Heat and Fluid Flow in Emerging Technologies

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Mechanical and Process Engineering

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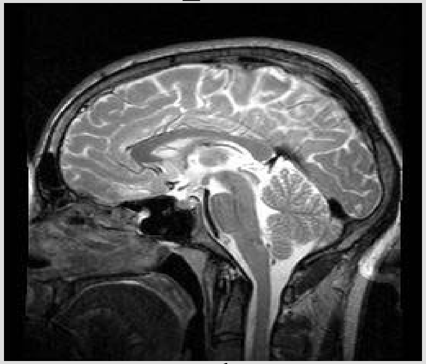
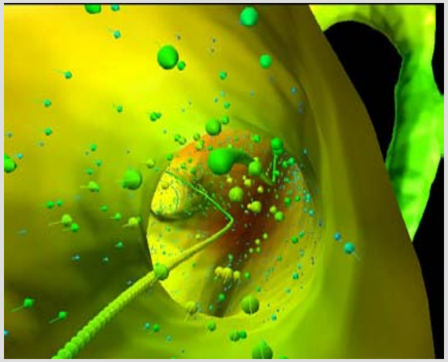
2004 Hawkins Memorial Lecture
Purdue University

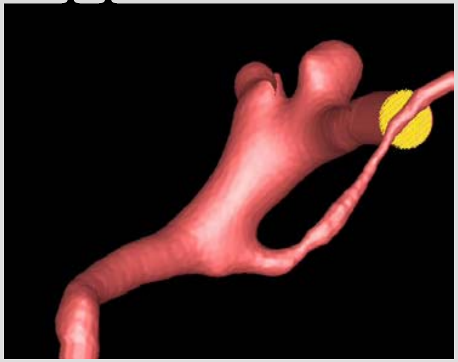
Laboratory of Thermodynamics in Emerging Technologies at ETH

www.ltnt.ethz.ch

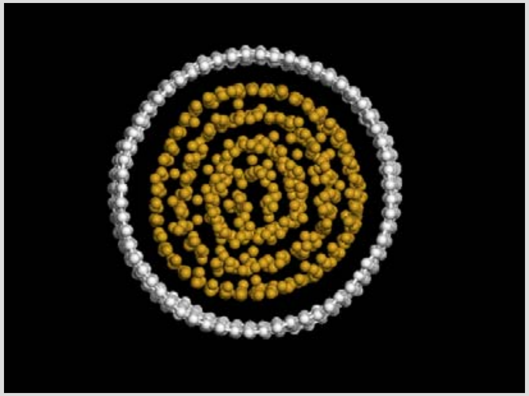
- Bio- Trasport Phenomena for Medical Applications

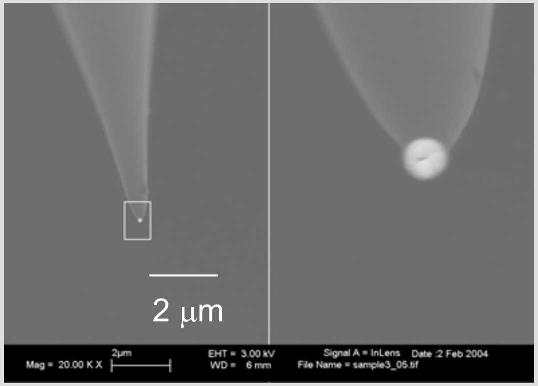


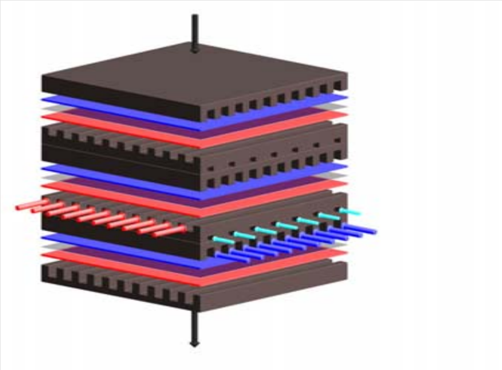




- Micro- and Nanosclale Energy Conversion and Transport including Physics at the Molecular level







Outline

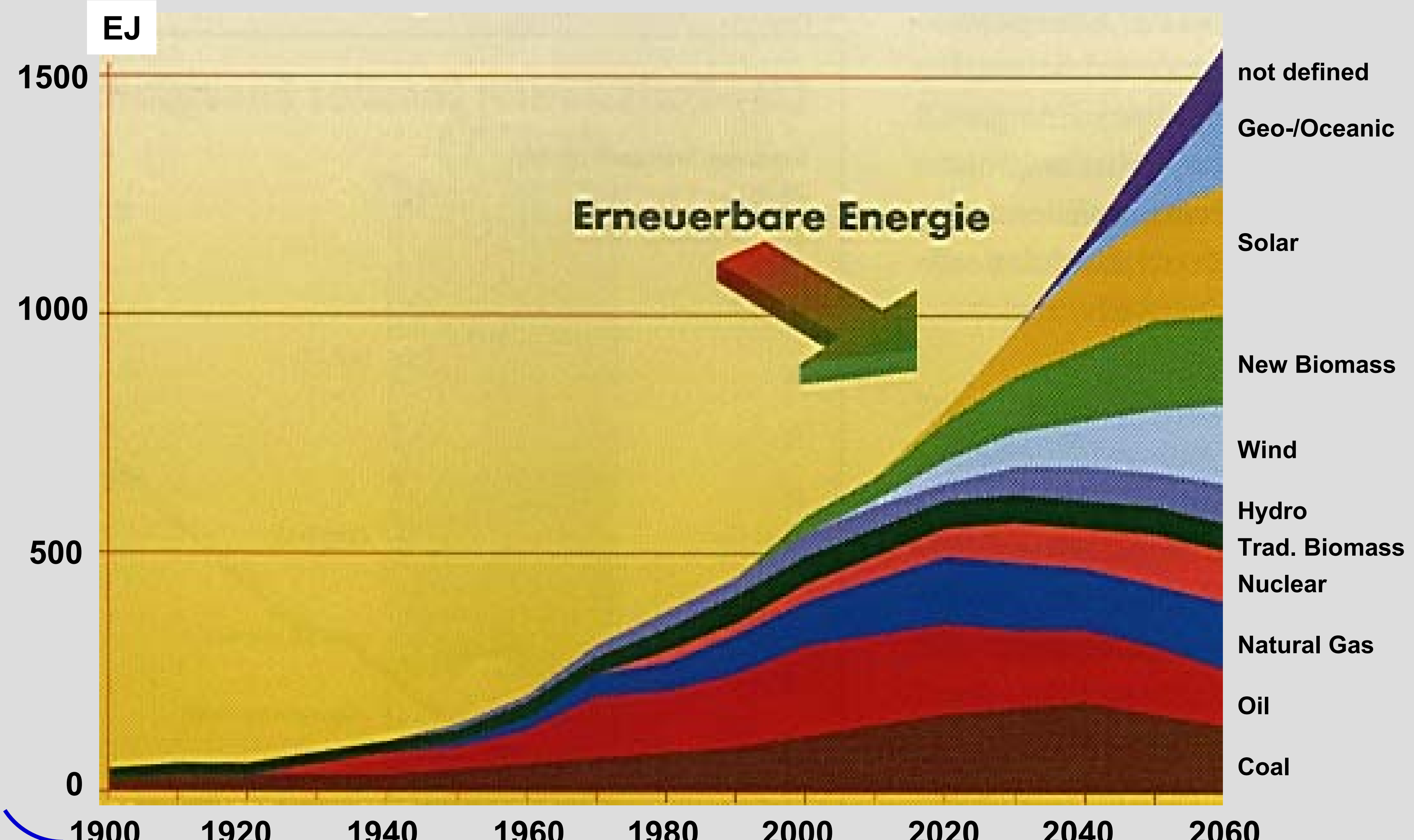
- Emerging Trends Related to Energy Conversion and Transport: **General Aspects**
- Energy **Conversion:**
  - Energy Convertors: Fuel cells
- Energy and Fluid **Transport:**
  - Nanoscale Transport Phenomena: Nanoinks-Nanotubes
  - Transport Phenomena in the Human Body
    - Aneurisms
    - Cerebrospinal Fluid Diagnostics & Control

Estimate:

By 2025, renewable resources are expected to provide between 5% and 10% of the world's energy, and as much as 50% by 2050.

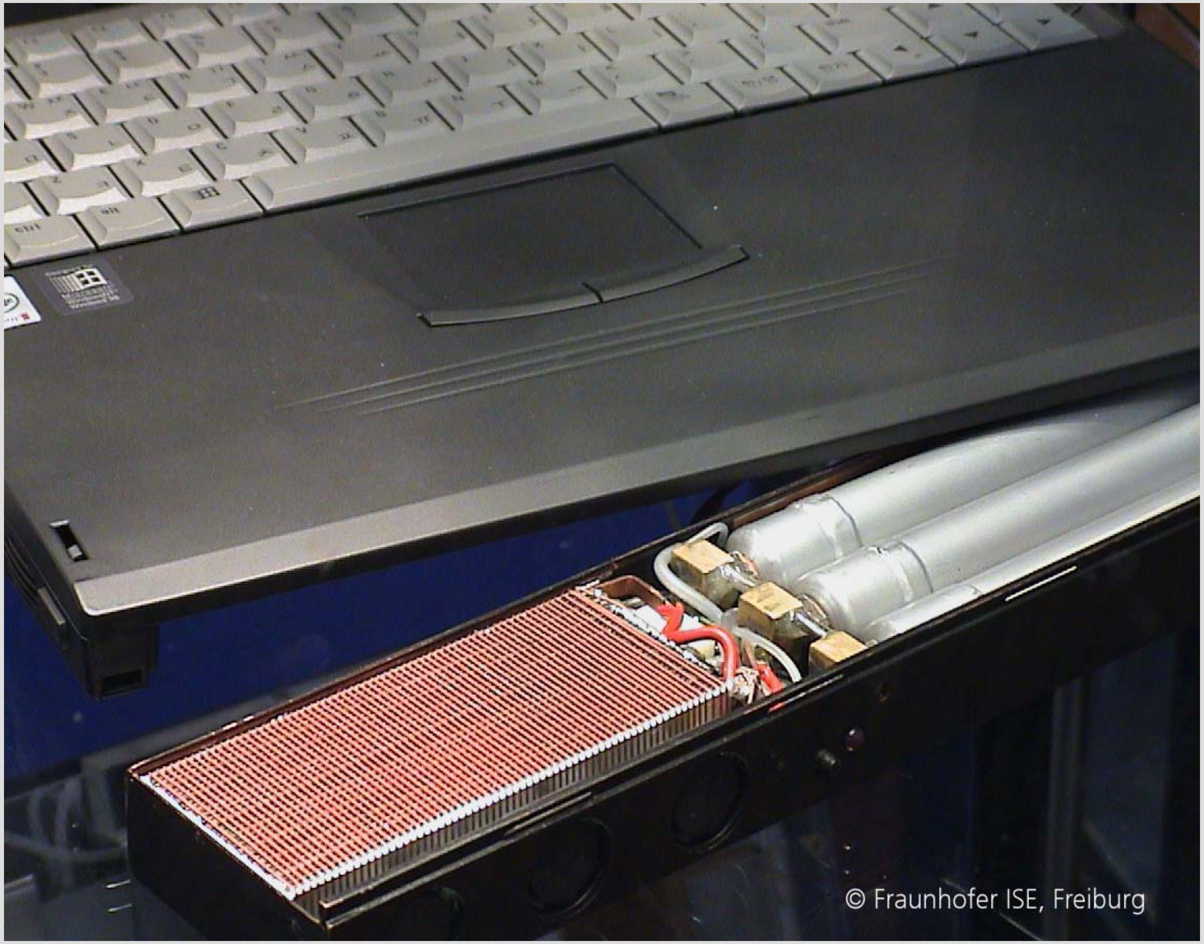
WORLD ENERGY CONSUMPTION

Scenario: ***Sustainable Growth***

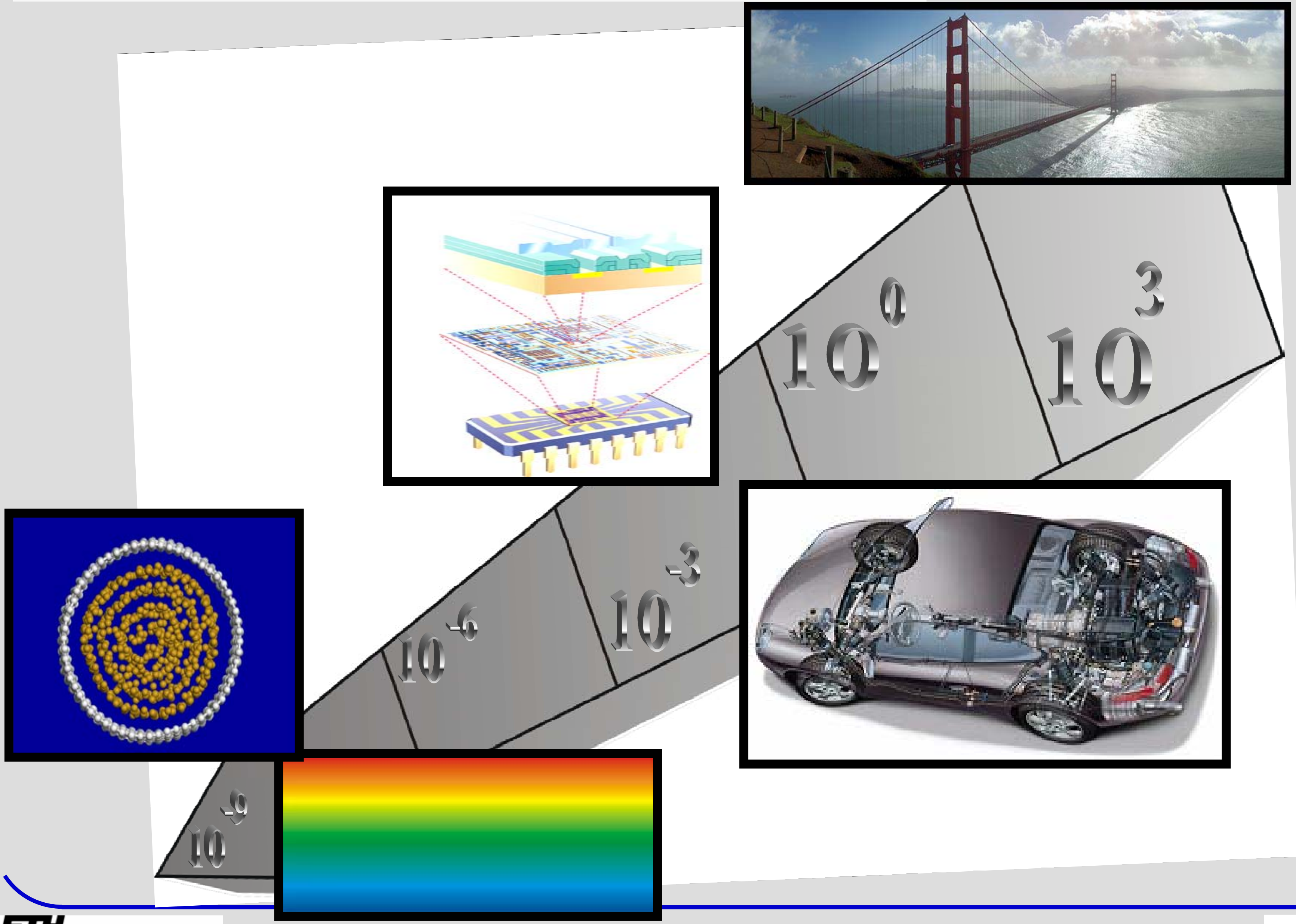


Novel(?) Energy Convertors: The Fuel Cell
Direct energy conversion from chemical to electrical

Fuel Cell System
for a 50 W_{max} Laptop
(Fraunhofer Inst. Freiburg)

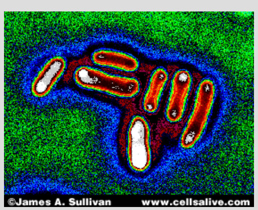


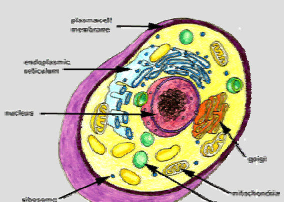
The Fuel cell concept is over 150 years old (Sir William Grove in 1839). Grove used porous platinum electrodes and sulfuric acid as the electrolyte bath. William White Jaques later substituted phosphoric acid in the electrolyte bath and coined the term „fuel cell“.

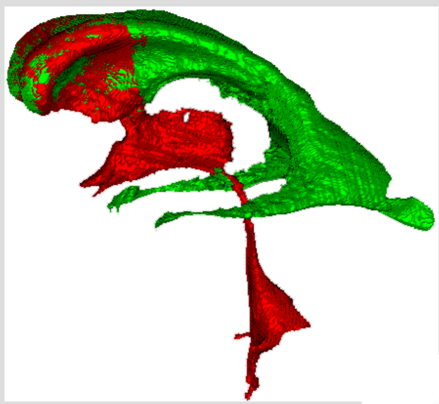

10^-9
10^-6
10^-3
10^0
10^3

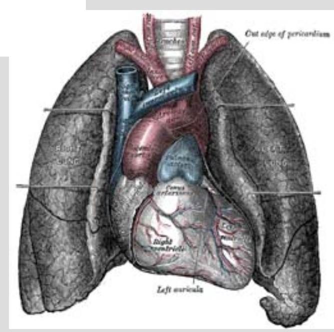
Transport Phenomena in Biomedical Engineering:

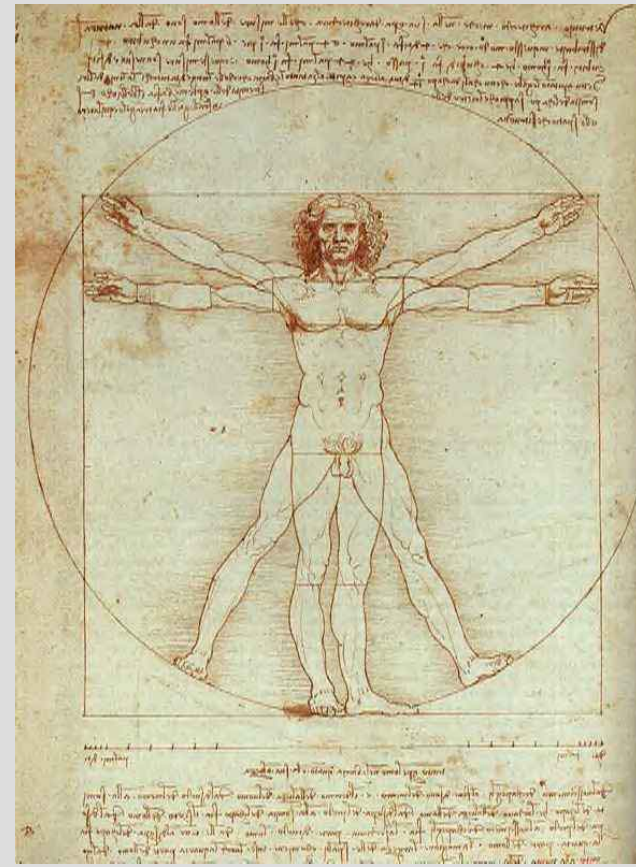
From the cell level to the organ level involving physiology











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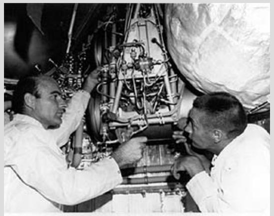
Current Fuel Cell Applications and Challenges

- Transportation (e.g. cars, boats, buses)
- Domestic combined heat and power generation
- Distributed power generation
- Integration of fuel cells in gas turbine combined cycles
- Power generation for portable applications (e.g. laptop computers, cell phones)

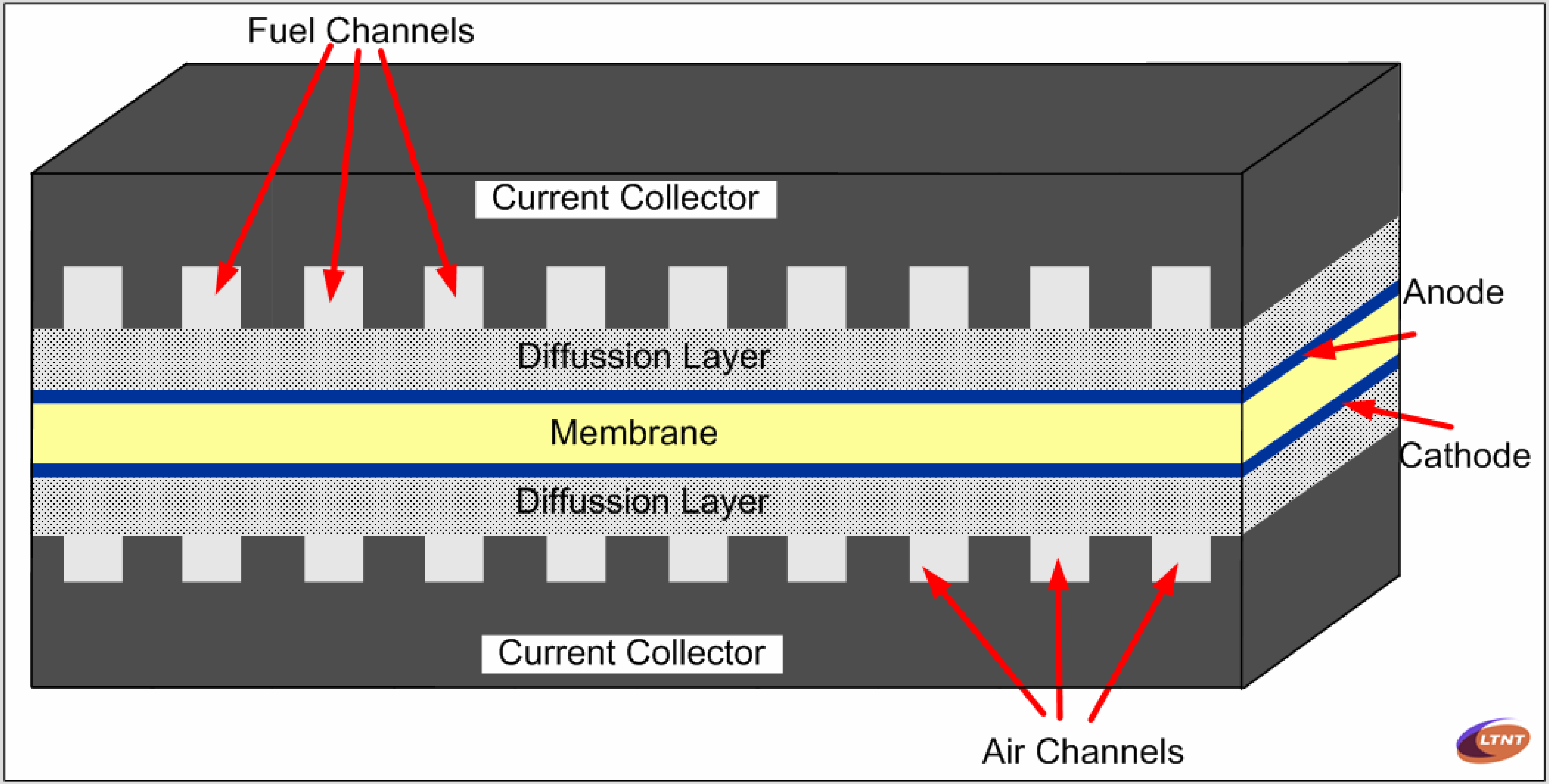
- Competition with other technologies
- Manufacturing and materials cost
- Durability and dependability
- Production of hydrogen
- On board hydrogen storage
- Getting hydrogen to consumers
- Safety
- Public acceptance



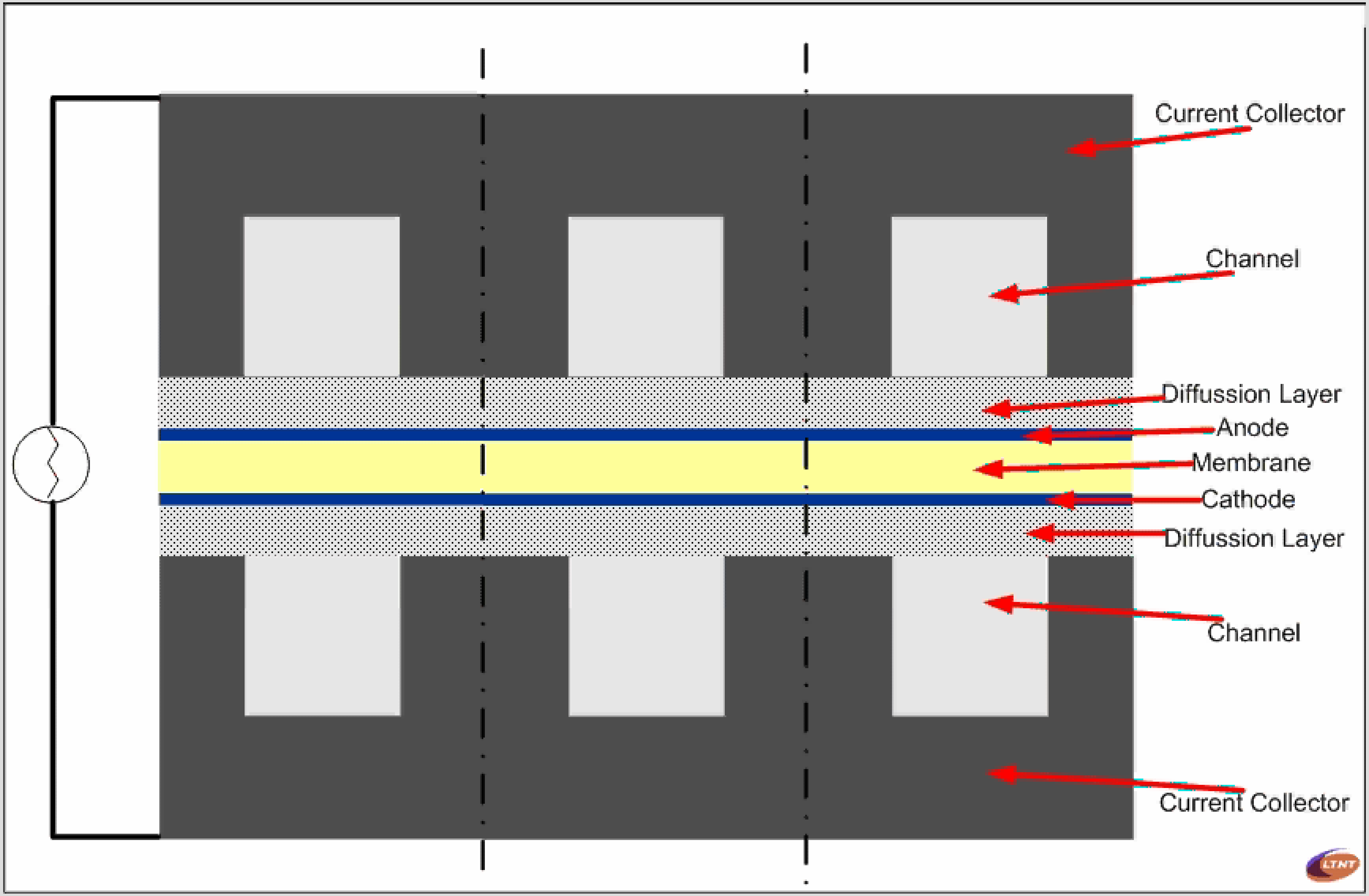


Types of Fuel Cells

	Mobile Ion	*Operating Temperature*
Polymer electrolyte fuel cells (PEFC)	H+	50-120°C
Direct methanol fuel cells (DMFC)	H+	50-120°C
Phosphoric acid fuel cells (PAFC)	H^+	220°C
Solid oxide fuel cells (SOFC)	O^{2-}	500-1000°C
Molten carbonate fuel cells (MCFC)	CO_3^{2-}	650°C
Alkaline fuel cells (AFC)	OH^-	50-200°C


Fuel Channels
Current Collector
Anode
Diffussion Layer
Membrane
Cathode
Diffussion Layer
Current Collector
Air Channels

Working Principles and Engineering Design



Fuel Cell Modeling

- Transport phenomena in the fuel cell

  - fluid mechanics, single and two-phase flow regimes

  - multicomponent mass transfer

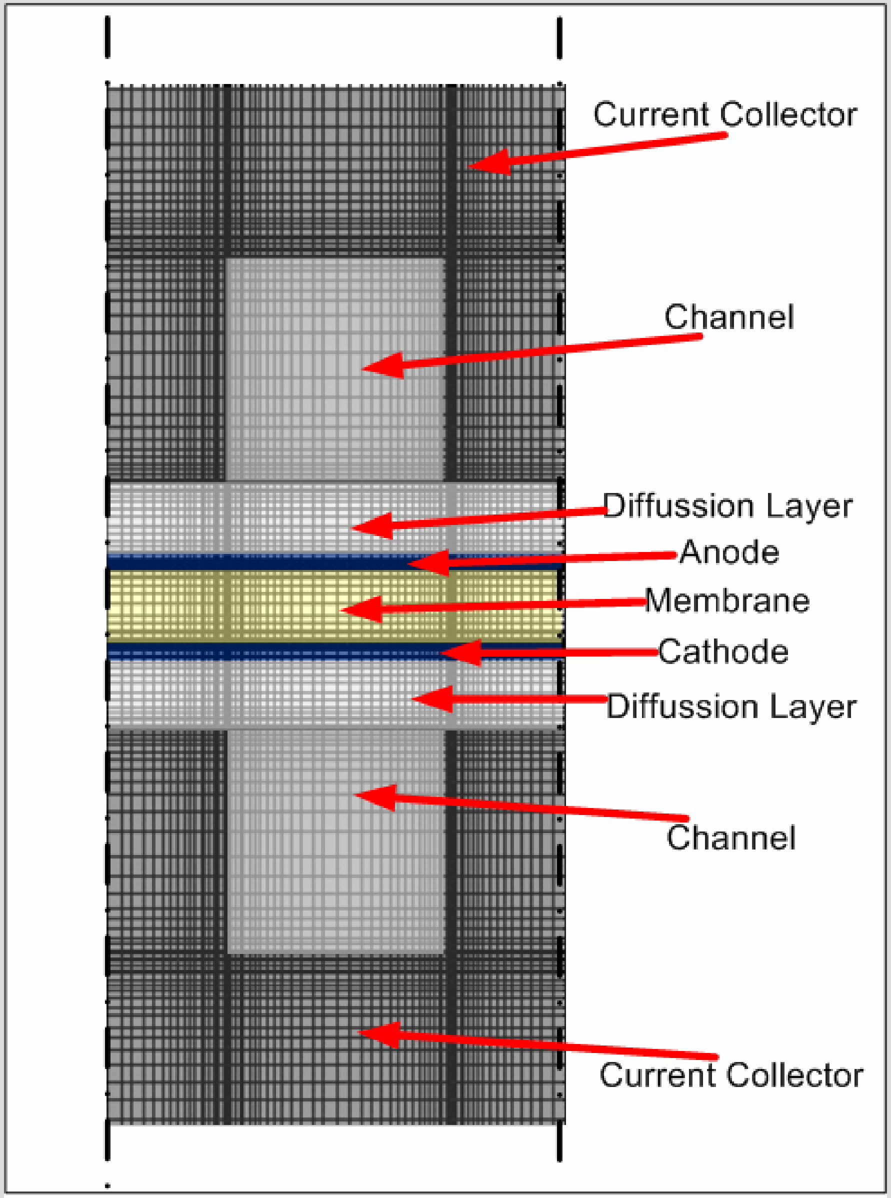
  - heat transfer

  - electron and proton transport

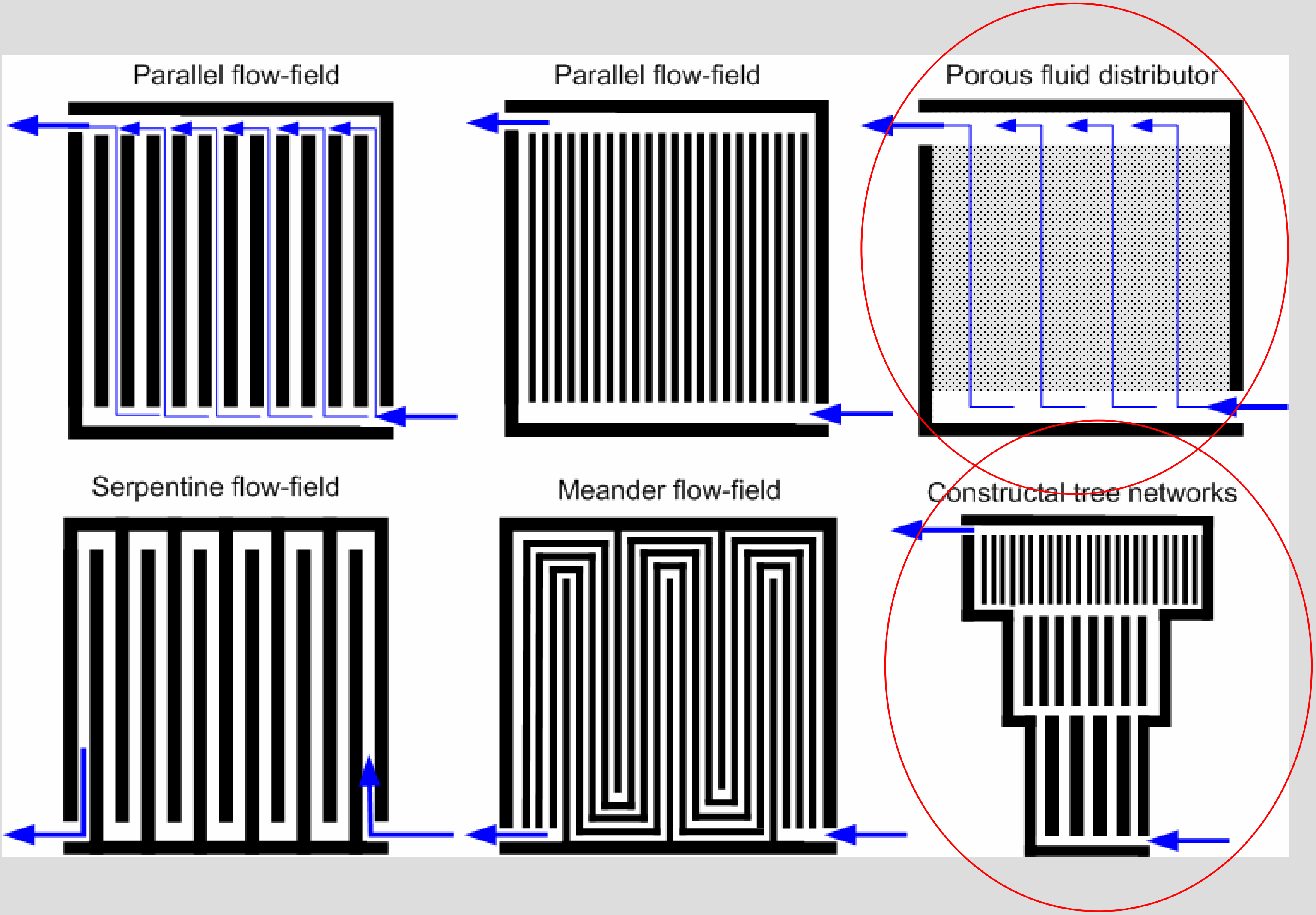
  - electrochemistry

- Modeling provides an improved scientific understanding of the fundamental transport phenomena.

- It allows for scientifically based optimization instead of trial and error procedures.

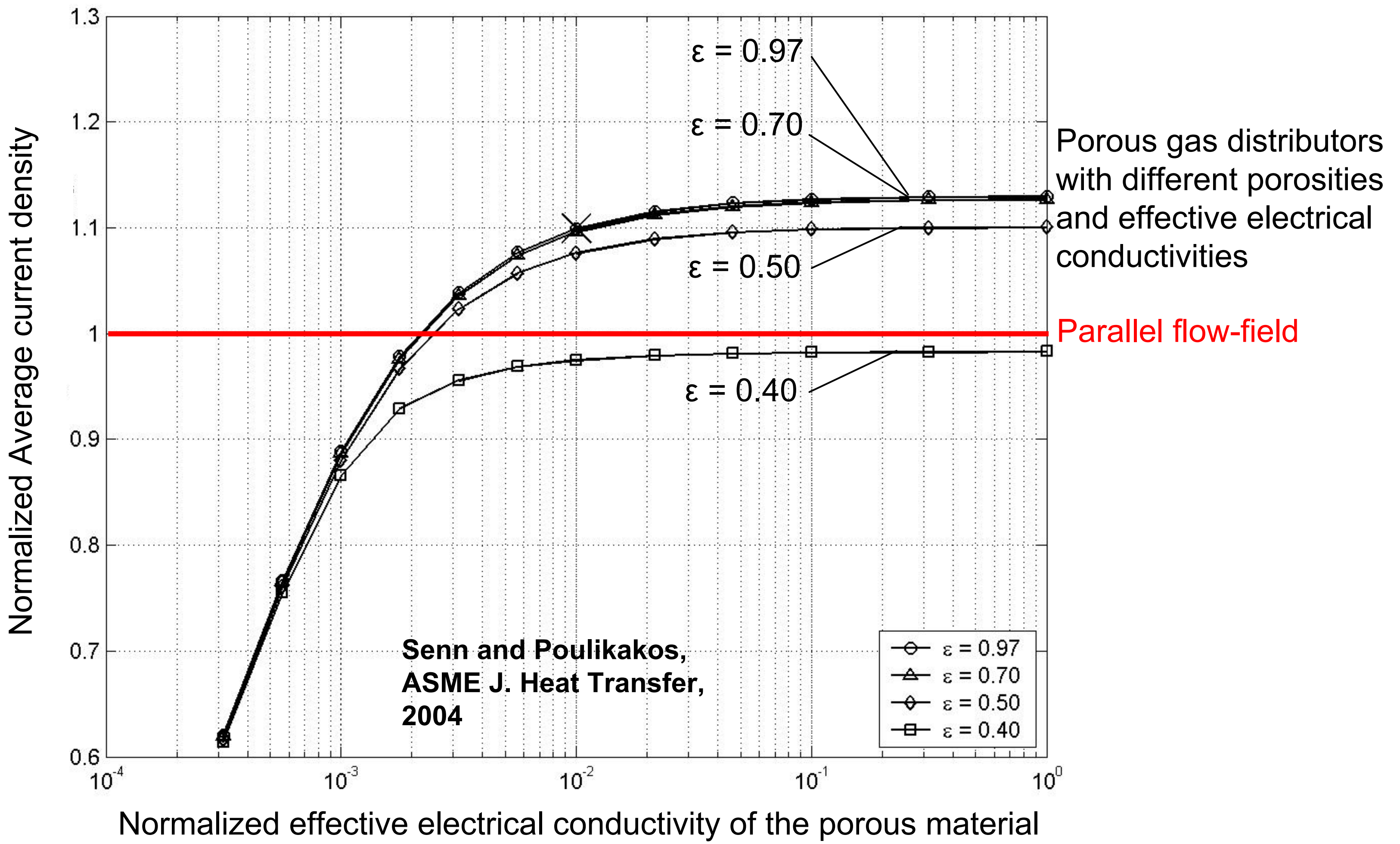


Fluid Distribution in Polymer Electrolyte Fuel Cells



Fluid Distribution in Polymer Electrolyte Fuel Cells

Performance analysis of porous fluid distributors and comparisons with a traditional channeled parallel flow-field

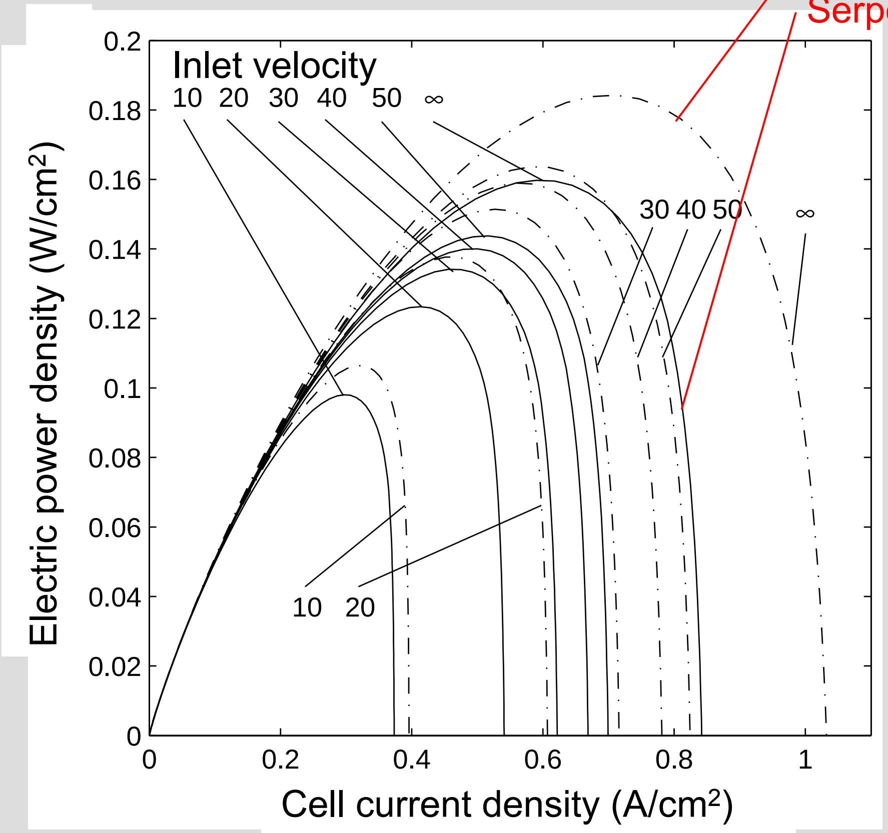


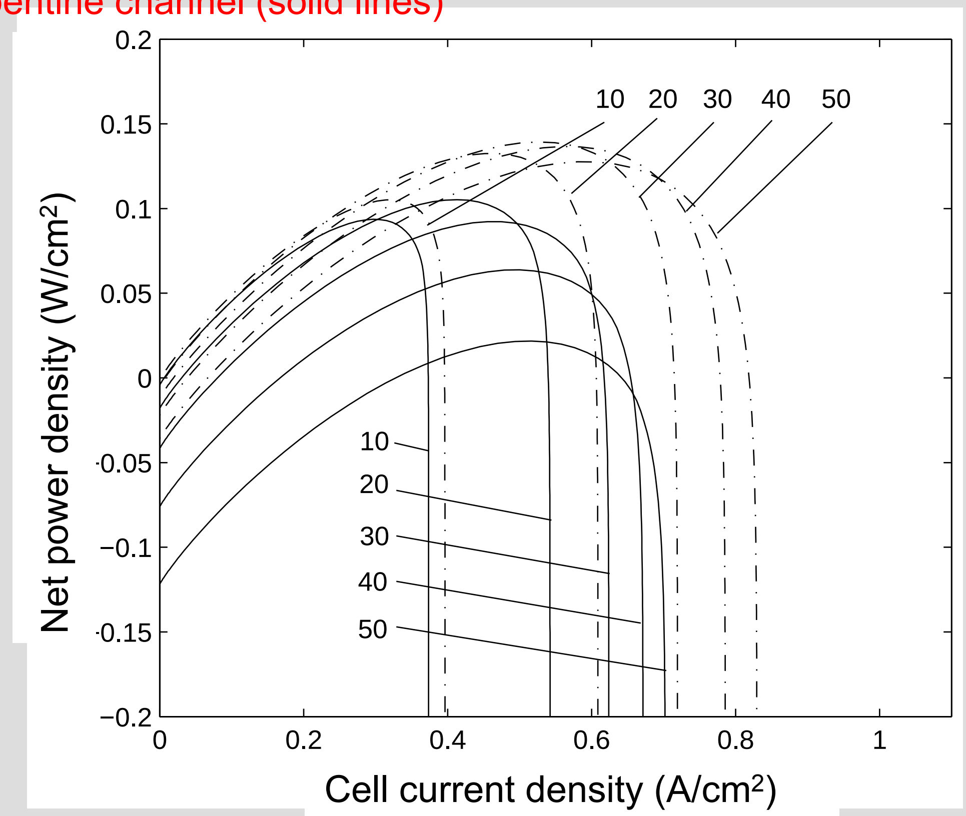
Fluid Distribution in Polymer Electrolyte Fuel Cells

Performance analysis of tree network channel systems and comparisons with traditional serpentine flow-fields

Net power density = electric power density – pumping power density

Tree network channel system (dashed lines)
Serpentine channel (solid lines)

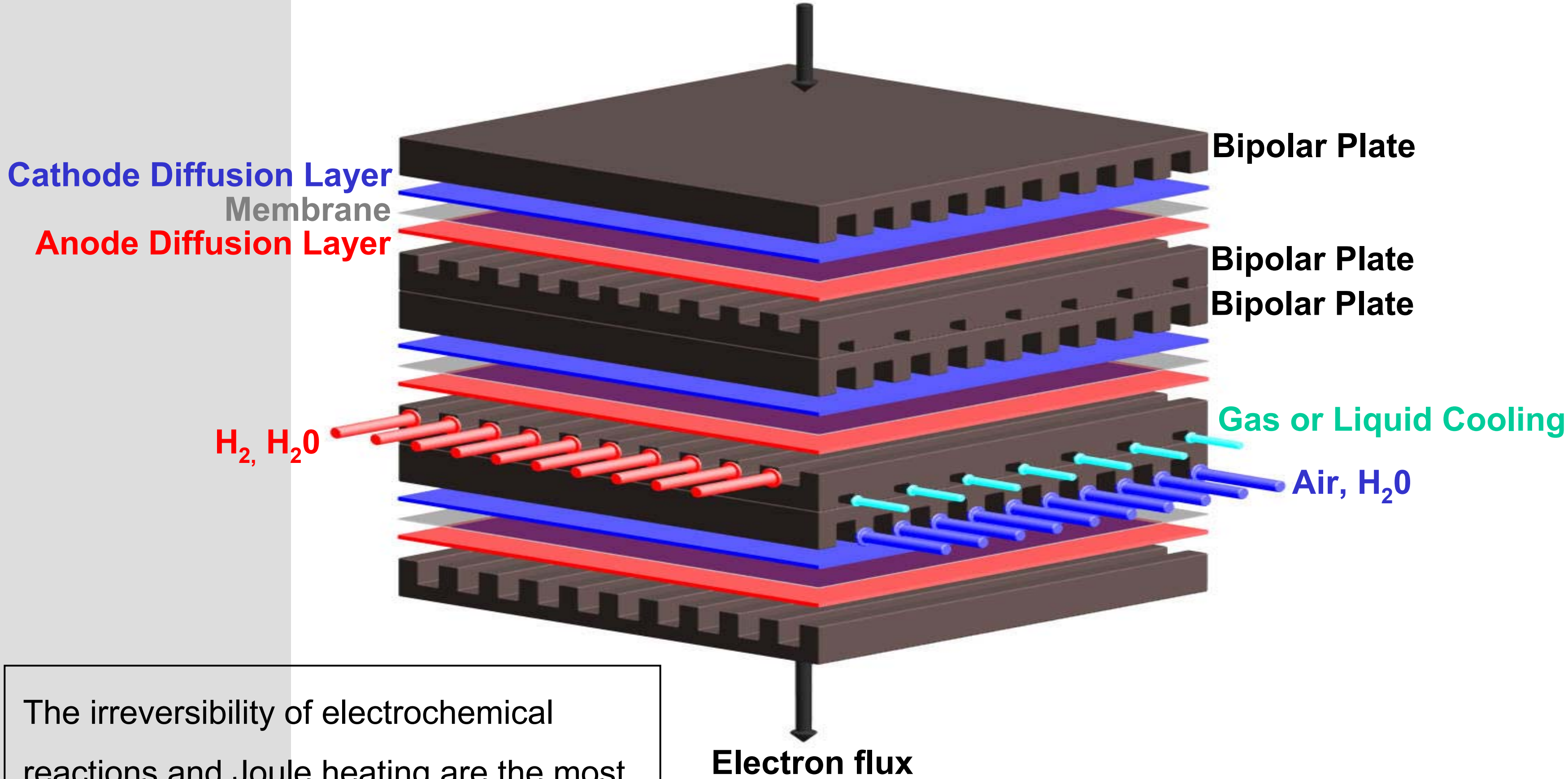




Senn and Poulikakos,J. Appl. Phys., 2004

Thermal Management in Polymer Electrolyte Fuel Cells

Schematic of a fuel cell stack with cooling layers between the bipolar plates



The irreversibility of electrochemical reactions and Joule heating are the most important factors causing heat generation inside PEM fuel cells.

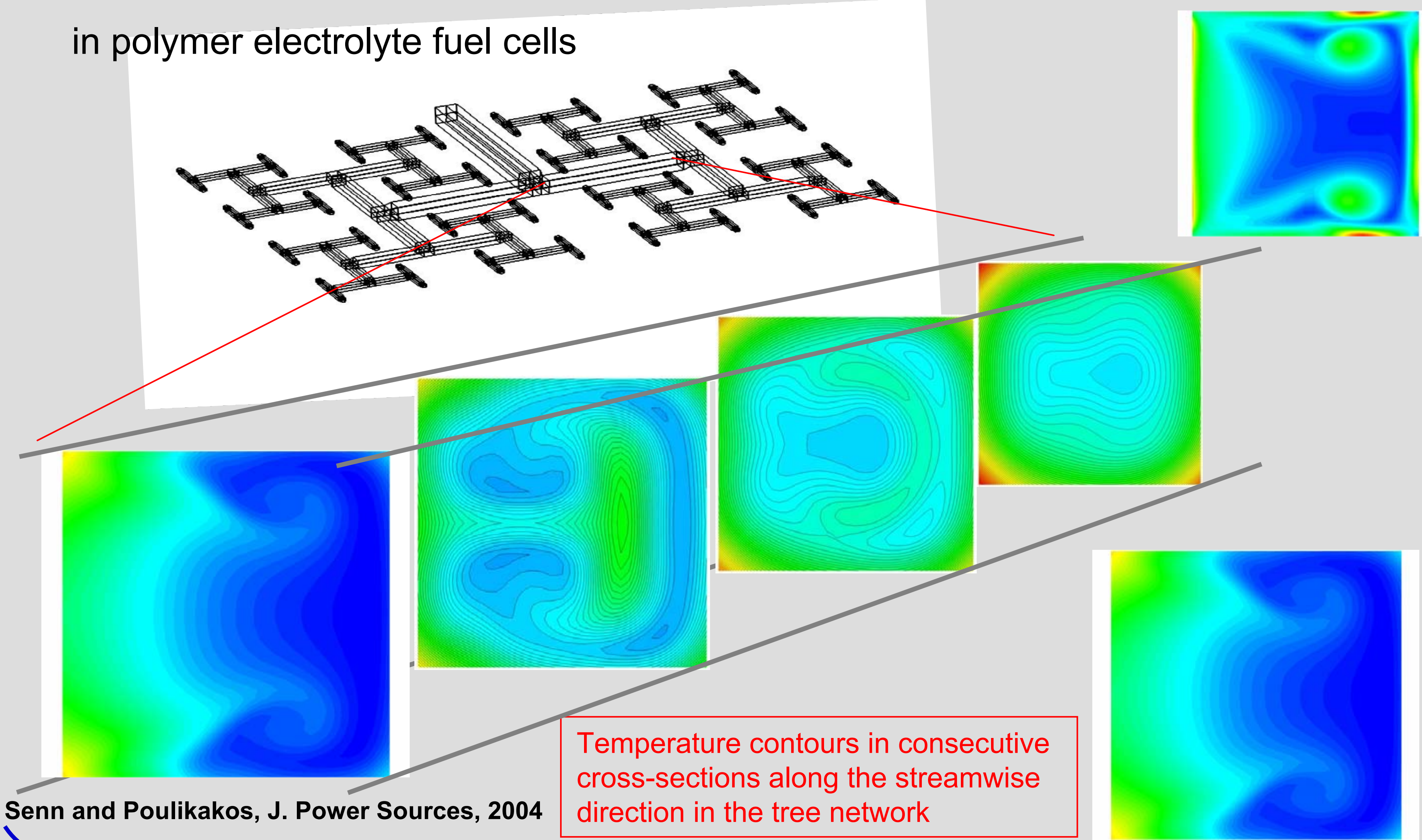
Source: IKB, ETH Zurich

Thermal Management in Polymer Electrolyte Fuel Cells

Tree network channels for thermal management

in polymer electrolyte fuel cells

Vorticity contours



Temperature contours in consecutive cross-sections along the streamwise direction in the tree network

Senn and Poulikakos, J. Power Sources, 2004

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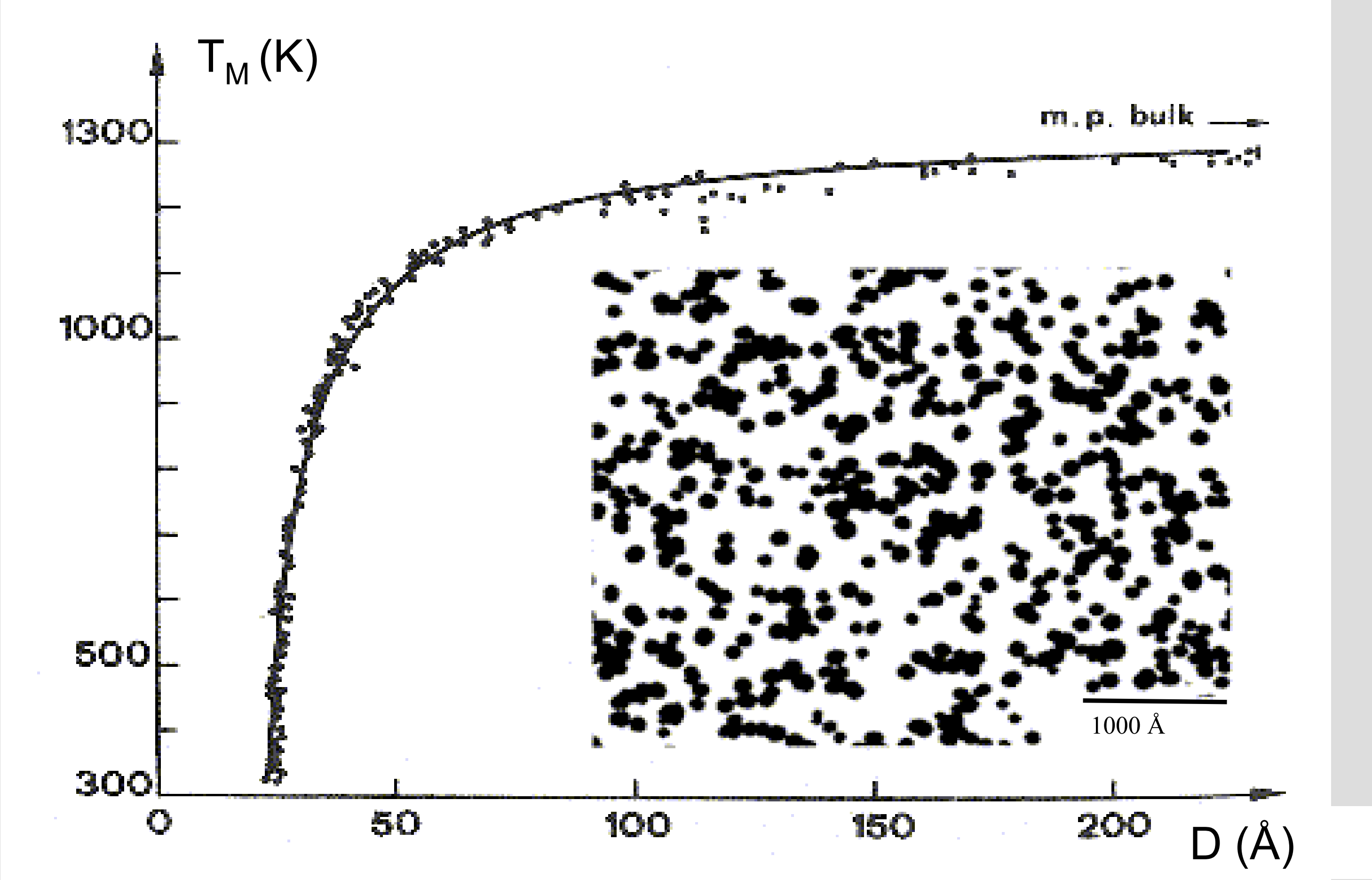
Micro- Nanomanufacturing with Nanoparticles: Use their unique properties in Nanoinks



Buffat and Borel, 1976 EPFL

Fountain-Pen for Gold Nanoink Laser Writing

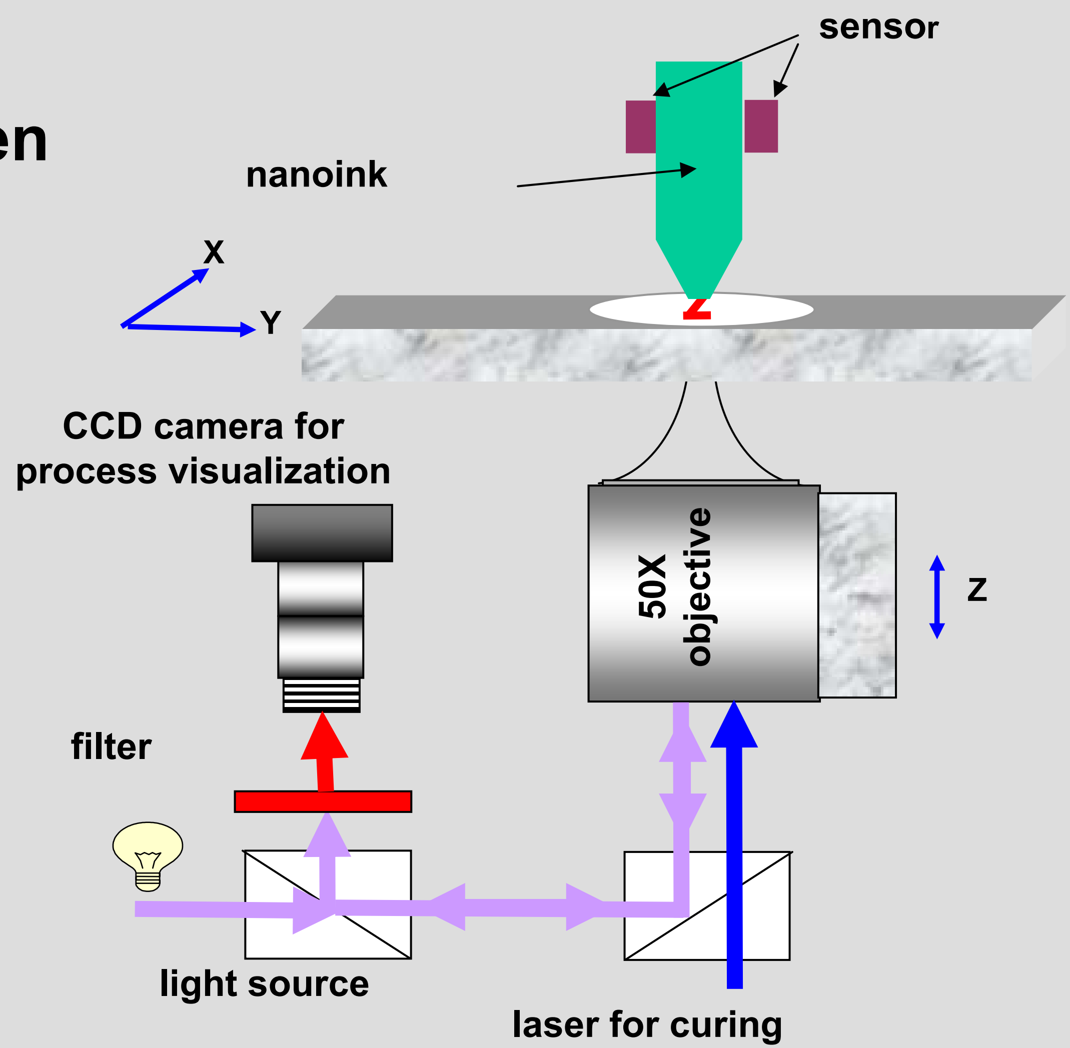
Novel applications in microelectronics demand further reduction of sizes and manufacturing costs:

- no clean-room
- Flexible and “online” production

High density electronics require sub-micrometer size resistors:

- Writing with fountain pen principle of nanoink of resistor material
- Laser Curing

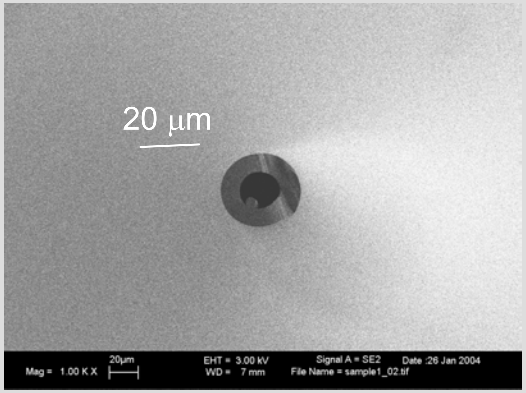
Fountain Pen Setup:

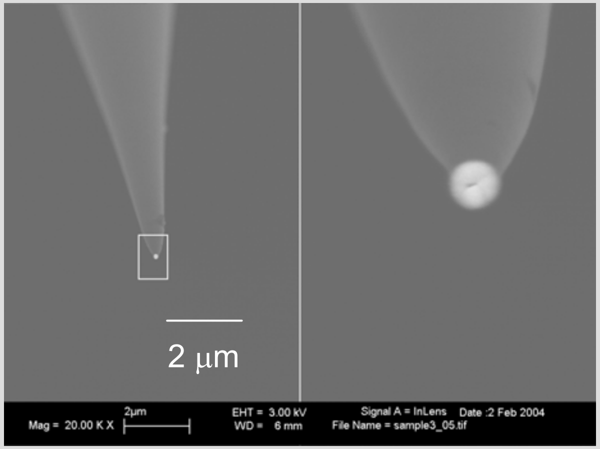


- ink-layer thickness can be controlled, with tip-sample gap regulation.

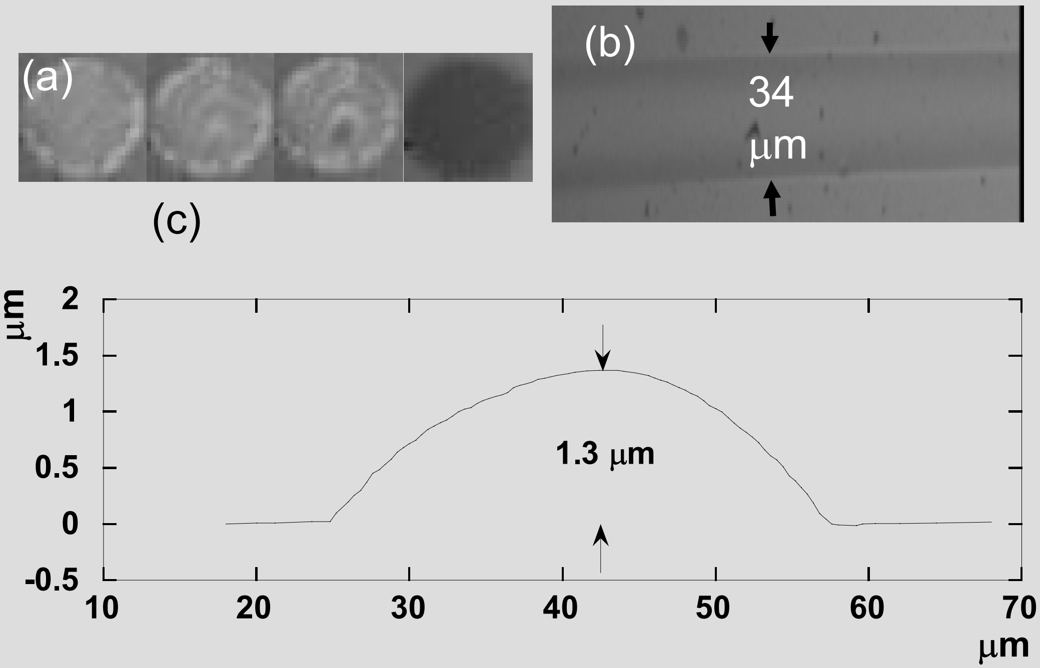
→ thin layers need less energy for curing, polymer substrates become feasible!

- Size of the conductor line can be reduced, by reducing pipette opening .



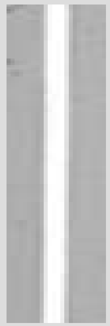


Printing nanoparticle ink

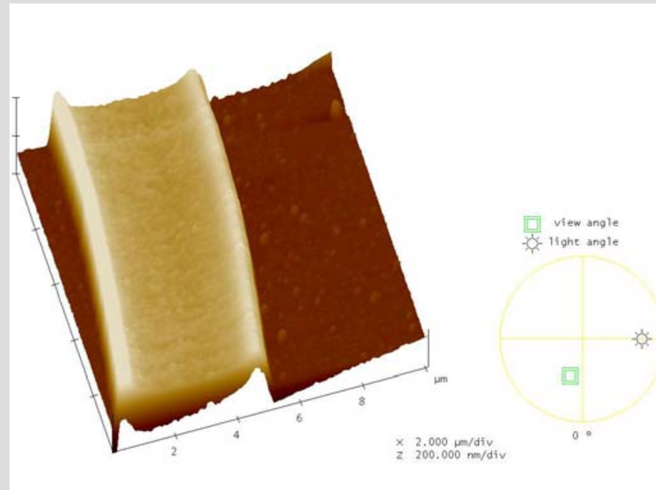


(a) Light microscopy images of wetting of the substrate,
(b) Au nanoparticles ink written on the substrate, and
(c) cross sectional view of the line in (b) by shear force microscopy.
The width of the patterned ink is 34 μm, which is around the same size of the pipette opening. The contact angle is measured at 7.5 degrees.

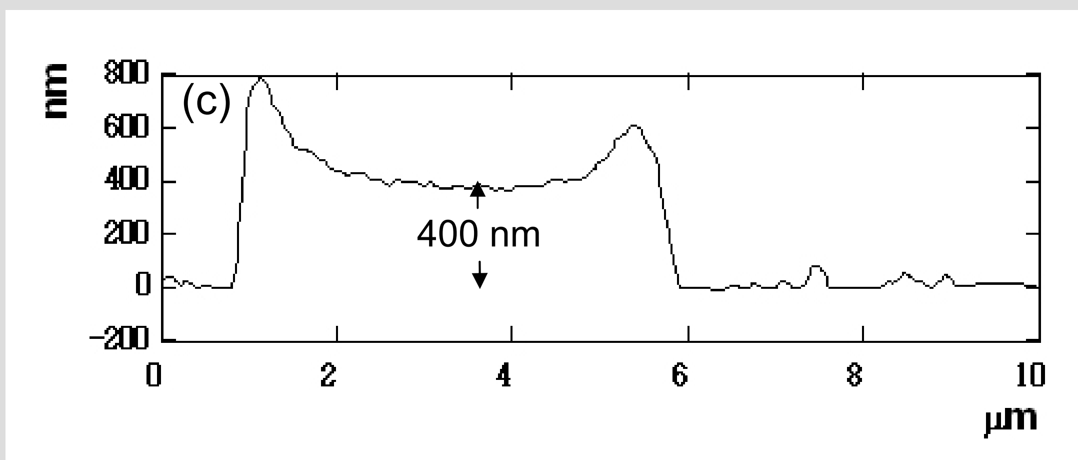
Microline Curing



(a)

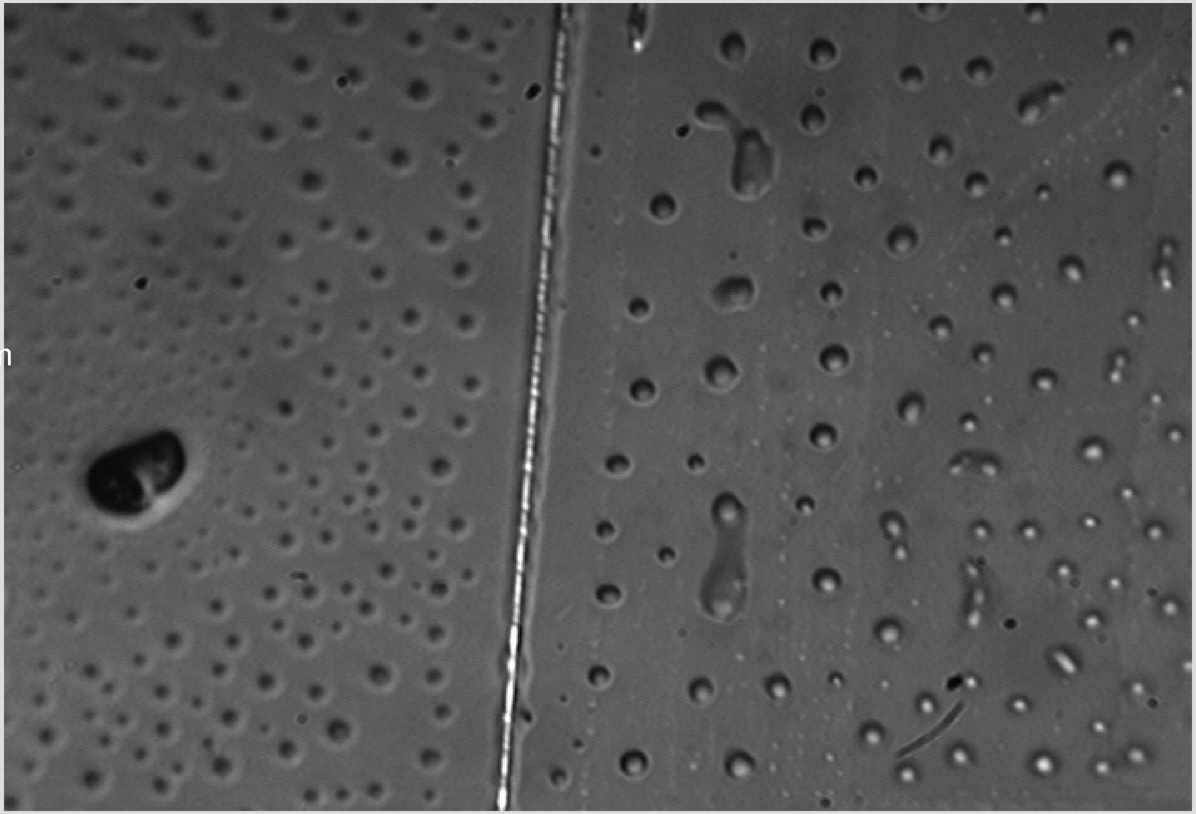


(b)



Writing sub-micrometer (800nm)-wide resistors:

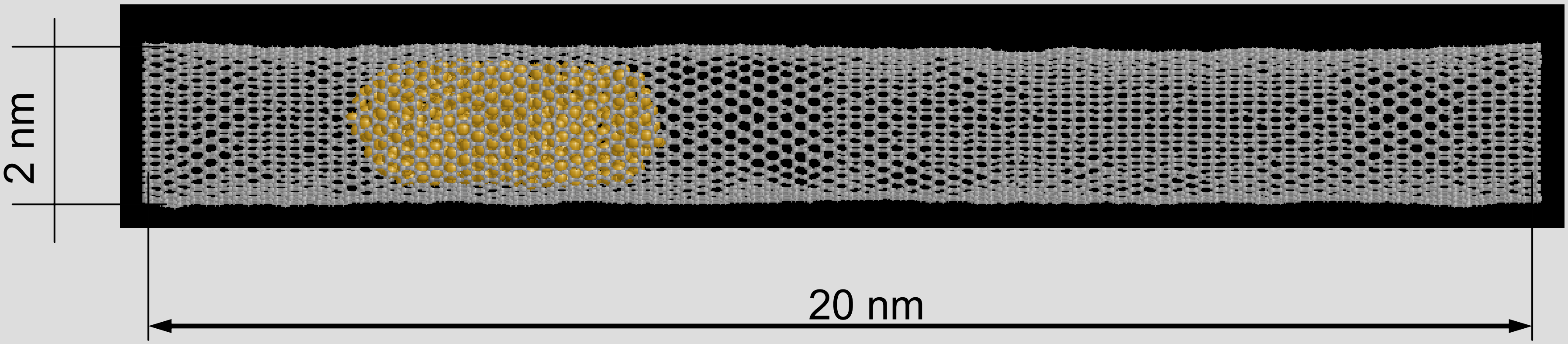
10 μm



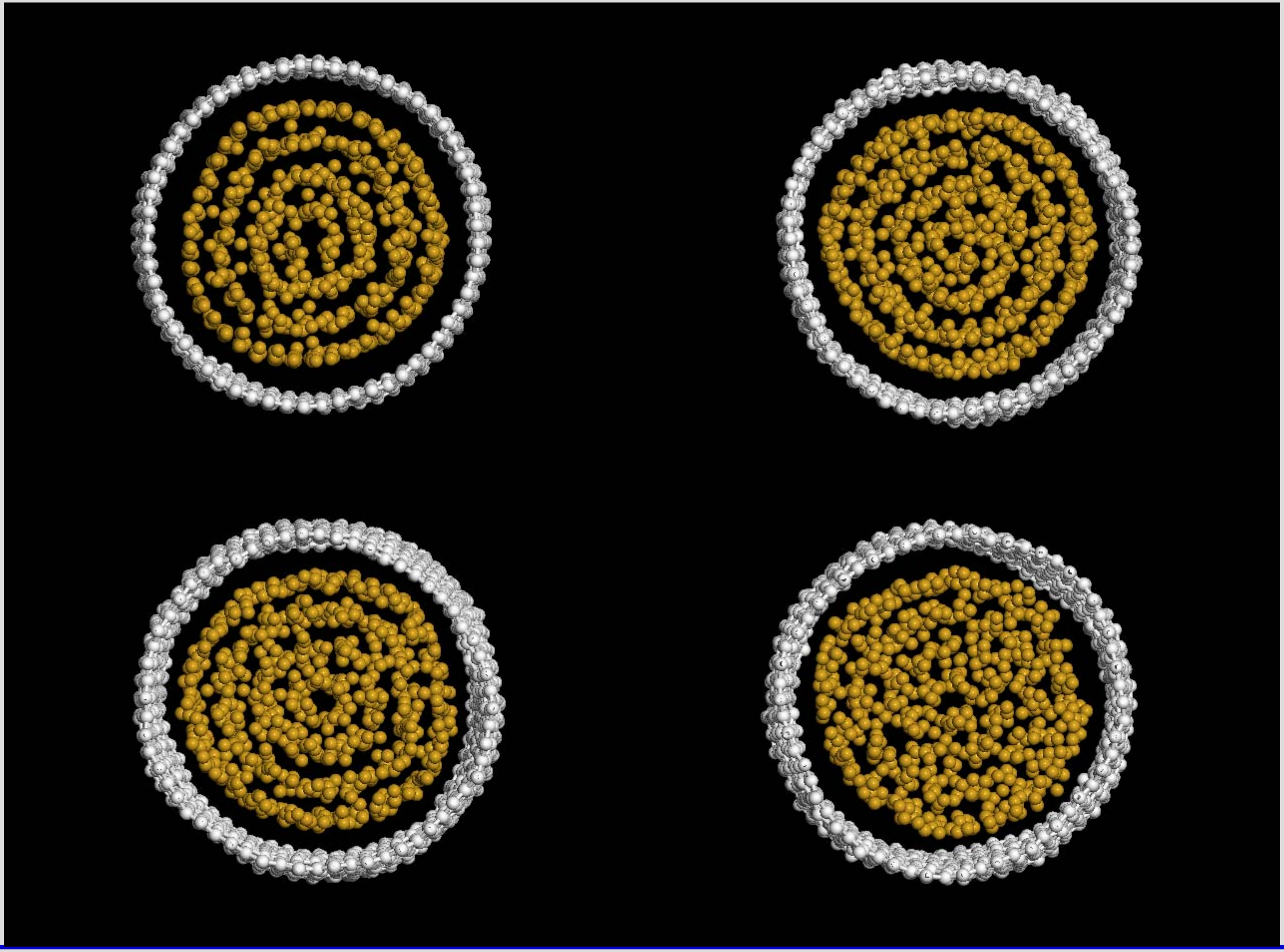
10 μm

Gold Nanoparticles embebbed in Carbon Nanotubes

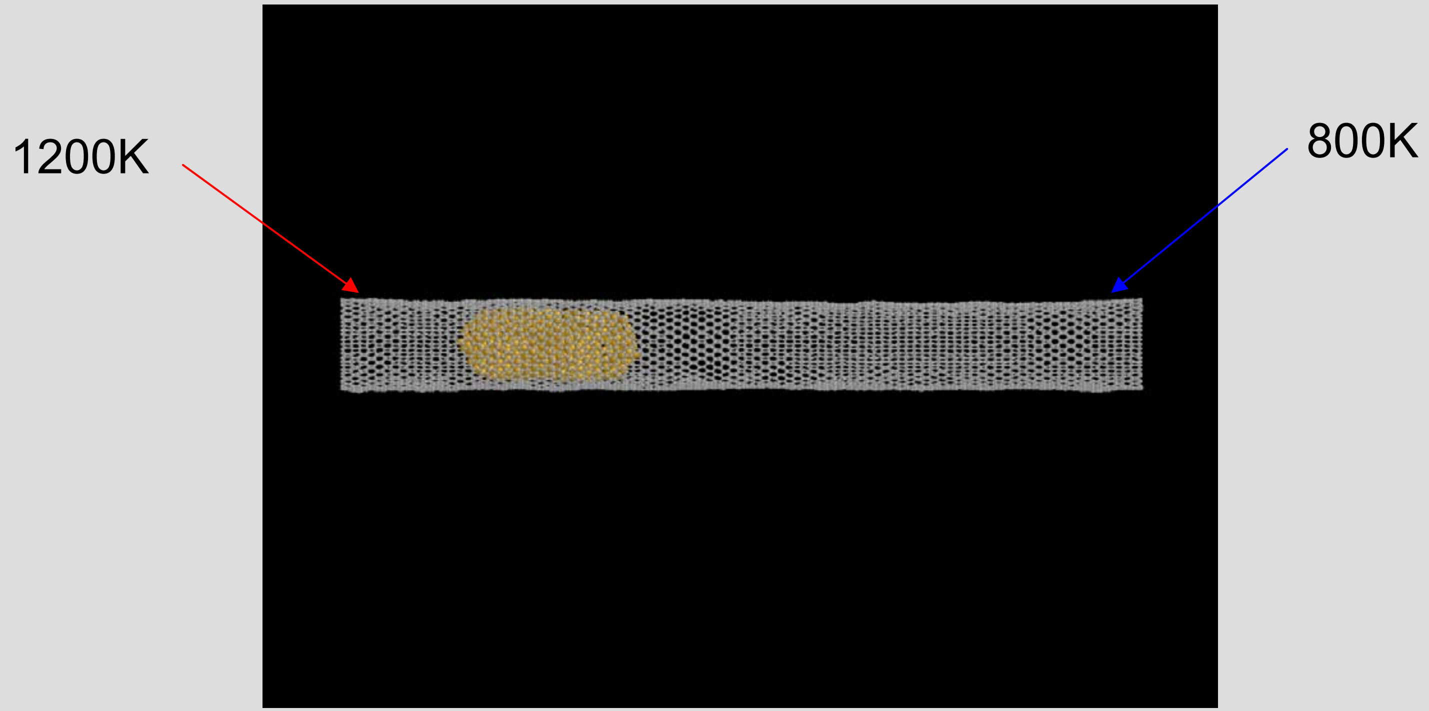
Studied geometry



Lattice structure at four different temperatures (400, 1000, 1200, 1500)



CNT with pinned ends



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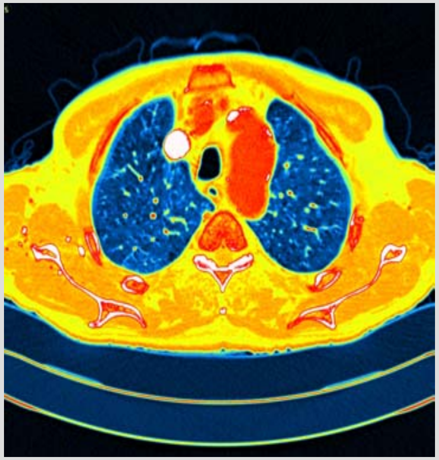
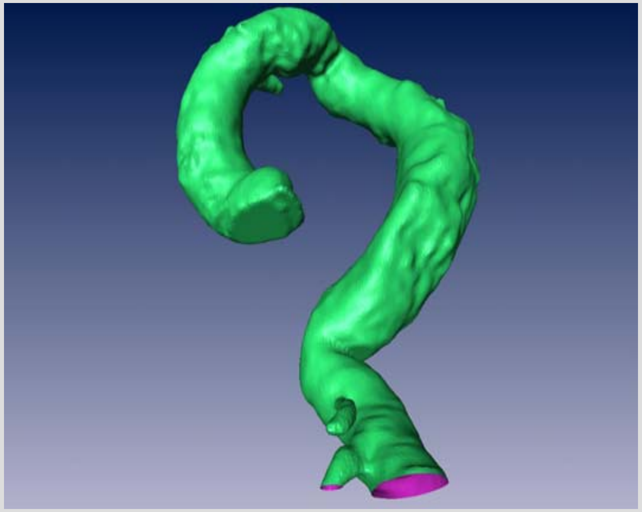
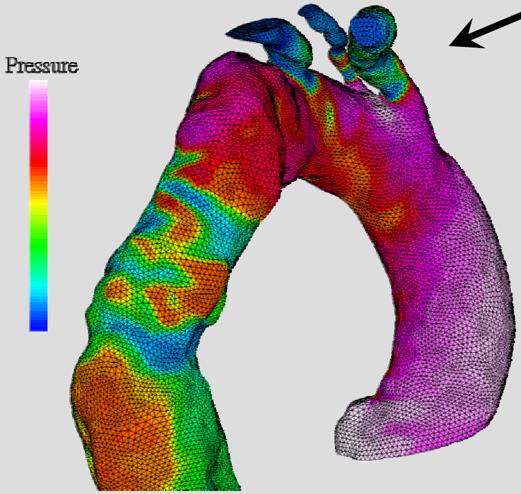
The Vision: The Virtual Medical Subject



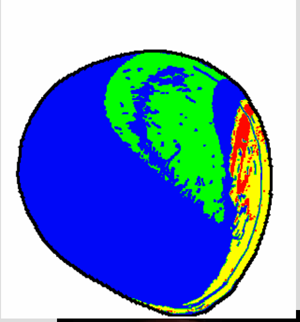
From medical imaging...



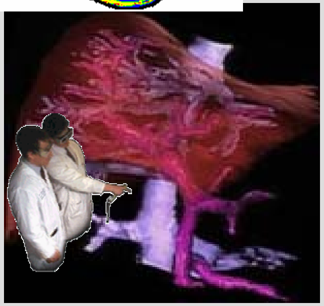
...via geometric models...



..to simulations of systems...



...for insight...



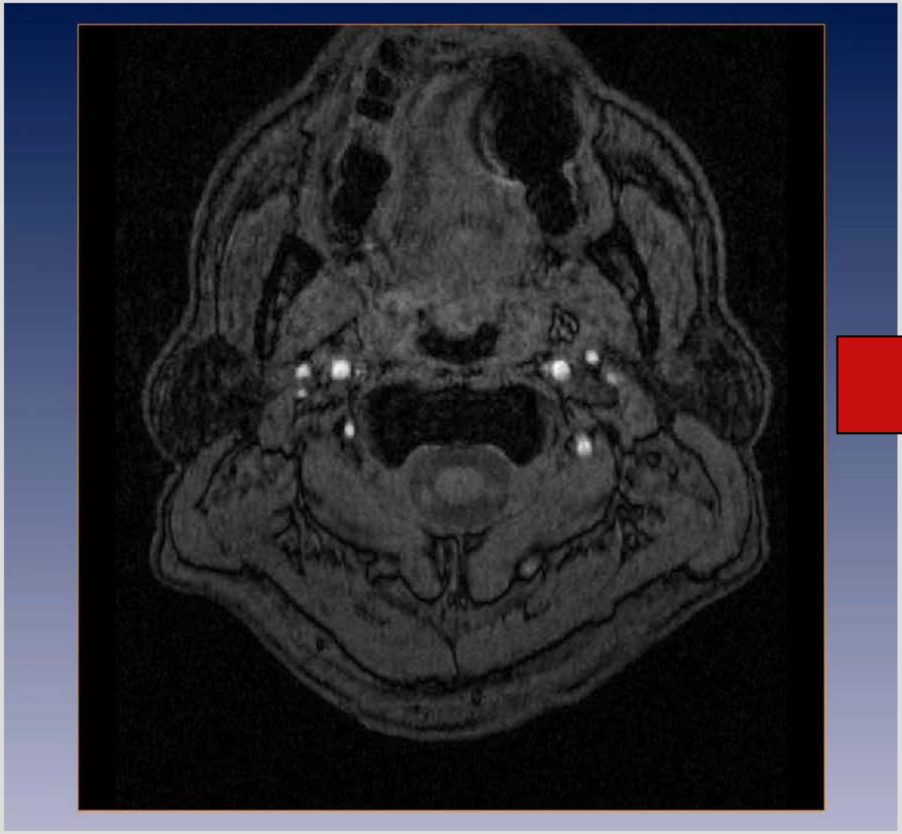
... and clinical tools

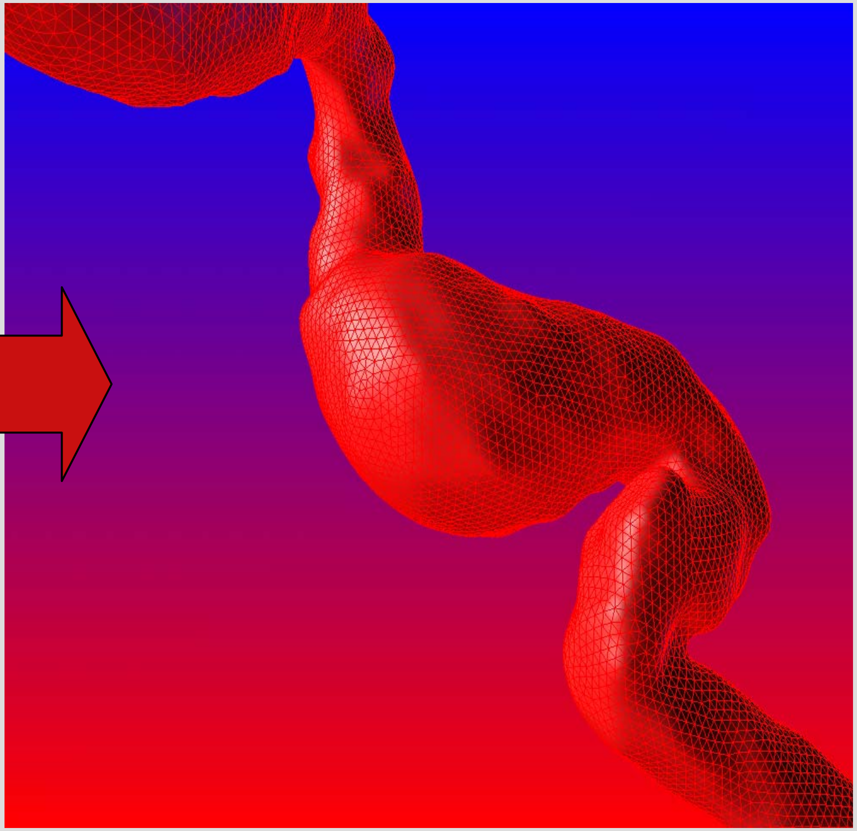
Biologically Oriented Computational Study of Cerebral Aneurysms

- 3%-5% of the general population
- Detection feasible, intervention empirical
- 30% of all aneurysm ruptures are immediately lethal
- An additional 40% lead to death within 4 weeks, if not treated

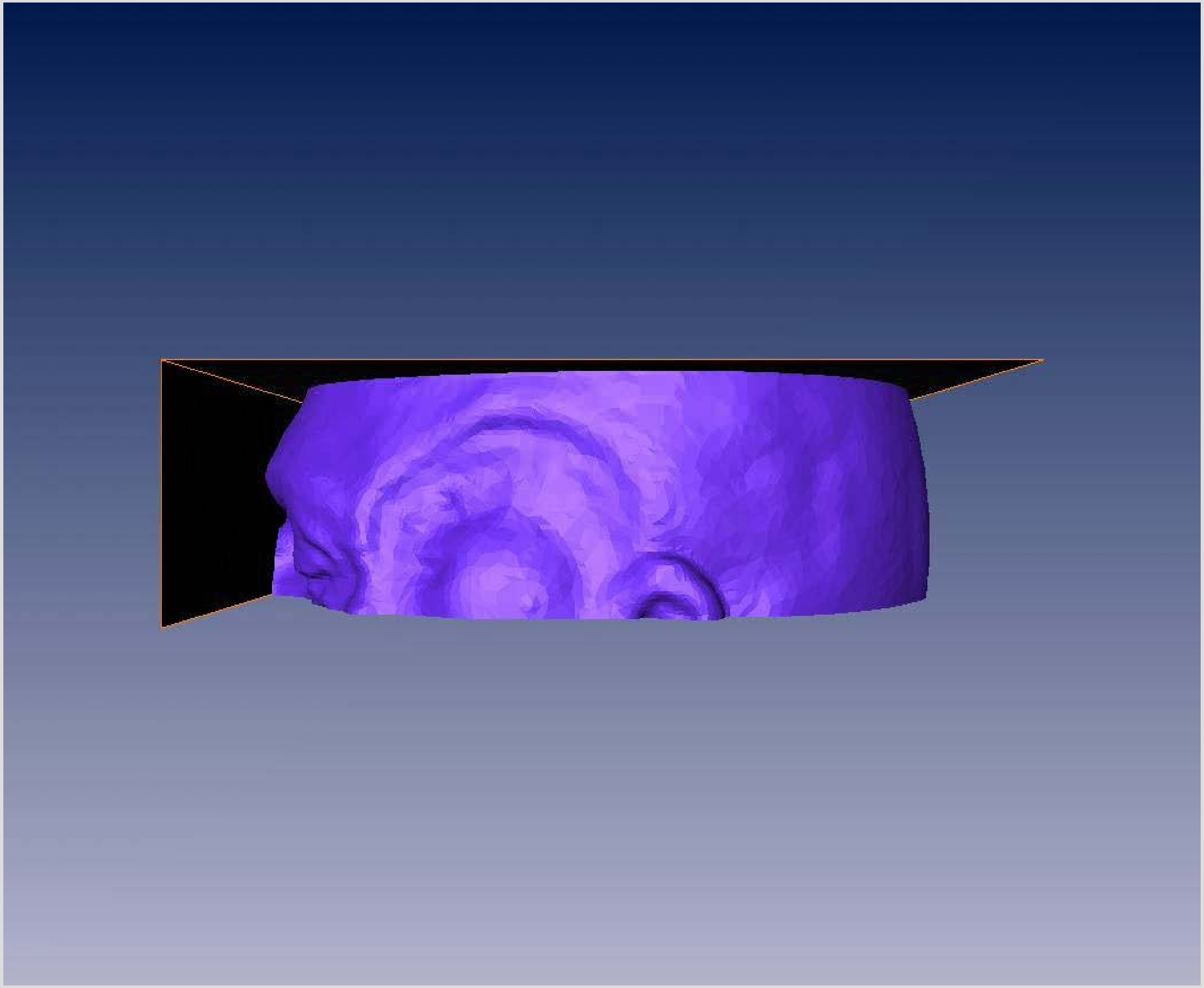
- Patient-Specific calculations
- Haemodynamics Evolution with the aneurysm growth progression
- Biological modeling of the aneurysmal wall

Patient-Specific Calculations

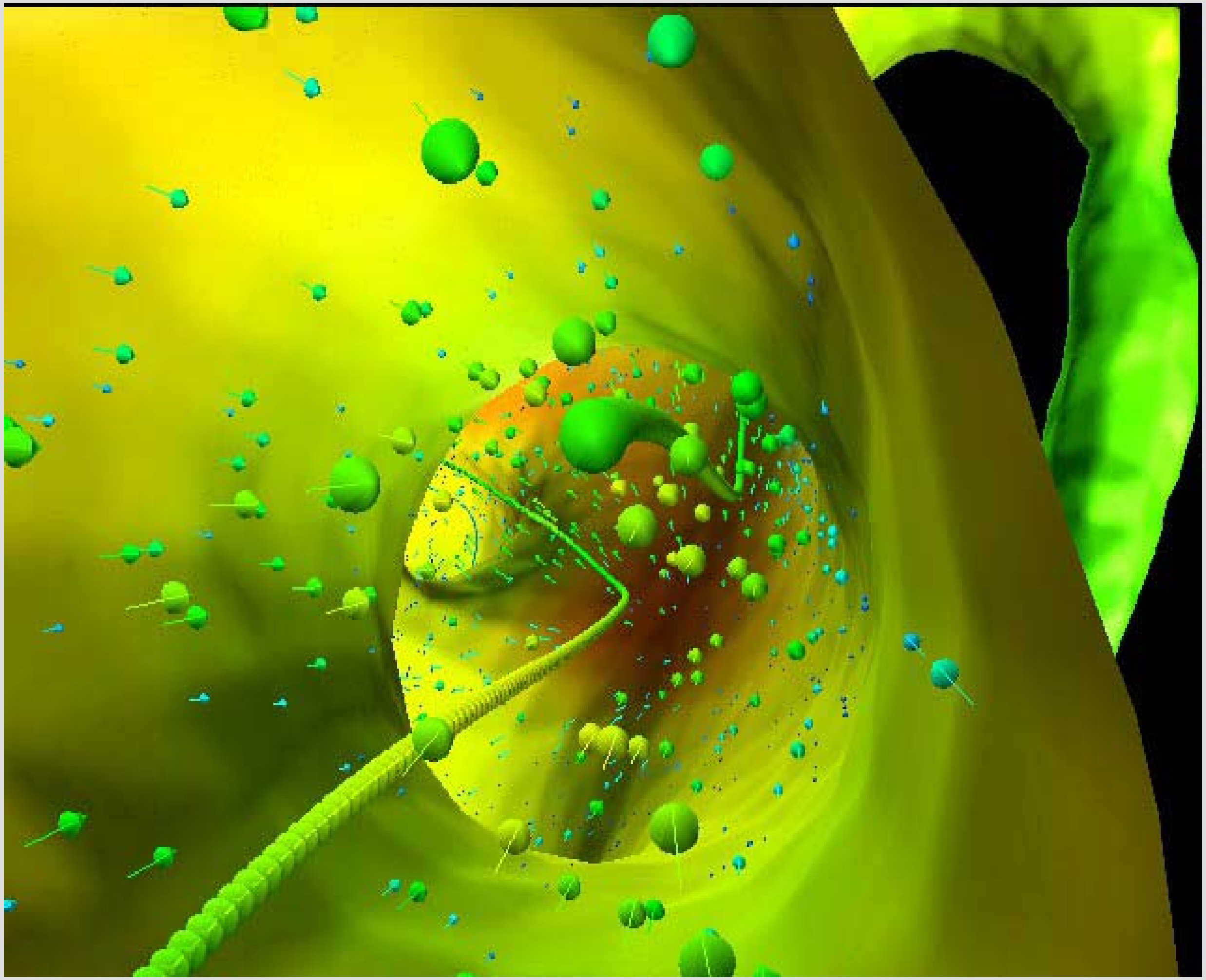


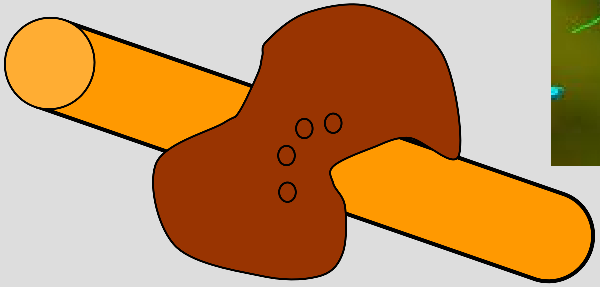


Patient-Specific Calculations

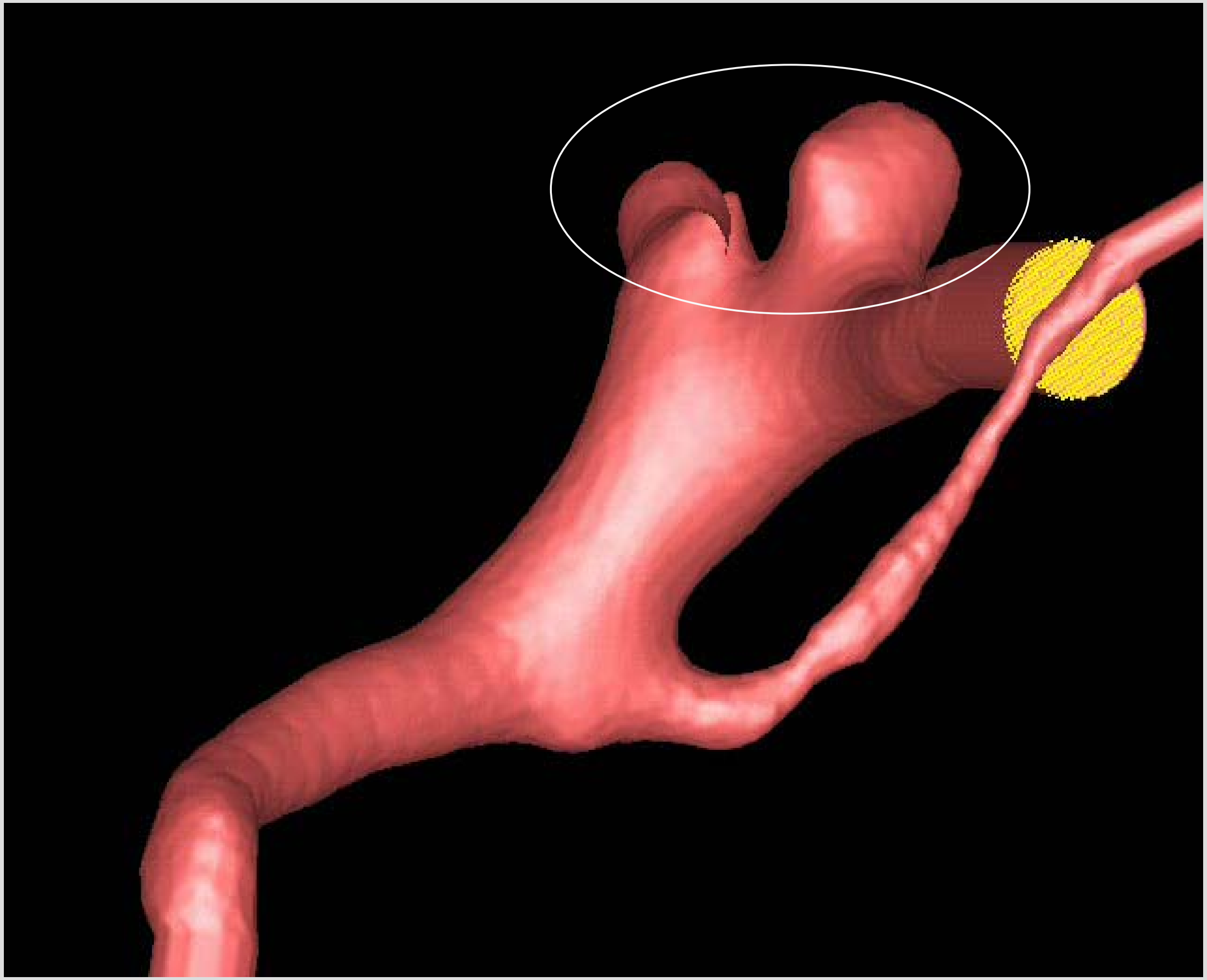


Simulation-Enhanced Virtual Endoscopy

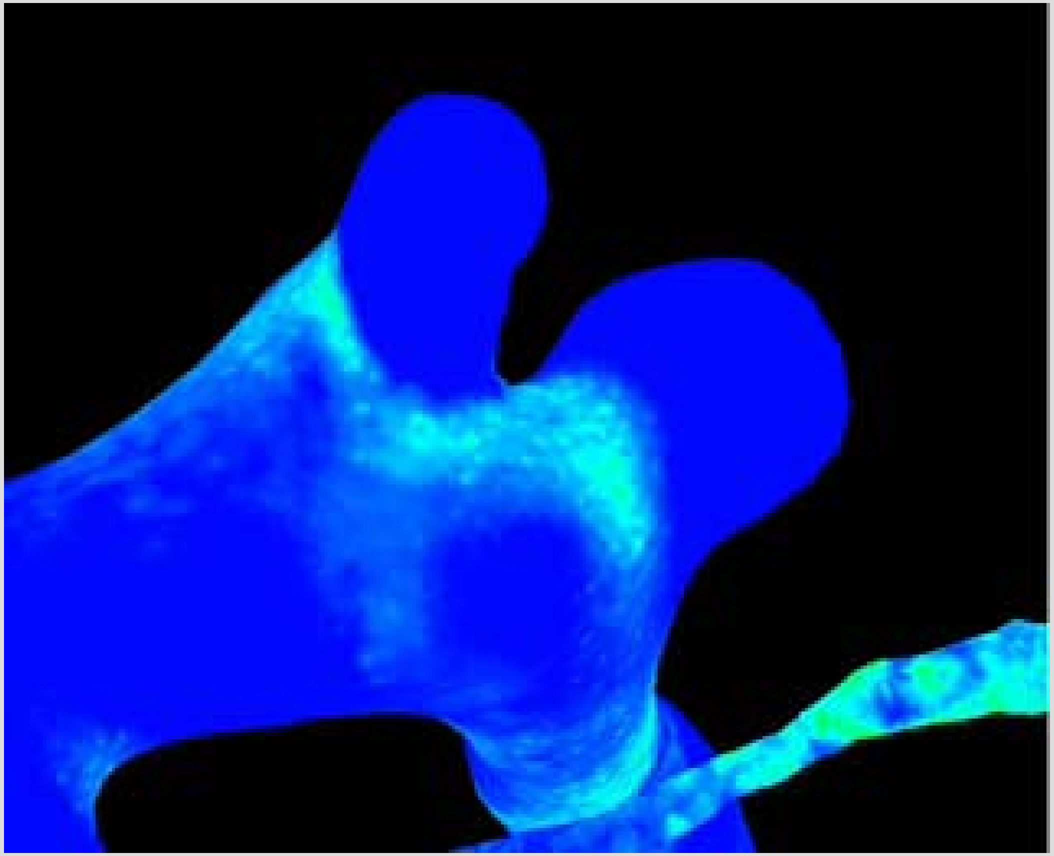




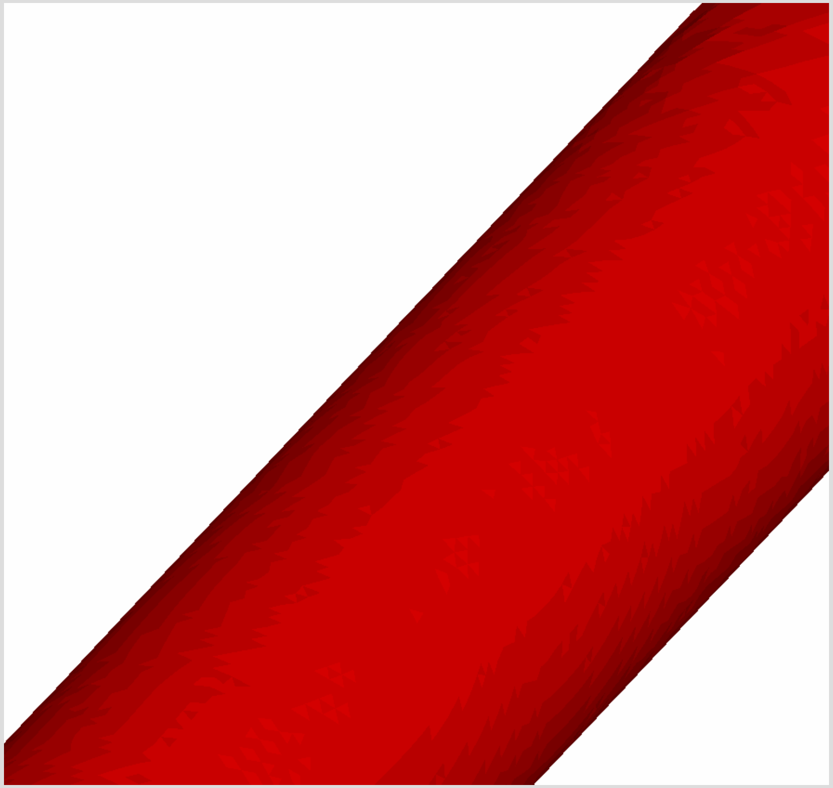
- Unsteady Computation
- Double Aneurism-Right Internal Carotid Artery
- Lagrangian Markers



Unsteady Computation,
Right Internal Carotid Artery
Wall Shear Stress



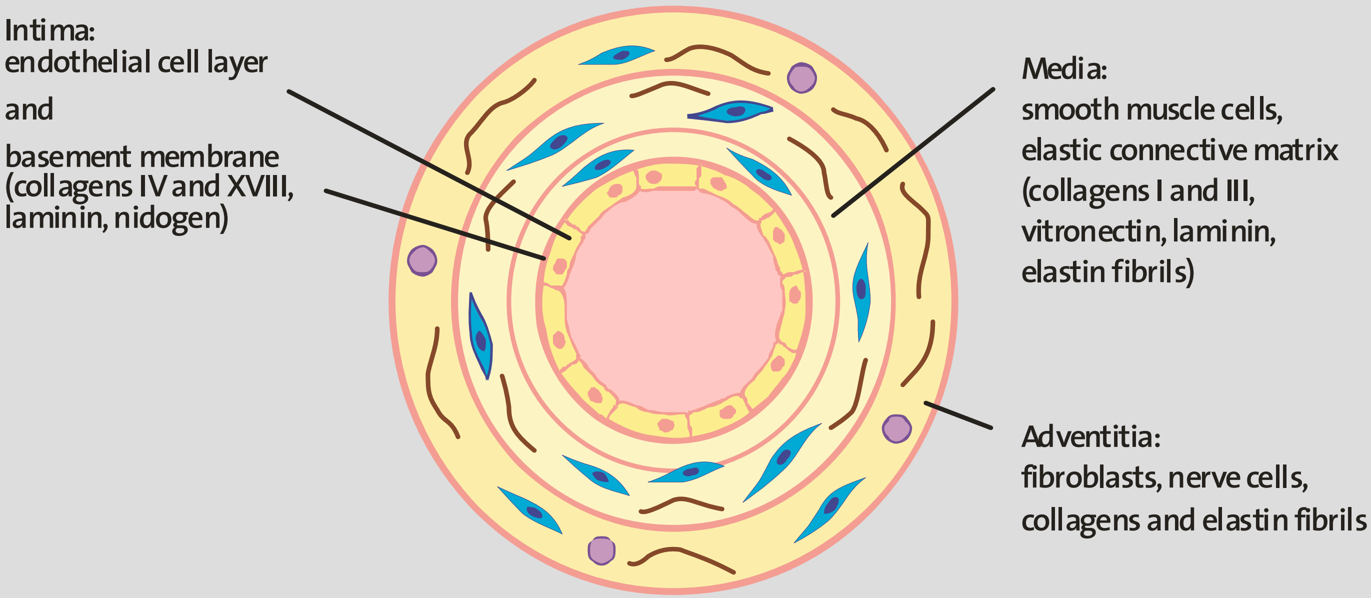
Haemodynamics and Aneurysm Evolution



- Artificial growth of an idealized geometry
- Pressure dependent geometrical evolution
- Steady state calculations

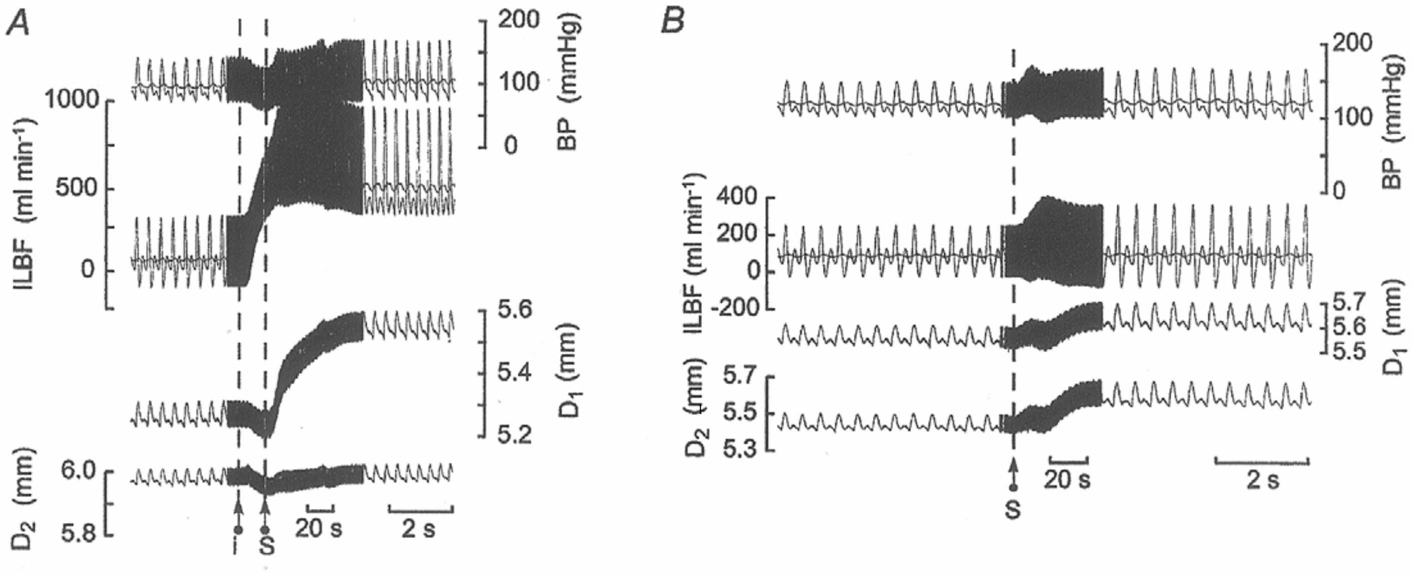
Target : To identify the evolution of the haemodynamic patterns of variables that are stimulating the arterial wall function, such as shear stress and pressure

Modeling of the aneurysmal wall



Biological modeling based on the function of the different arterial layers

Endothelium relaxation function



HM Snow, F Markos, D O'Regan and K. Pollock "Characteristics of arterial wall shear stress which cause endothelium-dependent vasodilation in the anaesthetized dog" J. Phys. Vol. 531, 843-848, 2001.

A: Experimental (in vivo) results showed that the response of an artery with endothelium (D_1) to the increment of the blood flow is a significant enlargement of the diameter while for an artery without endothelium (D_2) the same increment causes enlargement that corresponds to the pressure change.

Cerebrospinal Fluid Diagnostics & Control
Development of a Knowledge Base

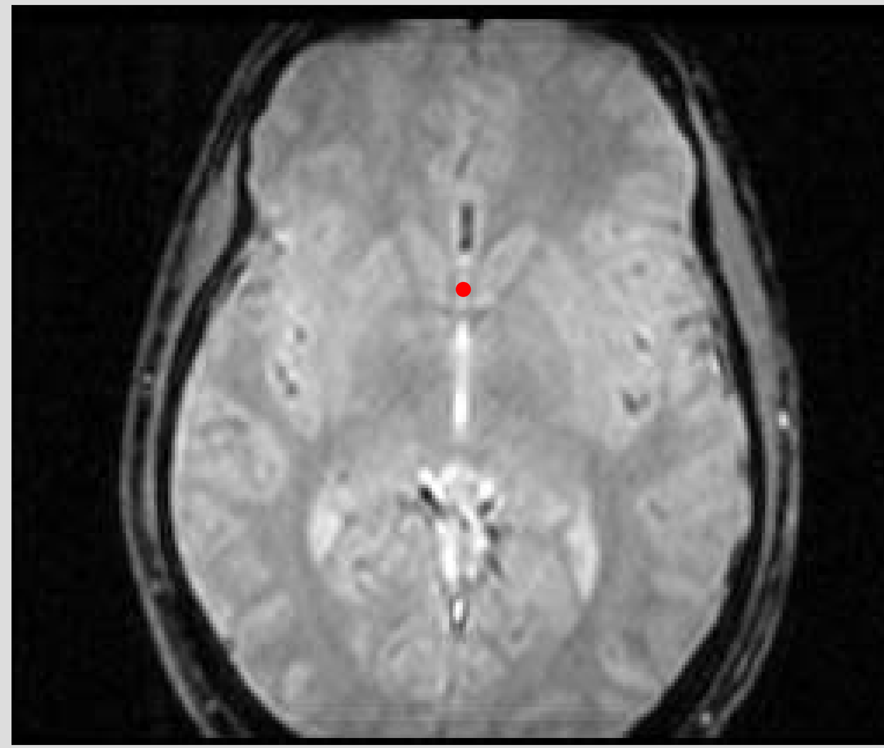
Participating ETH Units:

- Laboratory for Thermodynamics in Emerging Technologies (LTNT) (Principal Investigator)
- Computer Vision
- Measurement and Control Laboratory (IMRT)
- Institute of Biomedical Engineering, Biophysics Group

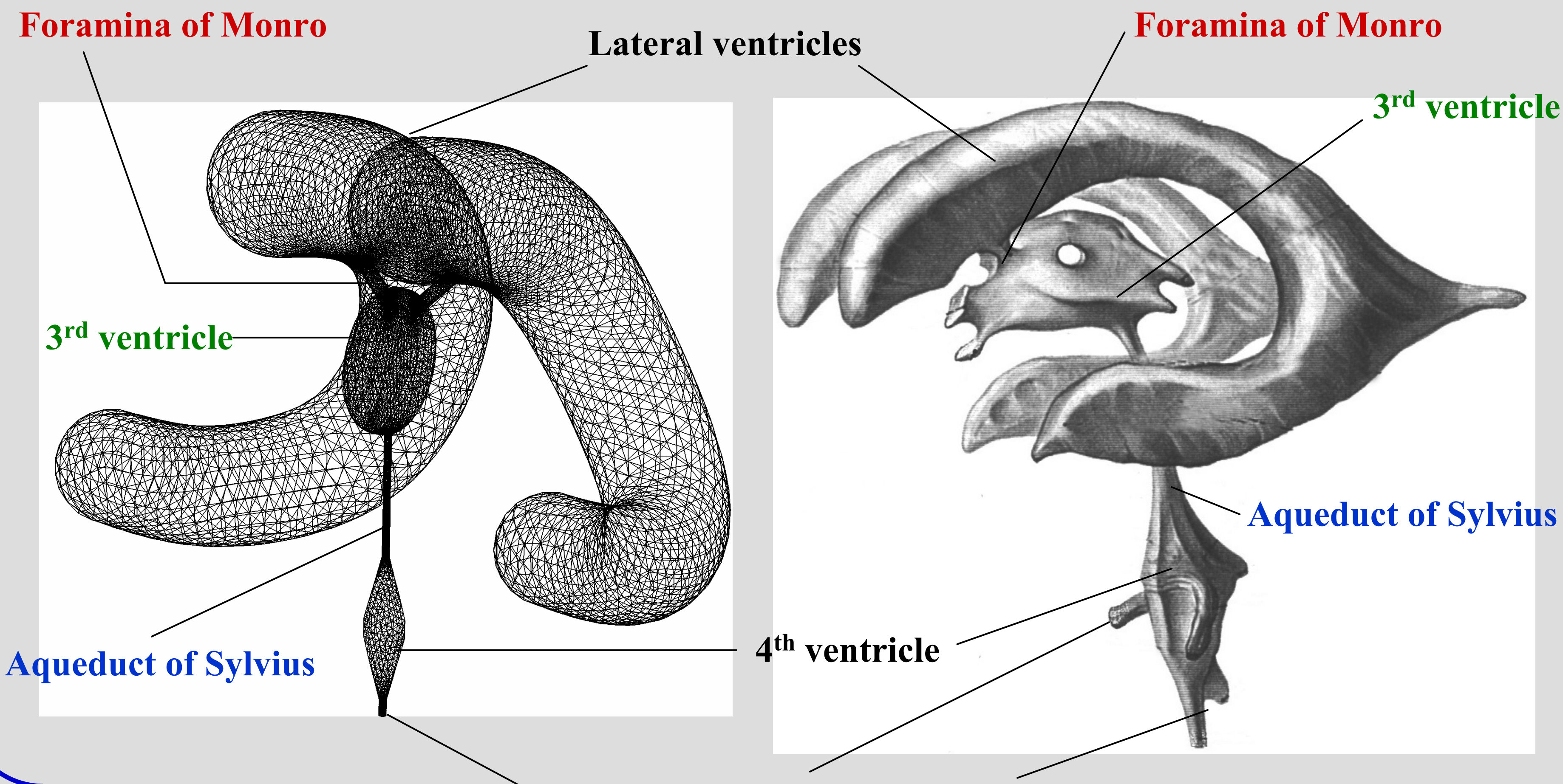
Participating External Units :

- Neuroradiology, University Hospital, Zurich
- Bioengineering – Imperial College for Science, Technology and Medicine, London, U.K.
- Mechanical Engineering, Oxford University
- CFD Research Corporation, Hunstville AL, USA
- Institute of Anatomy, University of Bern

Brain Motion /Phase Contrast

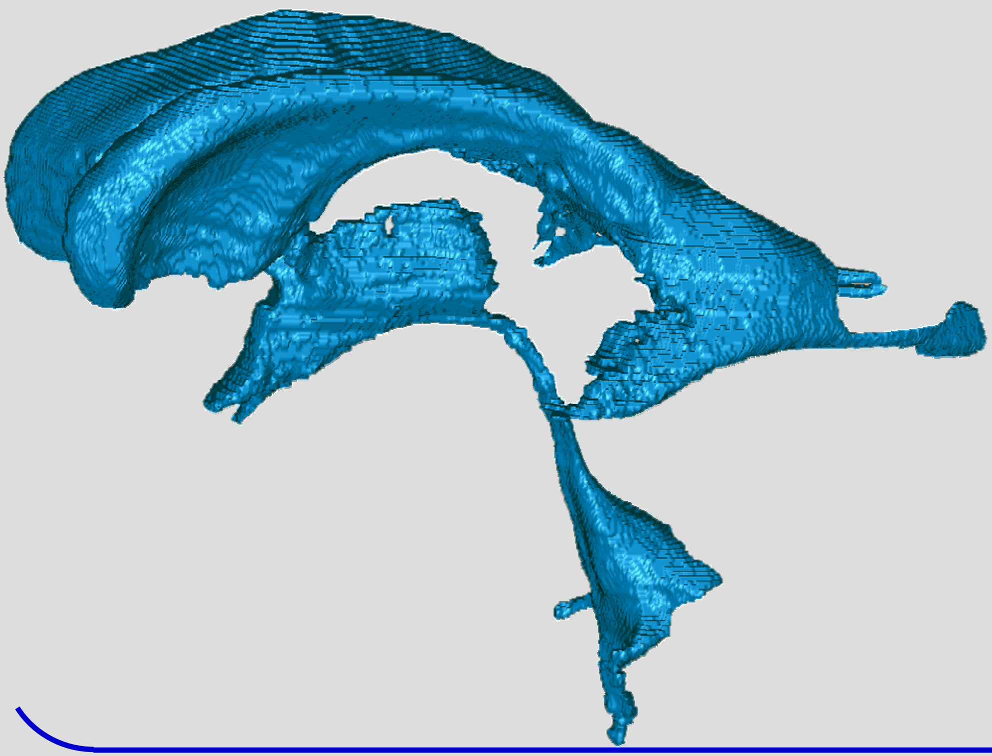


Simplification of Actual Geometry

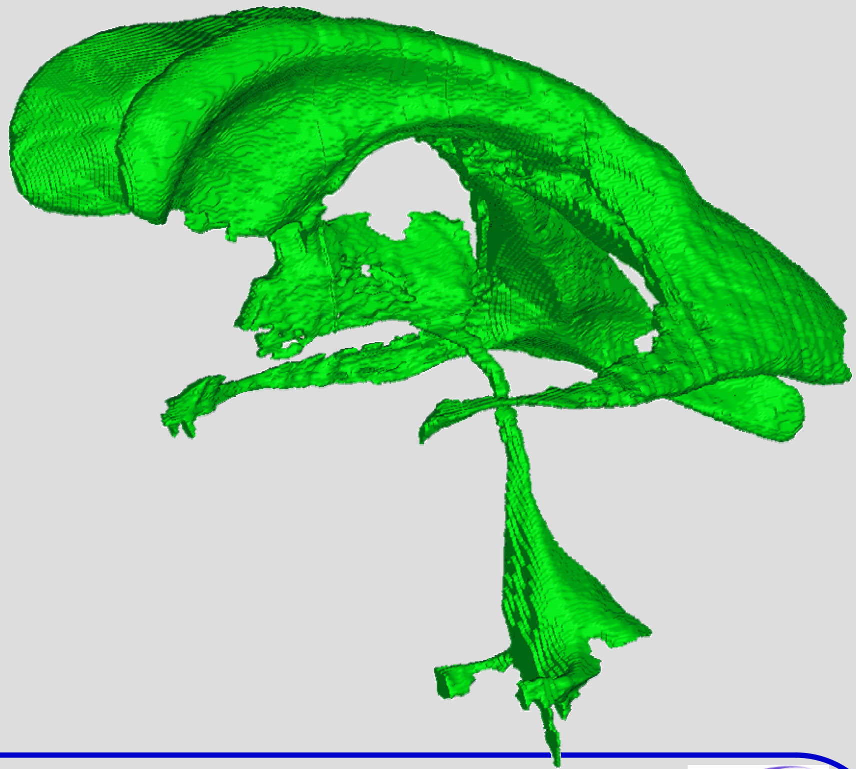


Registration of Datasets

Segmentation from Axial Scanning

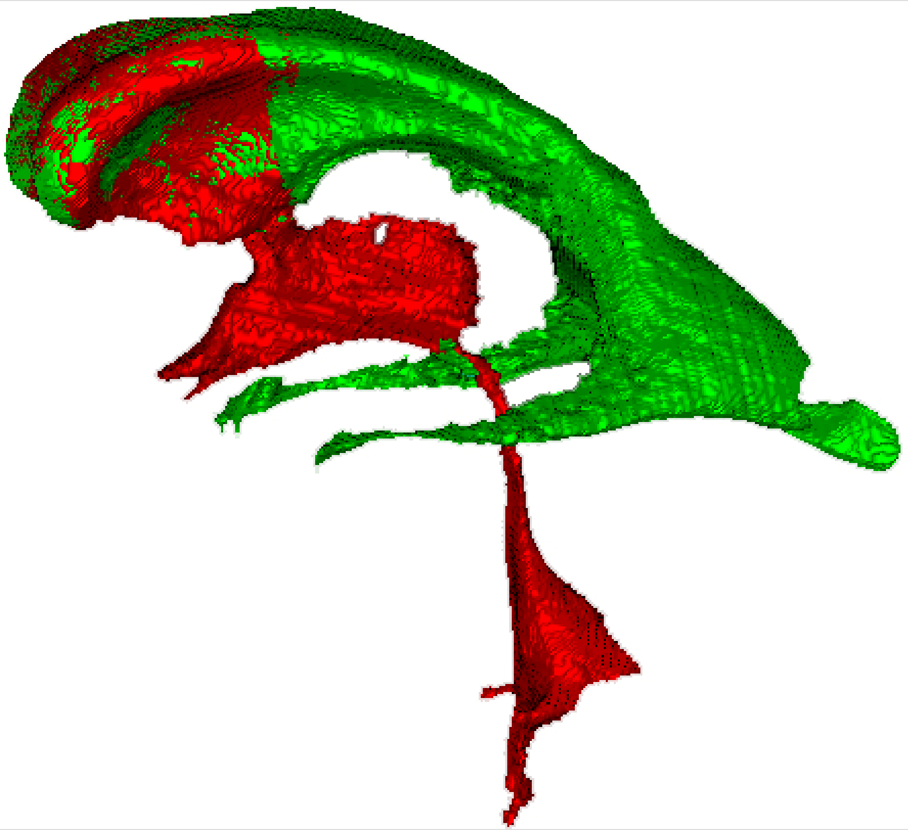


Segmentation from Coronal Scanning



Registration of Datasets

Combination of Segmentation from Axial and Coronal Scanning



Brain Motion / Tagging

Inst. Biophysics ETH Zurich

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