Numerical Methods in Biomechanics

ME-484

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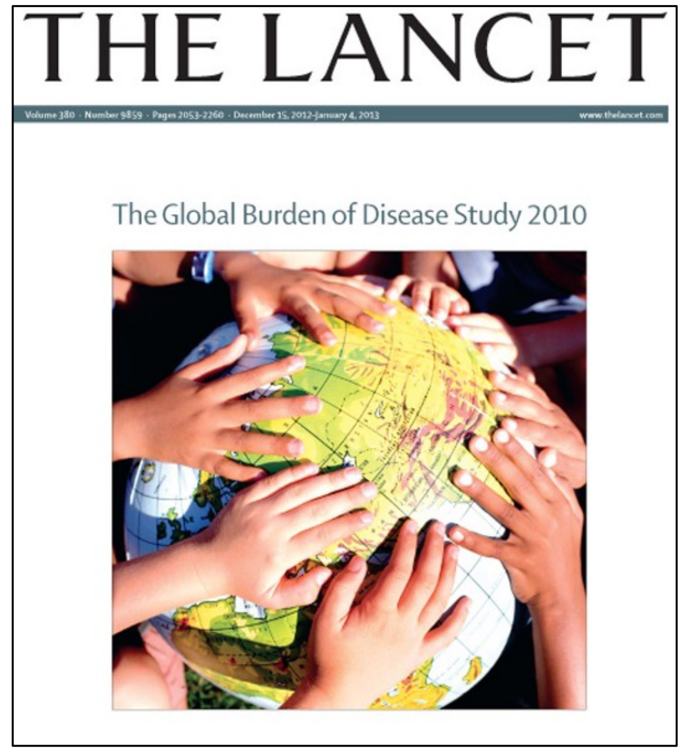
What for?

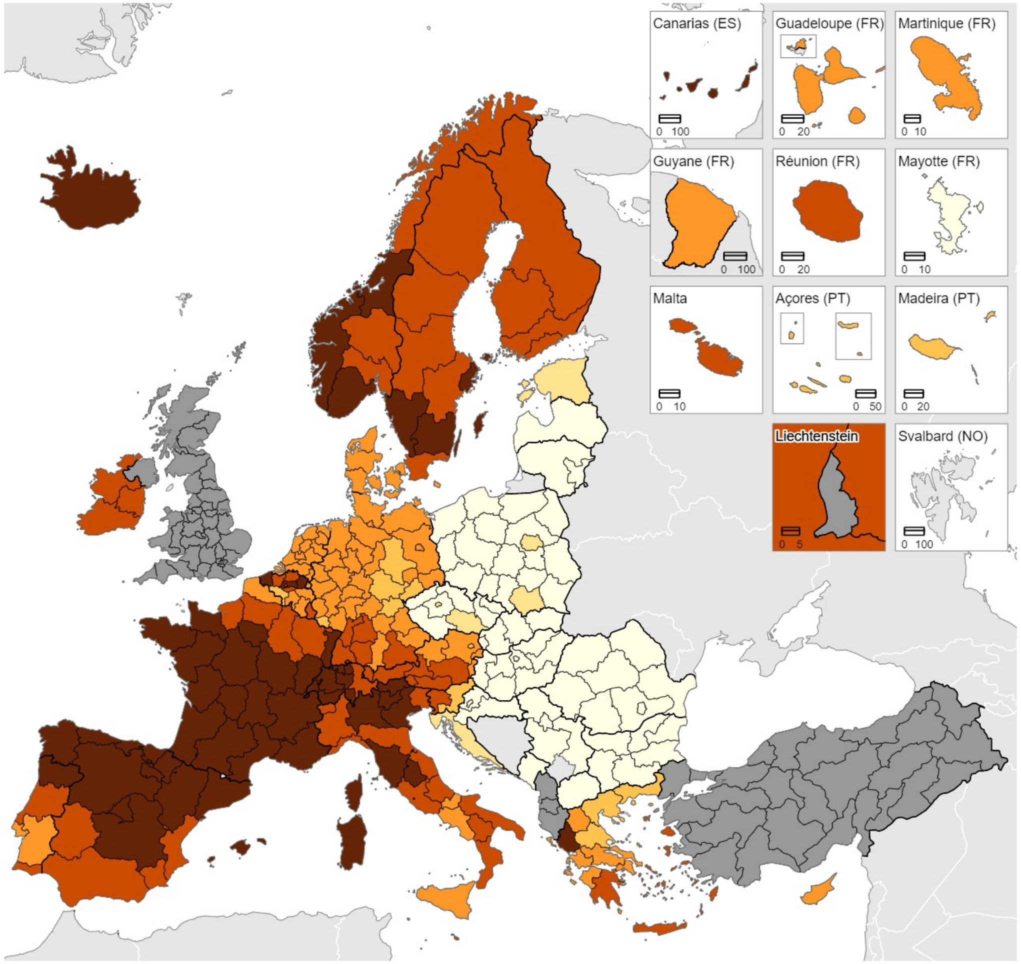
"Since 1970, men and women worldwide have gained slightly more than **ten years of life expectancy** overall, but they spend more years living **with injury and illness**."



DOI:10.1016/S0140-6736(12)61729-2

Life expectancy at 65 years, 2021

(by NUTS 2 region; in years)



Administrative boundaries: © EuroGeographics © UN–FAO © Turkstat
Cartography: Eurostat – IMAGE, 03/2023

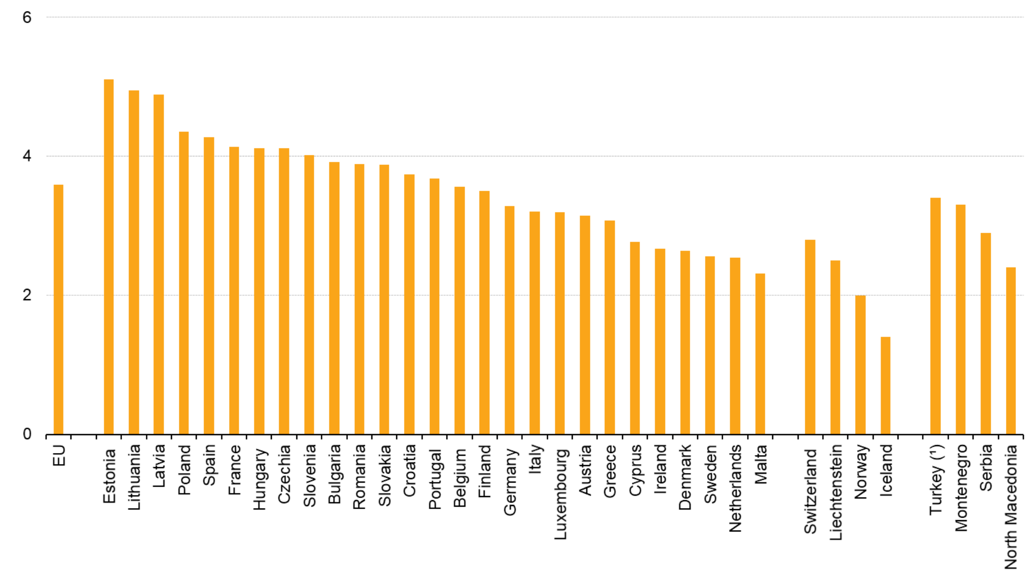
EU = 19.3 years

- ≥ 21.0
- 20.0 – < 21.0
- 19.0 – < 20.0
- 18.0 – < 19.0
- 17.0 – < 18.0
- < 17.0
- Data not available

Estonia, Cyprus, Latvia, Luxembourg and Malta are single regions at this level of detail. Data not available for Bosnia and Herzegovina, Albania, T
iye and Ukraine. Data available for other candidate countries: Montenegro, North Macedonia and Serbia
Source: Eurostat (dataset code demo_r_mlifexp)

Life expectancy at age 65, gender gap, 2021

(years, female life expectancy - male life expectancy)



(¹) 2019 instead of 2021

Source: Eurostat (online data code: demo_mlexpec)

Life expectancy at age 65, 1980-2021

(years)

	Total							Males							Females						
	1980	1990	2000	2010	2019	2020	2021	1980	1990	2000	2010	2019	2020	2021	1980	1990	2000	2010	2019	2020	2021
EU (¹)	:	:	:	19,4	*20,2*	19,3	19,2	:	:	:	17,4	18,3	17,4	17,3	:	:	:	21,0	21,8	21,0	20,9
Belgium	15,0	16,8	17,8	19,6	20,6	19,3	20,4	12,9	14,3	15,6	17,6	18,9	17,6	18,5	16,8	18,8	19,7	21,3	22,1	20,8	22,1
Bulgaria	13,6	14,0	14,1	15,6	16,3	15,1	13,6	12,6	12,7	12,7	13,8	14,2	12,9	11,6	14,6	15,2	15,3	17,1	18,1	17,1	15,5
Czechia (²)	13,0	13,7	15,7	17,4	18,4	17,3	16,7	11,2	11,7	13,7	15,5	16,4	15,2	14,5	14,4	15,3	17,2	19,0	20,1	19,1	18,6
Denmark	15,7	16,1	16,9	18,4	19,8	19,8	19,6	13,6	14,0	15,2	17,0	18,4	18,4	18,3	17,7	17,9	18,3	19,7	21,0	21,2	20,9
Germany	14,9	16,3	18,0	19,5	19,9	19,7	19,5	12,8	14,0	15,8	17,8	18,3	18,0	17,8	16,3	17,7	19,6	20,9	21,4	21,2	21,1
Estonia	14,2	14,4	15,4	17,4	19,0	19,0	17,5	11,8	12,0	12,7	14,3	15,8	15,9	14,5	15,6	15,8	17,1	19,5	21,1	21,1	19,6
Ireland (³)	:	15,2	16,4	19,3	20,8	20,7	20,5	:	13,3	14,6	17,7	19,4	19,4	19,2	:	17,0	18,0	20,8	22,1	21,9	21,8
Greece	16,2	17,0	18,0	19,7	20,4	20,0	19,2	15,2	15,7	16,7	18,2	19,0	18,5	17,6	17,0	18,1	19,2	21,0	21,7	21,4	20,7
Spain	16,4	17,5	18,8	20,9	22,0	20,5	21,4	14,7	15,5	16,6	18,6	19,8	18,4	19,2	17,9	19,2	20,7	22,9	23,9	22,4	23,5
France (⁴)	:	:	19,3	21,3	*22,0*	21,2	21,4	:	:	16,8	18,9	19,8	19,0	19,2	:	:	21,4	23,4	23,9	23,1	23,3
Croatia (²)	:	:	:	16,7	17,9	17,1	16,3	:	:	:	14,7	15,9	15,1	14,4	:	:	:	18,2	19,5	18,8	18,1
Italy (⁵)	:	17,2	18,9	20,4	21,4	20,1	20,6	:	15,2	16,7	18,3	19,7	18,3	18,9	:	18,9	20,7	22,1	22,9	21,7	22,1
Cyprus	:	:	17,2	19,7	20,3	20,3	19,5	:	:	15,9	18,3	18,9	19,1	18,1	:	:	18,3	21,0	21,5	21,5	20,9
Latvia	:	:	:	16,1	17,4	17,0	15,6	:	:	:	13,1	14,4	14,0	12,7	:	:	:	18,1	19,4	19,1	17,6
Lithuania	15,3	15,6	16,1	16,7	17,9	16,8	16,1	13,4	13,3	13,6	13,8	14,8	13,6	13,2	16,6	17,0	17,8	18,8	20,0	19,1	18,2
Luxembourg	14,7	16,7	18,1	19,6	20,9	20,2	20,7	12,6	14,3	15,5	17,3	19,2	18,5	19,0	16,5	18,5	20,1	21,6	22,4	21,8	22,2
Hungary	13,3	13,9	15,1	16,5	16,9	16,2	15,5	11,6	12,1	13,0	14,1	14,8	14,0	13,2	14,7	15,4	16,7	18,2	18,6	17,9	17,3
Malta (⁶)	11,8	:	17,0	19,9	21,1	20,5	20,7	10,7	:	15,2	18,5	19,4	18,9	19,5	12,8	:	18,6	21,1	22,5	22,0	21,8
Netherlands	:	17,0	17,5	19,5	20,3	19,5	19,6	:	14,4	15,4	17,7	19,0	18,2	18,2	:	19,1	19,3	21,0	21,4	20,7	20,8
Austria	14,9	16,6	18,1	19,8	20,3	19,6	19,6	12,9	14,4	16,0	17,9	18,7	17,9	18,0	16,3	18,1	19,6	21,4	21,7	21,0	21,1
Poland (⁷)	:	14,6	15,8	17,6	18,5	17,1	16,4	:	12,4	13,5	15,1	16,1	14,6	14,0	:	16,2	17,5	19,5	20,4	19,2	18,4
Portugal (⁸)	14,7	15,7	17,4	19,3	20,6	19,8	20,3	13,1	14,0	15,4	17,2	18,5	17,8	18,3	16,1	17,1	19,1	21,0	22,3	21,6	22,0
Romania (⁹)	13,4	14,3	14,8	16,1	16,9	15,7	14,6	12,5	13,2	13,4	14,2	14,9	13,4	12,5	14,2	15,2	15,9	17,6	18,6	17,7	16,4
Slovenia	:	15,6	16,9	19,2	20,1	18,9	19,3	:	13,3	14,2	16,8	18,1	16,9	17,2	:	17,1	18,7	21,0	21,8	20,6	21,2
Slovakia	13,7	14,3	15,0	16,3	17,9	17,1	15,4	12,0	12,3	12,9	14,1	15,7	14,8	13,3	15,2	16,0	16,7	18,0	19,7	18,9	17,1
Finland	15,1	16,2	17,8	19,7	20,6	20,6	20,4	12,6	13,8	15,5	17,5	18,8	18,8	18,6	17,0	17,8	19,5	21,5	22,3	22,2	22,1
Sweden	16,3	17,4	18,6	19,8	20,9	20,2	20,9	14,3	15,4	16,7	18,3	19,6	18,9	19,6	18,1	19,2	20,2	21,2	22,1	21,4	22,1
Iceland	17,5	18,1	18,9	19,9	21,0	21,1	21,2	15,7	16,4	17,8	18,3	20,0	20,3	20,5	19,3	19,8	19,8	21,5	22,0	22,0	21,9
Liechtenstein (10)	:	:	17,5	20,7	21,3	19,8	21,9	:	:	15,2	19,6	20,0	18,1	20,7	:	:	19,5	21,8	22,5	21,5	23,2
Norway	16,4	16,8	18,1	19,7	20,8	21,0	20,8	14,3	14,6	16,1	18,0	19,6	19,8	19,8	18,2	18,7	19,9	21,2	21,9	22,1	21,8
Switzerland	16,5	17,7	19,2	20,9	21,7	20,8	21,6	14,3	15,3	17,0	19,0	20,3	19,3	20,1	18,2	19,7	20,9	22,5	23,0	22,2	23,0
Montenegro	:	:	:	16,3	16,6	15,7		:	:	:	15,2	15,1	13,9		:	:	:	17,3	17,8	17,3	
North Macedonia	:	:	14,1	15,0	15,9	14,4	13,7	:	:	13,1	13,9	14,9	13,0	12,5	:	:	15,1	16,0	16,9	15,7	14,9
Albania	:	:	:	:	18,1	16,6		:	:	:	:	17,5	15,6		:	:	:	:	18,7	17,7	
Serbia	:	:	13,6	15,2	16,2	15,0		:	:	12,5	14,0	14,8	13,4		:	:	14,6	16,2	17,3	16,5	
Turkey	:	:	:	17,3	18,4	:		:	:	:	15,6	16,6	:		:	:	:	18,7	20,0	:	

(¹) 2010, 2015, 2017, 2019 and 2021: breaks in series. 2019, 2020 and 2021: provisional.

(²) 2021: break in series.

(³) 2019: estimated

(⁴) 2019, 2020, 2021: provisional

(⁵) 2019: break in series

(⁶) 2021: provisional.

(⁷) 2000 and 2010: break in series. 2020:provisional. 2021: estimated and provisional.

(⁸) 2021: Break in series, provisional.

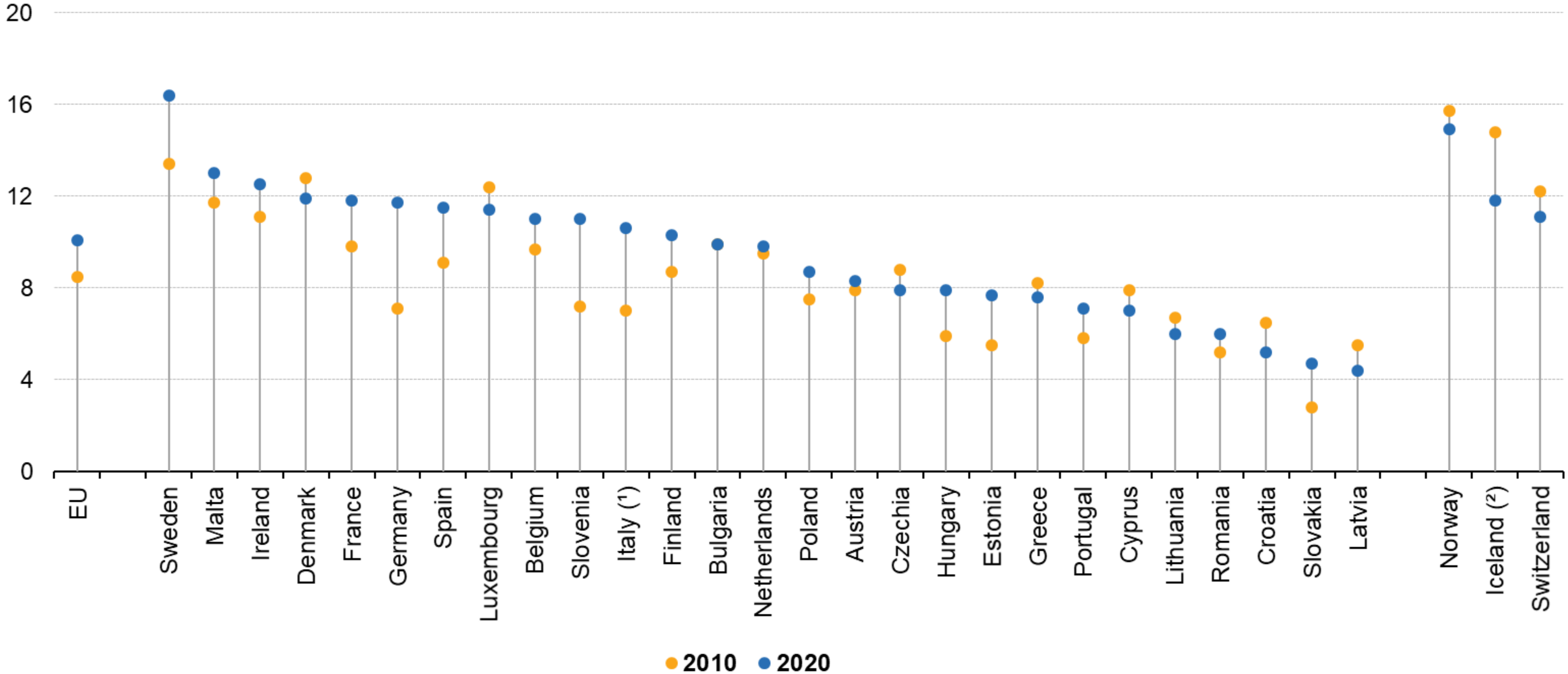
(⁹) 2020 and 2021: estimated

(10) 2021: estimated.

Source: Eurostat (online data code: demo_mlexpec)

eurostat

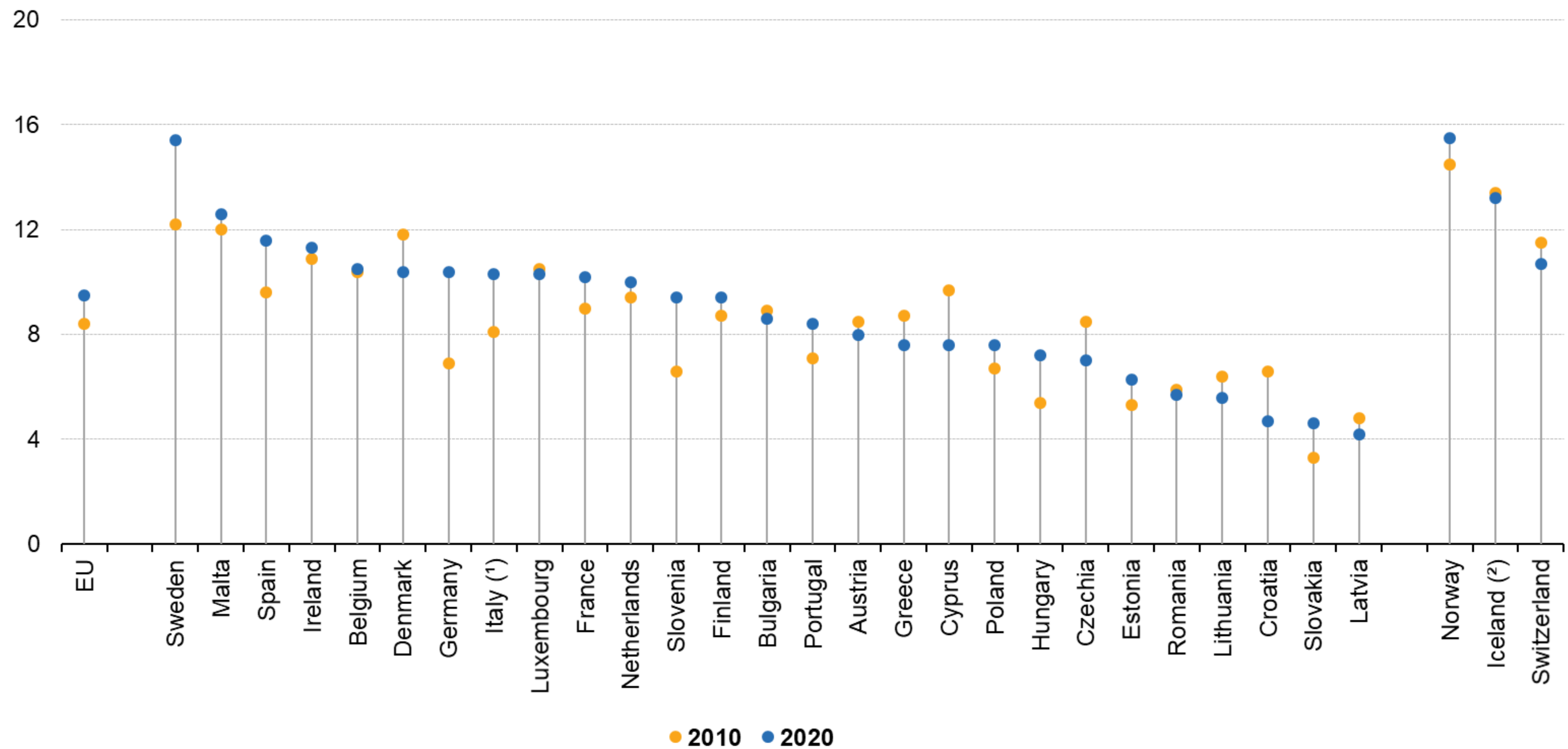
Healthy life years in absolute value at 65 - females
(2010-2020)



(¹) 2011 data instead of 2010.
(²) 2018 data instead of 2020.
Source: Eurostat (online data code: hlth_hlye)

eurostat

Healthy life years in absolute value at 65 - males
(2010-2020)



(¹) 2011 data instead of 2010.
(²) 2018 data instead of 2020.
Source: Eurostat (online data code: hlth_hlye)

eurostat

Original article | Published 17 February 2023 | doi:10.57187/smw.2023.40043
Cite this as: Swiss Med Wkly. 2023;153:40043

Trends in the disability-free life expectancy in Switzerland over a 10-year period: an analysis of survey-based data

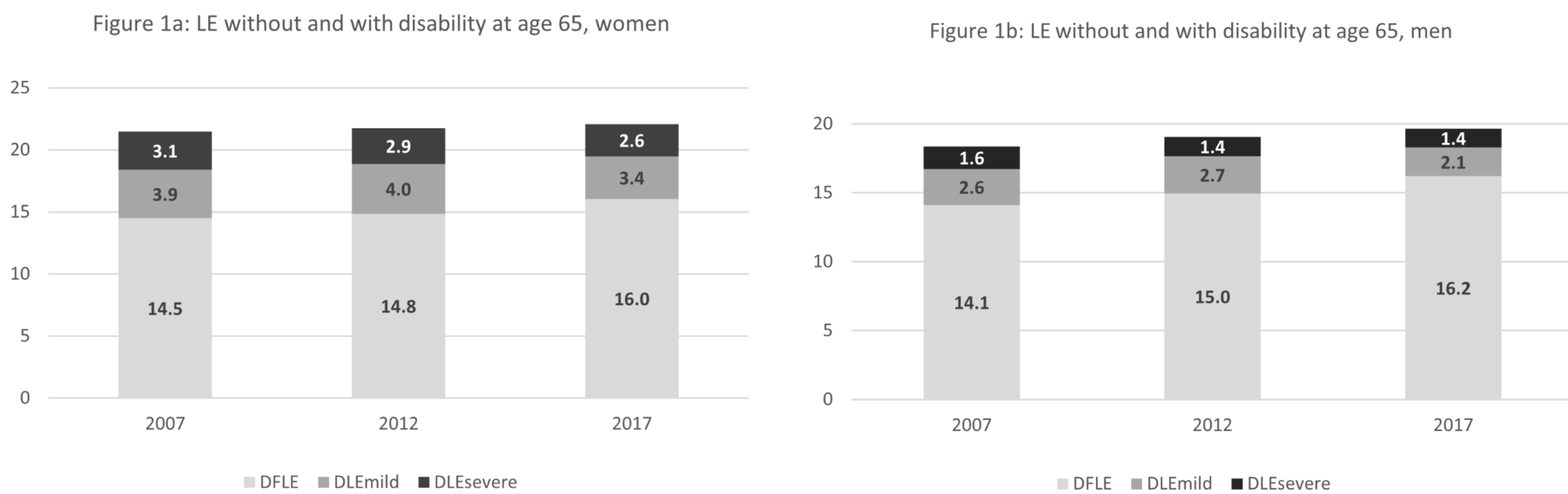
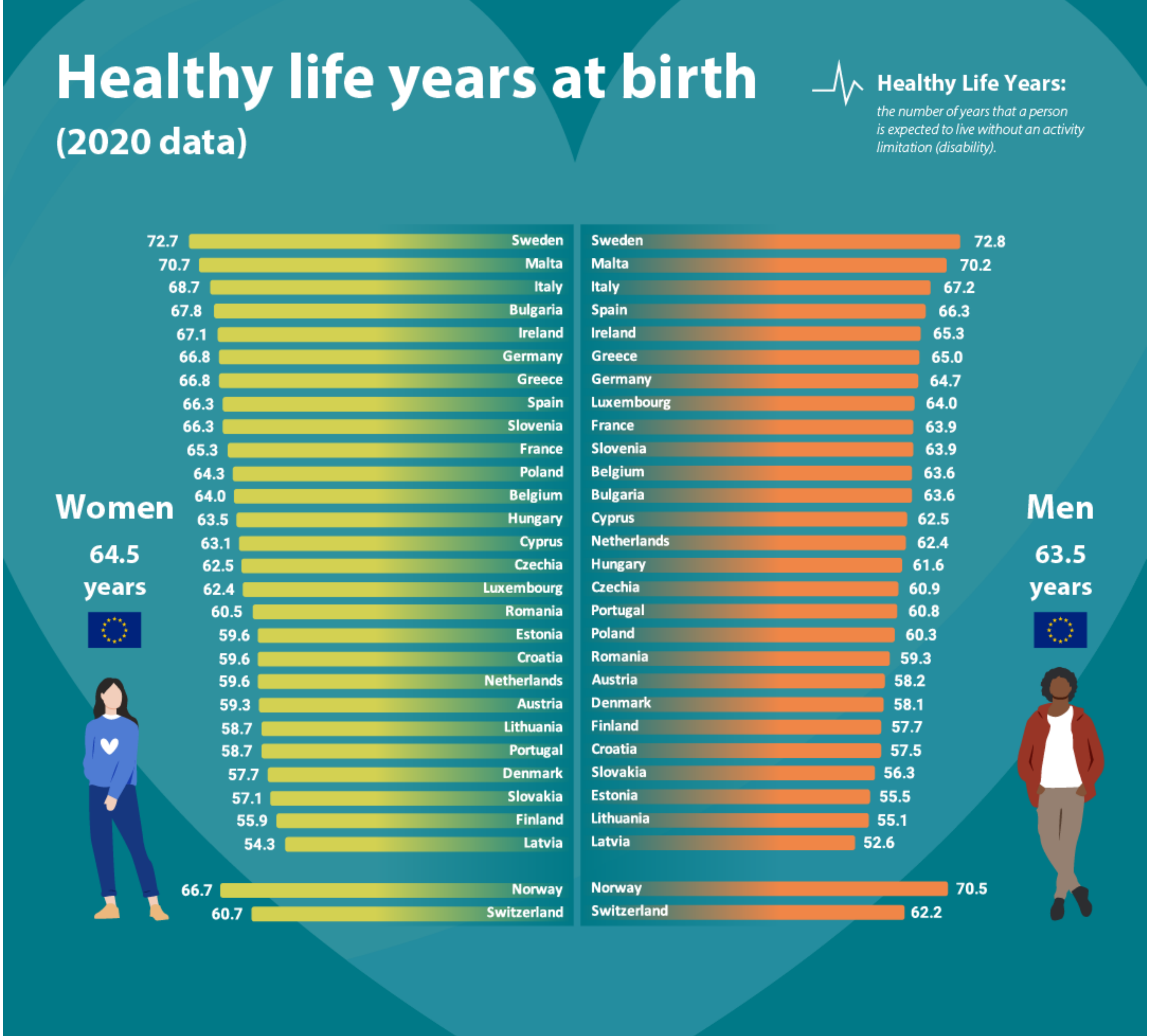
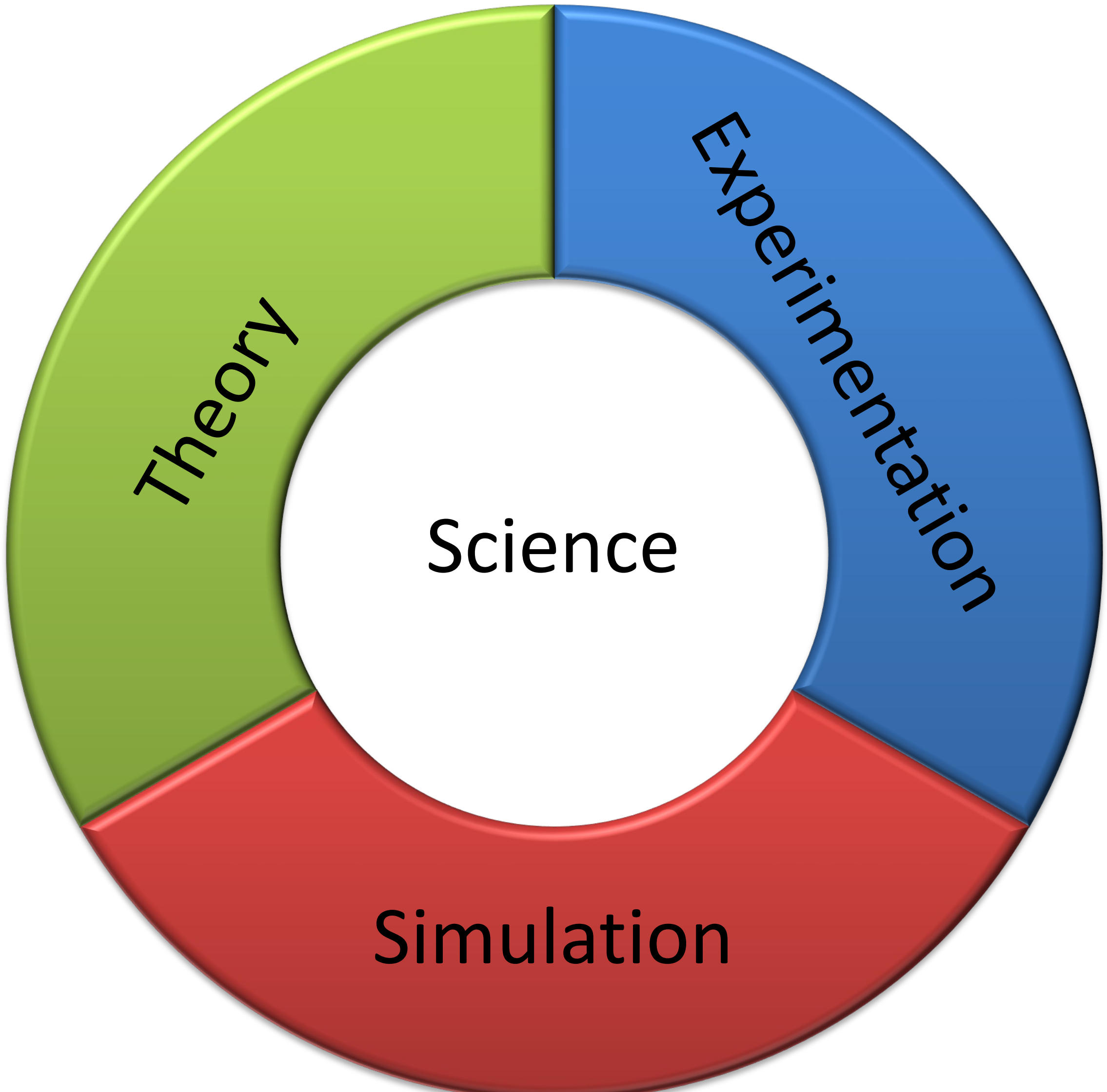


Figure 1: Trend in life expectancy without (DFLE), with mild (DLE_{mild}), and with severe (DLE_{severe}) disability at 65 and 80 years of age, by sex. Mean values for DFLE and LED_{mild} and LED_{severe}.



ec.europa.eu/eurostat

3 Pillars of science



Objectives of numerical modeling

- Analyze (understand) observations
- Test hypotheses
- Design experimental setup
- Design (pre-tests) of medical devices
- Improve treatments, surgical techniques
- Improve preoperative planning

Advantages of Numerical Methods

- Efficiency to solve problem (no analytical solution)
- Large scope of problems (physics, biology, chemistry)
- Cheap (material)
- Easy (conceptually)
- Access to all system quantities (not measurable)
- Not dangerous (chemicals)
- No ethical issue (animal/human experiment)

Drawback of Numerical Methods

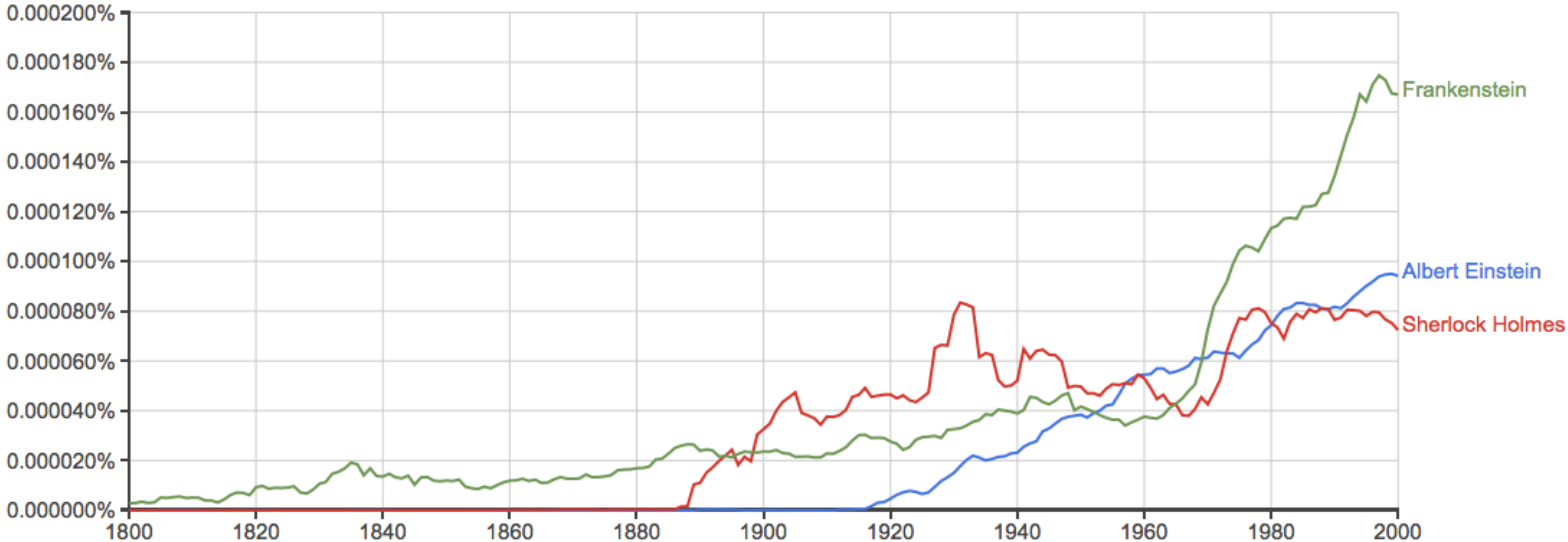
- Complexity (variability) of living tissues
- Correlation (validation) with experiments difficult
- More method-oriented than problem-oriented
- Qualitative rather then quantitative

New trend

From specialty towards integration

- Multi-scale (body, systems, organ, cell, molecule)
- Multi-physics (solid, fluid, reactions)
- Multi-disciplinary (engineer, biology, medicine)

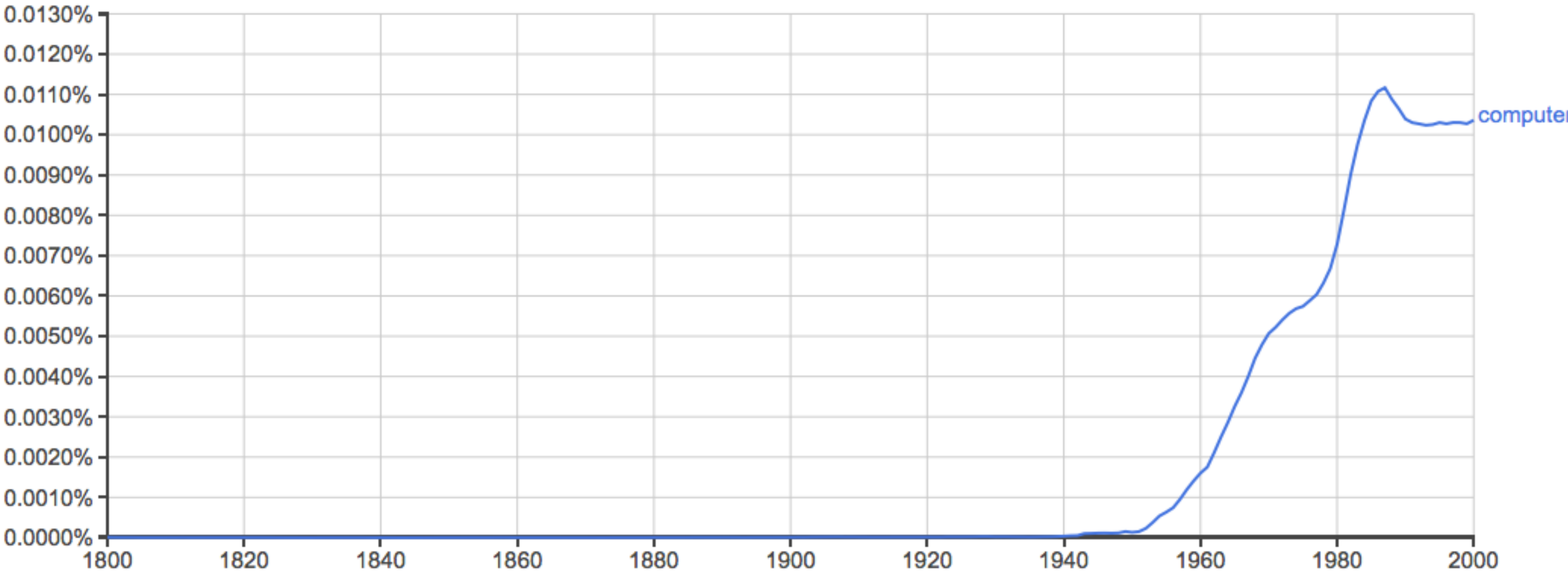
Word frequency



Google Books Ngram Viewer

http://books.google.com/ngrams

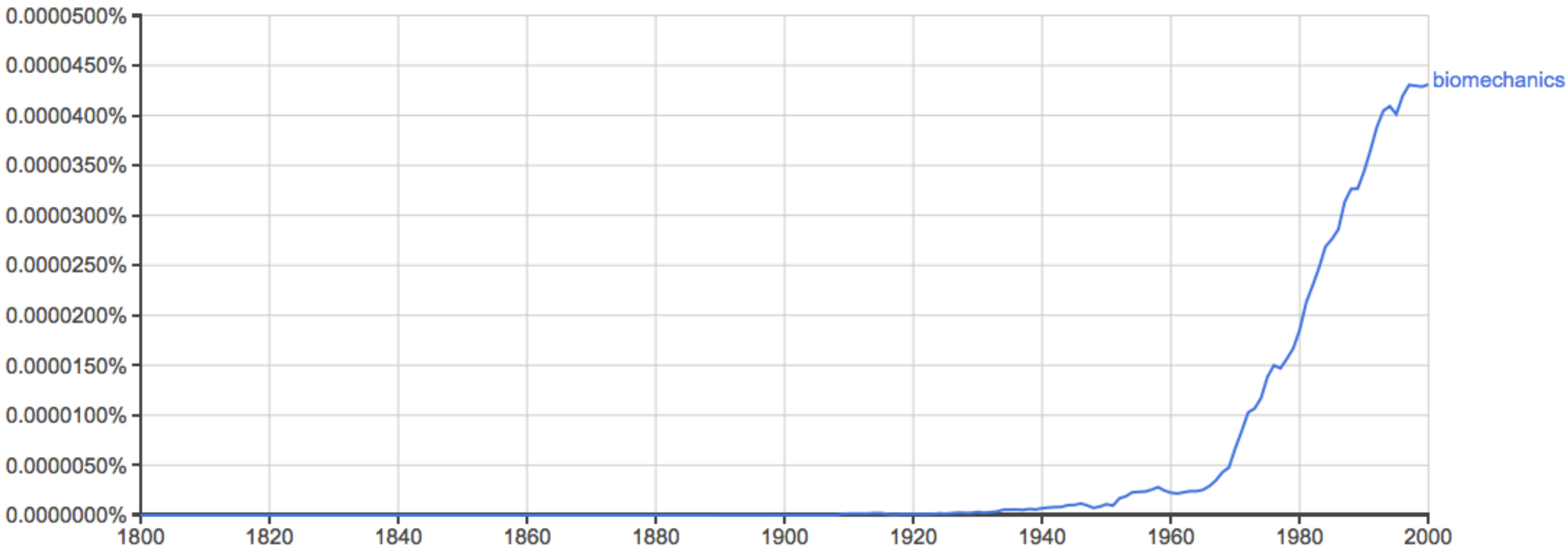
Word frequency



Google Books Ngram Viewer

http://books.google.com/ngrams

Word frequency



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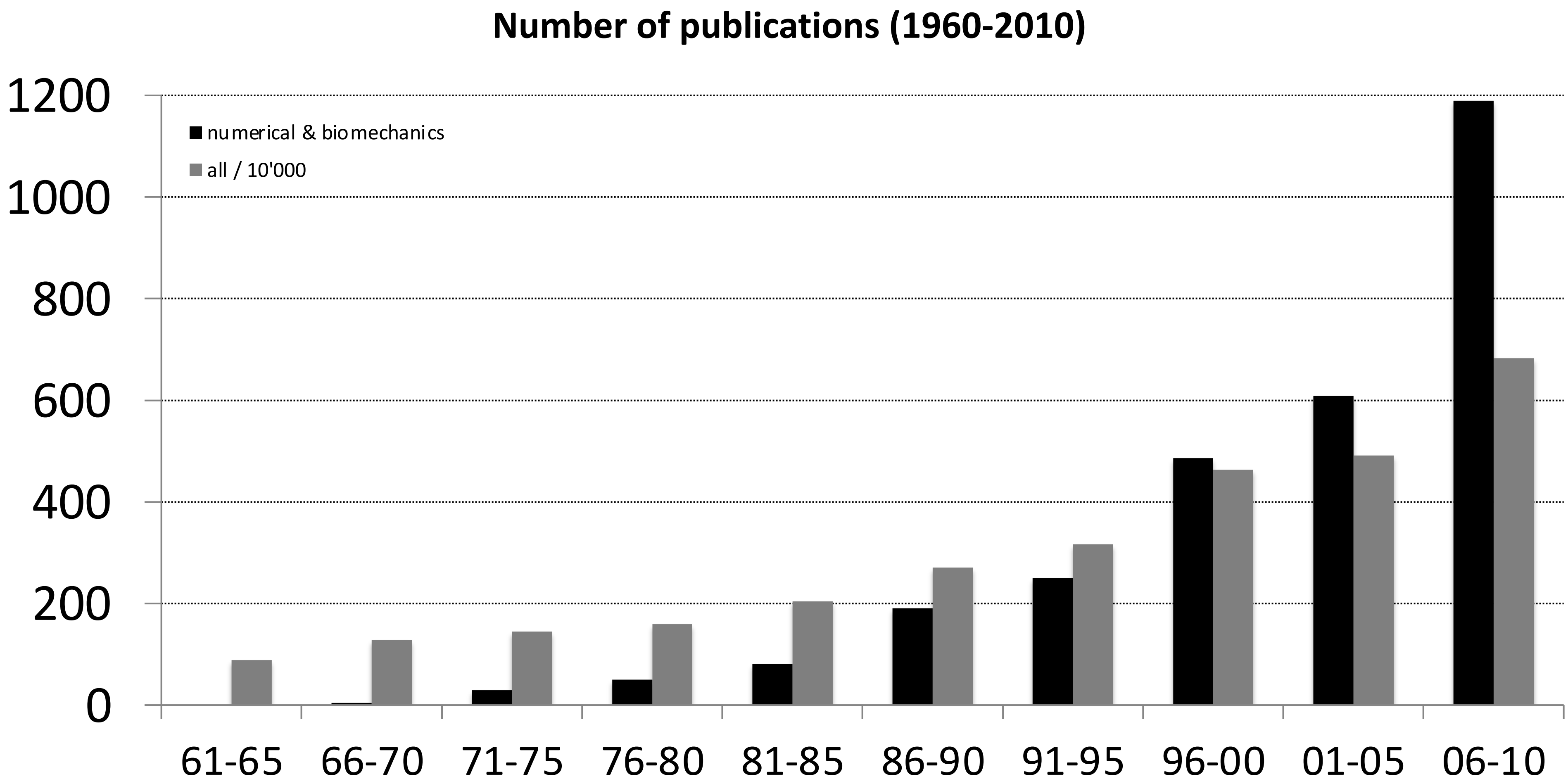
http://books.google.com/ngrams

Relative Importance in Science



“numerical” + “biomechanics” from www.scopus.com

Course objectives

- Realize the importance of numerical methods
- Replace important (known) concepts in context
- Learn & apply these methods (partly)
- Get a critical thinking about these methods
- Develop skills with examples and exercises
- Realize a mini-project
- Introduce COMSOL software

Content

W01: Organization, introduction, and examples
W02: External lecturers
W03: Partial Differential Equations
W04: Solid mechanics (Orthopedics)
W05: Fluid mechanics (Cardiovascular)
W06: Midterm project presentations
W07: Finite Element Method
W08: Midterm evaluation
W09: Multiphysics and coupling
W10: Example 1
W11: Example 2
W12: Example 3
W13: Final project presentation

Organization

- Course: theory and examples
- Exercises with COMSOL
- Mini-project in group with COMSOL
  - Oral presentation
  - Written report
- Midterm evaluation
- Written exam

http://moodle.epfl.ch/course/view.php?id=14383

Evaluation

• Midterm test:	1/4 of the final grade
• Project presentation:	1/4 of the final grade
• Project report:	1/4 of the final grade
• Written exam:	1/4 of the final grade

Exercises

- Comsol
- 10 exercises (sessions of 45 minutes)
  - 3 based on Comsol tutorials
  - 7 related to biomechanics, with increasing complexity
- Room
  - INF 3: Windows 10, 8GB I7-4770 @3.4GHz
  - INF 213: student laptop (Comsol installation)
- Assistants
  - Check in moodle

Midterm test

- ~~A "simple" exercise, with Comsol in 2x45 min~~
- ~~In room INF 3~~
- ~~Grade: 6 points for 6 questions~~
  - ~~Present and comment methods~~
  - ~~Present and comment results~~

- COVID: Replaced by a report on a selected subject

Final exam

- No simulations
- Part 1 related to the course (3 points)
- Part 2: related to your project (3 points)

Project

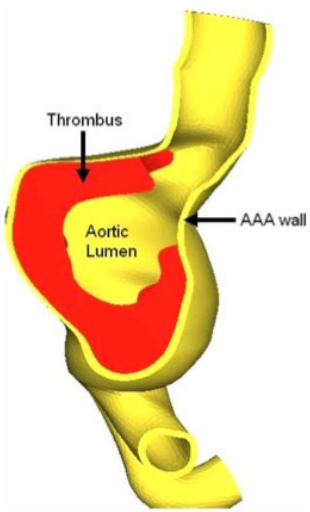
- In group of 3-5 students, mixed sections
- Corresponds to 40 h of work per group member
- Related to biomechanics, bioengineering
- Focus on numerical modeling, with Comsol
- Based on a published paper (simplify & extend)
- Open to propositions
- Midterm presentation (W06), about 10 min
- Final presentation (W13), about 10 min
- Project report (6 pages conference proceeding)
- Comsol files
- Final exam

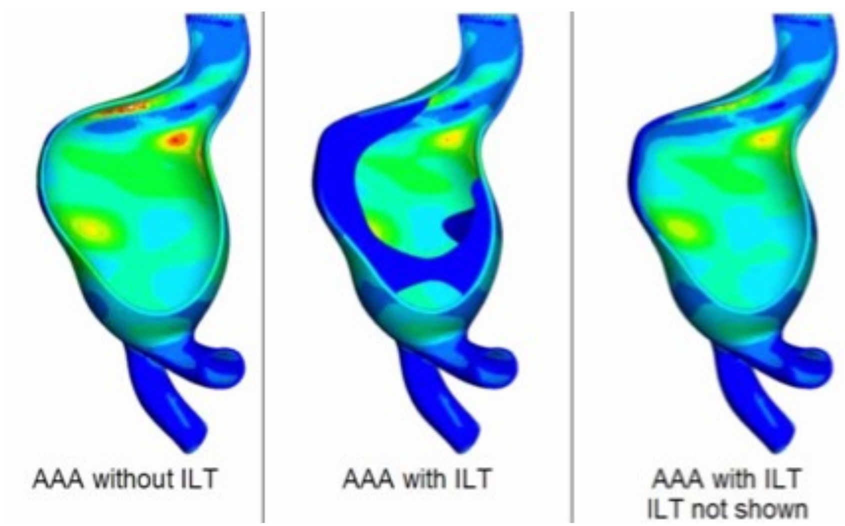
Mini-project suggestion 1

Intraluminal thrombus and risk of rupture in patient specific abdominal aortic aneurysm - FSI modeling

http://dx.doi.org/10.1080/10255840802176396

- Simplified geometry
- Parameter analysis: aneurism size, wall thickness, etc





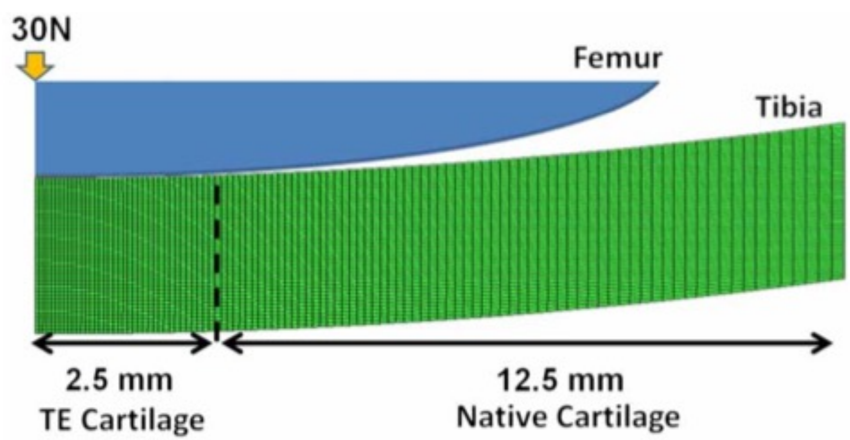
(See moodle document: Article aneurysm)

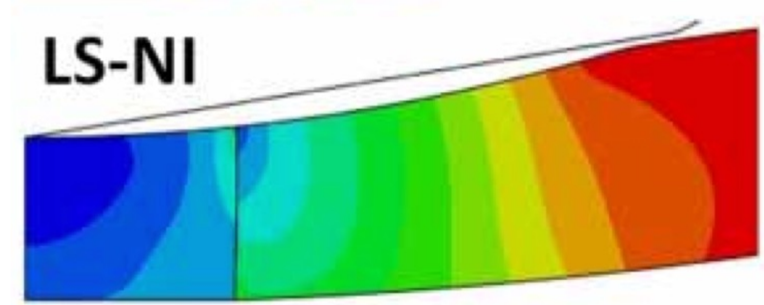
Mini-project suggestion 2

Finite element study of a tissue-engineered cartilage transplant in human tibiofemoral joint

http://dx.doi.org/10.1080/10255842.2011.585974

- Simplified constitutive model
- Inhomogeneity, femur, menisci, loading





Minimum principal strain

(See moodle document: Article cartilage)

Mini-project example 1

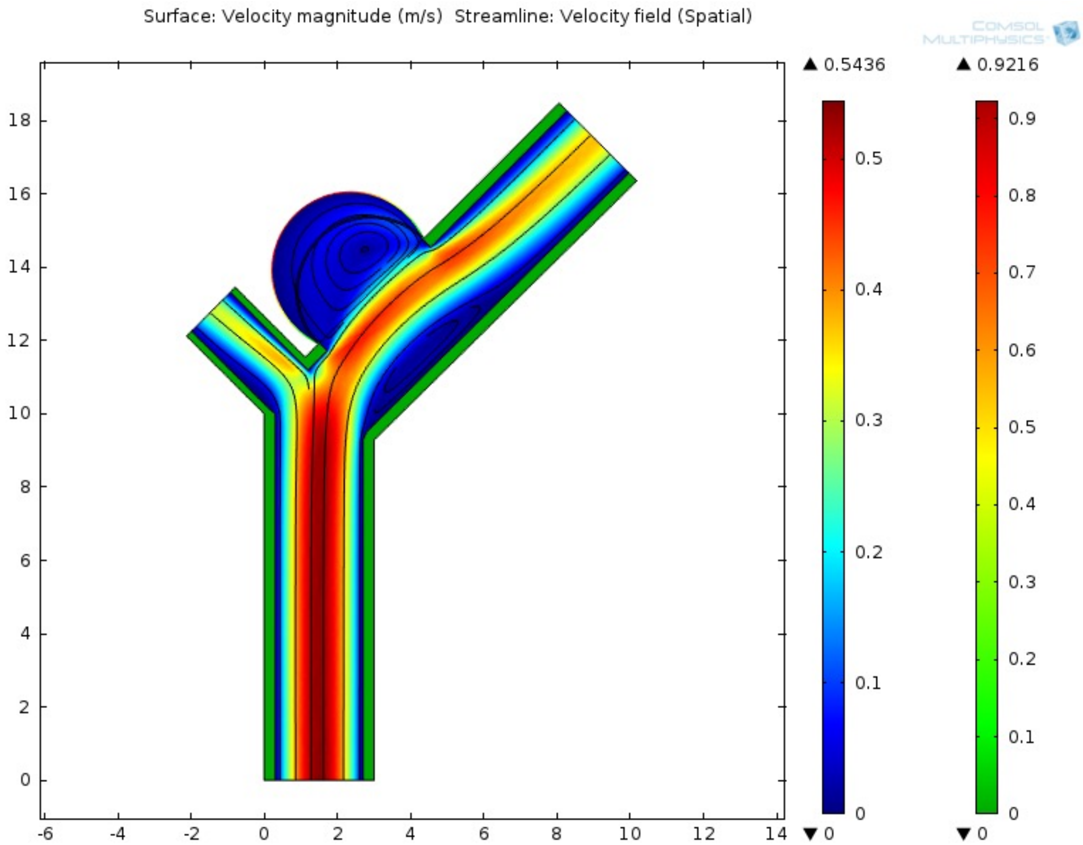
Model of a cerebral aneurysm

NMB project 2012

Coralie Dessauges and Emilie Farine

Effect of some parameters

2D vs. 3D



(See moodle document: Project report example)

Mini-project example 2

Modelling 2-phase flow on a microfluidic device

NMB project 2014

Gopal Krishnamani,

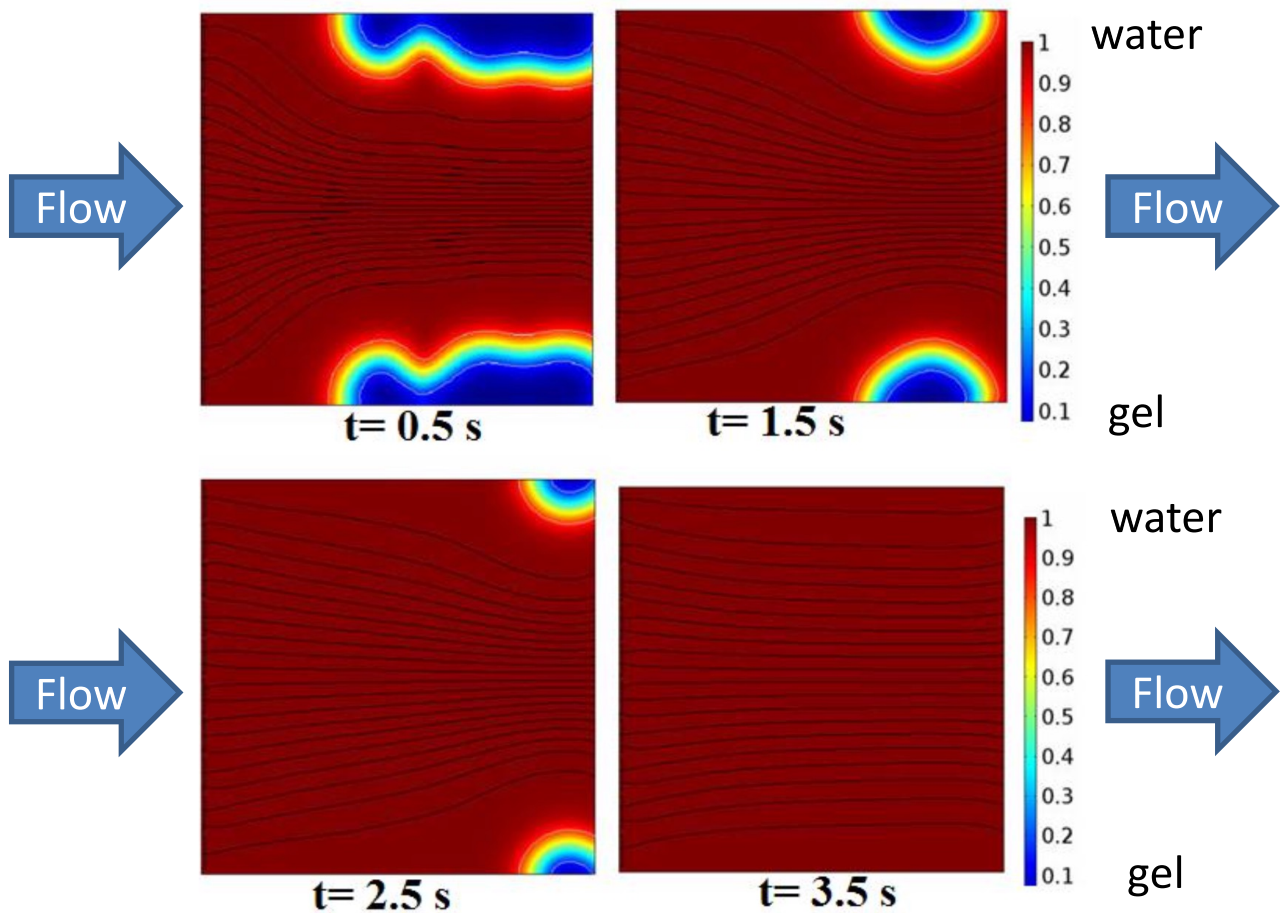
Kunal Sharma,

Paul Brunet

Effect of some parameters

2D model

2-phase flow



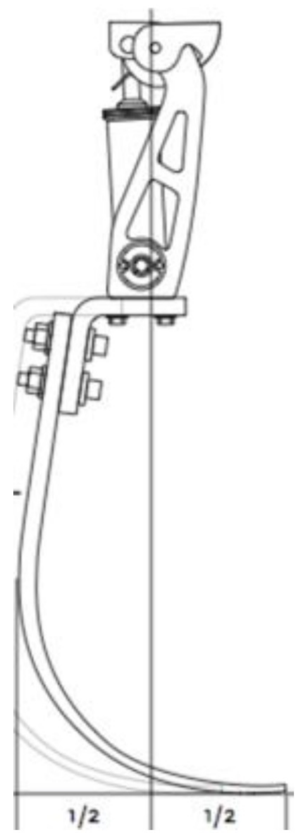
(See moodle document: Project report example)

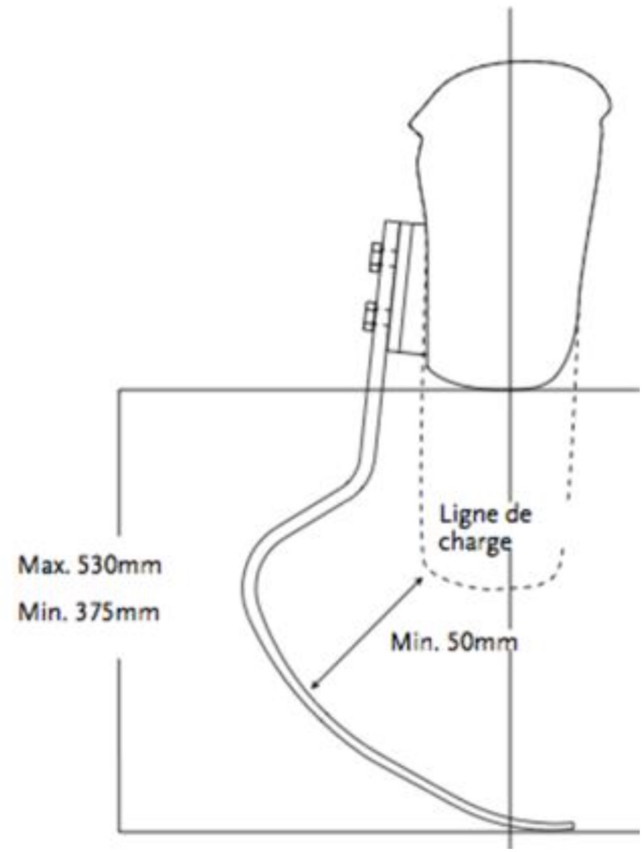
Mini-project example 3

Comparison of 2 sprinter amputee prostheses

NMB project 2014
Yann Amouyal,
Timothée Bacle,
Emilia Gouy,
Denis Stauffer

Solid models
2D & 3D models





(See moodle document: Project report example)

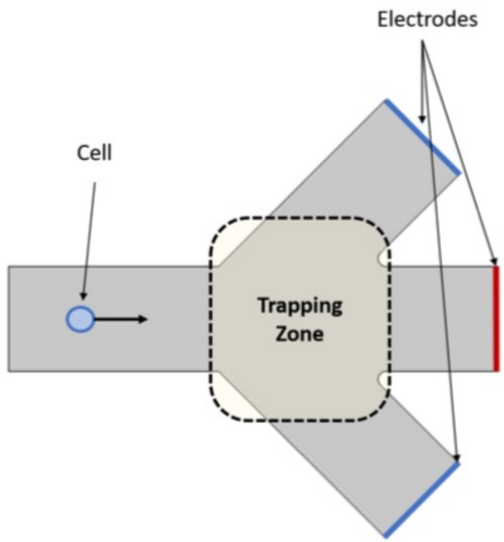
Mini-project example 4

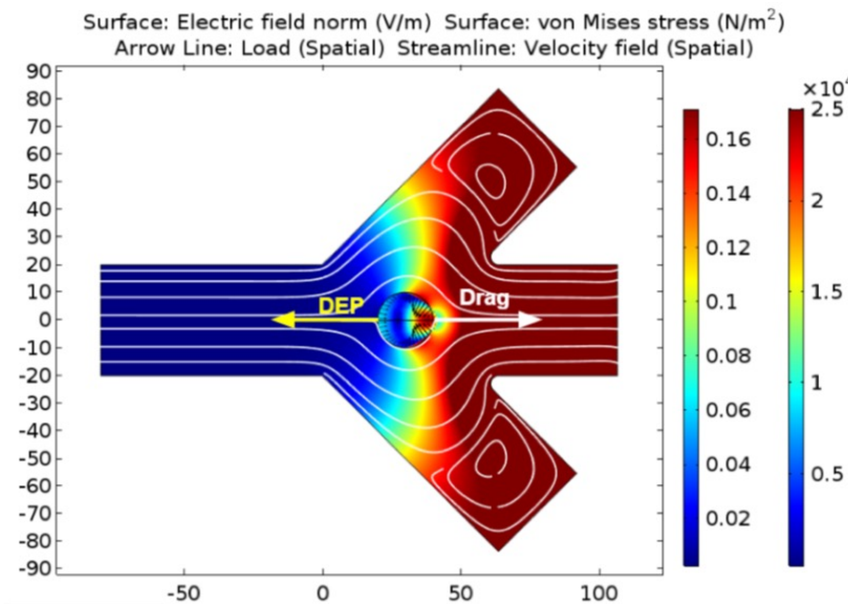
Optimization of Dielectrophoretic Cell Trapping in a Microfluidic Channel

NMB project 2017
Claire Amadio,
Alexandre Kehren,
Hadrien Meriah

Solid mechanics
Fluid mechanics
Electromagnetism
Heat

2D models





(See moodle document: Project report example)

Article sources for project

- www.scopus.com
- Computer Methods in Biomechanics and Biomedical Engineering
- Journal of Biomechanics
- Clinical Biomechanics
- Medical Engineering and Physics
- Annals of Biomedical Engineering
- Comsol conferences (www.comsol.com)

History

The development of numerical methods has followed the growth of computer power, starting slowly 50 years ago and extending very rapidly today.

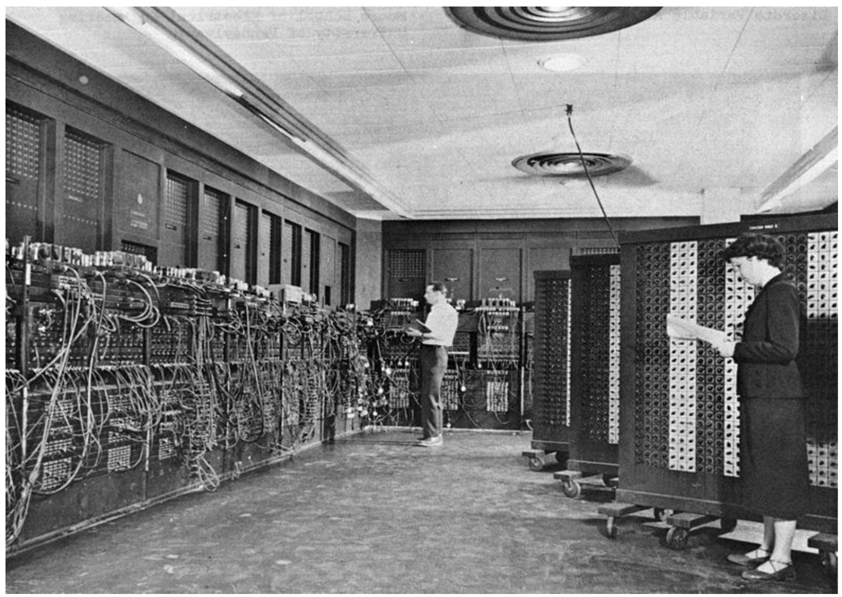
History

- Bio-engineering, as numerical modeling, can be both originated to World War II.

- Numerical modeling in bioengineering followed the recent rapid evolution of numerical techniques and computers performances.

Where it started

ENIAC (Electronic Numerical Integrator And Computer), 1946-55, 30 tons, 350 flops



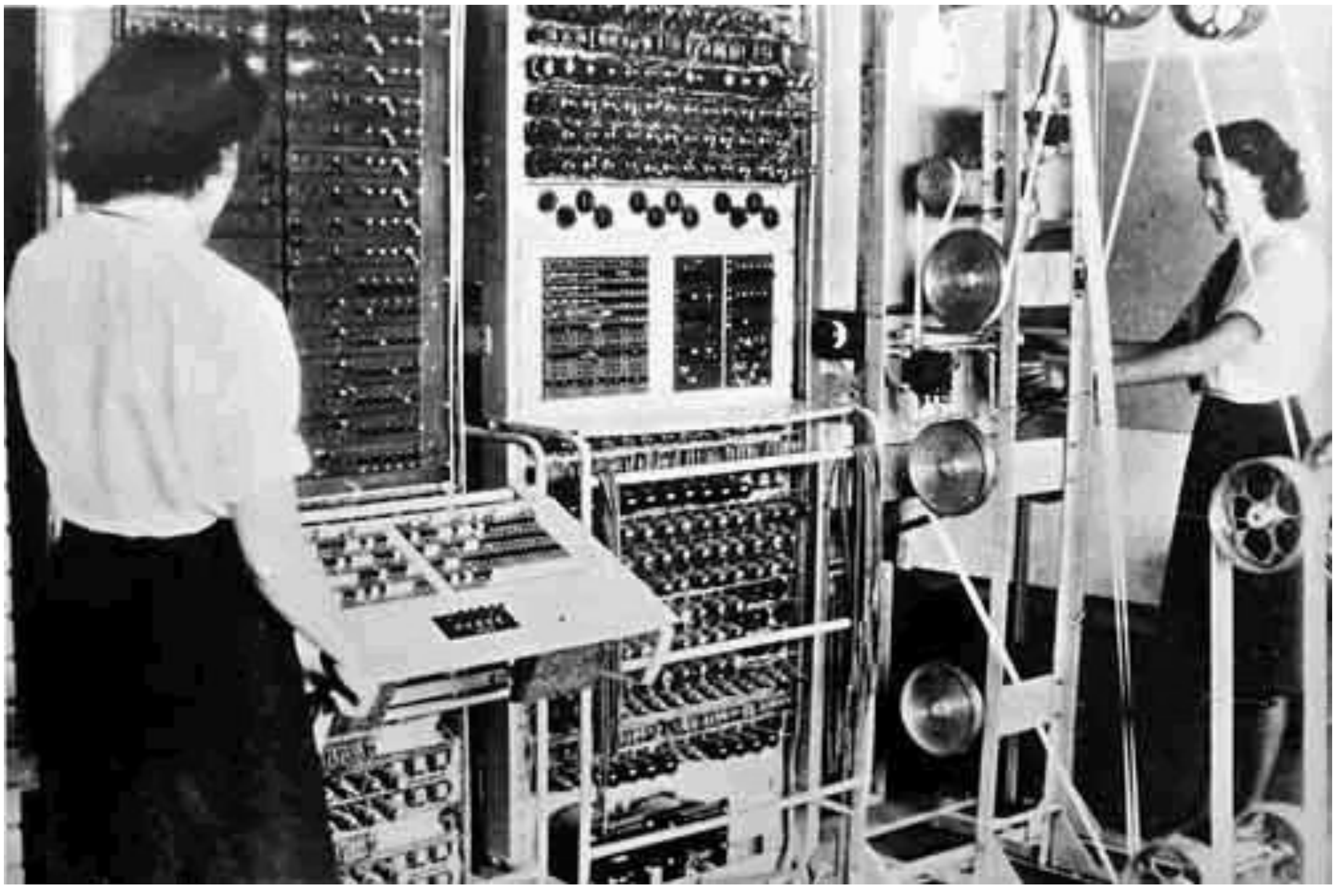
1946, U.S. Army photo

Where it started

Z3, 1941, Germany, Aircraft design

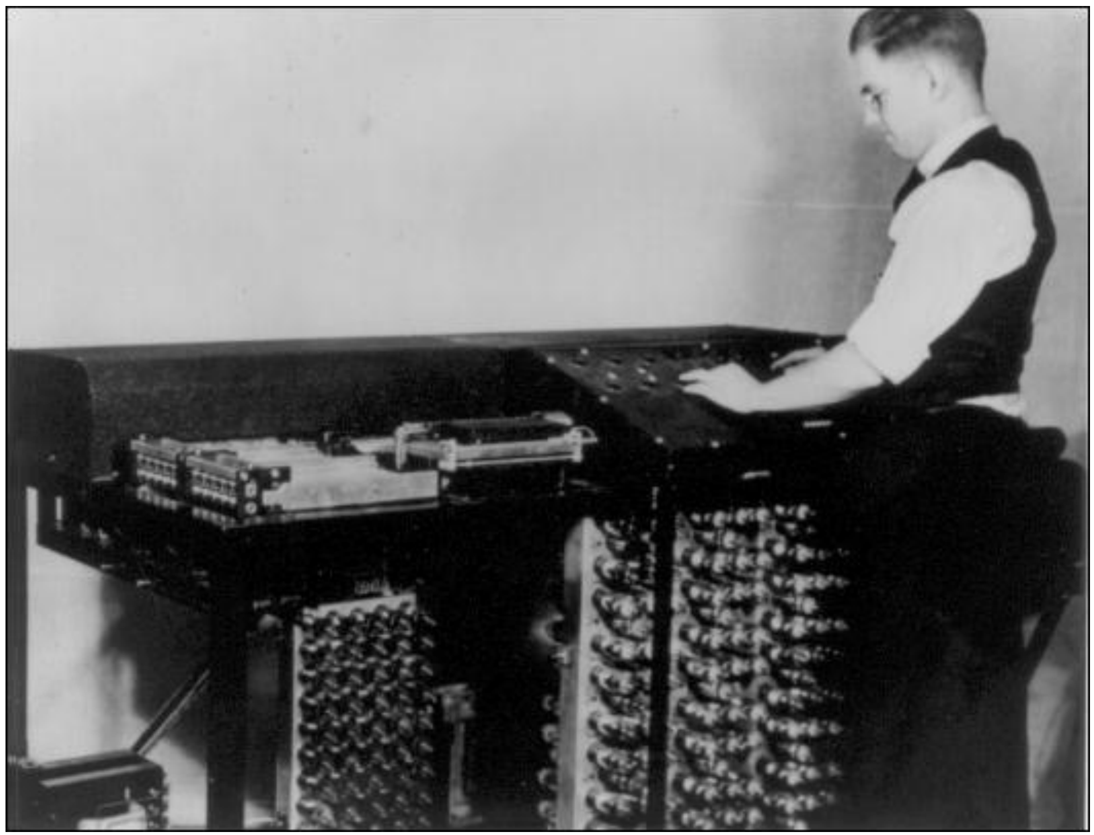
Where it started

Colossus, 1943, UK, decrypt German messages



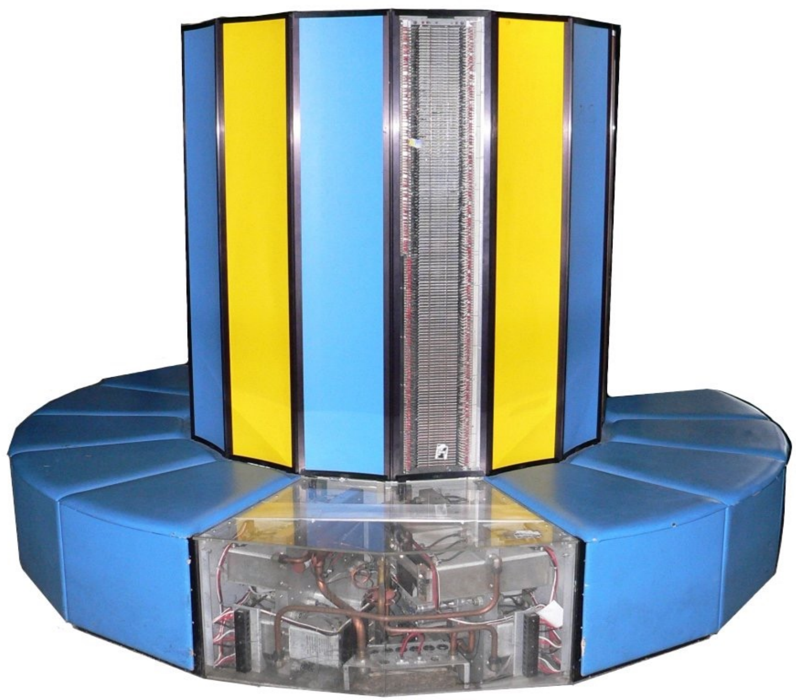
Where it started

ABC (Atanasoff–Berry Computer), 1941, systems of linear equations



30 years later…

CRAY-1, Los Alamos (1976), EPFL (1986-88)
100 megaFlops



Today’s supercomputers

IBM Blue Gene/Q, EPFL (2013)

173 teraFLOPS (10^{12} FLOPS)

Today's supercomputers

HPE SGI 8600 system (EPFL, 2018)

> 1 petaFLOPS (10^{15} FLOPS)

https://www.hpcwire.com/2018/07/10/hpe-epfl-launch-blue-brain-5-supercomputer/

Today’s supercomputers

Summit (IBM)

200 petaFLOPS (10^{15} FLOPS)

https://www.ornl.gov/directorate/ccsd

Today’s supercomputers

Swiss National Supercomputing Centre, Lugano

HPE Cray EX, 4’719 TFlops, 2024

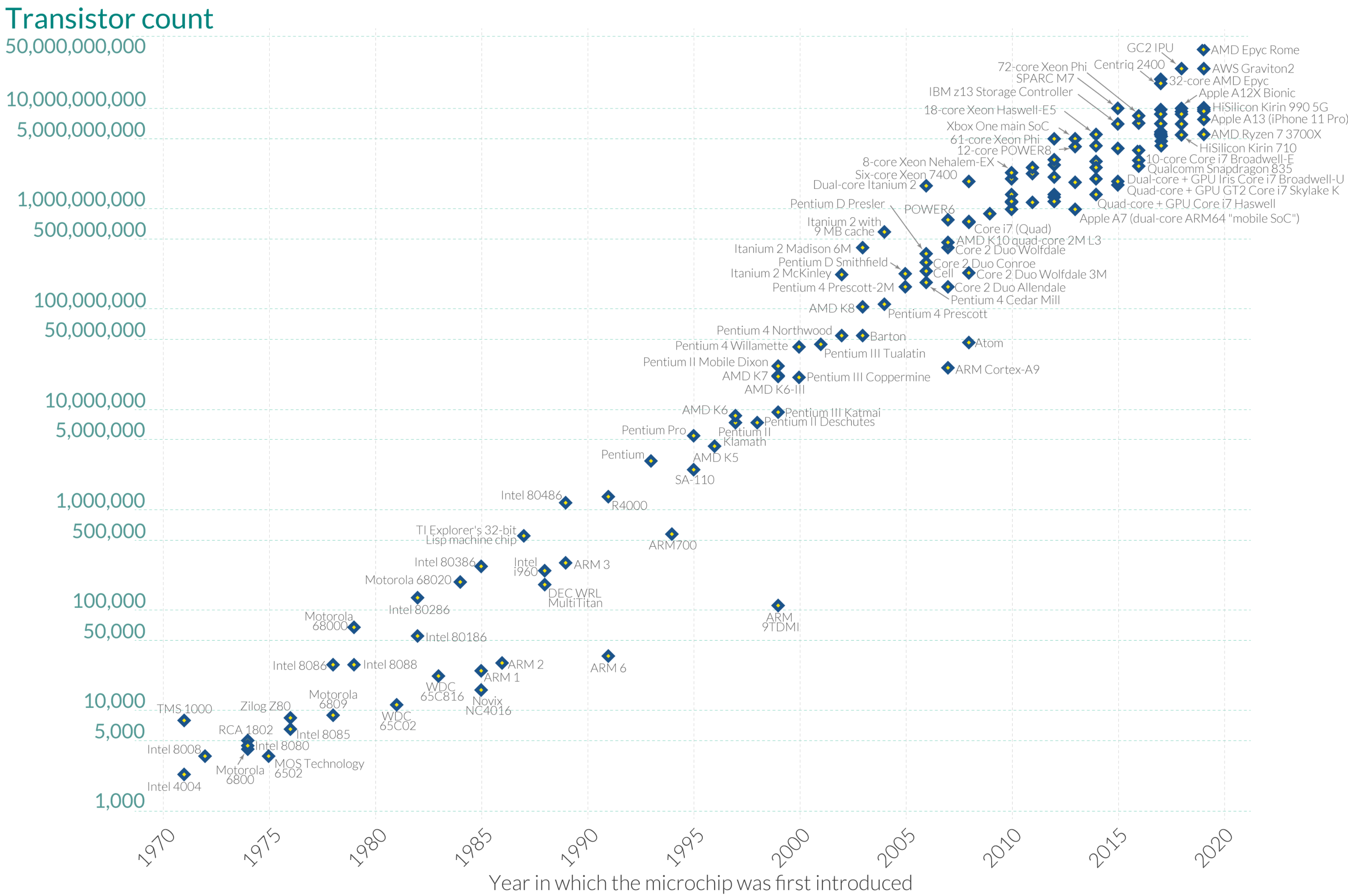
https://www.cscs.ch/computers/alps

Today's laptop

≈ 1 teraFLOPS

Moore's Law: The number of transistors on microchips has doubled every two years

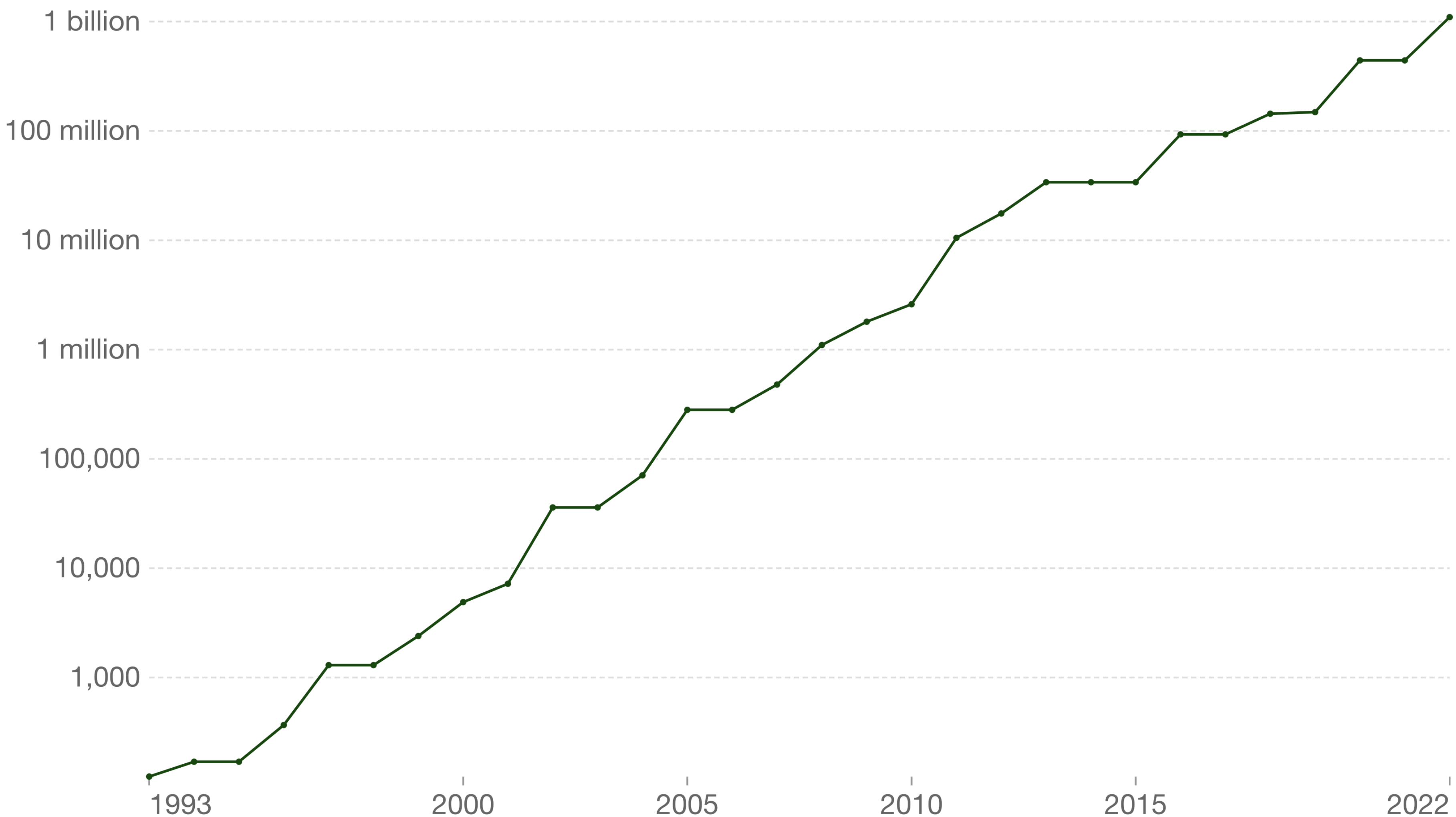
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years.
This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems.

Computational capacity of the fastest supercomputers

The number of floating-point operations[1] carried out per second by the fastest supercomputer in any given year. This is expressed in gigaFLOPS, equivalent to 10^9 floating-point operations per second.

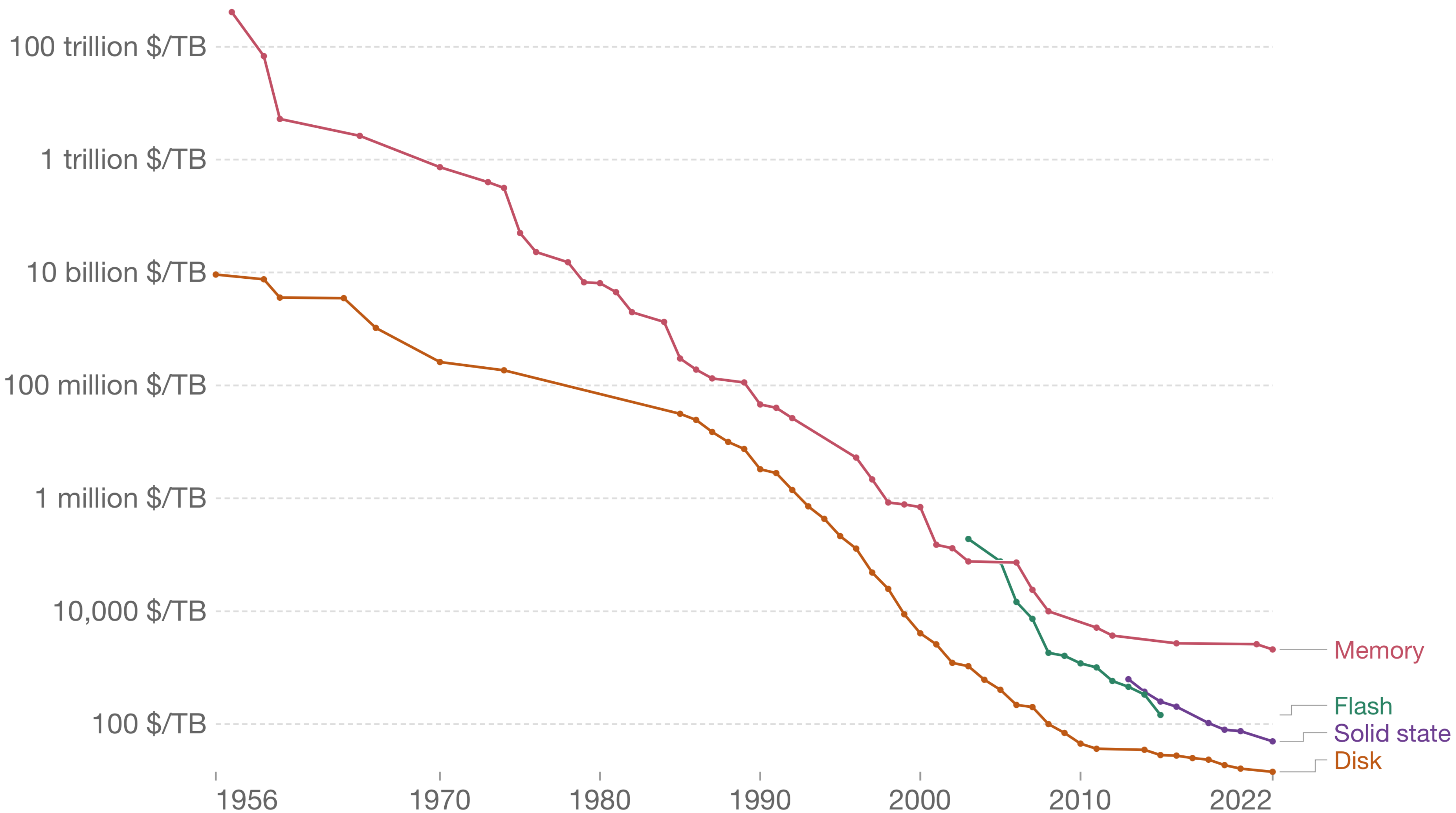


Source: TOP500 Supercomputer Database (2023)

1. Floating-point operation: A floating-point operation (FLOP) is a type of computer operation. One FLOP is equivalent to one addition, subtraction, multiplication, or division of two decimal numbers.

Historical cost of computer memory and storage

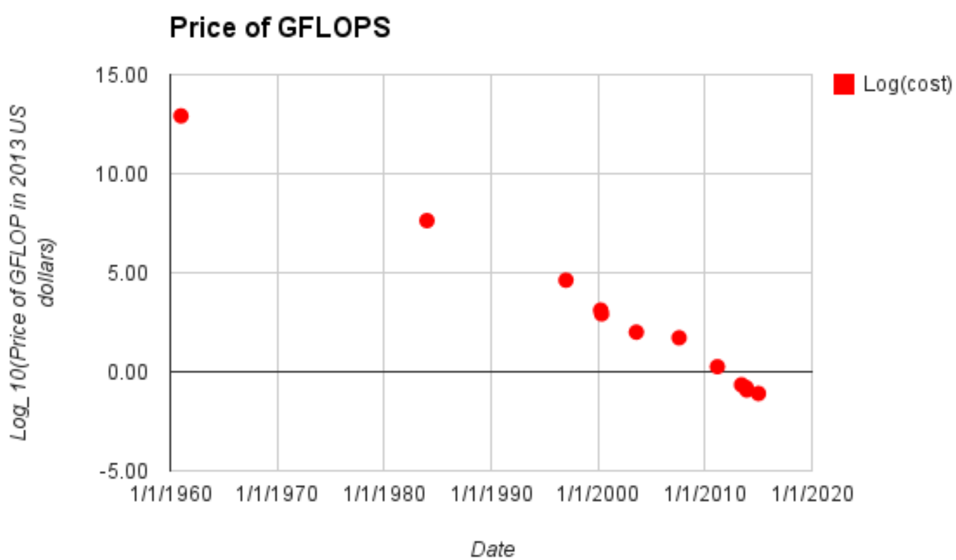
This data is expressed in US dollars per terabyte (TB). It is not adjusted for inflation.

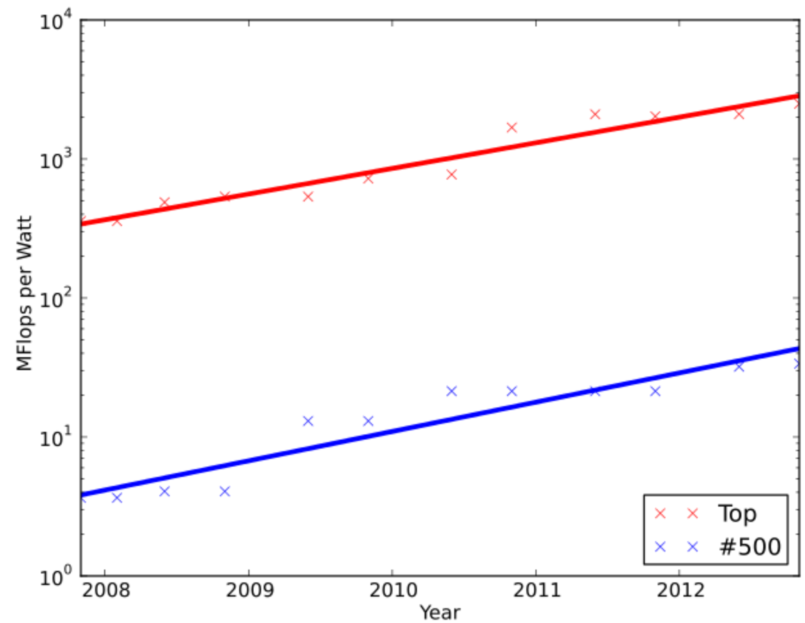


Source: John C. McCallum (2022)

Note: For each year, the time series shows the cheapest historical price recorded until that year.

FLOPS/$ and FLOPS/W





https://aiimpacts.org/trends-in-the-cost-of-computing/

https://en.wikipedia.org/wiki/Performance_per_watt

Today's computer

- Efficient (personal/workstation) computers
- Efficient simulation software
- User-friendly simulation software
- Numerical technics are commonly used as a tool by engineers and scientists

History of Numerical Methods (PDE)

- Variational principle (1900)
- Finite Difference Methods (1930)
- Implicit methods (1950)
- Finite Element Method (1960)

Thomee, V. (2001). From finite differences to finite elements - A short history of numerical analysis of partial differential equations. Journal of Computational and Applied Mathematics 128(1-2): 1-54.

Numerical modeling in Bioscience

- Bioengineering
  - Design of experiment/devices, hypothesis testing
  - Multi-physics, chemistry
- Molecular modeling
  - Mapping between mRNA and protein expression levels
- Bioinformatics
  - Identify similarities in gene sequences

Applications in Bioengineering

- Artificial organs
  - Design phase, improvement of existing
  - mechanical resistance, transport, etc.
- Tissue engineering
- Biomedical instrumentation
- Research tool

Typical problems

- Orthopedics
  - Joint prostheses (Mechanical failure, wear, osteo-integration
  - Tissue engineering
  - Surgical technique
- Cardiovascular
  - Aneurisms
  - Stent
- Artificial Organs
  - Gas transport in lungs
  - Transport phenomena in artificial kidney
- Regenerative medicine
  - Tissue engineering, extra-cellular matrix transport

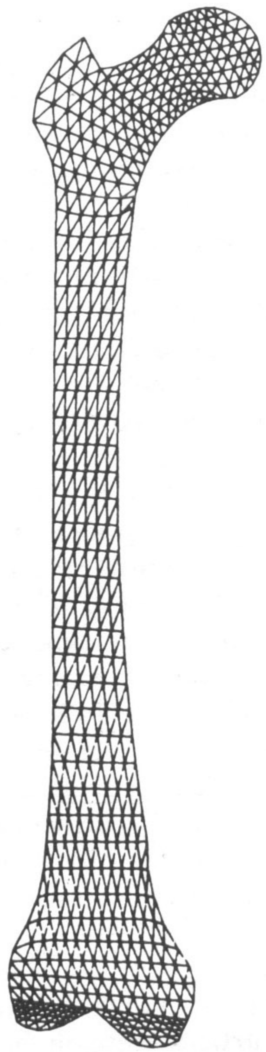
Medical Companies

- Conception / Improvement
- Development
- Optimization
- Evaluate uncertainties
- Risk analysis
- Prepare for mechanical testing (ISO, ASTM)
- Communication, marketing

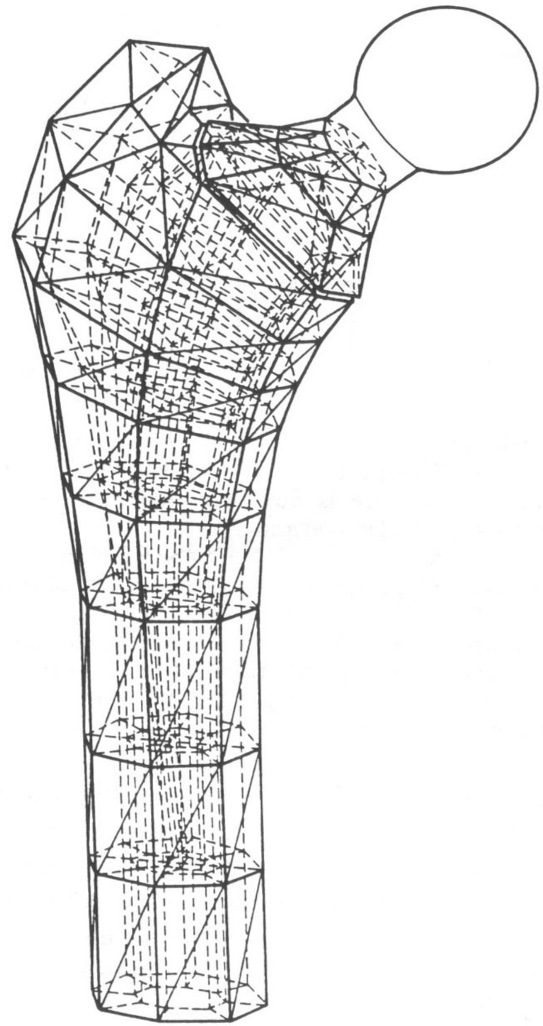
Modeling Techniques

- Multi-scale (level) modeling
  - Organ, Tissue
  - Limb, joint, tissue, interfaces, micro-structures, cells
  - Sequential: pre-computed micro-scale for macro-scale
  - Concurrent: on-the-fly micro-scale for macro-scale
- Multi-physics
  - Solid mechanics (rigid multi-body, deformable solid)
  - Fluid mechanics (transport)
  - Heat (cement polymerization)
  - Chemicals (biological reactions)
  - Electromagnetism (devices)

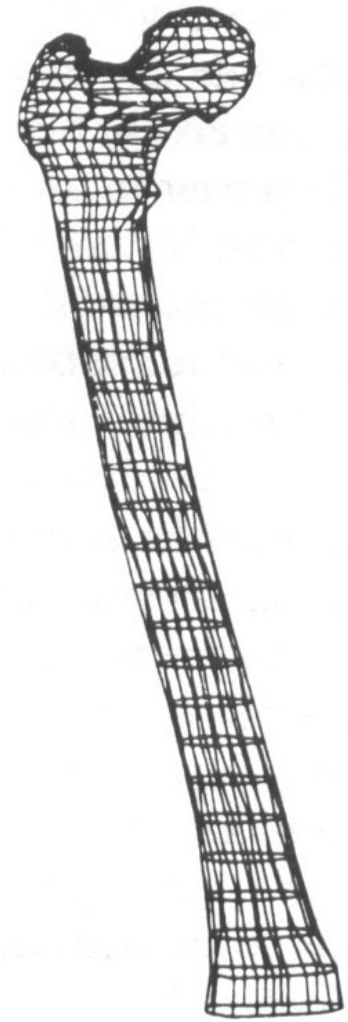
First numerical models



Brekelmans 72

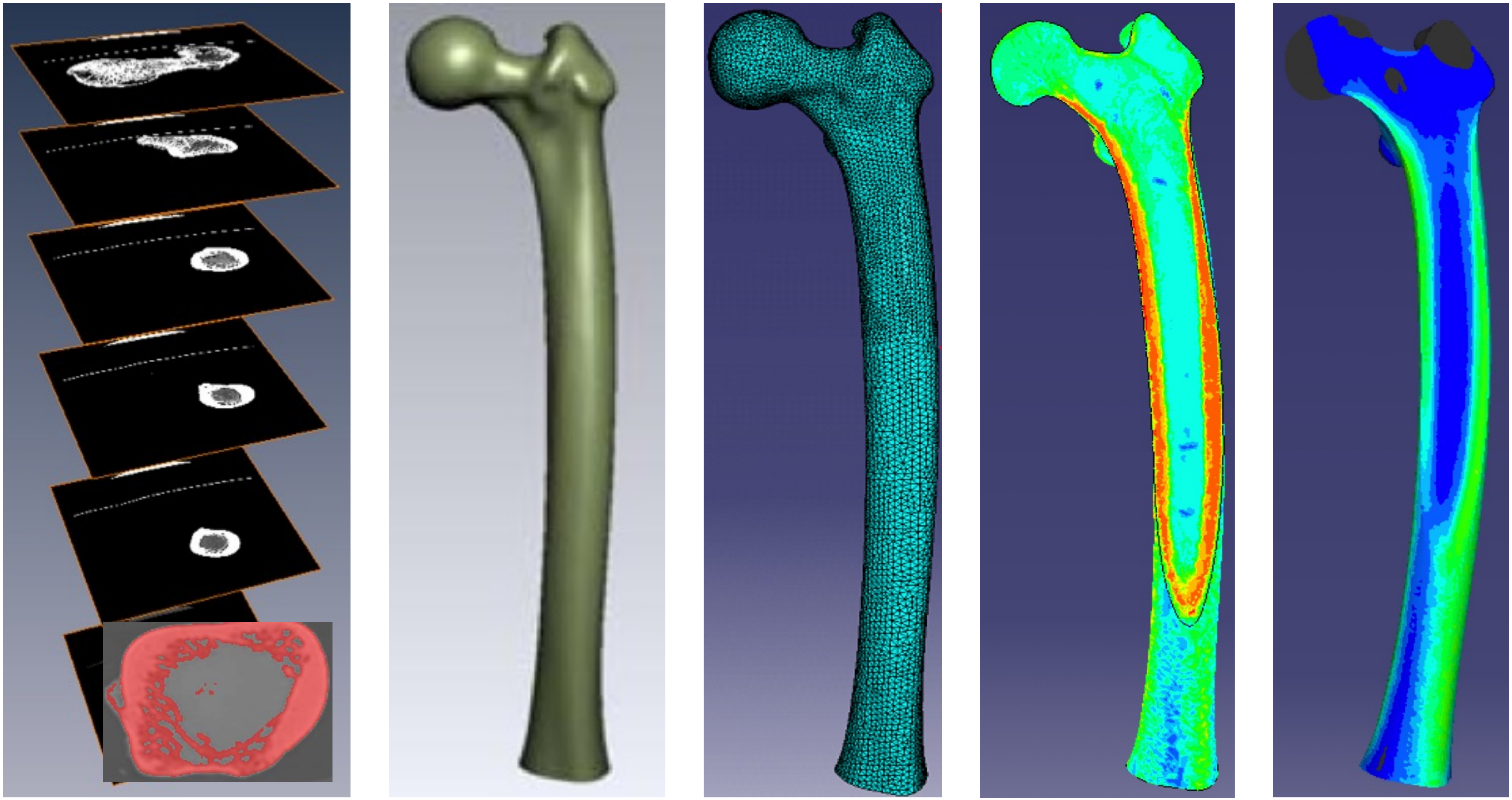


Roehrle 77



Rohlmann 82

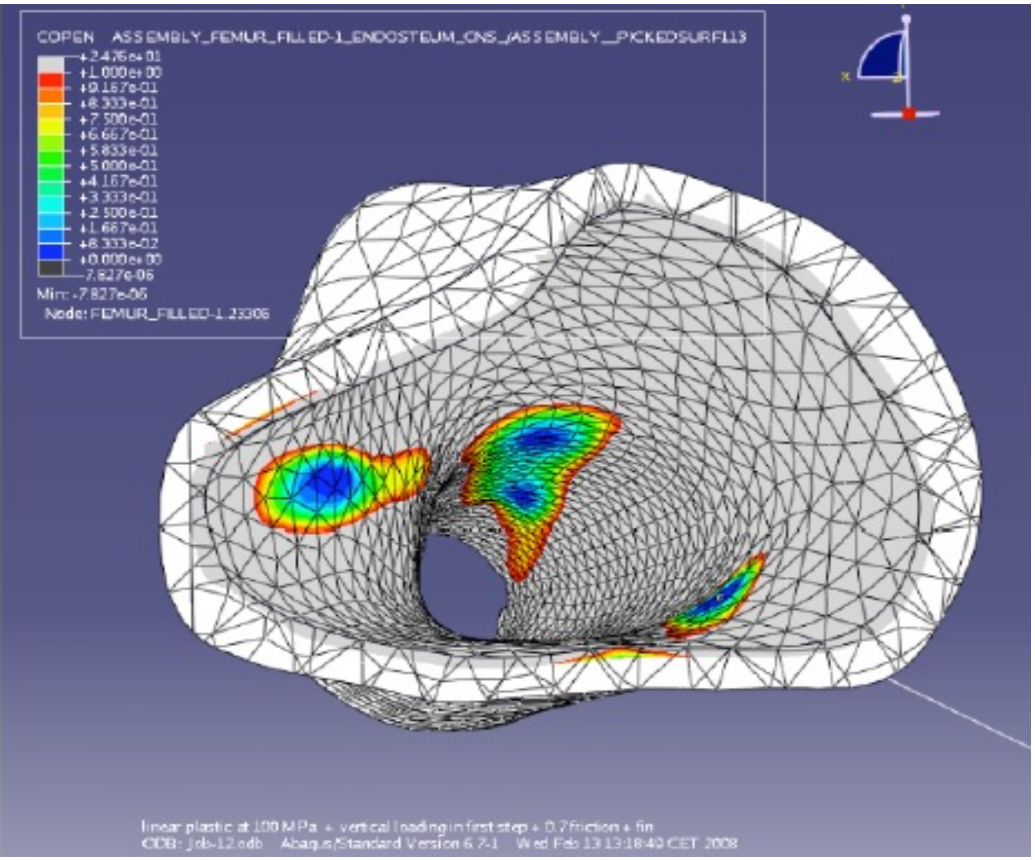
Hip



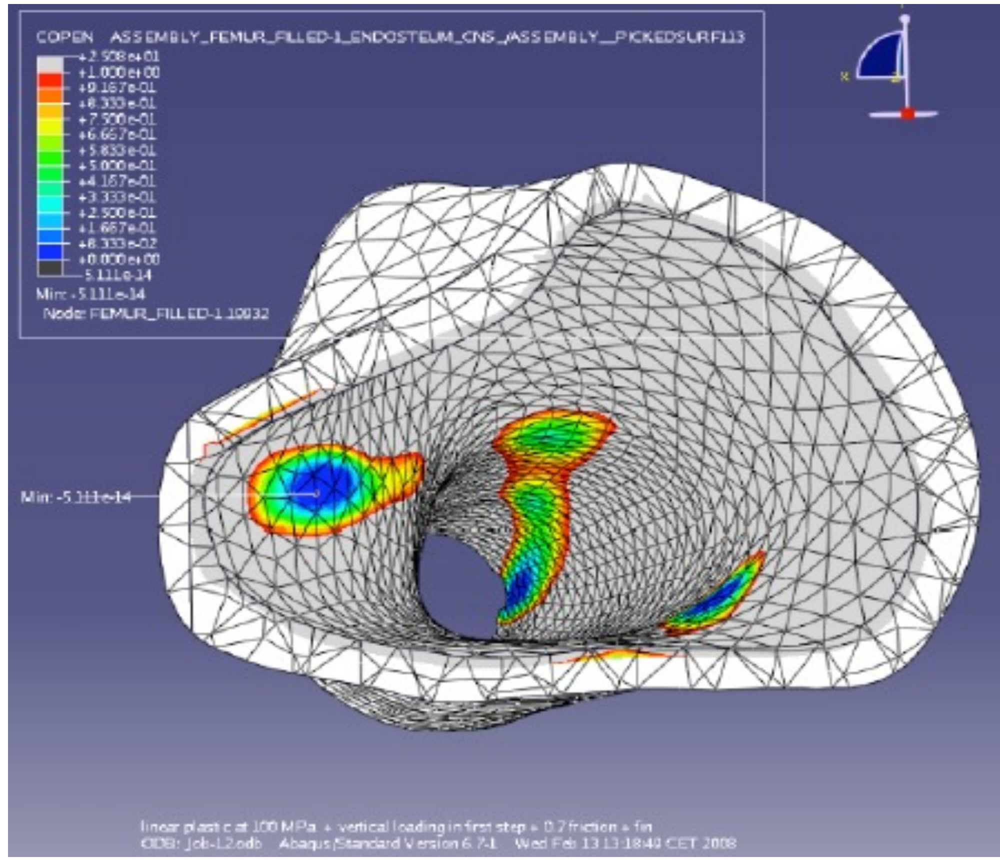
EPFL-LBO (M. Gortchacow)

Hip

No load



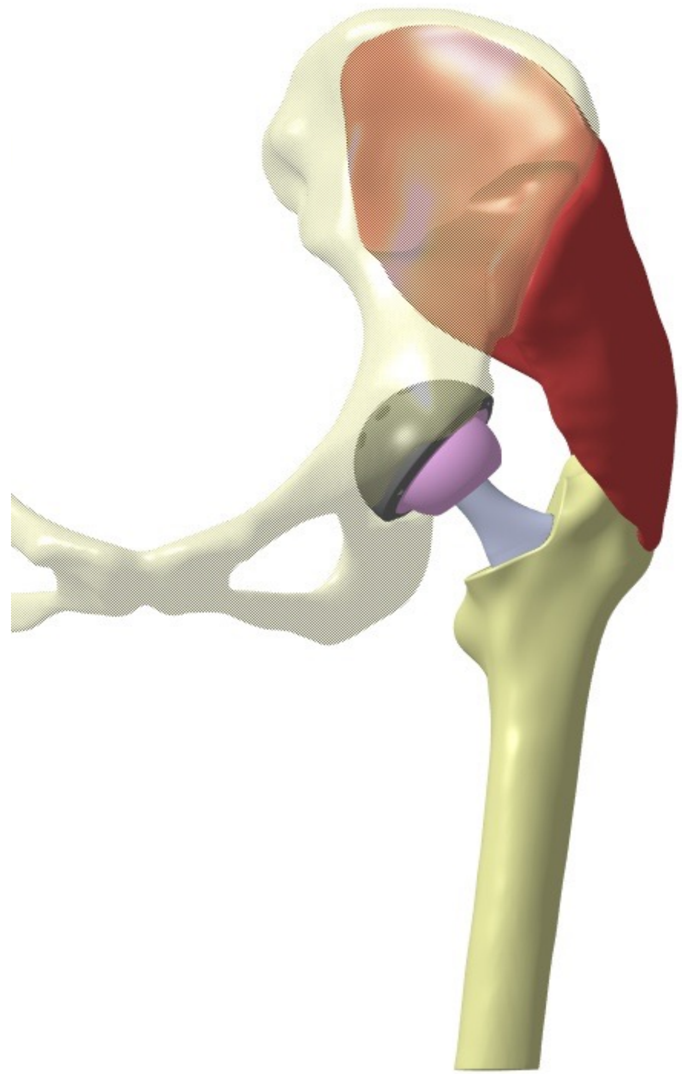
Walking load



EPFL-LBO (M. Gortchacow)

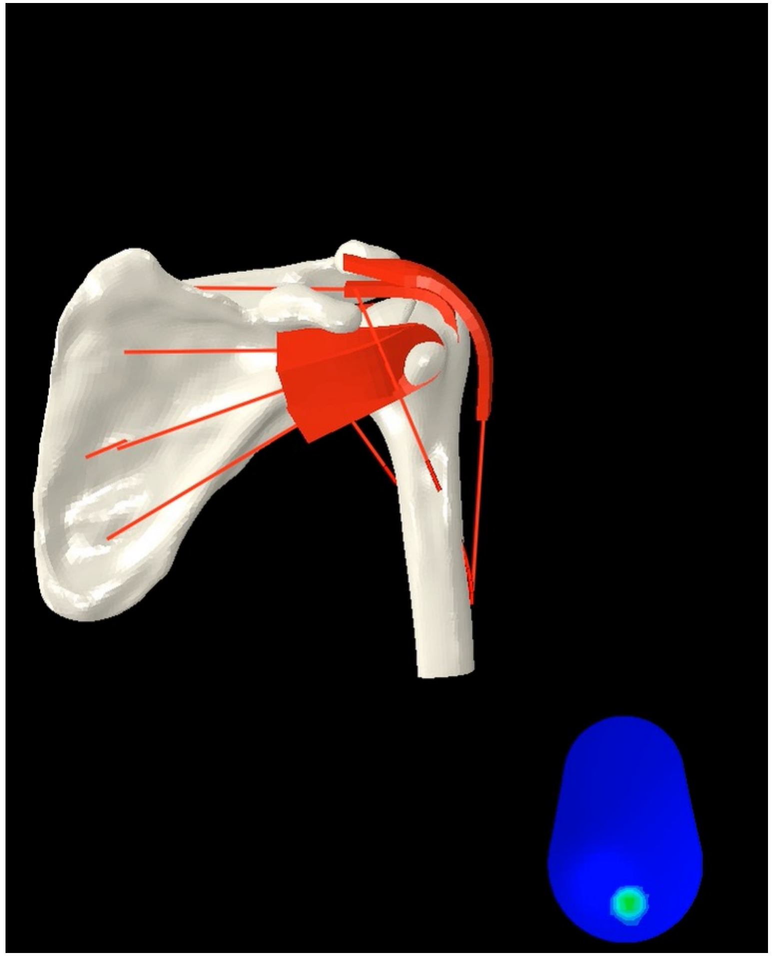
HIP

- Numerical model from CT
- Gluteus medius (volume)
  - 3 fibers (ant., middle, post.)
- Anatomical vs. medialized cup
- Gait
  - Abduction-adduction
  - Flexion-extension
- 15 patients



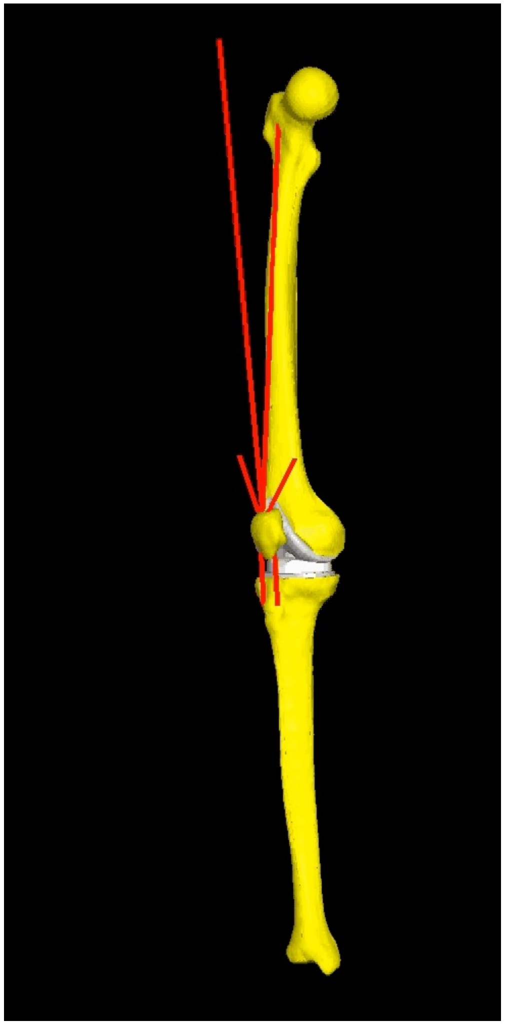
EPFL-LBO (A. Terrier)

Shoulder



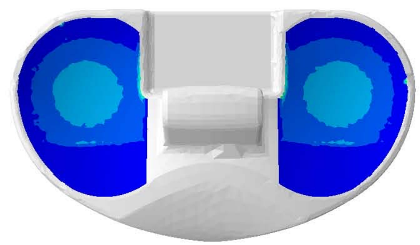
EPFL-LBO (A. Terrier)

Knee



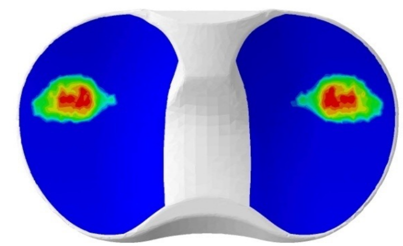
Polyethylene contact pattern (max/mean)
at 60° of knee flexion

FIRST



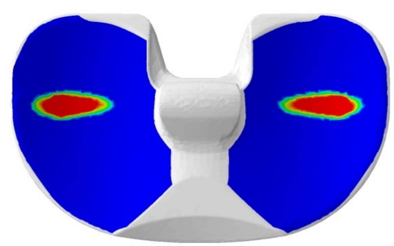
11 Mpa / 3 MPa

PFC



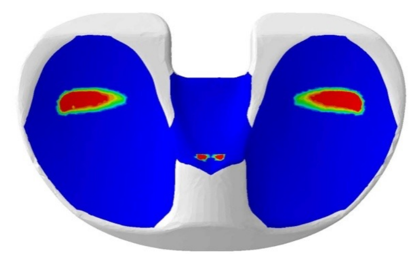
21 Mpa / 11 MPa

NexGen LPS flex



32 Mpa / 17 MPa

HLS

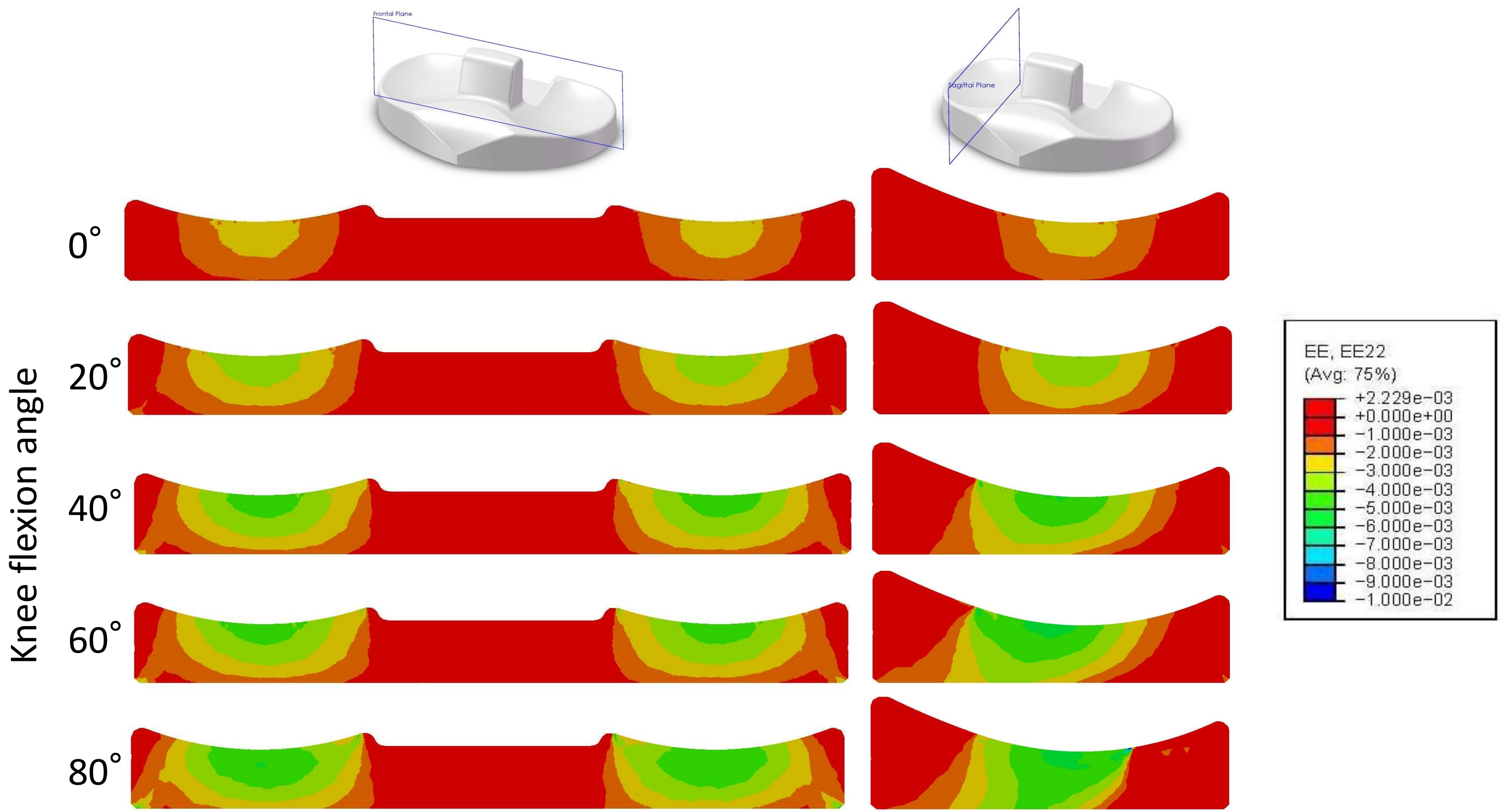


56 Mpa / 18 MPa

EPFL-LBO (A. Terrier)

Knee

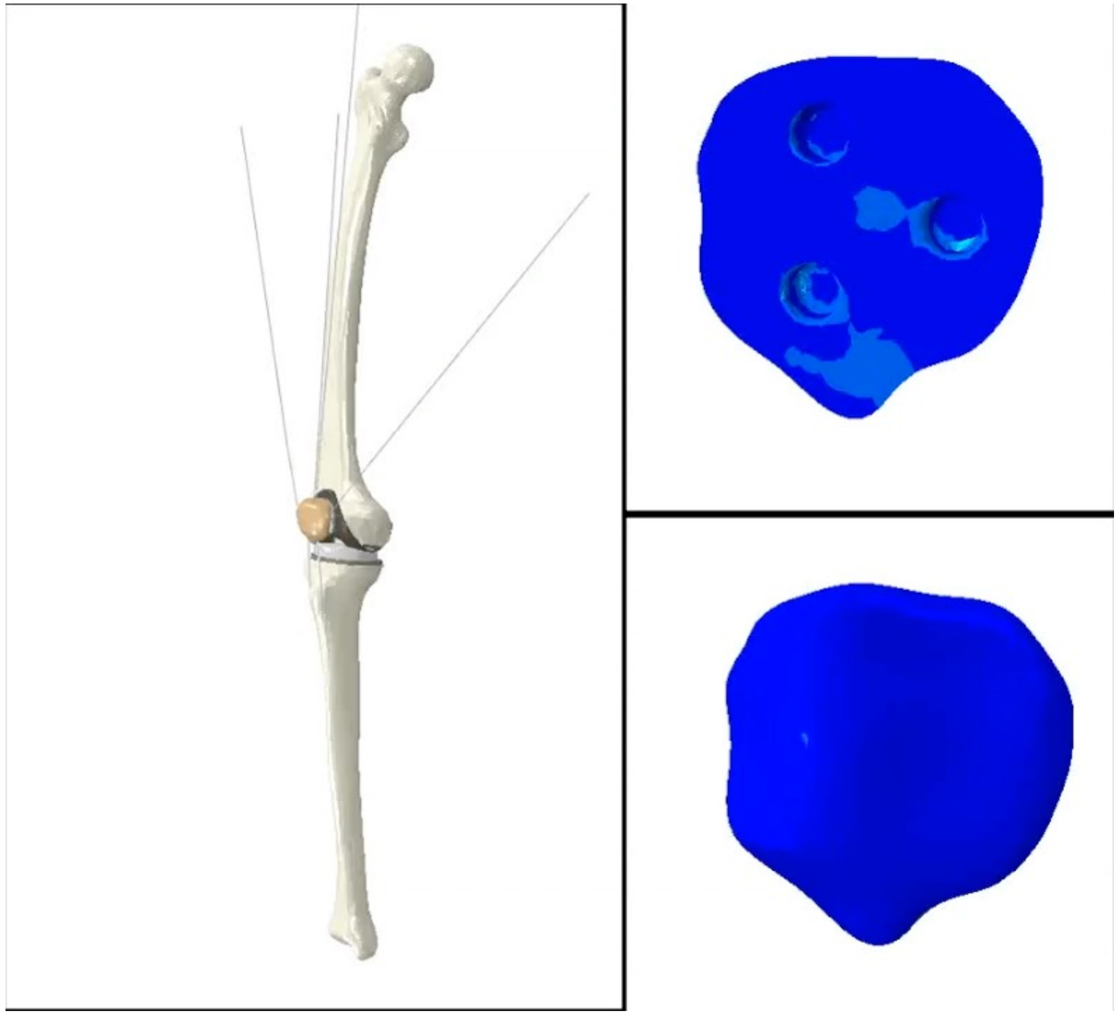
Smart Implants for Orthopedics Surgery (SImOS)



EPFL-LBO (A. Terrier)

Knee

Total Knee Arthroplasty (TKA)



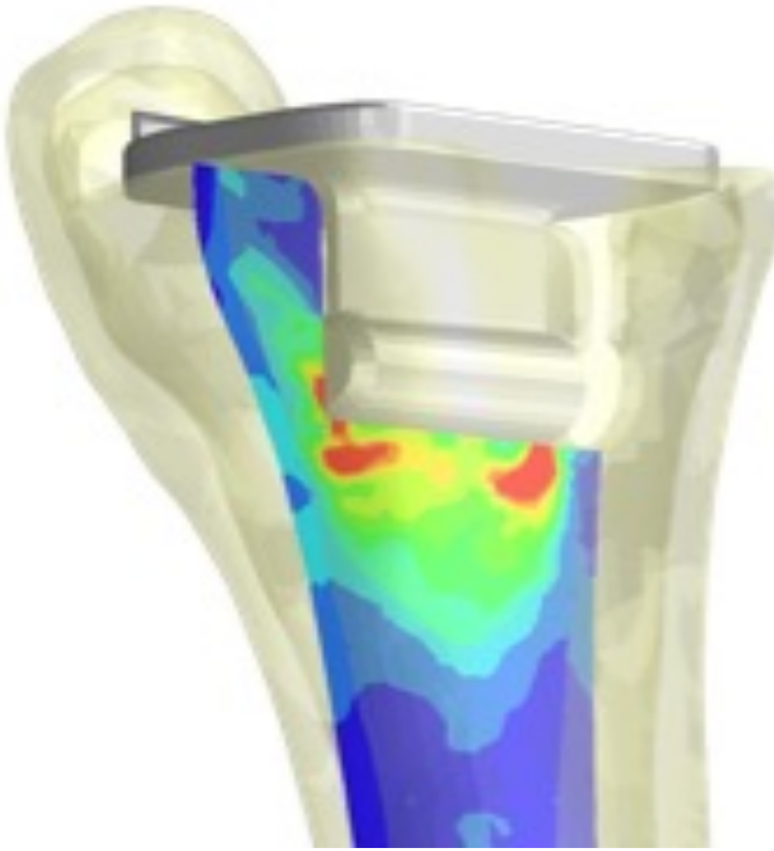
TKA with patellar component

TKA without patellar component

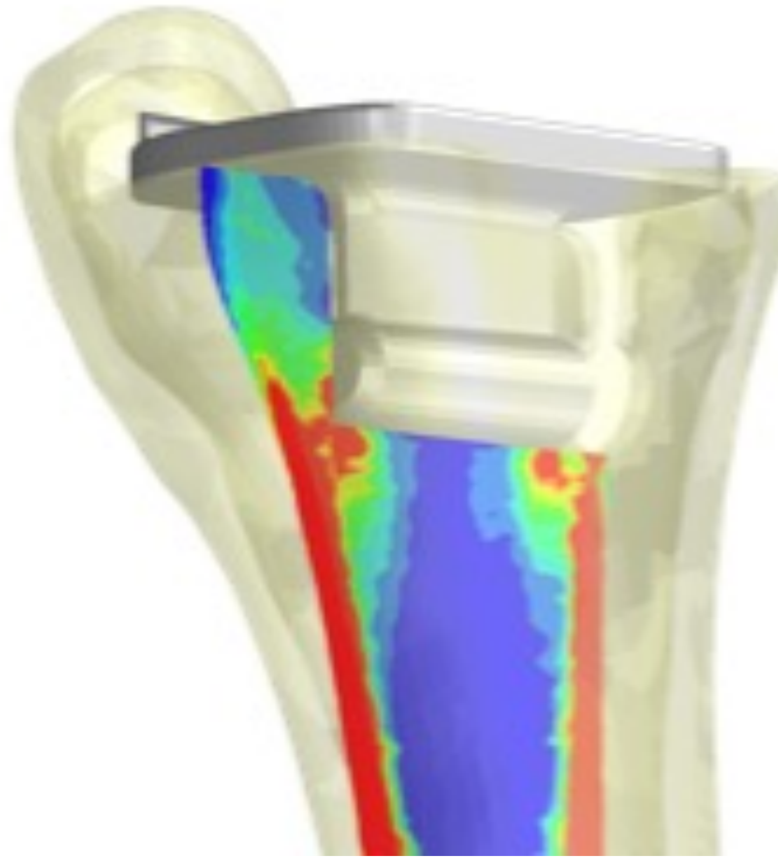
EPFL-LBO (A. Latypova)

Ankle

Total Ankle Replacement (tibial component)



Bone strain

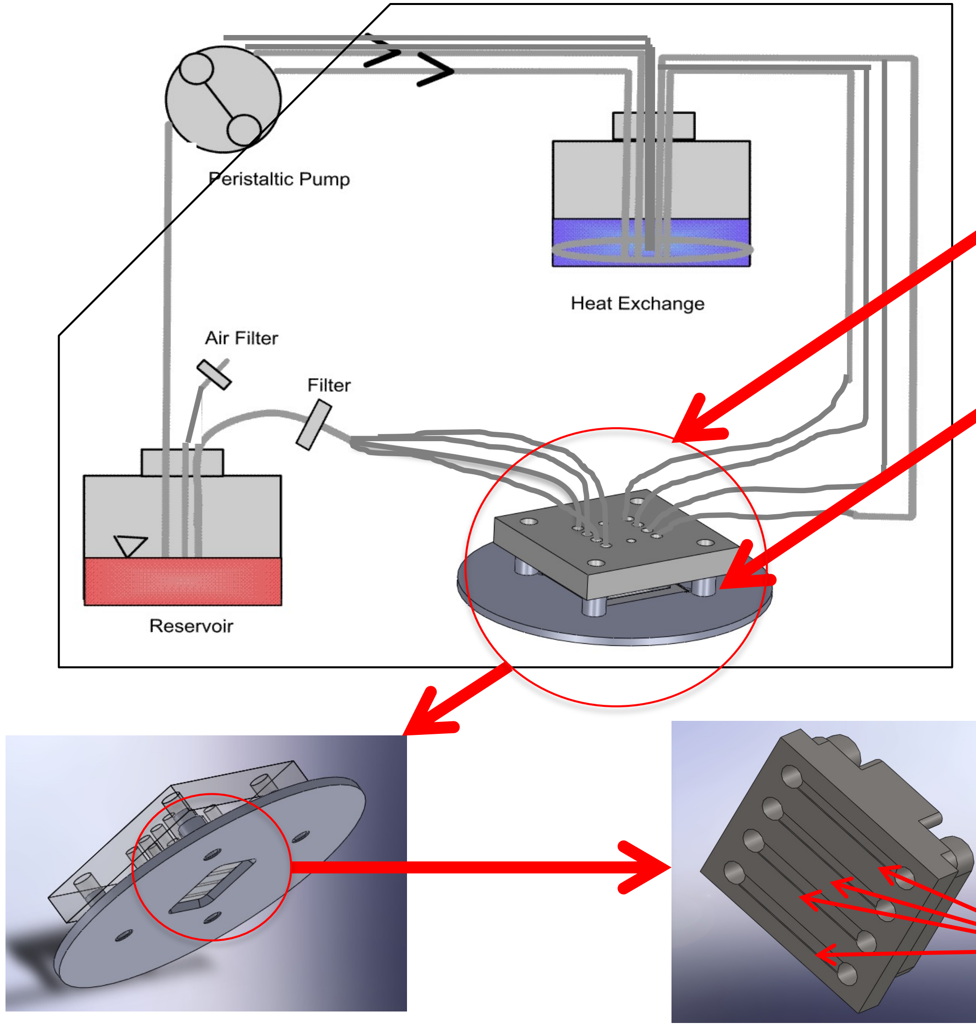


Bone stress

EPFL-LBO (A. Terrier)

Design of a flow chamber

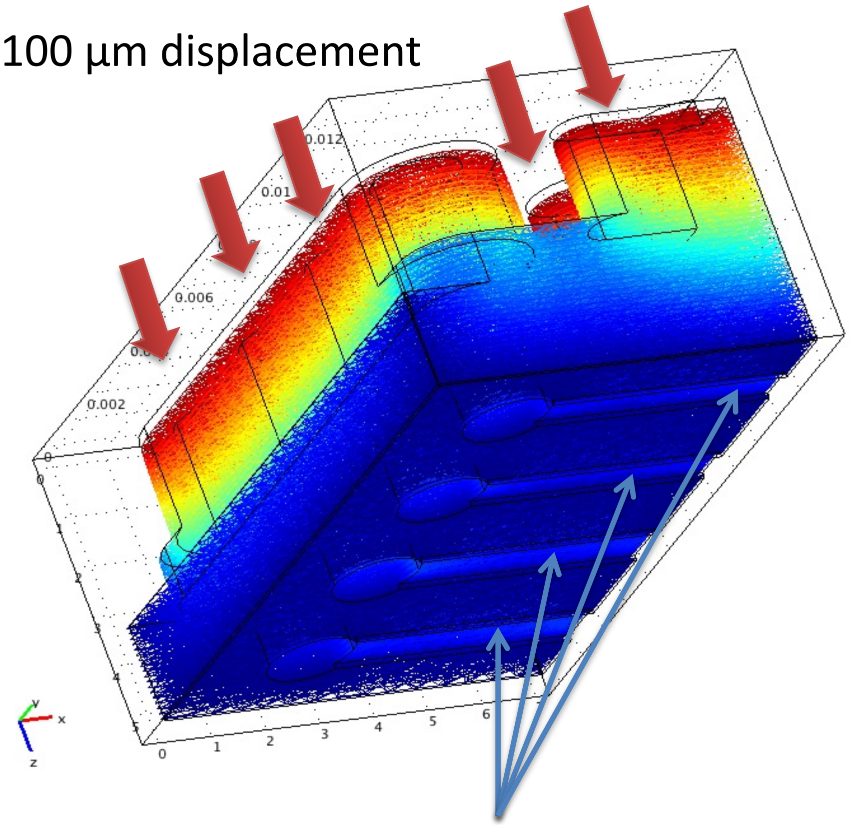
Effect of spacer height on channel deformation



EPFL-LBO (M. Gortchacow)

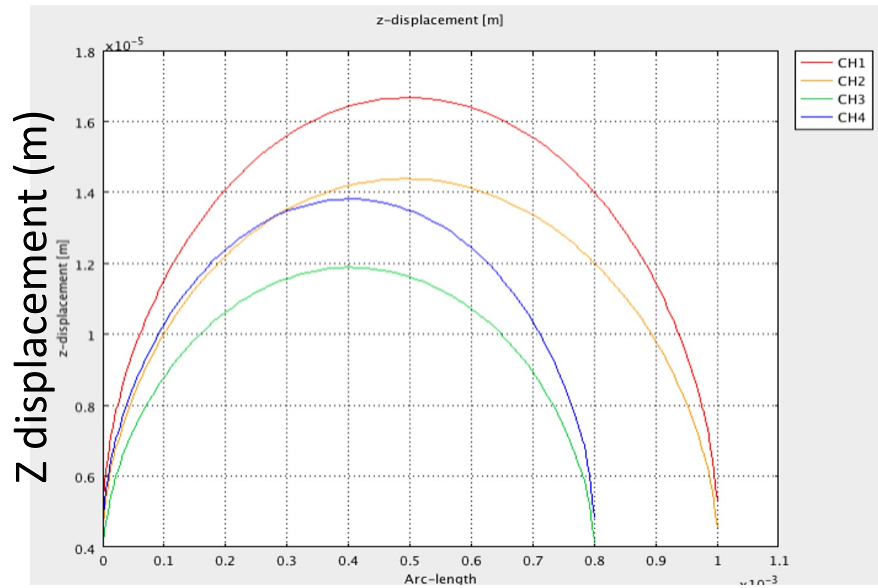
Flow channel deformation

100 µm displacement



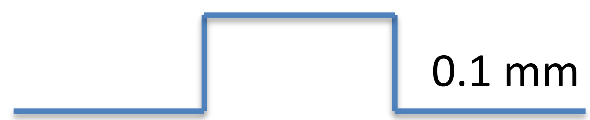
Channels

Vertical Displacement at channel center



Channel width

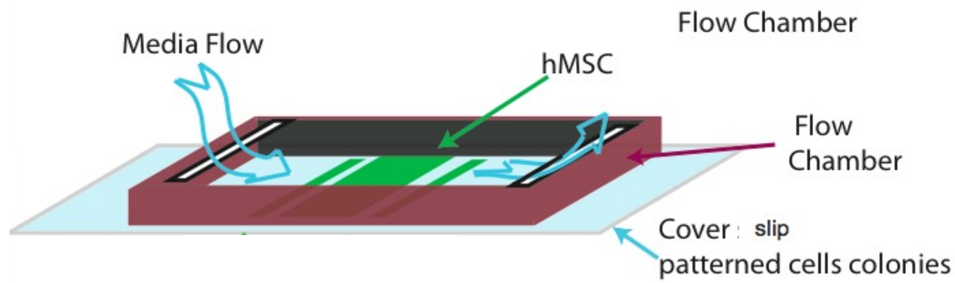
0.8 or 1 mm

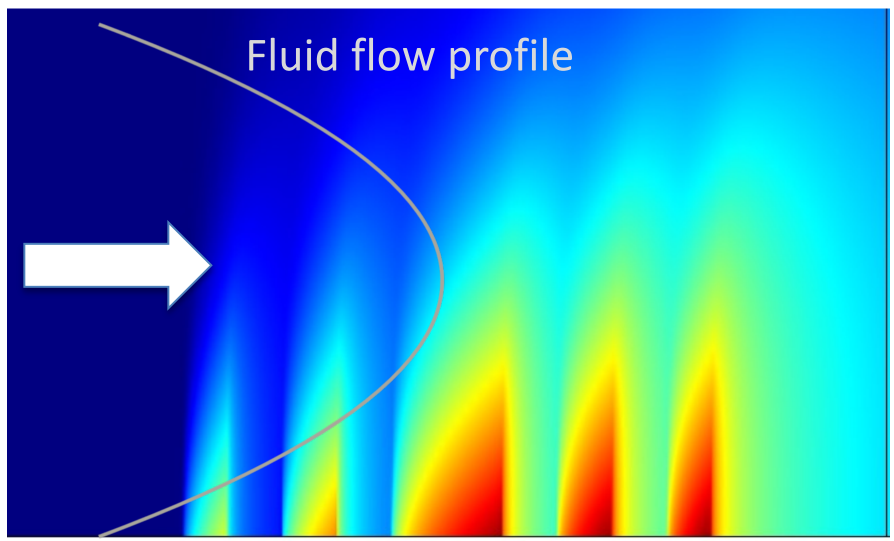


0.1 mm

EPFL-LBO (M. Gortchacow)

Design of the experiment

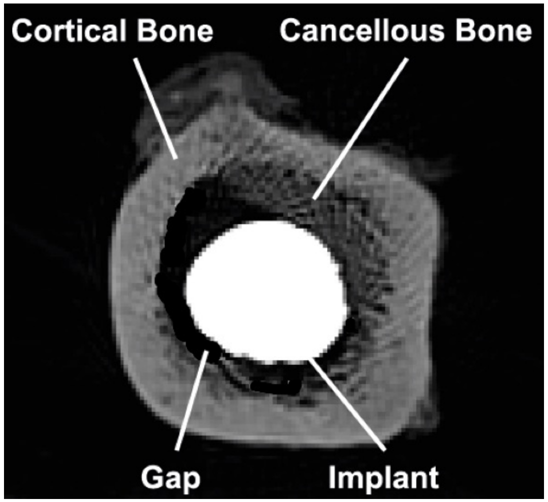




Morphogen concentration

EPFL-LBO (M. Gortchacow)

Fluid Flow Within Bone-Implant Gap



$$-\nabla\sigma = 0$$ Navier

$$S\frac{\partial p_f}{\partial t} + \nabla\cdot\left[-\frac{\kappa}{\mu}\nabla p_f\right] = -\alpha_B\frac{\partial \varepsilon_{vol}}{\partial t}$$ Darcy's & continuity

$$\sigma = \mathbf{C}(E,\nu)\varepsilon(\mathbf{u}) - \alpha_B p_f$$

$$p_f = \frac{1}{S}(\zeta - \alpha_B\varepsilon_{vol})$$ Biot

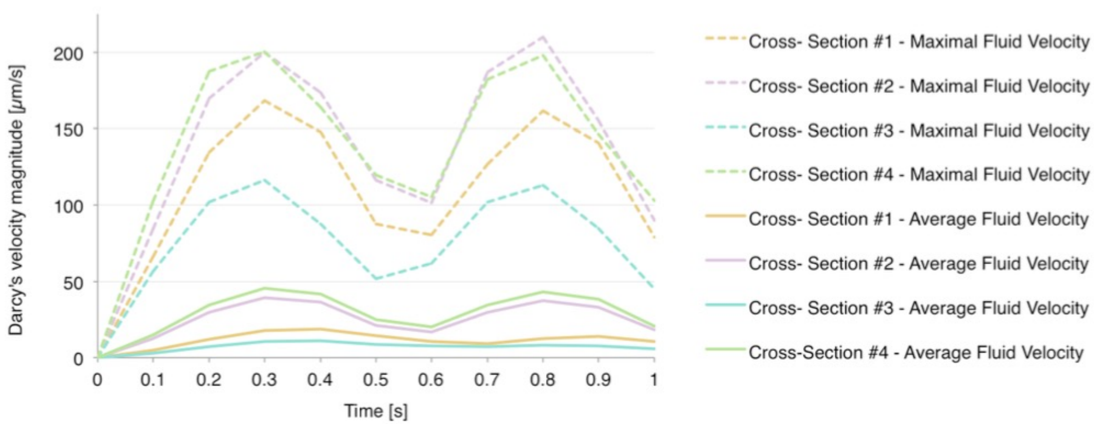


Figure 1 - Average and maximal interstitial fluid velocity in granulation tissue during one load cycle

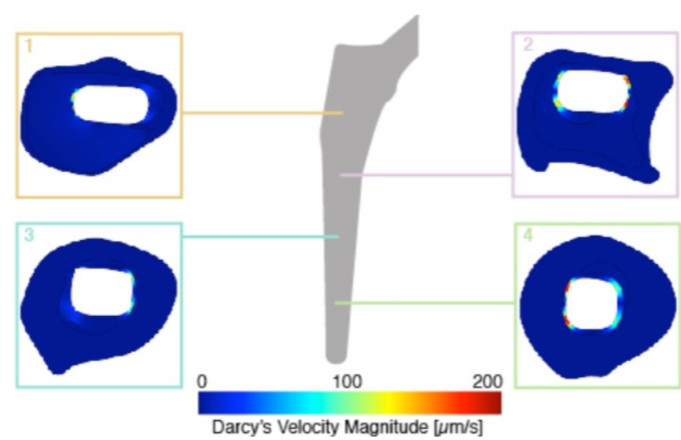
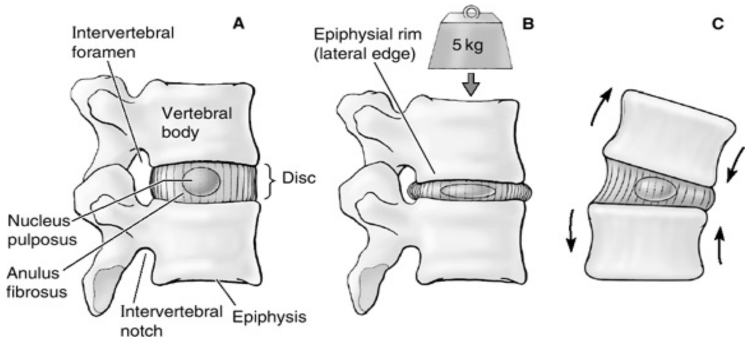
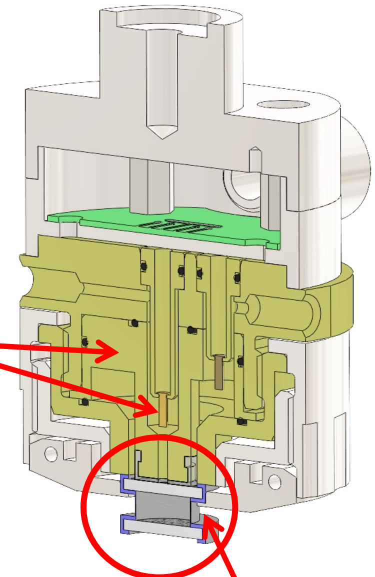


Figure 2 - Interstitial fluid velocity at the bone-implant interface around a cementless femoral stem

EPFL-LBO (Malfroy Camine 2015)

Design of a micro-calorimeter



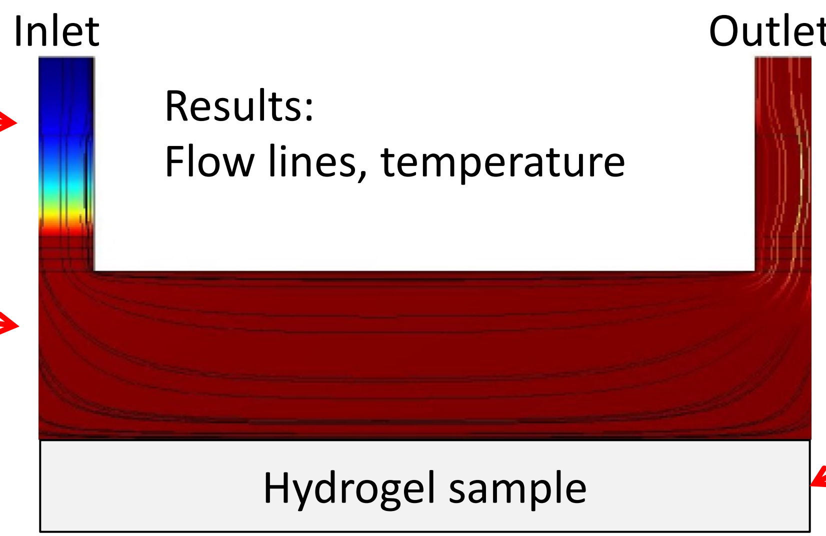


Thermistors

Hydrogel sample

Perfusion tubes
Fluid flow (Navier-Stokes equ.)

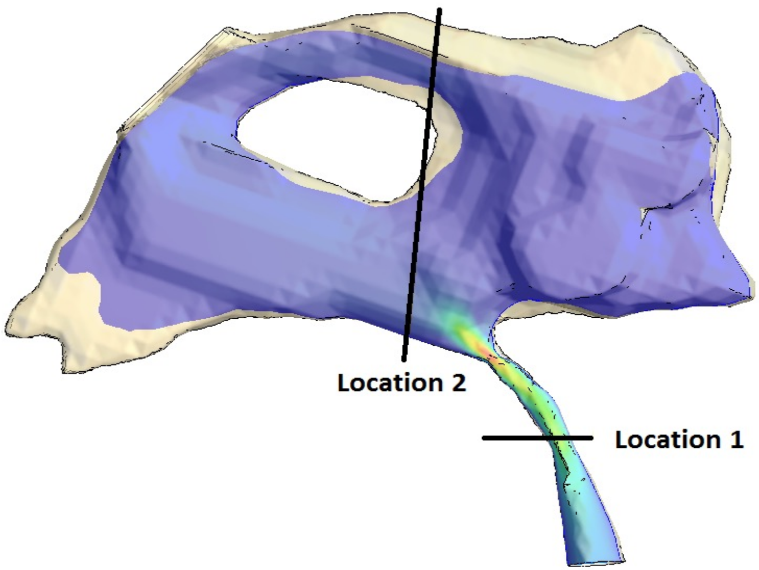
Porous filter
Fluid flow (Brinkman equ.)
Temperature (Heat equ.



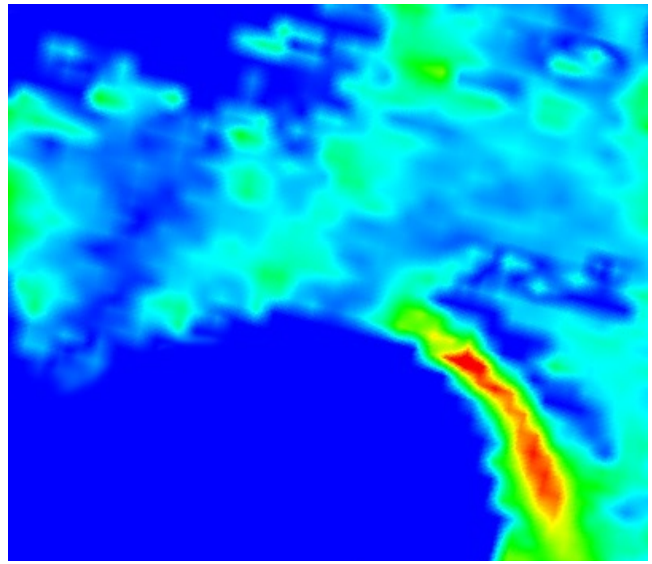
EPFL-LBO (A. Vogel)

Cerebrospinal Fluid Flow

Simulation of flow velocity in the aqueduct of Sylvius and third ventricle



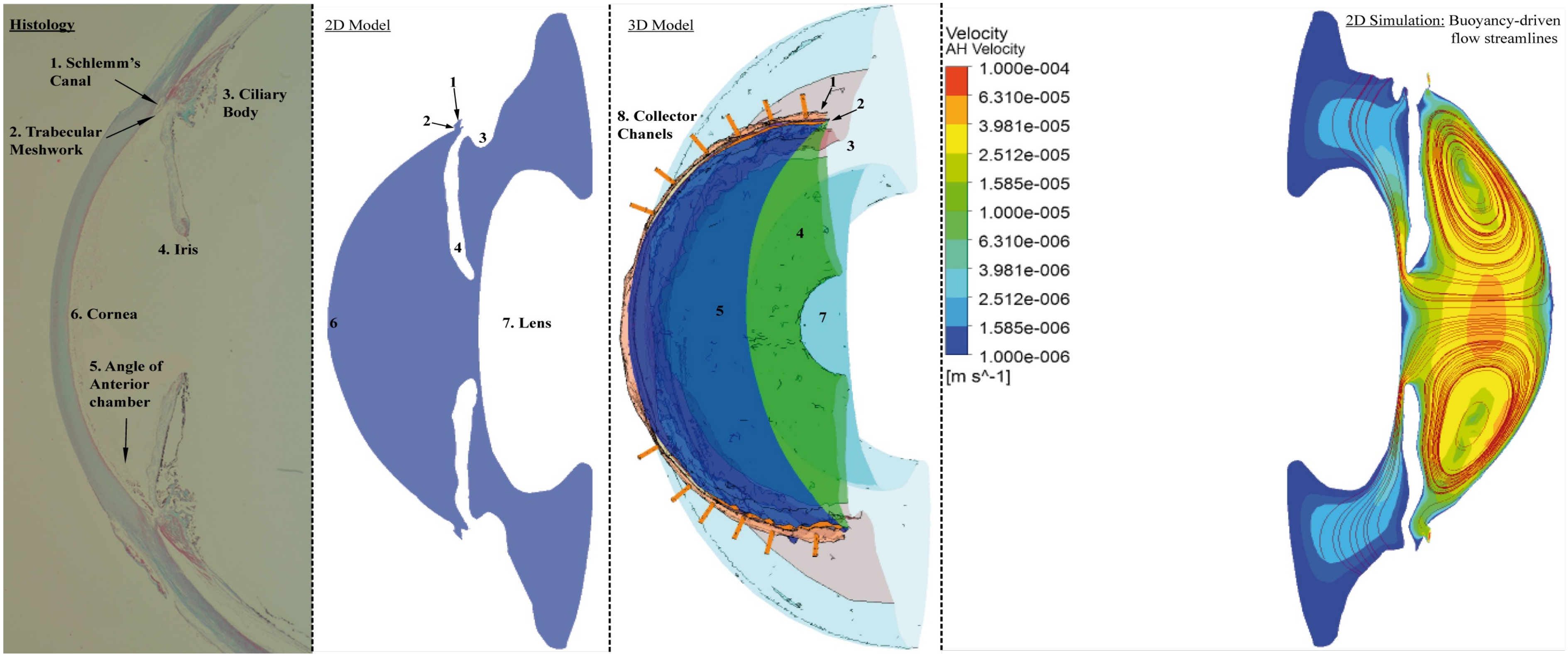
Simulation



Measurement (MRI)

EPFL-LHTC (T. Yiallourou)

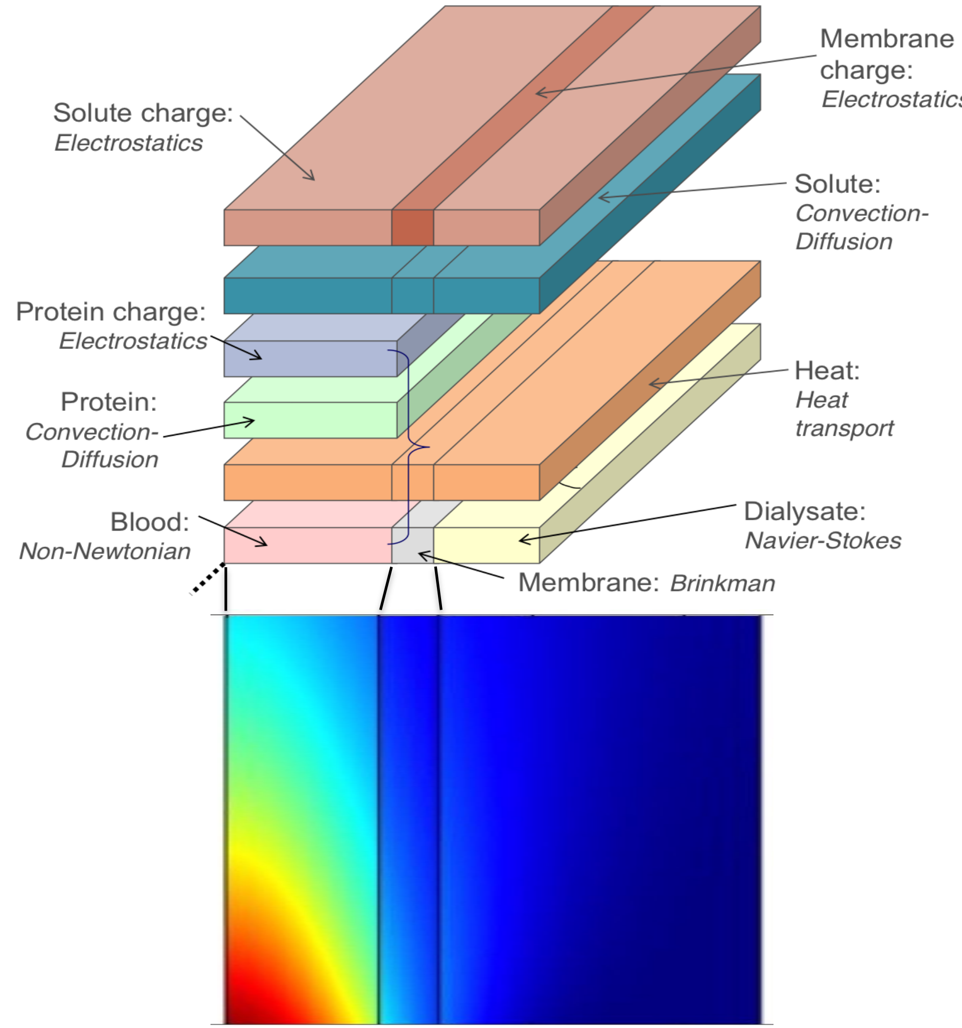
Glaucoma drainage device



EPFL-LHTC (A. Villamarin)

Artificial kidney

- Solute transport
- Non-Newtonian blood
- Osmotic pressure
- Protein convection
- Fluid flow, pressure
- Heat
- Ionic charges



Waste concentration

Department of Biomedical Engineering, Louisiana Tech University (Prof S. Conrad)

Summary

- Advantages of numerical methods
  - Between theory and experiment
  - Reduce time of development
  - Reduce costs
  - Reduce risks
  - Increase understanding
  - Increase creativity
- Applications
  - Test hypotheses
  - Parameters analysis
  - Phenomena understanding
  - Rapid prototyping (feasibility analysis) of complex systems or devices