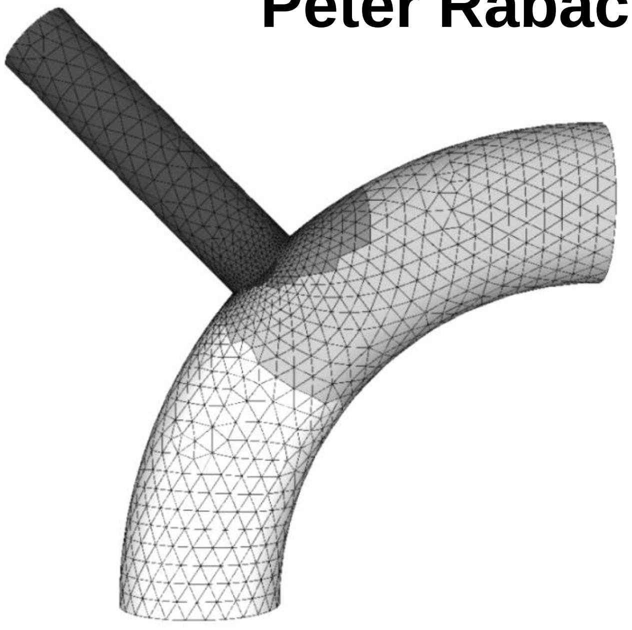
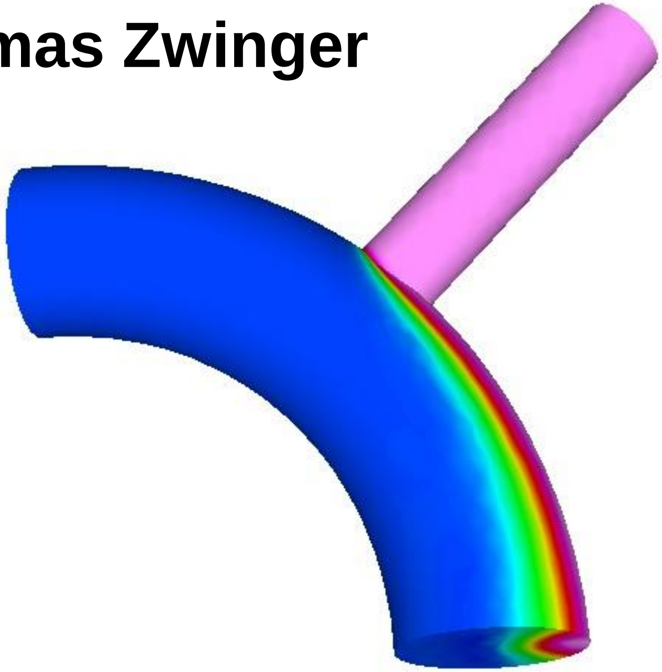
PARA2012 – Elmer Tutorial

An afternoon with the most popular open source Finite Element Code

Peter Råback and **Thomas Zwinger**





Program

- Introduction to Elmer (Råback)
- Demo ElmerGUI (Zwinger)
  - the graphical interface to Elmer
- Elmer from the command line (Zwinger)

- 10 minutes break (~13:45)

Program

- Parallel runs with Elmer (Zwinger)
  - Workflow from partitioning, computation to unification of results
- Specific Issues with Parallel runs (Råback)
  - Postprocessing, scalability, linear algebra, bottlenecks in workflow
- Interactive part (~1 hour):
  - Tutorials (hands on)
  - Installation
  - Basic programming
  - Enhanced post-processing

Elmer

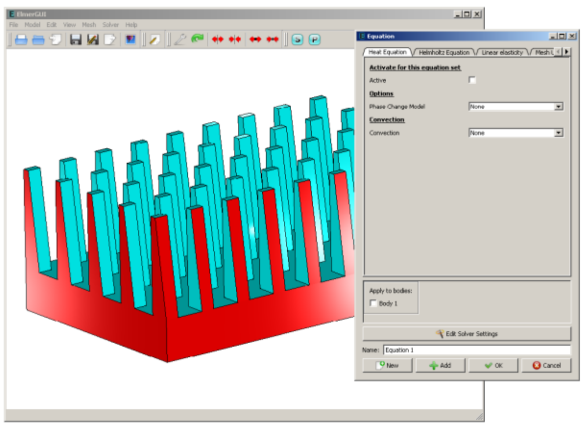
Open Source Finite Element Software for Multiphysical Problems

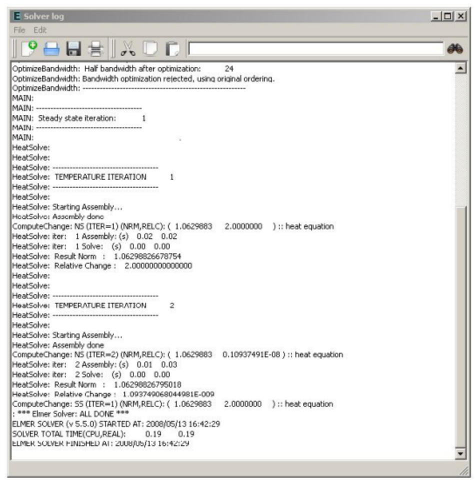
ElmerTeam

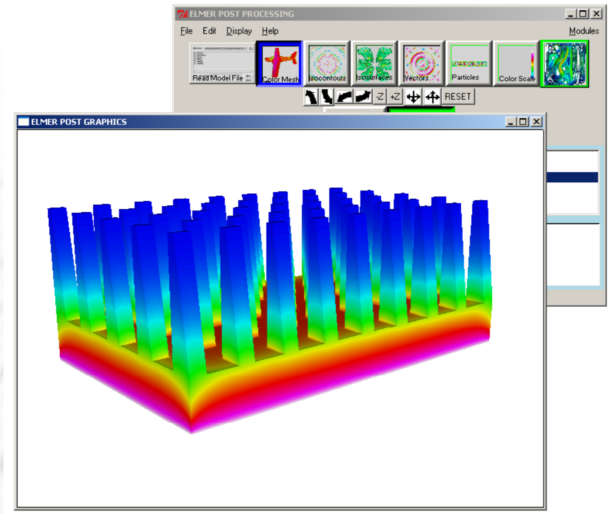
CSC – IT Center for Science Ltd.

PARA2012 Tutorial
Finlandia Hall, June 2012

Elmer – A finite element software for multiphysical problems







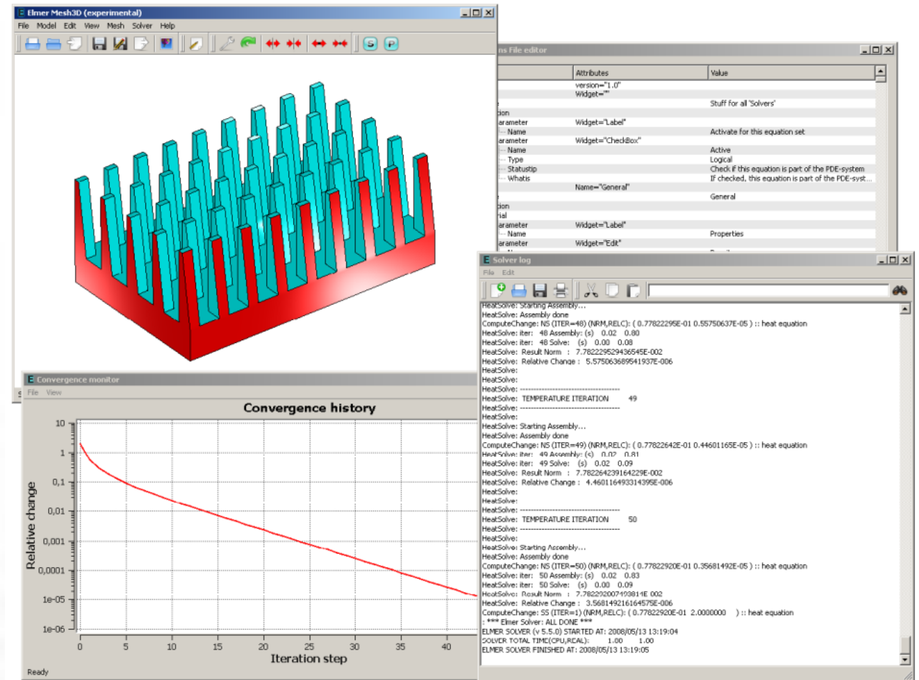
ElmerGUI + ElmerSolver + ElmerPost

ElmerGrid

ElmerFront

ElmerGUI

- Graphical user interface of Elmer
  - Based on the Qt library (GPL)
  - Developed at CSC since 2/2008
- Mesh generation
  - Plugins for Tetgen, Netgen, and ElmerGrid
  - CAD interface based on OpenCascade
- Easiest tool for case specification
  - Even educational use
  - Parallel computation
- New solvers easily supported through GUI
  - XML based menu definition
- Also postprocessing with VTK



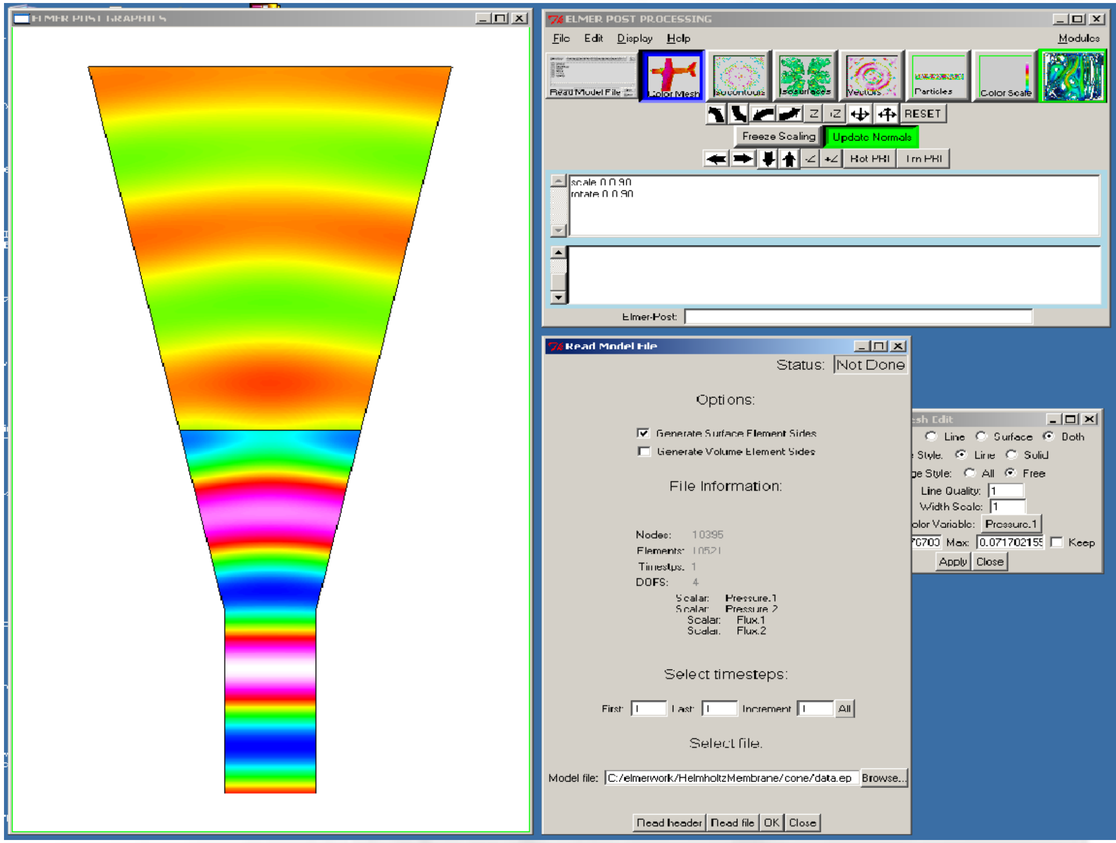
ElmerSolver

- Assembly and solution of the finite element equations
- Parallelization by MPI
- Note: When we talk of Elmer we mainly mean ElmerSolver

```
> ElmerSolver StepFlow.sif
MAIN: ==========================================
MAIN:  E L M E R  S O L V E R  S T A R T I N G
MAIN:  Library version: 5.3.2
MAIN: ==========================================
MAIN:
MAIN: -----------------------
MAIN: Reading Model ...
...
...
SolveEquations: (NRM,RELC): ( 0.34864185 0.88621713E-06  ) :: navier-stokes
: *** Elmer Solver: ALL DONE ***
SOLVER TOTAL TIME(CPU,REAL):         1.54        1.58
ELMER SOLVER FINISHED AT: 2007/10/31 13:36:30
```

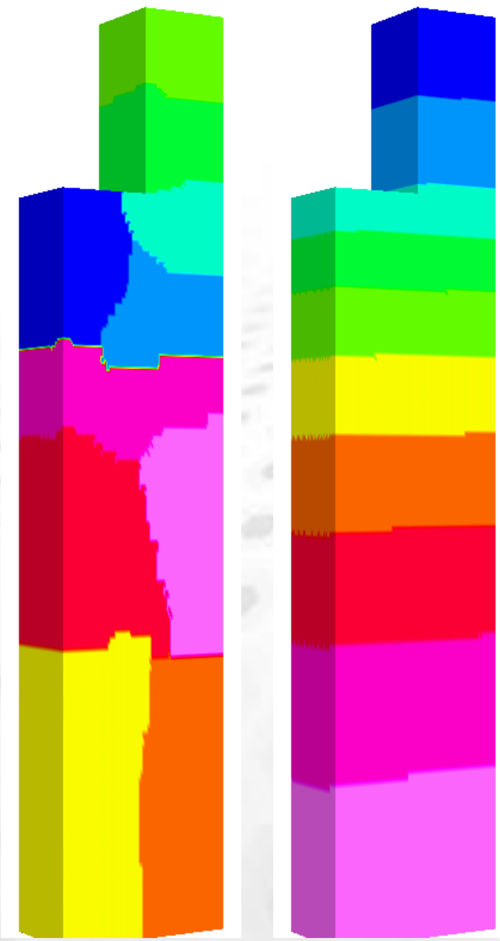
ElmerPost

- Based on the FUNCS program
  - written in late 80’s and early 90’s by Juha Ruokolainen
- All basic presentation types
  - Colored surfaces and meshes
  - Contours, isosurfaces, vectors, particles
  - Animations
- Includes MATC language
  - Data manipulation
  - Derived quantities
- Output formats
  - ps, ppm, jpg, mpg
  - animations



ElmerGrid

- Creation of 2D and 3D structured meshes
  - Rectangular basic topology
  - Extrusion, rotation
  - Simple mapping algorhitms
- Mesh Import
  - About ten different formats: Ansys, Abaqus, Fidap, Comsol, Gmsh,…
- Mesh manipulation
  - Increase/decrease order
  - Scale, rotate, translate
- Partitioning
  - Simple geometry based partitioning
  - Metis partitioning
    Example: `> ElmerGrid 1 2 step -metis 10`
- Usable via ElmerGUI
  - All features not accessible (partitioning, discont. BC,…)



Elmer – Numerical Methods

- Time-dependency
  - Static, transient, eigenmode, scanning
- Discretization
  - Galerkin, Discontinous Galerkin (DG)
  - Stabilization, Bubbles
  - Lagrange, edge, face, and p-elements
- Matrix equation solvers
  - Direct: Lapack, Umfpack, (SuperLU, Mumps, Pardiso)
  - Iterative Krylov space methods (HutIter & Hypre)
  - multigrid solvers (GMG & AMG) for “easy” equations (own & Hypre)
  - Preconditioners: ILU, BILU, Parasails, multigrid, SGS, Jacobi,…
- Parallellism
  - Parallel assembly and solution (vector-matrix product)
- Adaptivity
  - For selected equations, works well in 2D

Elmer - Physical Models

- Heat transfer
  - Heat equation
  - Radiation with view factors
  - convection and phase change
- Fluid mechanics
  - Navies-Stokes (2D & 3D)
  - Turbulence models: *k*-ε, *v*^{2}-*f*, *VMS*
  - Reynolds (2D)
- Structural mechanics
  - Elasticity (unisotropic, lin & nonlin)
  - Plate, Shell
- Free surface problems
  - Lagrangian techniques
  - Level set method (2D)
- Mesh movement
  - Extending displacements in coupled problems
  - ALE formulation
- Acoustics
  - Helmholtz
  - Linearized time-harmonic N-S
- Species transport
  - Generic convection-diffusion equation
- Electromagnetics
  - Emphasis on steady-state and harmonic analysis
  - New Whitney element formulation for magnetic fields
- Electrokinetics
  - Poisson-Boltzmann
  - Poisson-Nernst-Planck
- Quantum mechanics
  - DFT (Kohn Scham)
- Particle Tracker
- ….

Application Fields – Poll (Status 5/2012)

CSC

What are your main application fields of Elmer?

You may select up to **5** options

Heat transfer	☑	53	**29%**
Fluid mechanics	☑	53	**29%**
Solid mechanics	☑	39	**21%**
Electromagnetics	☐	26	14%
Quantum mechanics	☐	3	2%
Something else (please specify)	☐	11	6%

Total votes : 185

Submit vote

Elmer – Selected multiphysics features

- Solver is an asbtract dynamically loaded object
  - Solver may be developed and compiled without touching the main library
  - No upper limit to the number of Solvers
  - Currently ~50 different Solvers, roughly half presenting physical phenomena
- Solvers may be active in different domains, and even meshes
  - Automatic mapping of field values
- Parameters of the equations are fetched using an overloaded function allowing
  - Constant value
  - Linear or cubic dependence via table
  - Effective command language (MATC)
  - User defined functions with arbitrary dependencies
  - As a result solvers may be weakly coupled without any *a priori* defined manner
- Tailored methods for some difficult strongly coupled problems
  - Consistant modification of equations (e.g. artificial compressibility in FSI, pull-in analysis)
  - Monolitic solvers (e.g. Linearized time-harmonic Navier-Stokes)

Short history of Elmer

- 1995 Elmer development was started as part of a national CFD program
  - Collaboration with TKK, VTT, JyU, and Okmetic Ltd.
- After the initial phase the development driven by number of application projects
  - MEMS, Microfluidics, Acoustics, Crystal Growth, Hemodynamics, Glaciology, …
- 2005 Elmer published under GPL-license
- 2007 Elmer version control put under sourceforge.net
  - Roughly 400 000 lines of code
- 2010 Used wordwide by thousands (?) of researchers
  - About 1500 downloads of the Windows binary each month
  - ~50000 visits to community forum from ~120 countries during last year
- Readily available in major Linux systems
- Application projects are nowadays mainly international
  - Used in a number of EU-projects
  - Central tool in computational glaciology
- May 2012 ElmerSolver library to be published under LGPL

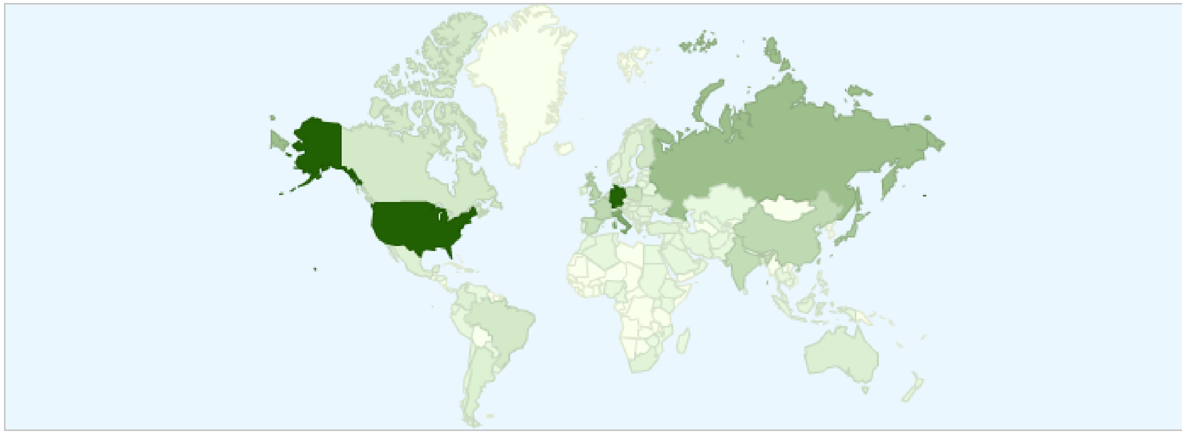
Elmer - Developers

- Current main developers
  - CSC: Mika Malinen, Juha Ruokolainen, Peter Råback, Sampo Sillanpää, Thomas Zwinger
- Other/past developers & contributors
  - CSC: Mikko Lyly, Erik Edelmann, Jussi Heikonen, Esko Järvinen, Jari Järvinen, Antti Pursula, Ville Savolainen,…
  - VTT: Martti Verho
  - TKK: Jouni Malinen, Harri Hakula, Mika Juntunen, Mikko Byckling
  - Trueflaw: Iikka Virkkunen
  - Open Innovation: Adam Powell
  - LGGE: Olivier Gagliardini, Fabien Gillet-Chaulet
  - University of Uppsala: Jonas Thies
  - etc… (if your name is missing, please ask it to be added)

16k Windows downloads at sf.net in a year

Home / WindowsBinaries (Change File)

Date Range: 2011-06-01 to 2012-06-01



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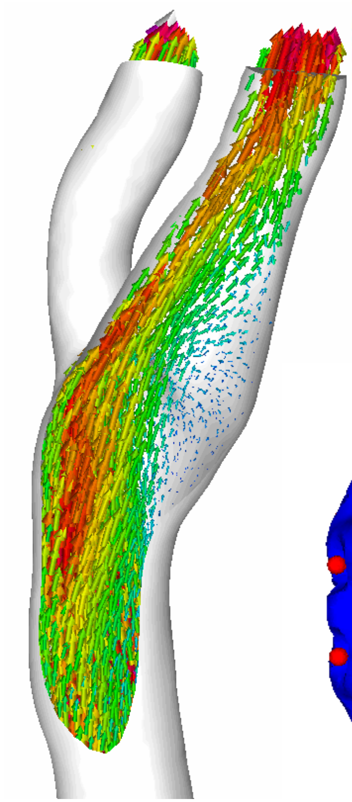
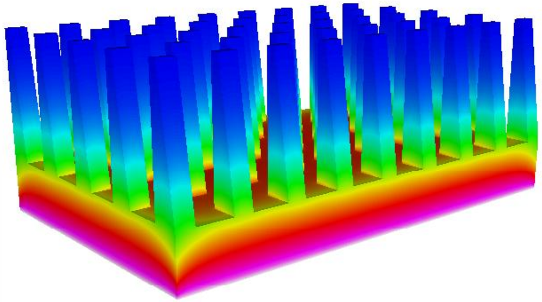
16 214
In the selected date range

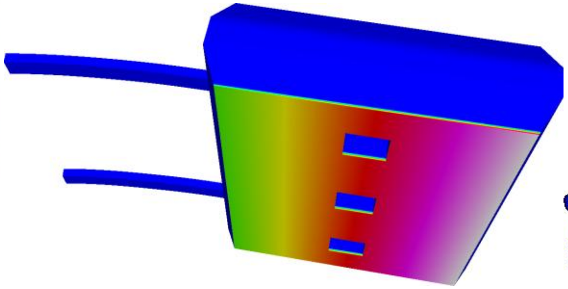
TOP COUNTRY
United States
15% of downloaders

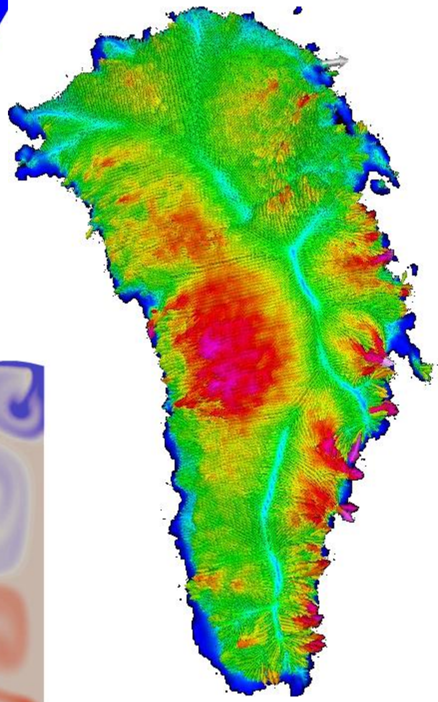
TOP OS
Windows
94% of downloaders

	Country	Downloads
1.	United States	2,553
2.	Germany	2,529
3.	Italy	1,342
4.	Russia	975
5.	Japan	789
6.	United Kingdom	609
7.	France	548
8.	China	529
9.	India	483
10.	Spain	400
11.	Poland	385
12.	Finland	305

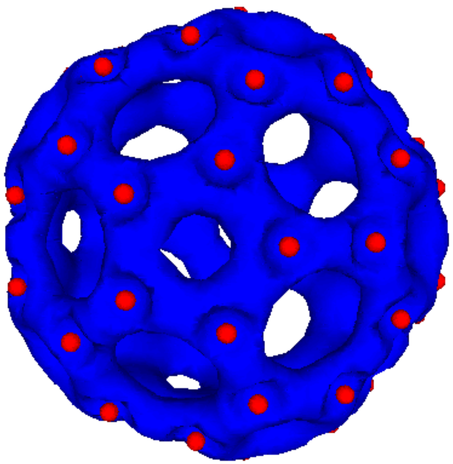


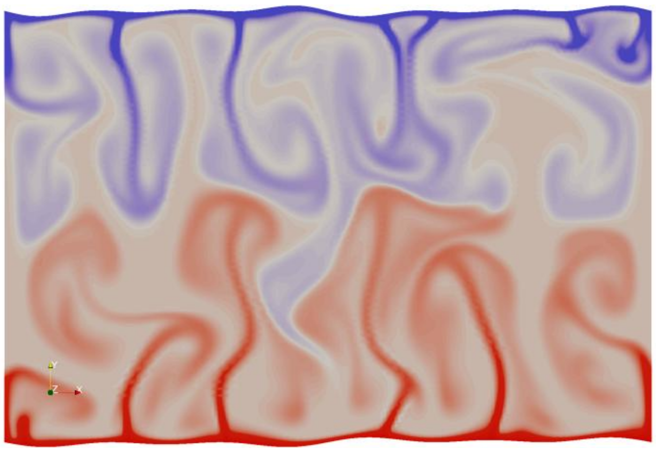


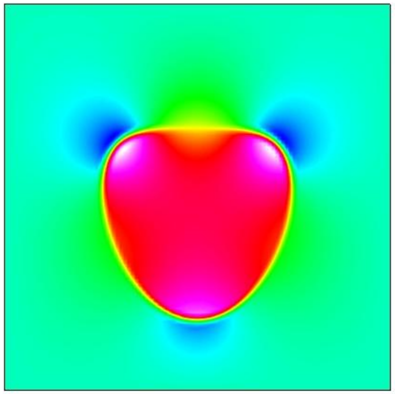


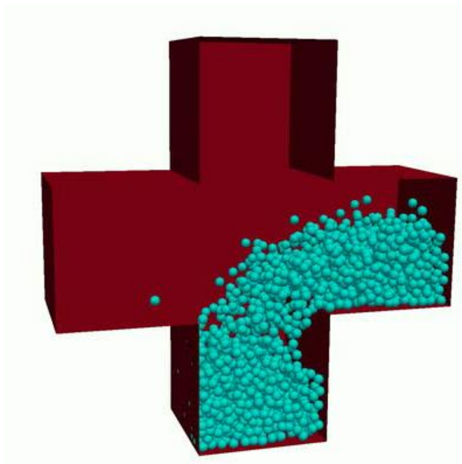


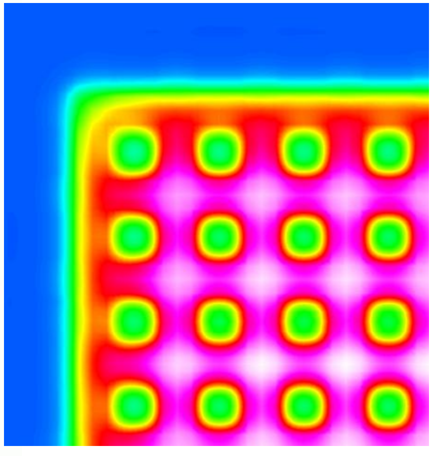
Elmer Simulations

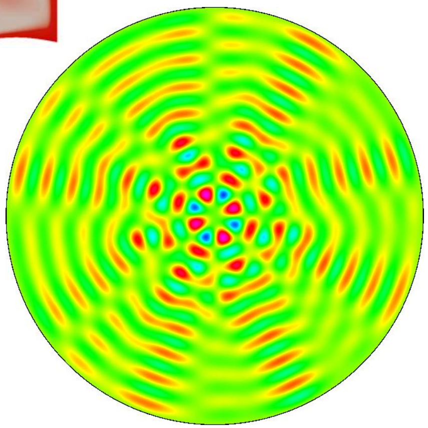








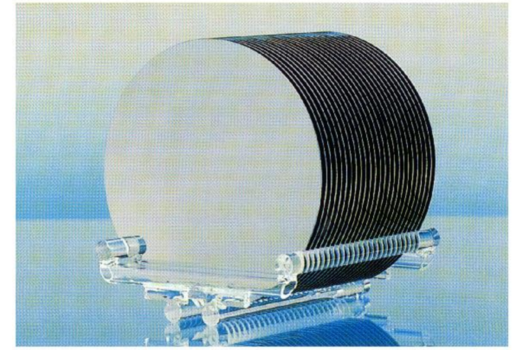




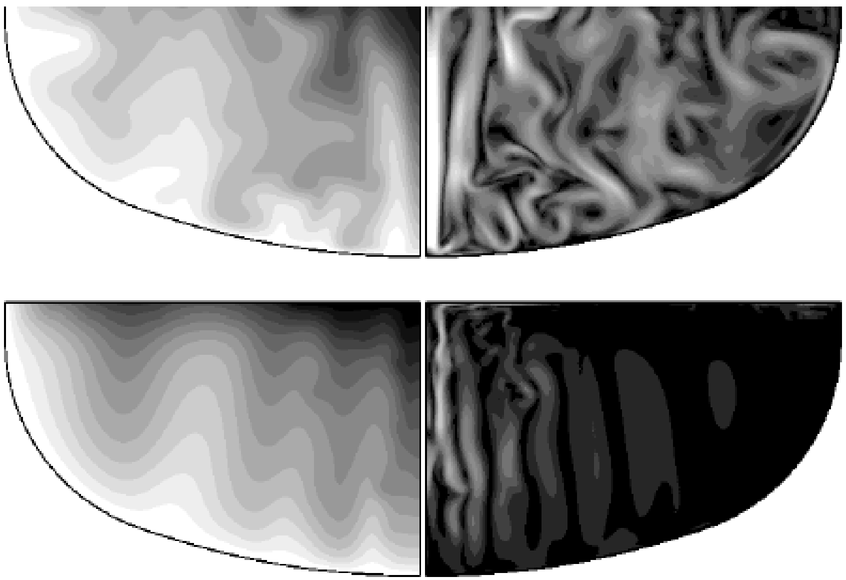
Figures by Esko Järvinen, Mikko Lyly, Peter Råback, Timo Veijola (TKK) & Thomas Zwinger

Czockralski Crystal Growth

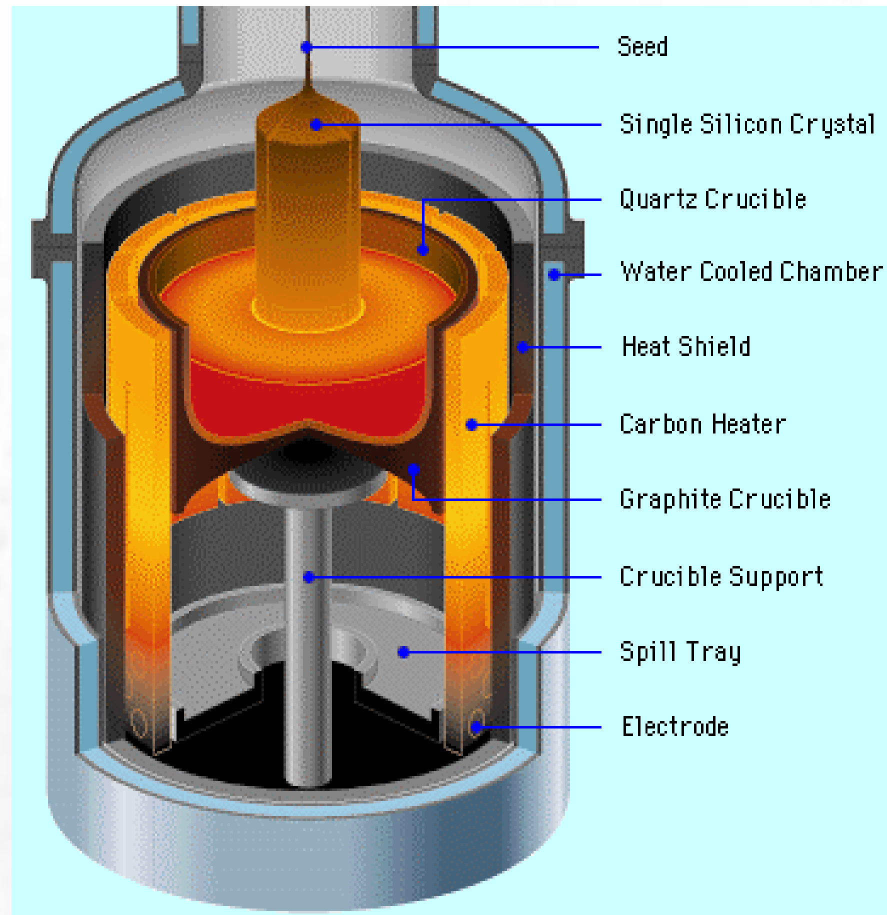
- Most crystalline silicon is grown by the Czhockralski (CZ) method
- One of the key application when Elmer development was started in 1995



Figures by Okmetic Ltd.



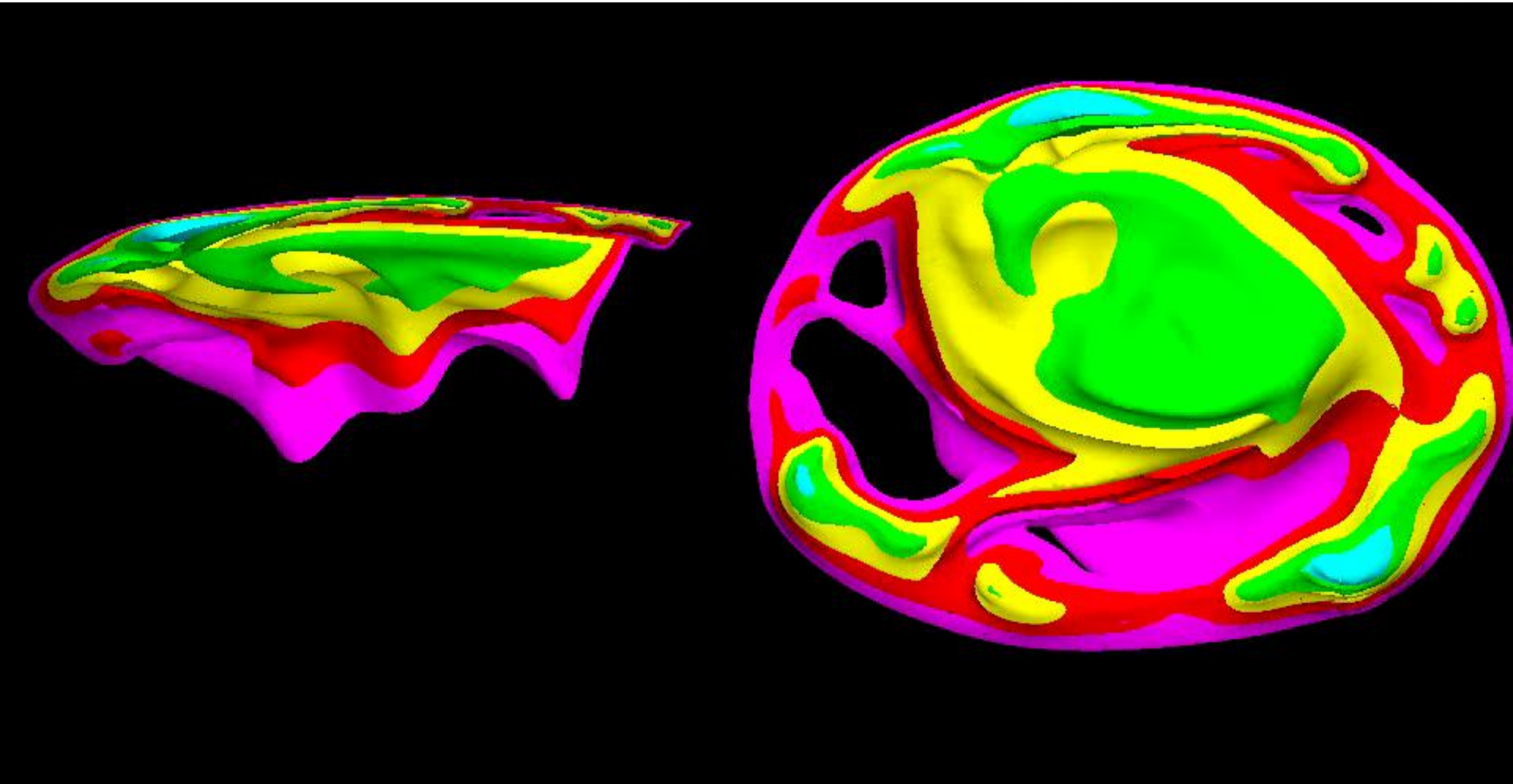
V. Savolainen et al., *Simulation of large-scale silicon melt flow in magnetic Czochralski growth,* J. Crystal Growth 243 (2002), 243-260.



CZ-growth: Transient simulation

Parallel simulation of silicon meltflows using stabilized finite element method (5.4 million elements).

Simulation Juha Ruokolainen, animation Matti Gröhn, CSC



MEMS: Inertial sensor

- MEMS provides an ideal field for multi-physical simulation software
- Electrostatics, elasticity and fluid flow are often inherently coupled
- Example shows the effect of holes in the motion of an accelerometer prototype

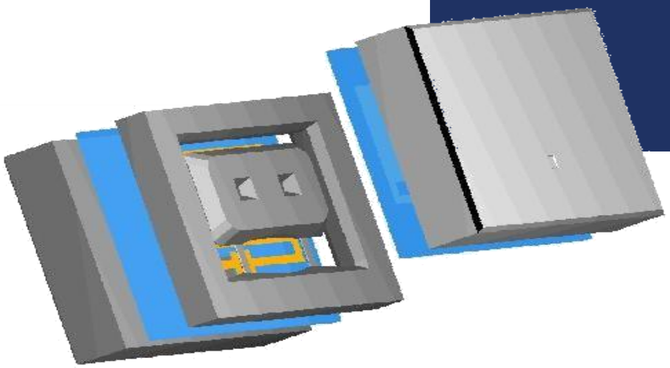
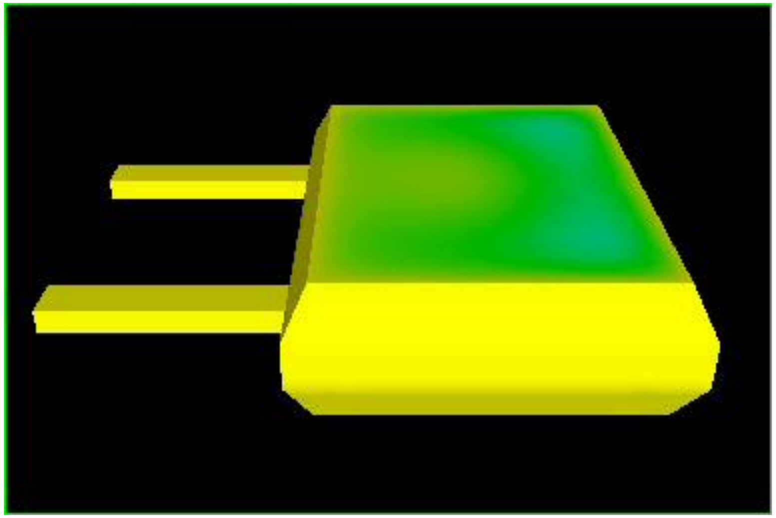
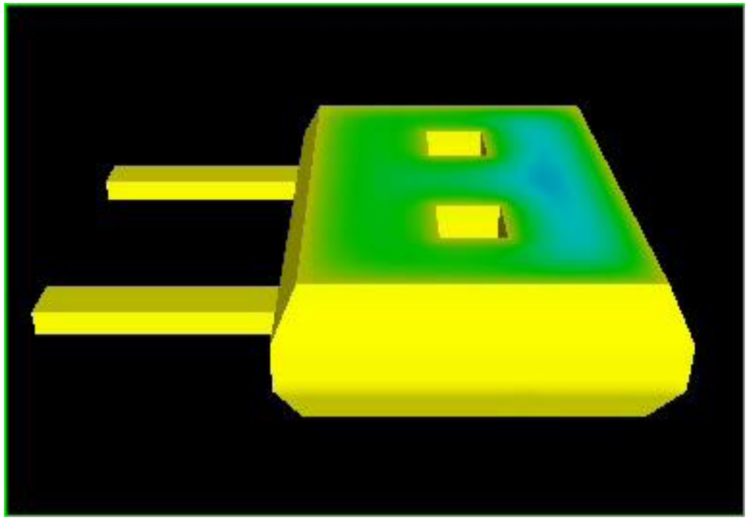


Figure by VTI Technologies

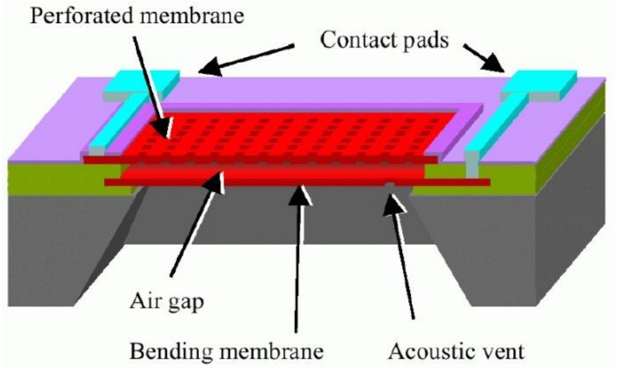


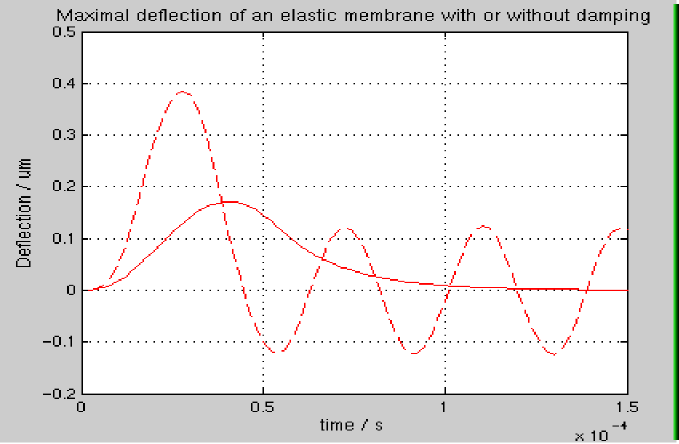


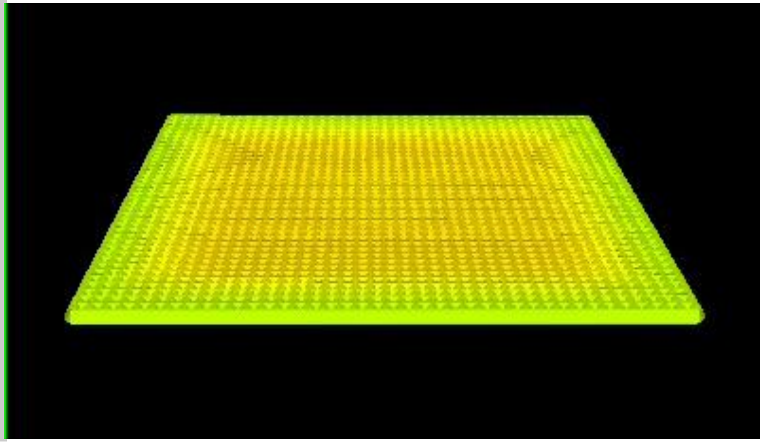
A. Pursula, P. Råback, S. Lähteenmäki and J. Lahdenperä, *Coupled FEM simulations of accelerometers including nonlinear gas damping with comparison to measurements*,
J. Micromech. Microeng. **16** (2006), 2345-2354.

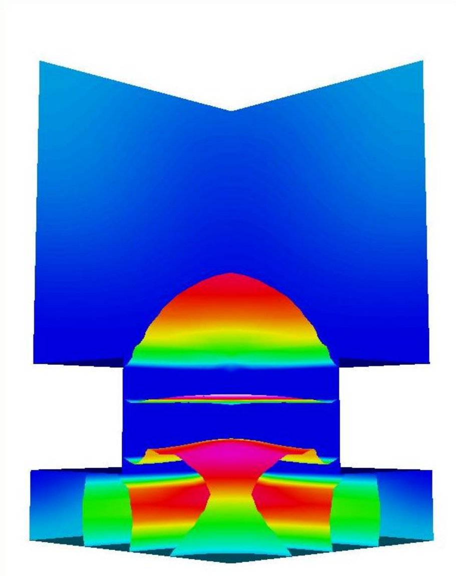
MEMS: Microphone membrane

- MEMS includes often geometrical features that may be modeled with homogenization techniques
- Simulation shows the damping oscillations of a perforated micromechnical membrane



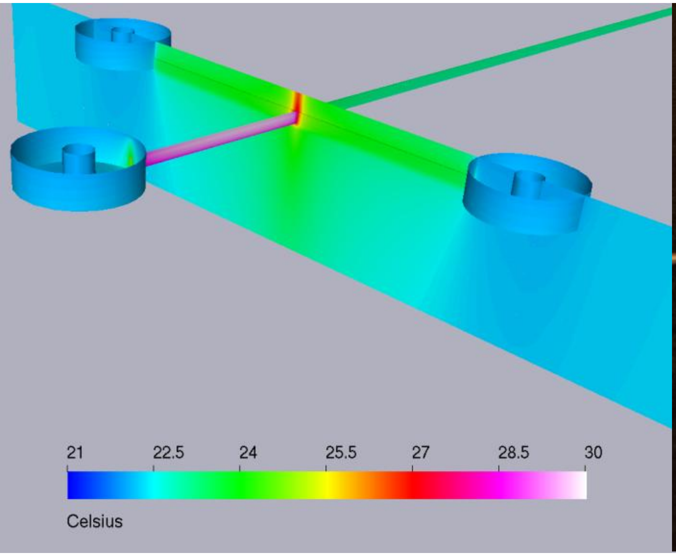


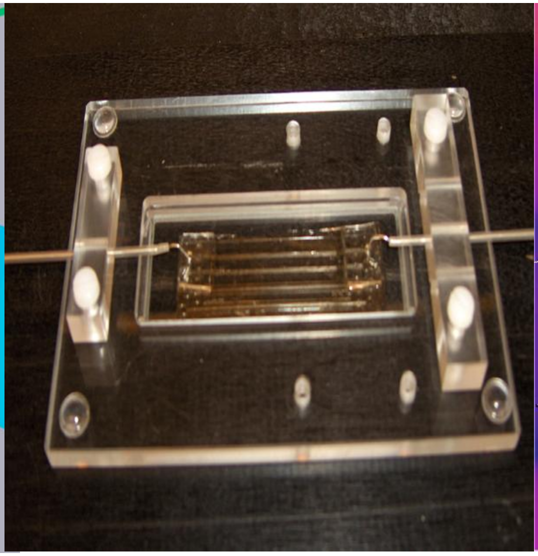


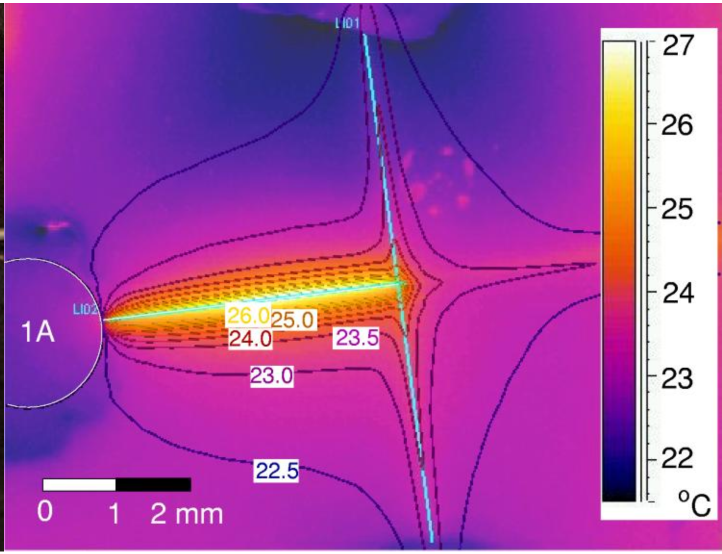


P. Råback et al., *Hierarchial finite element simulation of perforated plates with arbitrary hole geometries*, MSM 2003.

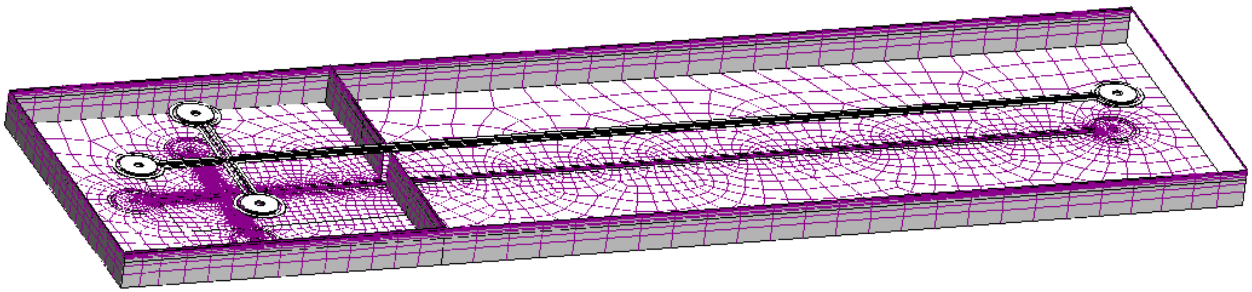
Microfluidics: Flow and heat transfer in a microchip







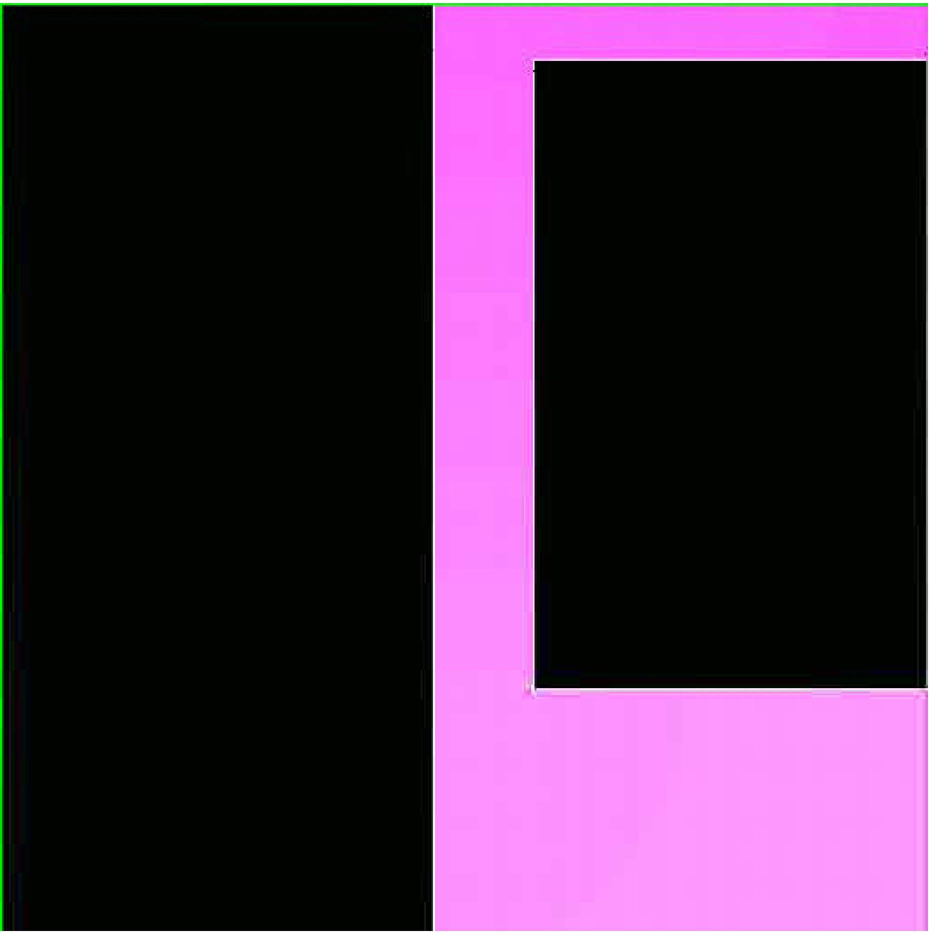
- Electrokinetically driven flow
- Joule heating
- Heat Transfer influences performance
- Elmer as a tool for prototypin
- Complex geometry
- Complex simulation setup



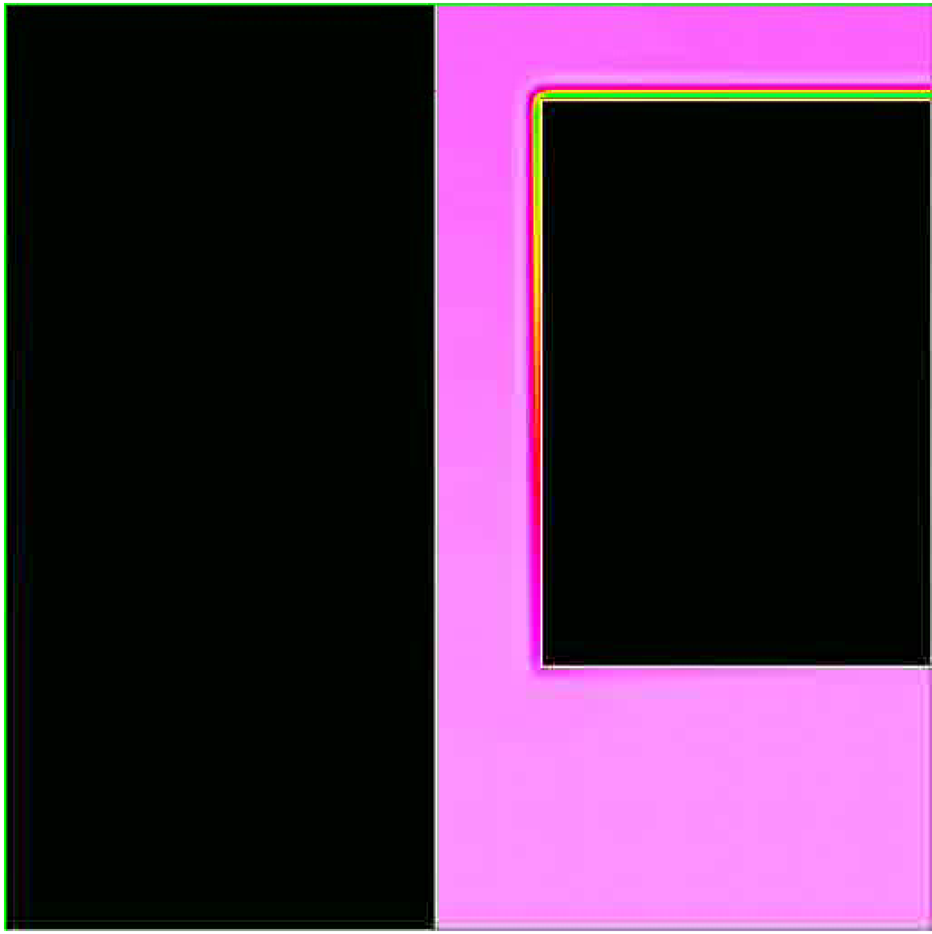
T. Sikanen, T. Zwinger, S. Tuomikoski, S. Franssila, R. Lehtiniemi, C.-M. Fager, T. Kotiaho and A. Pursula, Microfluidics and Nanofluidics (2008)

Acoustics: Losses in small cavities

Temperature waves resulting from the Helmholtz equation



Temperature waves computed from the linearized Navier-Stokes equation

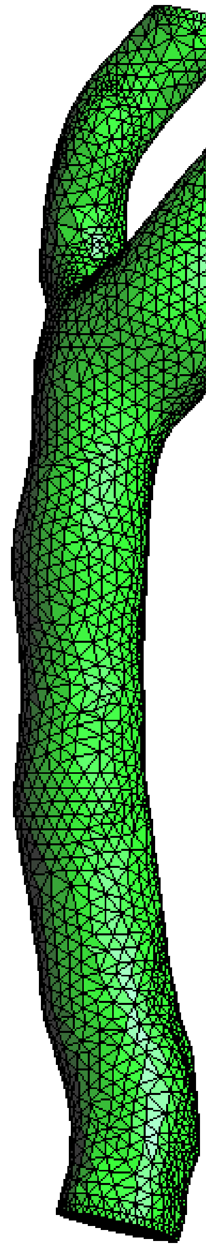


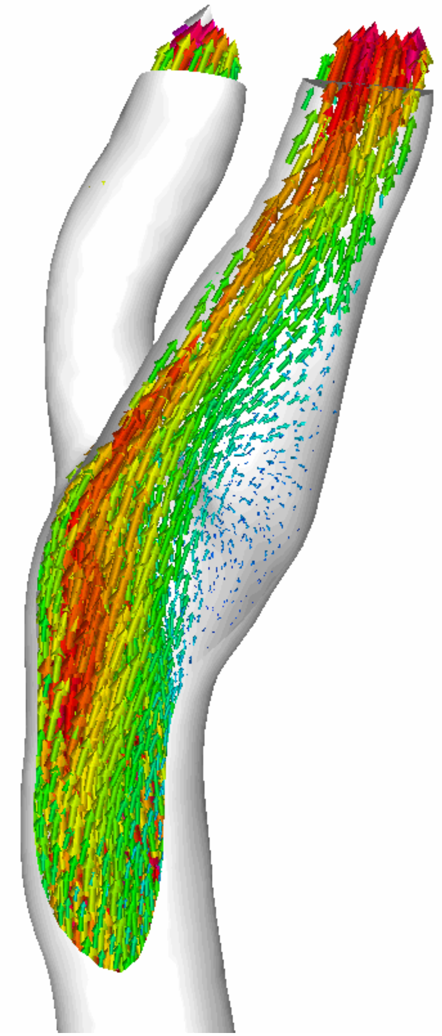
M. Malinen, *Boundary conditions in the Schur complement preconditioning of dissipative acoustic equations*, SIAM J. Sci. Comput. 29 (2007)

Computational Hemodynamic

- Cardiovascular diseases are the leading cause of deaths in western countries
- Calcification reduces elasticity of arteries
- Modeling of blood flow poses a challenging case of fluid-structure-interaction
- Artificial compressibility is used to enhance the convergence of FSI coupling

E. Järvinen, P. Råback, M. Lyly, J. Salonius. *A method for partitioned fluid-structure interaction computation of flow in arteries. Medical Eng. & Physics*, **30** (2008), 917-923

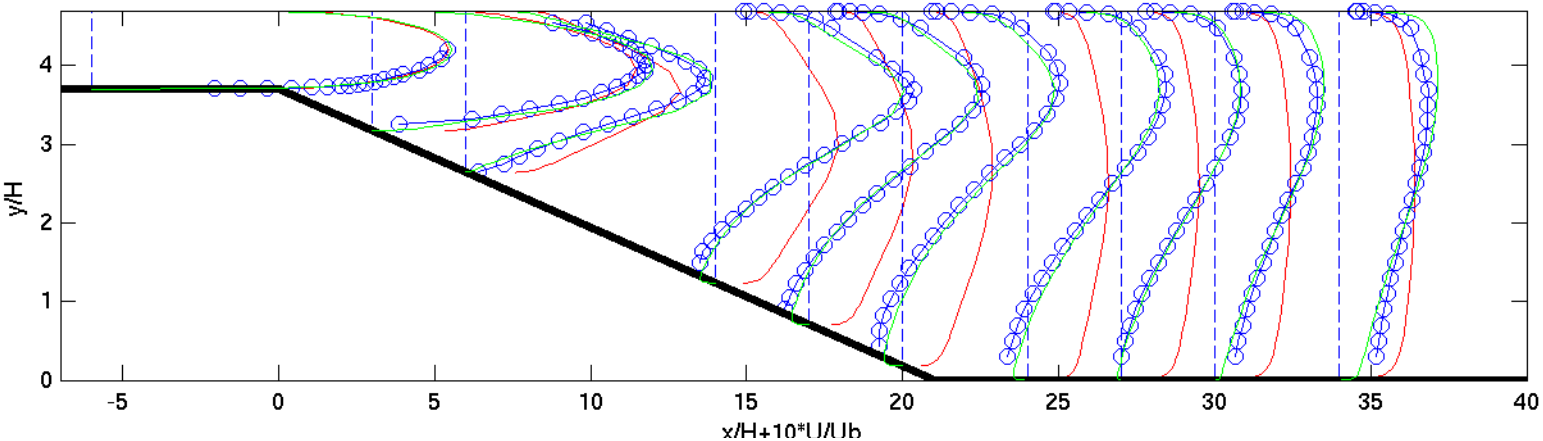




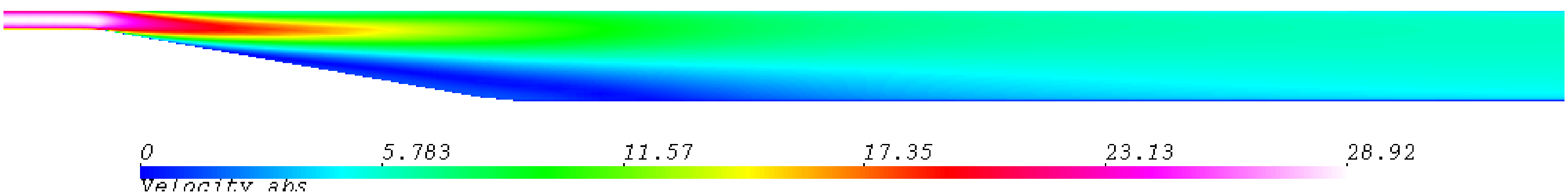
Blood flow in carotid artery accounting FSI interaction

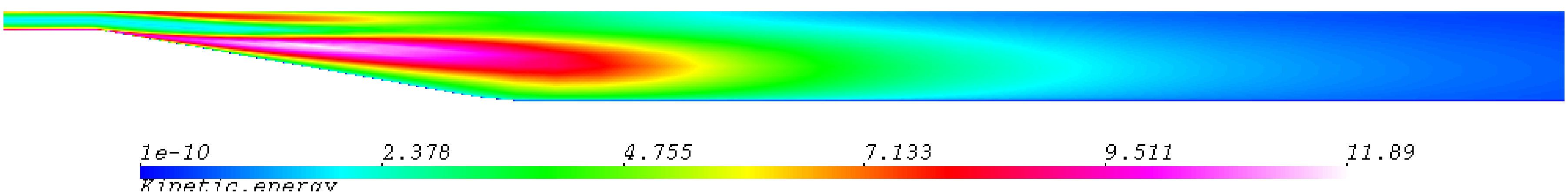
RANS turbulence modeling

Comparison of k-ε vs. v^2-f –turbulence models (red



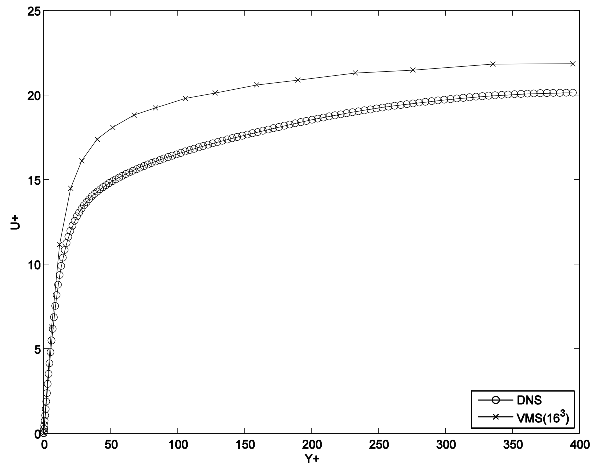
Simulation J. Ruokolainen, CSC



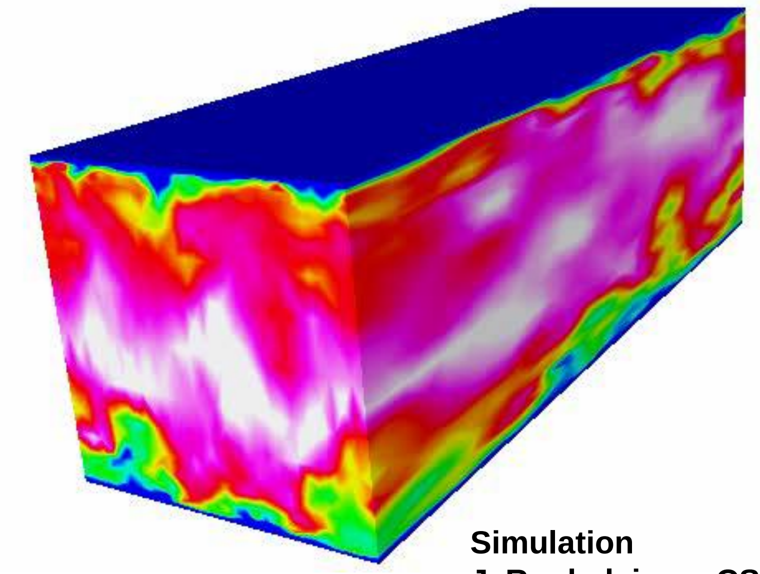


VMS turbulence modeling

- Large eddy simulation (LES) provides the most accurate presentation of turbulence without the cost of DNS
- Requires transient simulation where physical quantities are averaged over a period of time
- Variational multiscale method (VMS) by Hughes et al. Is a variant of LES particularly suitable for FEM
- Interation between fine (unresolved) and coarse (resolved) scales is estimated numerically
- No ad'hoc parameters



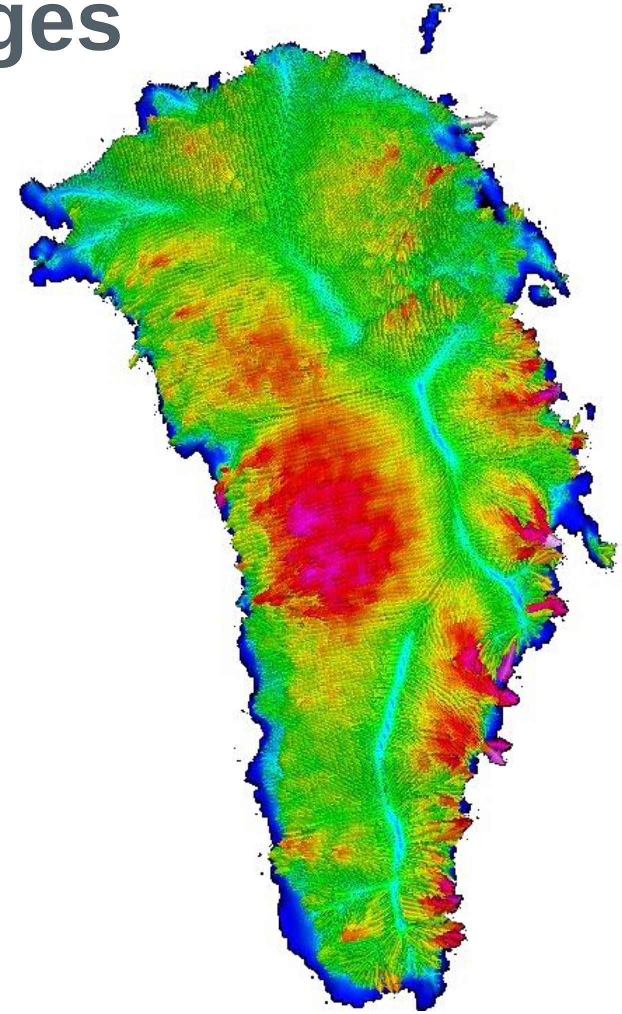
Plane flow with Re_τ=395



Simulation
J. Ruokolainen, CSC

Glaciology: Grand challenges

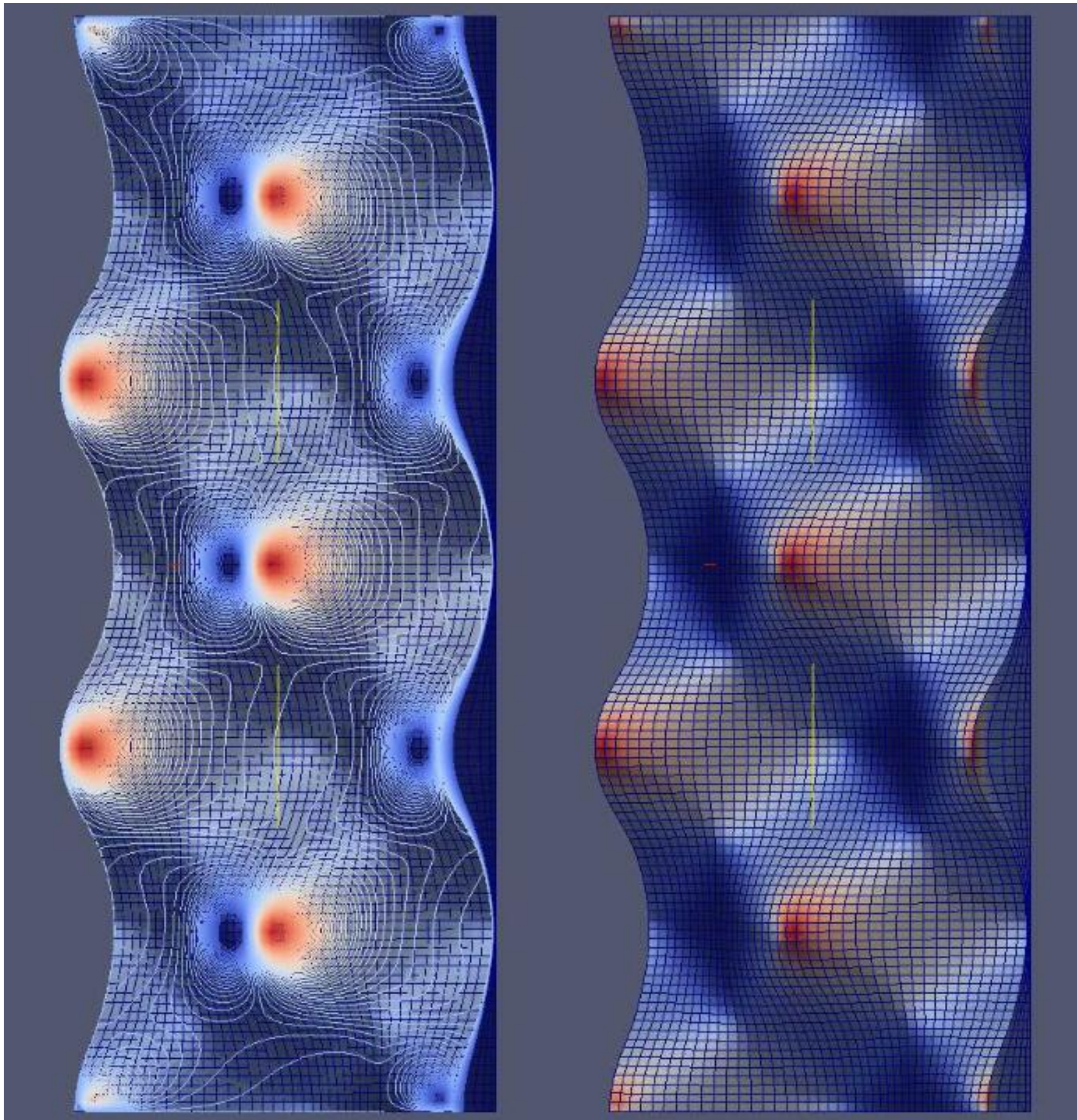
- Elmer is the leading code for 3D ice flow simulation even internationally
- Elmer uses full Stokes equation to model the flow
- Currently the mostly used tool in the area
  - British Antarctic Survey
  - University of Grenoble
  - University of Sapporo
- Simulations of continental ice sheets very demanding
- Climate change makes the simulations very important



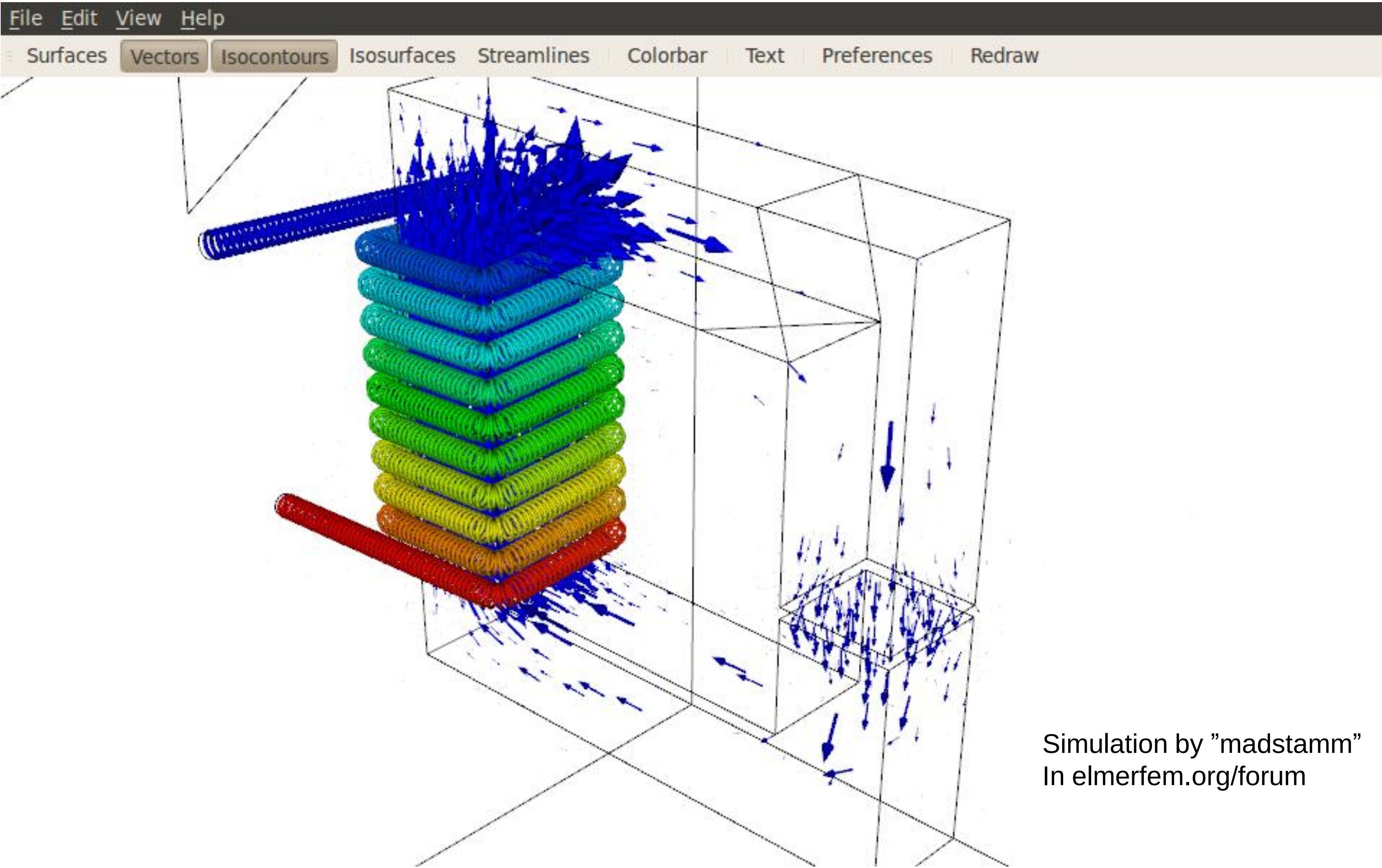
Simulation T. Zwinger, CSC

EHDL of patterned surfaces

- Solution of Reynolds & nonlinear elasticity equations
- Simulation Bengt Wennehorst, Univ. Of Hannover, 2011



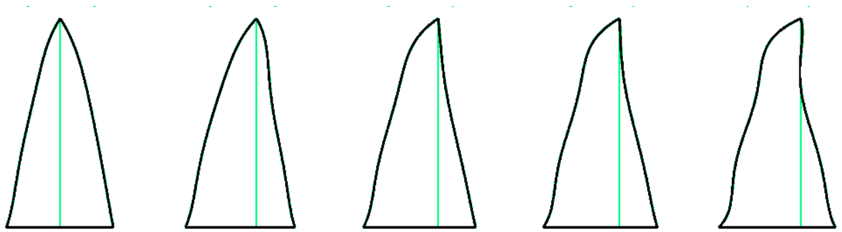
Whitney element Solver



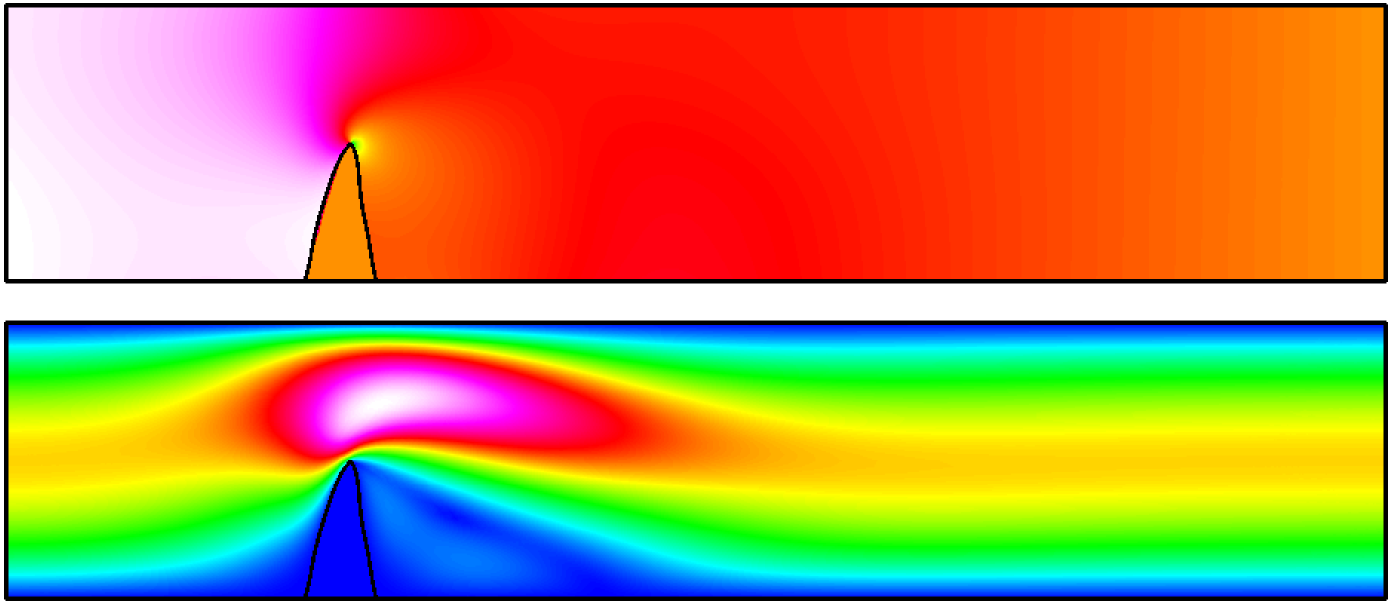
Simulation by "madstamm"
In elmerfem.org/forum

Optimization in FSI

- Elmer includes some tools that help in the solution of optimization problems
- Profile of the beam is optimized so that the beam bends as little as possible under flow forces



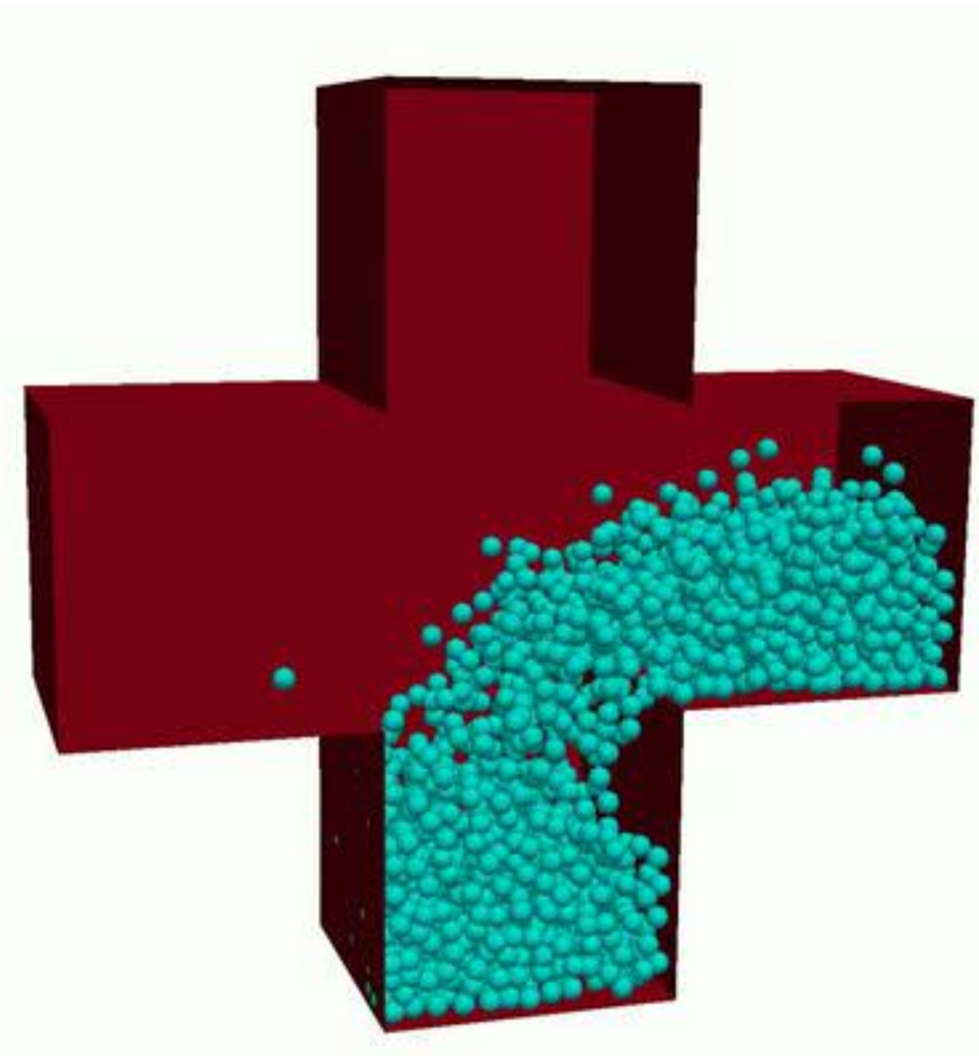
Optimized profiles for Re={0,10,50,100,200}



Pressure and velocity distribution with Re=10

Simulation Peter Råback

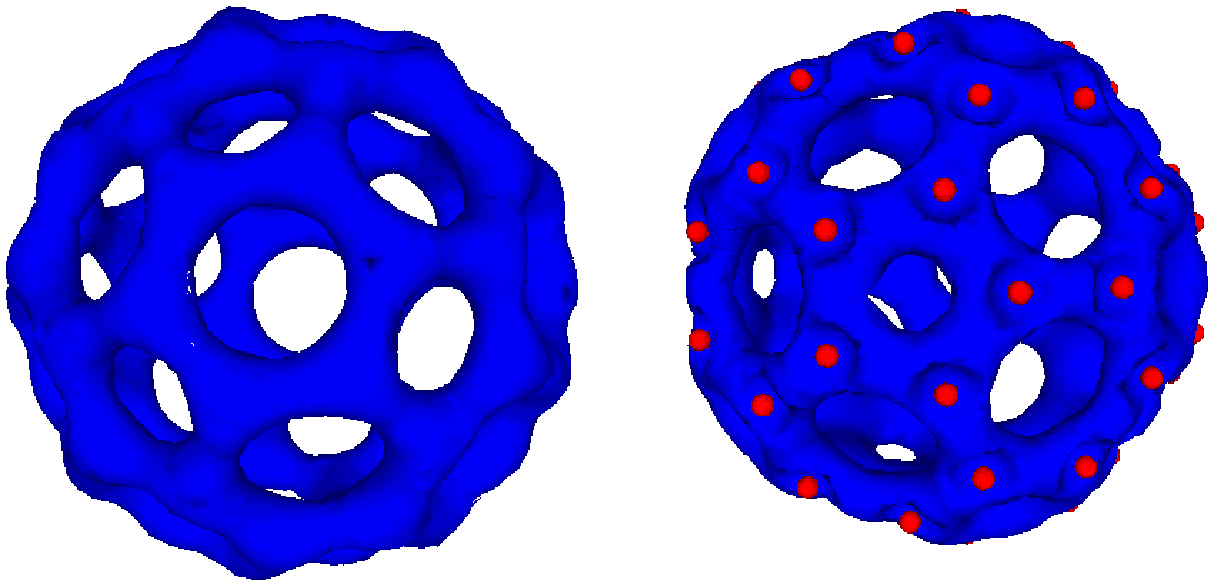
Particle tracker - Granular flow



Quantum Mechanics

- Finite element method is used to solve the Kohn-Sham equations of density functional theory (DFT)

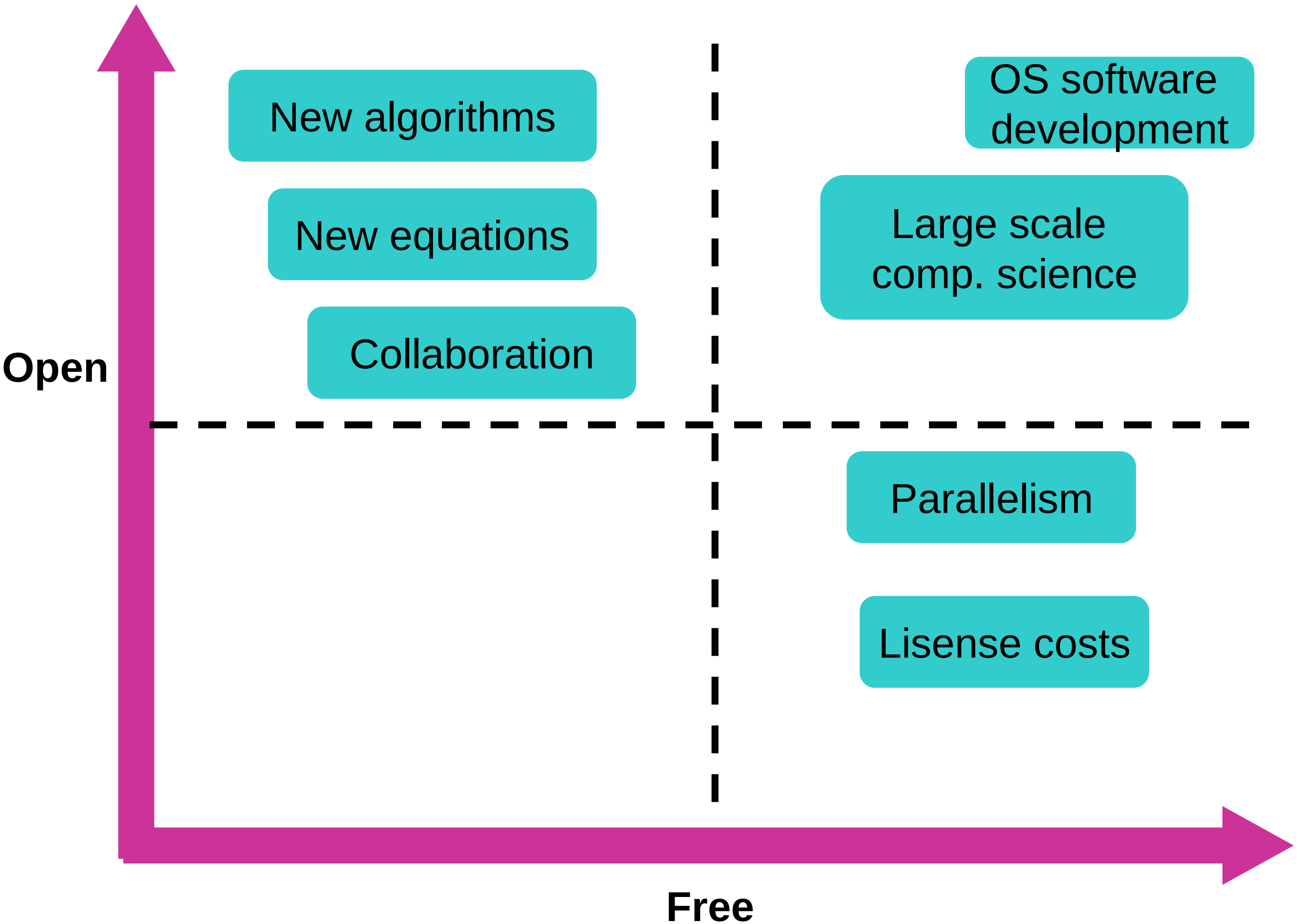
- Charge density and wave function of the 61st eigenmode of fullerine C60
- All electron computations using 300 000 quadratic tets and 400 000 dofs



Simulation Mikko Lyly, CSC

Reasons to use open source software

free as in ”beer” vs. free as in ”speech”



Most important Elmer resources

- http://www.csc.fi/elmer
  - Official Homepage of Elmer
  - Overview, examples, compilation, …
  - pointers to other sources of information
- http://sourceforge.net/projects/elmerfem/
  - Version control system: svn
  - Binaries
- www.elmerfem.org
  - Discussion forum, wiki & doxygen
- Further information: Peter.Raback@csc.fi

- Thank you for your attention!