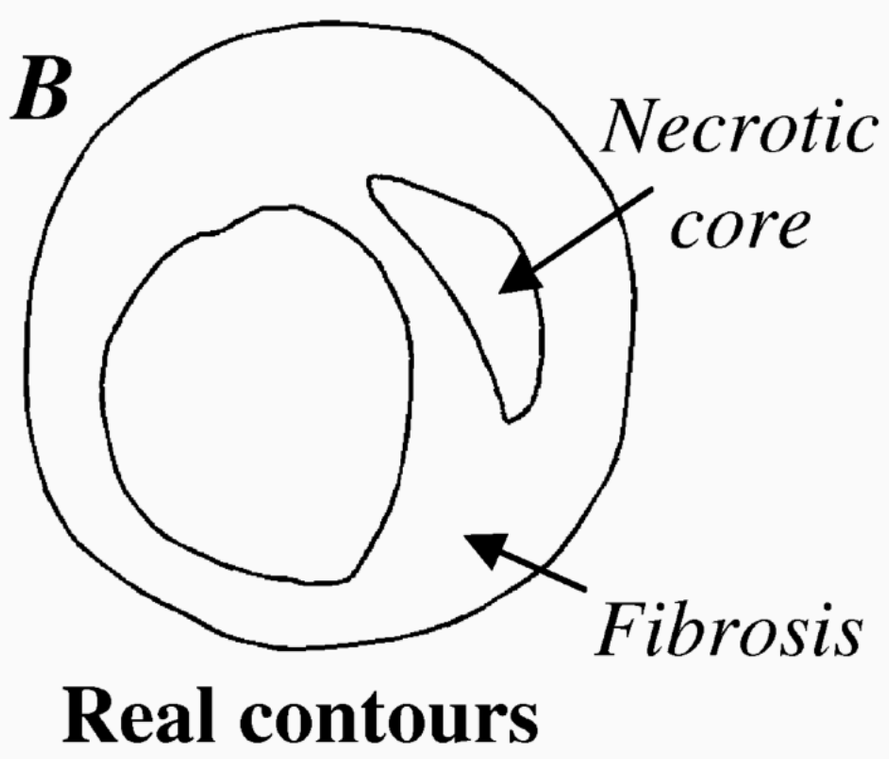
2nd iteration
(N=2079, $\varepsilon = 0.05$)

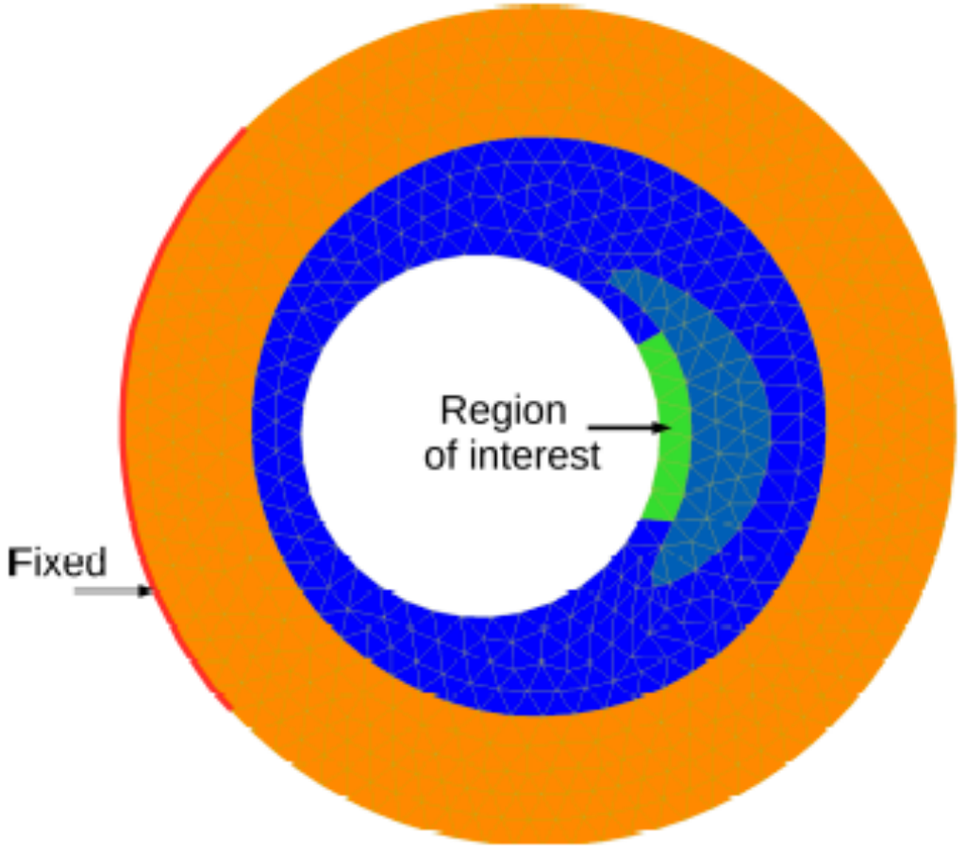


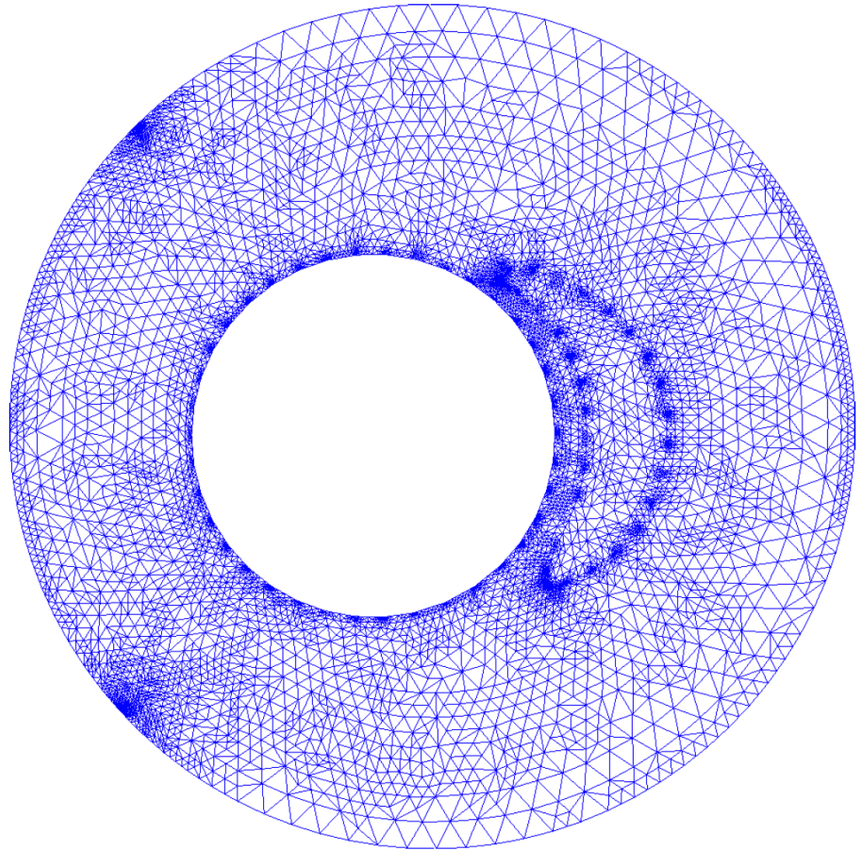
6th iteration
(N=15028, $\varepsilon = 3.10^{-3}$)

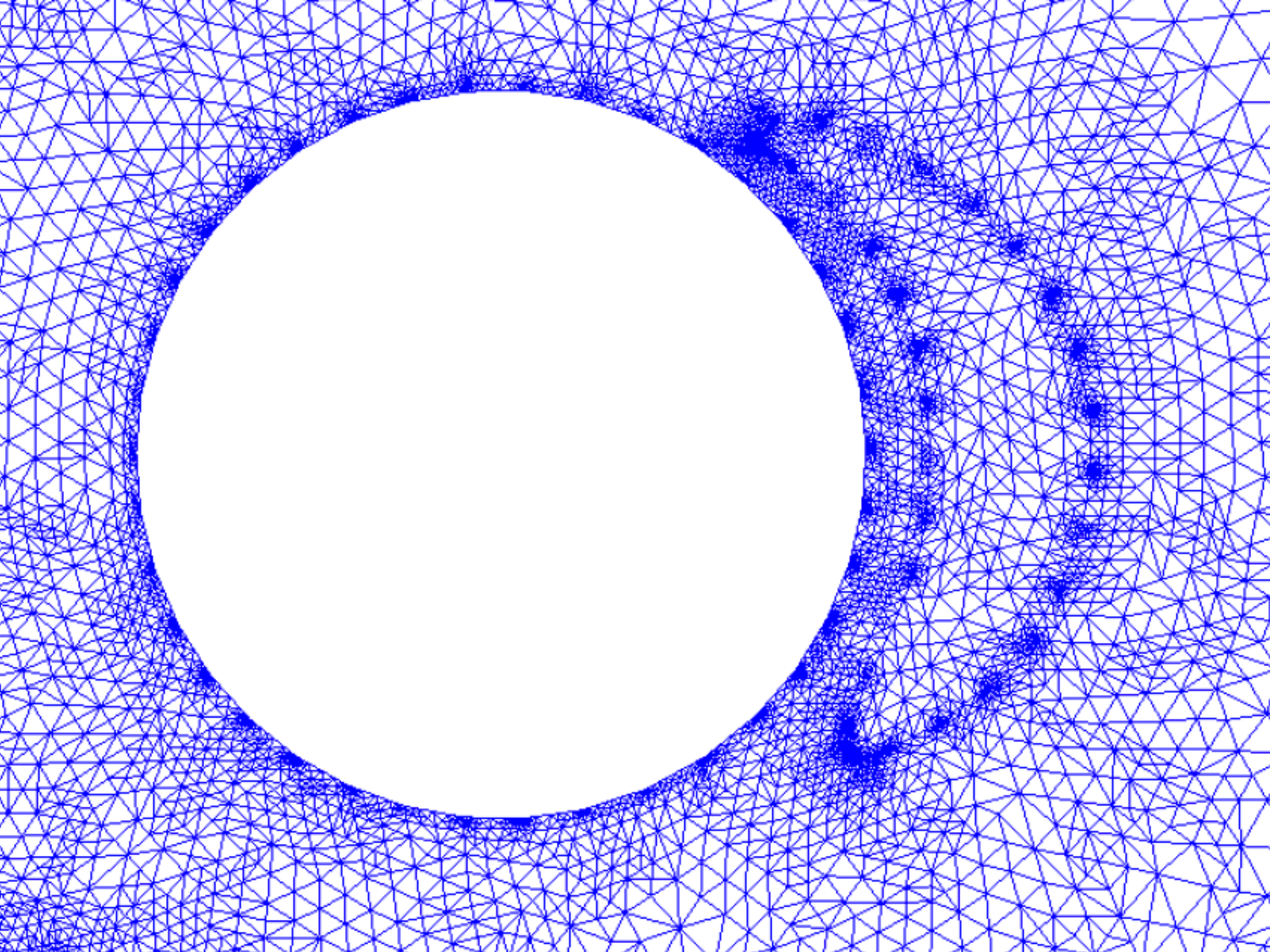
J_2 : similar results.


A
1 mm
IVUS – Plaque # 1

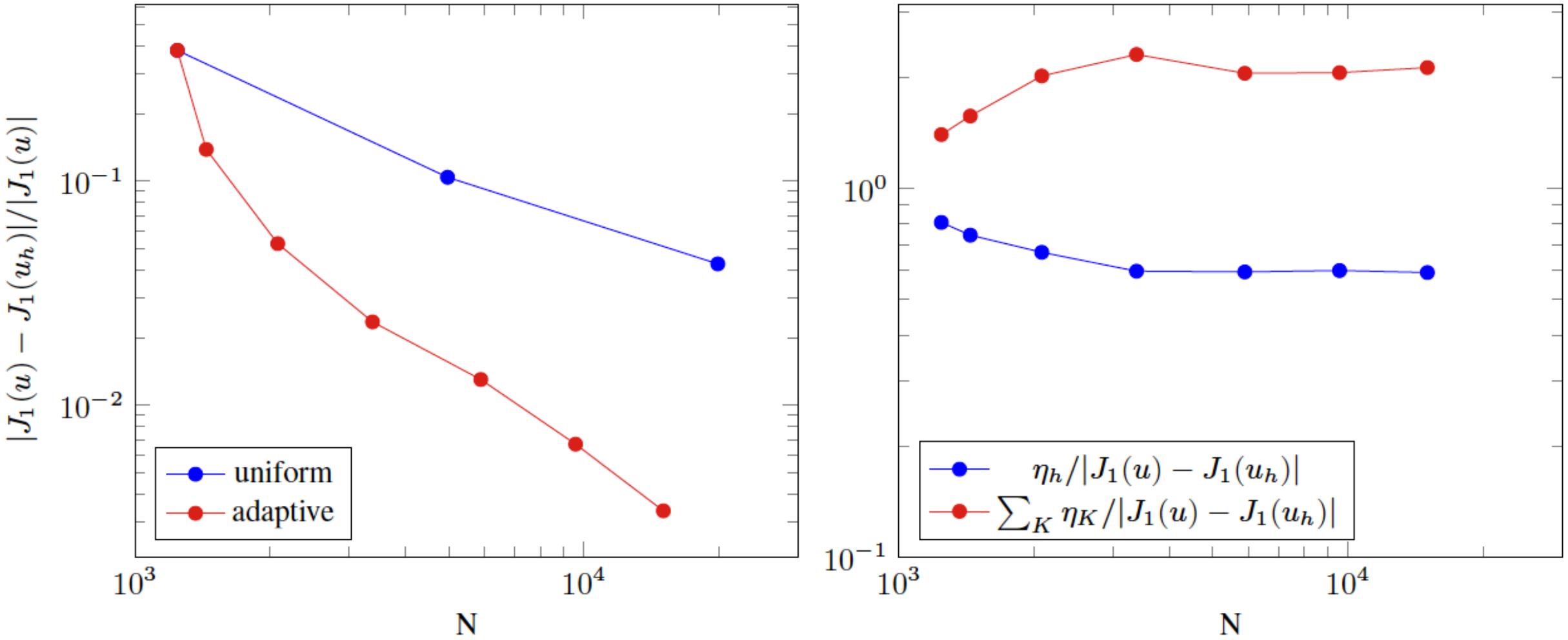

B
Necrotic core
Fibrosis
Real contours


Region of interest
Fixed



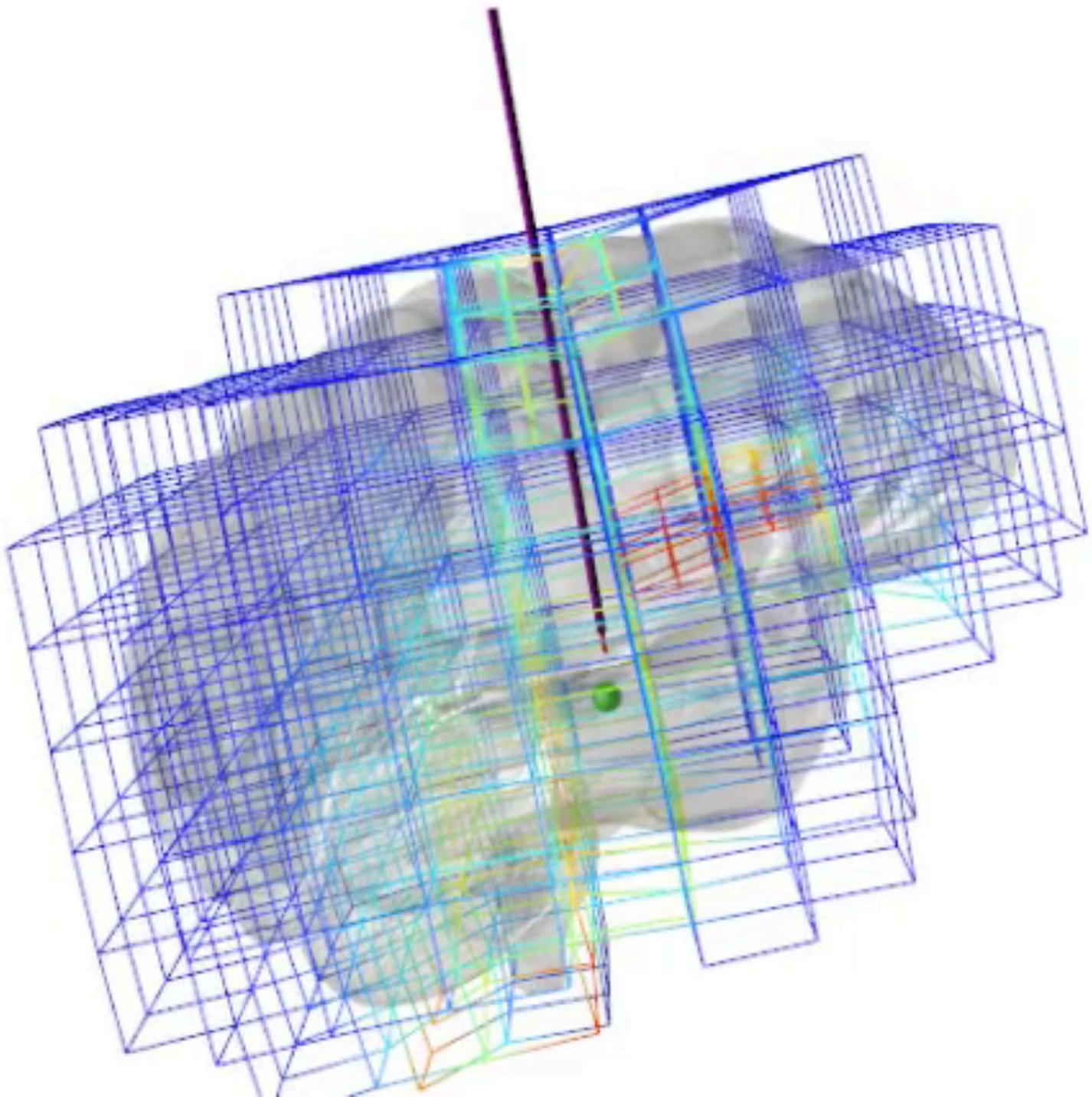


Effectivity



uniform vs. adaptive (left) / efficiency (right)

Cannula insertion



Speed

ms

sec

min

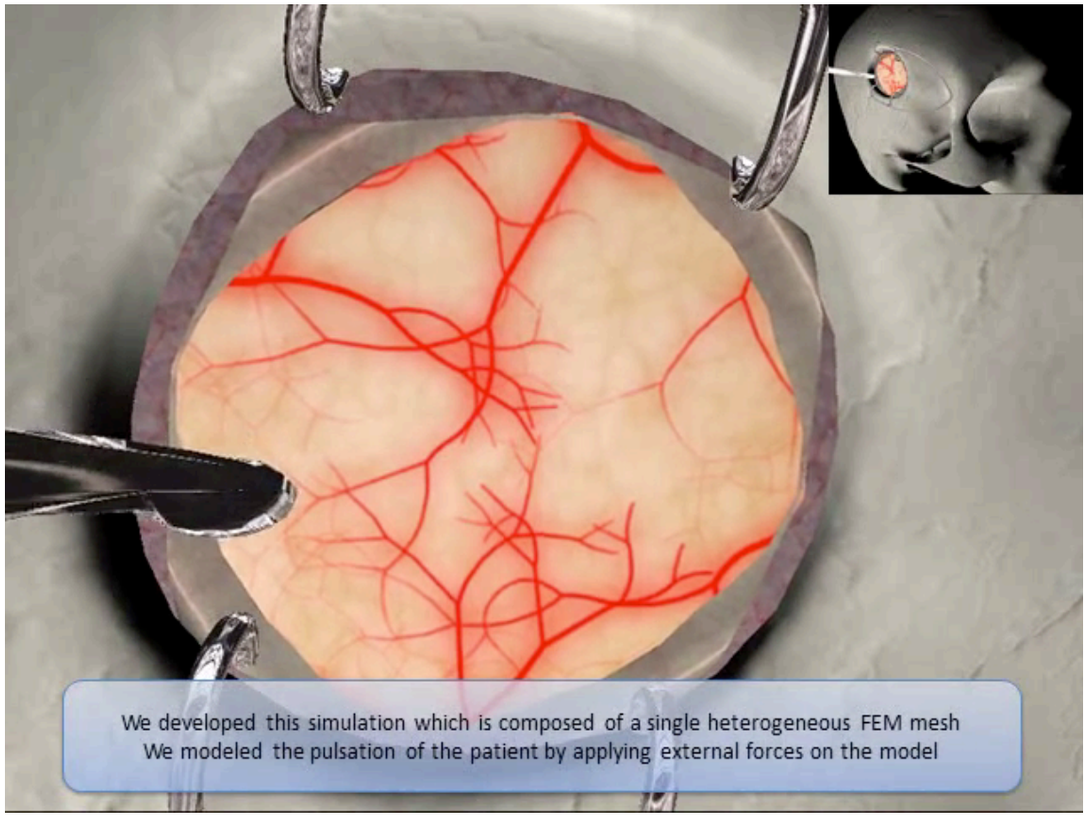
min

hours

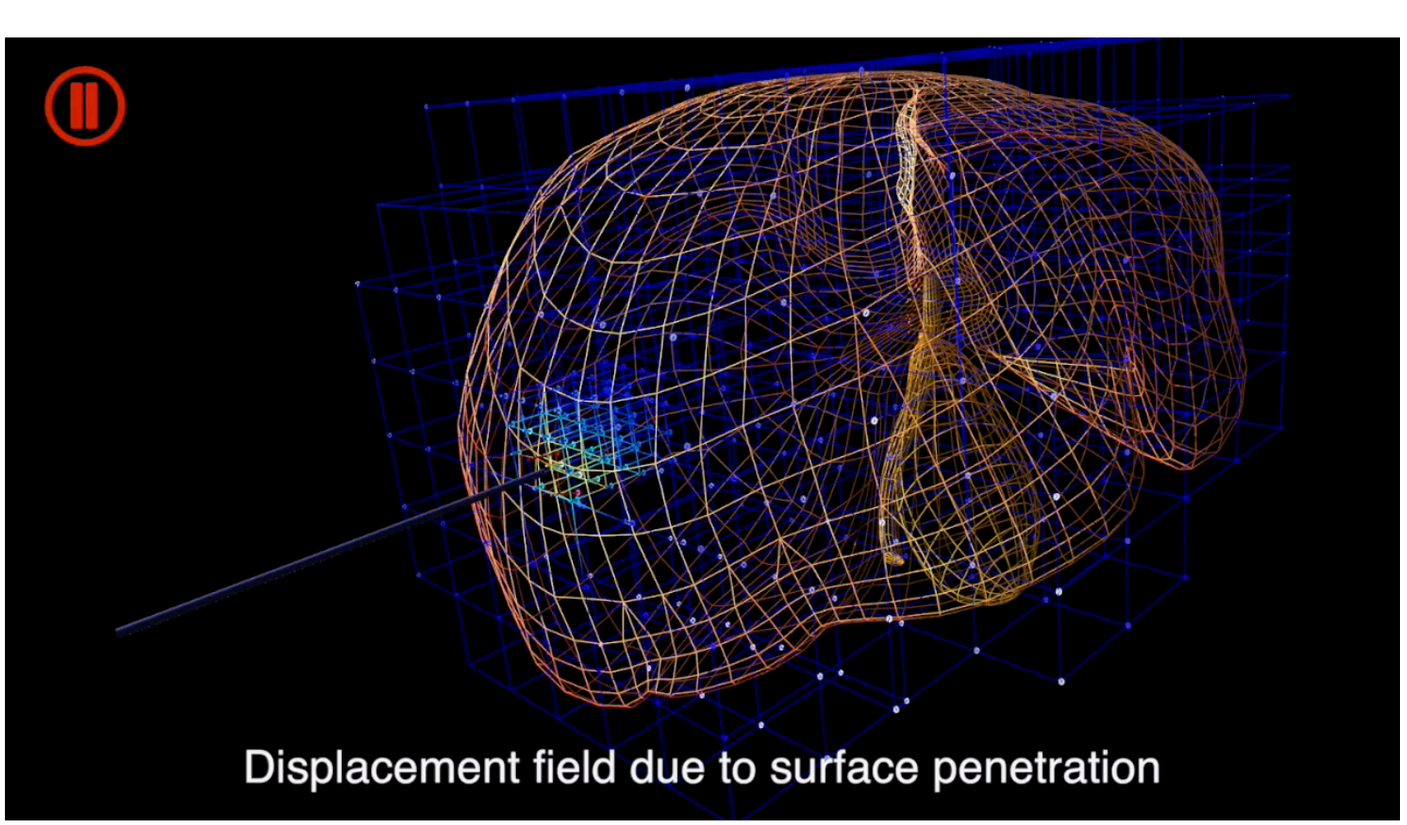
days

Surgical training

Surgical guidance



The surgeon trains as on a flight simulator
Courtecuisse et al, MEDIA, 2014

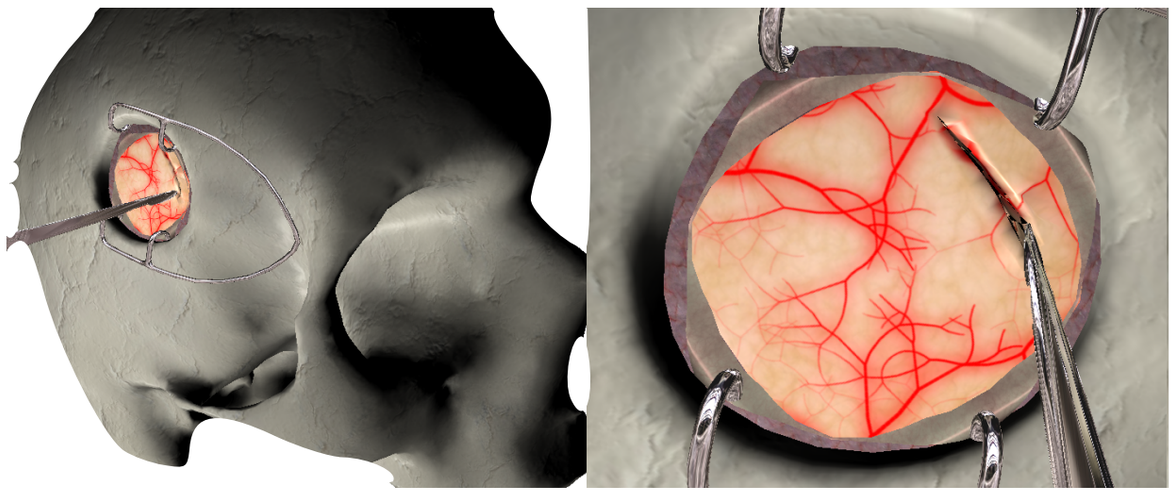


The surgeon is guided during the operation Bui et al, IEEE TBME, 2017

NEXT CHALLENGES

ERC RealTCut
Train surgeons safely on simulators

- Generic material models: *a priori.*
- Errors in quantities of interest for cuts in linear materials.
- Interactive simulations (solution in ms).

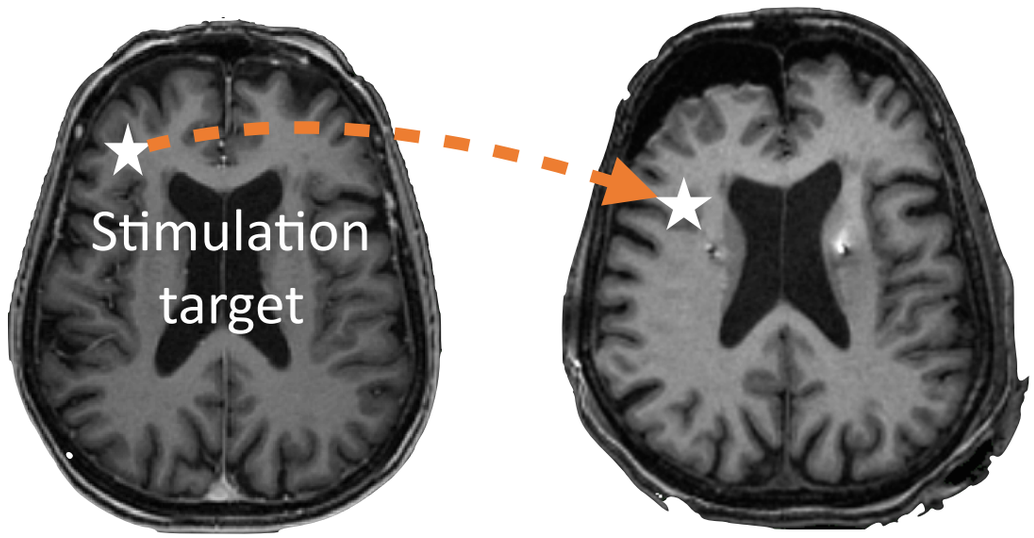


Courtecuisse, 2014, Implicit method for cutting in real-time. MEDIA

A generic organ is sufficient.

Future
Surgical assistance and planning

- Data-driven material models (real-time).
- Error control in quantities of interest for strong non-linearities, multi-field…
- Clinical time scales (solution in minutes).

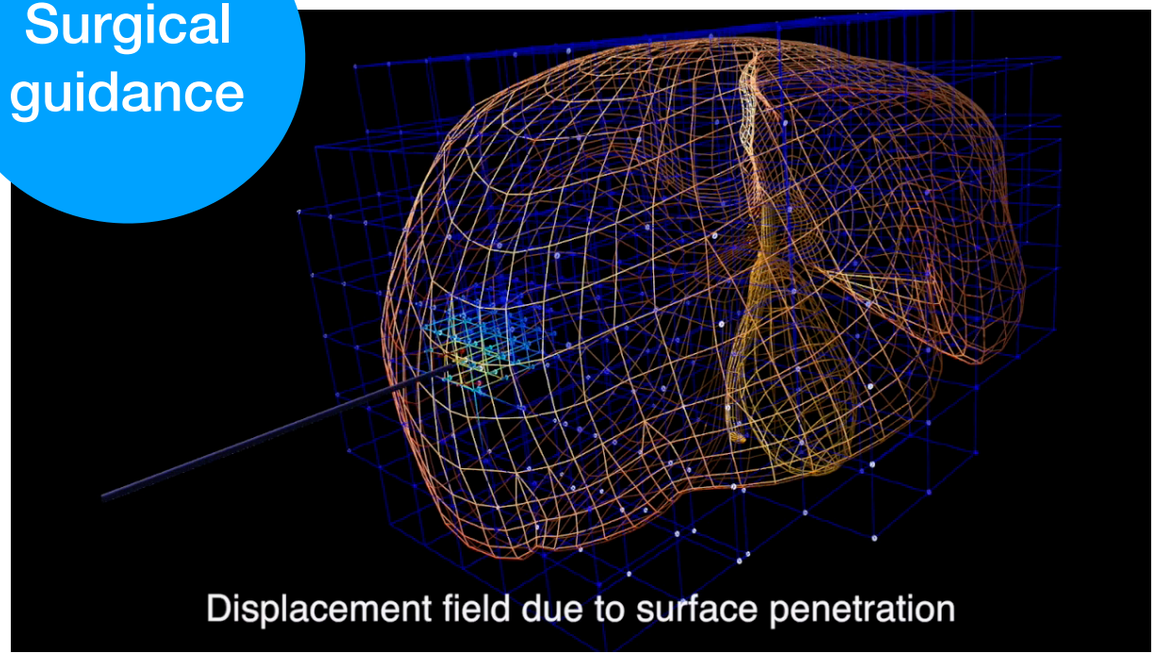


Predict shift of brain target.

Patient specificity is essential.

From surgical training to surgical planning and assistance

Surgical guidance

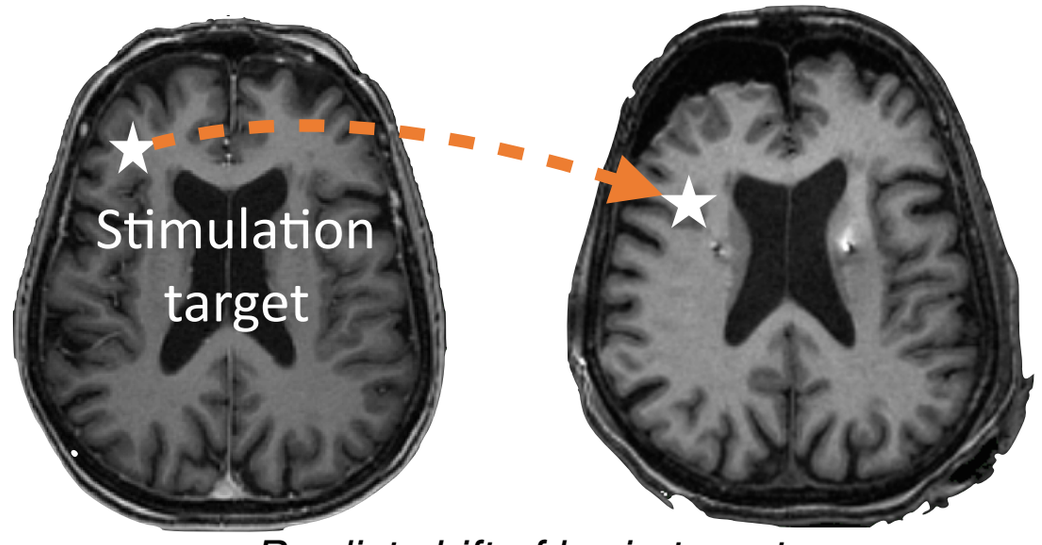


QUESTION: What (material) model should be used for a given patient?

Future

Surgical assistance and planning

- Data-driven material models (real-time).
- Error control in quantities of interest for strong non-linearities, multi-field…
- Clinical time scales (solution in minutes).

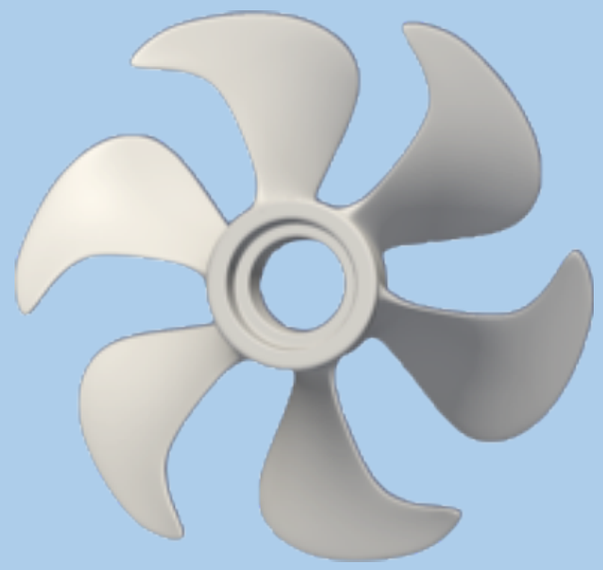


Predict shift of brain target.

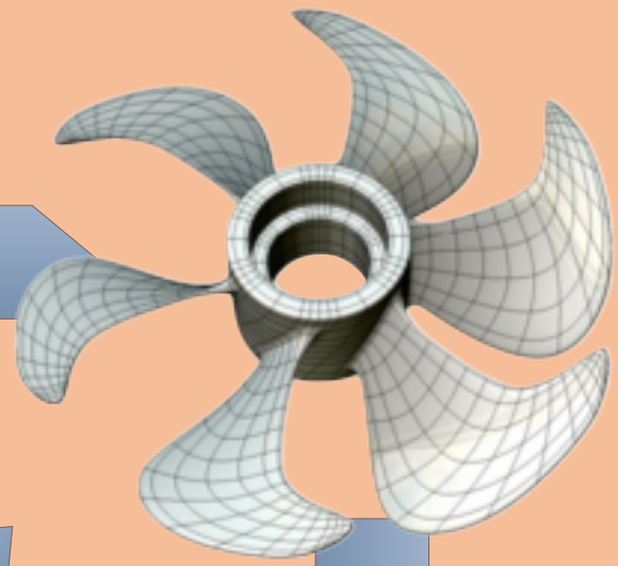
Patient specificity is essential.

What we do in engineering modelling and simulations

GEOMETRICAL MODEL



DISCRETISATION



Verification

A POSTERIORI ERROR CONTROL

MATERIAL MODELS

Phenomenological

Elasticity/Plasticity

Crack growth law (Paris…)

Fracture energy

Maximum tensile strength

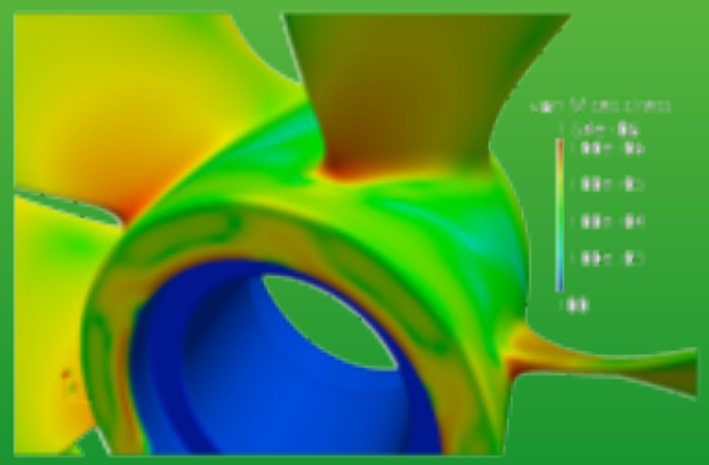
Multi-scale

Debonding, Fibre pull-out

Fibre breakage, interface

fracture, grains, dislocations,

NUMERICAL SOLUTION



Validation & parameter identification

EXPERIMENTS

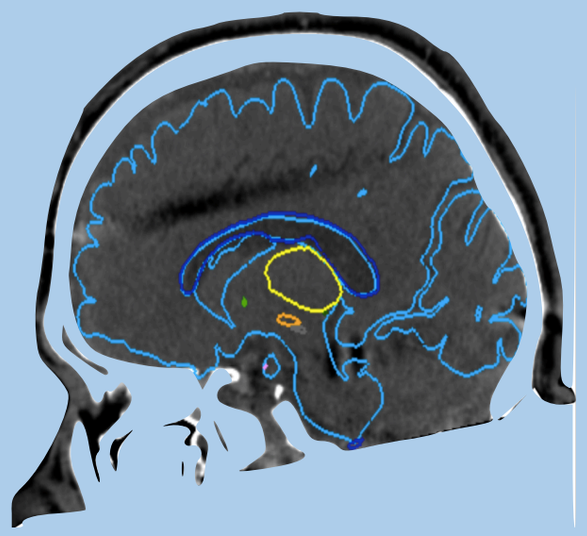
CONVENTIONAL APPROACH

erc

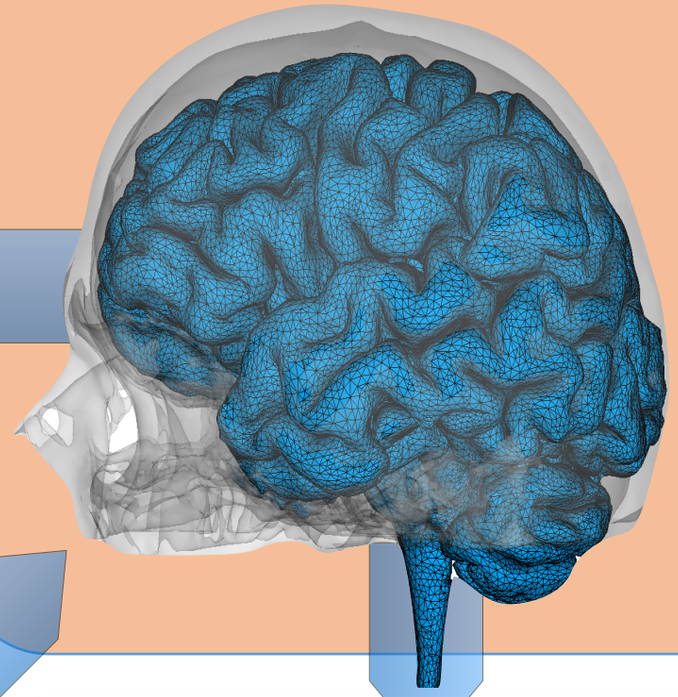
RealTCut

We cannot do in biomechanics…

IMAGE/MODEL



DISCRETISATION



Verification

A POSTERIORI ERROR CONTROL

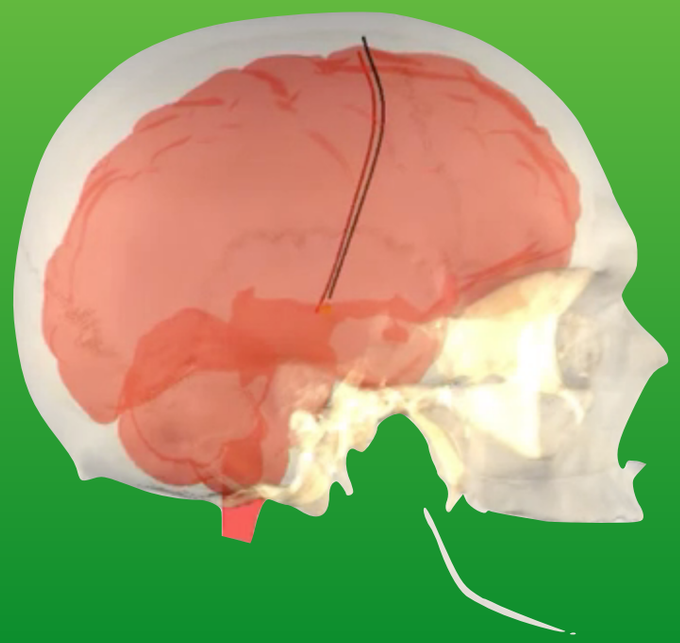
MATERIAL MODELS

Phenomenological
Neo-Hookean, Ogden, …
Multi-scale
cutting, fracture,

???

Patient specific ???

NUMERICAL SOLUTION

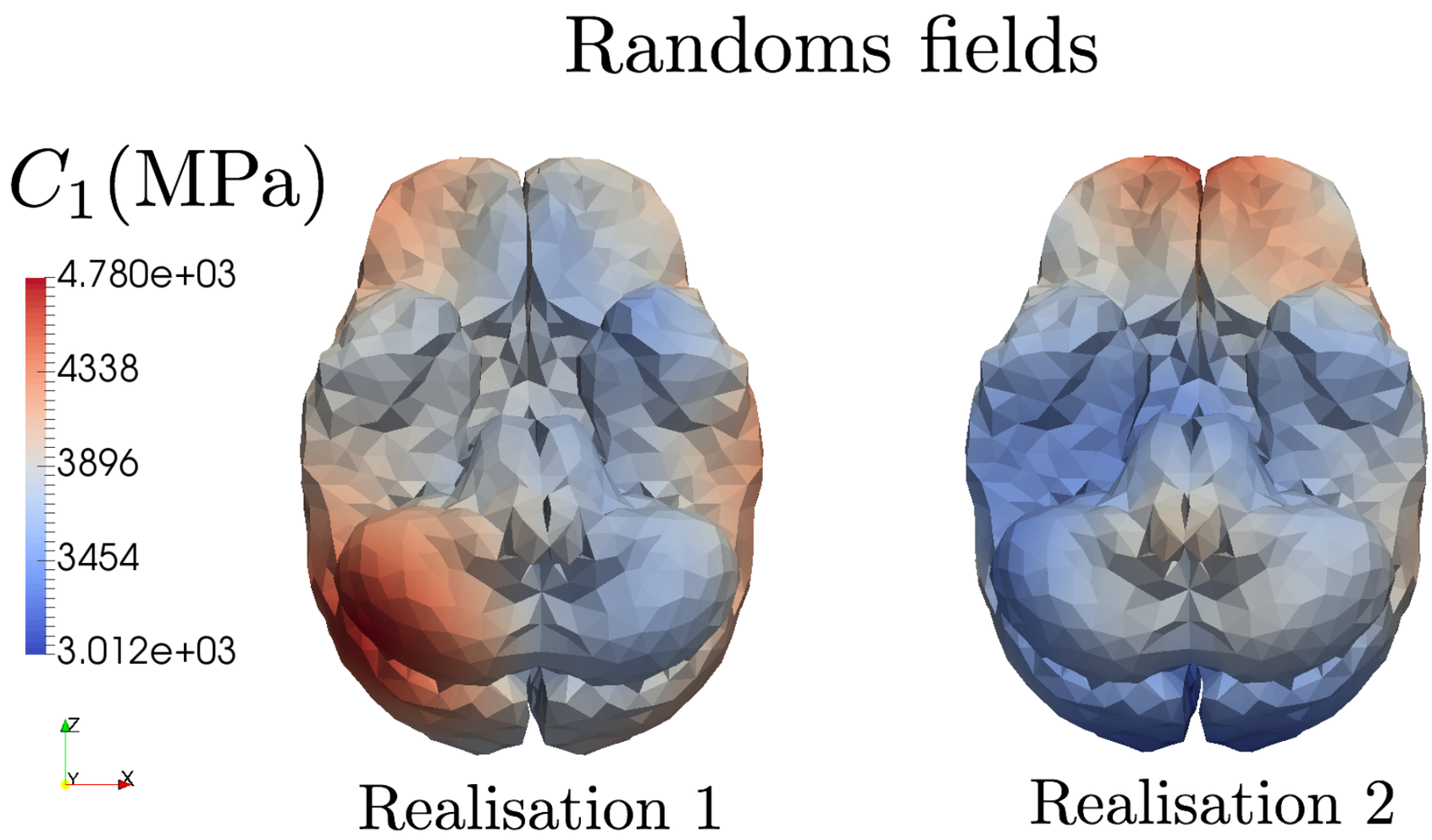


Validation & parameter identification

EXPERIMENTS ???

Assuming the material model is representative, what is the influence of each parameter in the model?

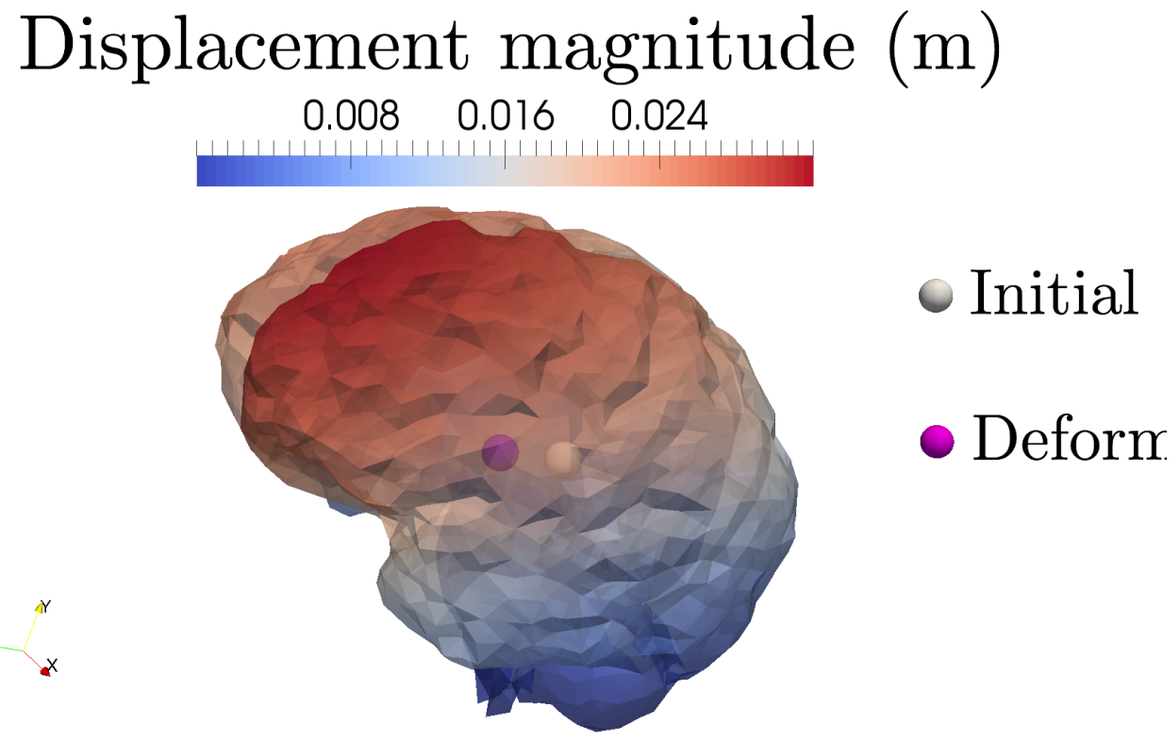
- Different methods: Karhunen–Loève expansion [Adler 2007], Fast Fourier transform [Nowak 2004].

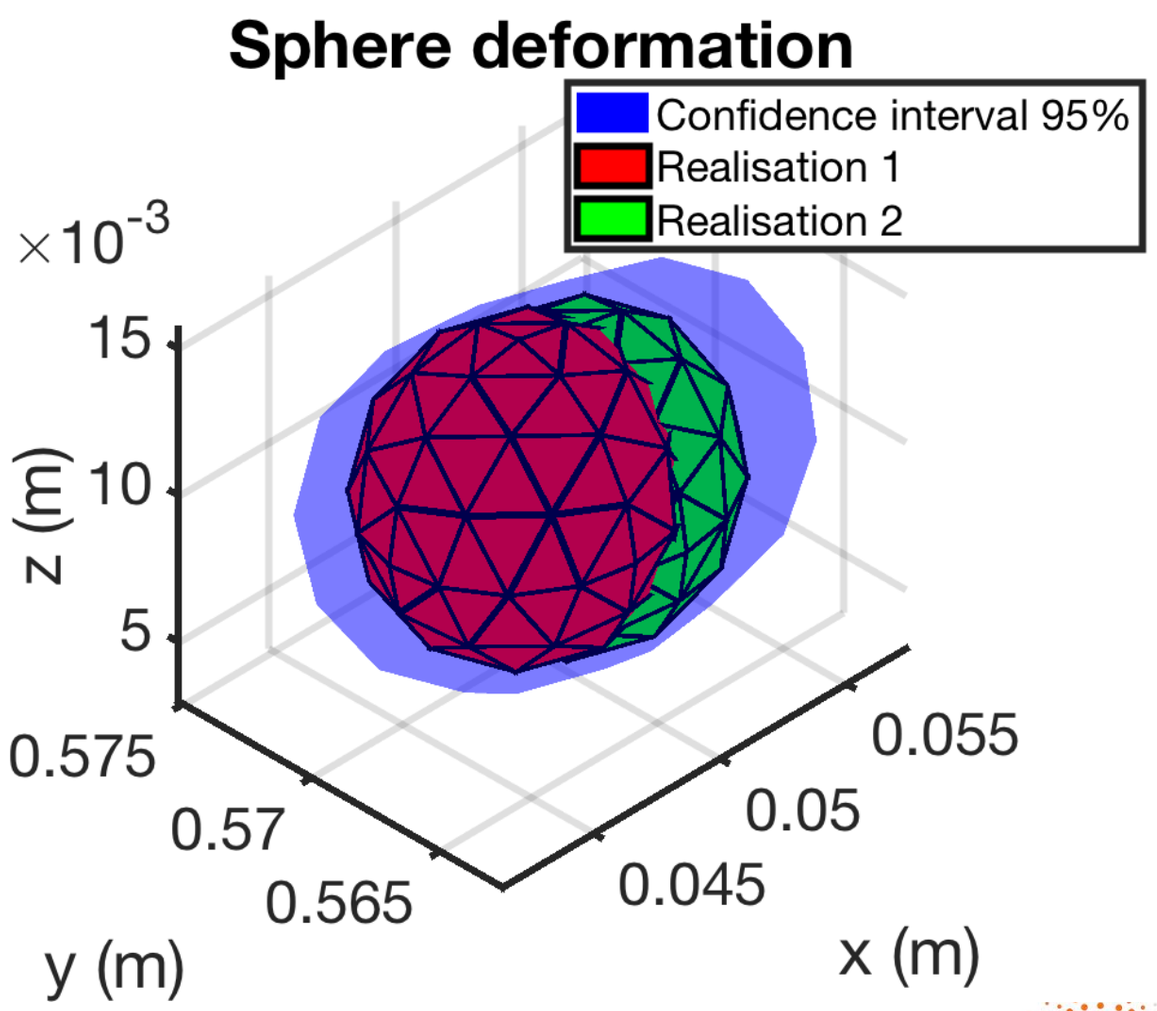


Two realisations of RF, with a log-normal distribution, for the parameter C_1 (in MPa).

Stéphane Pierre Alain BORDAS, Department of Computational Engineering & Sciences University of Luxembourg

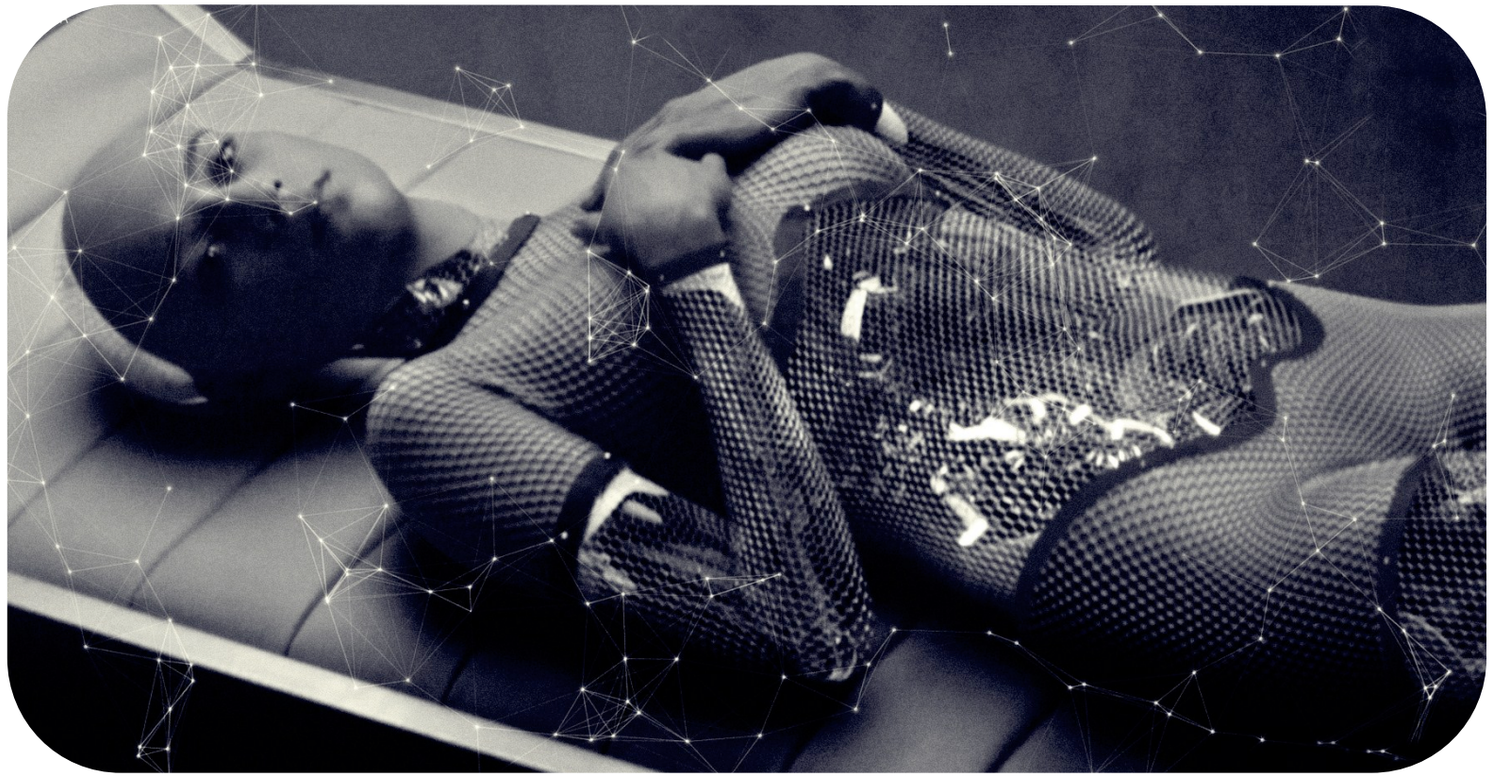
Confidence level in predicting the target location





What is the influence of material parameters on computed quantities of interest?

DIGITAL TWIN OF THE PATIENT



Alex Garland, *Ex Machina*, 2015

Treatment simulation

Scales of interest

Disease evolution

INFORMATION

"Inspection" interval

Fitness

REAL PATIENT

DATA

Environment Conditions

Health

Organ state

Disease

Digital twin concept

Actual aircraft	**Digital aircraft model**
Life prediction and extension	Situation awareness
High fidelity modeling and simulation	Certification and design methods

Requires real-time data assimilation, and model update…

Medicine

The average drug developed by a major pharmaceutical company costs at least $4 billion, and it can be as much as $11 billion.

Mechanics

The development cost of the A380

11 billion euros…

of the dreamliner…

$32 billion

Prior Knowledge

Prior Knowledge

Hypothesis

Domain expert

Prior Knowledge

(Big) Data

Hypothesis

Domain expert

Prior Knowledge

Computational Science

HPC

(Big) Data

Hypothesis

Domain expert

Prior Knowledge

Computational Science

HPC

(Big) Data

Hypothesis

Domain expert

Conclusions

Prior **Knowledge**

Data-driven modelling

(Big) Data

Hypothesis

Domain expert

Conclusions

Prior Knowledge

Feedback

Posterior Distribution

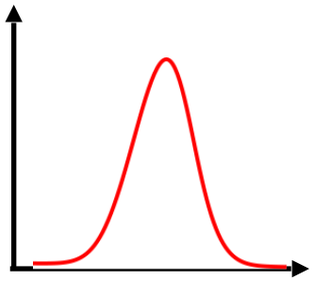
Bayesian Inference

Data

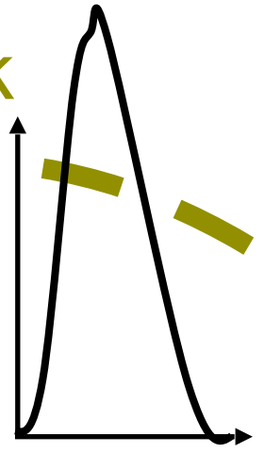
Hypothesis

Updates

Prior Knowledge

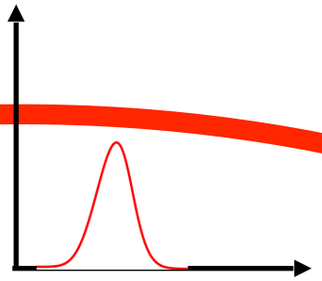


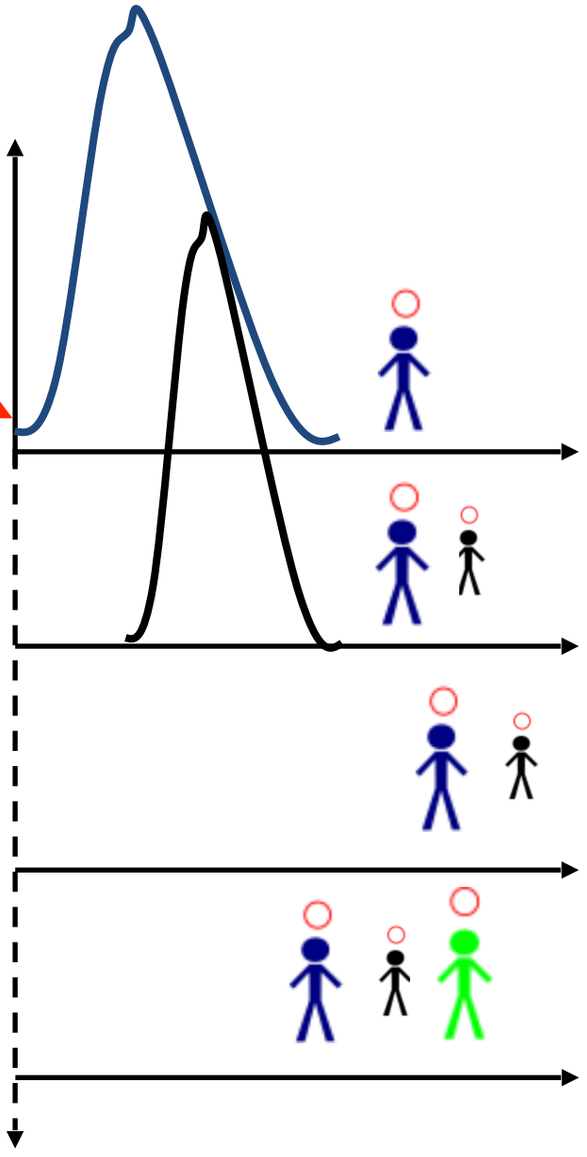
Feedback



Posterior Distribution

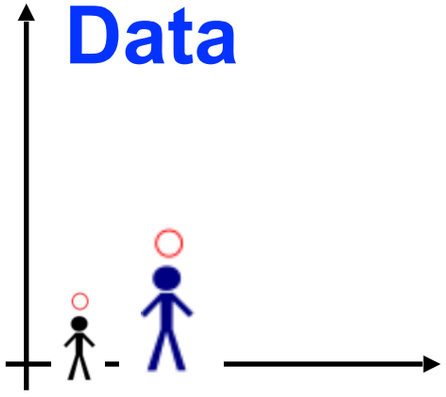
Bayesian Inference





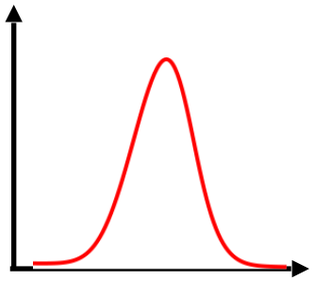
Updates

Data

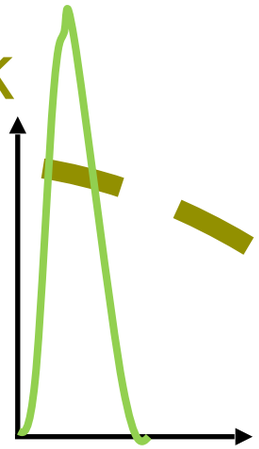


Hypothesis

Prior Knowledge

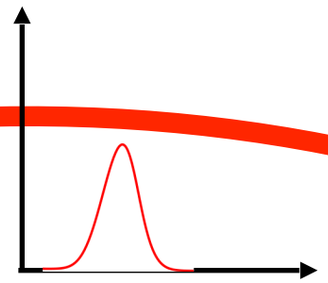


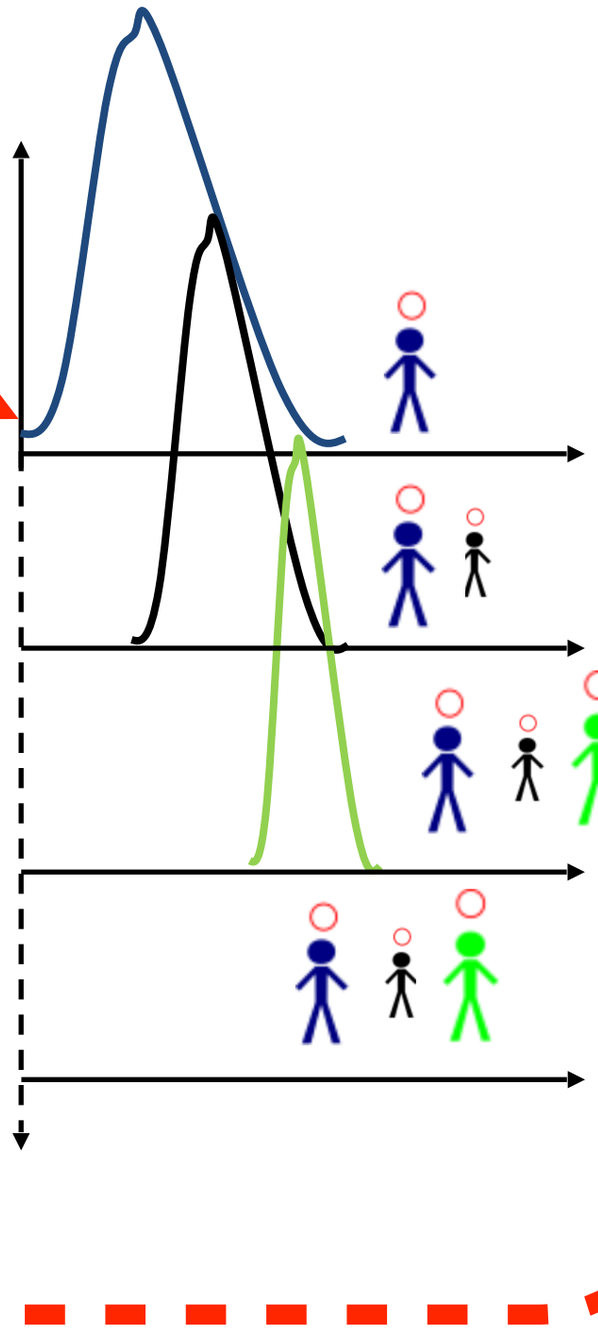
Feedback



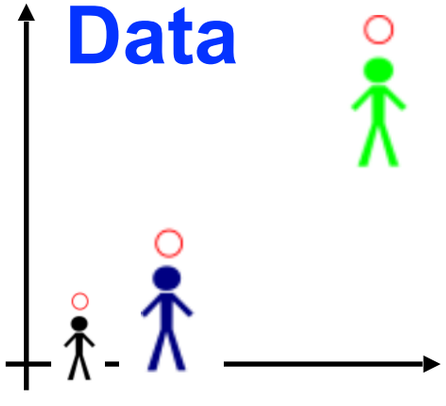
Posterior Distribution

Bayesian Inference



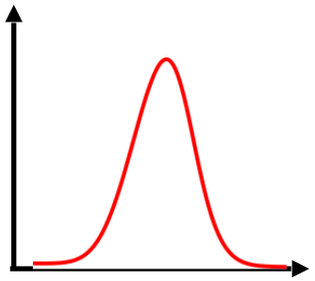


Data

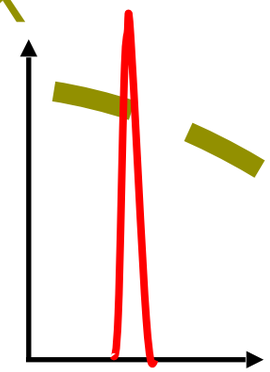


Hypothesis

Prior Knowledge

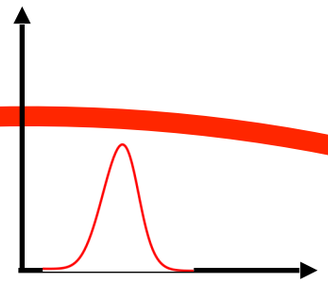


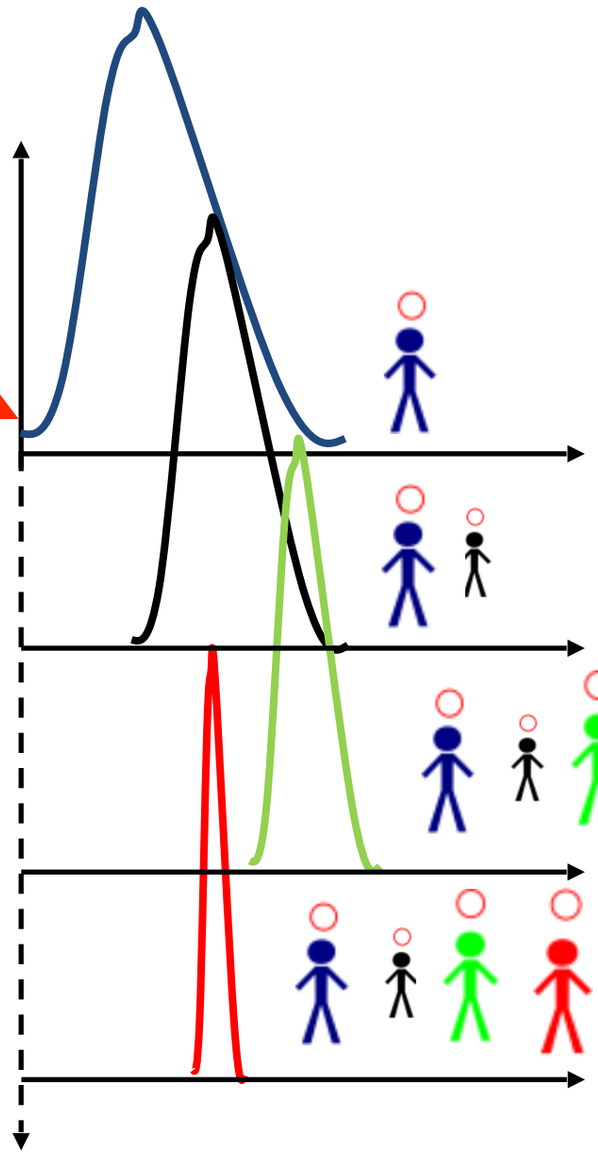
Feedback



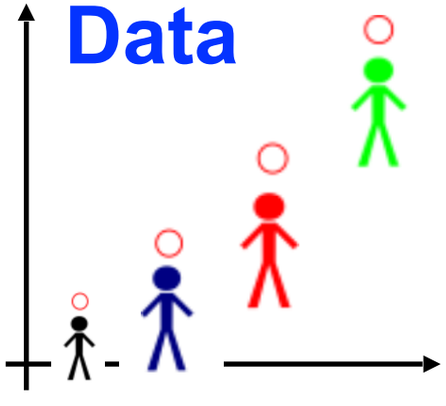
Posterior Distribution

Bayesian Inference





Data



Hypothesis

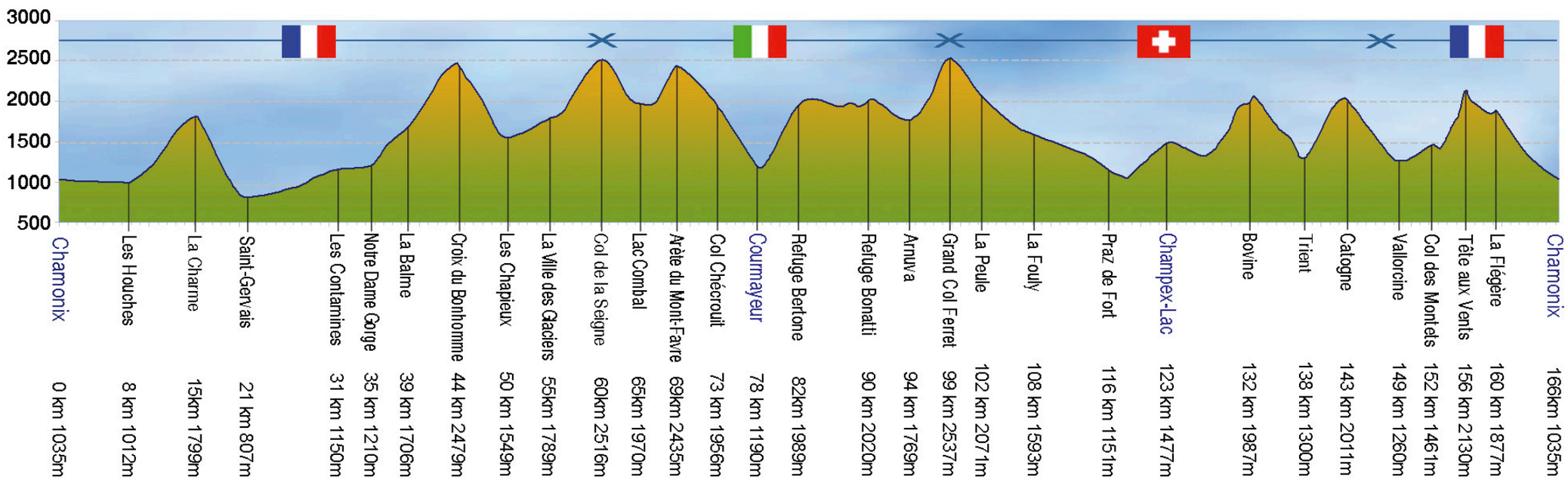
Conclusions

- **Understanding and optimisation of fracture of heterogeneous materials**
  - multi-scale methods are being developed
  - these methods are expensive
  - model selection remains an open problem
  - variability of the material properties exacerbate these difficulties
  - taking into account realistic situations remains elusive
  - coupling with sensing systems may be the future

… mechanical twinning

real-time simulations could also help engineers gain insight into complex non-intuitive phenomena by allowing to probe, quickly, the parameter space and design space

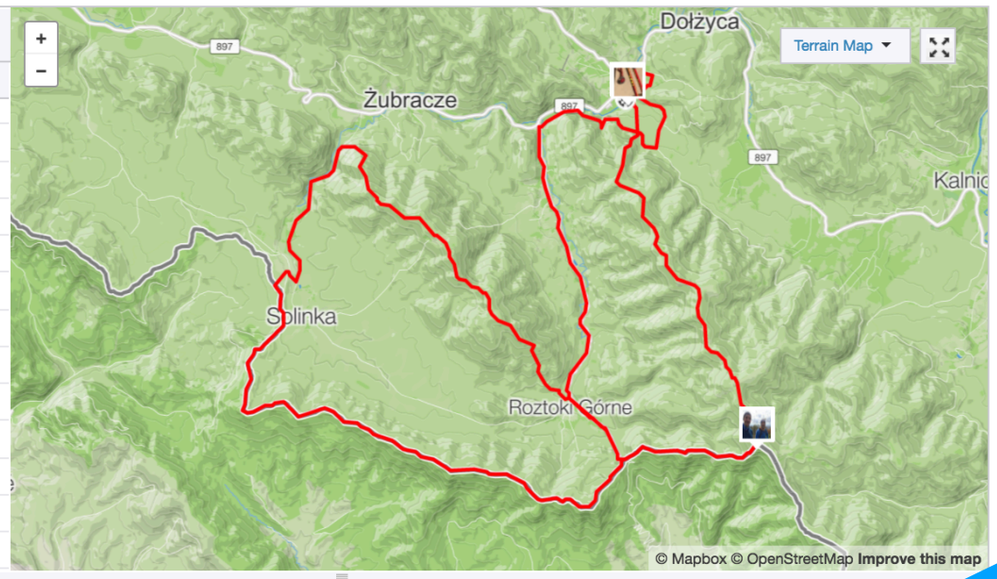
Partners and Funding



UTMB 177km running D+ 10,300m

Splits

KM	Pace	GAP	Elev
40	12:40 /km	6:59 /km	126 m
41	10:57 /km	7:00 /km	78 m
42	8:02 /km	6:29 /km	10 m
43	21:32 /km	11:59 /km	112 m
44	9:50 /km	7:12 /km	55 m
45	9:09 /km	7:54 /km	-56 m
46	9:44 /km	8:11 /km	-4 m
47	9:07 /km	8:17 /km	-36 m
48	8:30 /km	7:32 /km	-71 m
49	7:06 /km	6:26 /km	-94 m
50	7:45 /km	6:15 /km	-68 m
51	8:58 /km	7:11 /km	-211 m
0.6	9:17 /km	8:06 /km	-42 m

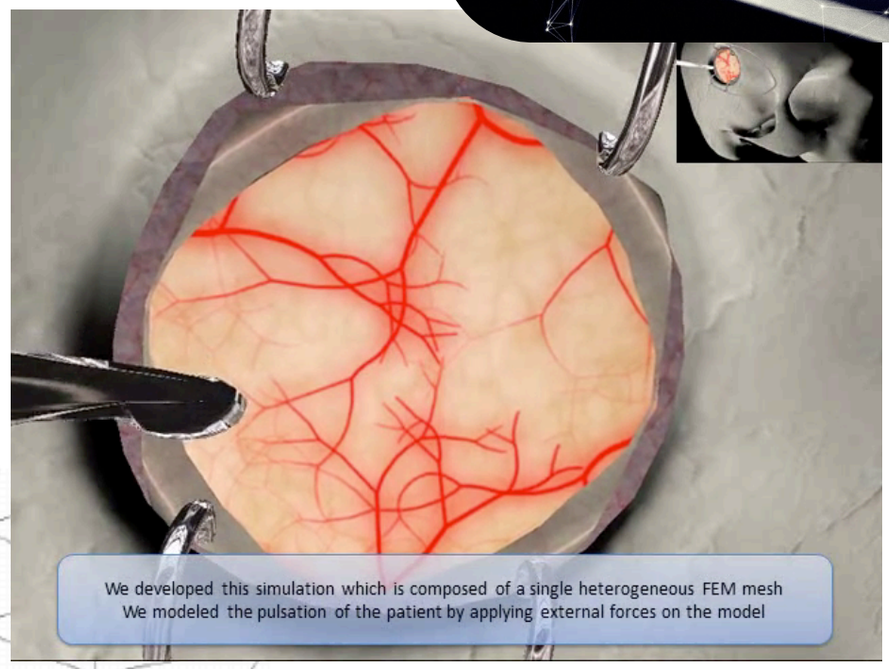


52km running D+ 2500m

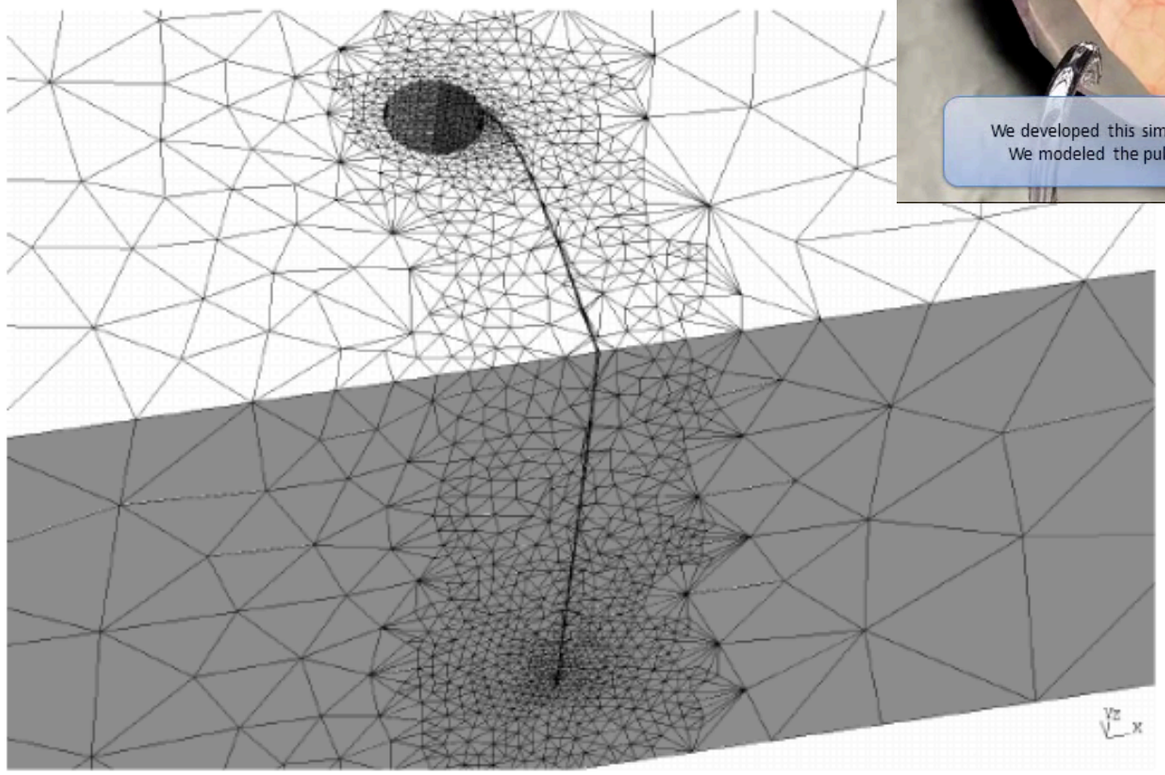
20km walking D+500m

Alex Garland, *Ex Machina*, 2015

Personalised surgery medicine



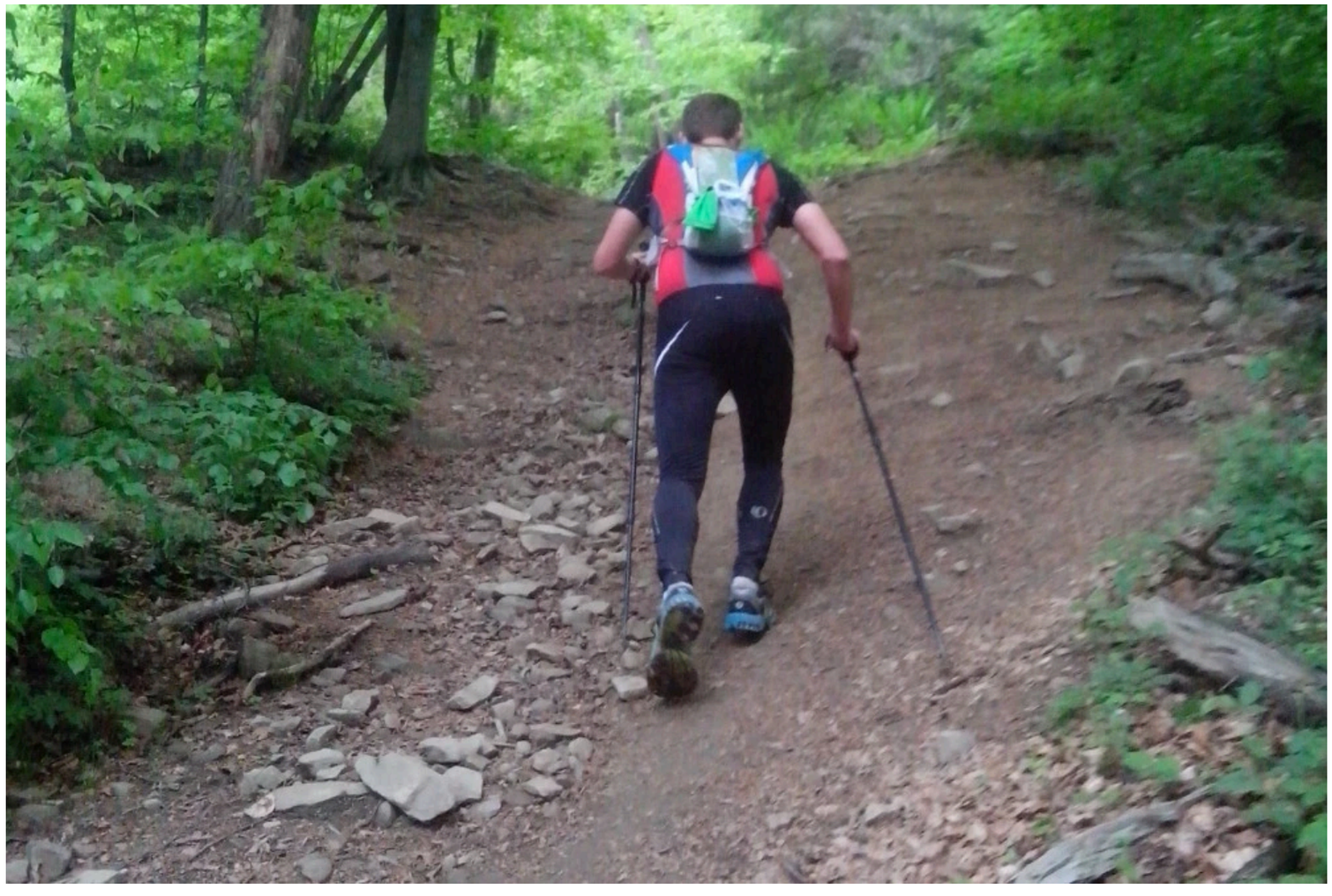
Error-controlled surgical training



Error-controlled fracture mechanics

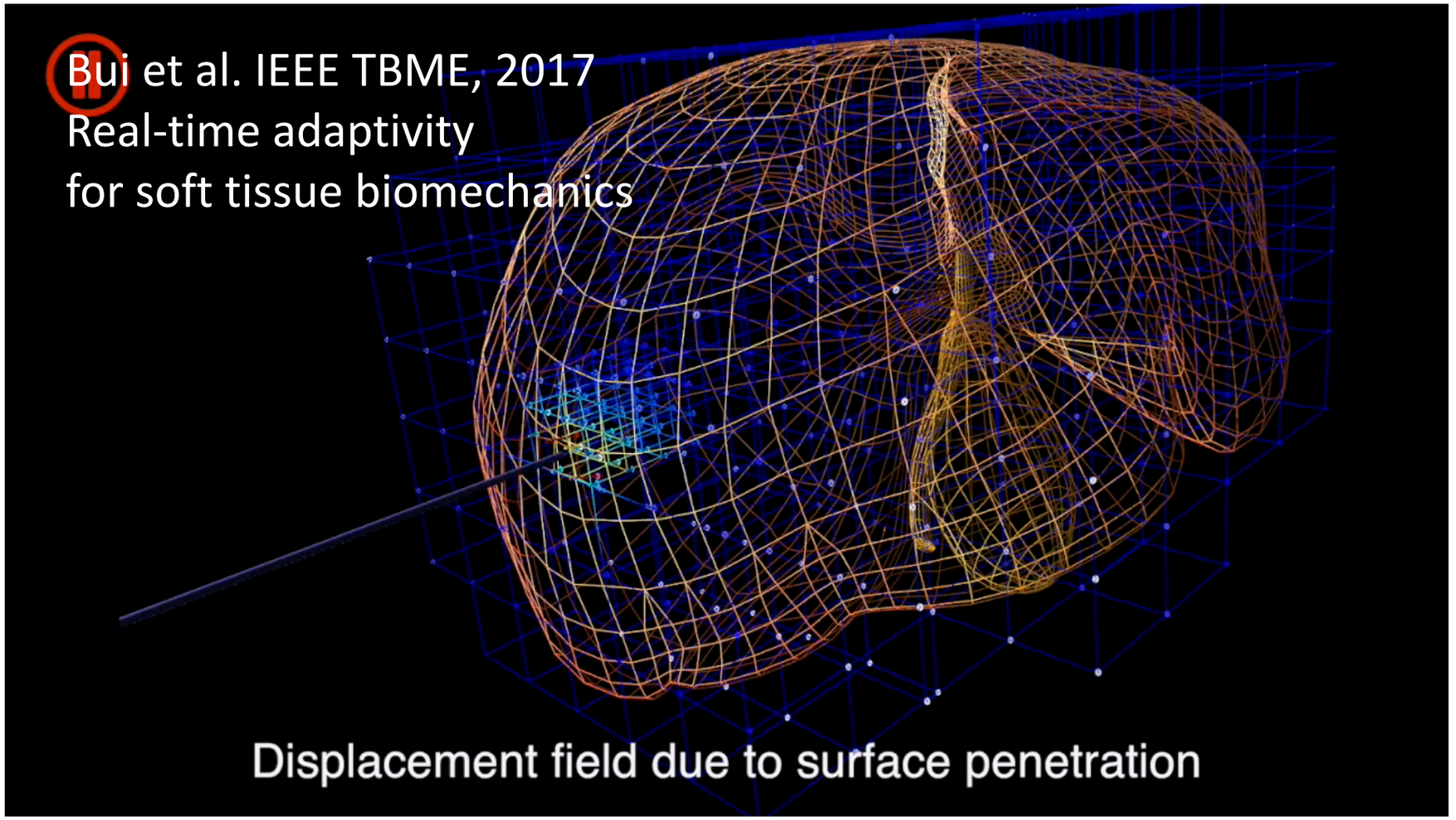
A bit of suffering…

$$\overbrace{\pi(\text{param.}|\text{obs.})}^{\text{Posterior}} = \frac{\overbrace{\pi(\text{param.})}^{\text{Prior}} \times \overbrace{\pi(\text{obs.}|\text{param.})}^{\text{Likelihood}}}{\underbrace{\pi(\text{obs.})}_{\text{Evidence}}}$$



But much more fun!

$$\overbrace{\pi(\text{param.}|\text{obs.})}^{\text{Posterior}} = \frac{\overbrace{\pi(\text{param.})}^{\text{Prior}} \times \overbrace{\pi(\text{obs.}|\text{param.})}^{\text{Likelihood}}}{\underbrace{\pi(\text{obs.})}_{\text{Evidence}}}$$



Thank you for your attention!

http://legato-team.eu

Download the presentation here: http://hdl.handle.net/10993/34088

Data | Abstraction | Method | Discover

POD
Prioritise
Manifold learning
Discrete Systems
Reduced bases
RD8 Energy harvesting
Experiment snapshots
RD5 3D printing
Optimize
Accelerate
Best model
MapReduce
Principal Component Analysis
in Silico data
RD6 PDE selection
Continuous Systems
RD4 Materials
RD9 Interfaces
Detect
Gene regulatory network
Predict
Statistical Inversion
GRACE data
RD2 Gravity
Maps
Quantify uncertainty
RD3 Hydro-Ecology
Bayesian statistics
RD1 Water Cycle
GNSS data
Information theory
RD16 Neuro-feedback
Select
Control
Optimise
Understand
Stochastic PDEs
Propagate uncertainty
Clinical data
RD12 Biomarkers
RD13 Cell re-program
Machine learning
Economic data
Medical image
RD10/11 Cells
Deep learning
Graphs
Design
RD7 Molecular crystals
RD14 Economy
Social data
Diagnose
RD15 Psycho-pathology
RD17 Social Media
RD18 Mobility
Infer
Simulation database
RD19 Well-being
SHARE Data
Instagram
Mobility data
Forecast
Profiling
Network Analytics
Classify

CAST

Numerical analysis

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LMAP, Pau, UMR CNRS 5142 (Roland Becker, Daniela Capatina, Robert Luce)

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IMT, Toulouse, UMR CNRS 5219 (Patrick Hild)

ICJ, Lyon, UMR CNRS 5208 (Yves Renard)

MATHISCE, EPFL, Lausanne, Suisse (Marco Picasso)

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LMB, Besançon, UMR CNRS 6623 (Julien Yves Rolland)

National Physics Laboratory, Londres, Royaume-Uni (Stéphane Chrétien)

I2M, Marseille, UMR CNRS 7373 (Michel Duprez, Florence Hubert)

Meshes

SME TexiSense, Grenoble (Marek Bucki, Mathieu Bailet, Antoine Perrier)

Université Technique Federico Santa Maria, Santiago du Chili (Claudio Lobos)

Funding

Région Bourgogne Franche-Comté (“Convention Région 2015C-4991. MENELAS”).

Centre National de la Recherche Scientifique (“Convention 232789 DEFI InFIniTI 2017 - MEFASIM”).

ERC RealTCut

Agence Math Entreprises (“Convention Projets Exploratoires MethASim”).

CAST

Biomechanics

TIMC-IMAG, Grenble, UMR CNRS 5525 (Yohan Payan, Jacques Ohayon, Jean-Louis Martiel)

GIPSA-Lab, Grenoble, UMR CNRS 5216 (Pascal Perrier)

Institut de Biomécanique Humaine Georges Charpak, Arts&Métiers Paris-Tech (Pierre-Yves Rohan)

FEMTO-ST, Besançon, UMR CNRS 6174 (Emmanuelle Jacquet, Jérôme Chambert, Arnaud Lejeune)

Reference

S Bordas, M Bucki, F Chouly, M Duprez, V Lleras, C Lobos, A Lozinski, PY Rohan, S Tomar. Quantifying discretization errors for soft-tissue simulation in computer assisted surgery : a preliminary study. 2017. hal-01616322. Proceedings EuroMech 595

Meshes

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Agence Math Entreprises (“Convention Projets Exploratoires MethASim”).

More details

Multi-scale fracture FOE, Seattle

http://orbilu.uni.lu/bitstream/10993/18804/1/FOE_Seattle_Bordas.pdf

http://orbilu.uni.lu/bitstream/10993/18804/2/FOE_Seattle_Bordas_Movie.m4v

3D Fracture isogeometric methods

Other presentations and papers

What makes Data Science different?

http://hdl.handle.net/10993/30235

Error control in deep brain stimulation simulations

http://hdl.handle.net/10993/30937

Energy-minimal crack growth

http://hdl.handle.net/10993/29414

Uncertainty Quantification in biomechanics

http://hdl.handle.net/10993/28618

Real-time error estimation for needle insertion

http://hdl.handle.net/10993/28624

Bayesian parameter identification in mechanics

http://orbilu.uni.lu/bitstream/10993/29561/3/template.pdf

http://orbilu.uni.lu/bitstream/10993/28631/1/1606.02422v4.pdf

Plenary talk at DAMAS2017, Kitakyushu, Japan

http://hdl.handle.net/10993/31720

Plenary talk at XDMS2017, Umeå, Sweden

http://orbilu.uni.lu/handle/10993/31487

2017 Short course Lecture Notes, CISM, Udine, Italy

http://hdl.handle.net/10993/31585

Other course material

http://orbilu.uni.lu/bitstream/10993/31585/37/UDINE_2017_ShortCoursePDF_files_BORDAS.zip

http://orbilu.uni.lu/bitstream/10993/31585/38/UDINE_2017_CourseNotes_Powerpoint_BORDAS.zip

http://orbilu.uni.lu/bitstream/10993/31585/39/UDINE_2017_CourseNotes_Keynote_BORDAS.zip

http://orbilu.uni.lu/bitstream/10993/31585/40/UDINE_2017_handwrittenNotes_BORDAS.pptx

Live your life to the fullest

The Butcher's Race

by haveolimits

"Somebody behind me is gasping wheezily. The branches are beating my calves and face, the stones splattering from under my shoes. I hear the voice of tens of feet. Around me the woods and the darkness. High in the beech branches, the flashing moon.