SimBio: A generic environment for bio-numerical simulation

G. Lonsdale

Overview:

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

Illustrated partly with pre-project developments

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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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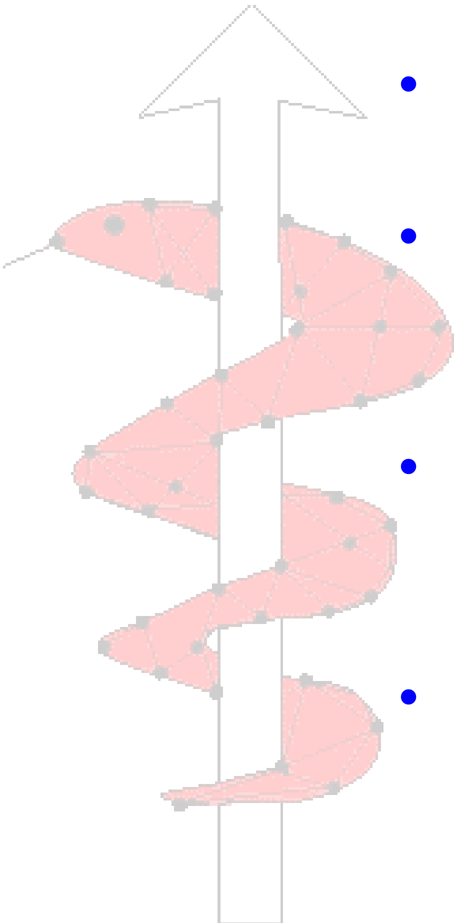
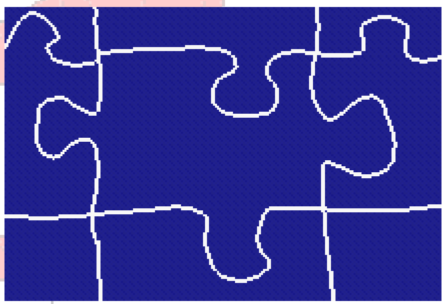
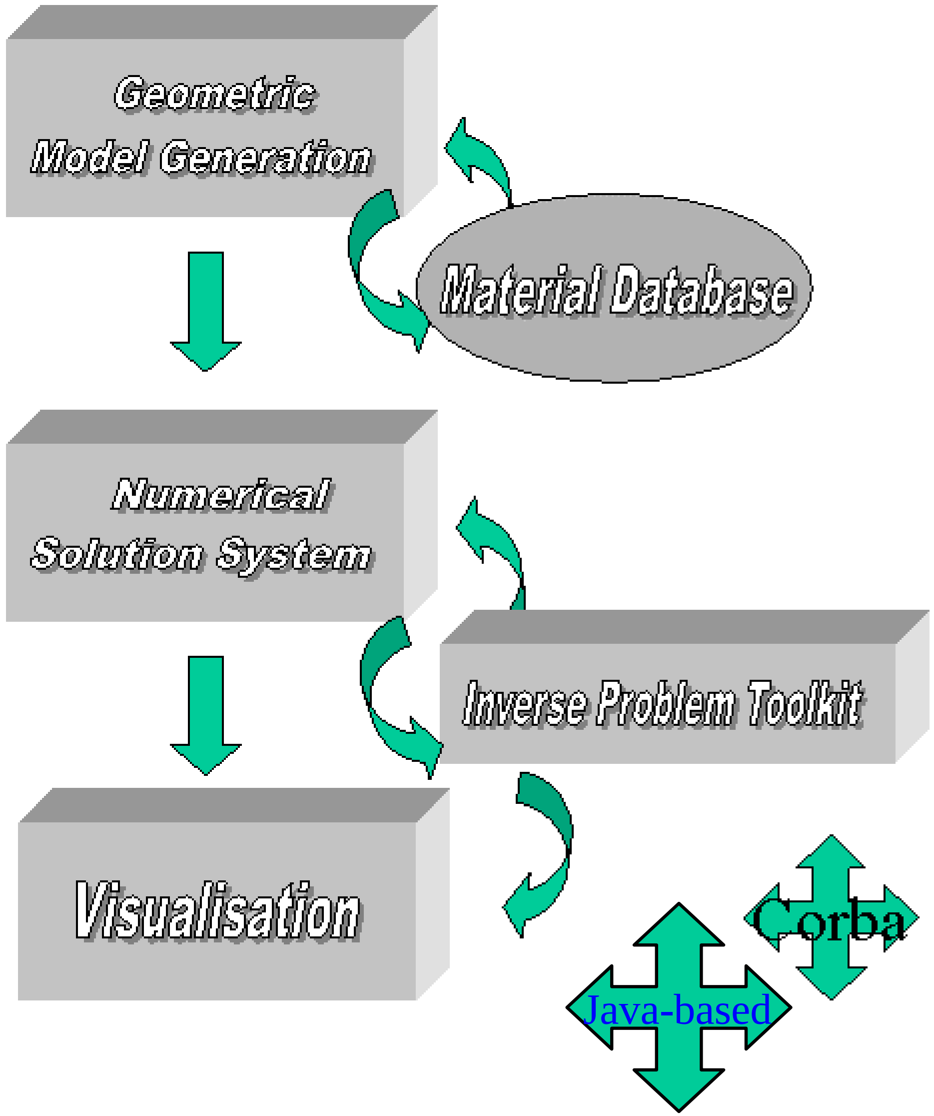
SimBio Environment Components



- 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

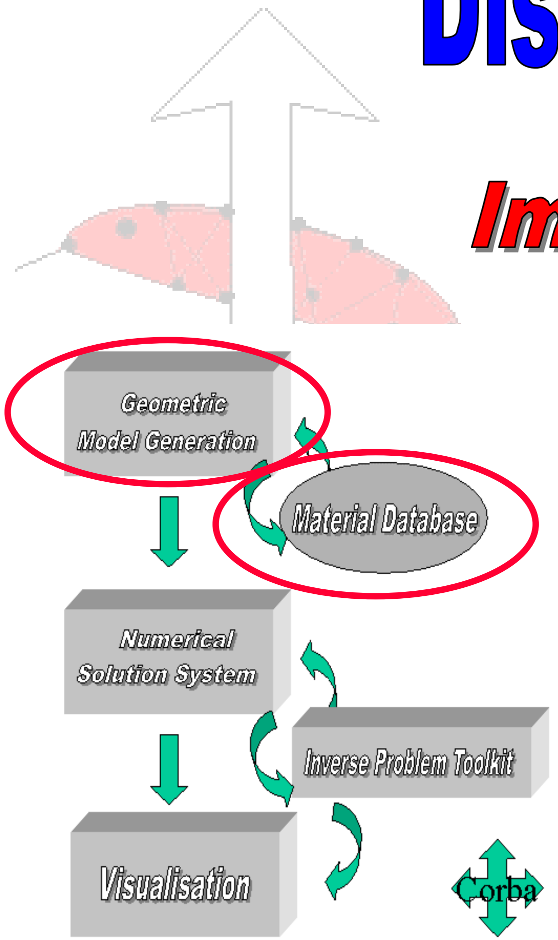

Image Segmentation
& registration

Mesh generation

Material Modelling
(database)

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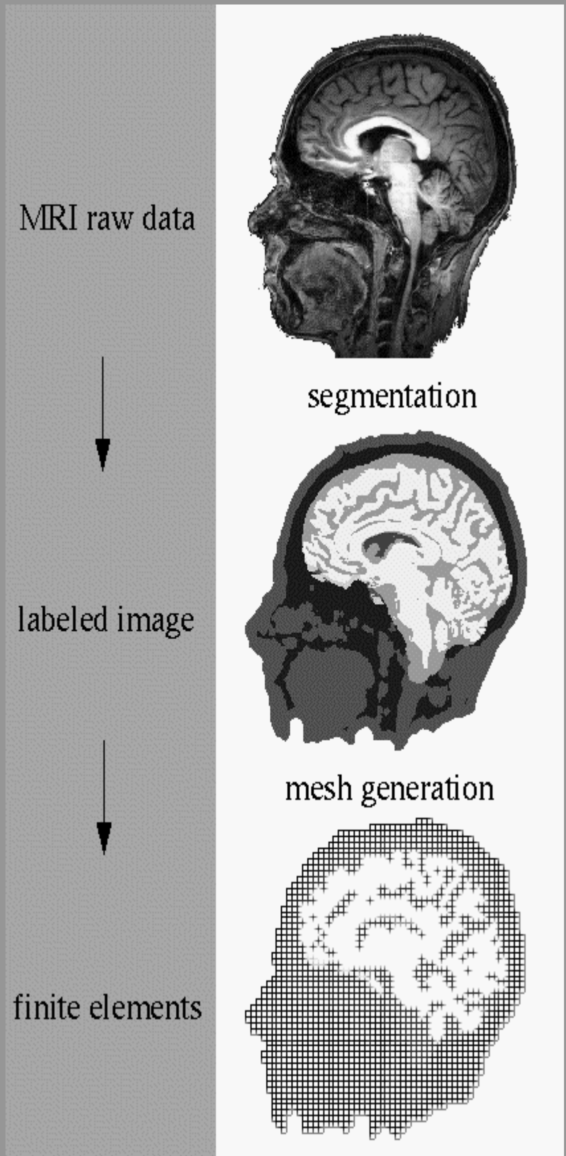
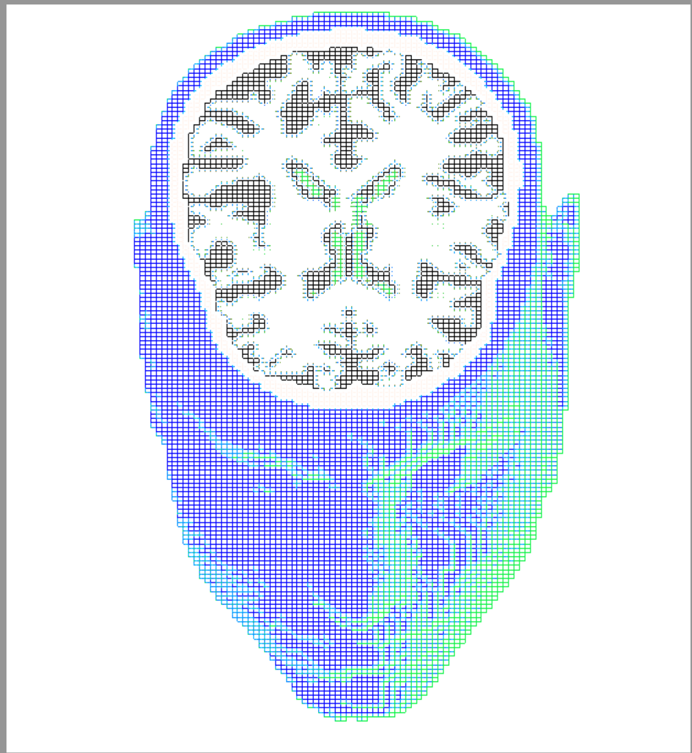
Example: Modelling head geometry

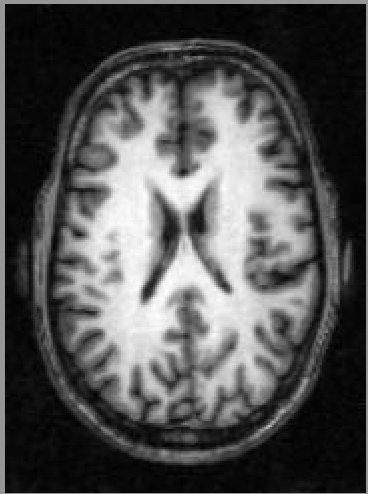
From magnetic resonance images (MRI) to finite element meshes of the human head



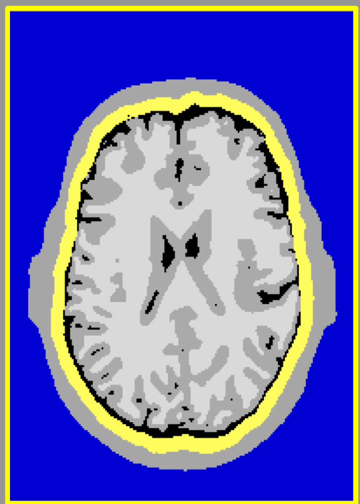


Segmentation & Registration of multimodal MRI data

T1



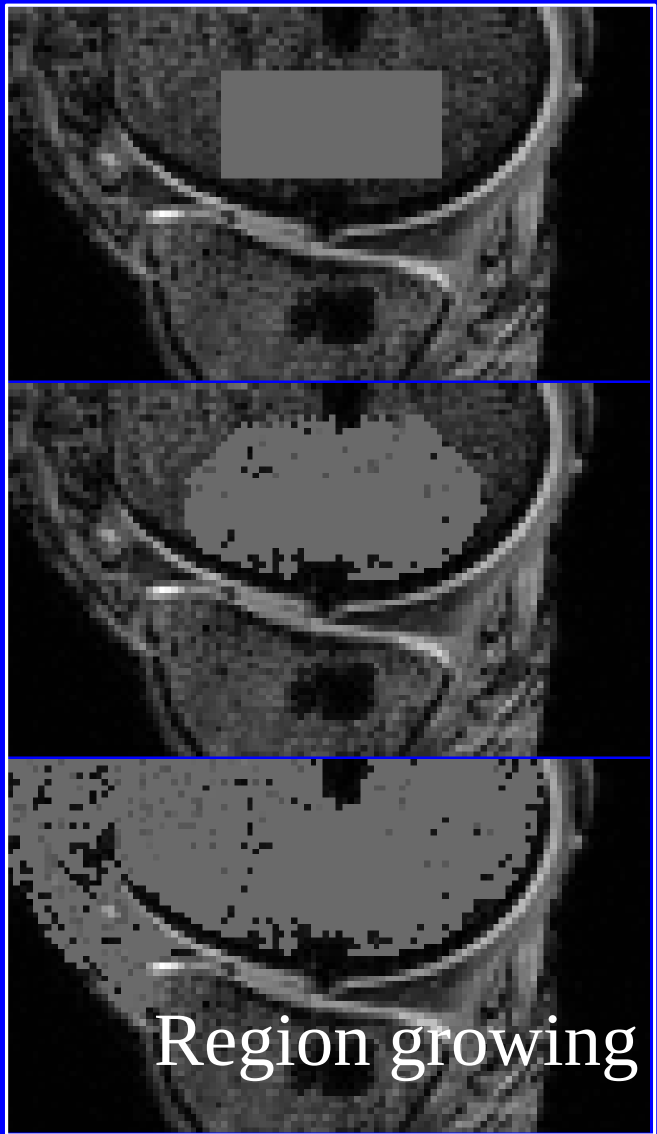
PD

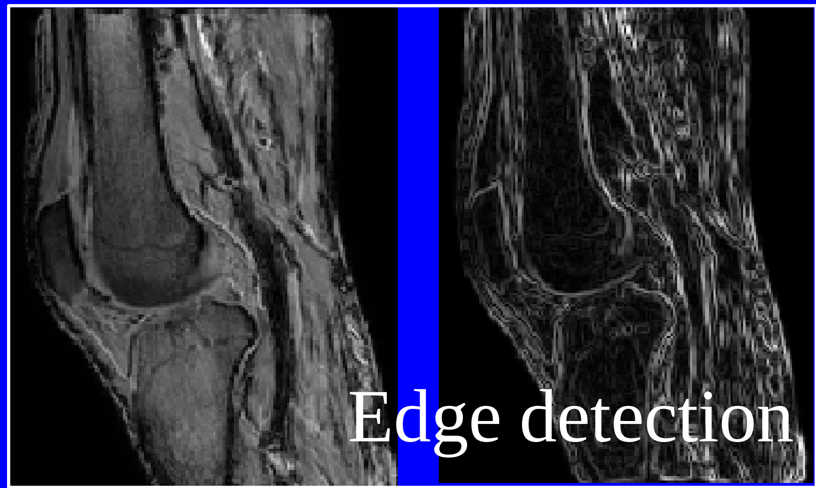


Segmentation result

- **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)**

Current Segmentation results for knee modelling





VGrid

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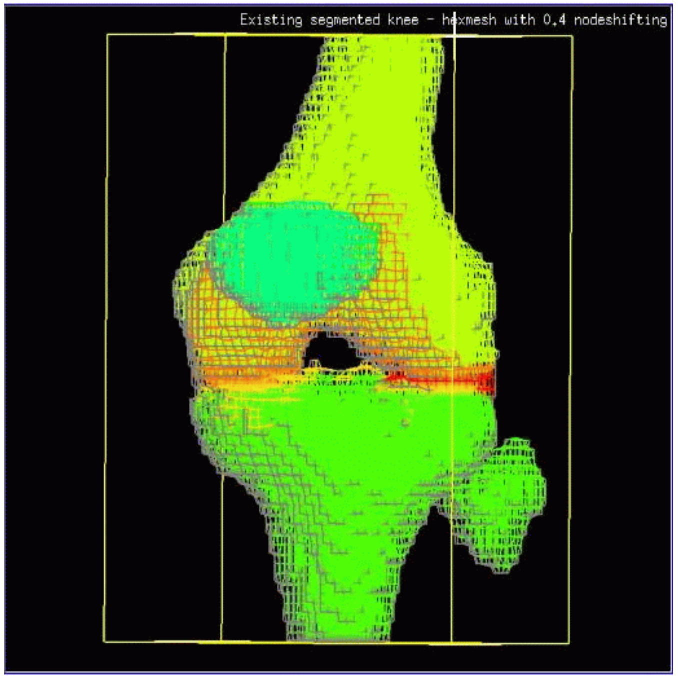
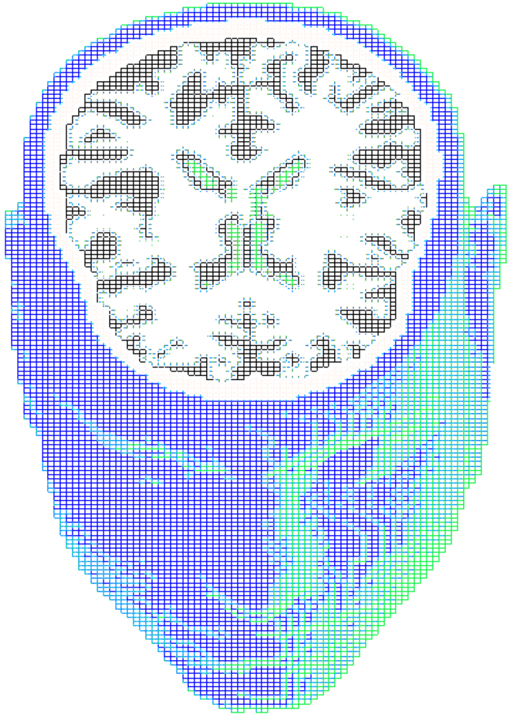
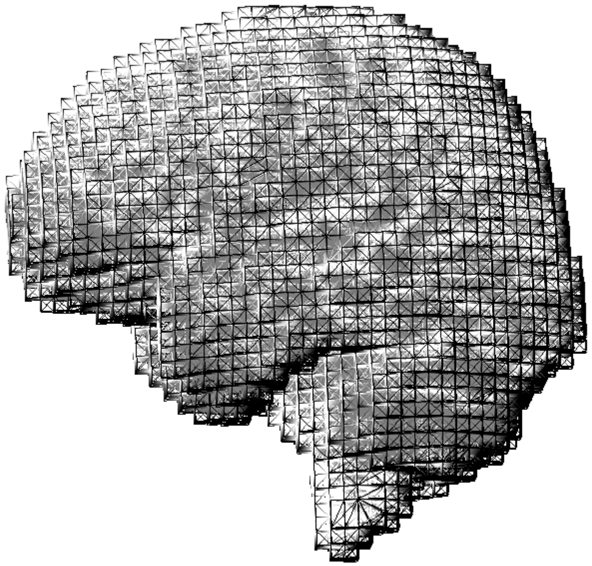
Generates FE meshes consisting of hexahedral and tetrahedral elements

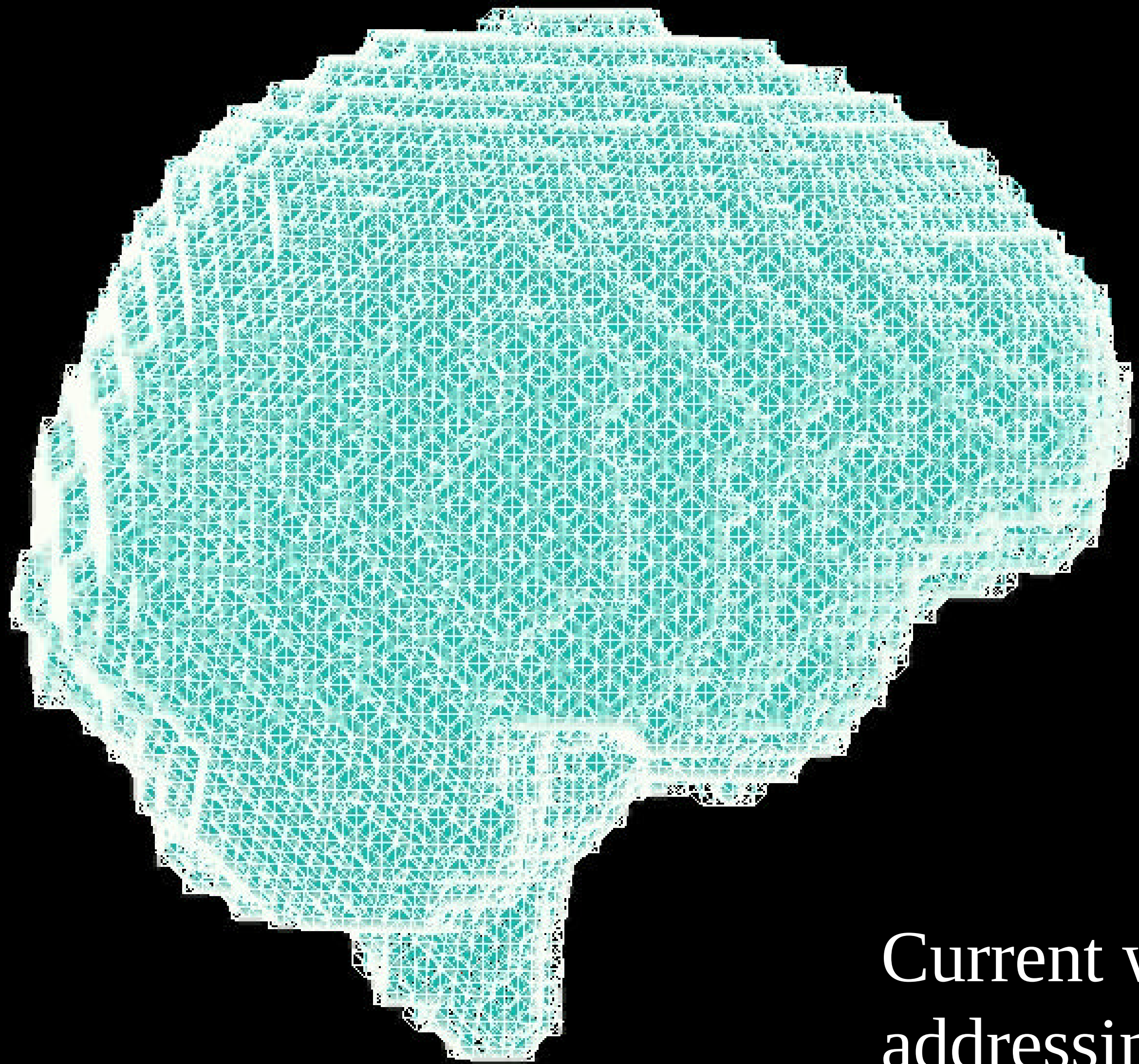






VGrid

3-D Brain model:



Current work addressing surface smoothing

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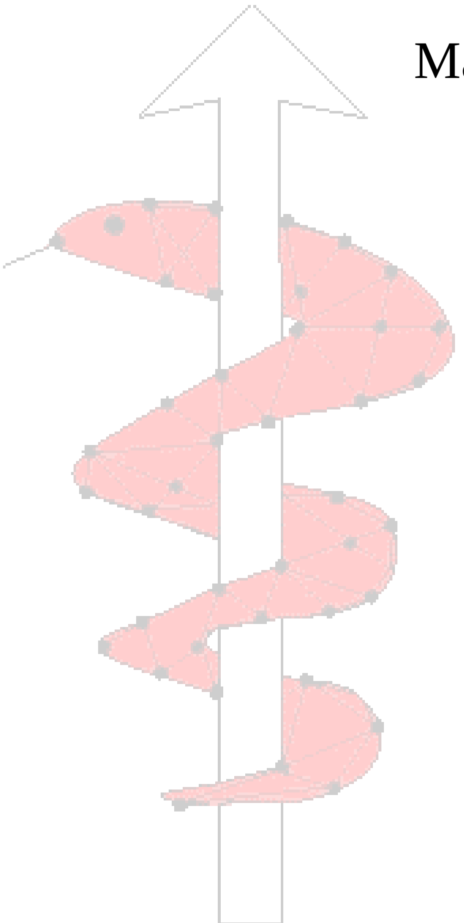
Material Database

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

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Magnetic Resonance Strain Imaging MRSI

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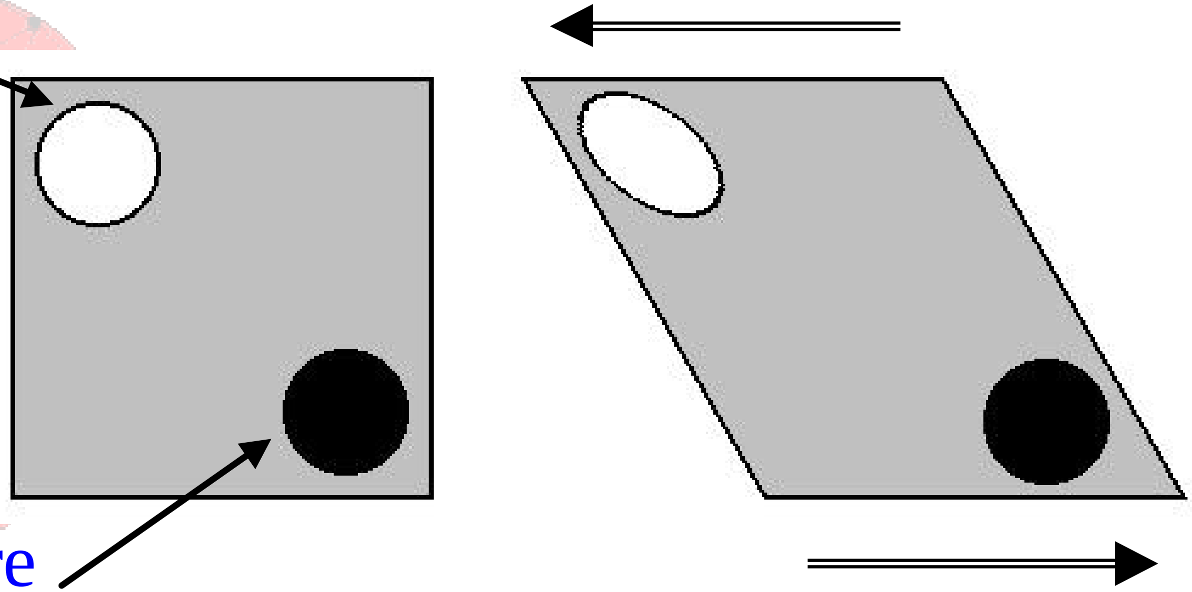
CNRS

The principle

Spheres embedded in a cube of known mean deformability

Soft sphere



Hard sphere

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

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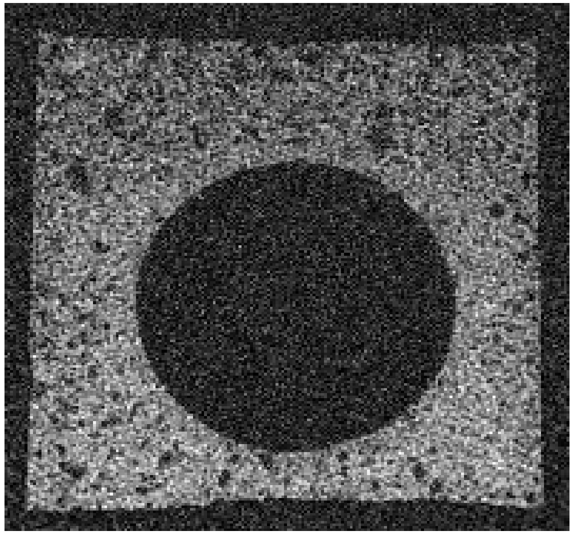
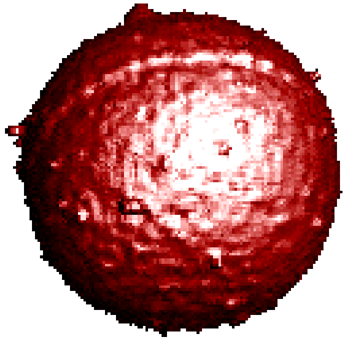
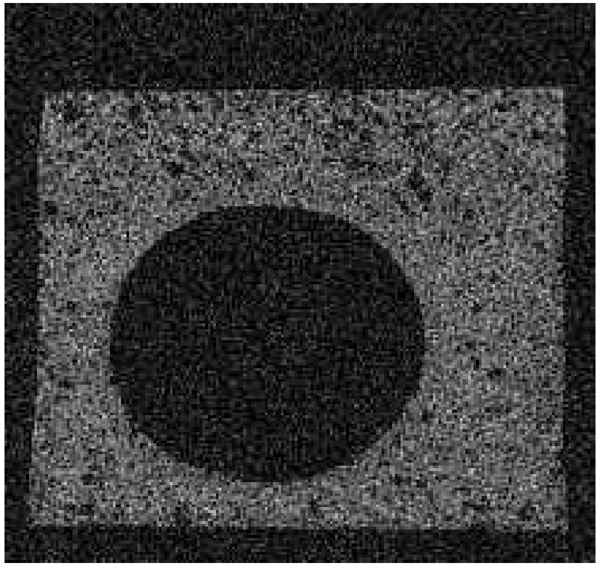
MRI images of deformed & non-deformed structure visualised with CNRS tool Volview

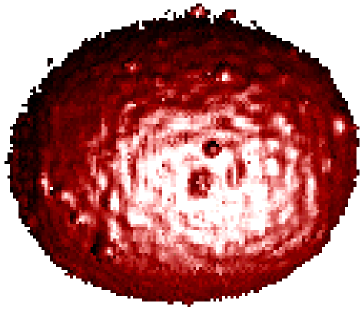


relaxed

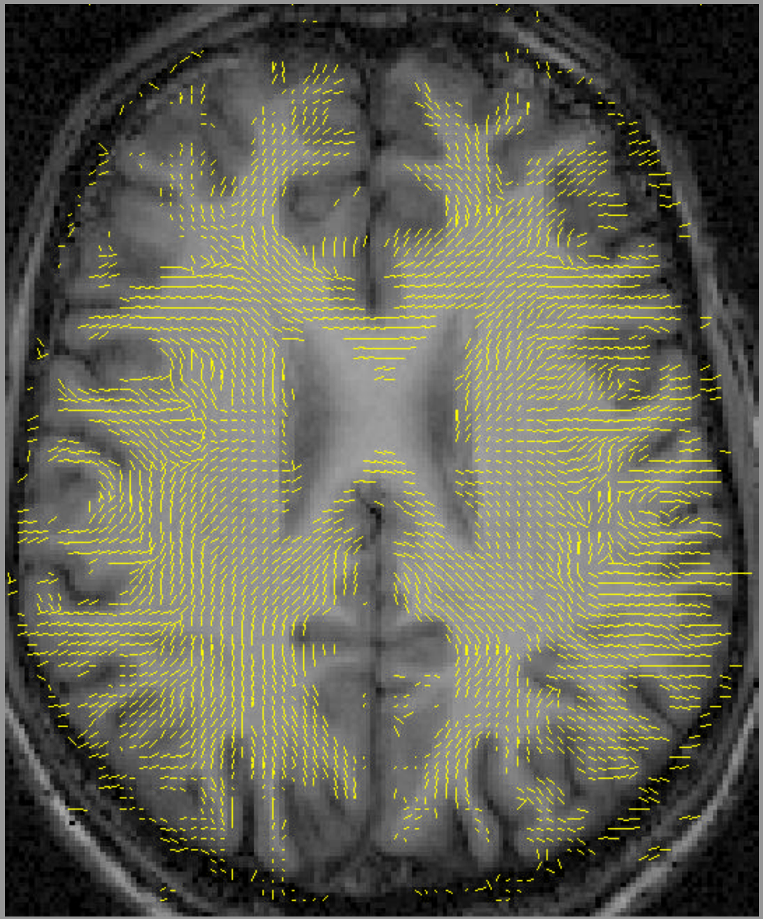




compressed



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)

Whole brain diffusion measurements are the prerequisite to model the head as an anisotropic FE volume conductor

Numerical Solution System

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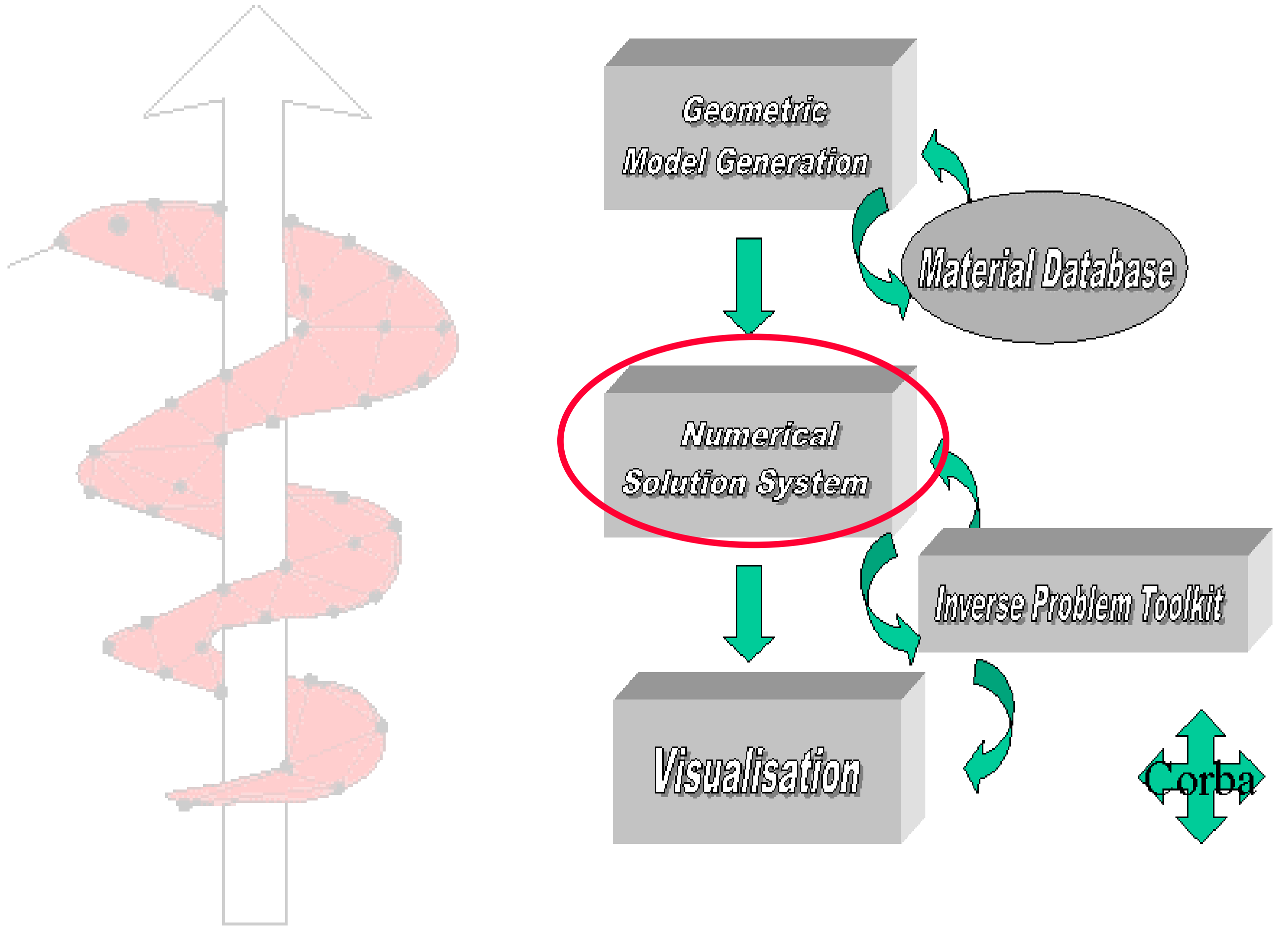

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Numerical Solution System

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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. HeadFEM,
2. S-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-interface, ..

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Numerical Solution System

Software use for the SimBio Applications:

- S-CAUCHY - source localisation in the brain
- HeadFEM - for Head biomechanics
- PAM-SAFE - for Knee prosthesis mechanics

- DRAMA - supporting S-CAUCHY & HeadFEM
- Solvers - AZTEC, AMG solver, NEC Krylov solvers in S-CAUCHY & HeadFEM

Examples

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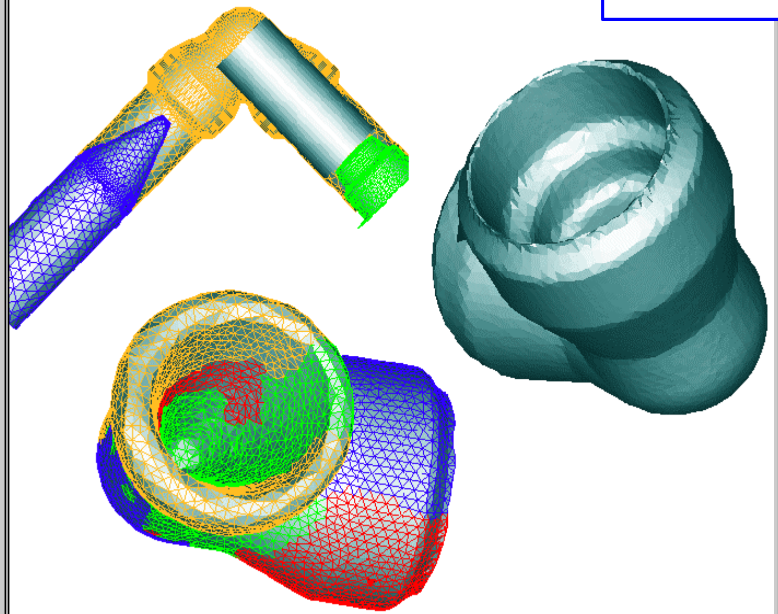
DRAMA

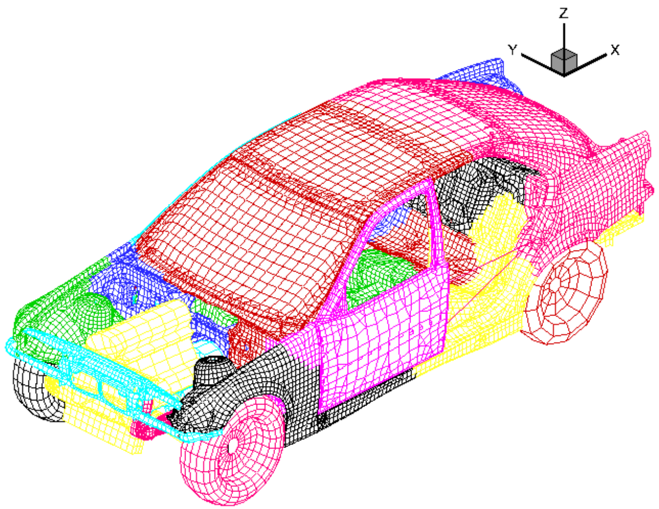
Developed in ESPRIT project 24953

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

- Can of course be used for static partitioning.
- Also provides partitioning to improve iterative solver convergence



Courtesy of Transvalor



Courtesy of BMW

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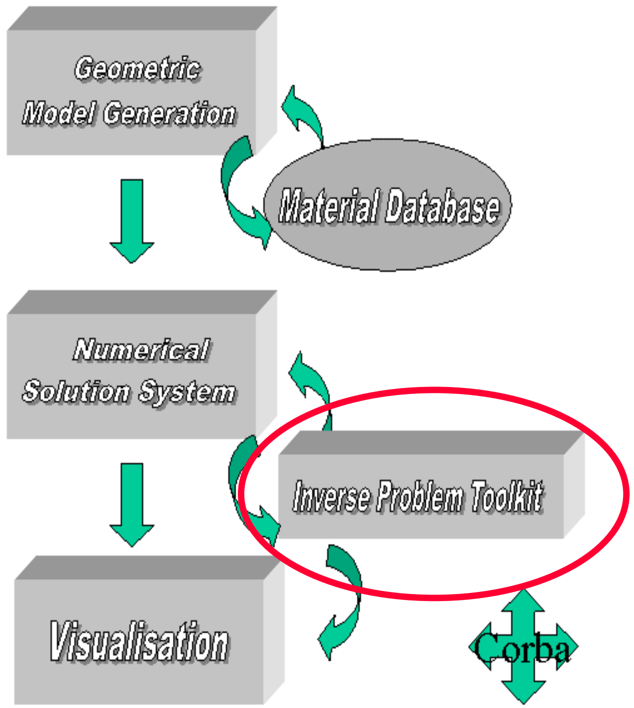
Inverse Problem Toolkit

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, MUSIC, ...
Optical Flow Techniques

Source localisation
Neurosurgical planning

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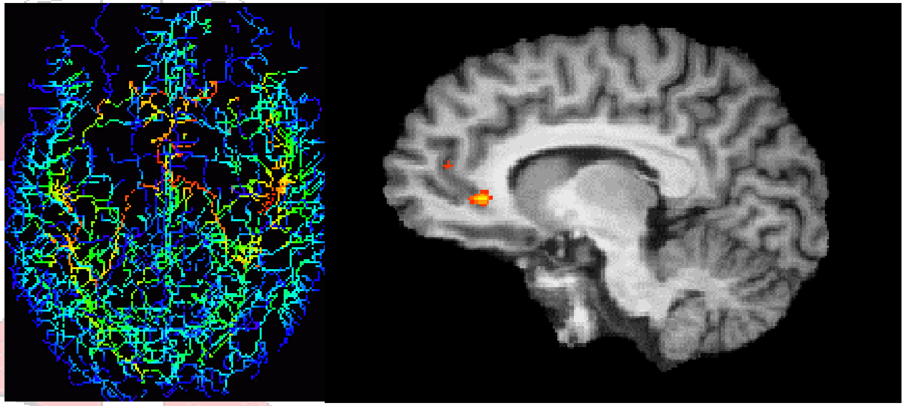
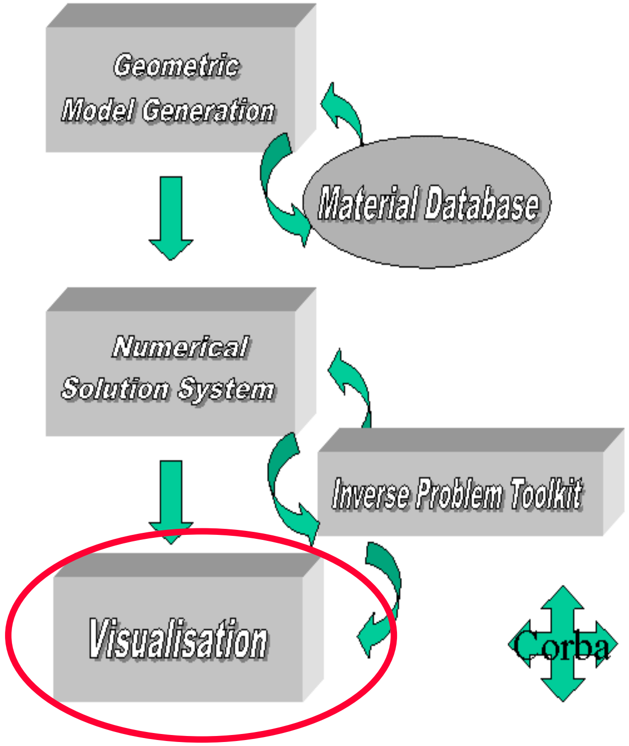
Visualisation





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

Option: Virtual or Augmented Reality

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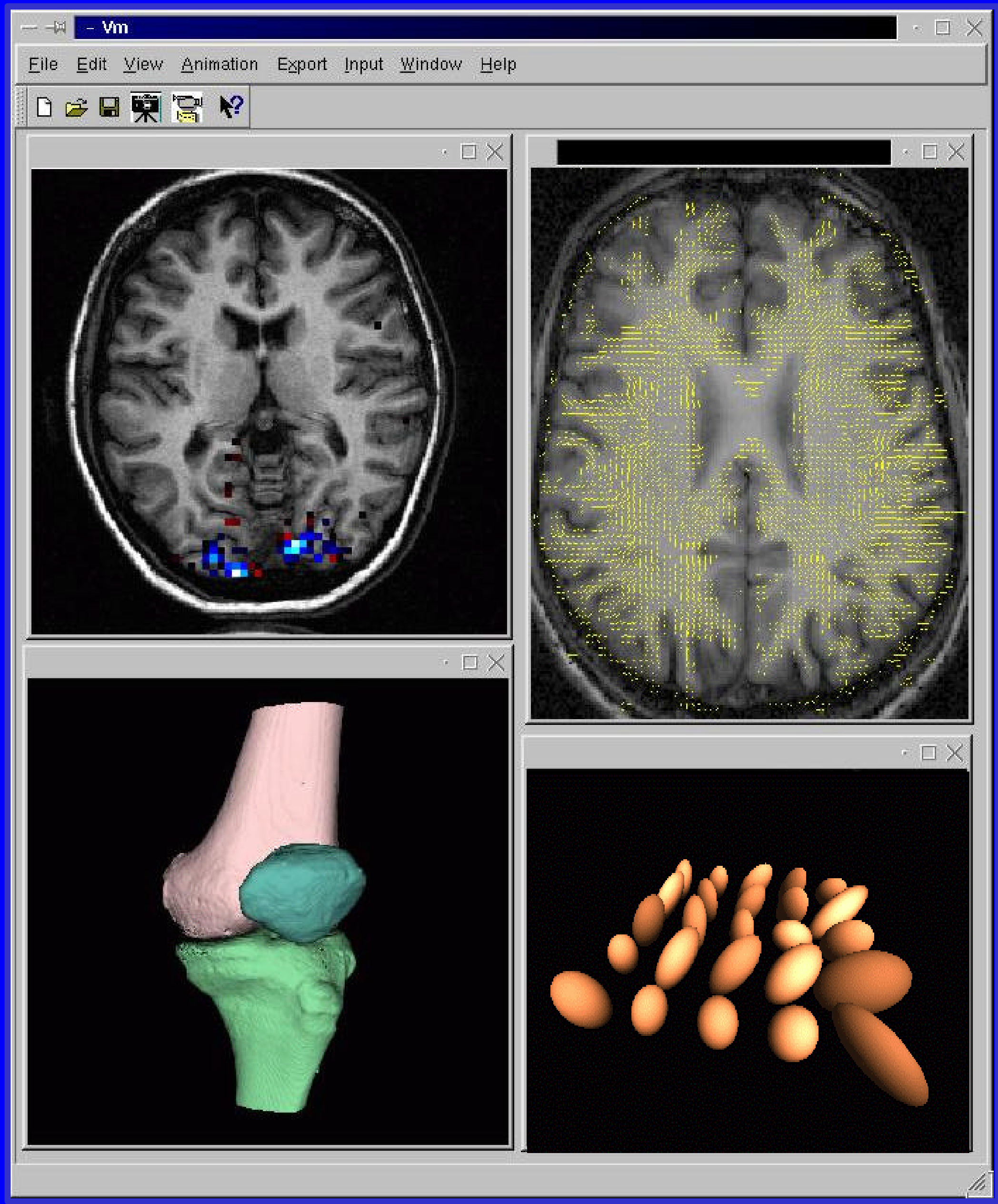
Current design view of VM tool



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SimBio Applications

Electromagnetic Source Localisation in the Head

Biomechanics of the human head

Knee Prosthesis Design

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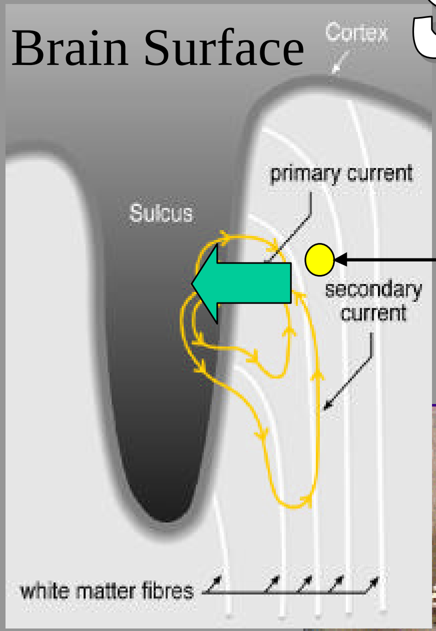
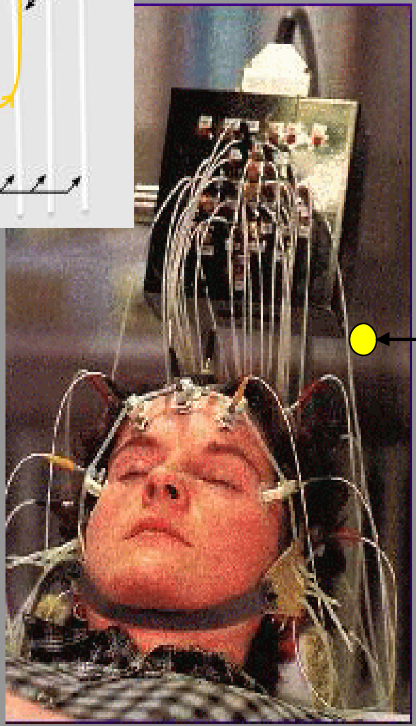
Source localisation: Motivation



It is daily practice in clinical routine to localise

dipolar current sources in the brain



based on EEG and

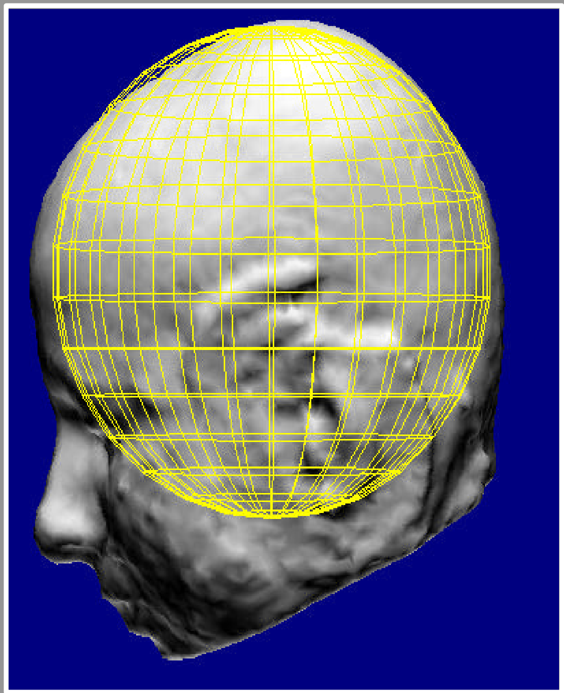
MEG measurements.

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

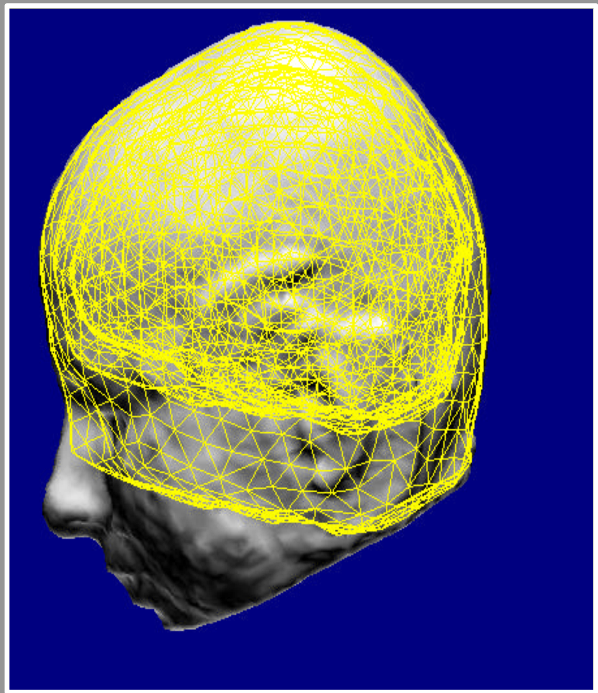
Modelling head conductivity

Possible source localisation techniques

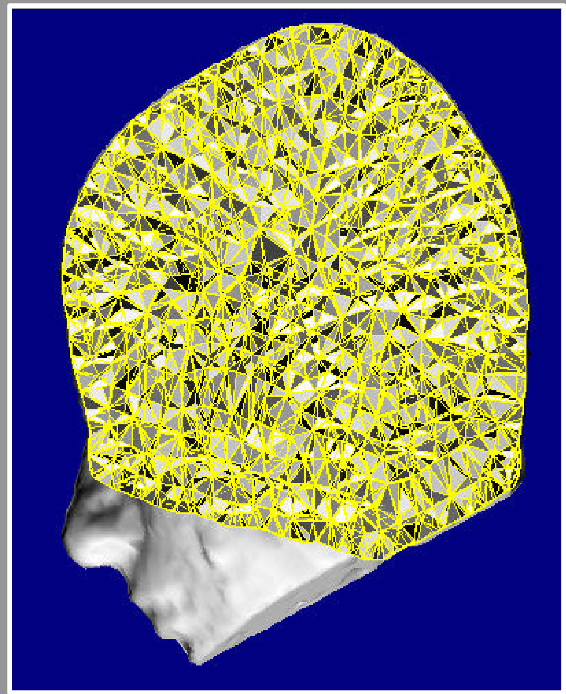
3 concentric shells:



Boundary elements:



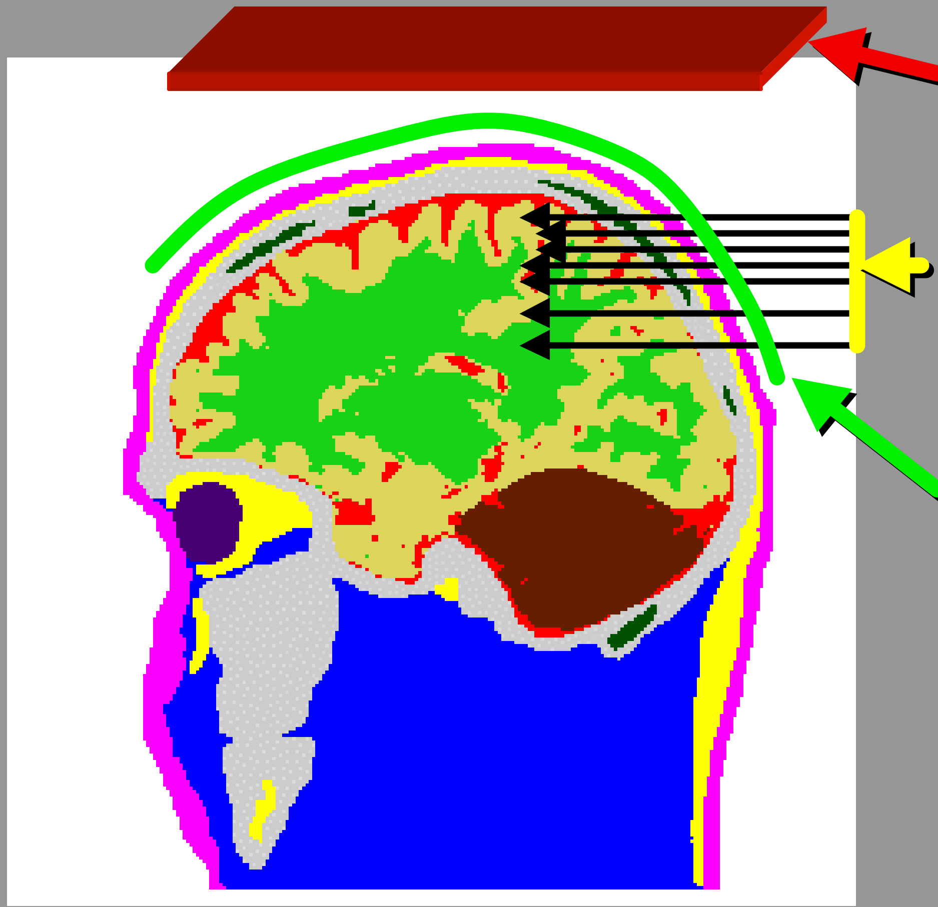
Finite elements:



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

Preliminary Simulations

(Haueisen et al., 1999):



Magnetic field sampling plane
(15 x 15 points)

dipoles in 7 different depths

Electric potential sampling
(300 points)

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

Source localisation: Conclusion on anistropy

Anisotropy seems to have

a minor influence on source localization

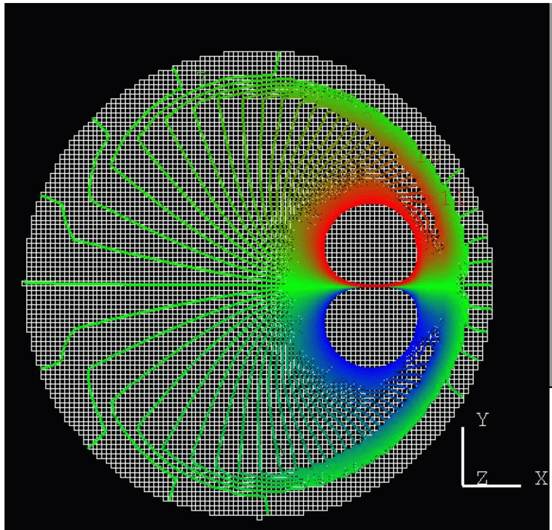
but a major influence on dipole

strength estimation.

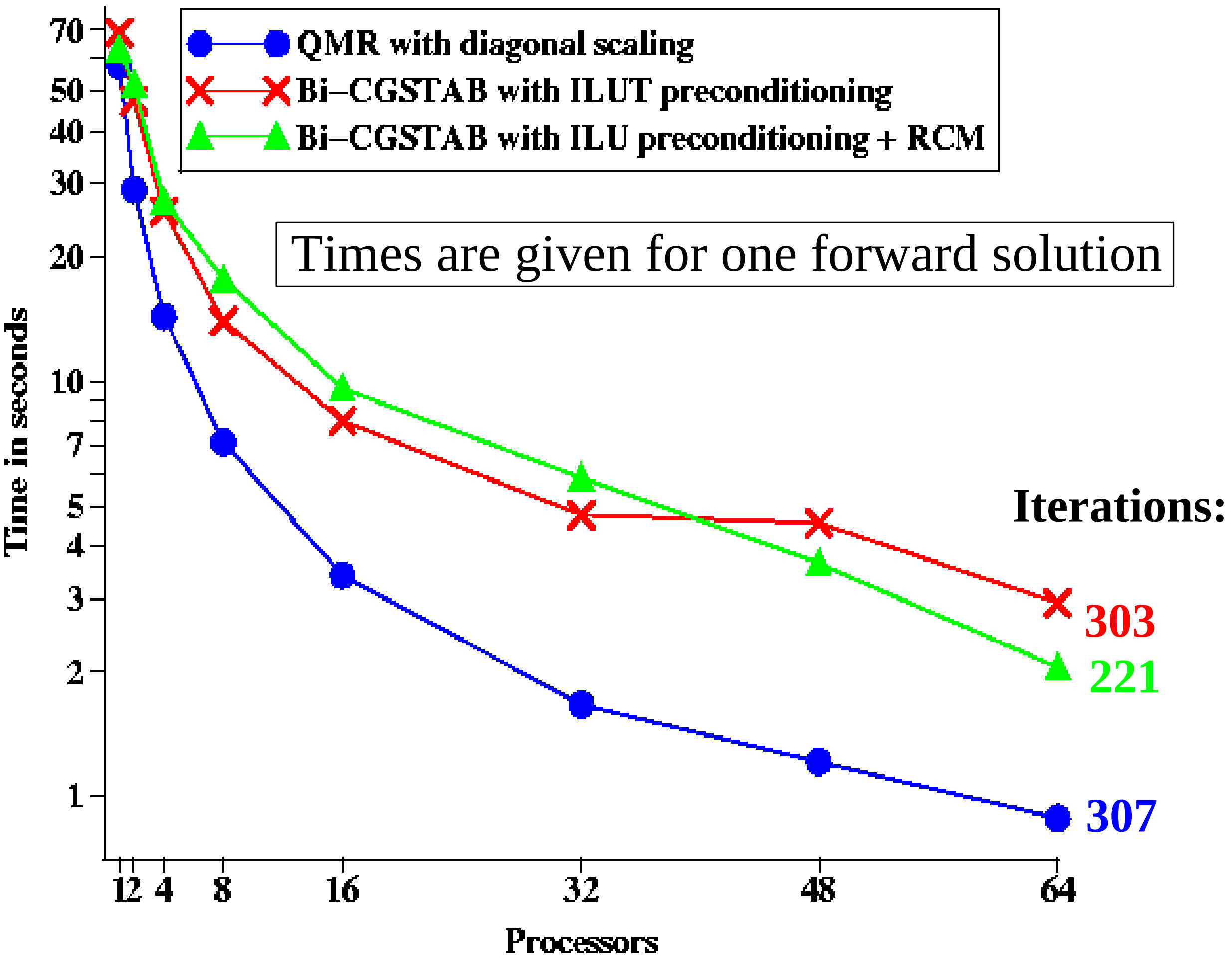
Nevertheless: An electric potential correlation of 0.98 still corresponds to a difference in source location of about 0.5-0.8 cm

Solver Performance

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



A forward solution with anisotropic skull conductivity



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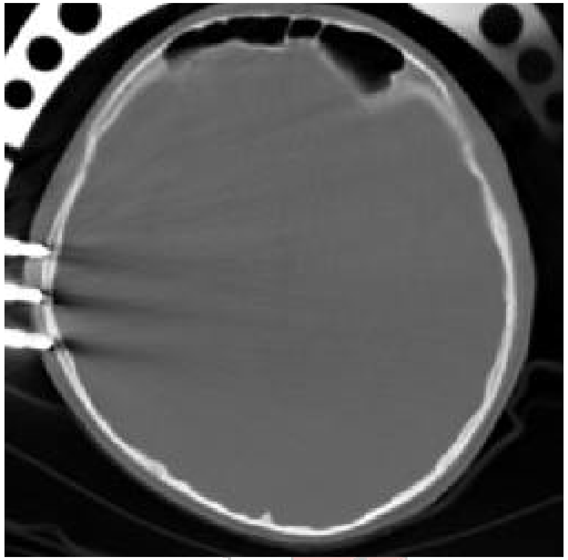
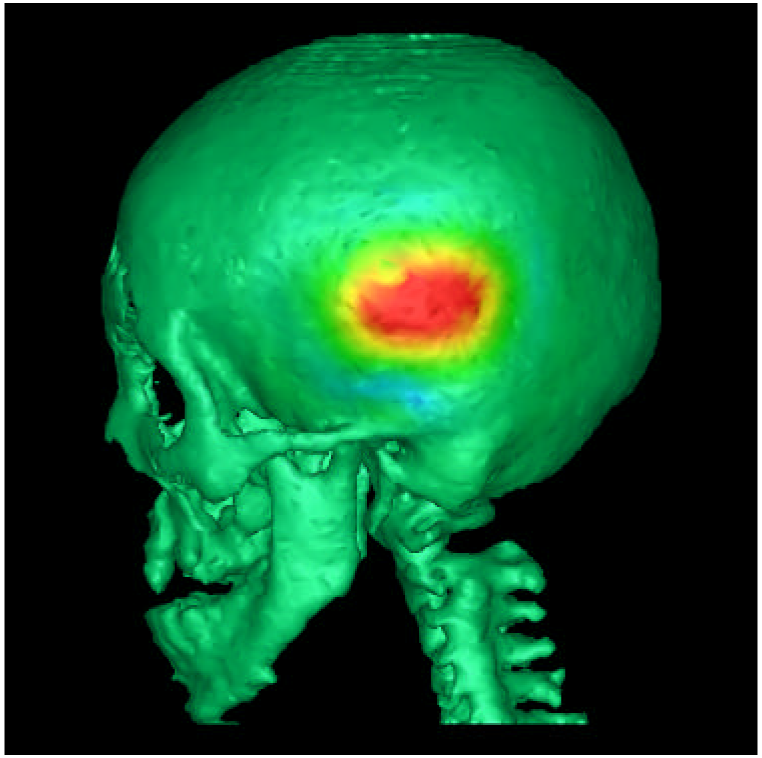
Facio-Surgical Planning



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 !



A visualisation of the displacements induced by the halo (HeadFEM results visualised by VM predecessor)

HeadFEM parallel performance head-impact simulation

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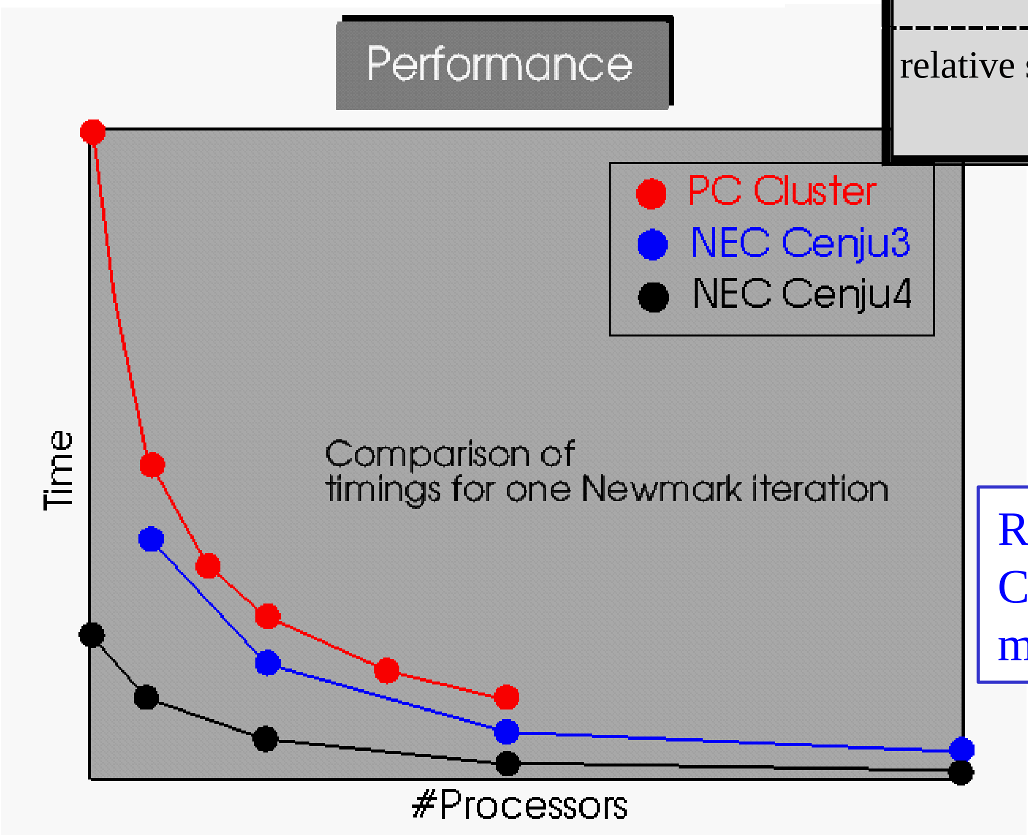
No. Processors	24	32	48	64
Time in secs.	47.4	35.9	24.4	19.0
relative speed-up	**1.0**	1.32	1.94	2.50

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



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

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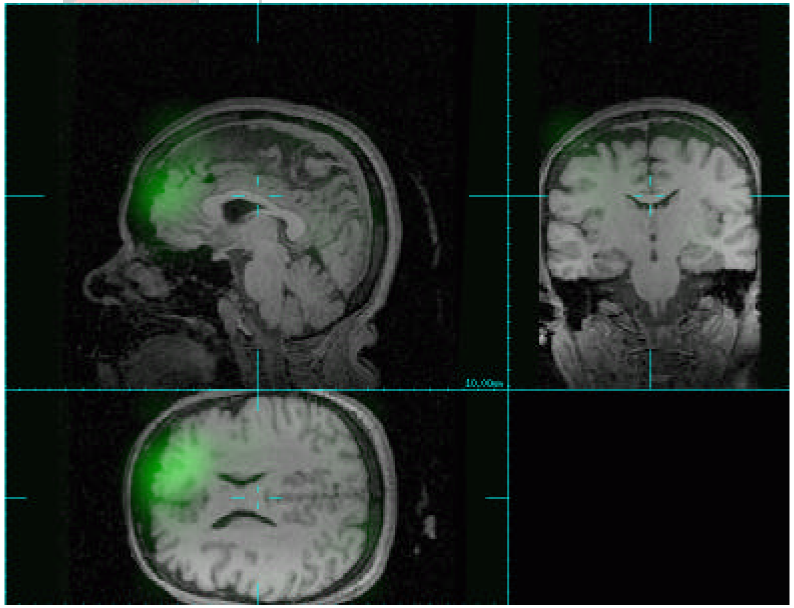
Neuro-Surgical Planning

Whenever 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 exactly 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”

ESPRIT HPCN PST Project

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- 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.

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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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A Gait cycle simulation with the Knees Up model

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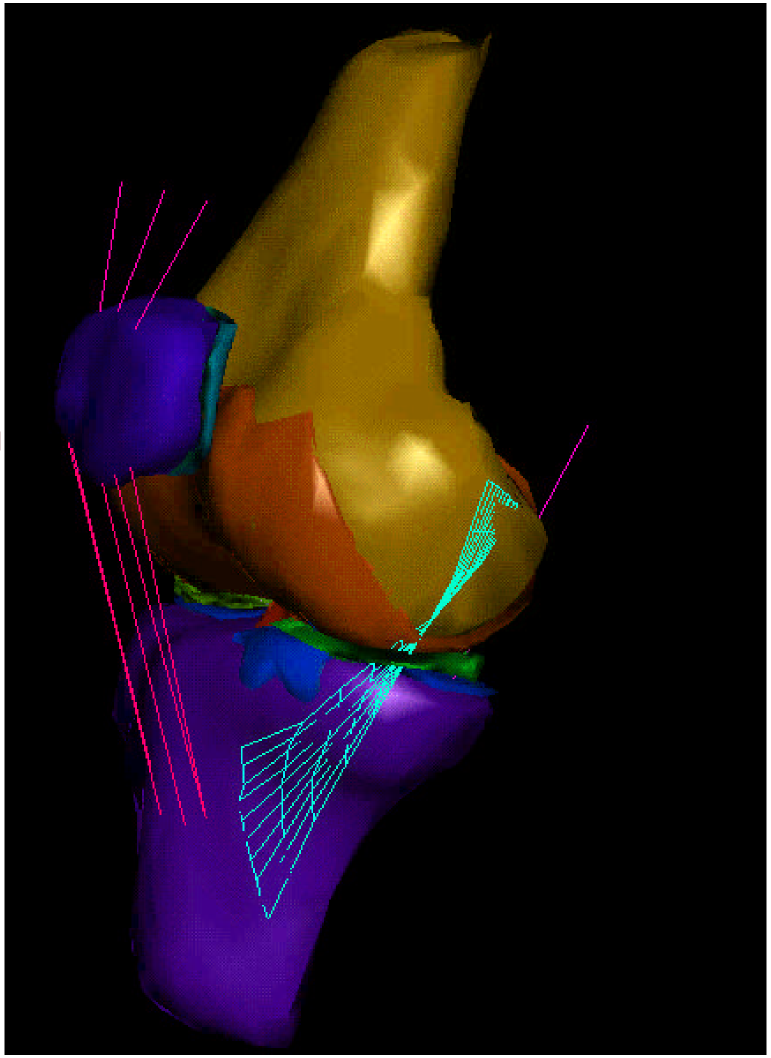

Modelling:
U. Sheffield & ESI
Simulation with
PAM-SAFE

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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

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NEC