Faculty of Sciences, Technology and Communication

Modelling & Simulation

from mechanics to medicine

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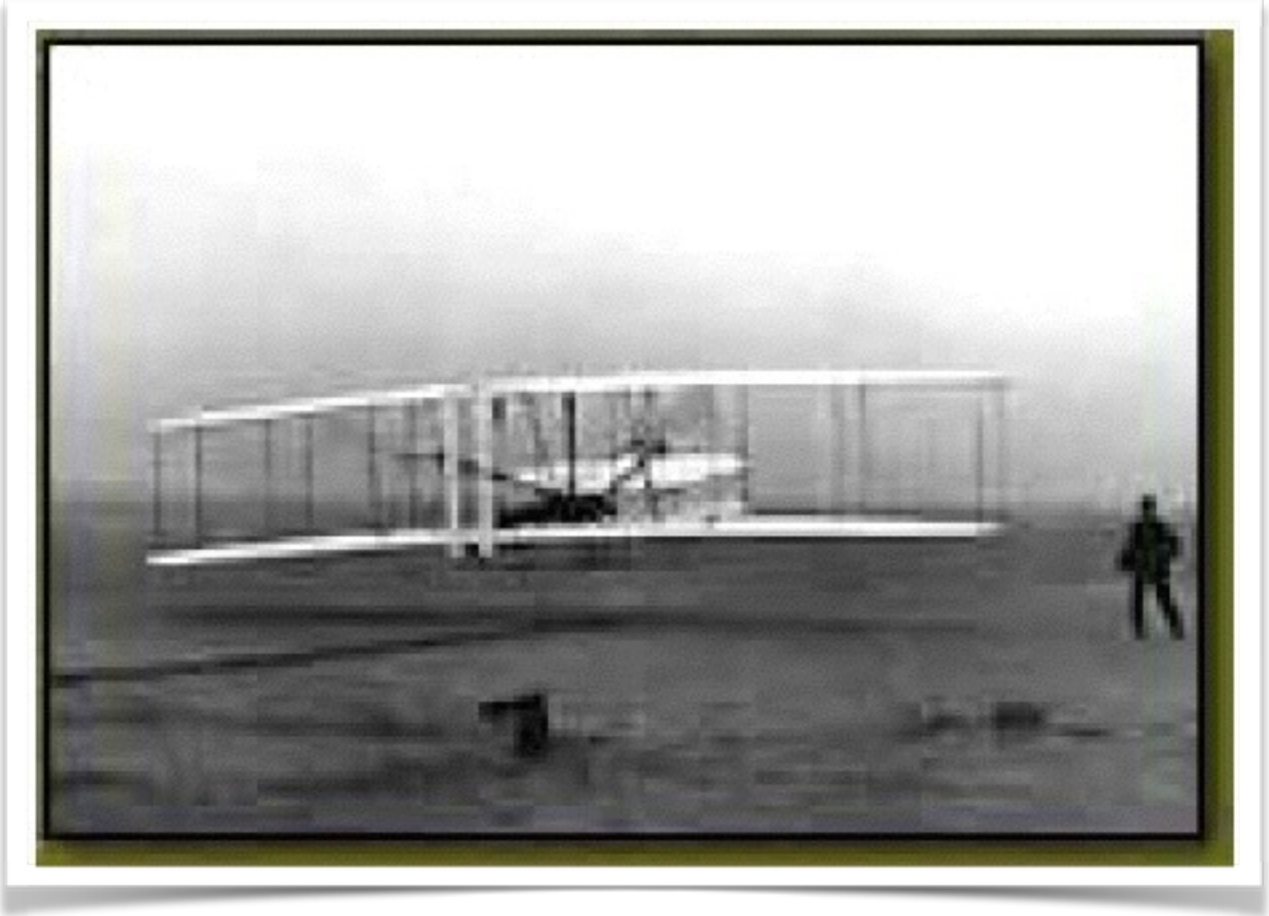
Wilbur and Orville Wright

Wright Flyer

10:35am Dec 17, 1903

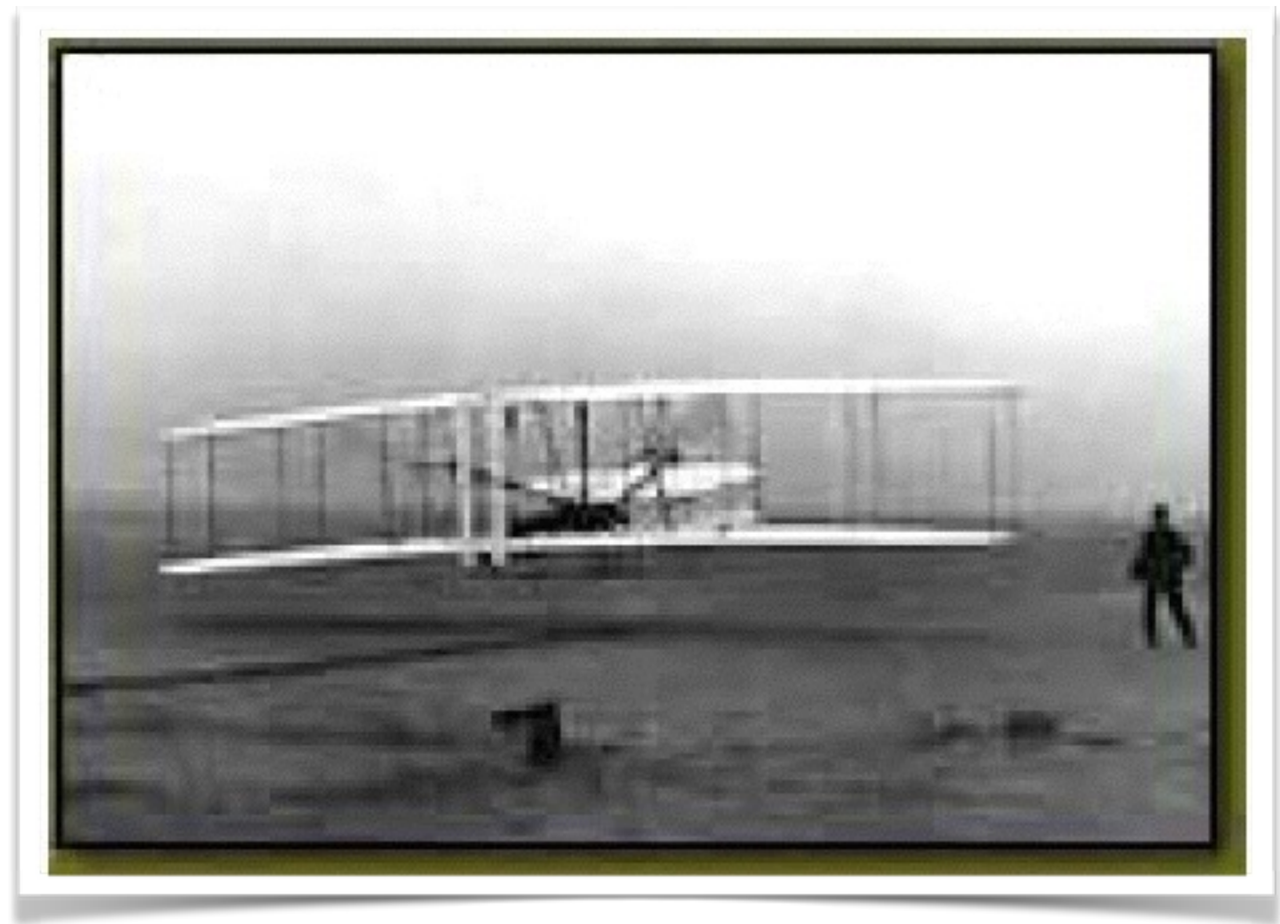


Wilbur and Orville Wright

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

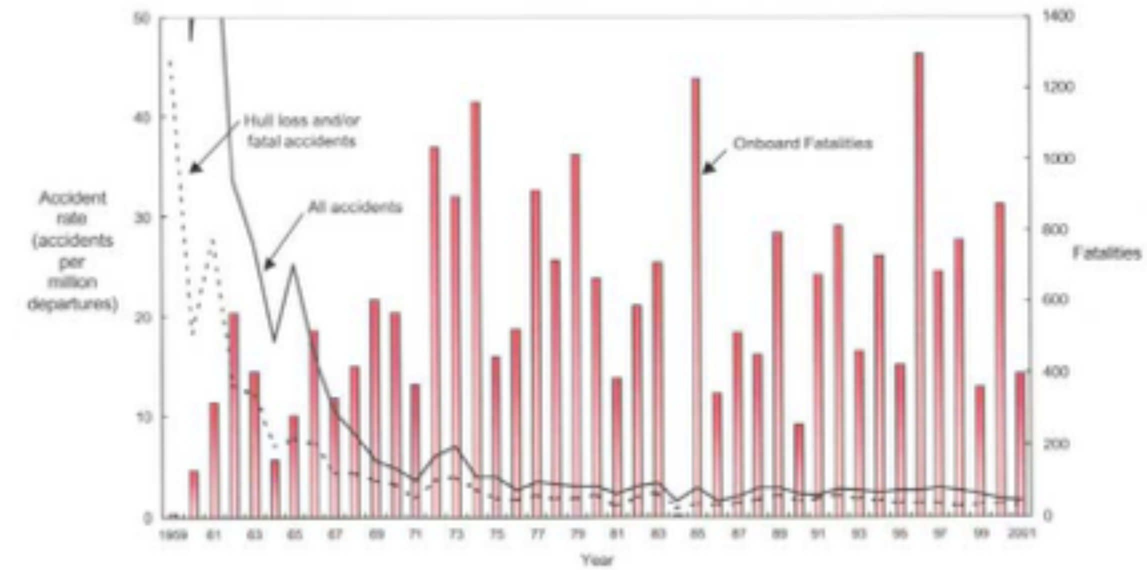


Aircraft safety

20,000 years

Worldwide statistics

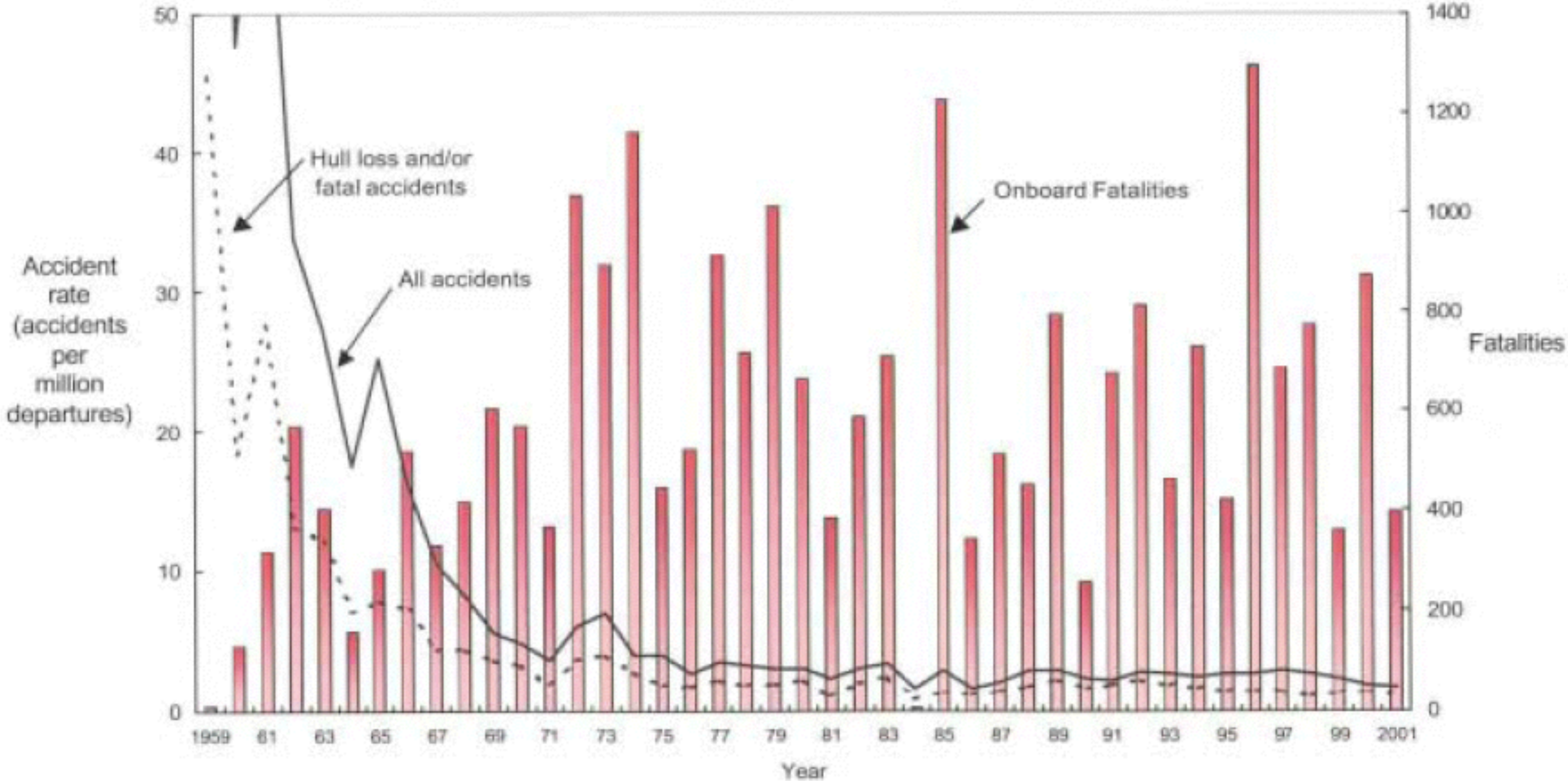
[1959-2001] 1,307 commercial jet aircraft losses



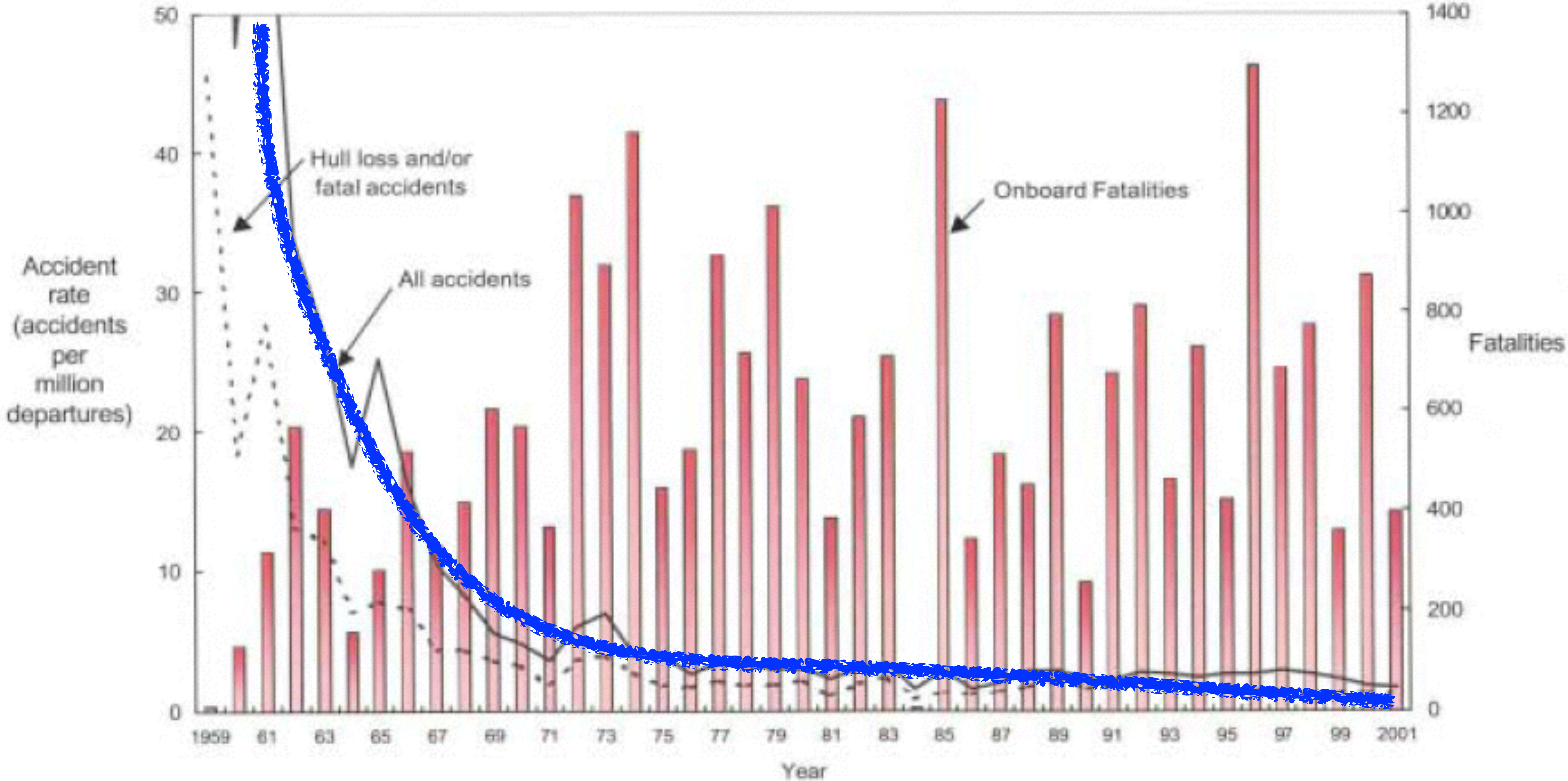
Today:

1 accident per 1,000,000 departures

Accident rates and fatalities/year

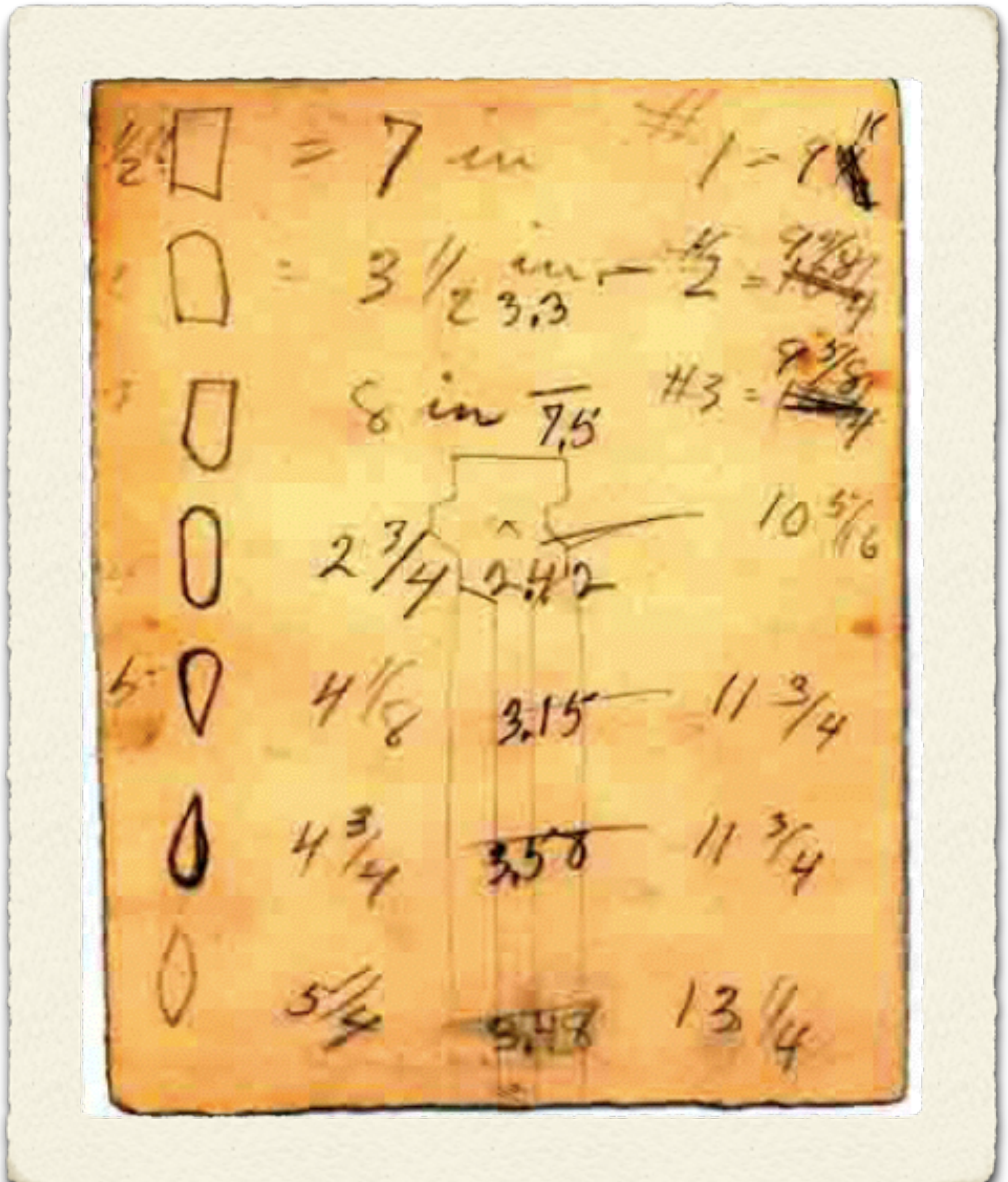


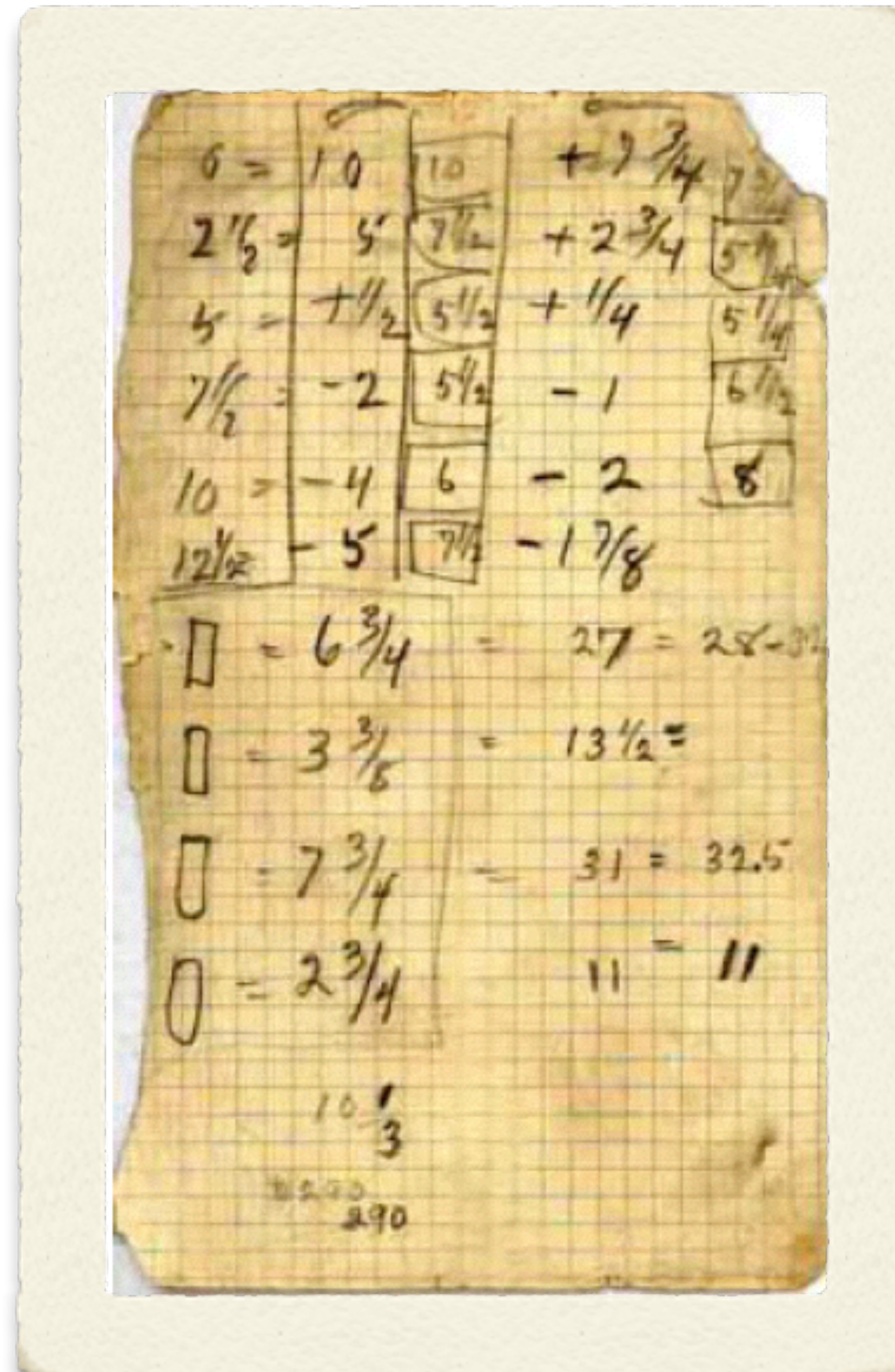
Accident rates and fatalities/year



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

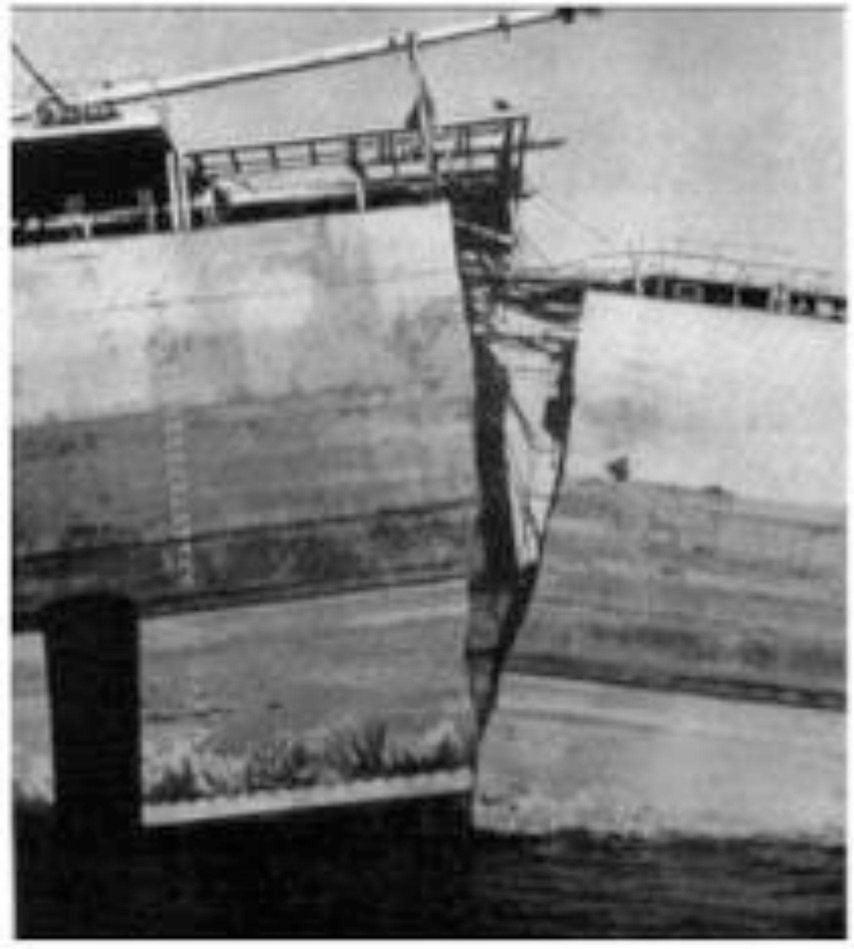
Bird strikes

Aloha airlines accident - fatigue cracks at corners

Novel convertible aircraft

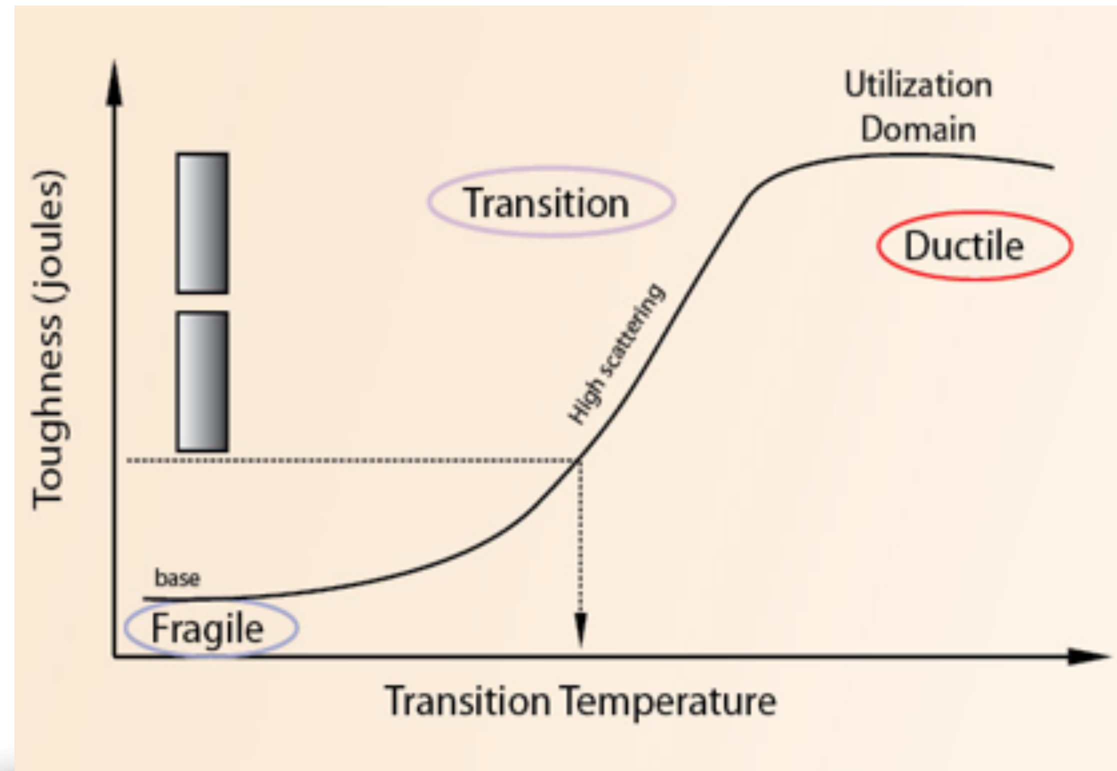
Learning from experience

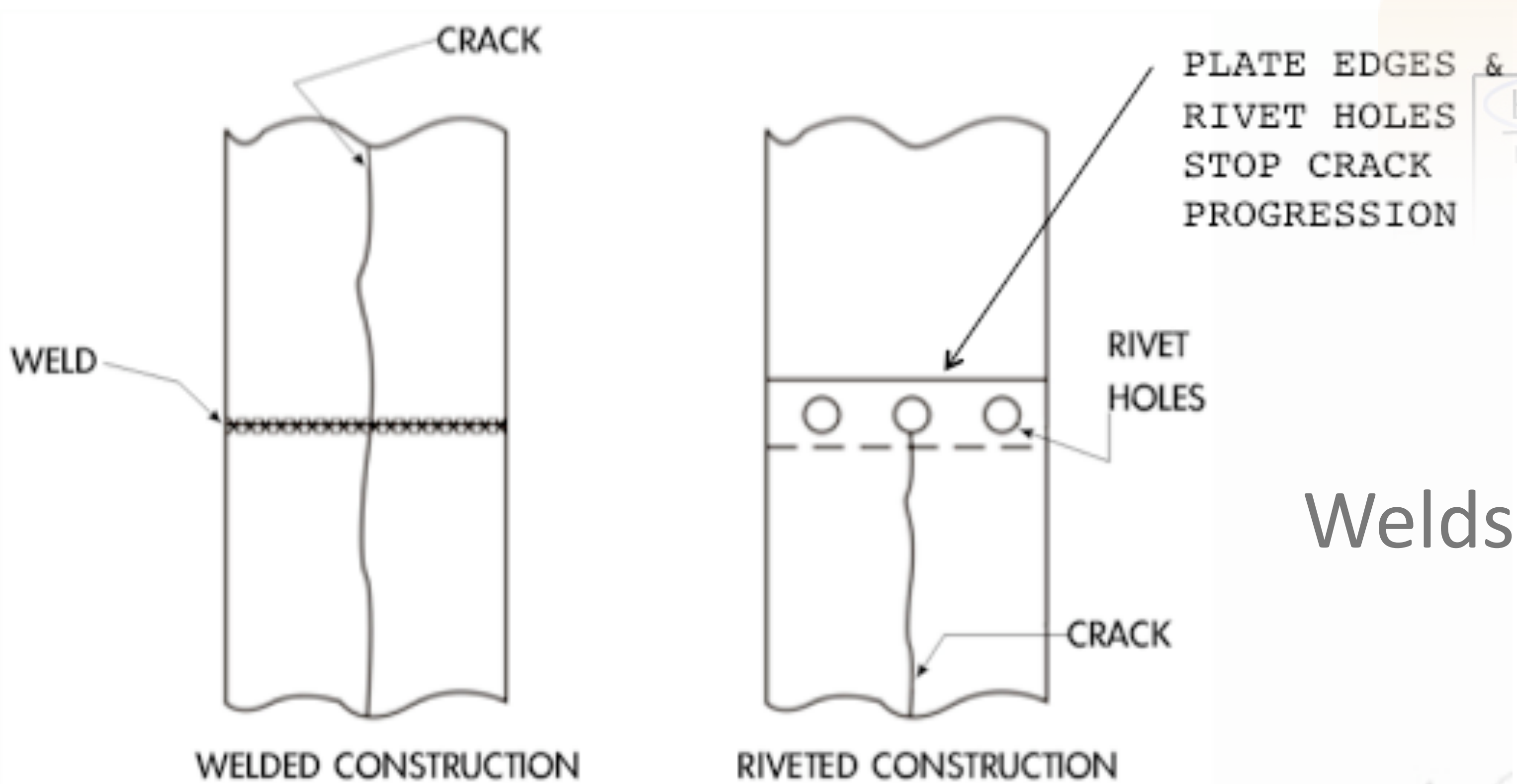
The Liberty Ships



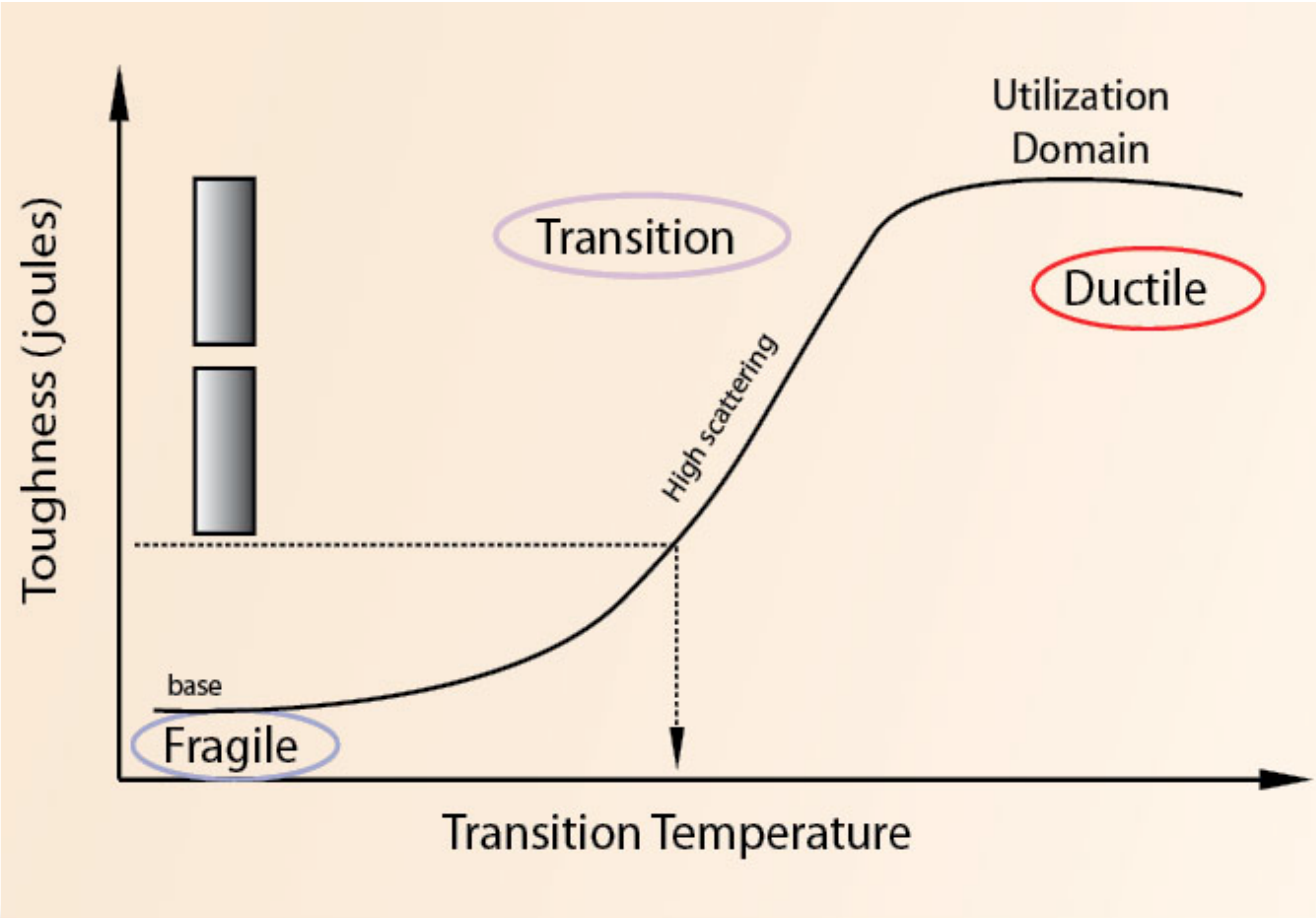
Learning from experience

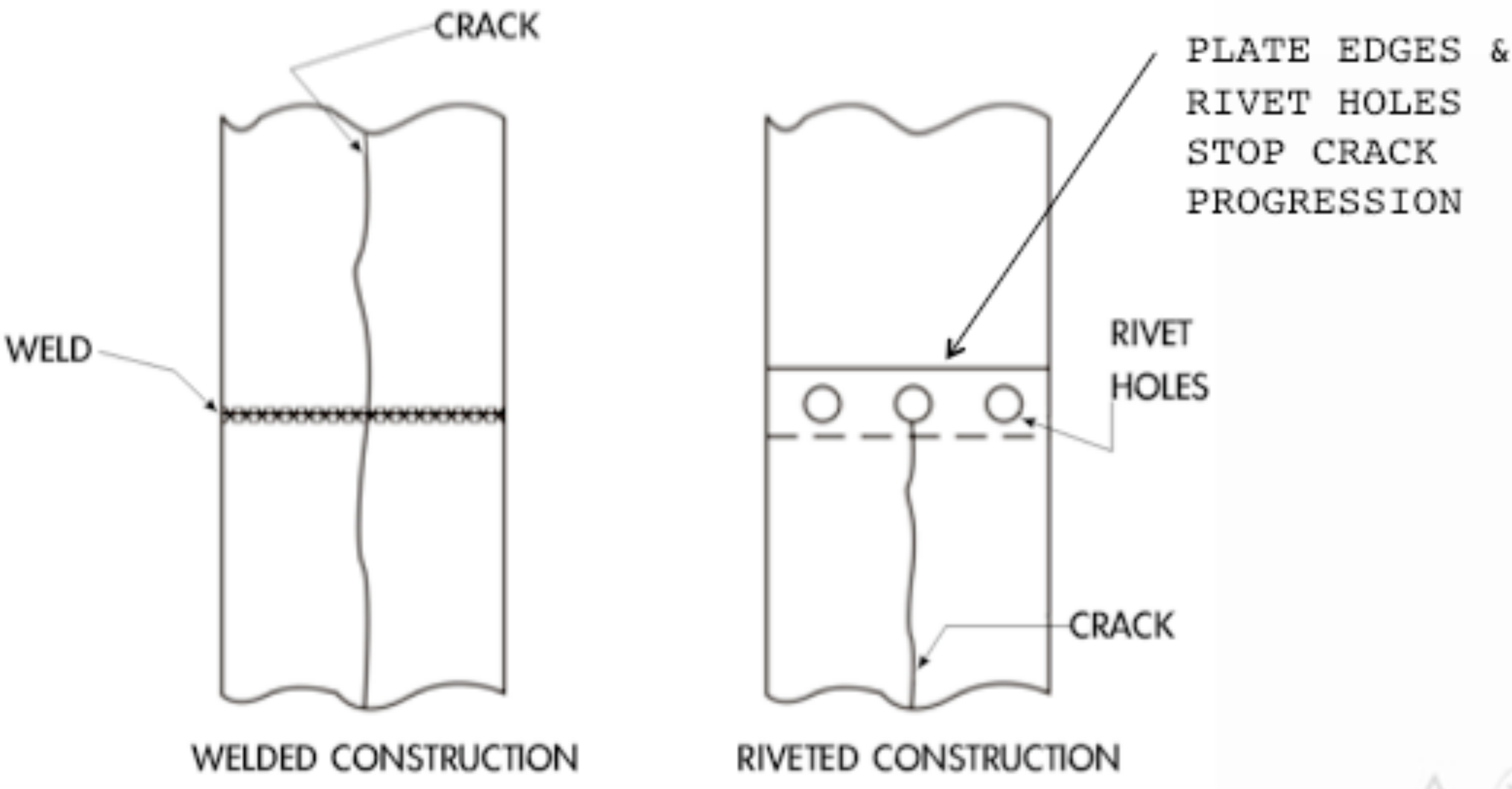
At low temperatures, steel becomes more brittle



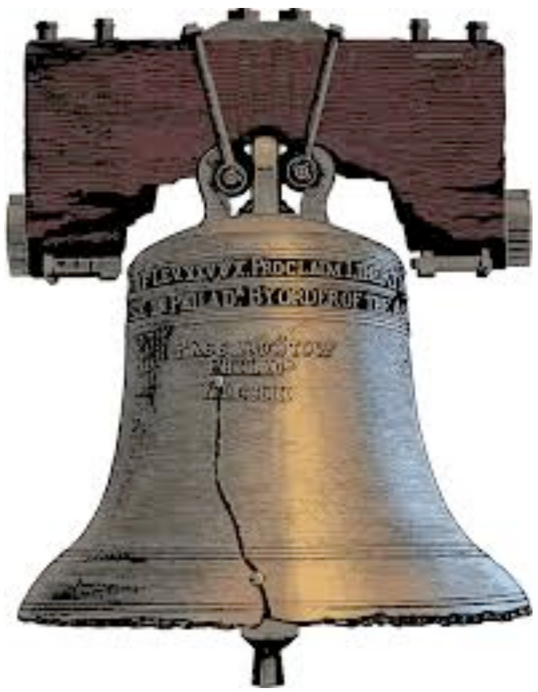


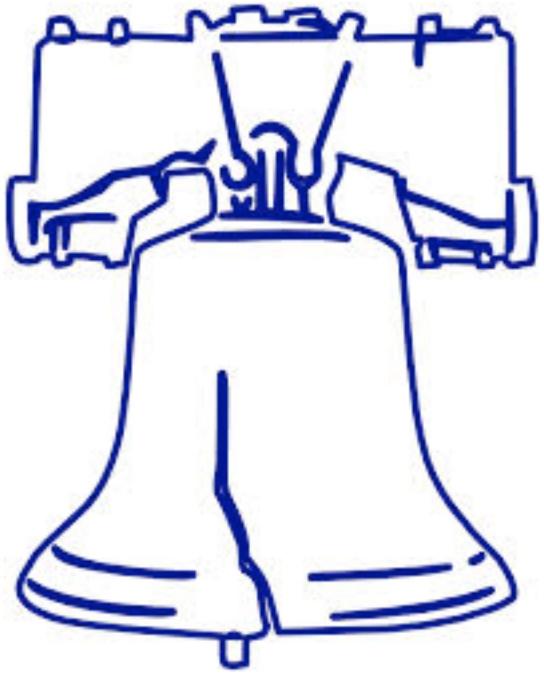
Weds are not good crack arrestors


Utilization
Domain
Transition
Ductile
High scattering
Toughness (joules)
base
Fragile
Transition Temperature


CRACK
PLATE EDGES & RIVET HOLES STOP CRACK PROGRESSION
WELD
RIVET HOLES
CRACK
WELDED CONSTRUCTION
RIVETED CONSTRUCTION

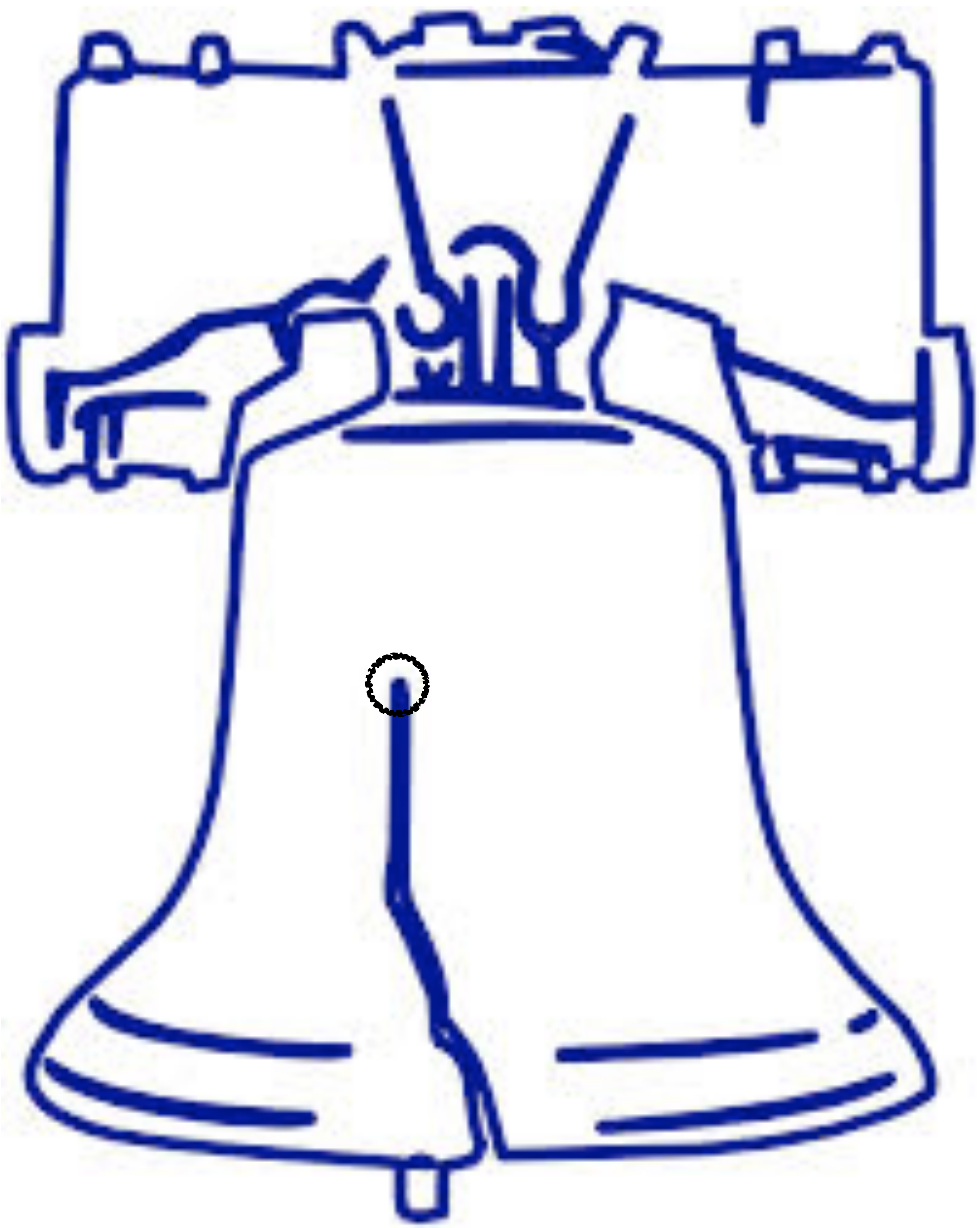
Learning from experience





The liberty bell
(Philadelphia)

Learning from experience



The liberty bell
(Philadelphia)

Learning from experi**ments**

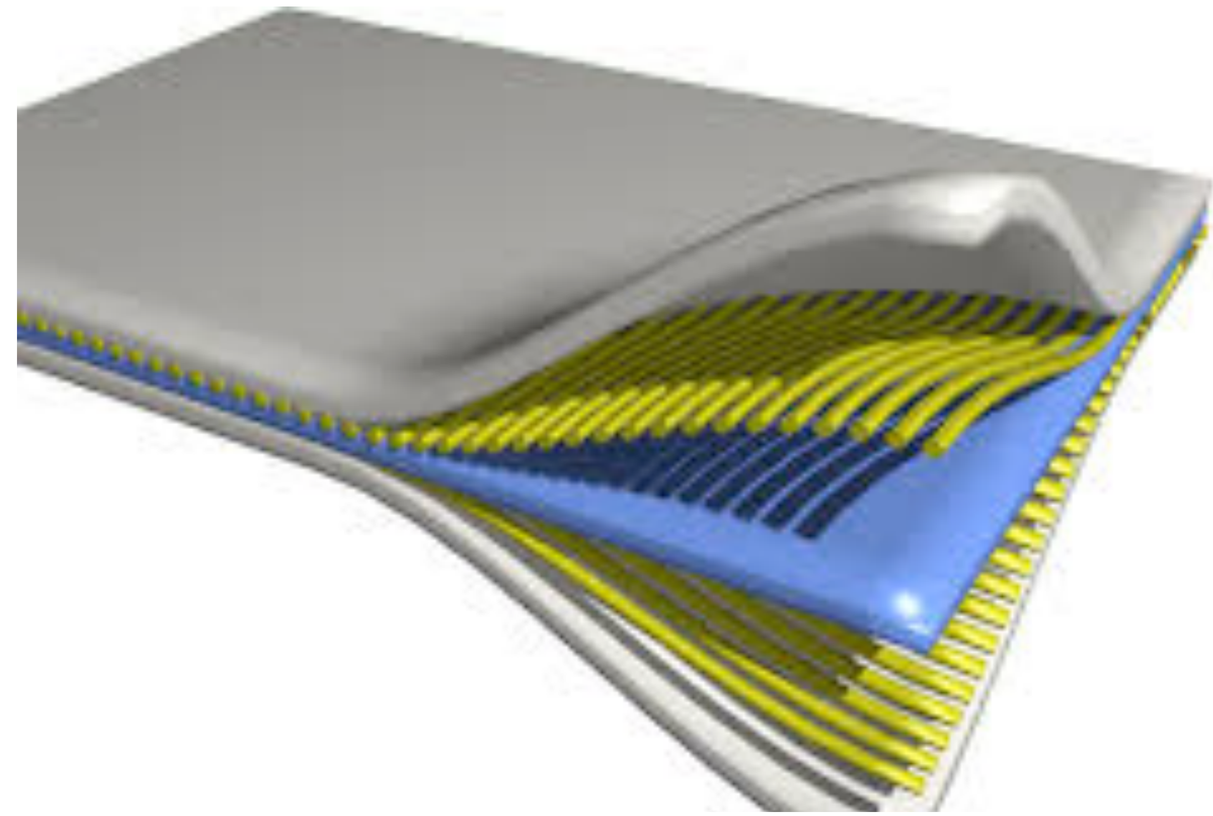
World's largest wind tunnel (2014)

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

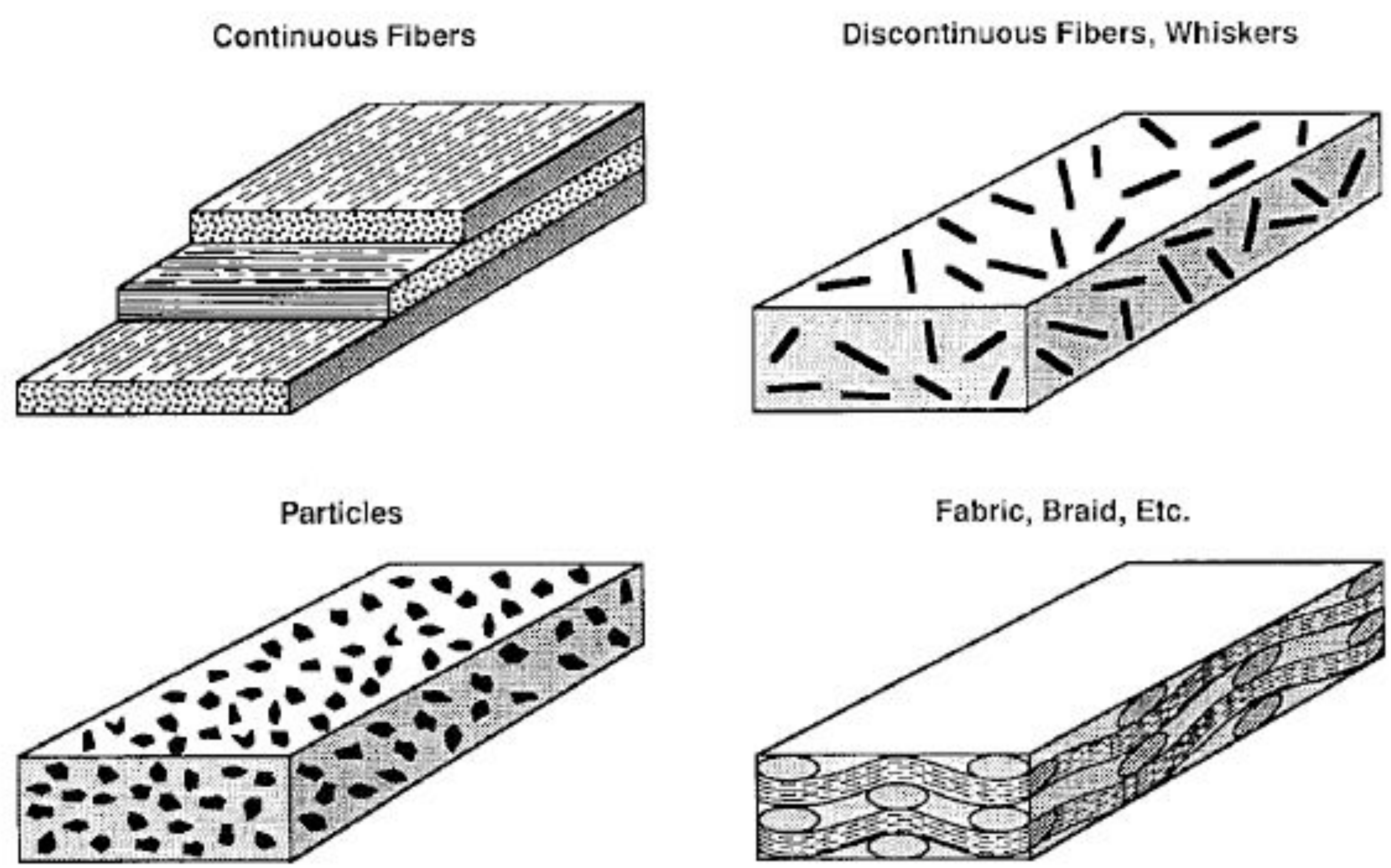
teaching...

New materials for more payload

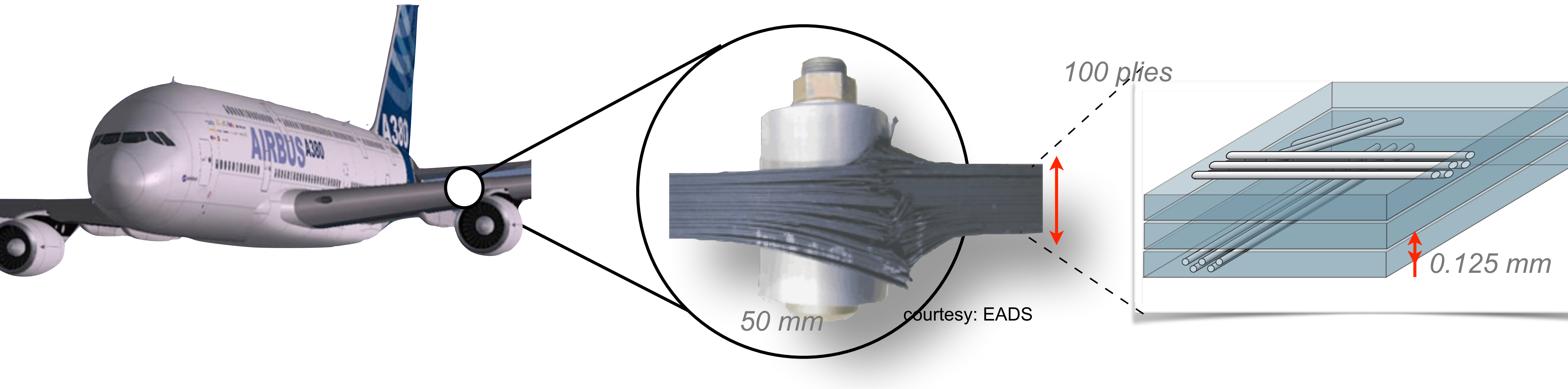
Introduction of composite materials have reduced the weight of structures by 20%



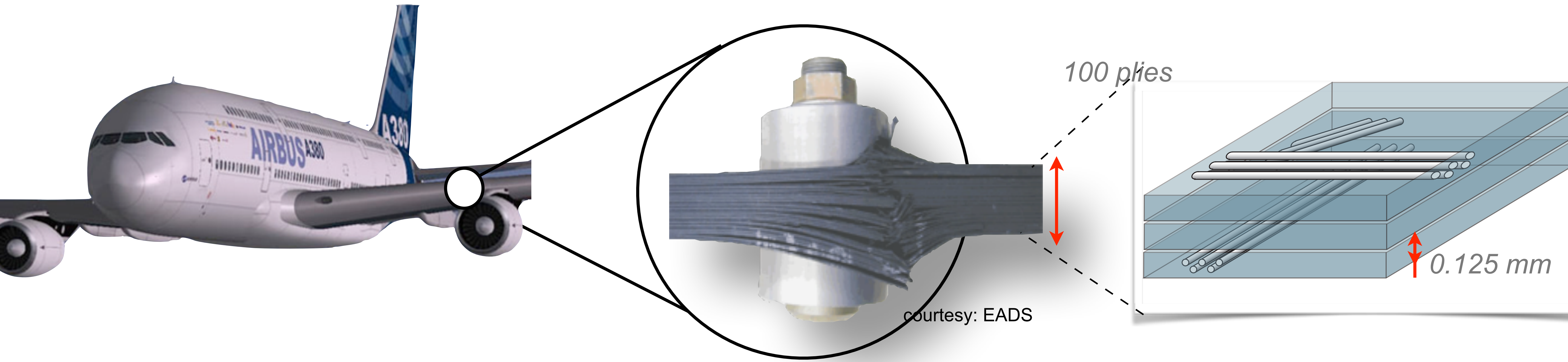
Over 1,000km saving of 8,660kg of fuel [A340-300]



Material complexity

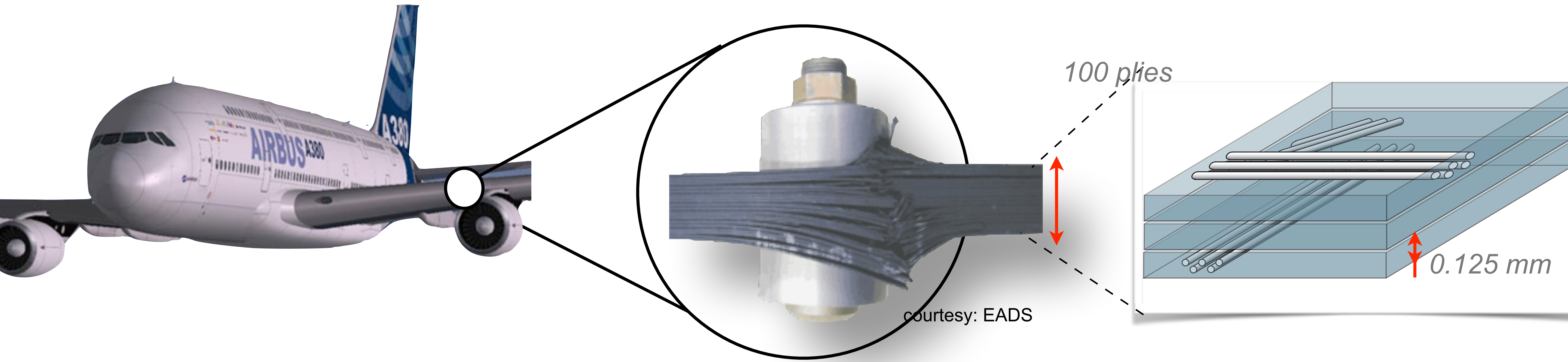


Material complexity



- Heterogeneous & multi-functional
- Experiments required to attain sufficient confidence in their behavior are increasingly costly

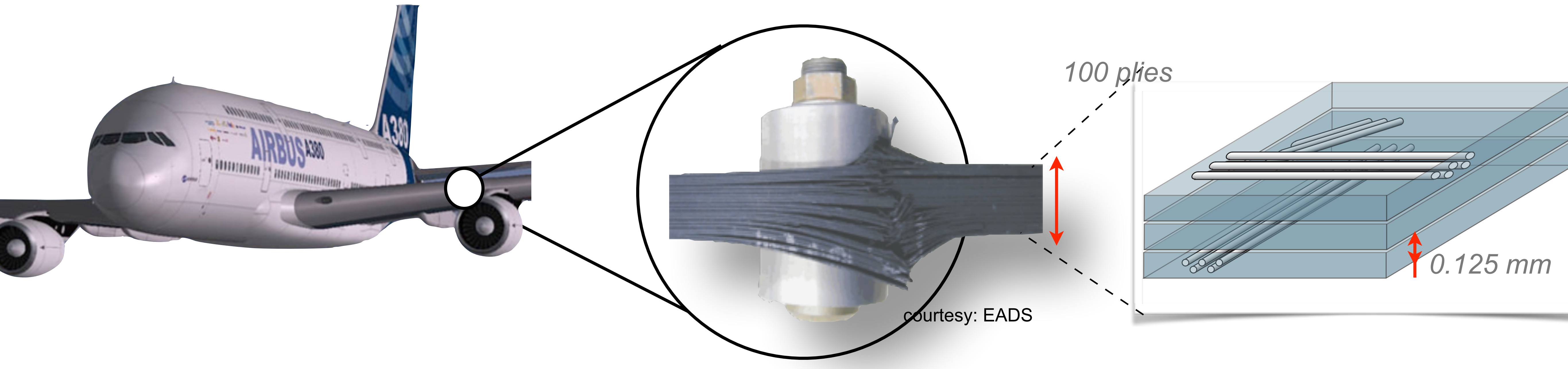
Material complexity



- Heterogeneous & multi-functional
- Experiments required to attain sufficient confidence in their behavior are increasingly costly
- Factor-of-Safety or probabilistic based methods cannot handle unknown unknowns

- Lack of similitude between testing (experimental) and operating conditions — also encountered in geophysics...

Material complexity



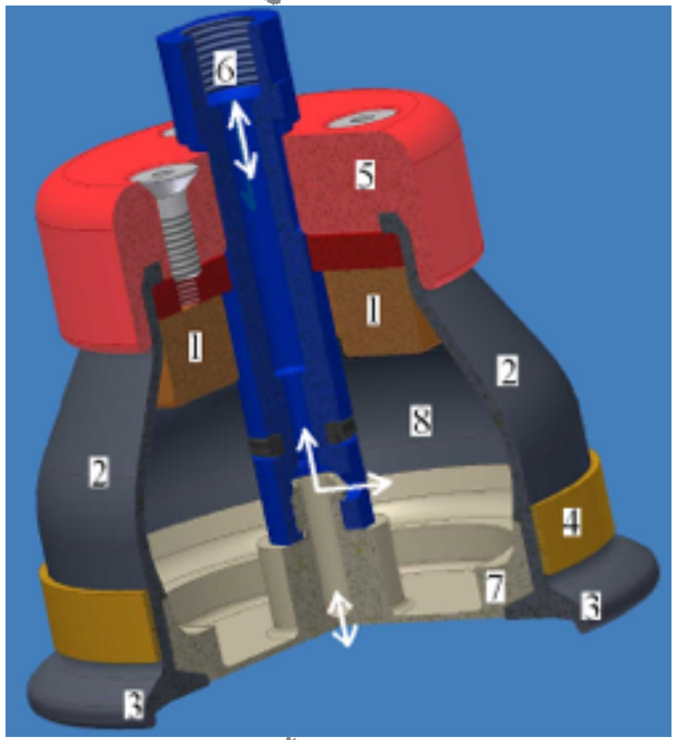
- Heterogeneous & multi-functional
- Experiments required to attain sufficient confidence in their behavior are increasingly costly
- Factor-of-Safety or probabilistic based methods cannot handle unknown unknowns - lack of similitude

- Move **away from heuristics** and experience-based engineering
- Develop **fundamental understanding** of physical processes (degradation, ...)
- Reduce weight

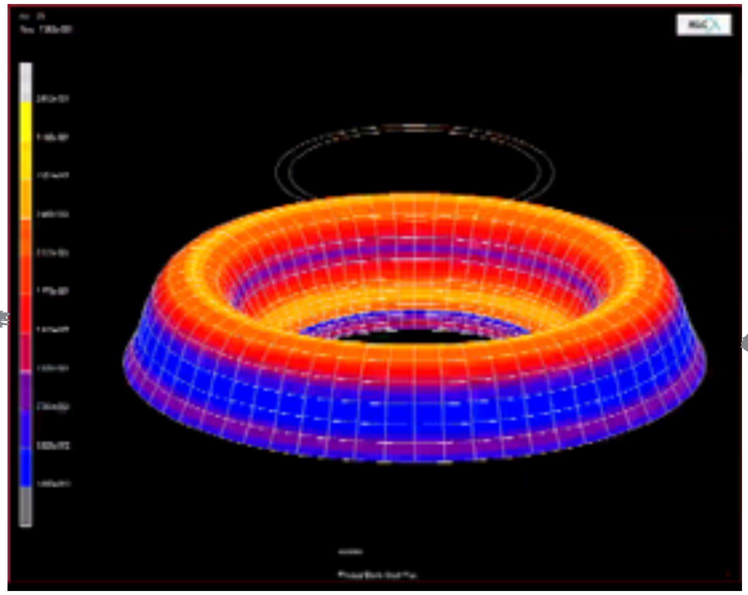
product-specific

Increase product durability?

Virtual model of the device



Virtual testing & Simulation



Analysis of the results

market-specific

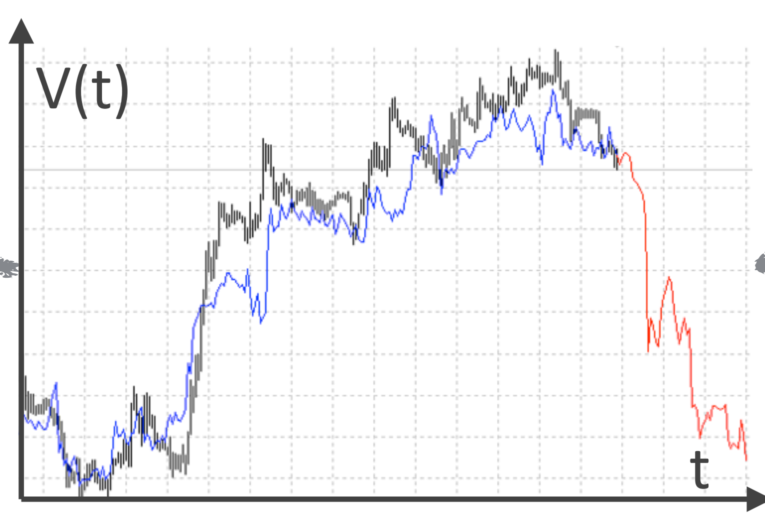
Buy or sell?

Identify behaviour

$$\frac{\partial V}{\partial t} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + rS\frac{\partial V}{\partial S} - rV = 0$$

Mathematical model + initial conditions

Real-time future option pricing



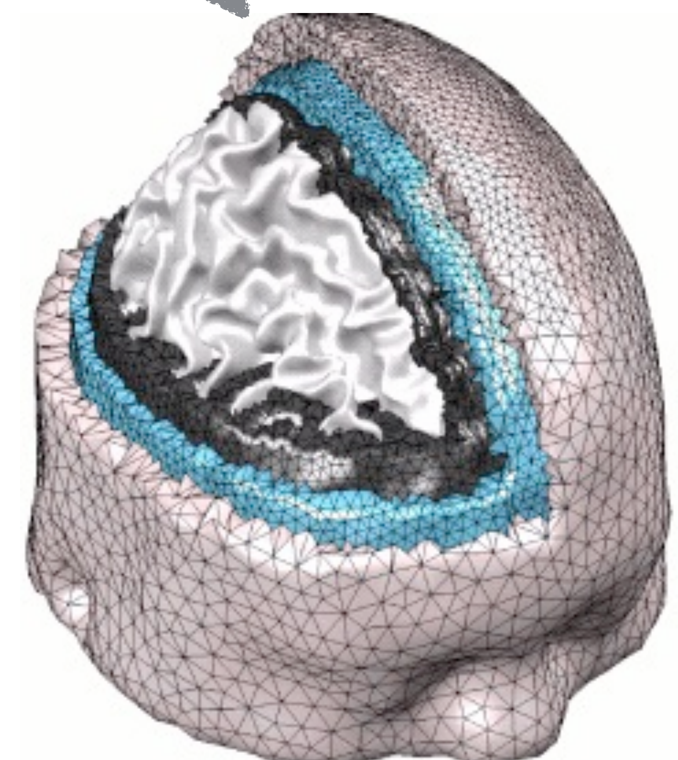
patient-specific

Devise effective deep brain stimulation

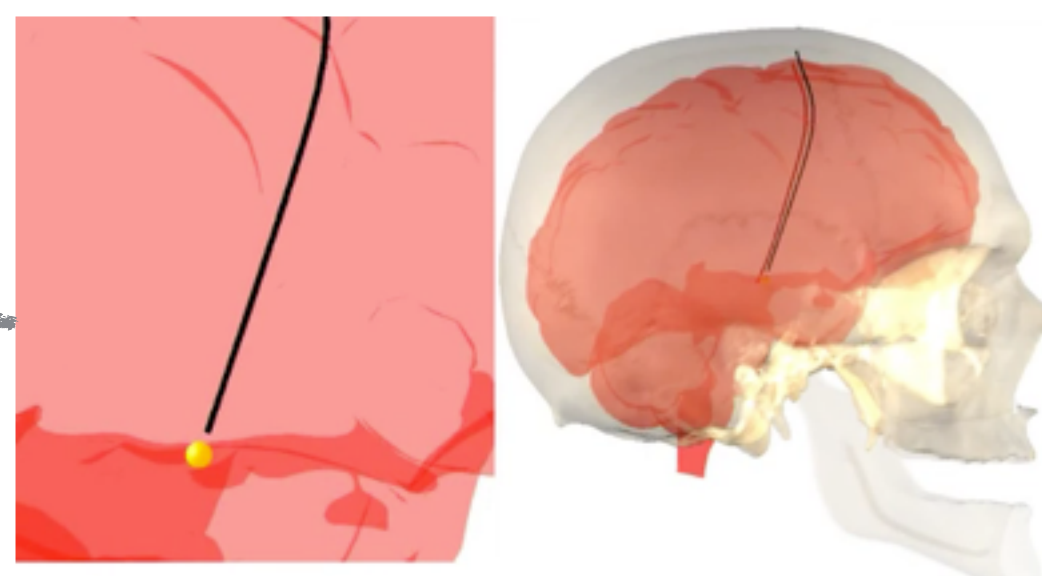
- reach the target area
- maintain contact with the electrode

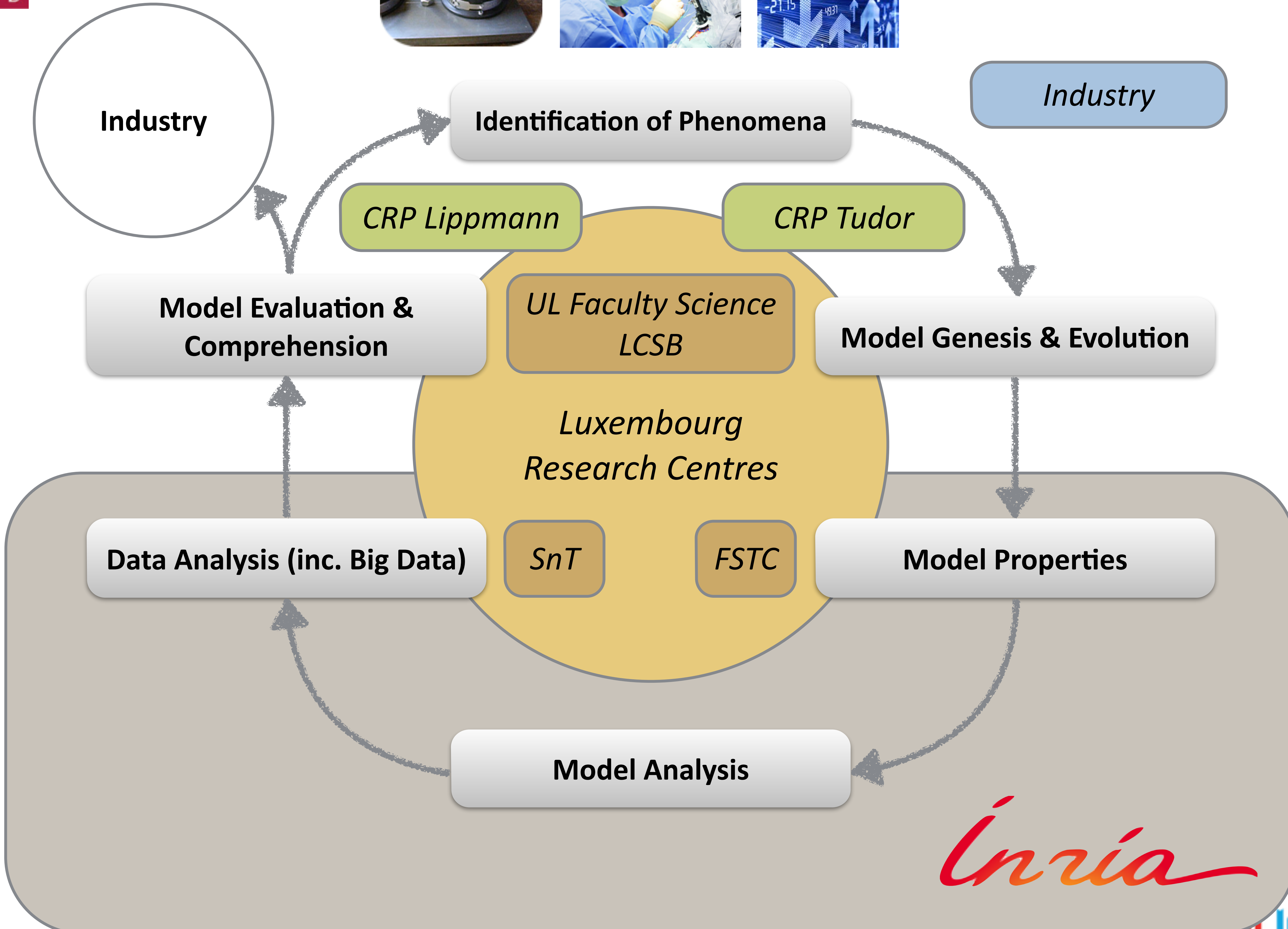
Electrode separates from target

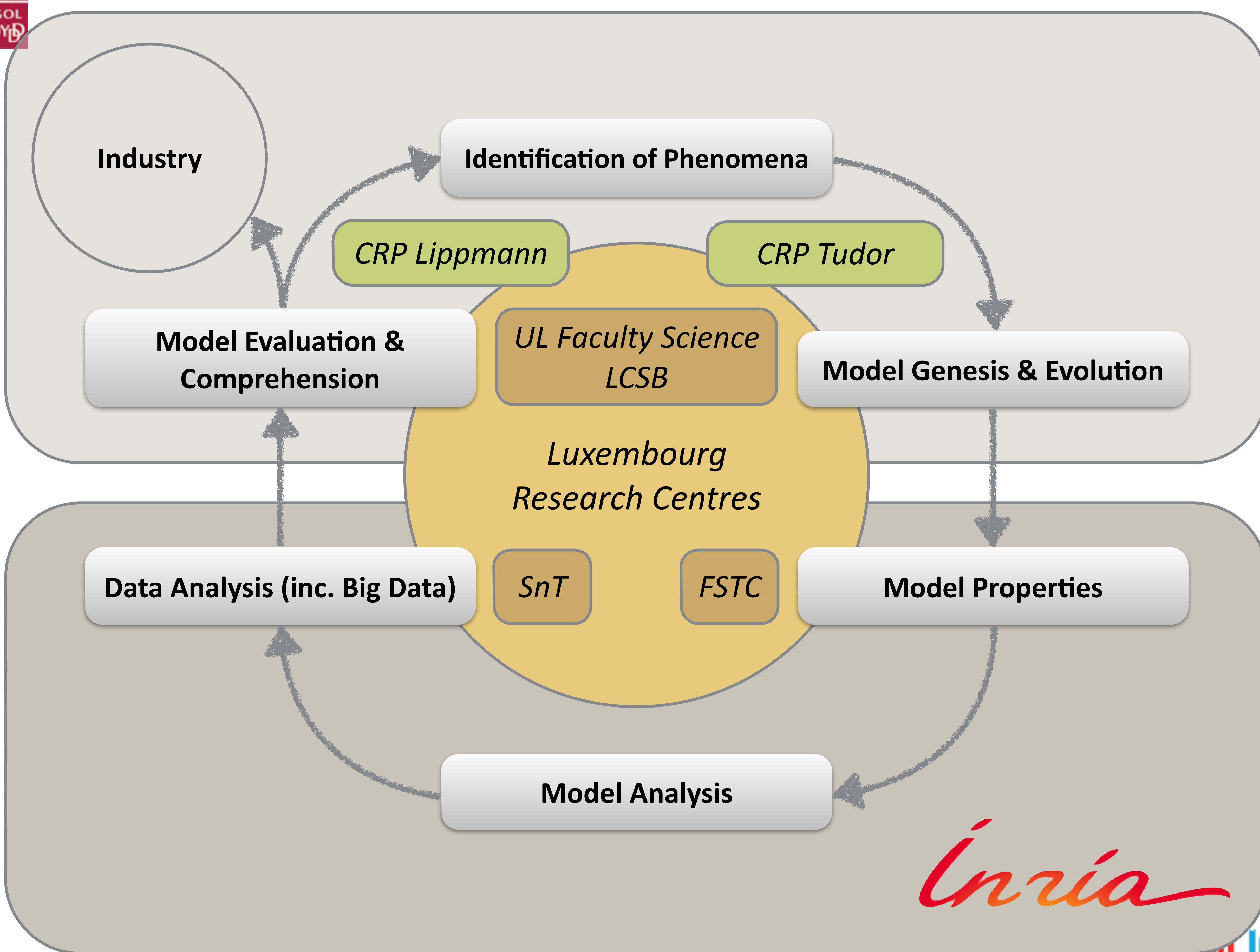
Model of the brain material



Predict electrode behaviour




Industry
Identification of Phenomena
Industry
CRP Lippmann
CRP Tudor
Model Evaluation &
Comprehension
UL Faculty Science
LCSB
Model Genesis & Evolution
Luxembourg
Research Centres
Data Analysis (inc. Big Data)
SnT
FSTC
Model Properties
Model Analysis


Industry
Identification of Phenomena
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Model Evaluation & Comprehension
UL Faculty Science LCSB
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Data Analysis (inc. Big Data)
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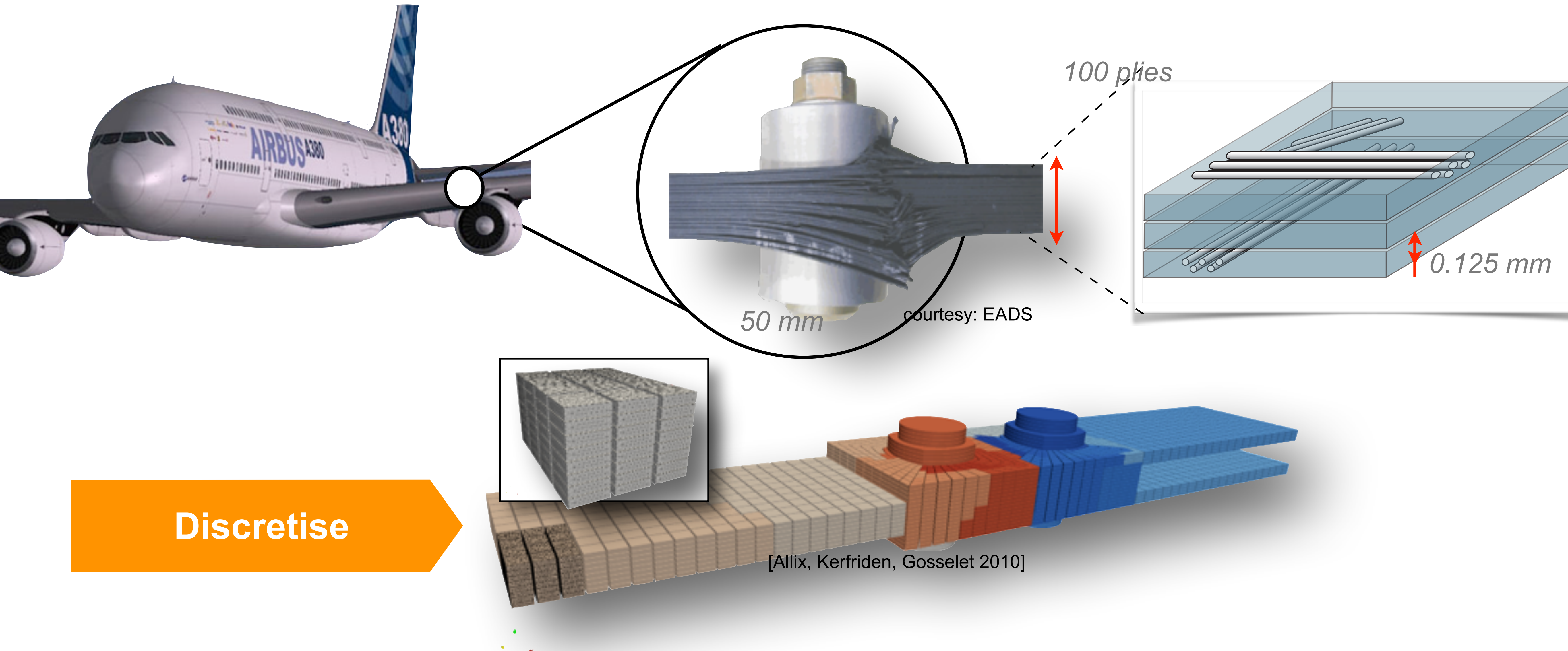
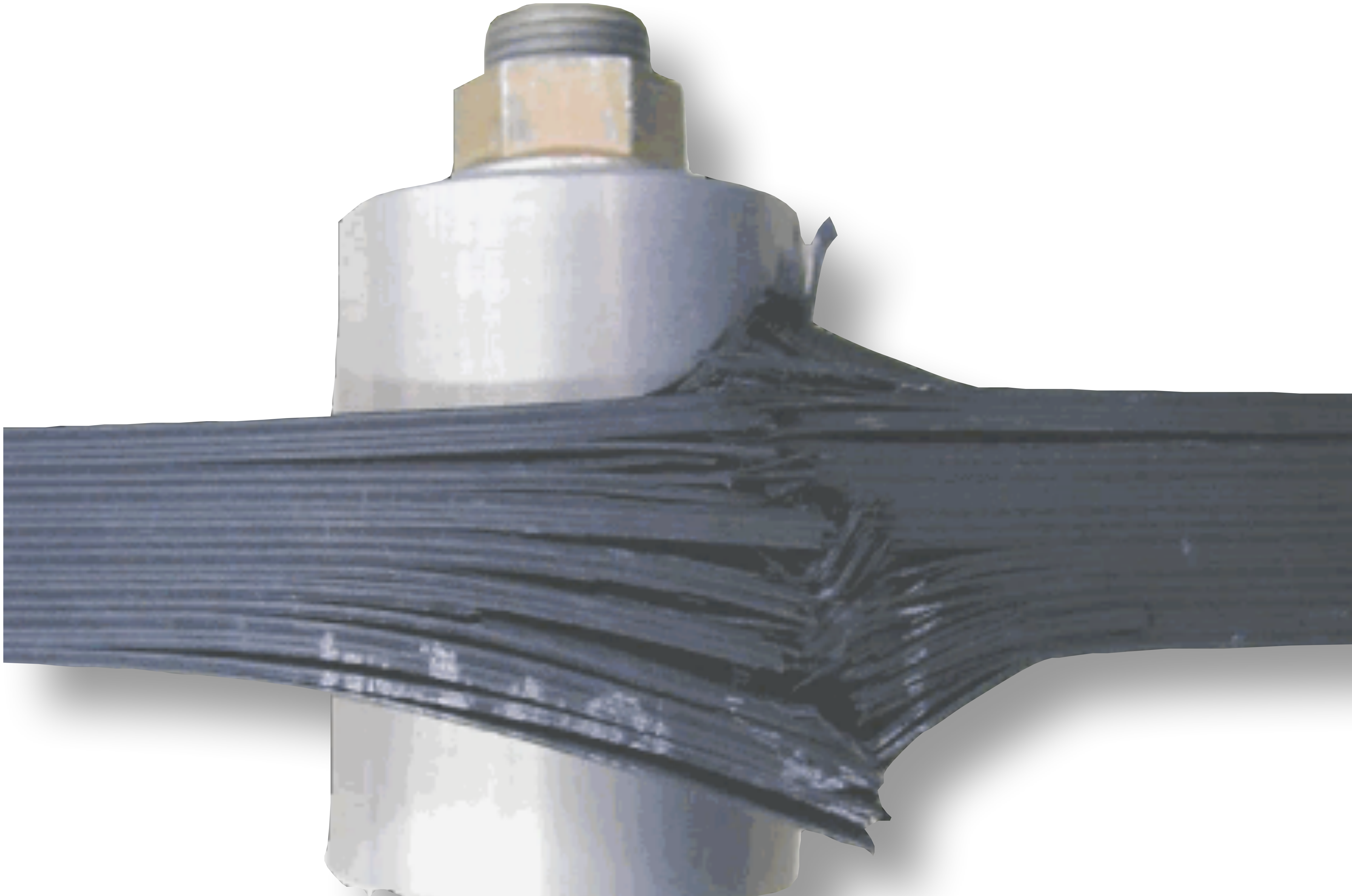
FSTC
Model Properties
Model Analysis

New kinds of experiments for new kinds of models



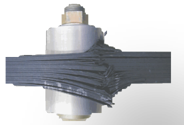
Kerfriden, Allix, Gosselet, Bordas *et al*, 2009, 2010, 2011, 2012, 2013, 2014

A bolted joint

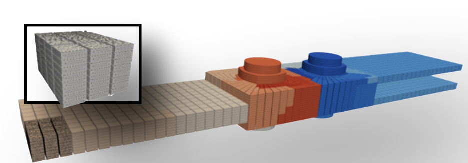


A380 giant

Large structures 

Small features 

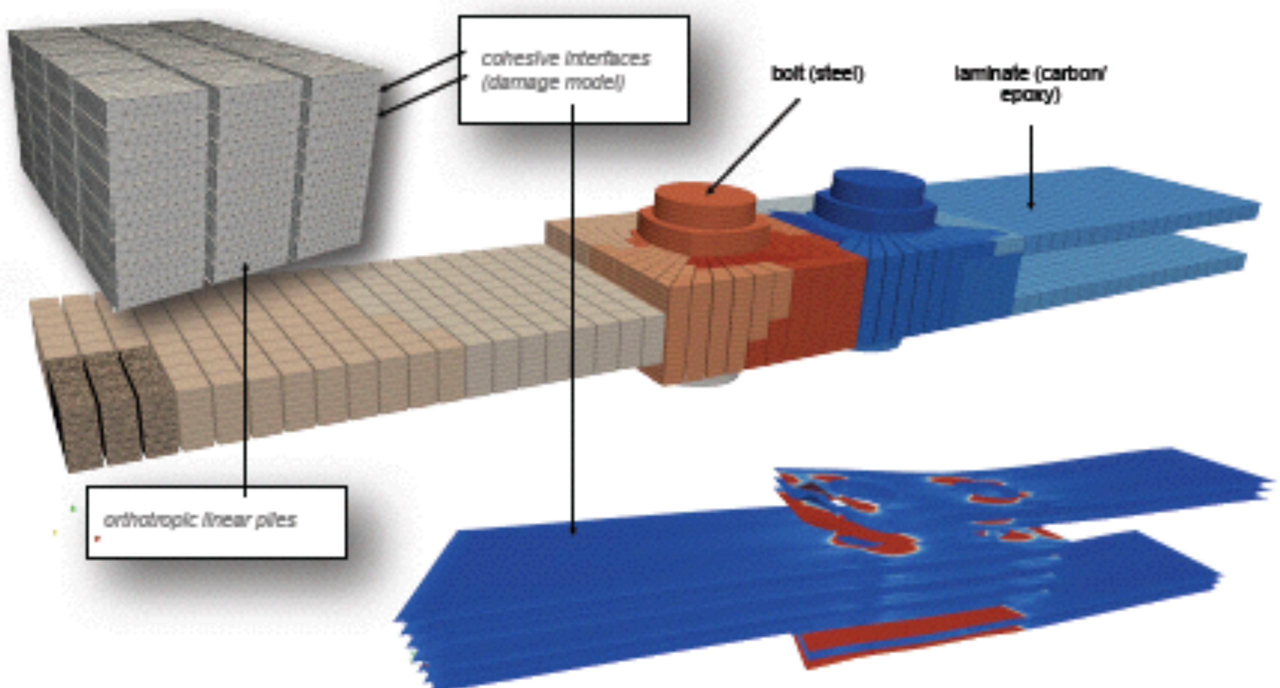
Very large problems



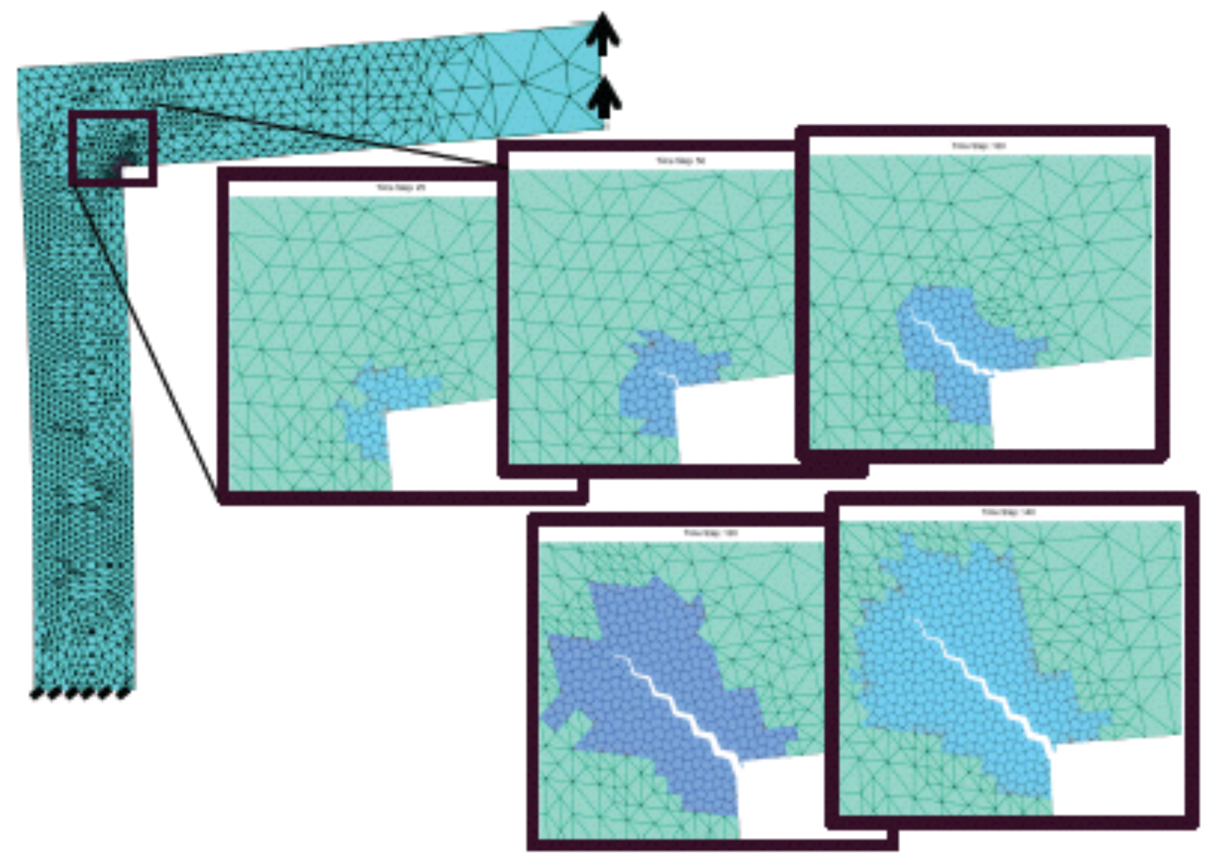
Model reduction - physics-based (1)

- Multilevel methods to reduce CPU time by orders of magnitude and devise robust, efficient code/model coupling

    - HPC Adaptive multiscale models/solvers with controlled accuracy



[Kerfriden et al., 2010]



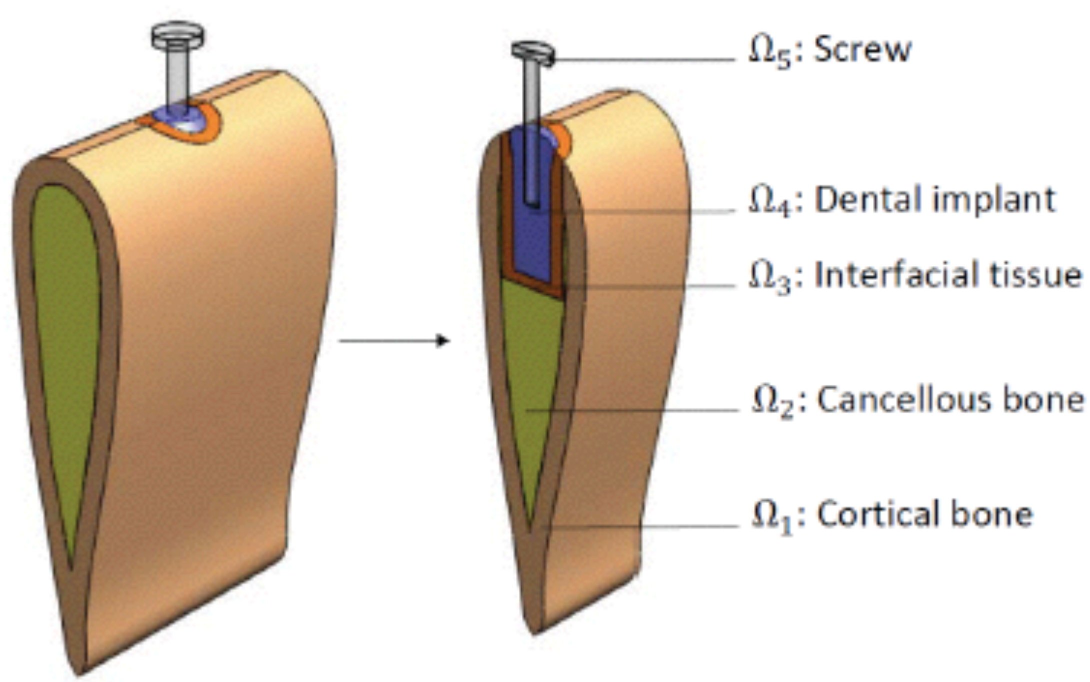
[Akbari et al., 2013]

Open problem: adaptive error controlled algorithms for model and discretization error. Use the right model at the right place/time.

Model reduction - algebraic (2)

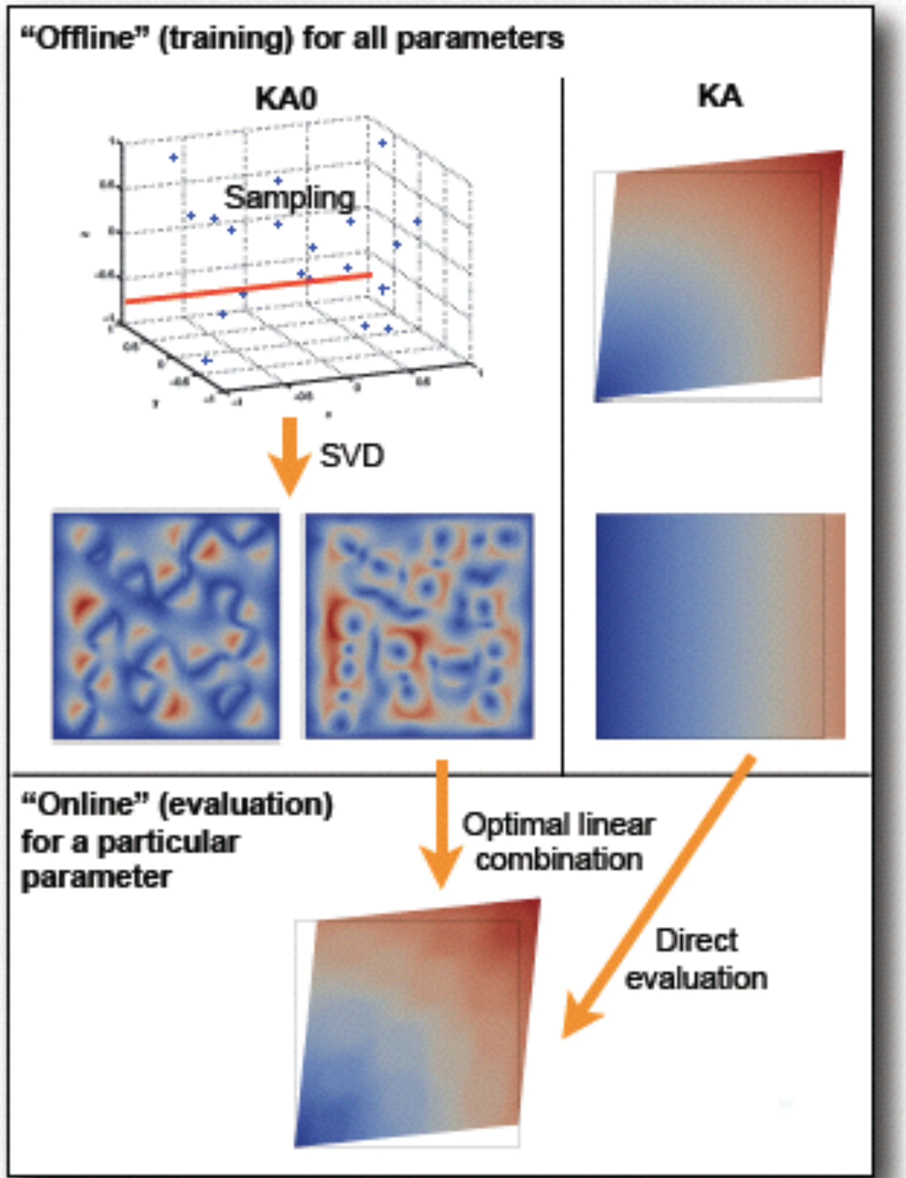
- Multilevel methods to reduce CPU time by orders of magnitude and devise robust, efficient code/model coupling

  - Virtual chart with controlled accuracy via ROM for multiscale modelling and real-time optimisation



[Hoang et al., 2013]

"offline" / "online" strategy



[Kerfriden et al., 2013]

Open problem: algebraic model reduction for non-linear problems with localisation - fracture, moving interfaces

NASA's digital twin

Actual aircraft

Digital aircraft model

Life prediction and extension

Situation awareness

High fidelity modeling and simulation

Certification and design methods

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…

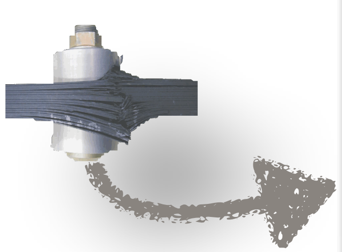
of the dreamliner…

32 billion US$

Mechanics

Macro (wing) - Micro (carbon fibres)

Environmental effects (Temperature, irradiation…)



Medicine

Macro (Body, Physiology) to micro (microbes, needle/ scalpel…)

Patient's environment, living conditions, habits…

Organ properties depend strongly on age, gender, …

Medicine

Clean hands before assisting childbirth to avoid infections

In 1847 in Vienna, Ignaz Semmelweis (1818–1865) marginalized and attacked by professional peers

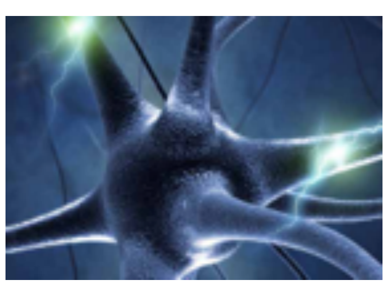
Mechanics

Use rivets to arrest cracks
Avoid sharp angles

Liberty ships, Aloha airlines accident…

“Digital Twin” (Medic)

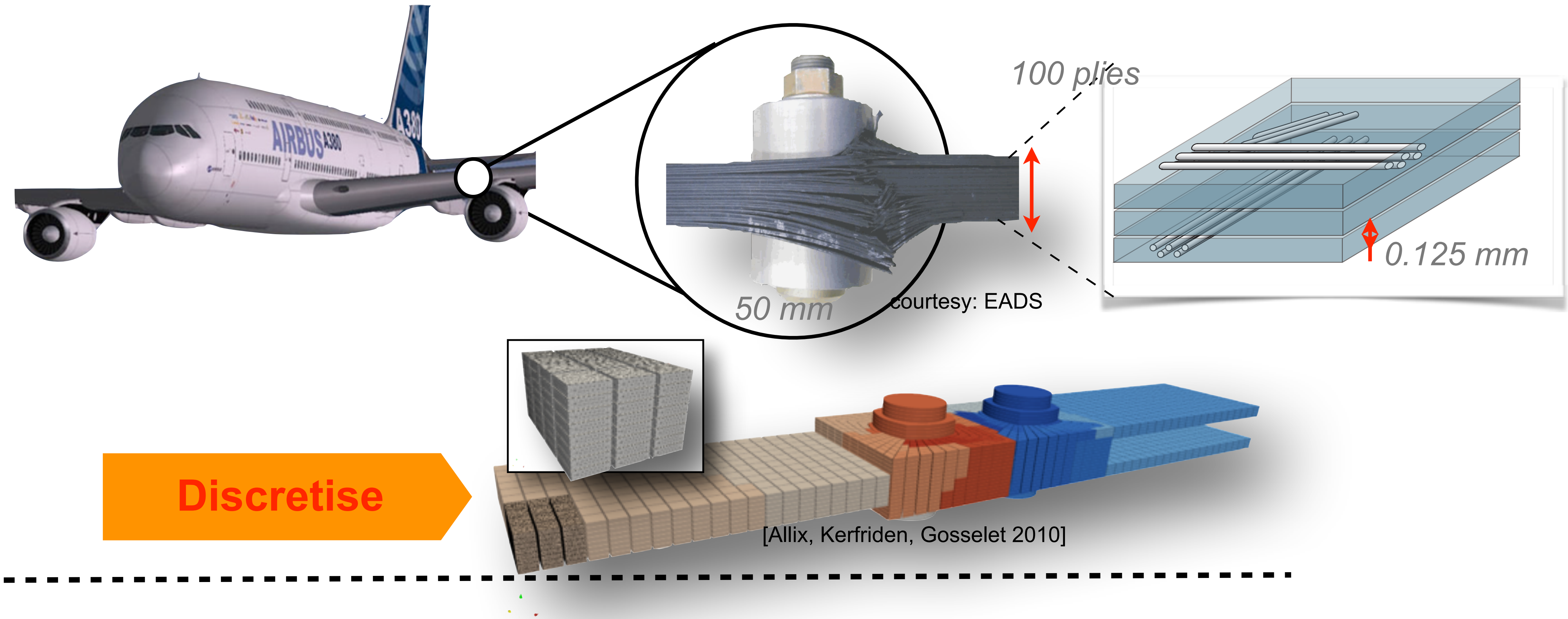
“Digital Twin” (NASA)



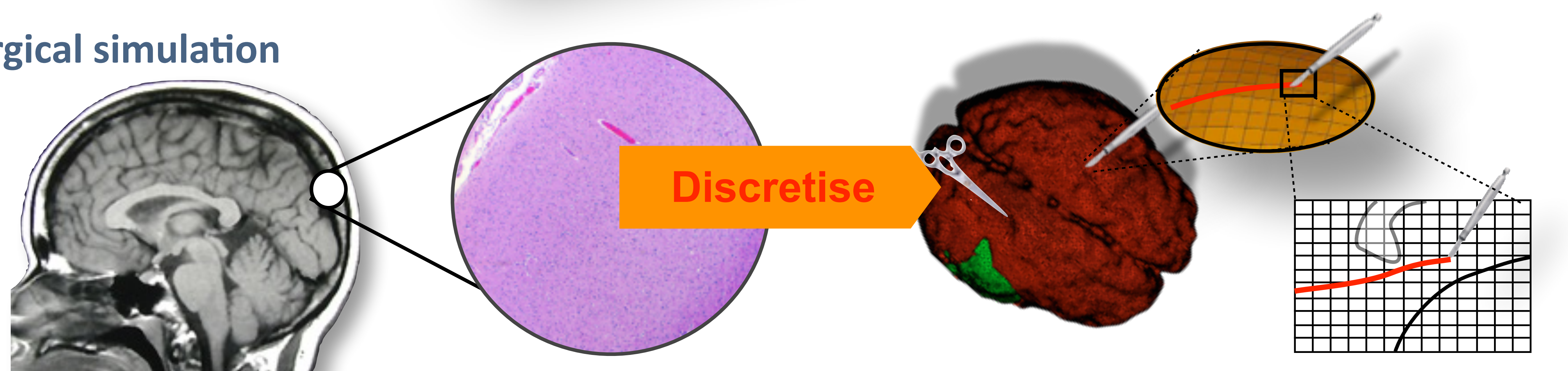
Personalisation

Patient/plane-specific simulation

Practical early-stage design simulations (interactive)



Surgical simulation

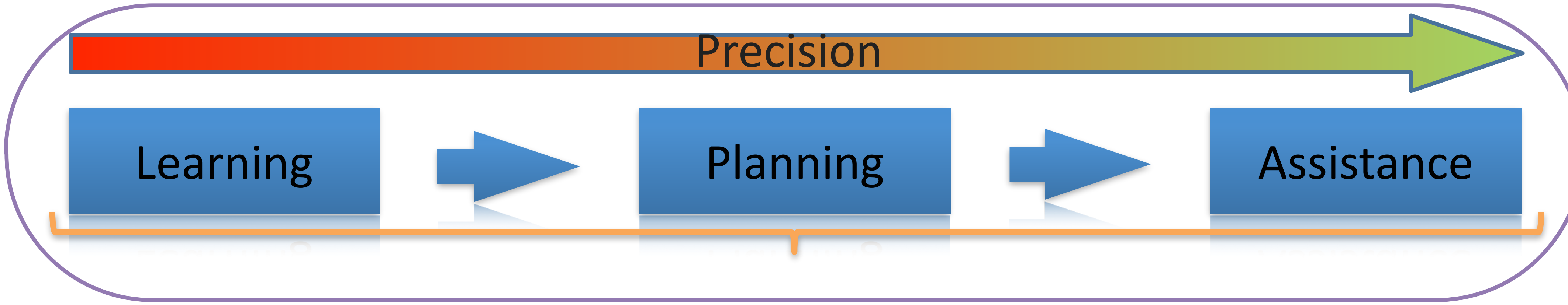


- Reduce the problem size while controlling the error (in QoI) when solving very large (multiscale) mechanics problems

Surgical simulation

RealTcut

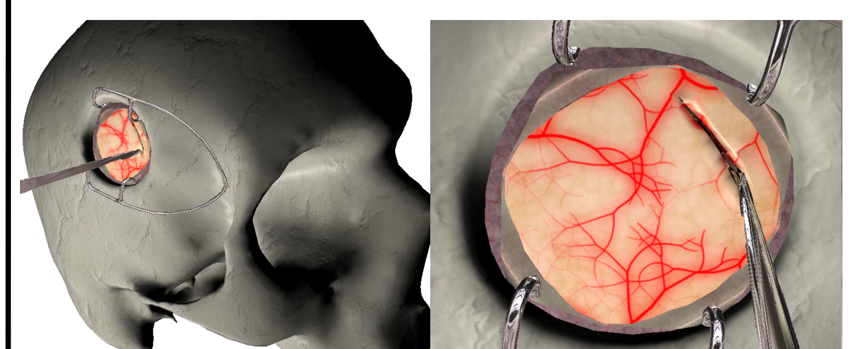
erc



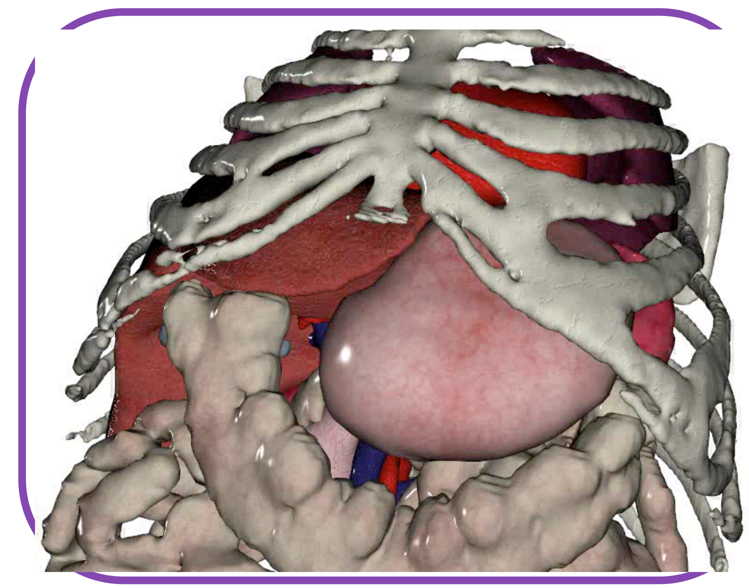
Cataract Surgery

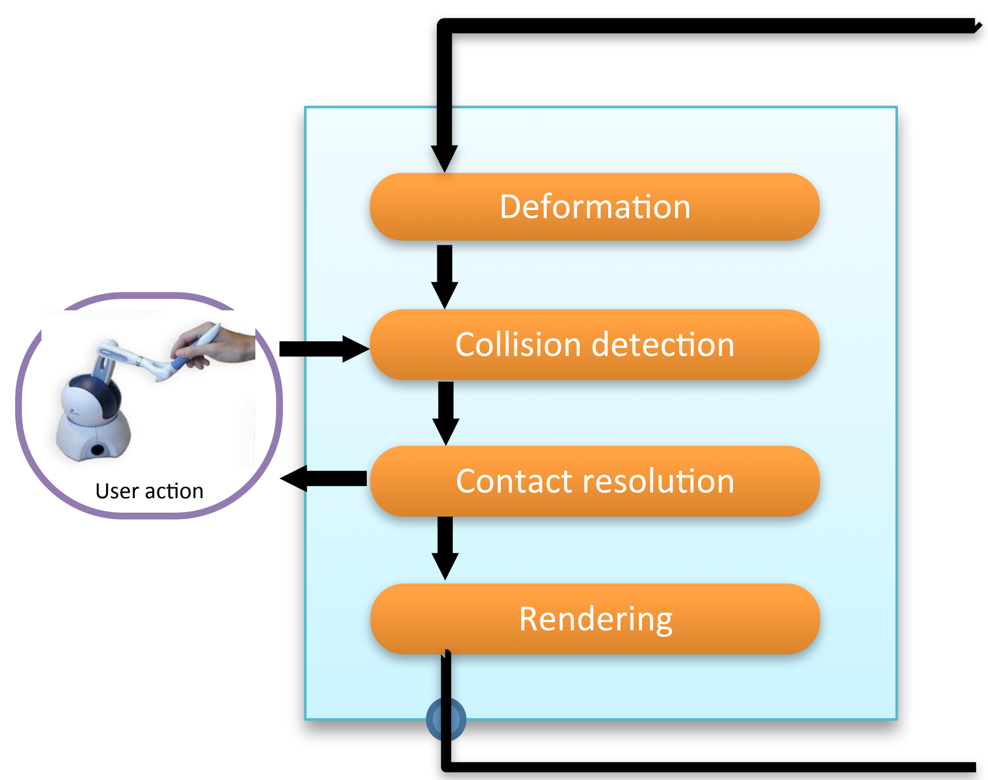
Abdominal minimally invasive surgery simulation (Inria, Shacra)

First implicit, interactive method for cutting with contact



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



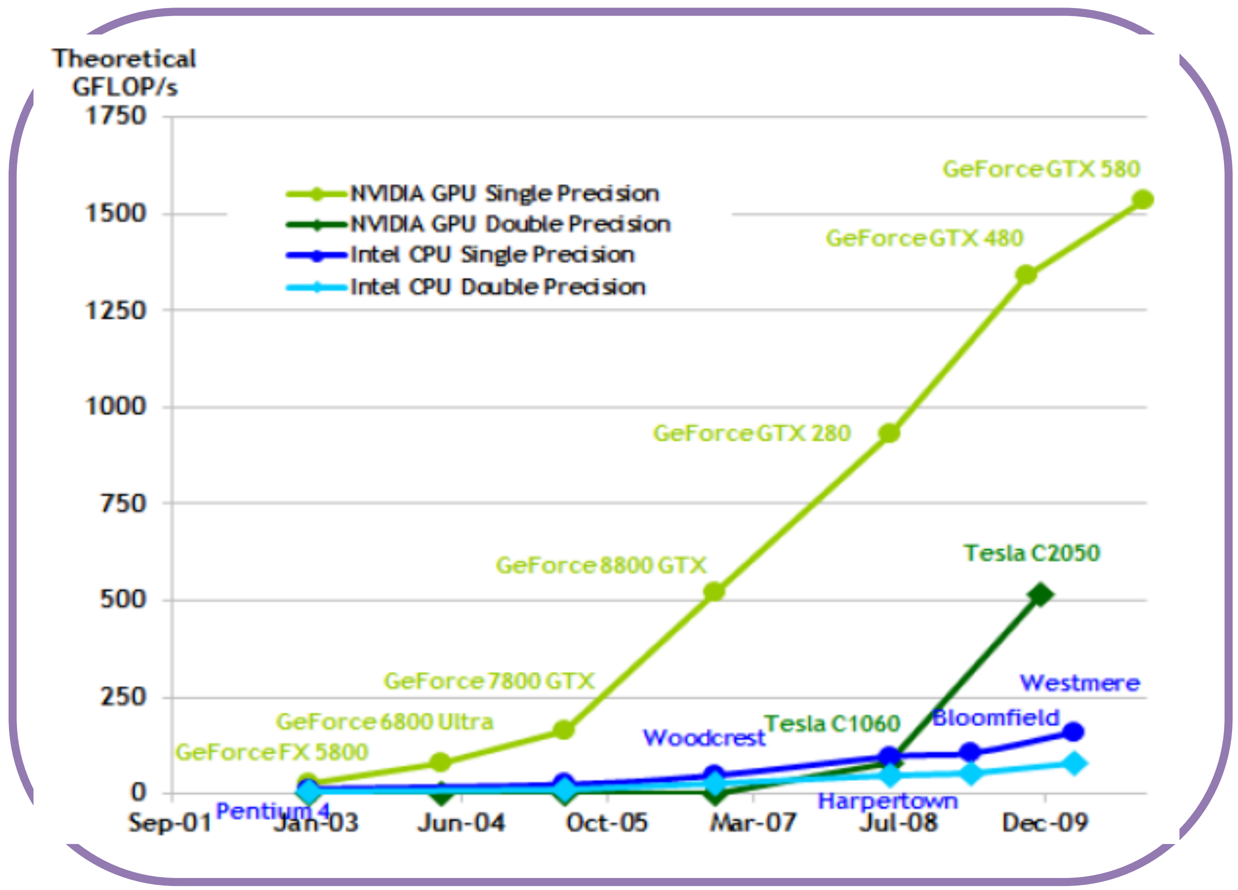

Deformation
Collision detection
Contact resolution
Rendering
User action

Difficult to increase the frequency of processors

Heat dissipation

Electric consumption

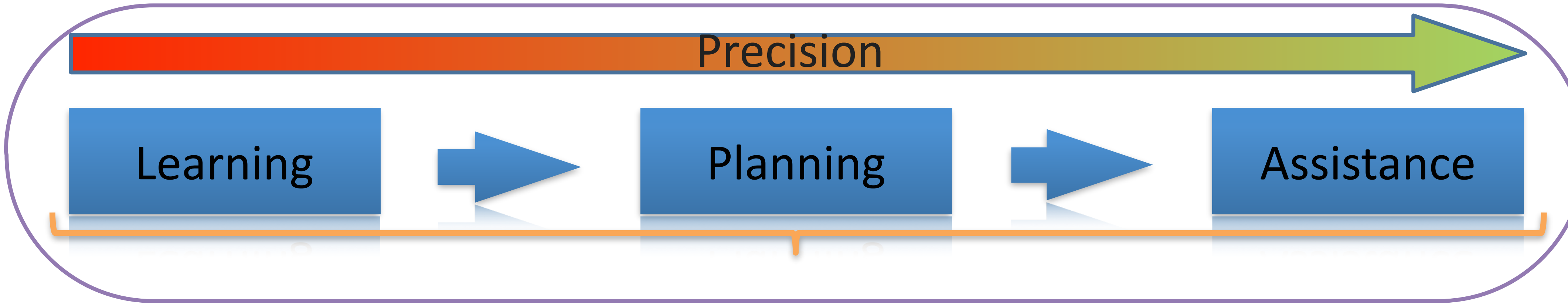
Parallelization of algorithms



Surgical simulation

RealTcut

erc



Cataract Surgery

Inria

Abdominal minimally invasive surgery simulation (Inria, Shacra)

Inria

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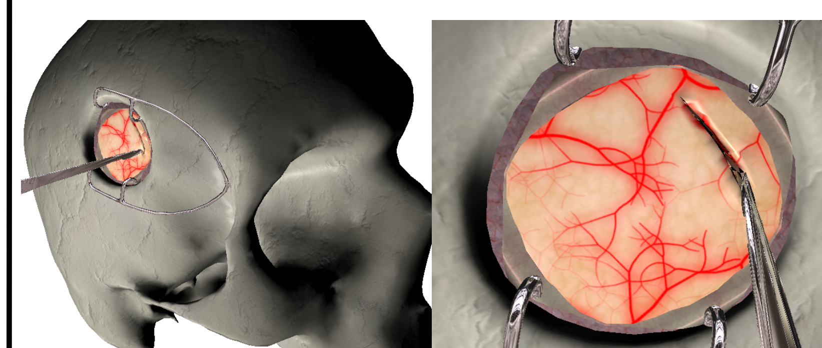
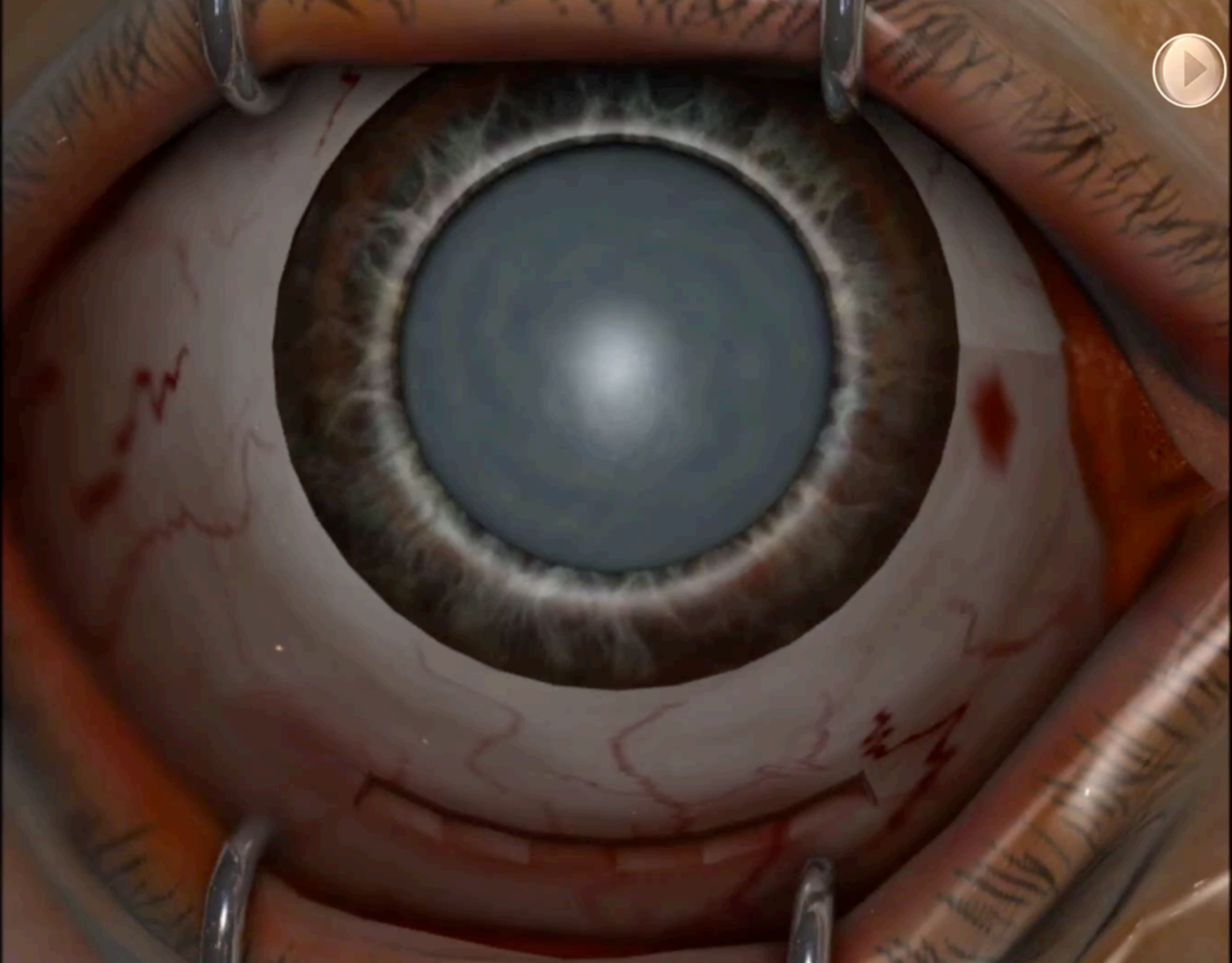


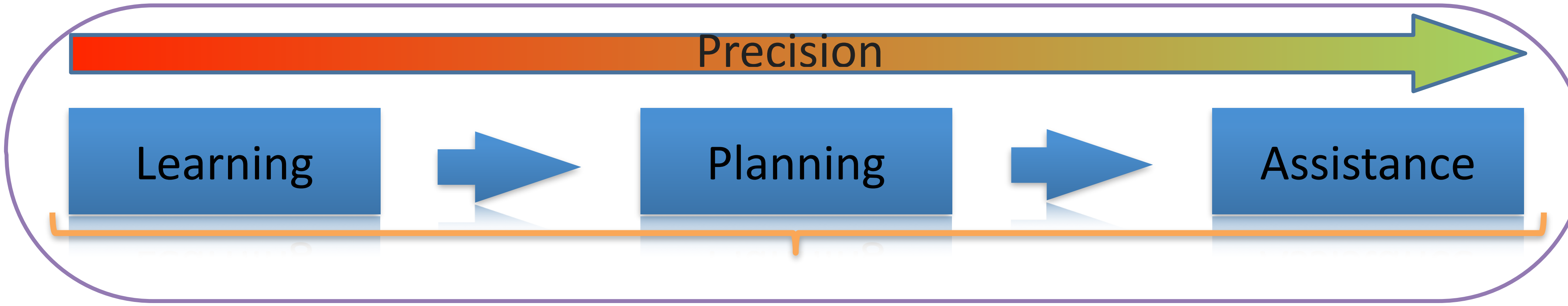
[Courtecuisse et al., MICCAI, 2013 and Medical Image Analysis, 2014]



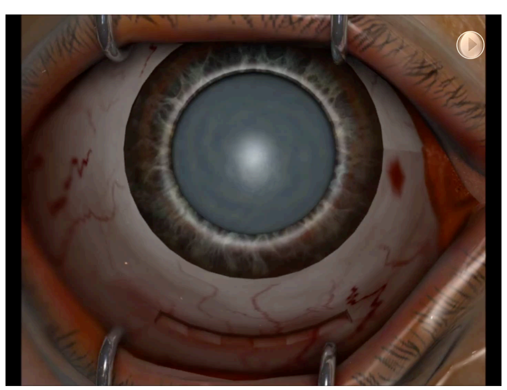
Surgical simulation

RealTcut

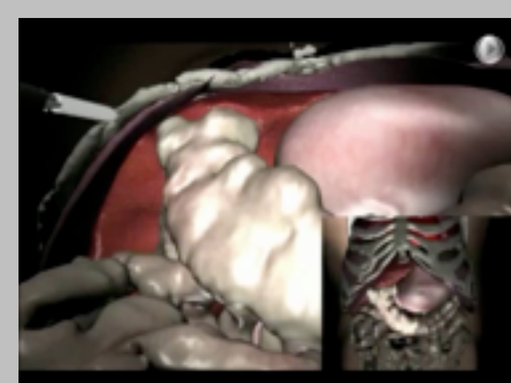
erc



Cataract Surgery



Abdominal minimally invasive surgery simulation (Inria, Shacra)



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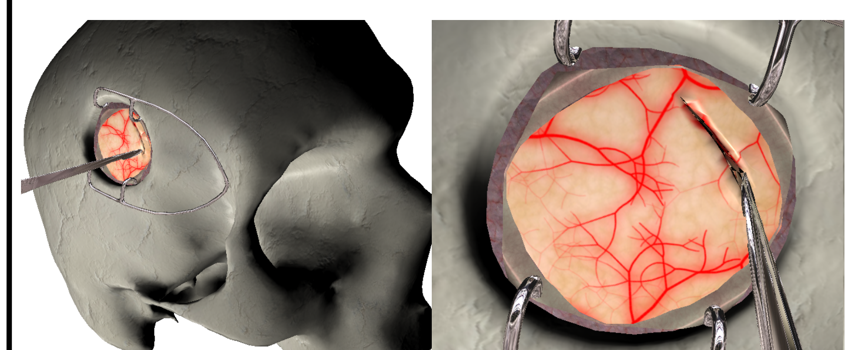

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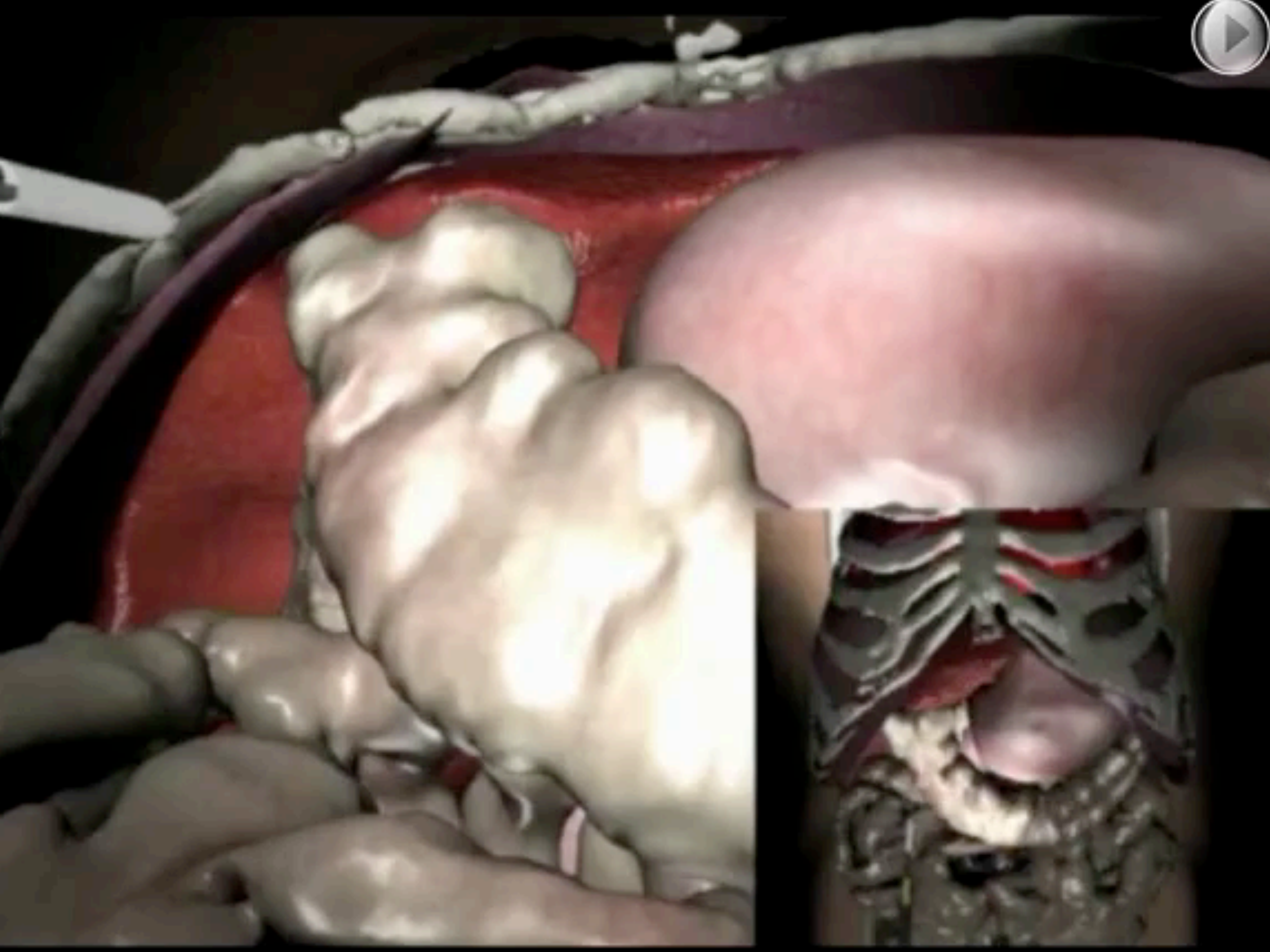
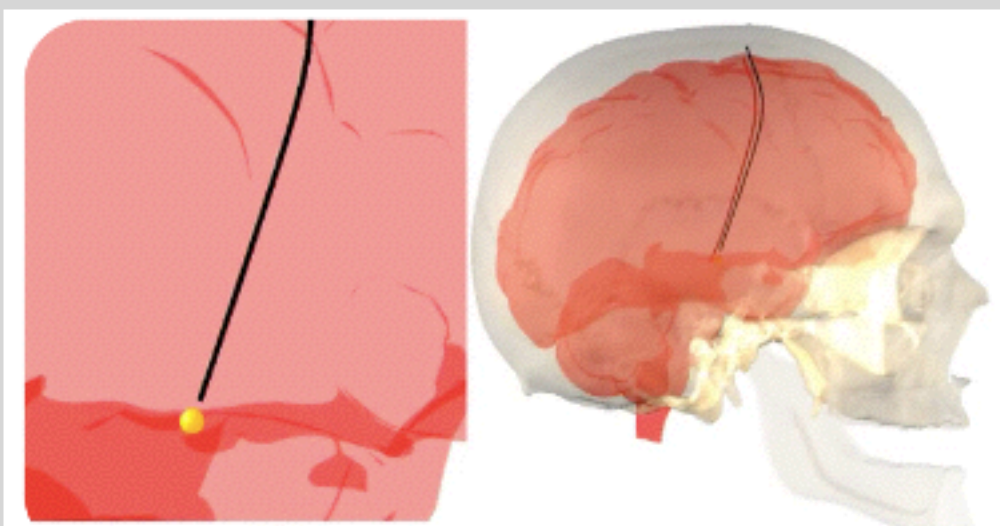


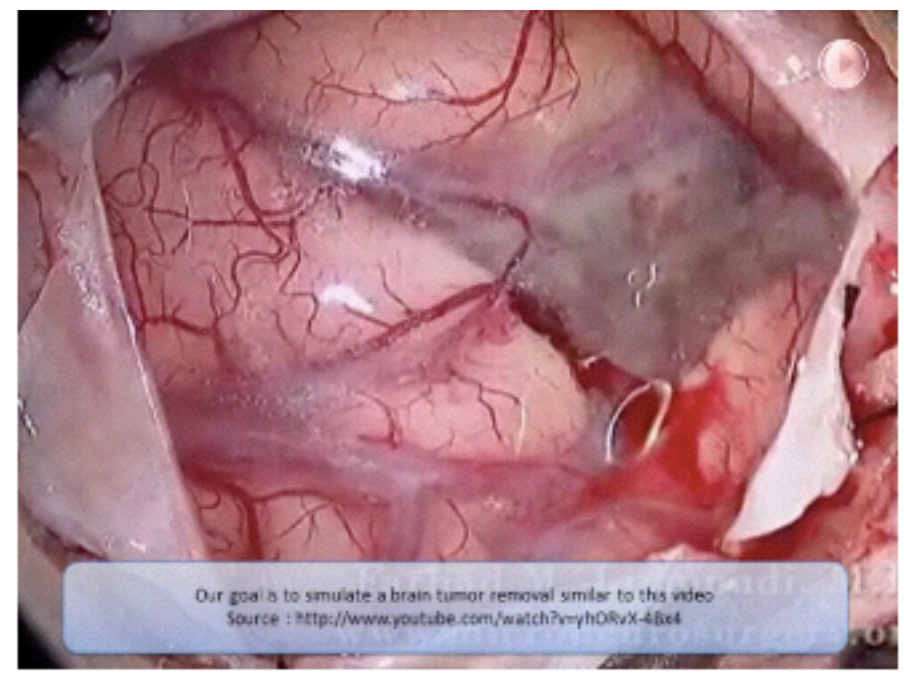
…not exactly brain surgery

Deep-brain stimulation



Cotin et al., 2013, 2014

Brain tumor resection



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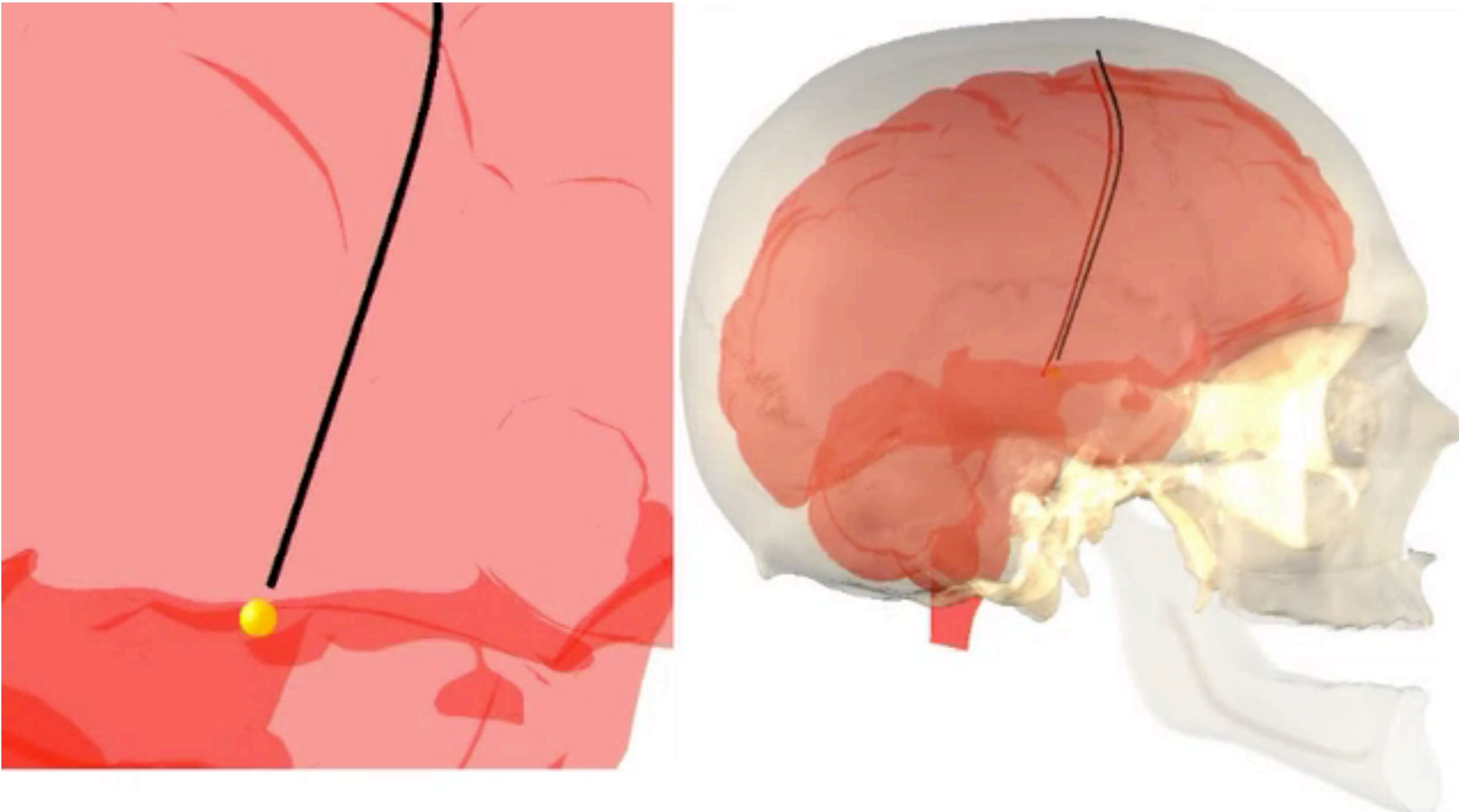
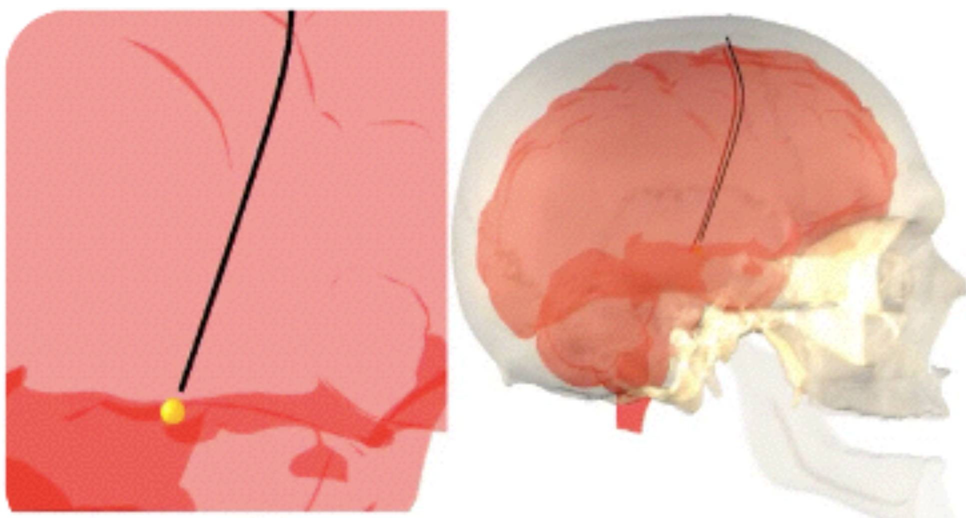


Deep-brain stimulation

…not exactly brain surgery

Deep-brain stimulation



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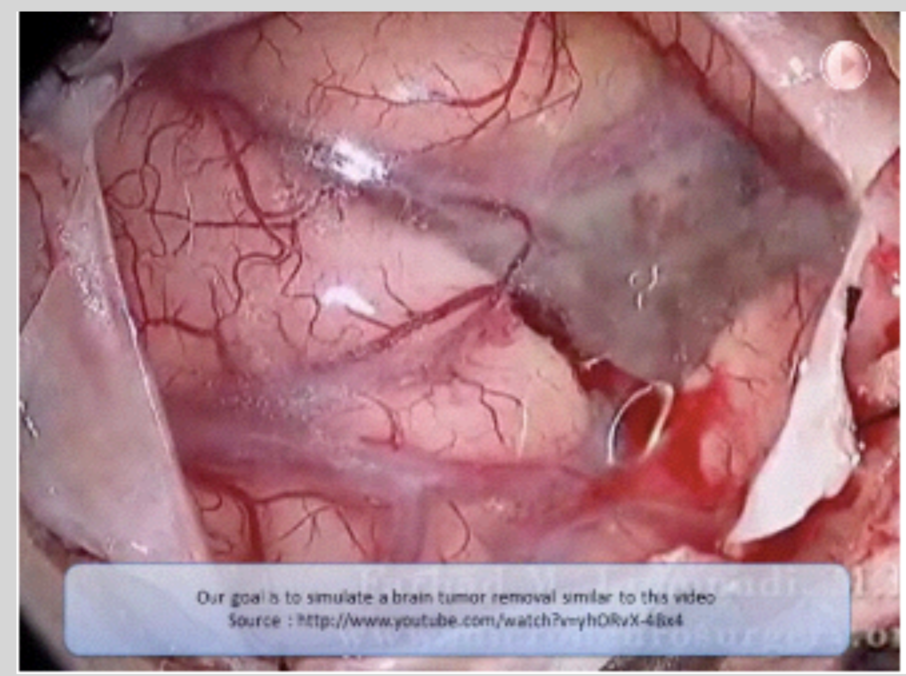
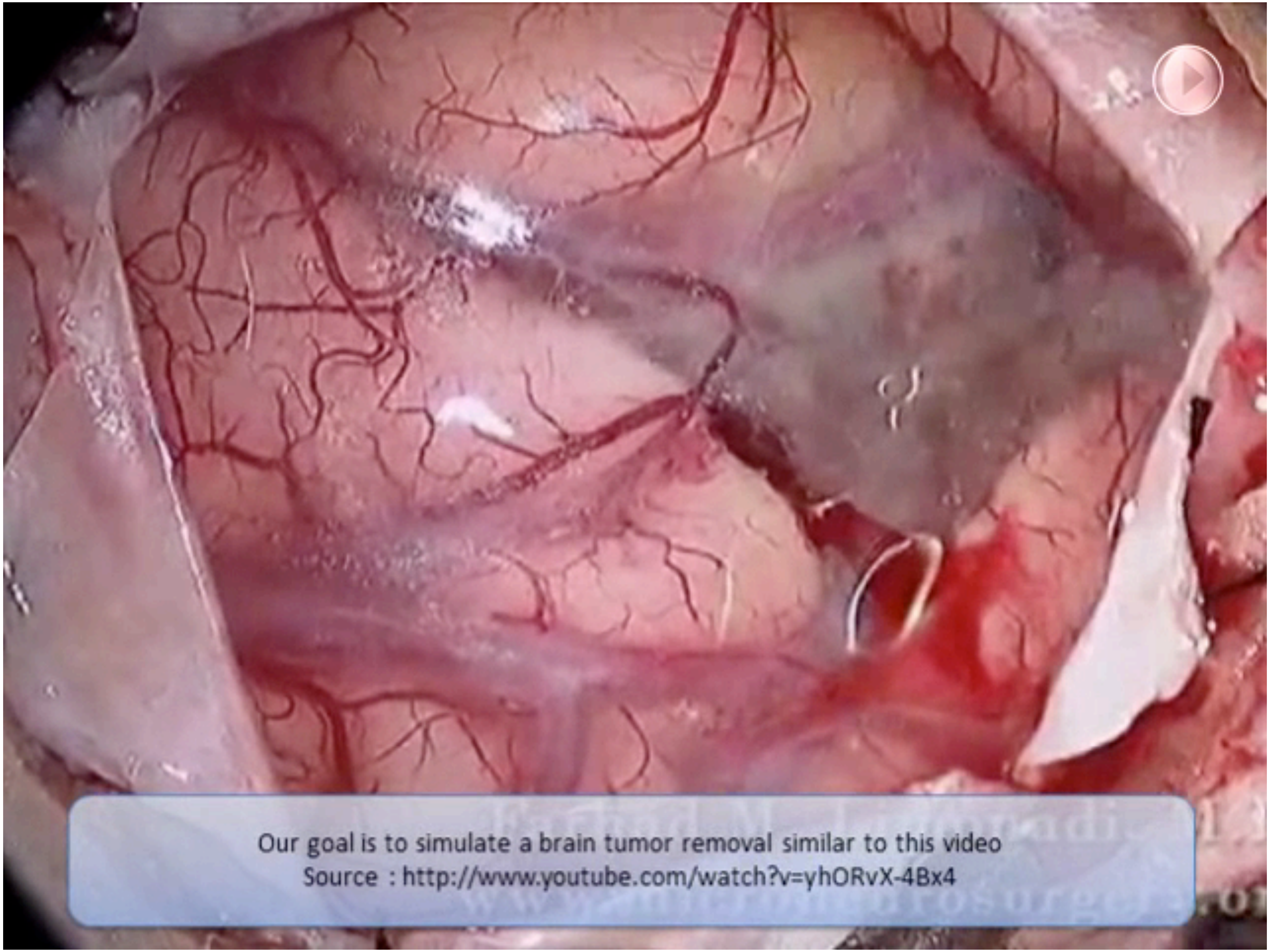
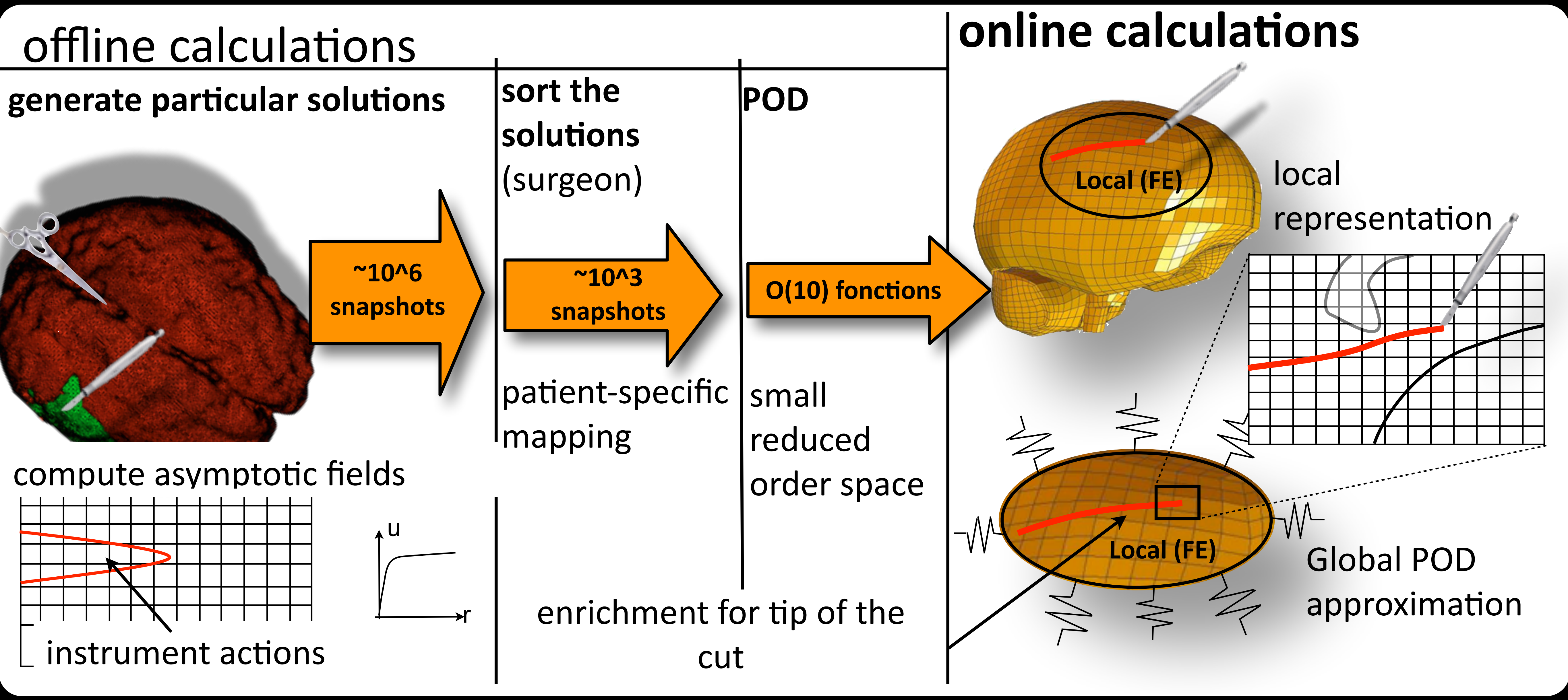


[Courtecuisse et al., MICCAI, 2013 and Medical Image Analysis, 2014]

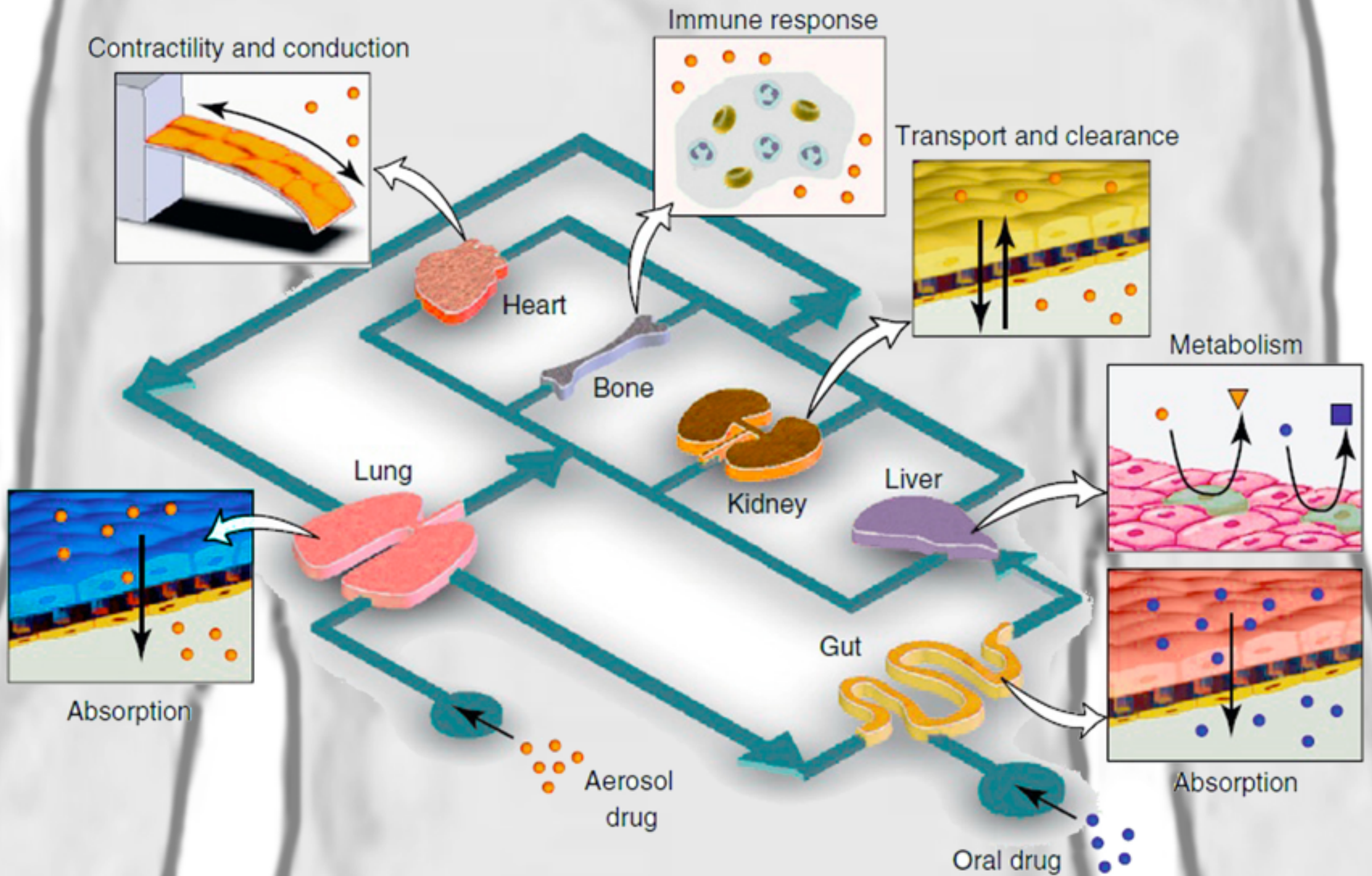
Tumour resection



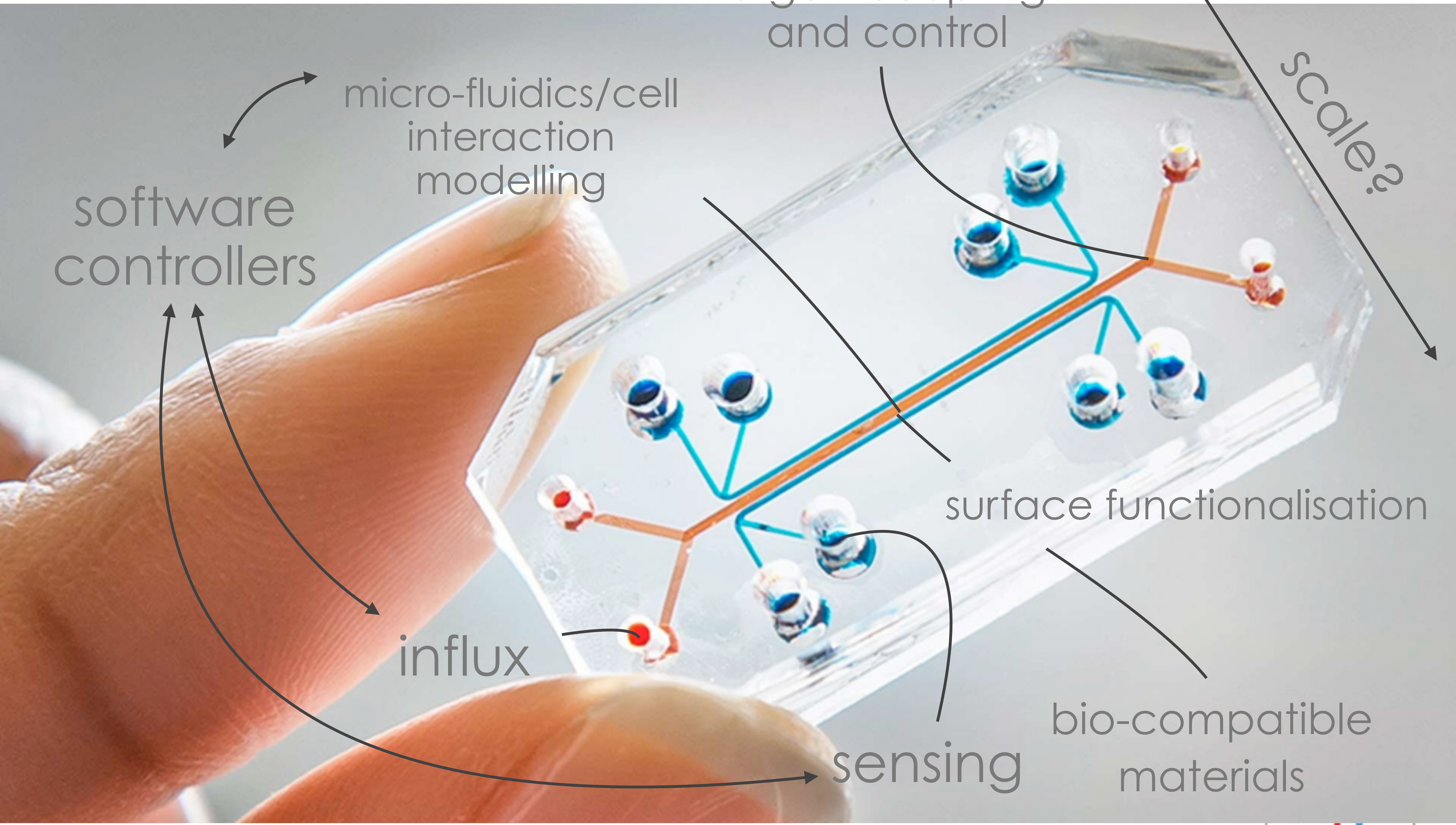

offline calculations
online calculations
generate particular solutions
sort the solutions (surgeon)
POD
~10^6 snapshots
~10^3 snapshots
O(10) fonctions
Local (FE)
local representation
patient-specific mapping
small reduced order space
compute asymptotic fields
u
r
instrument actions
enrichment for tip of the cut
Local (FE)
Global POD approximation

A few other directions for mechanics in medicine

Grand Challenge: Organs-on-a-chip
A Digital-Human-Twin

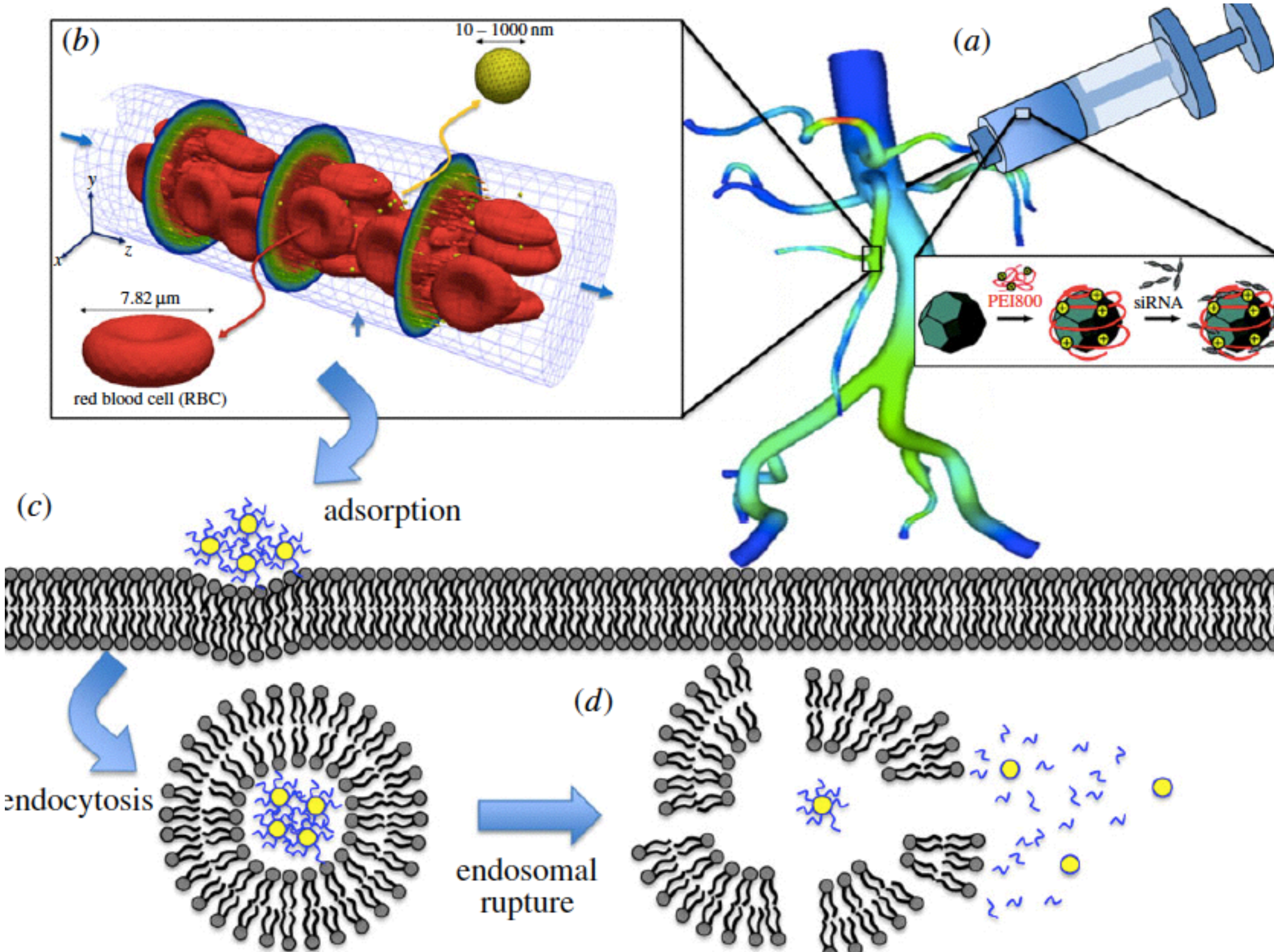


Multi-disciplinary modelling



adapted from Wyss institute, Harvard

Other directions for mechanics in medicine



J. R. Soc. Interface 2014 **11**, 20140301, published 28 May 2014

Other directions for mechanics in medicine

Optimal anatomy
mathematical, multi-scale homogenization theory to predict the characteristics of body parts, as they are most likely to emerge in the course of evolutionary selection.

J. R. Soc. Interface 2014 **11**, 20140301, published 28 May 2014

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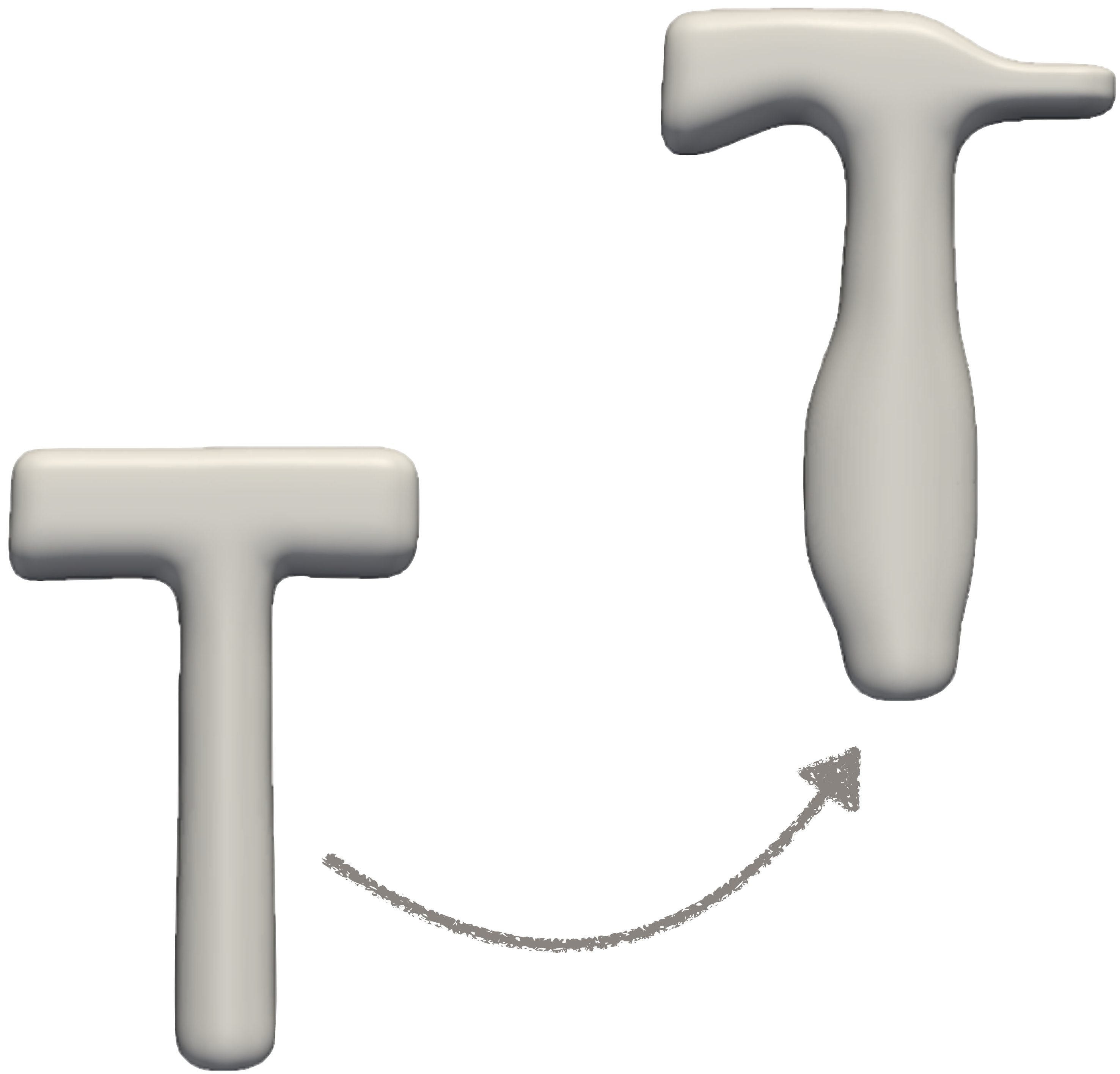


J. R. Soc. Interface 2014 **11**, 20140301, published 28 May 2014

not exactly brain surgery…

- **Medicine will rely increasingly on modeling and simulation**
  - understanding of physiological mechanisms and evolution
  - patient-specific drug design
  - patient-specific surgical operations

… medical twinning

…and perhaps not rocket science

- **Mechanics will rely increasingly on modeling and simulation to design, control, certify increasingly complex systems**
  - multiscale and multiphysics phenomena - fracture, …
  - self-aware self-healing/monitoring structures
  - simulations will have to be able to deal with the actual environment and operating conditions
  - real-time simulations will help gain insight into non-intuitive phenomena (composites, nano-scale…)

… but will require

- **Predictive models**
  - multiscale and multiphysics
  - adaptive - focusing effort only where required
  - model reduction - algebraic and physics-based
  - able to learn from real-time data

… mechanical twinning

Gracias por su atención

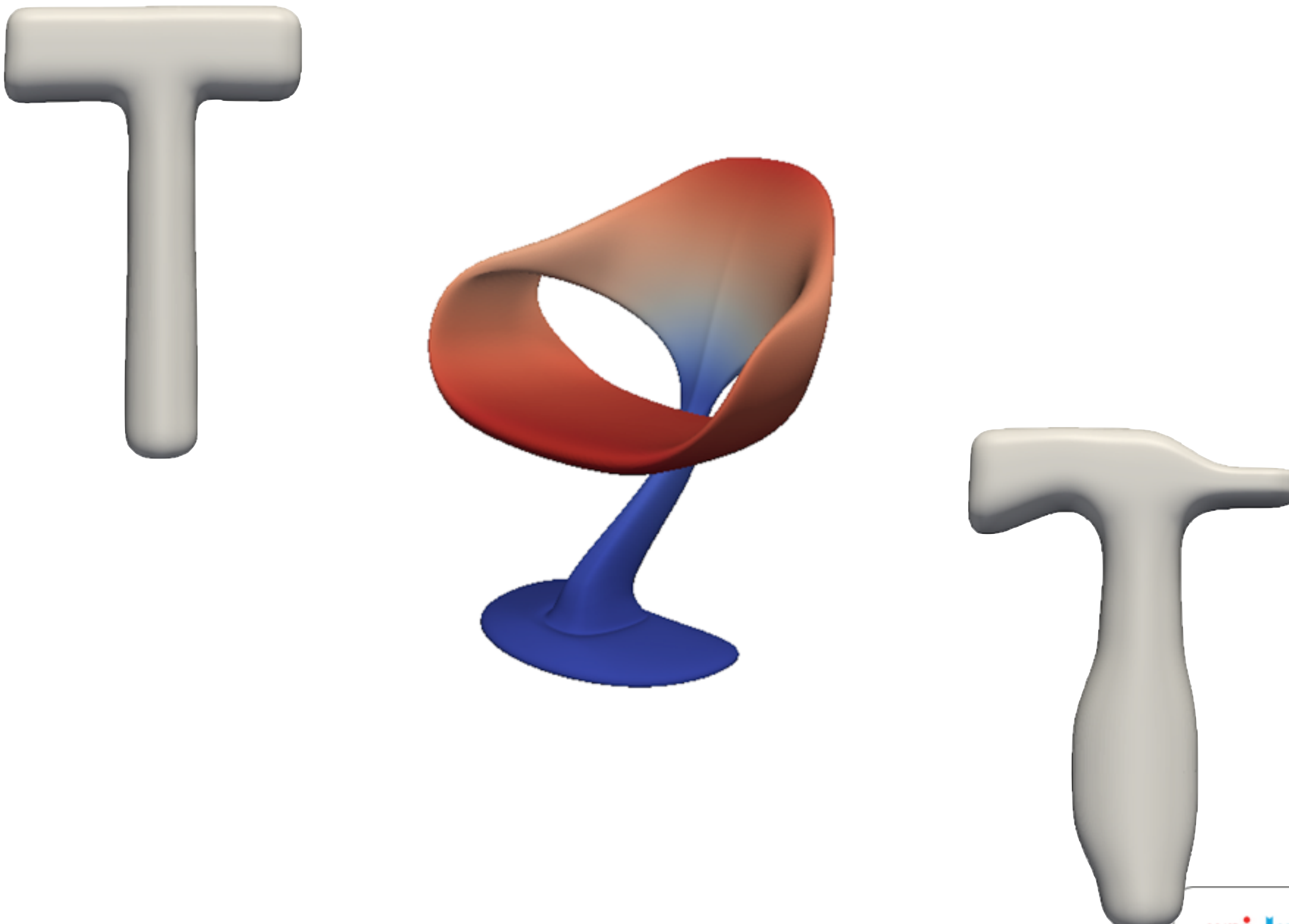
Merci de votre attention

Thank you for your attention

Danke für Ihre Aufmerksamkeit

Gracie per la vostra attenzione

stephane.bordas@alum.northwestern.edu +352 621 131 048



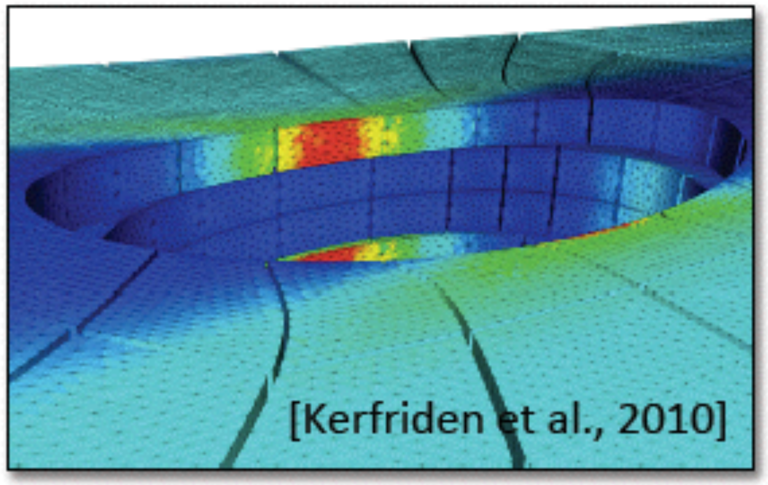
Summary of our lab's work (1)

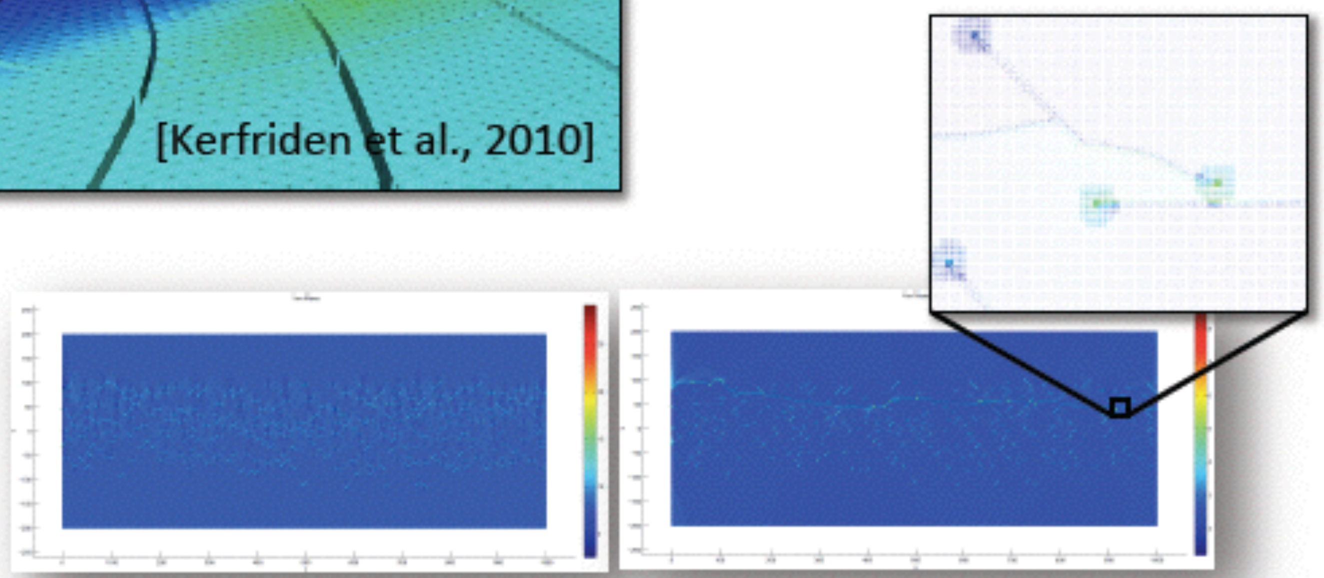
- Efficient numerical prediction of material and structural failure


L. Beex


S.P.-A. Bordas


P. Kerfriden

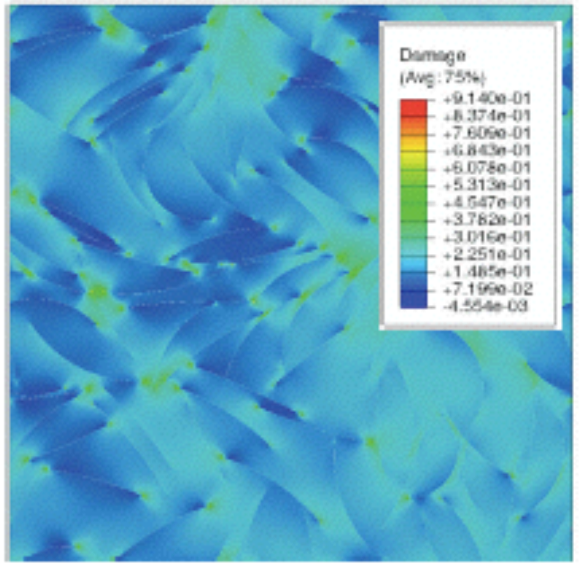

[Kerfriden et al., 2010]


Initial crack distribution

Final fracture

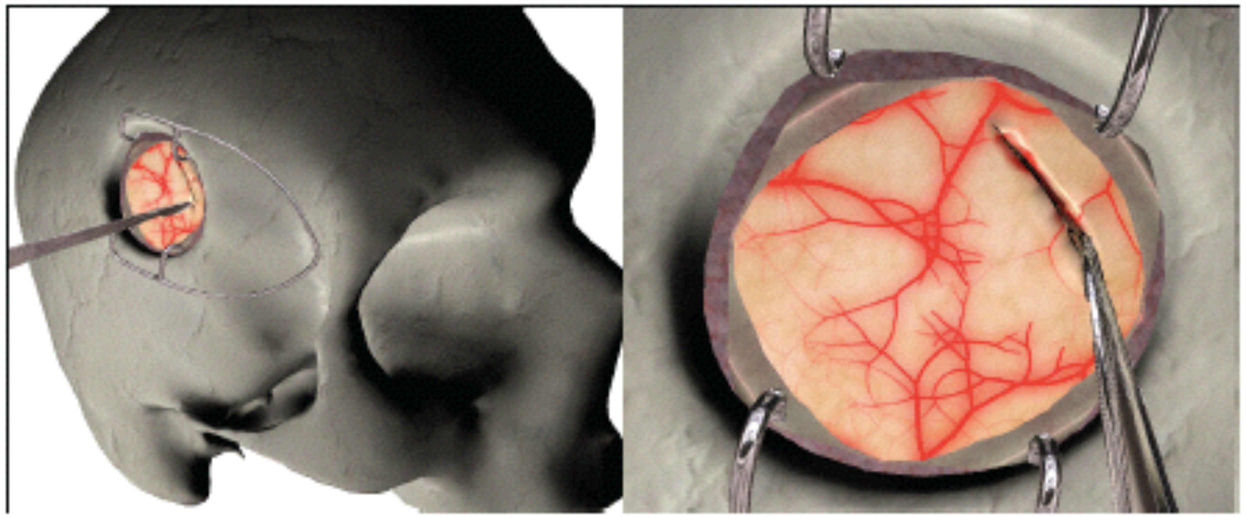
[Sutula et al., 2013]

- Characterisation and optimisation of composites


[Silani et al., 2013]

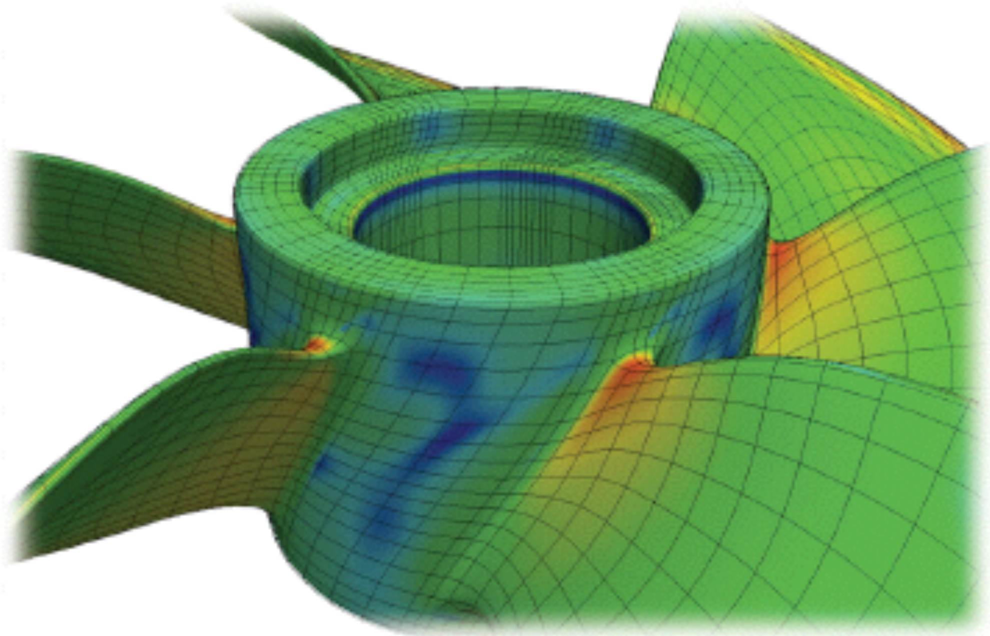
Summary of our lab's work (2)

- Interactive simulations of biological structures

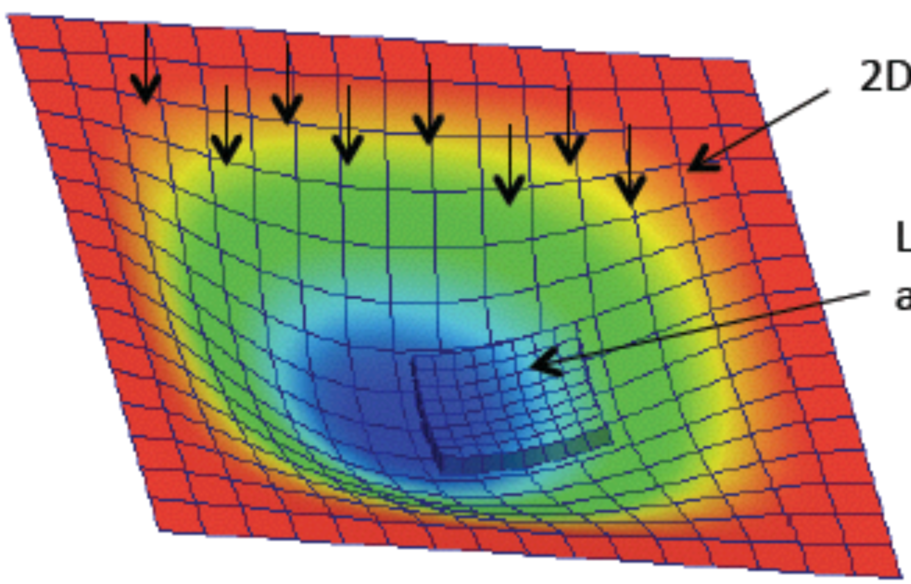


[Courtecuisse et al., 2013]

- Simplified Link between CAD/CT scans and analysis



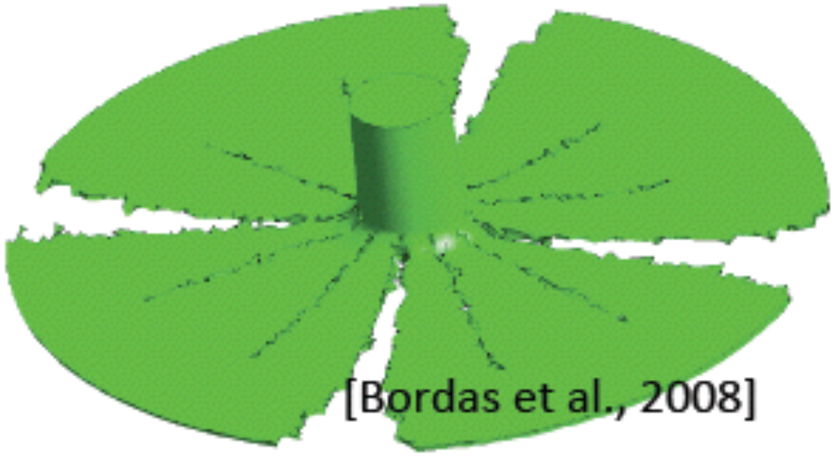
[Scott et al., 2013]



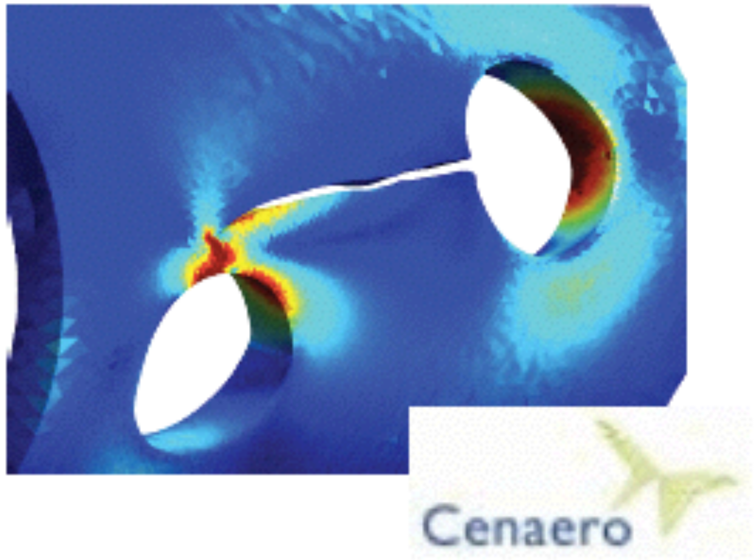
[Nguyen et al., 2013]

Summary of our lab's work (3)

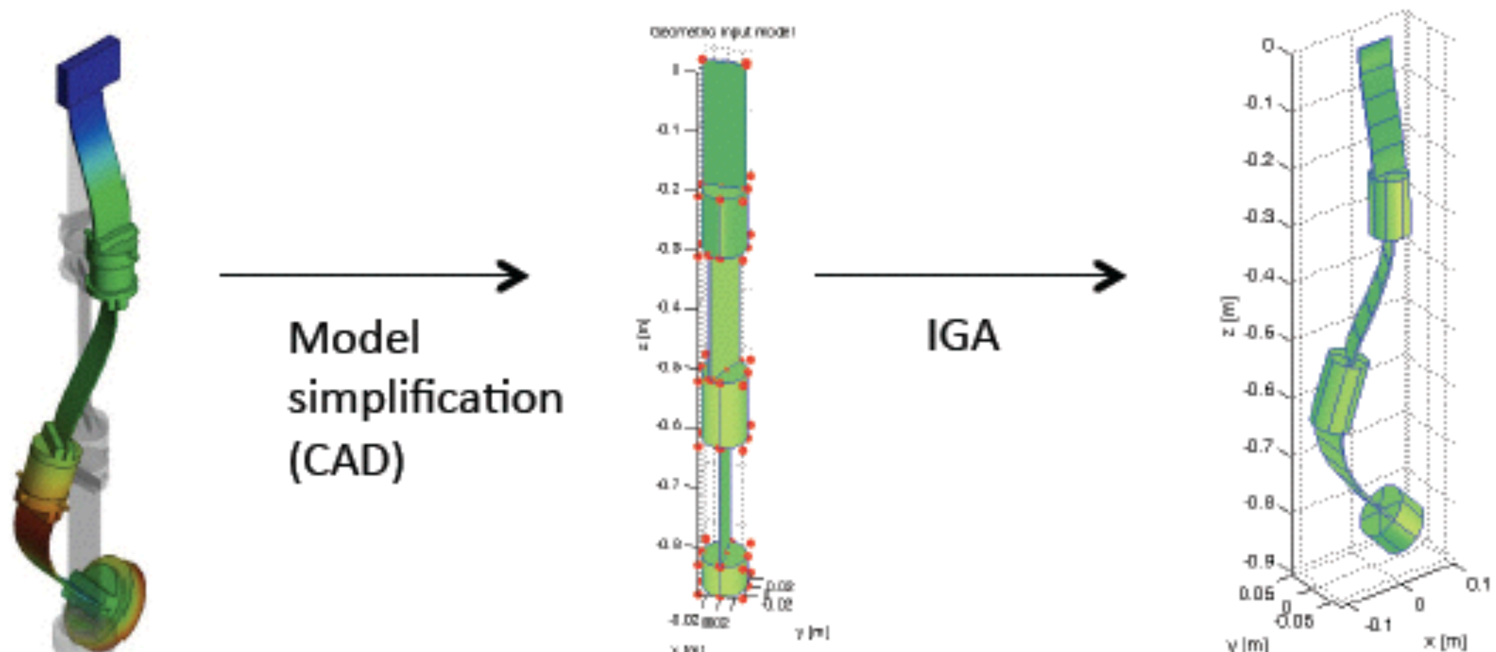
- Advanced discretization techniques for complex PDEs
  - XFEM/meshfree



Taylor bar problem
(dynamic fragmentation)



  - Isogemetric analysis

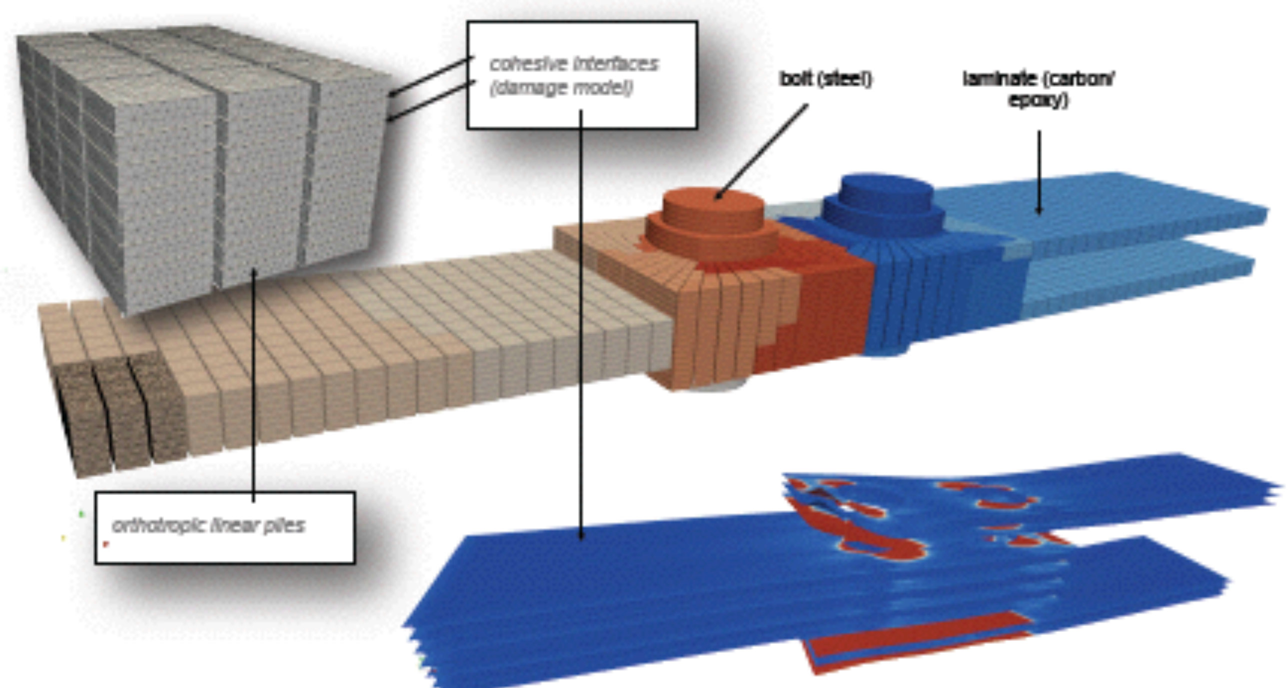


[Tornincasa et al., 2013]

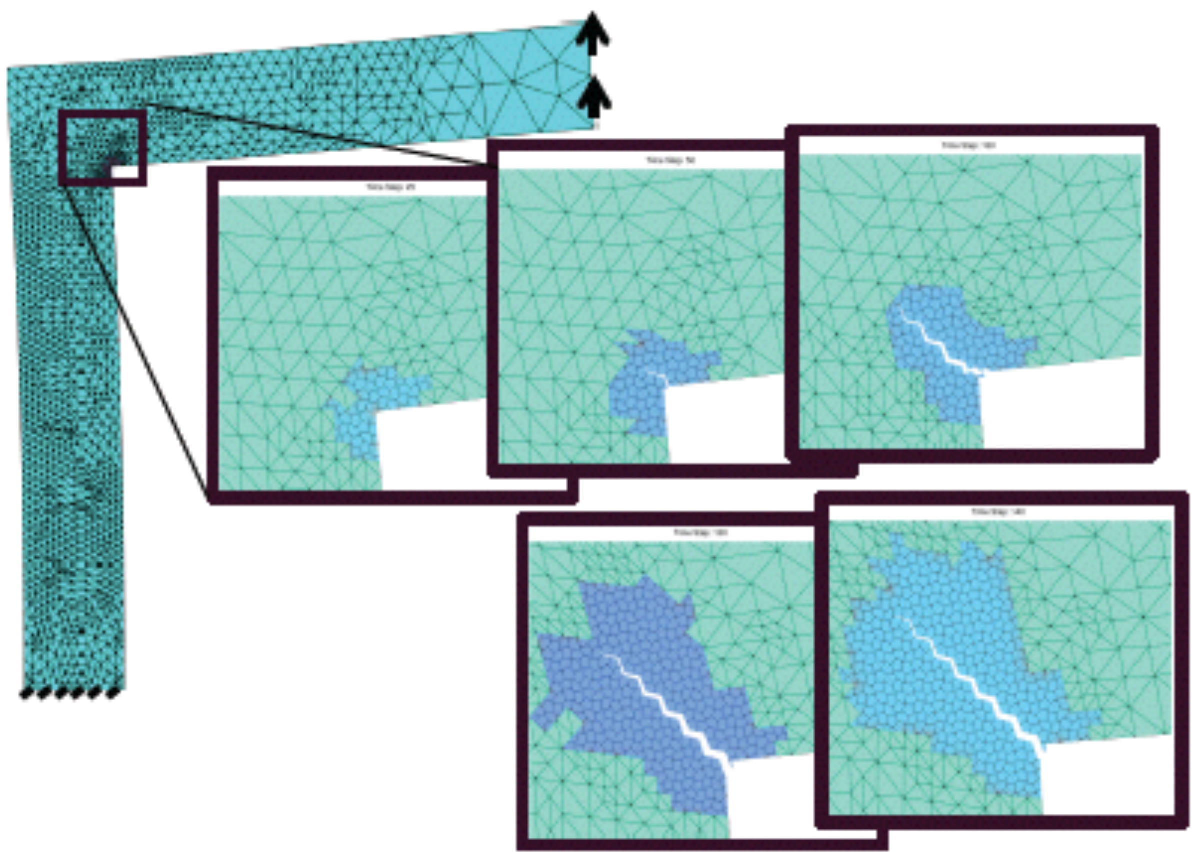
Summary of our lab's work (4)

- Multilevel methods to reduce CPU time by orders of magnitude and devise robust, efficient code/model coupling

  - HPC Adaptive multiscale models/solvers with controlled accuracy



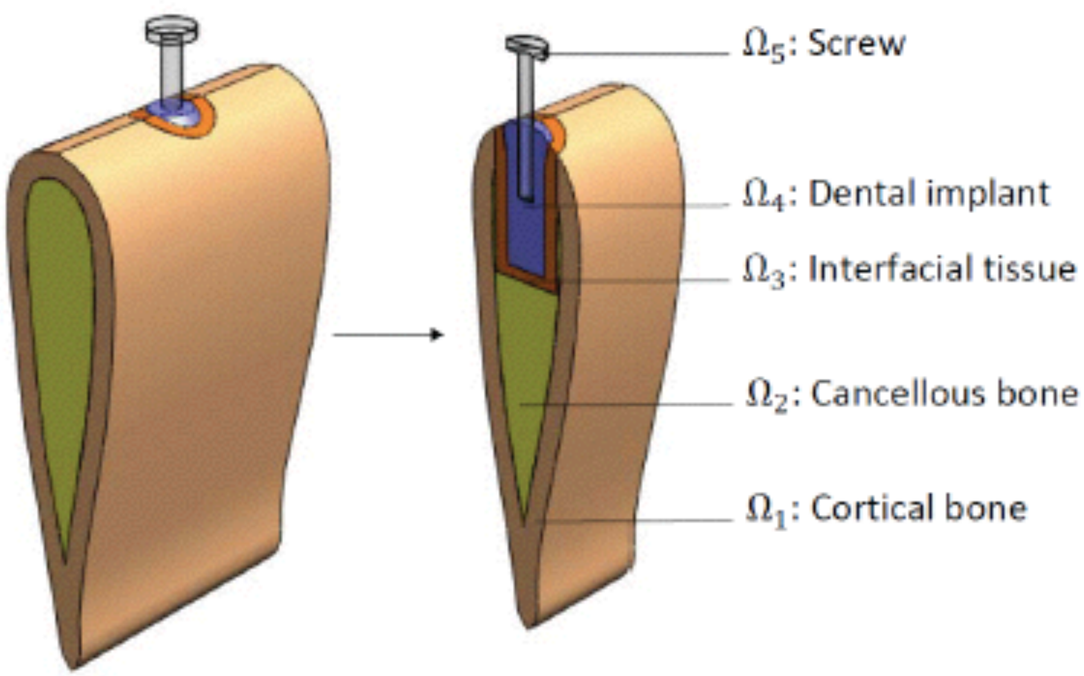
[Kerfriden et al., 2010]



[Akbari et al., 2013]

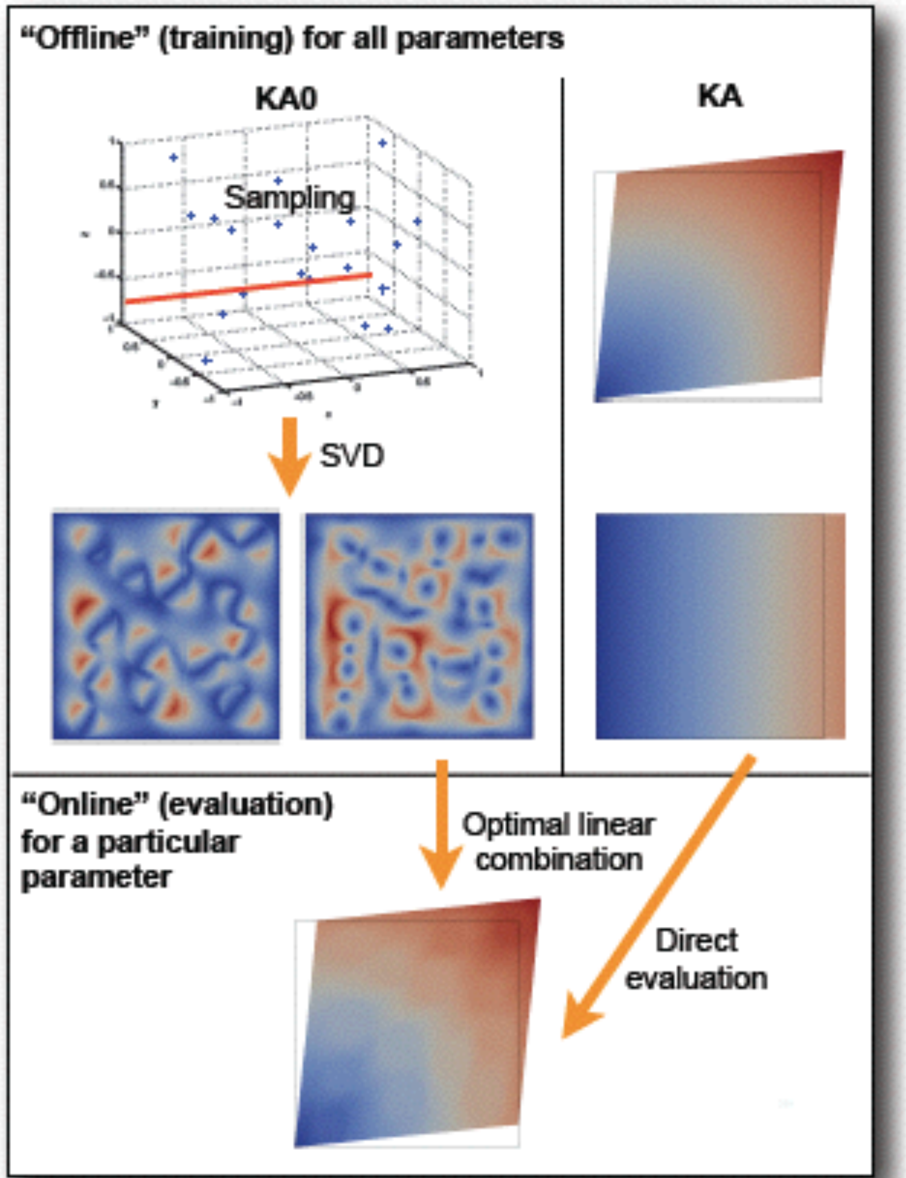
Summary of our lab's work (5)

- Multilevel methods to reduce CPU time by orders of magnitude and devise robust, efficient code/model coupling
  - Virtual chart with controlled accuracy via ROM for multiscale modelling and real-time optimisation

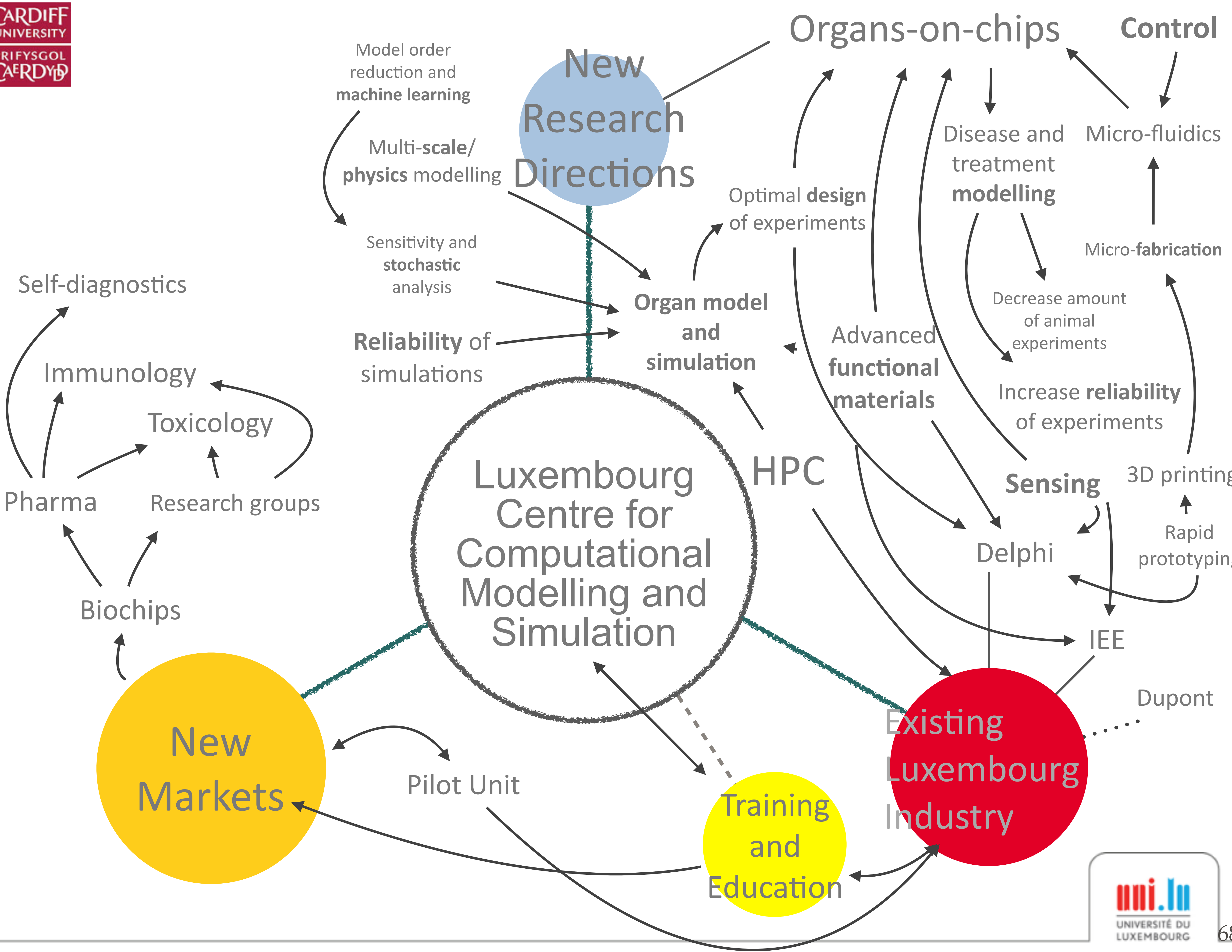


[Hoang et al., 2013]

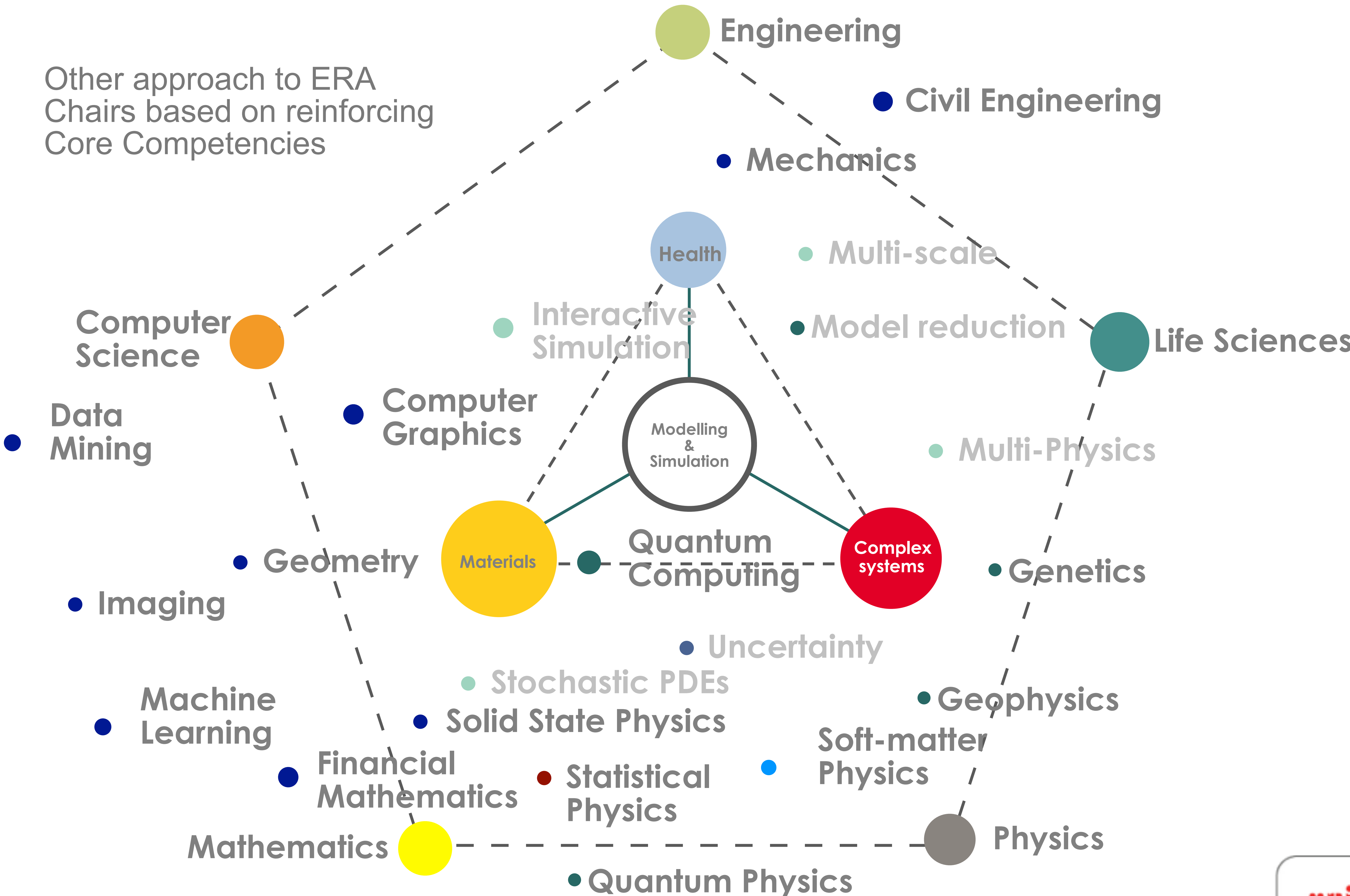
"offline" / "online" strategy



[Kerfriden et al., 2013]


Organs-on-chips
Control
Model order reduction and machine learning
New Research Directions
Multi-scale/ physics modelling
Sensitivity and stochastic analysis
Reliability of simulations
Organ model and simulation
Optimal design of experiments
Disease and treatment modelling
Micro-fluidics
Micro-fabrication
Decrease amount of animal experiments
Advanced functional materials
Increase reliability of experiments
Self-diagnostics
Immunology
Toxicology
Pharma
Research groups
Biochips
Luxembourg Centre for Computational Modelling and Simulation
HPC
Sensing
3D printing
Rapid prototyping
Delphi
IEE
Dupont
Existing Luxembourg Industry
New Markets
Pilot Unit
Training and Education

Other approach to ERA Chairs based on reinforcing Core Competencies



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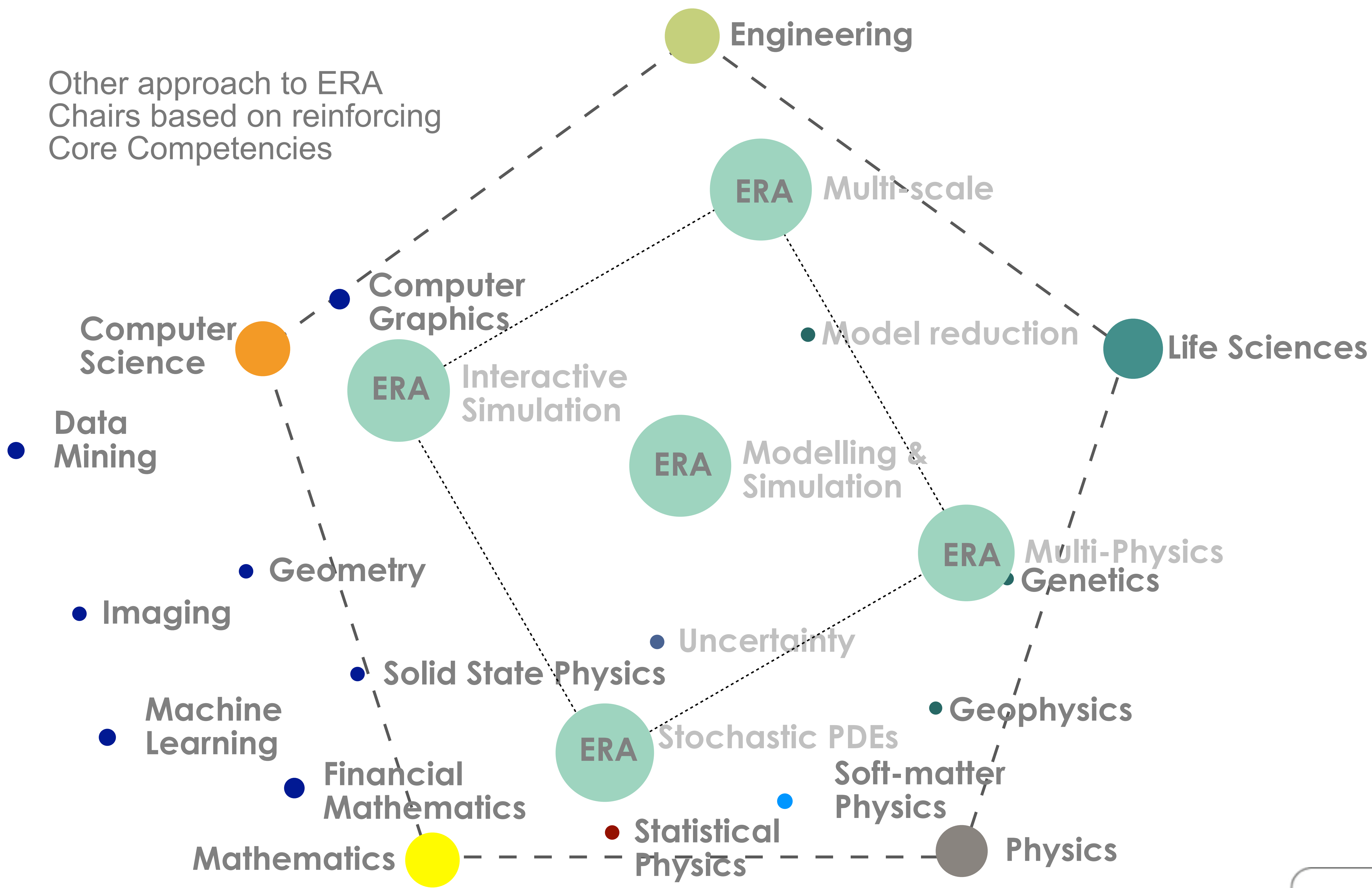

Scientific challenges