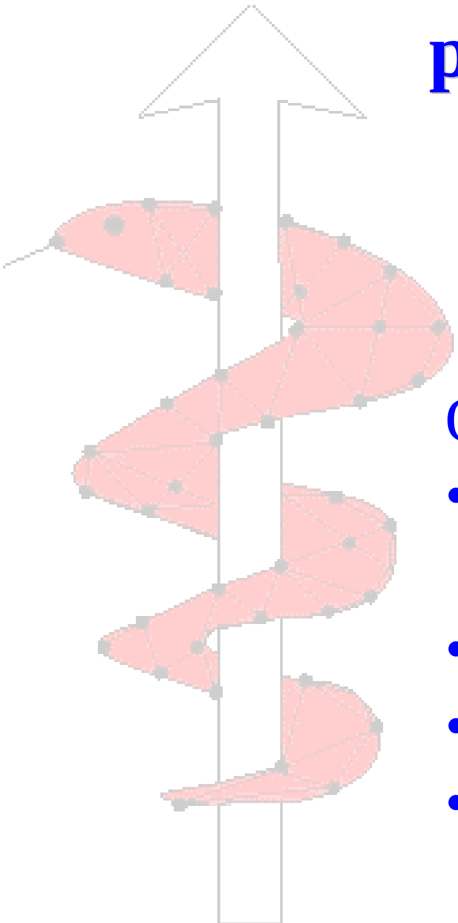
Project 10378

Bio-numerical simulations with SimBio: project aims and objectives

***G. Lonsdale*, R. Grebe, U. Hartmann,**
D. R. Hose, F. Kruggel,
J.M.T. Penrose, C. Wolters



Overview:

- Introduction to the project & SimBio environment
- Environment components
- SimBio (validation) applications
- Concluding remarks

} **Illustrated with pre-project developments**

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SimBio: A generic environment for bio-numerical simulation

Funded by the European Commission’s
5th Framework Programme
“Information Society Technologies” (IST)
Key Action: Essential Technologies and Infrastructures
Sector: Simulation & data visualisation

Project Duration:	36 Months
Commencement date:	1st April, 2000
Total effort:	410 person months

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The SimBio Consortium

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Participants	Country	Role
NEC Europe Ltd	UK	Co-ordinator
Max-Planck Insitute of Cognitive Neuroscience	D	Principal Contractor
A.N.T. Software B.V.	NL	Assistant Contractor
Biomagnetic Center, F. Schiller University, Jena	D	Assistant Contractor
K.U. Leuven	B	Assistant Contractor
CNRS - DR18	F	Assistant Contractor
Engineering Systems International S.A.	F	Principal Contractor
The University of Sheffield	UK	Principal Contractor
Smith & Nephew plc	UK	Assistant Contractor

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SimBio Objectives

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Central Objective

Improve clinical & medical practices by the use of "Bio-numerical simulation"

Key Feature

Patient-specific data ⟶ **Modelling and simulation**

Technical Objectives

The generic SimBio simulation environment

Interoperable components on distributed systems

Core HPC Components

Demonstrator applications will improve:

- **non-invasive diagnosis**
- **pre-operative planning**
- **prosthesis design & related operative procedures**

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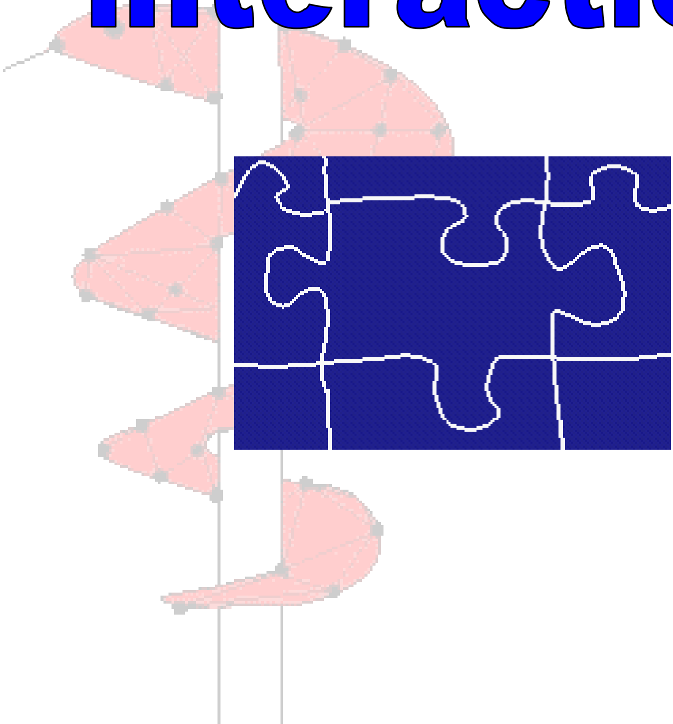
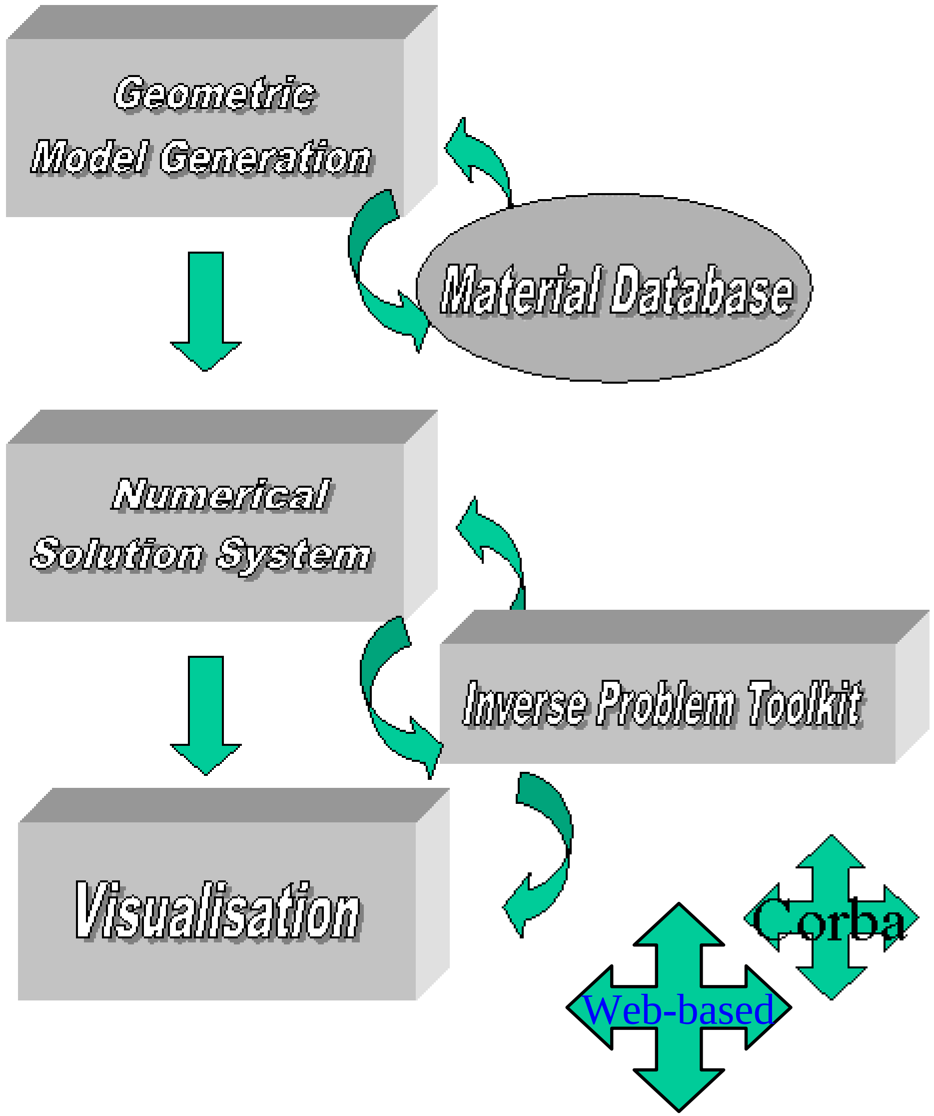
SimBio Environment Components

- Discrete Representation: transformation of scan-data to an FE mesh + tissue modelling
- Numerical Solution System: internal parallel FE solvers & library routines + interface to external solvers
- Inverse Problems: framework for inverse problem solution using above + modelling assessment
- Visualisation: internal advanced visualisation + interfaces to external tools

Component interaction





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Discrete Representation

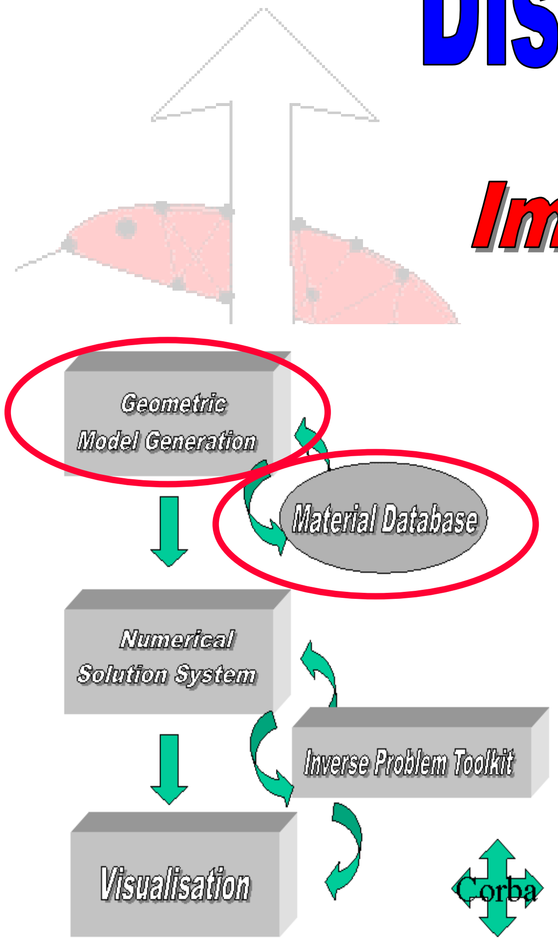

Image Segmentation & registration

Mesh generation

Material Modelling (database)

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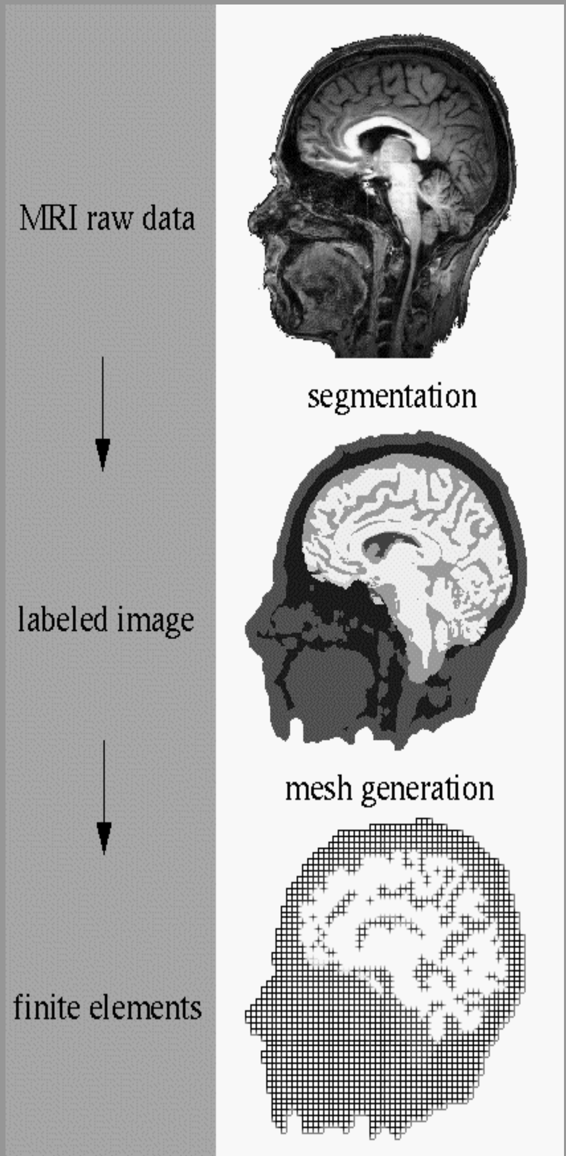
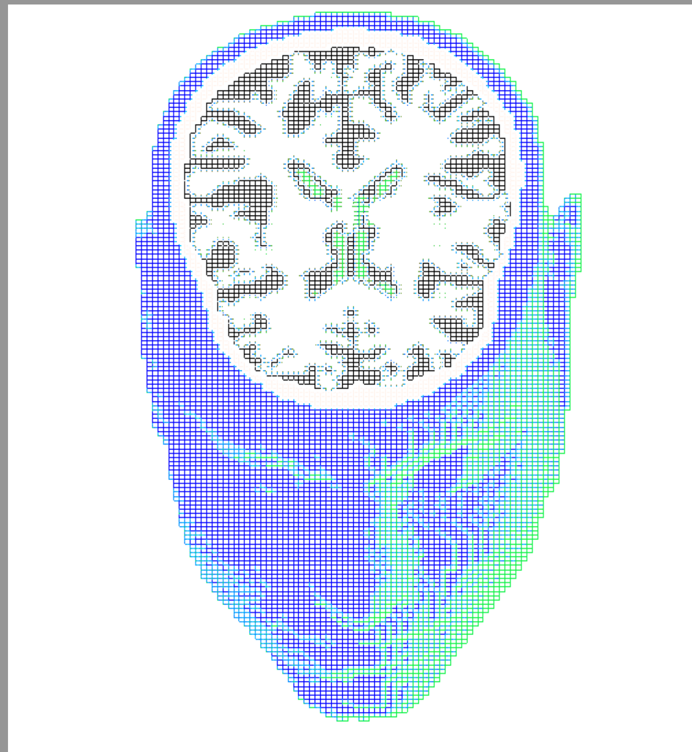
Example: Modelling head geometry

From magnetic resonance images (MRI) to finite element meshes of the human head

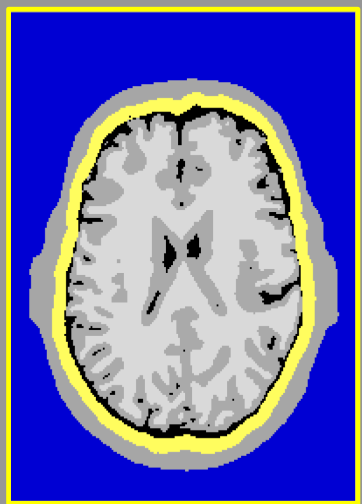




Segmentation through multimodal MRI

T1

PD



Segmentation result

- **T1-weighted MRI: Appropriate for ventricle, white matter, cortex and scalp segmentation**
- **PD (proton density)-weighted MRI: Appropriate for skull segmentation**
- **Registration of PD-image on T1-image by linear non-rigid edge registration of the segmented outer skull surfaces using genetic optimisation (Staib et al., 1994)**

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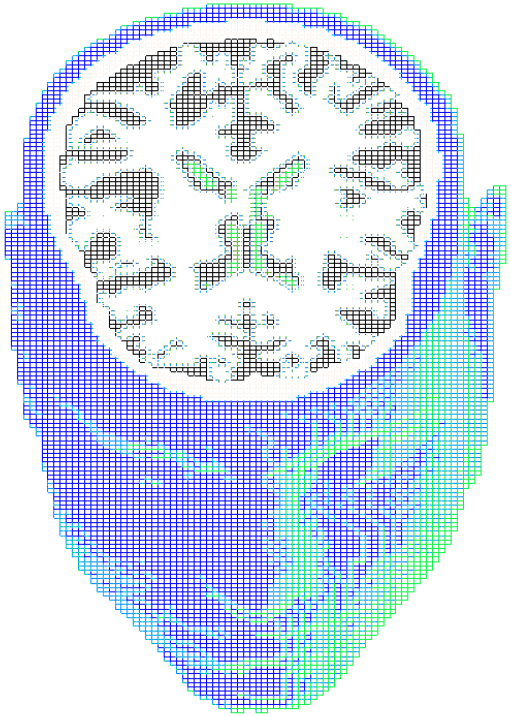
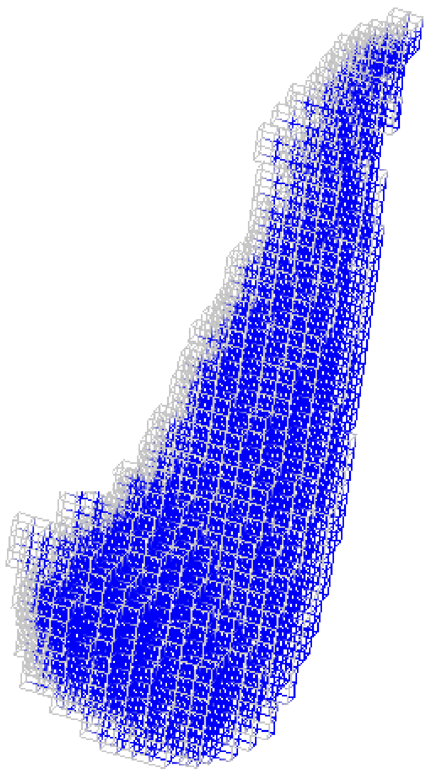
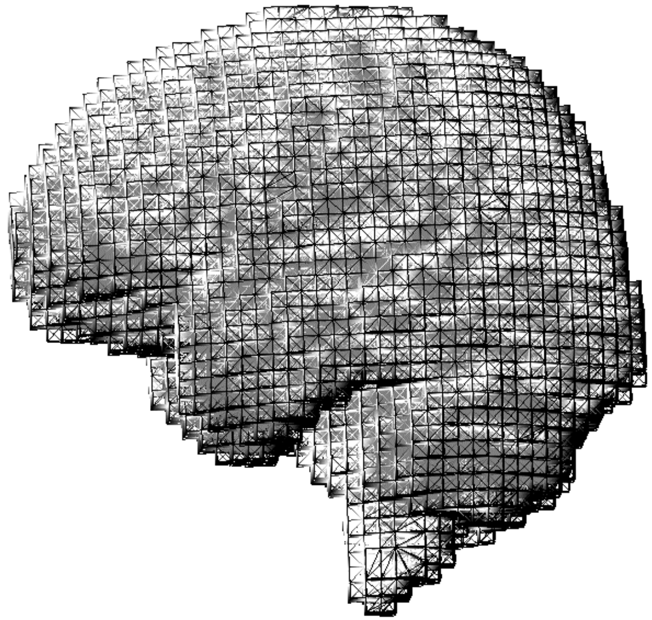
Hartmann, Kruggel (1998)

Generates FE meshes consisting of hexahedral and tetrahedral elements







Input: an image
Output: a mesh

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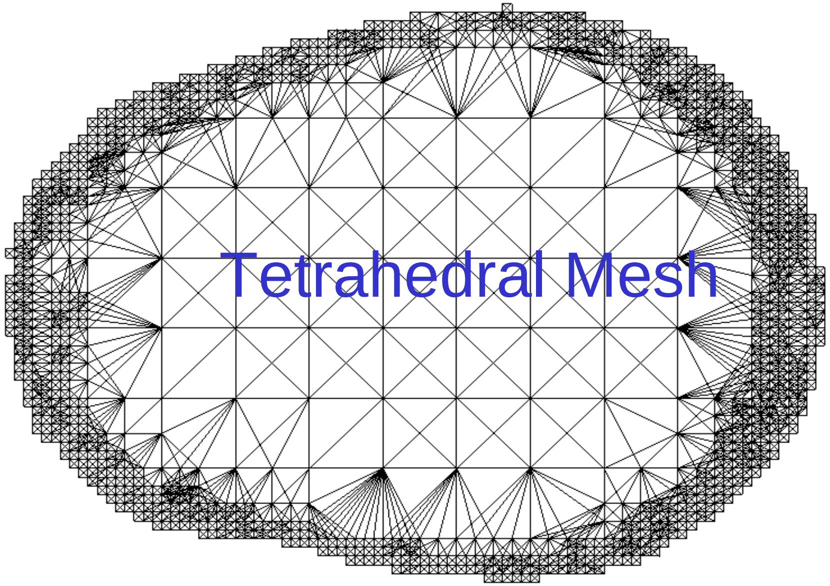
Algorithm has three phases:

- Subdivision Phase
- Collection Phase
- Tetrahedrisation



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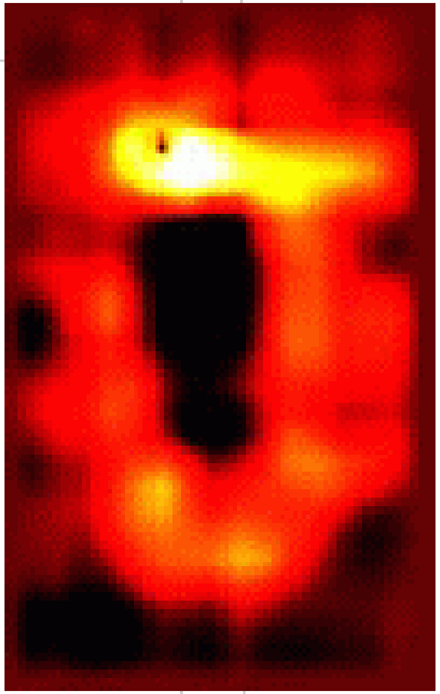
Material Database

Main techniques to be exploited within SimBio are:



Magnetic Resonance Strain Imaging

(a combination of magnetic resonance & ultrasound)

Diffusion Tensor Imaging

(a pure magnetic resonance technique)

Literature Values

Output: Images and values

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Compilation of the Material Database

Goal:

Evaluation and combination of individual

- geometrical,
- mechanical, and
- electrical properties

of an individual patient for introduction into individual simulations.

Bio-mechanical material database

Steps in data generation :

- data extraction from literature.
- MR Strain Imaging (MRSI) experiments isolated ex-vivo
  - brains
  - menisci.
- strains induced in-vivo for in vivo material properties.

Magnetic Resonance Strain Imaging MRSI

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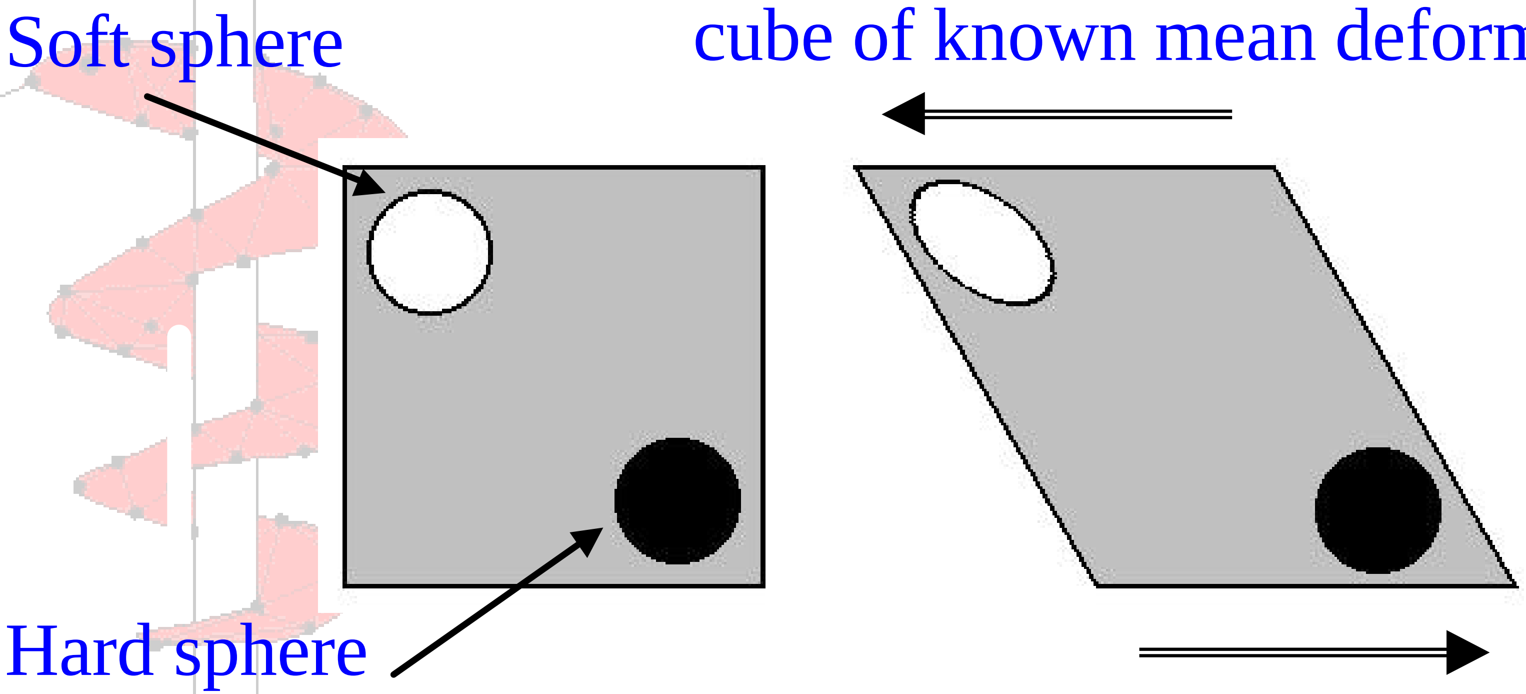
CNRS

The principle

Spheres embedded in a cube of known mean deformability



MRI - most appropriate to determine soft tissue geometry in-situ, in-vivo

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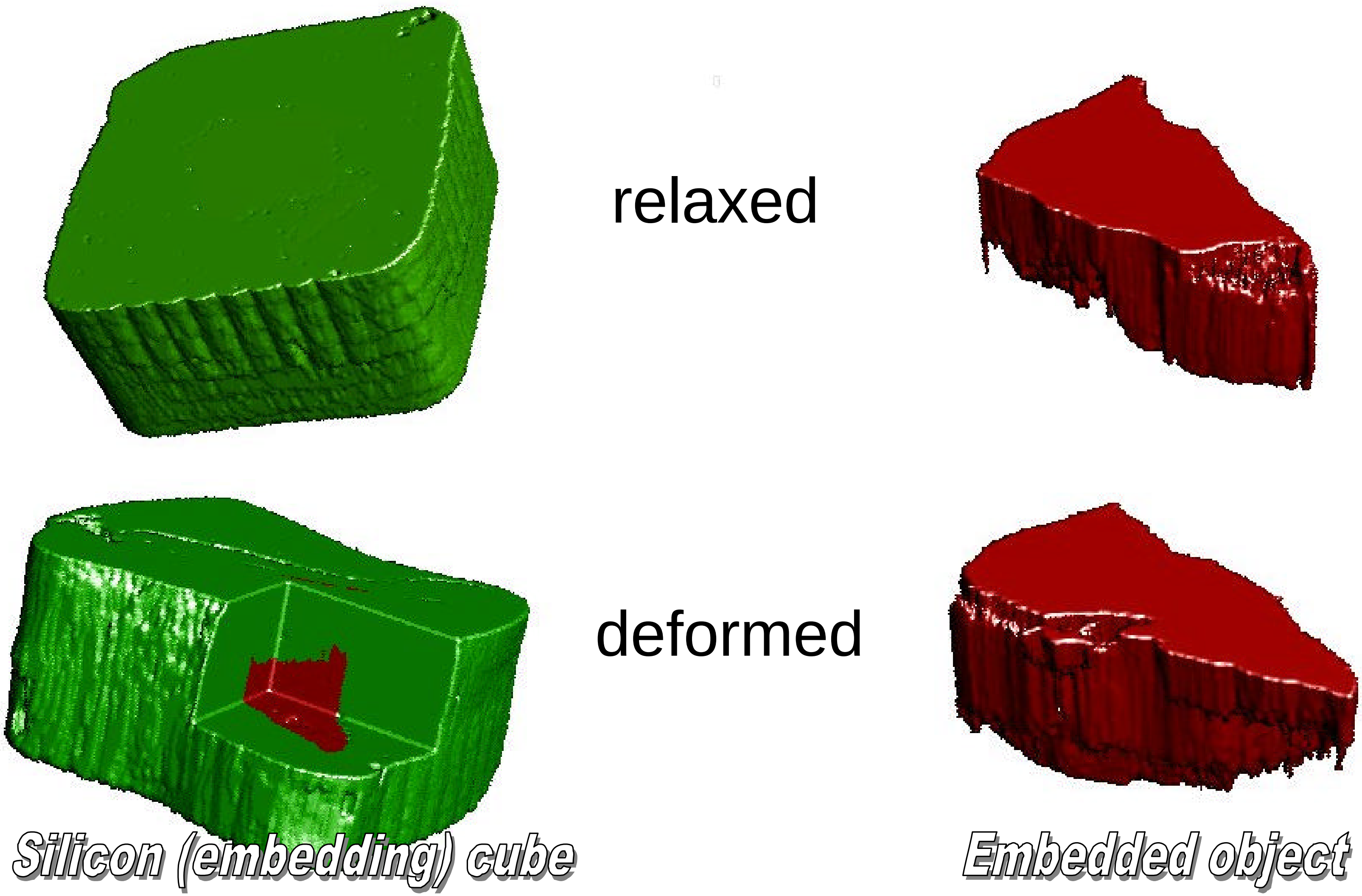
Example: A piece of turkey meat embedded in silicon.
MRI images visualised with CNRS tool Volview

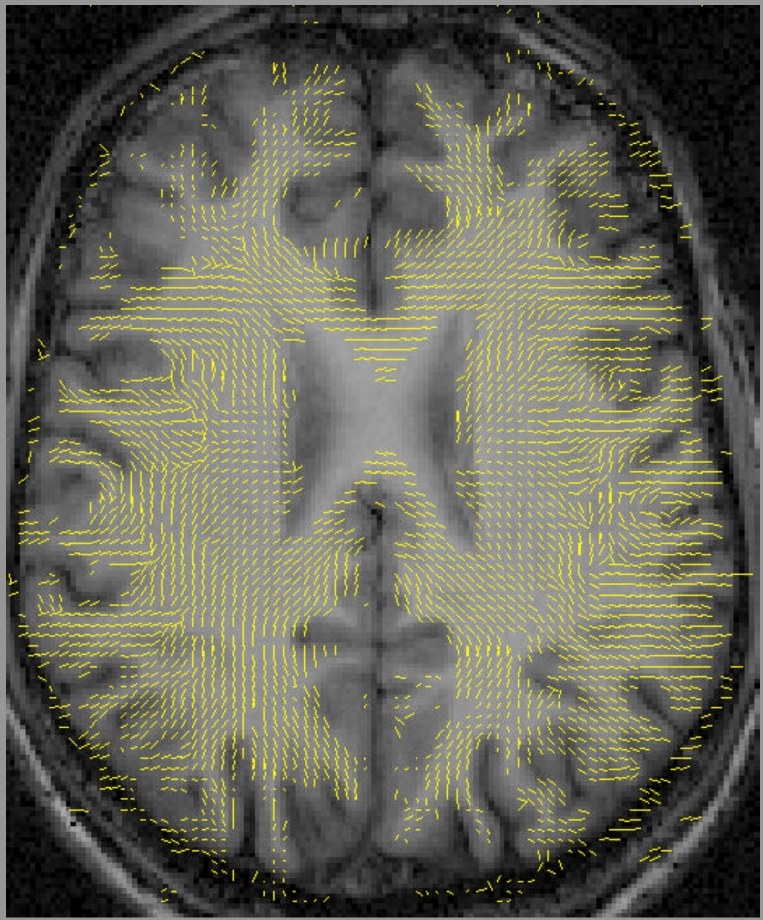


Bioelectric material database

Bioelectric material data generation

- MR technique called Diffusion Tensor Imaging (DTI)
- Measurement of DTI images of a BOI to generate an anisotropic conductivity map
    - animal head for model validation
    - human head

White matter conductivity tensors



(Basser et al., 1994):
Water diffusion and conductivity tensors share the same eigenvectors

A DTI-MRI fibre orientation map based on a U-FLARE sequence.
Eigenvector orientations corresponding to the largest eigenvalue are projected onto the imaging plane, and overlaid on a T_1 weighted image (MDEFT sequence)

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Numerical Solution System

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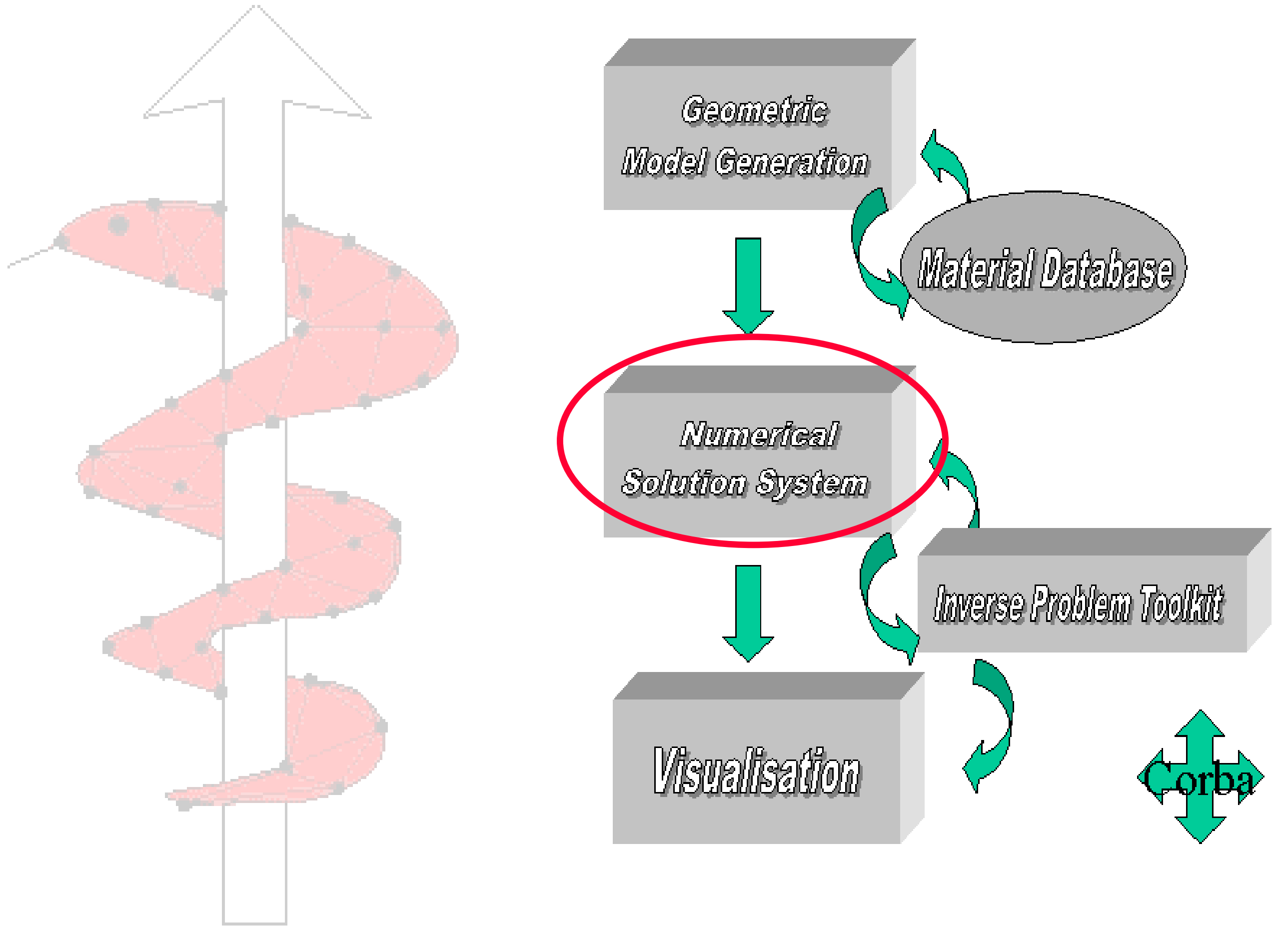

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Numerical Solution System

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Building on Existing Codes/Software:

FE techniques

Linear static, linear dynamic, geometrically nonlinear, nonlinear material models, partitioning techniques

FE techniques

1. Head_fem,
2. CAUCHY,
3. PAM-SAFE,

(4. DRAMA Library)

Numerical Solvers

preconditioned Krylov sub-space solvers, (multigrid, ... to be determined)

Numerical Solvers

NEC’s parallel MPI-based iterative solvers, AZTEC

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Head-fem

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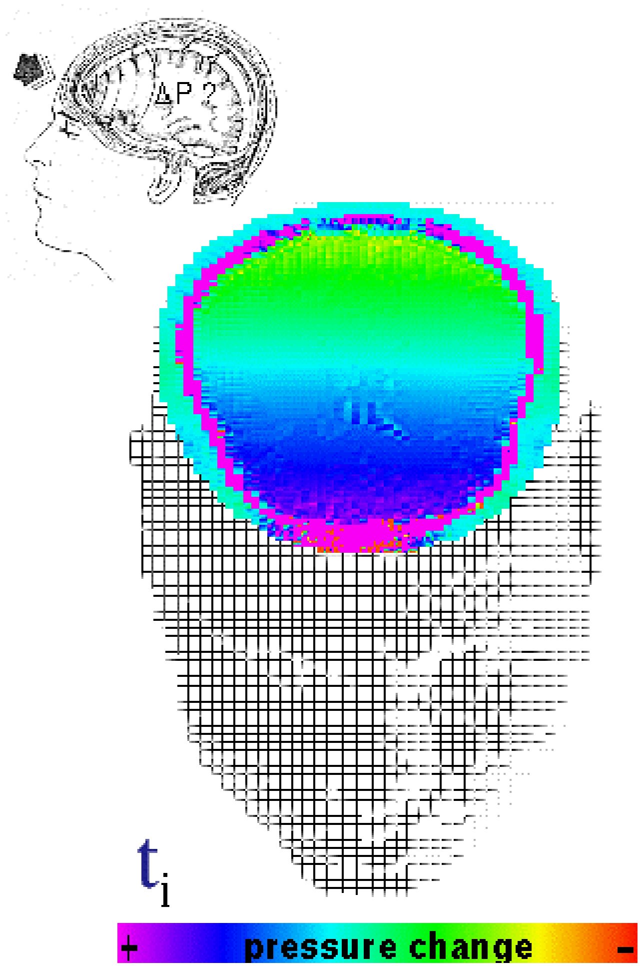
Enables

3D static and dynamic
linear elastic
parallel (MPI-based)
FE simulations
for bio-mechanical applications.



Methods currently used within head-fem:

- Newmark (implicit),
- preconditioned CG

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CAUCHY

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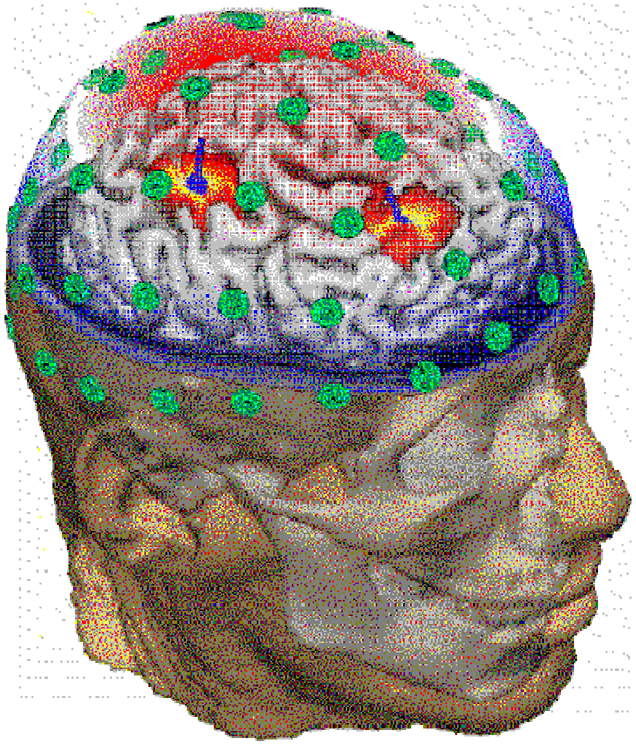
Enables

the solution of an inverse problem
posed by the search for
electric current sources
in the human brain
by exploiting EEG/MEG measurements.



Methods currently used within Cauchy
to solve the forward problem are:

- FEM
- sequential CG &
- coupling with parallel NEC solvers

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PAM-SAFE

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Designed for occupant safety
being extended for advanced dummy simulations
increasingly used for bio-mechanics

Solution Methods within PAM-SAFE

- parallel explicit solver - Lagrangian formulation
- contact/impact algorithms
- extensive Element library (shells, beams, bars...)
- large variety of constitutive models

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Bio-mechanical simulations for passenger safety simulations

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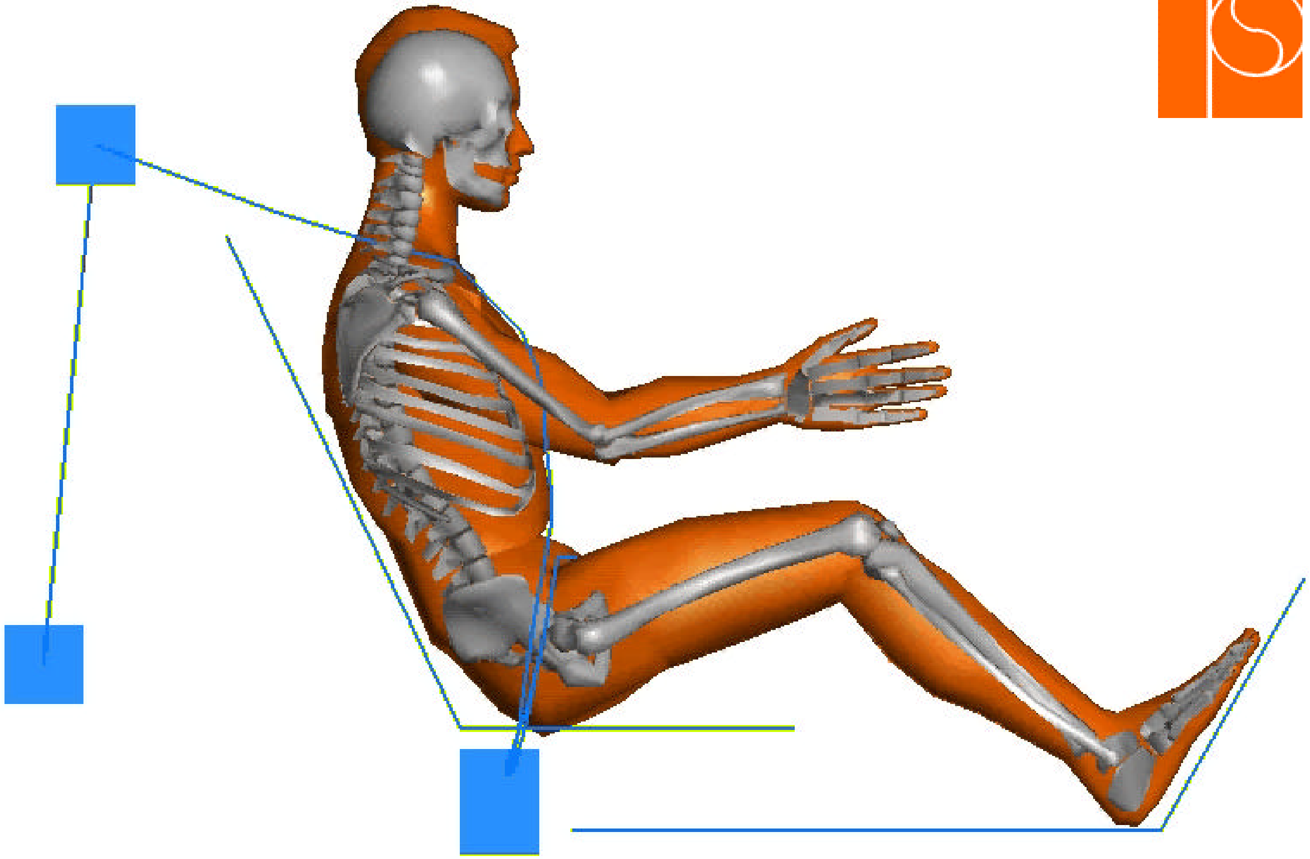

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DRAMA

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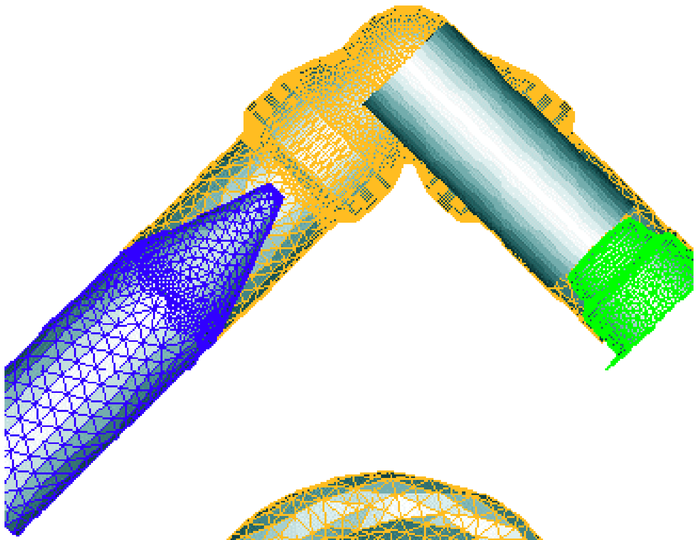
The DRAMA library is a tool
for dynamic load balancing
of parallel mesh-based applications.

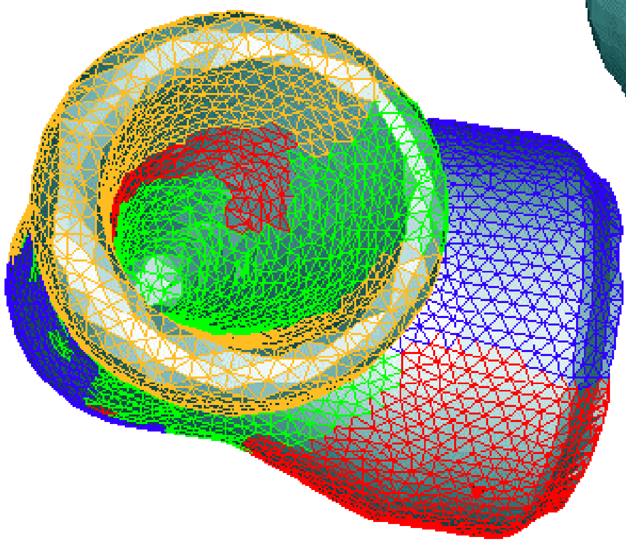
Can of course be used for static partitioning

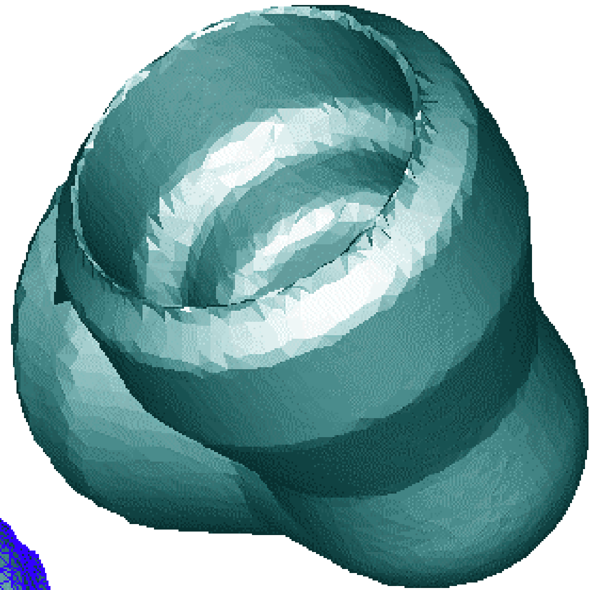
Parallel Partitioning techniques available within DRAMA:

- **graph partitioning (ParMeTis, pJostle)**
- **mesh migration**
- **geometric partitioning**

Forging of a pipe connector -
re-meshing & re-partitioning with DRAMA







FORGE3

Courtesy of

TRANSVALOR

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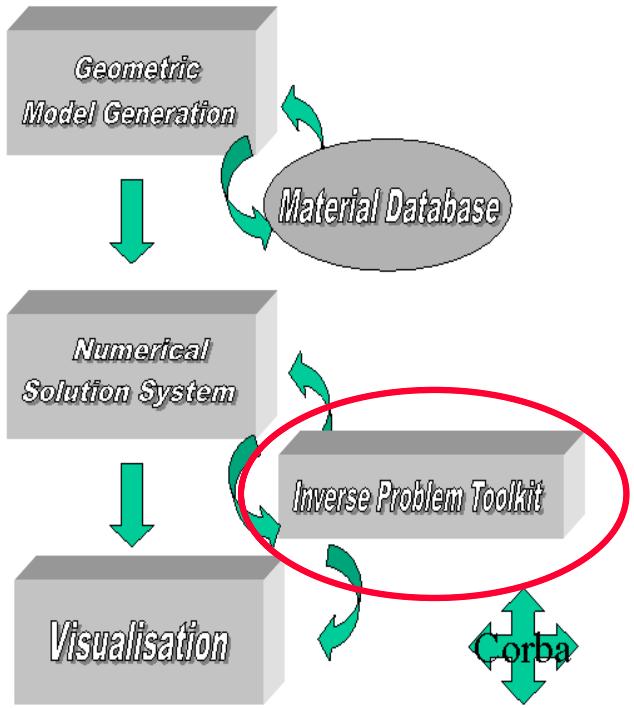
Inverse Problem Toolkit

One can use an inverse model to interprete measurements in terms of the underlying (mechanical or electrical) sources of the object of interest.



Algorithms

Simulated Annealing,
Simplex method,
Optical Flow Technique

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Visualisation

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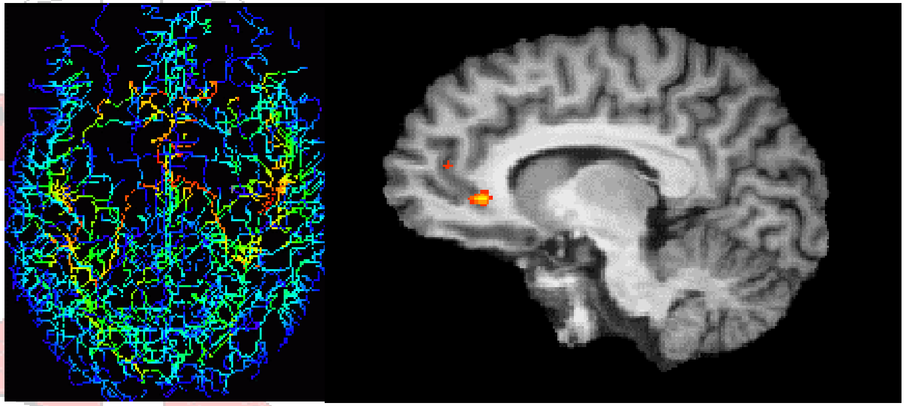
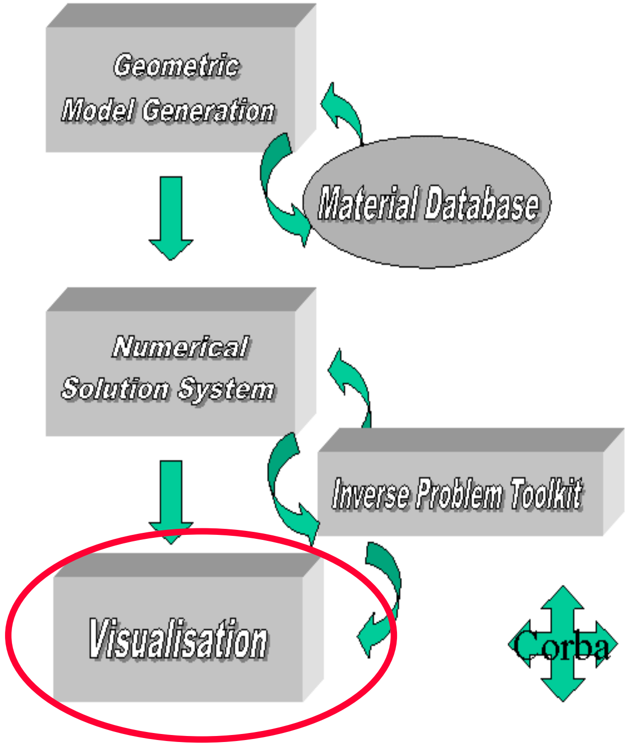


Display of 3D image data, 3D rendering, visualisation of all simulation results

Option: Virtual or Augmented Reality



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SimBio Applications

Electromagnetic Source Localisation in the Head

Biomechanics of the human head

Knee Prosthesis Design

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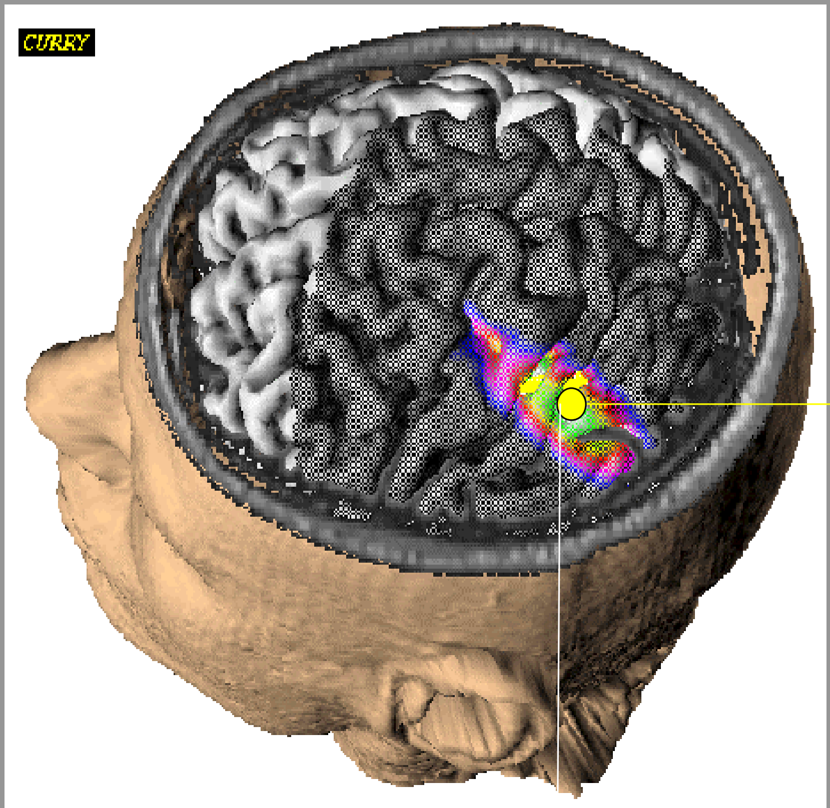
Motivation



A widespread technique to investigate the functional state of the brain is to record its

electromagnetic activity

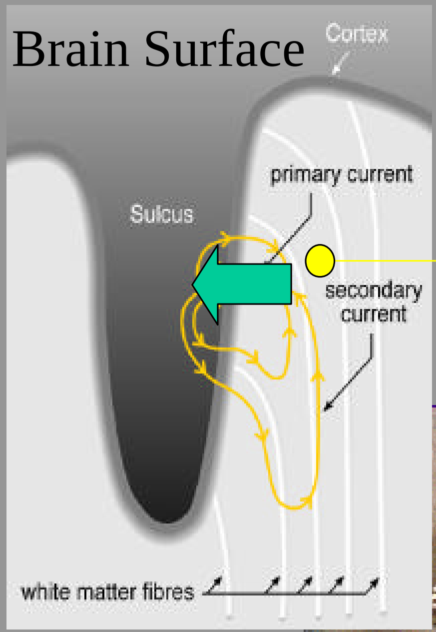
by means of

electroencephalography (EEG) and

magnetoencephalography (MEG)

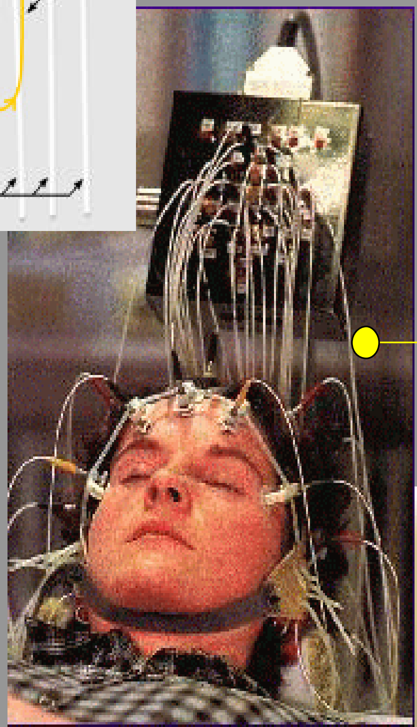
Such investigations are important
• to identify brain regions of dysfunction (e.g. caused by tumor growth) and
• to diagnose epilepsy.

Motivation



It is daily practice in clinical routine to localise

dipolar current sources in the brain

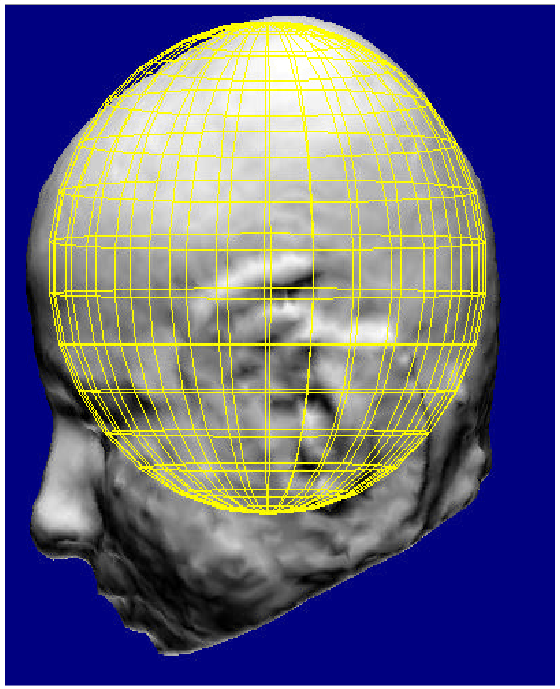


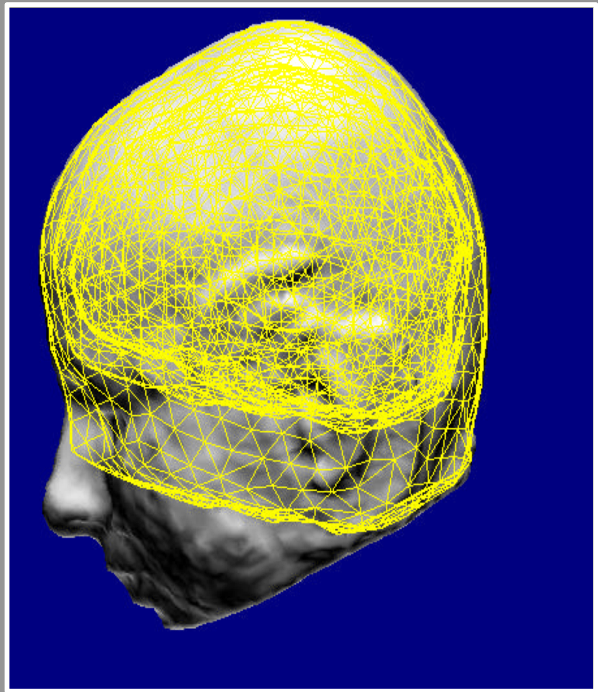
based on EEG and

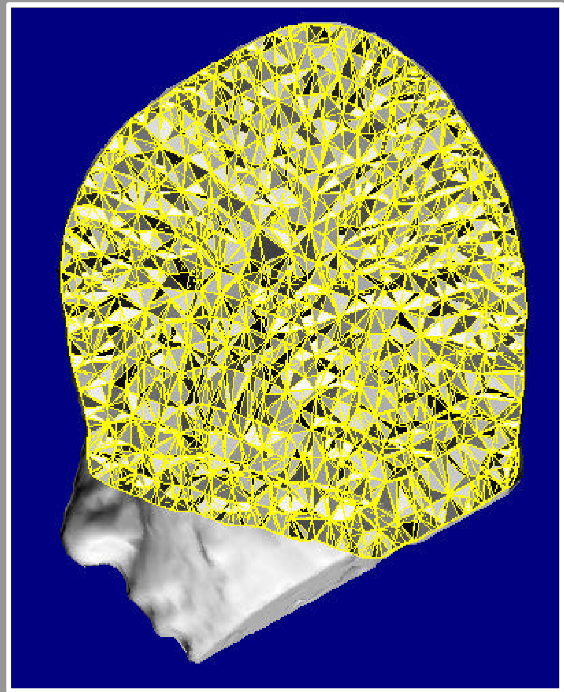
MEG measurements.

Modelling head conductivity

A short “history” of source localisation techniques





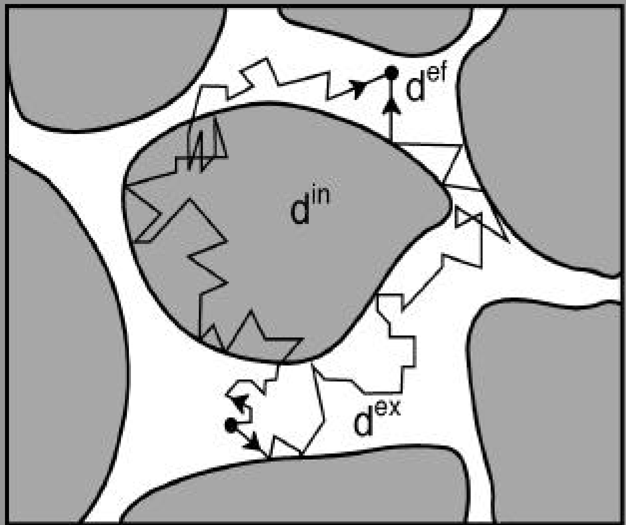


3 concentric shells: **Boundary elements:** **Finite elements:**

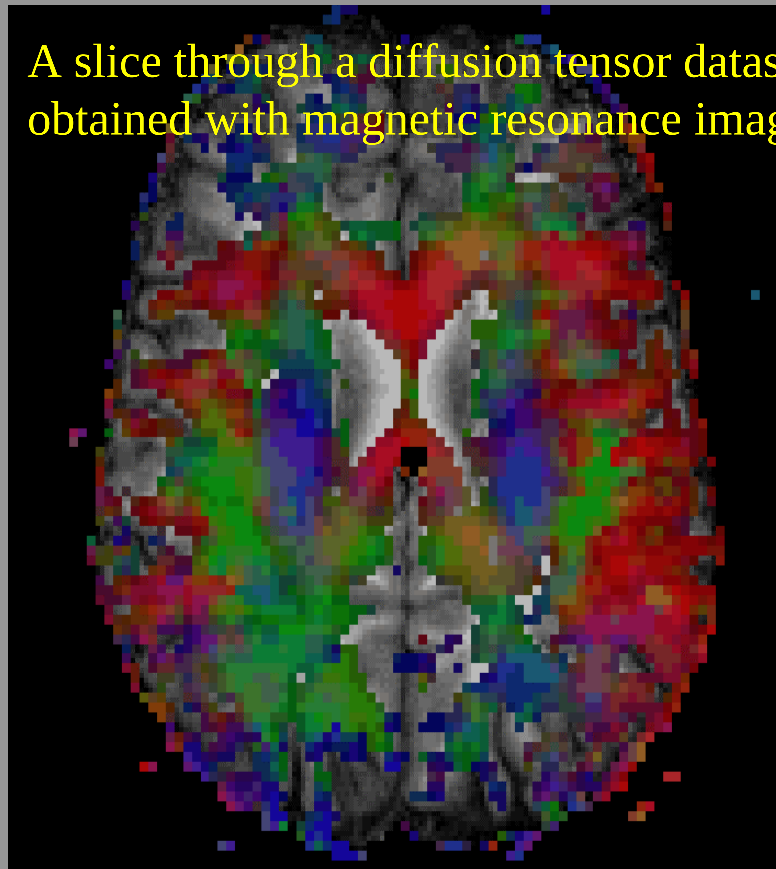
Only the Finite Element Method enables the modelling of internal brain structures and their physical properties!

Whole brain diffusion measurements

Are the prerequisite to model the head as an anisotropic FE volume conductor



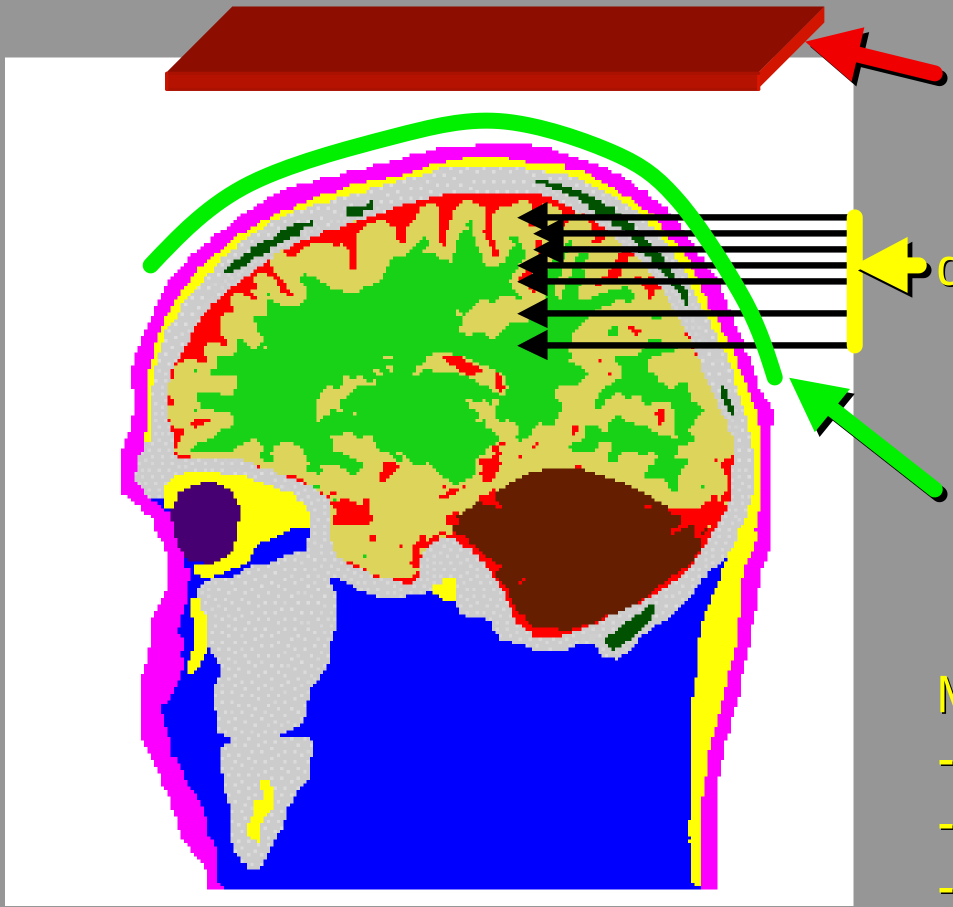
A proton in the brain on its "diffusive" walk through the cells.



This image encodes the major diffusion direction of the protons in the brain.
Proton diffusion behaviour in the brain is related to tissue conductivity!

Preliminary Simulations

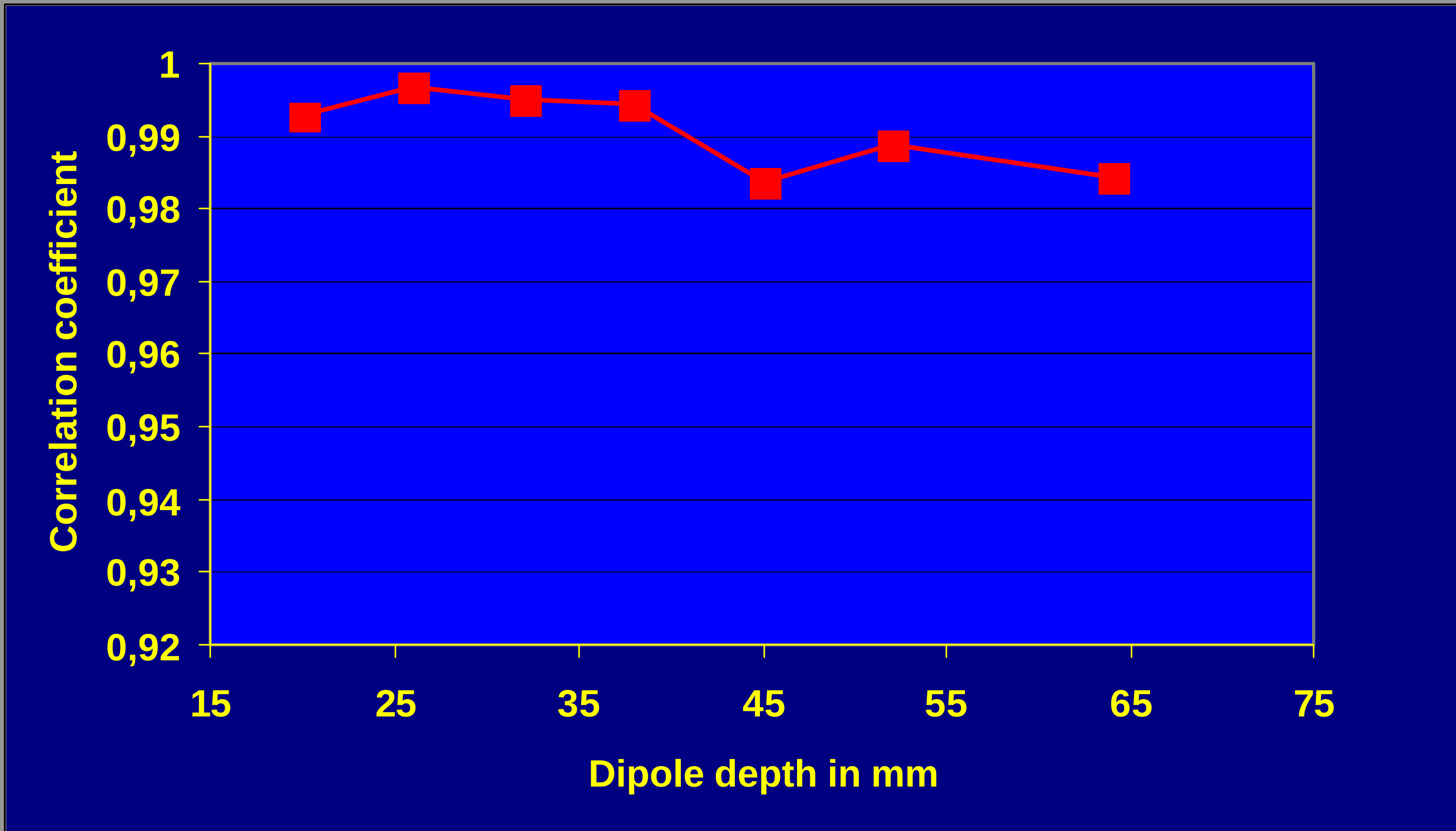
(Haueisen et al., 1999):



Models:
- isotropic inhomogeneous
- anisotropic (conductivity tensor)
- 3 compartment homogeneous

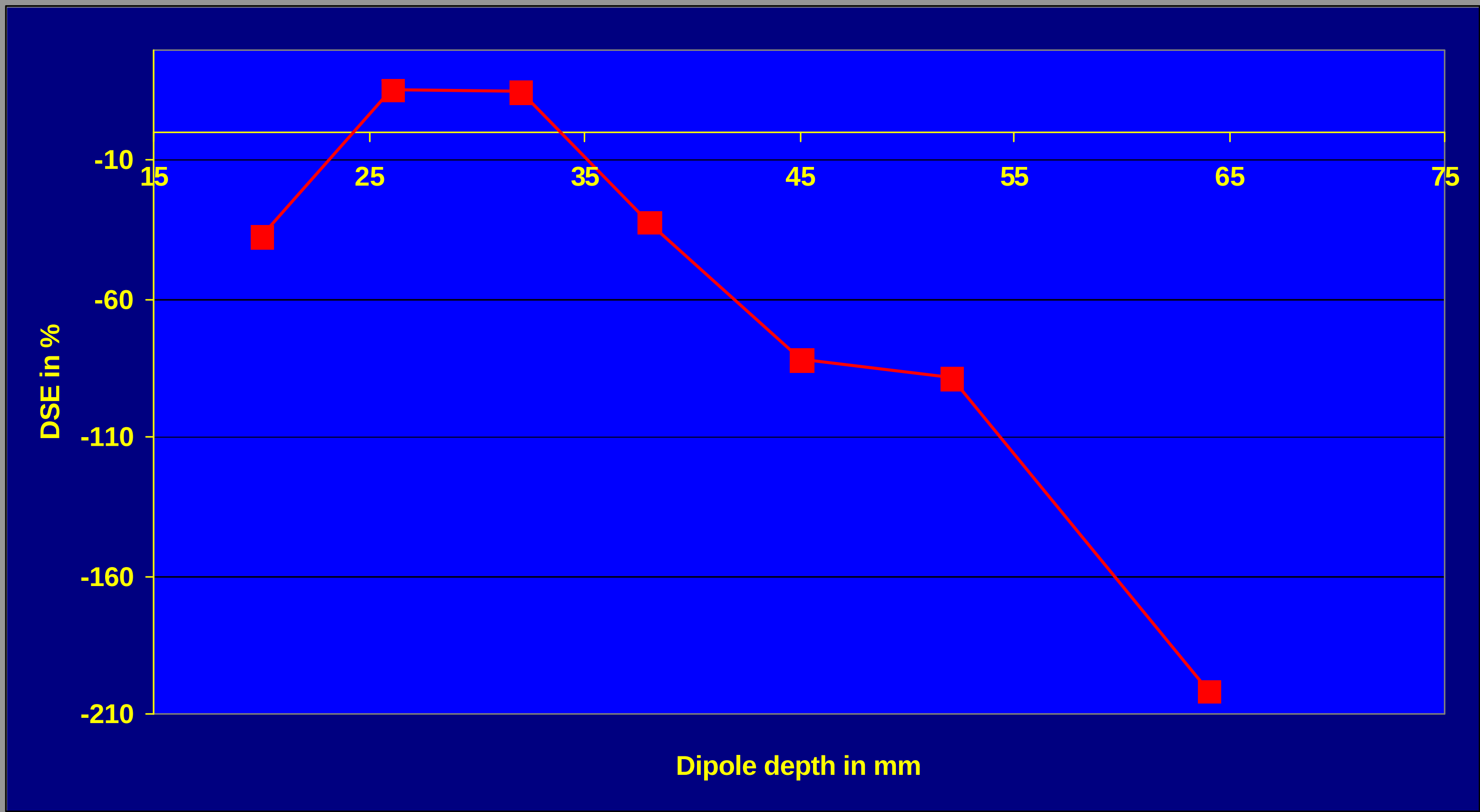
Results

Correlation between electric potentials computed with the isotropic and the anisotropic model



Results

Amplitude changes between electric potentials computed with the isotropic and the anisotropic model



(iso-aniso)/iso

Source localisation: Conclusion on anistropy

Anisotropy seems to have

a minor influence on source localization

but a major influence on dipole

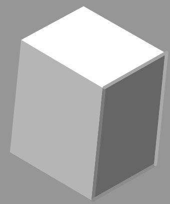
strength estimation.

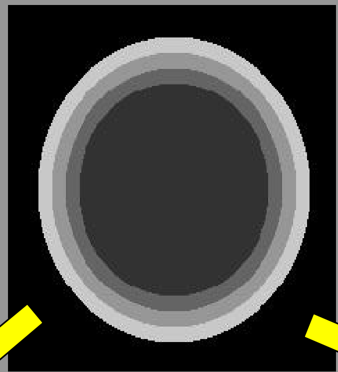
Nevertheless: An electric potential correlation of 0.98 still corresponds to a difference in source location of about 0.5-0.8 cm

Finite Element Studies - Forward Solution

Carried out with a spherical head phantom

Hexahedron

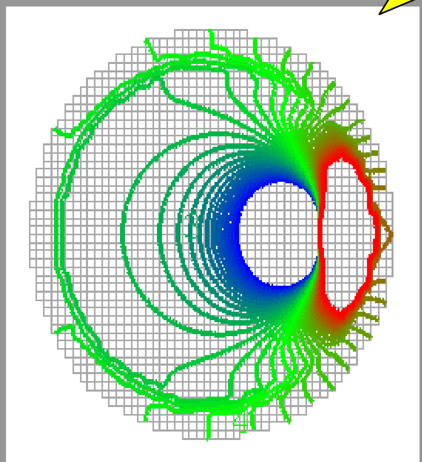




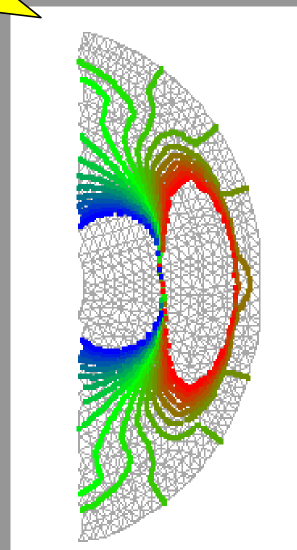
Tetrahedron

Volume conductor:

- **4 layer sphere model**
- **s_i= const. (i=1,..,4)**
- **s_{skull} : s_{scalp} = 1 : 80**



Visualisation of isopotential lines from -10^{-6} V to 10^{-6} V

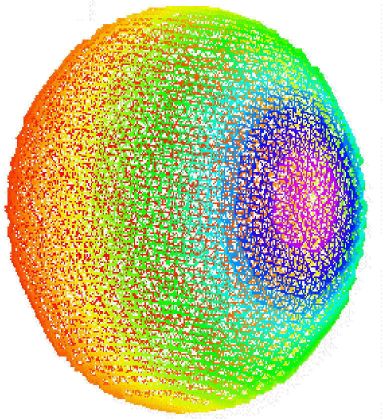


Nodes: 71.403
Elements: 65.360

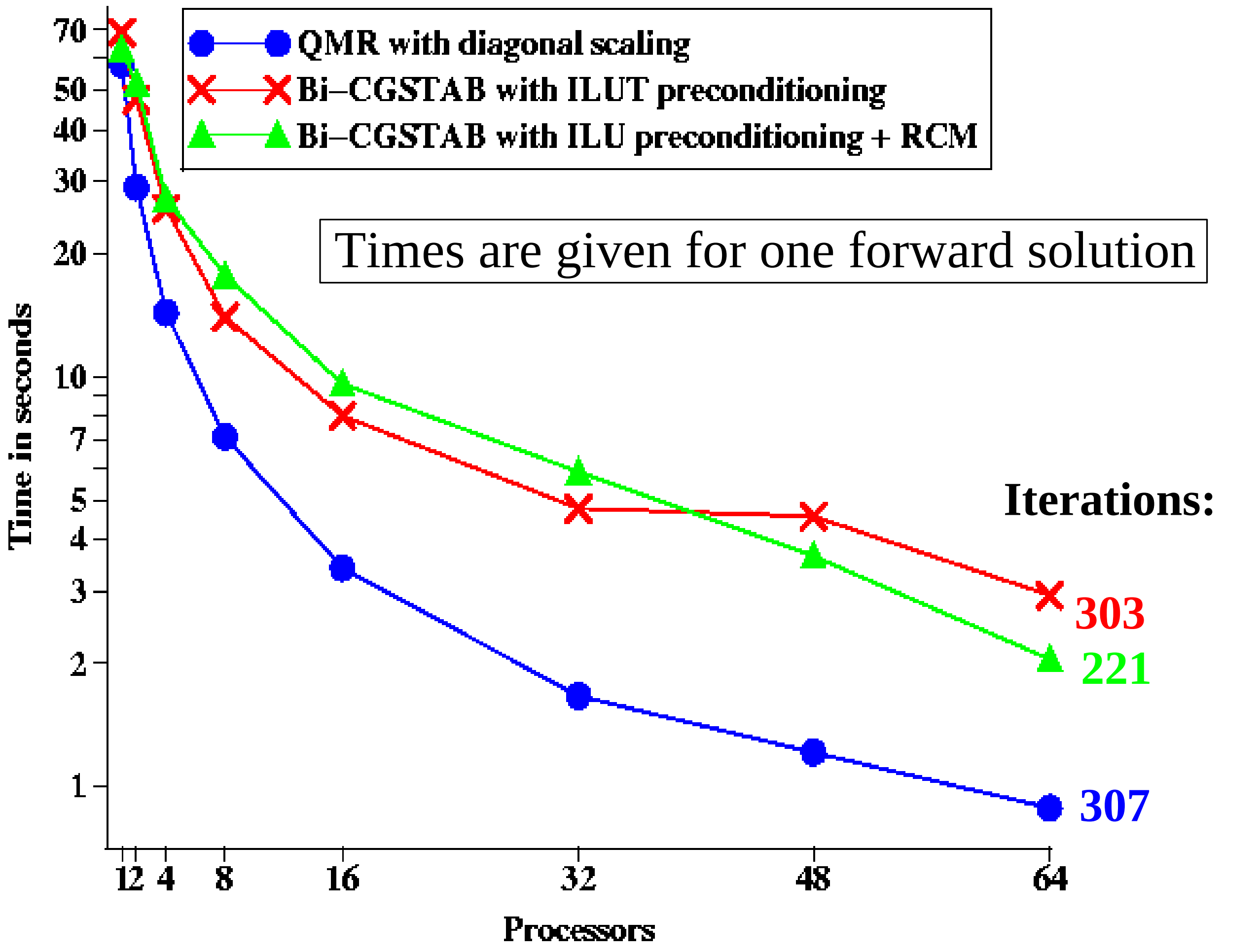
Nodes: 90.538
Elements: 541.802

Solver Performance

Order: 71,403; non-zeros: 1,402,157;
ILU threshold: 10^{-2}; NEC Cenju-4



A forward solution



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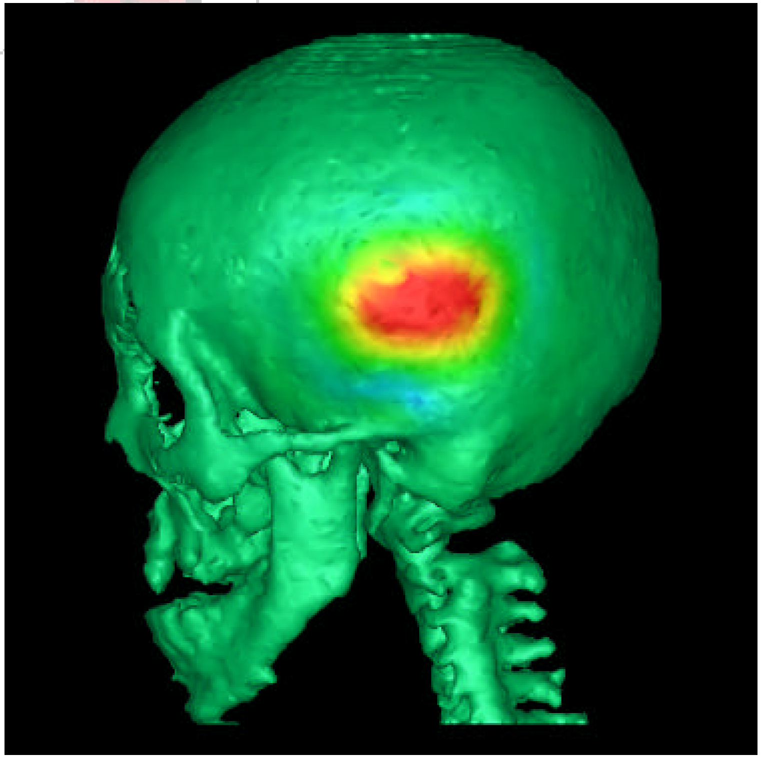
Facio-Surgical Planning

For shifting the skull bones a so-called halo is fixed to the head applying appropriate forces to the jaw.



The halo exerts high pressure to the skull at the locations where it is fixed !

There is a danger of the skull breaking.

A visualisation of the displacements induced by the halo (Head_fem results visualised by BRIAN)

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Head-fem parallel performance head-impact simulation

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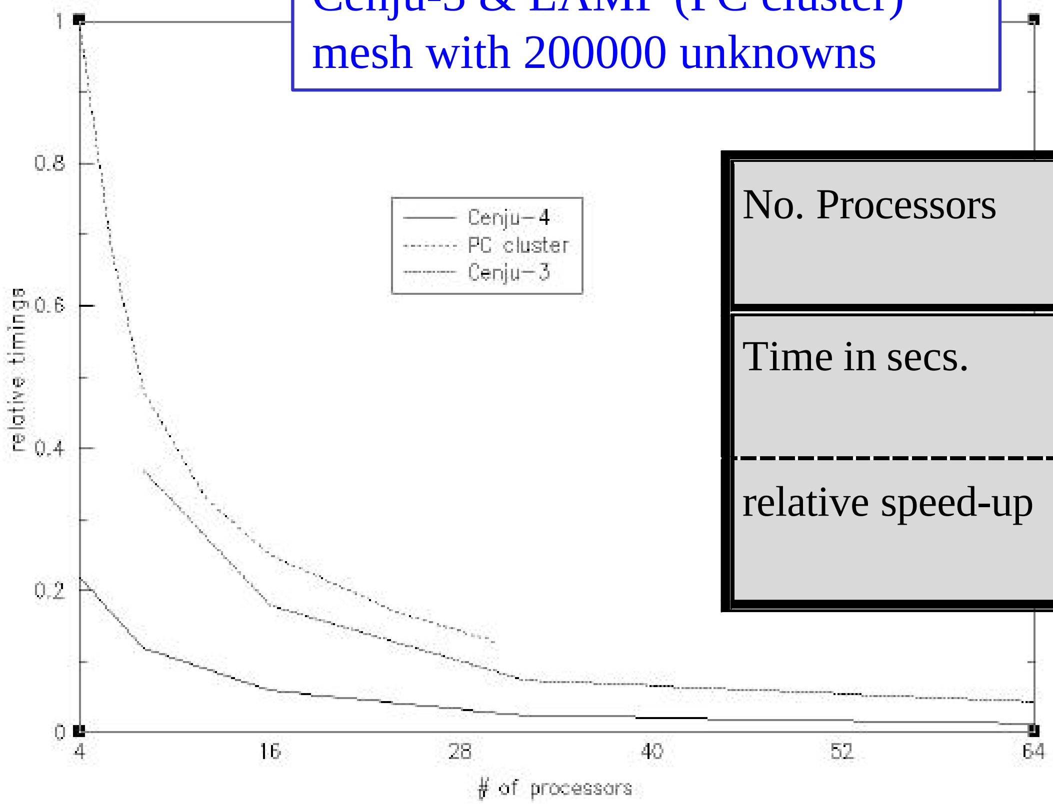
Relative performance on Cenju-4, Cenju-3 & LAMP (PC cluster) mesh with 200000 unknowns



No. Processors	24	32	48	64
Time in secs.	47.4	35.9	24.4	19.0
relative speed-up	**1.0**	1.32	1.94	2.50

Speed-up on Cenju-4
for 1 Newmark iteration
Mesh with 400000 unknowns

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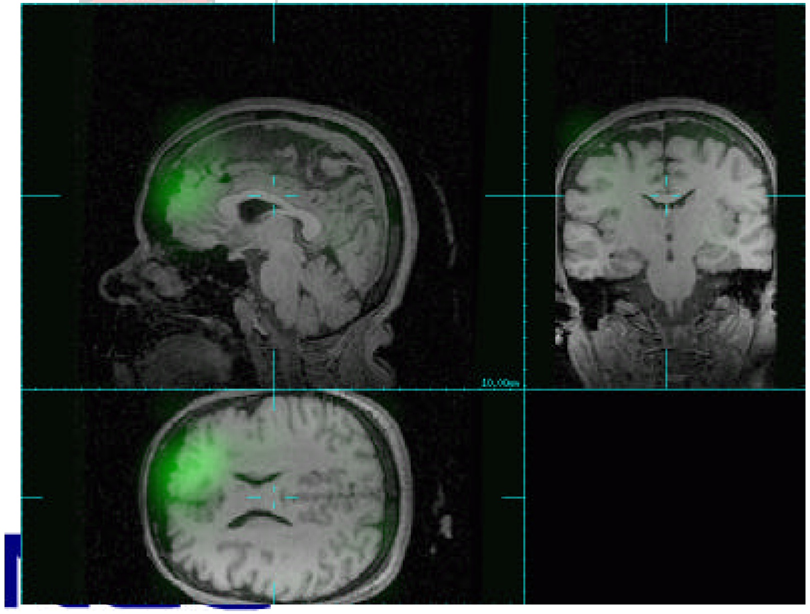
Neuro-Surgical Planning

When the skull is opened during operation, the brain shifts.
Pre-operative image data are not valid any more.
The neurosurgeons only have this data and their knowledge as a guidance.
Consequence: they do not know what they operate on!



Therefore it is of great importance
to estimate the brain shift and
to give hints to the neurosurgeon
of how the brain has moved.

Brain Shift
Visualisation

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Knees Up Project

- Aim: To produce a dynamic realistic 3D model of human knee including soft tissues.
- Achievements:
  - Acquired & processed detailed MRI data
  - Produced a 3D FE knee model consisting of main anatomical features & material properties
  - Used model to predict contact forces and kinematics in normal knees, diseased joints and prosthetic implants.

Summary of Current Status

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- **Knees Up**
  - **demonstrated capability**
  - **MRI ⟶ FE Model**
  - **one cadaveric knee**
  - ***semi*-automatic**
- **SimBio**
  - **patient applications**
  - **increased automation**
  - **clinical outcome studies**

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Knees Up geometric data

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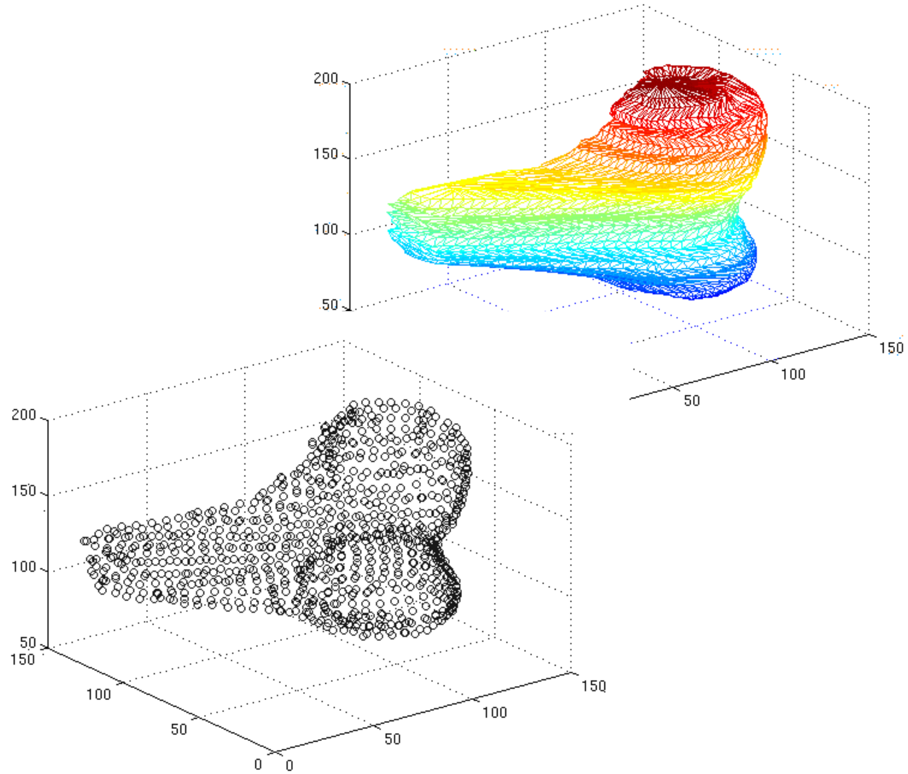
Derived from MRI scan slices



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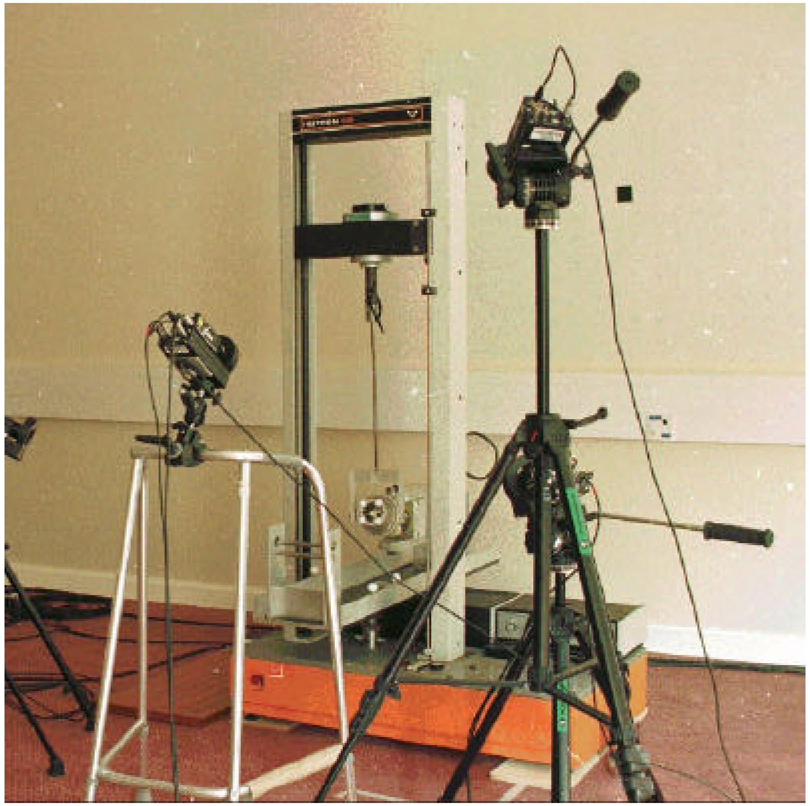
KneesUp kinematic data

Kinematic data on cadaver knee derived from tests using Instron machine & 3D video movement capture system



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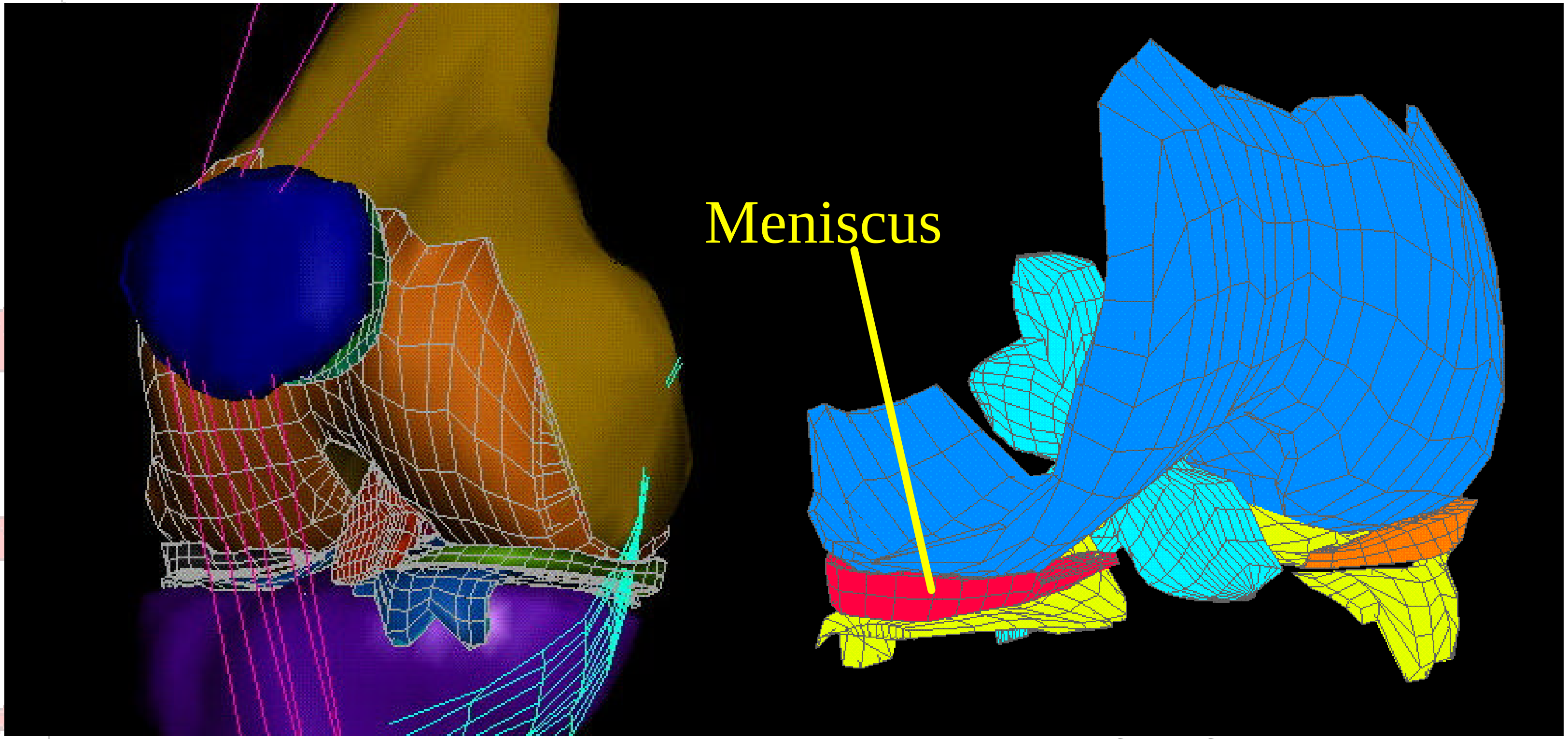
Finite Element model of knee



FE knee model showing muscle attachments

FE models of soft tissue components of knee

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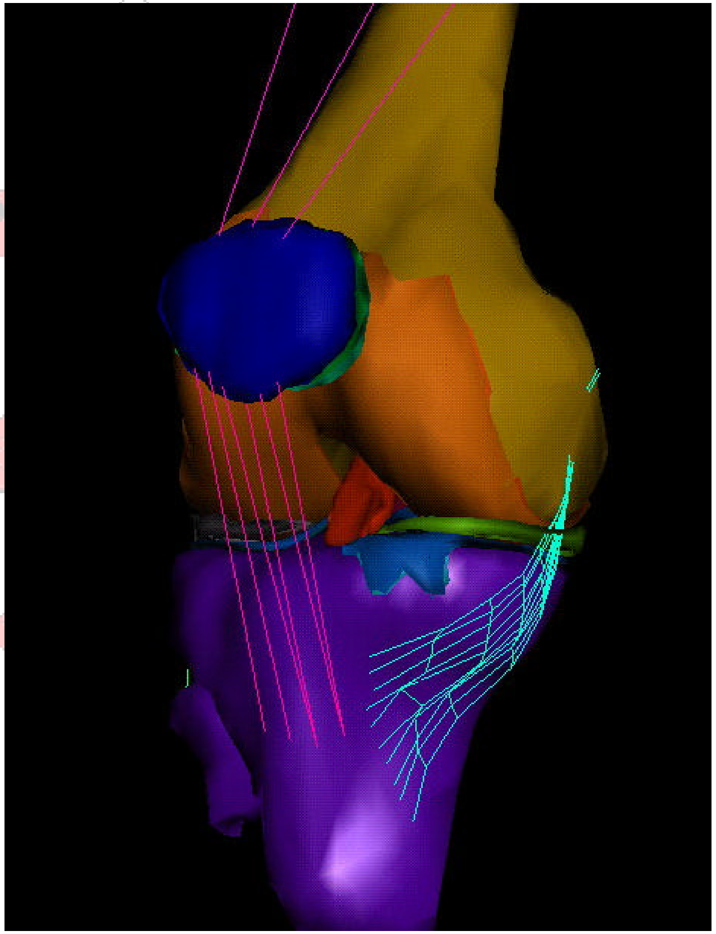
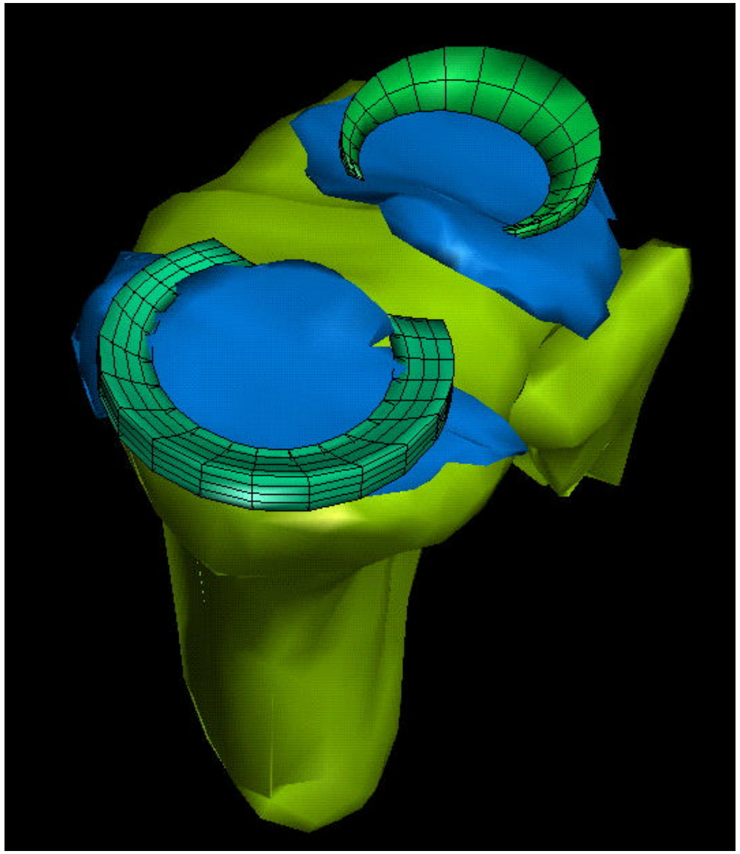
The Knees Up human knee model
and detail showing the meniscal replacement





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A Gait cycle simulation with the Knees Up model

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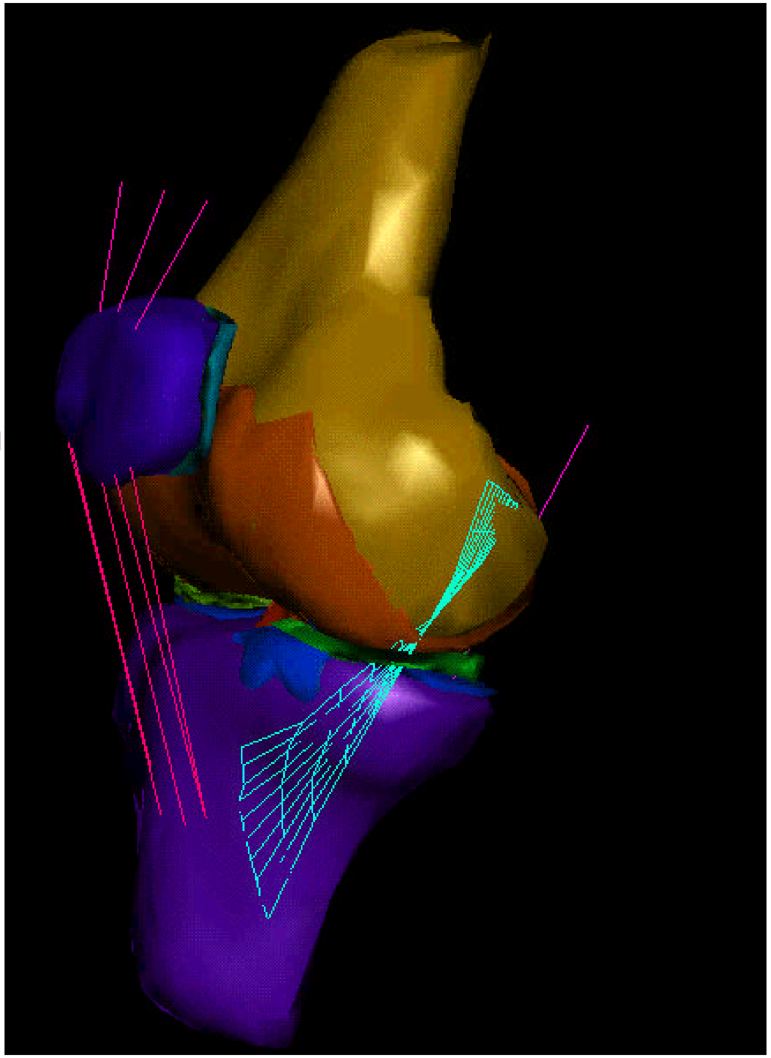

Modelling:
U. Sheffield & ESI
Simulation with
PAM-SAFE

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Concluding Remarks

- The SimBio environment will combine medical imaging & FEM techniques with up-to-date HPC technology
- The component-based distributed interaction will enable interaction (“networking”) of technological expertise (clinical ⇔ engineering ⇔ computing)
- The evaluator applications will improve options in/for:
  - ➢ diagnosis and analysis of neurological disorders
  - ➢ design of prostheses
  - ➢ neurosurgery

For further information: lonsdale@simbio.de

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