From medical imaging to numerical simulations

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joint work with A. Ancel [1] V. Chabannes [2] J. Jomier [3] M. Szopos[1]

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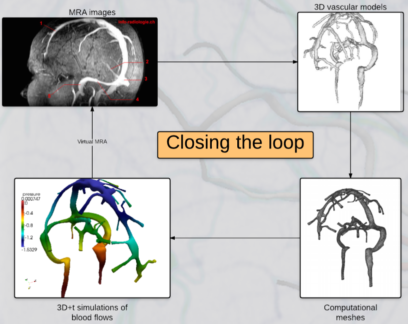
Vivabrain : A Multi-Disciplinary Project



Physics

- Medical imaging : MRI, MRA

Computer Science

- Image processing
- Model generation

Mathematics

- Numerical analysis
- Uncertainty quantification
- High performance computing

Medicine

- Vascular anatomy
- Haemodynamics

AngioTK Platform

From physical images to virtual images

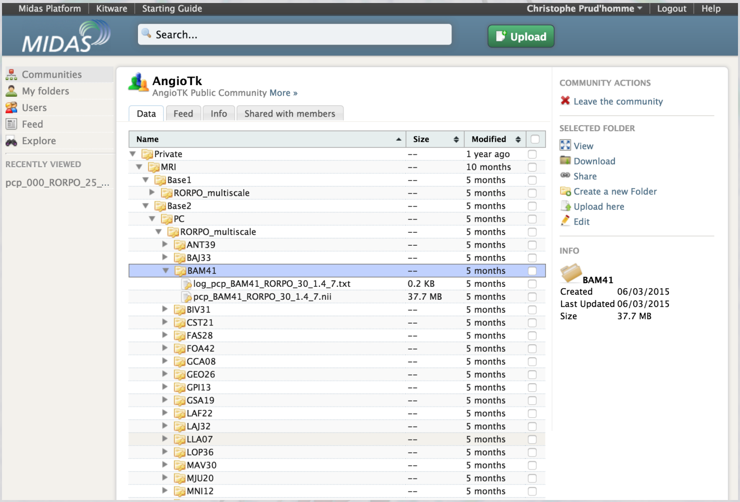
Simulate angiographic data in MRI based on realistic anatomical and dynamical models obtained from real data

Open Source Software

- ITK (Kitware): Angiographic images analysis
- FEEL++ (Feel++ Consortium): blood flow and rheology simulation
- VMTK / VTK: Mesh generation and processing
- RORPO(ESIEE,URCA): Path-opening
- GMSH: mesh generation and remeshing
- JEMRIS: MRI simulation

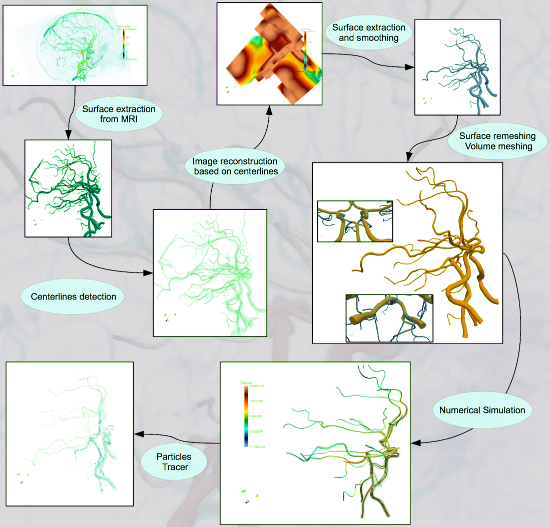
http://www.github.com/vivabrain/angiotk

AngioTK Platform: Open Data Server using MIDAS

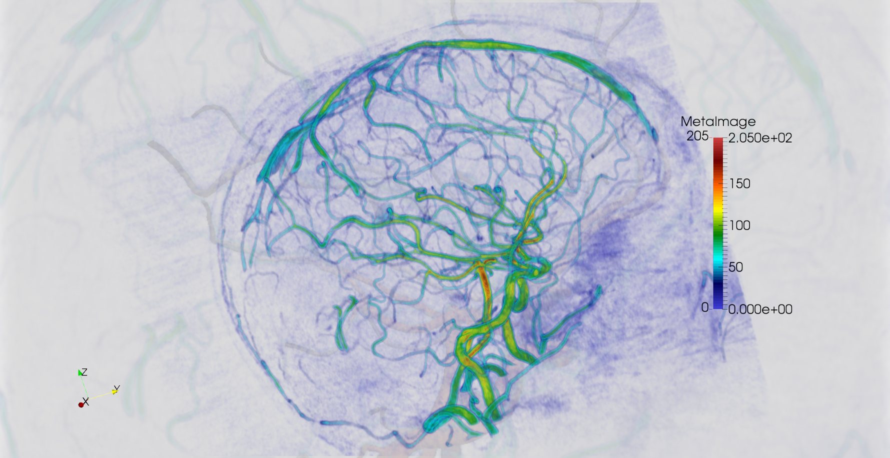


Stores 3D and 3D+t Vascular models and virtual angiographies
http://vivabrain.u-strasbg.fr

AngioTK Platform: A Software Pipeline

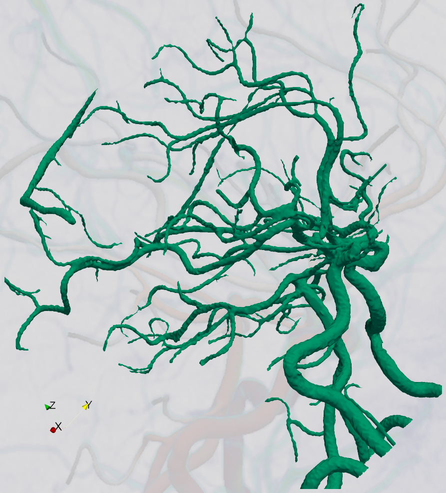


AngioTK Platform: Filtering using RORPO



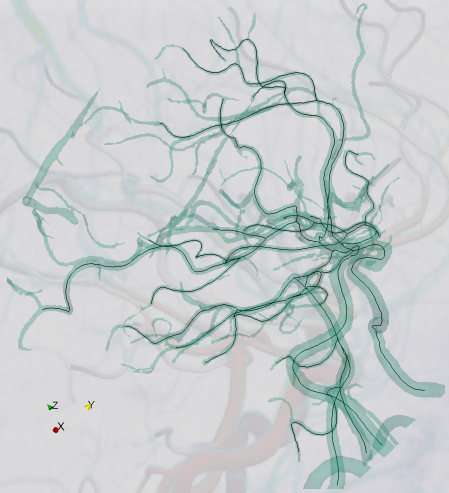
Starting from initial acquired data, filter it to emphasize tubular structures

AngioTK Platform: Segmentation/Surface extraction/Mesh processing using VMTK



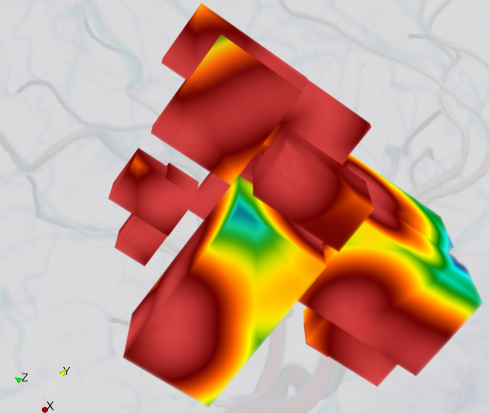
Extract veins and arteries using level-set segmentation; time ~40s

AngioTK Platform: Centerlines to define tubular structures



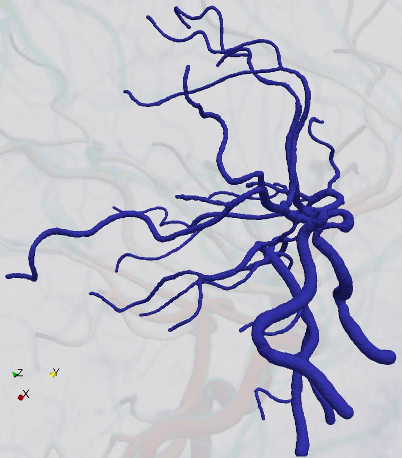
Centerline points associated to data (radius inscribed sphere); graphical tool for centerlines: seed points, corrections; time 20 min.

AngioTK Platform: Image reconstruction



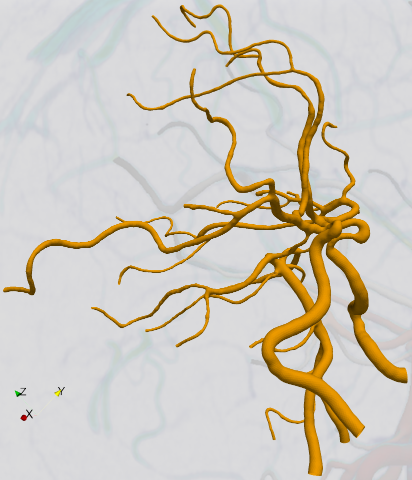
Build an image with a very good quality without artifacts using centerlines and compute signed distance function; controlled accuracy.

AngioTK Platform: Surface extraction



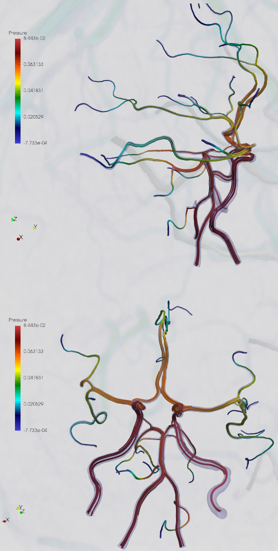
Extract the surface corresponding to level 0 of distance function; smooth, remesh if necessary; time ~30s

AngioTK Platform: Building computational mesh using GMSH



- Opening the tubular structure at extremities of centerlines
- Remesh the surface by using centerlines
  - Based on [1]
  - Good quality (frontal algo)
  - Same accuracy between small and large vessels
- Mesh the volume by using centerlines
- Optional : build the arterial wall (boundary layer extrusion with thickness as percent of radius)
- Partition the mesh for numerical simulation
- Current sample time: 10 min

Marchandise, E and Geuzaine, C and Remacle, JF Cardiovascular and lung mesh generation based on centerlines. *International journal for numerical methods in biomedical engineering.*, Vol. **29** 665–682, 2013.



Simulation using some Feel++ toolboxes:

- Fluid and Solid Mechanics and Interaction
- Convection-Diffusion

About the modeling :

- Blood models :
  - Incompressible Navier-Stokes
  - Newtonian and non-Newtonian
  - Inlets BC : Velocity, Pressure
  - Outlets BC : Free, Windkessel
- Arterial wall models
  - Elastic, hyper-elastic
  - Compressible, nearly-incompressible
  - BC : fixed, free, external tissue

Solvers :

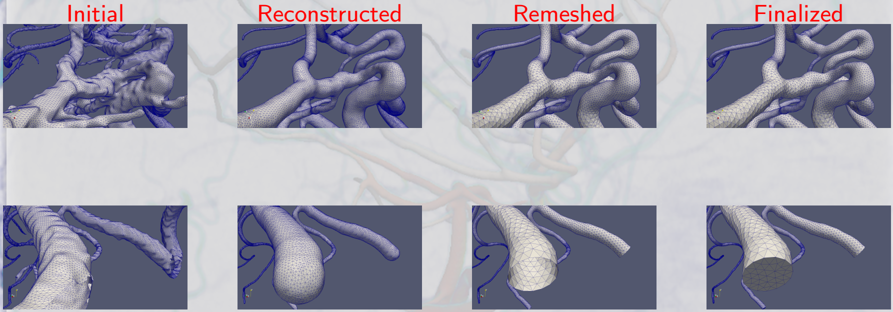
- Finite element method
- HPC (e.g. Prace) up to tens of thousands of cores

In-Situ Visualisation :

- Paraview/Catalyst (second per timestep)

Challenge: Computational mesh generation

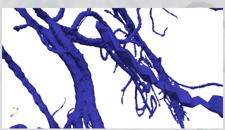
- Build good computational meshes and allow extension such as building vessel wall, currently we control the mesh quality and accuracy

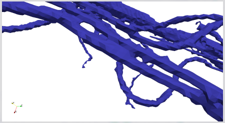


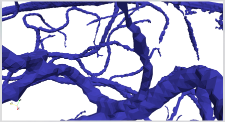
Challenge: Fusion of vessels

- Automate the process as much as possible, current difficulties centerlines and fusion of vessels

Initial Data







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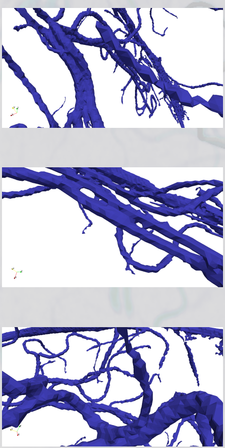
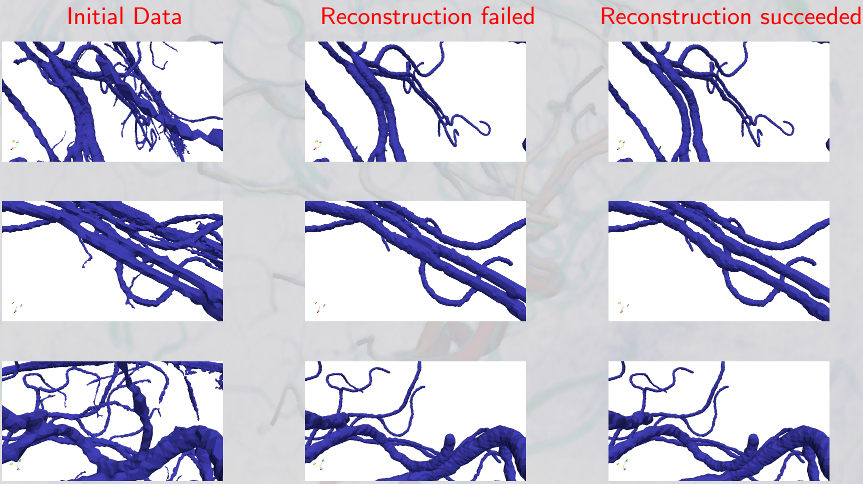
Initial Data



Reconstruction failed

Solution: Automatic Vessel Fusion Handling

- Automate the process as much as possible, current difficulties centerlines and fusion of vessels



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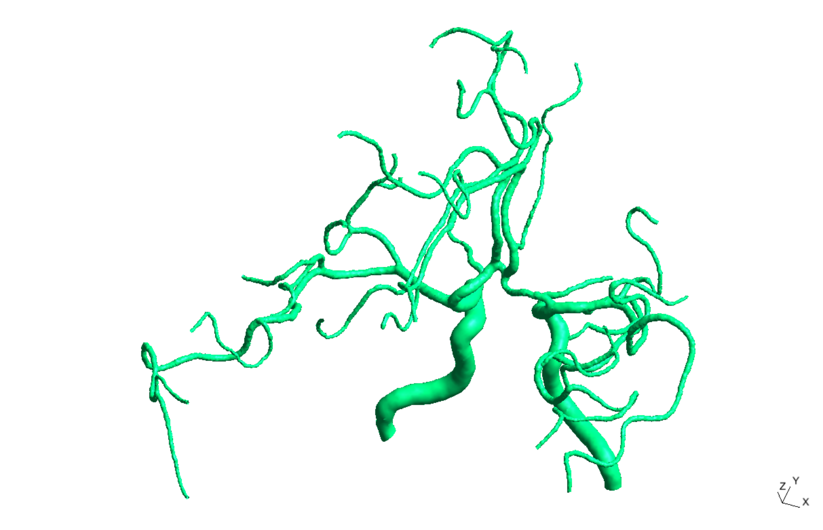
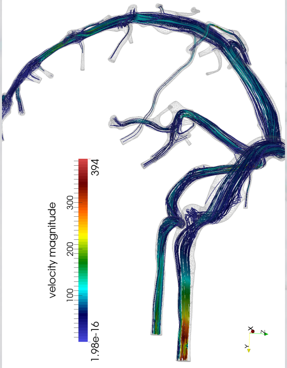


What do we do with these realistic geometries and simulations?

Study the influence of modeling choices in the cerebral venous network



Using a deterministic analysis framework, study the influence of

- Inflow boundary conditions
- Outflow boundary conditions
- Blood constitutive law : Newtonian vs non-Newtonian

HPC is a requirement: many simulations and very intensive post-processing computations!

V. Chabannes, M. Ismail, C. Prud'Homme, M. Szopos. Hemodynamic simulations in the cerebral venous network: A study on the influence of different modeling assumptions. Journal of Coupled Systems and Multiscale Dynamics, 2015, 3 (1), pp.23-37. <10.1166/jcsmd.2015.1062>

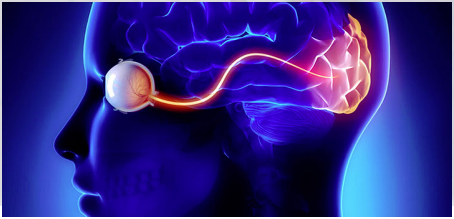
Eye2Brain project

Multiscale modeling of fluid-dynamical and metabolic links between eye and brain: towards ocular biomarkers for neurodegenerative disorders

Joint work with

- IUPUI **J. Arciero, L. Carichi, S. Cassani, D. Prada, G. Guidoboni**
- Glick Institute **A. Harris, B. Siesky**
- Politechnico di Milano **R. Sacco**
- U. Strasbourg **M. Szopos C. Prud'homme**

- AngioTK is the framework for constructing realistic geometries from medical images
- Feel++ is the underlying computational framework to support detailed views in the eye and in the brain of
  - blood flows
  - oxygen and metabolites transport



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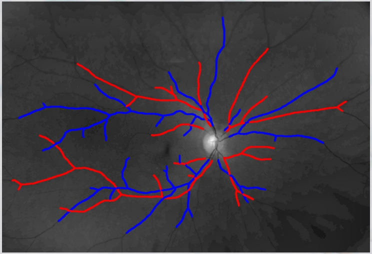
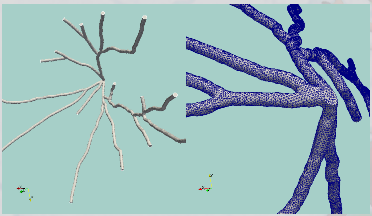
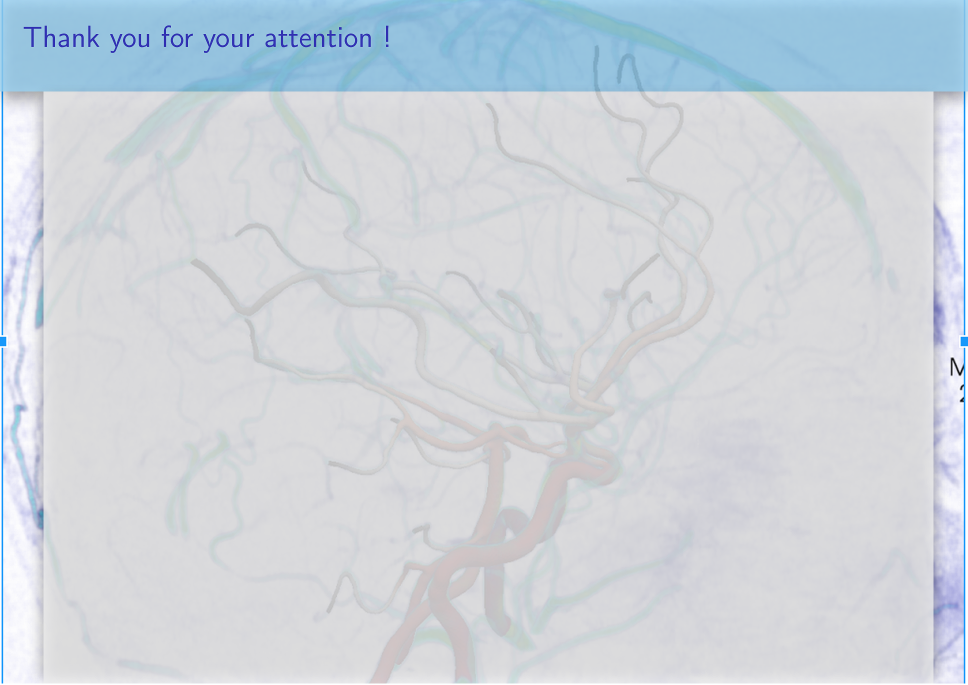
Eye2Brain project

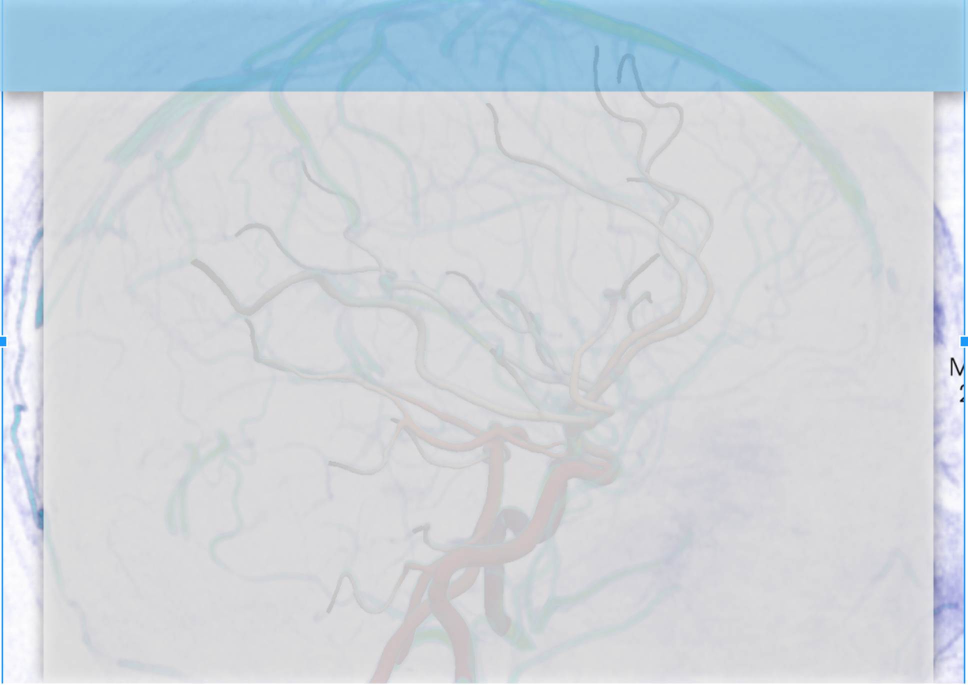




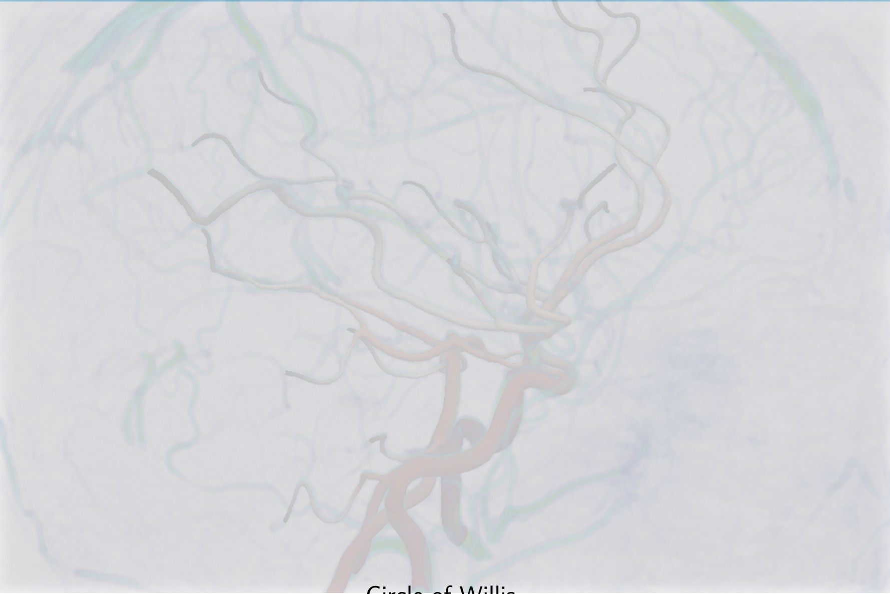
A first reconstruction from retina image of some vessels using AngioTK from a 2D image

Thank you for your attention !



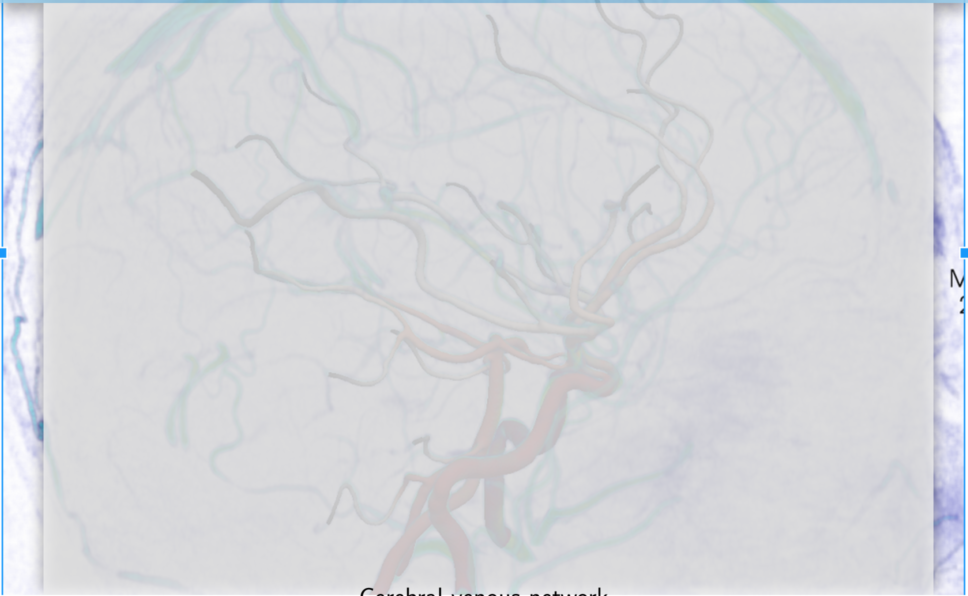


Example: MRI data of the vivabrain project



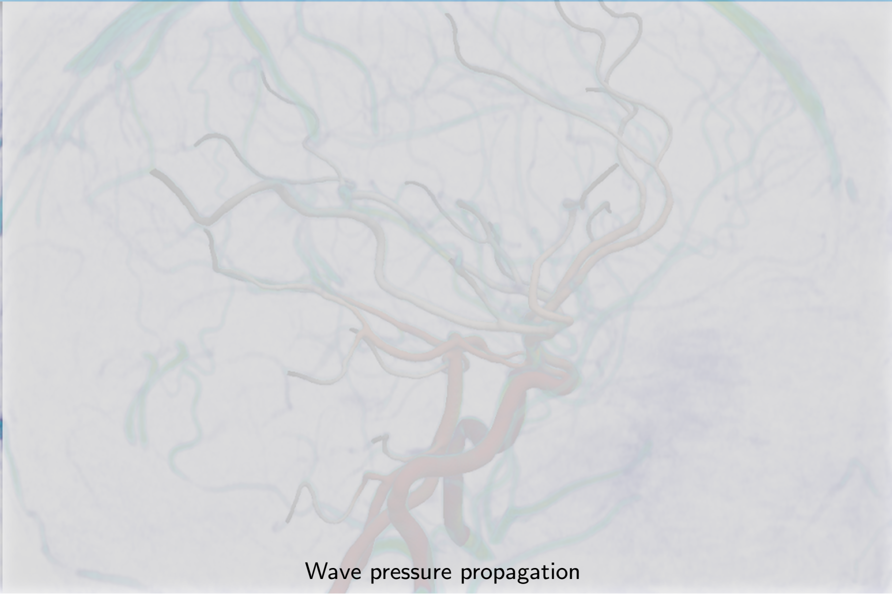
Circle of Willis

Example: IRM data of the vivabrain project



Cerebral venous network

Example: Phantom with FSI simulation



Wave pressure propagation

Services for AngioTK

- Custom development
- Deployment
- Consulting
- Training

Contacts

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- J. Jomier: julien.jomier@kitware.com

Finite Element Embedded Library and Language in C++

A Domain Specific Language for PDEs embedded in C++ providing a syntax very close to the mathematical language

Features

- Supports generalized arbitrary order Galerkin methods (cG, dG) in 1D, 2D and 3D
- Supports simplex, hypercube and high order meshes
- Supports seamless parallel computing, scales up to tens of thousands of cores (Tier-0/Prace,Tier-1/Genci)
- Supports large scale parallel linear and non-linear solvers (PETSc/SLEPc)

Contact

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Laplacian problem

$$\begin{cases} \text{Find } u \text{ such that :} \\ -\Delta u = 1 \quad \text{in } \Omega \\ \quad u = 0 \quad \text{on } \partial\Omega \end{cases} \boxed{\overset{\text{variational}}{\Longrightarrow} \text{formulation}} \begin{cases} \text{Find } u \in V_h \text{ such that} \\ \int_\Omega \nabla u \cdot \nabla v = \int_\Omega fv, \ \forall v \in V_h \end{cases}$$

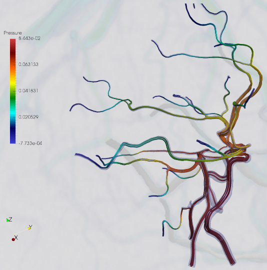
```
auto mesh = loadMesh(_mesh=new Mesh<Simplex<2ls);
auto Vh = Pch<2>( mesh );
auto u = Vh->element(), v = Vh->element();
auto f = expr( "2*x*y+cos(y):x:y" );
// a(u,v) = ∫_Ω ∇u · ∇v
auto a = form2(_trial=Vh,_test=Vh);
a = integrate(_range=elements(mesh),
              _expr=gradt(u)*trans(grad(v)) );
// l(v) = ∫_Ω fv
auto l = form1(_test=Vh);
l = integrate(_range=elements(mesh),
              _expr=f*id(v));
// u = 0 on ∂Ω
a+=on(_range=boundaryfaces(mesh),
      _rhs=l,_element=u,
      _expr=cst(0.) );
// solve algebraic system
a.solve(_rhs=l,_solution=u);
```

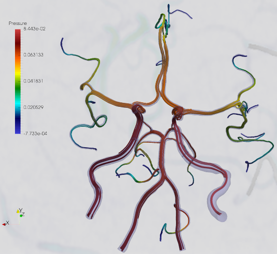
Stokes problem

$$\begin{cases} \text{Find } (u,p) \text{ such that :} \\ -\Delta u + \nabla p = 0 \quad \text{in } \Omega \\ \nabla \cdot u = 0 \quad \text{in } \Omega \end{cases} \quad \boxed{\overset{\text{variational}}{\Longrightarrow} \atop \text{formulation}} \quad \begin{cases} \text{Find } (u,p) \in V_h \times Q_h \text{ such that} \\ \int_\Omega \nabla u : \nabla v + p \nabla \cdot v = 0, \forall v \in V_h \\ \int_\Omega q \nabla \cdot u = 0, \ \forall q \in Q_h \end{cases}$$

```
auto mesh = loadMesh(_mesh=new Mesh<Simplex<2>>);
auto Vh = THch<1>( mesh ); // P2P1
auto U = Vh->element(), V = Vh->element();
auto u = U.element<0>(), v = V.element<0>();
auto p = U.element<1>(), q = V.element<1>();
// a(u,p,v,q) = ∫_Ω ∇u : ∇v − p ∇·v + q ∇·u
auto a = form2(_trial=Vh, _test=Vh);
a = integrate(_range=elements( mesh ),
              _expr=inner( gradt(u),grad(v) ) );
a +=integrate(_range=elements( mesh ),
              _expr=-idt(p)*div(v) + id(q)*divt(u) );
// l(v) = 0
auto l = form1(_test=Vh );
// u = g on wall
a+=on(_range=markedfaces(mesh,"wall"),_rhs=l,
      _element=u,_expr=g );
// solve algebraic system
a.solve(_rhs=l,_solution=U);
```

Some Feel++ Features





Simulation using Feel++ tool boxes:

- Fluid Mechanics
- Solid Mechanics
- Fluid-Structure Interaction

About the modelisation :

- Blood models :
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