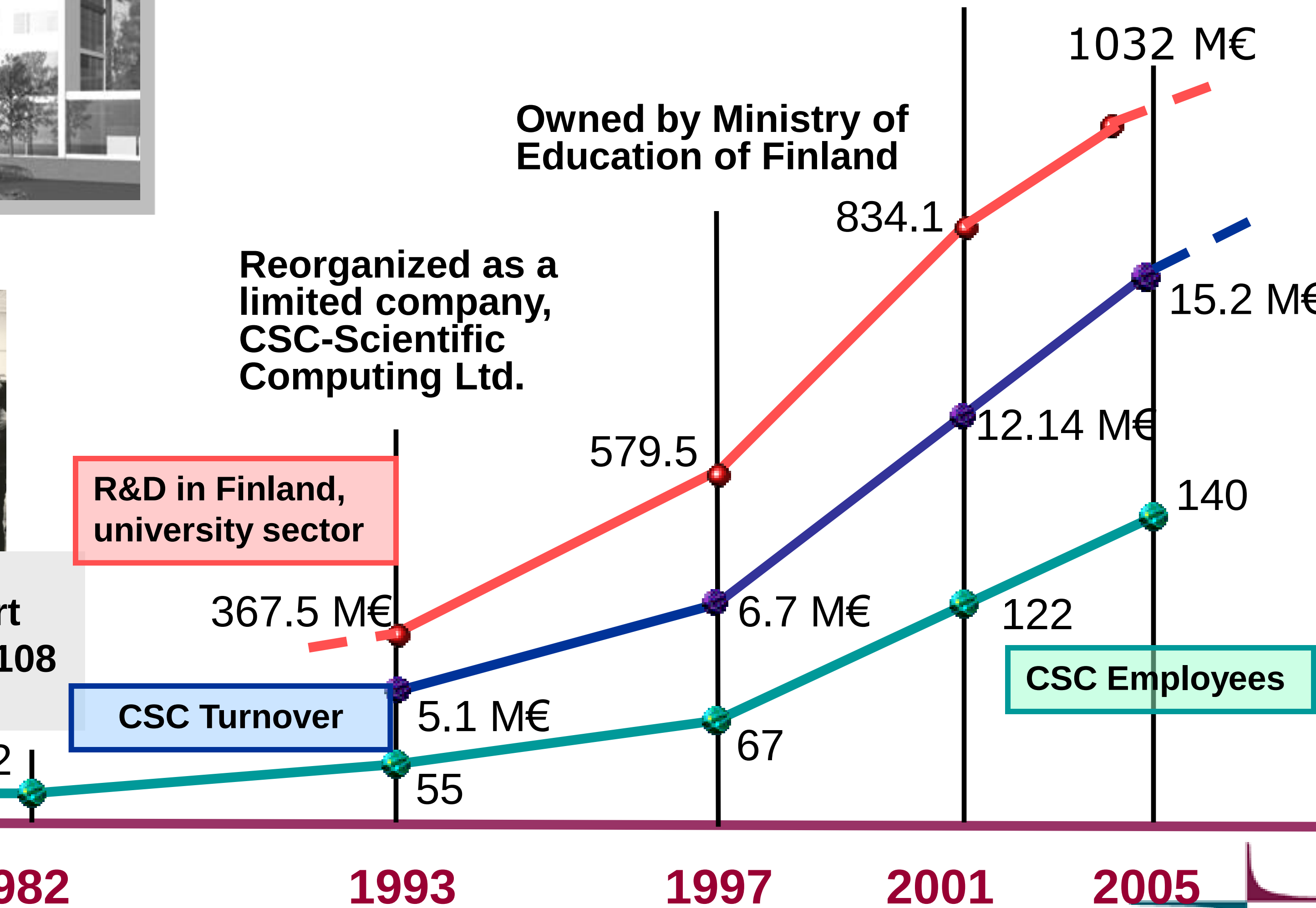
Elmer Basic Course 25.5.

- 9.00-9.30 Registration & Coffee
- 9.30 I Session
  Welcome (all)
  Overview of Elmer
  Demonstration of ElmerGUI
  Instructions for the exercices
- 11.30 Lunch
- 12.15 II Session
  Guided exercices with simple walk-through examples in heat transfer, fluid dynamics, structural mechanics, electromagnetics, and in glasiology.
- 14.00 Coffee
- 14.20 III Session
  Using Elmer with other pre- and postprocessors (PR)
  Exercices continue
  Customizing ElmerGUI (ML)
- 16.30 End of day

History of CSC

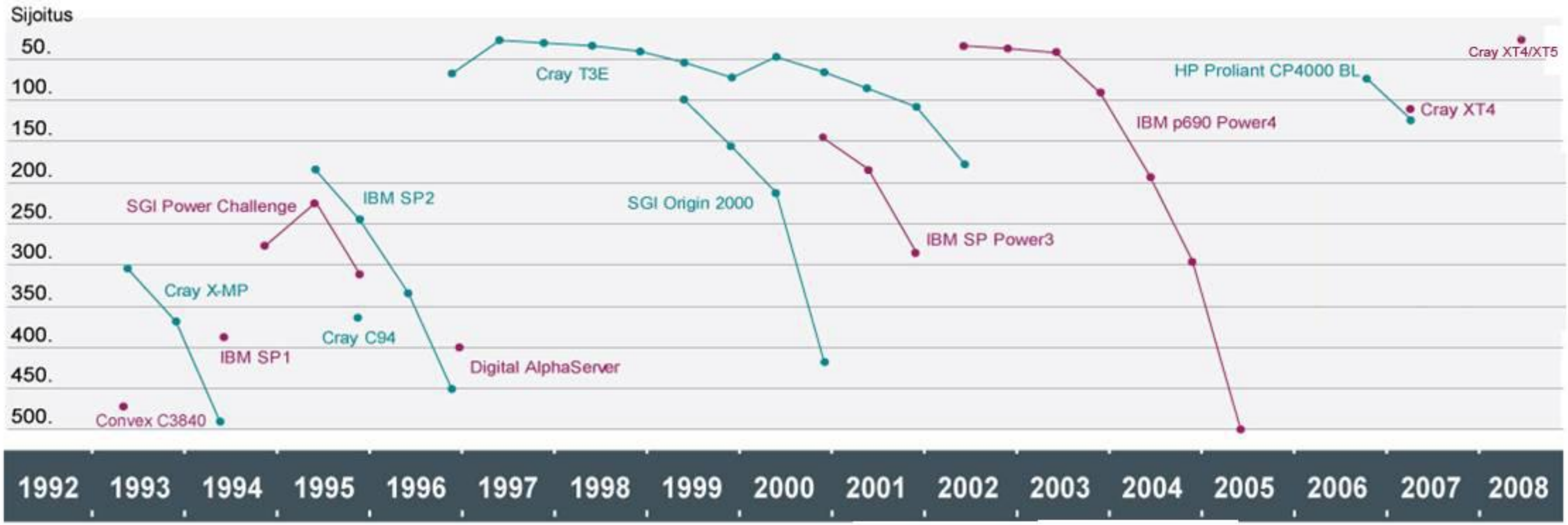
In 2008, officially named as *CSC – the IT center for science*



CSC's supercomputers at the top500 list

Univac 1108
-käyttöön 1971
-1 prosessori
-1 MB muistia
-huipputeho 0,093 Mflop/s
-oli aikanaan tehokas kone, mutta sitä ei kutsuttu supertietokoneeksi

1000 Mflop/s = 1 Gflop/s
1000 Gflop/s = 1 Tflop/s



Cray X-MP
-käyttöön 1989
-4 vektoriprosessoria
-0,5 GB muistia
-huipputeho 935 Mflop/s

Cray C94
-käyttöön 1995
-4 vektoriprosessoria
-2 GB muistia
-huipputeho 4 Gflop/s

CrayT3E
-käyttöön 1997
-544 prosessoria
-64 GB muistia
-huipputeho 384 Gflop/s

SGI Origin 2000
-käyttöön 1998
-128 prosessoria
-160 GB muistia
-huipputeho 76,8 Gflop/s

IBM SP Power3
-käyttöön 2000
-128 prosessoria
-64 GB muistia
-huipputeho 192 Gflop/s

IBM p690 Power 4
-käyttöön 2002
-512 prosessoria
-512 GB muistia
-huipputeho 2,2 Tflop/s

HP Proliant CP4000 BL
-käyttöön 2007
-1024 prosessoria
-4096 GB muistia
-huipputeho 10,6 Tflop/s

Cray XT4
-käyttöön 2007
-1012 prosessoria
-2024 GB muistia
-huipputeho 10,5 Tflop/s

Cray XT4/XT5
-käyttöön 2008
- 2356 prosessoria
- 10,3 Tb muistia
-huipputeho 86,7 Tflop/s

Elmer – an Open Source Finite Element Software for Multiphysical Problems

Peter Råback
CSC, Finnish IT Center for Science

Elmer Basic Course
25th May 2010, CSC, Espoo

CSC

Outline

- Introduction to Elmer
  - As a project
  - As a software
- Elmer & Multiphysics
- Examples on Elmer usage

Elmer - Background

- Solution of partial differential equations by FEM
- Elmer development was started in 1995 as part of a national CFD program, also funded by Tekes
  - Collaboration with TKK, VTT, JyU, and Okmetic Ltd.
- After the initial phase the development has been driven by number of application projects
  - MIKSU (2000-2003) Tekes, VTI Techologies, Vaisala, NRC: MEMS
  - Collaboration with Nokia (2003->): acoustics
  - PIIMA (2004-2005) Tekes & silicon industry: MEMS, microfluidics, crystal growth
  - LSCFD (2008-2010) Tekes, Okmetic: Large Scale CFD
  - Others: composite structures, optical fiber manufacturing, crystal growth, blood flow, glaciology
  - Computational glaciology: international collaboration
  - Number of thesis projects in universities
- Elmer includes a large number of physical models and modern numerical methods

Elmer goes Open Source

- 9/2005 Elmer published under GPL-license
- 10/2007 Elmer version control put under sourceforce.net
- Goals of the open source publication
  - Expand the Elmer community
  - New resources for code development
  - Improved verification process
  - No resources for a commercial spin-off
  - Free software good adverticiment for CSC
- Roughly 300 000 lines of code!
  - The whole IP of the software still owned by CSC
- Available at
  `http://www.csc.fi/elmer`
  `http://sourceforge.net/projects/elmerfem`

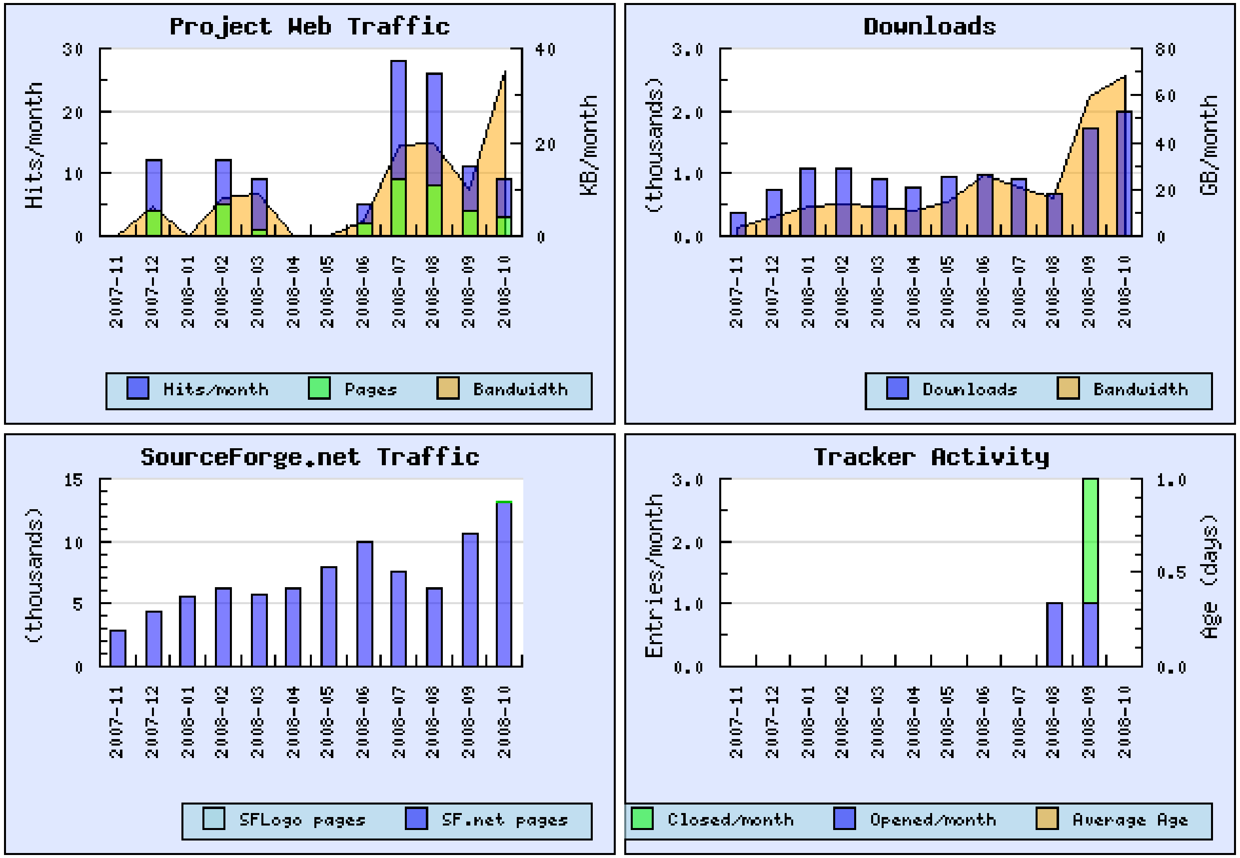
Fruits of Open Source publication

- Increased popularity
  - More than a thousand individual vistors on web-pages monthly
  - Significant number of serious users in different application areas, for example computational glasiology community.
- 2nd hand distribution
  - Several Linux distributions:
    Ubuntu, Debian and CAELinux
  - FreeBSD
  - Mac OS
  - Sun Grid (for a price of 1 e/h)
  - EGEE-grid
  - …
- Increased popularity and visibility means new opportunities
  - Funding in national and EU-projects
  - Collaboration in different areas using Elmer as the platform

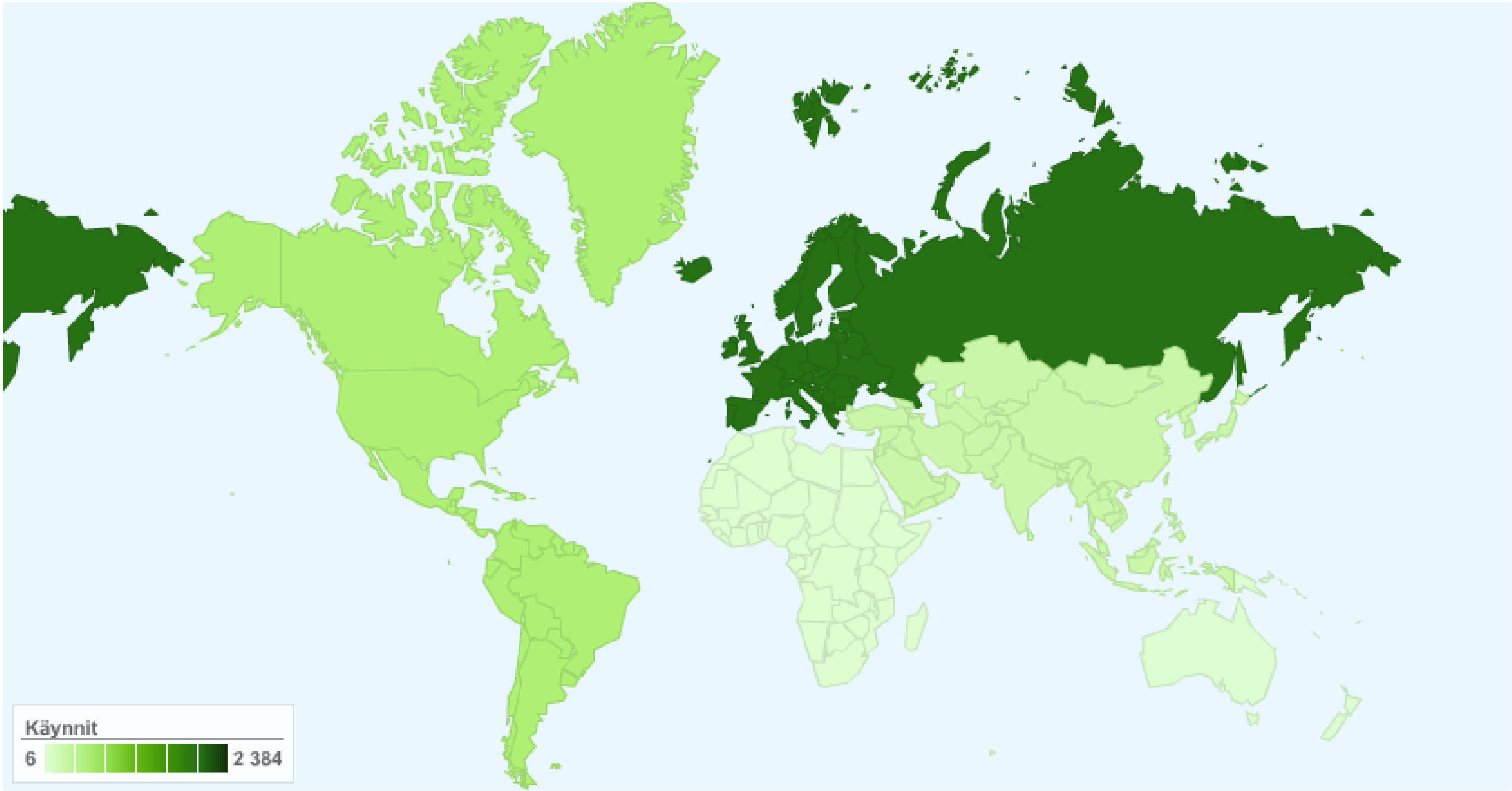
Elmer @sf

- Rank
  ~1000
- Downloads
  ~1000 / month

Usage Statistics For Elmer-fem



elmerfem.org statistics 3/2010: continents



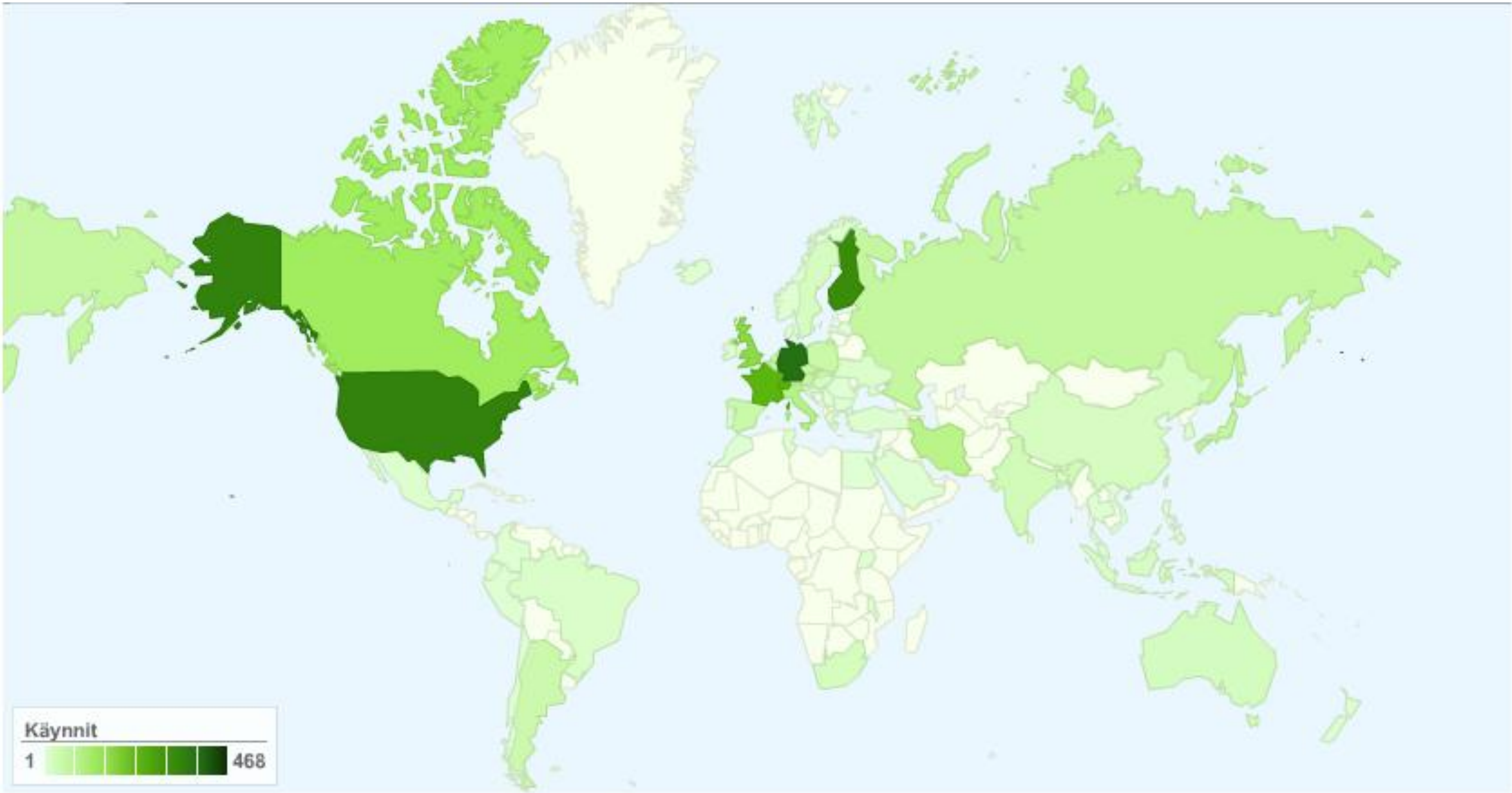
3 428 käyntiä 6 maanosasta

elmerfem.org statistics 3/2010: continents

Käynnit	Sivua/käyntikerta	Keskim. aika sivustossa	% uusia käyntejä
3 428	5,47	00:05:15	39,18 %
% sivuston kokonaismäärästä: 100,00 %	Sivuston keskiarvo: 5,47 (0,00 %)	Sivuston keskiarvo: 00:05:15 (0,00 %)	Sivuston keskiarvo: 38,89 % (0,75 %)

	Tietojen tarkkuustaso: Maanosa	Käynnit ↓	Sivua/käyntikerta	Keskim. aika sivustossa
1.	Europe	2 384	5,56	00:05:27
2.	Americas	668	5,41	00:04:19
3.	Asia	306	4,88	00:05:00
4.	Oceania	33	4,36	00:06:10
5.	Africa	31	5,71	00:08:56
6.	(not set)	6	12,83	00:16:09

elmerfem.org statistics 3/2010: countries

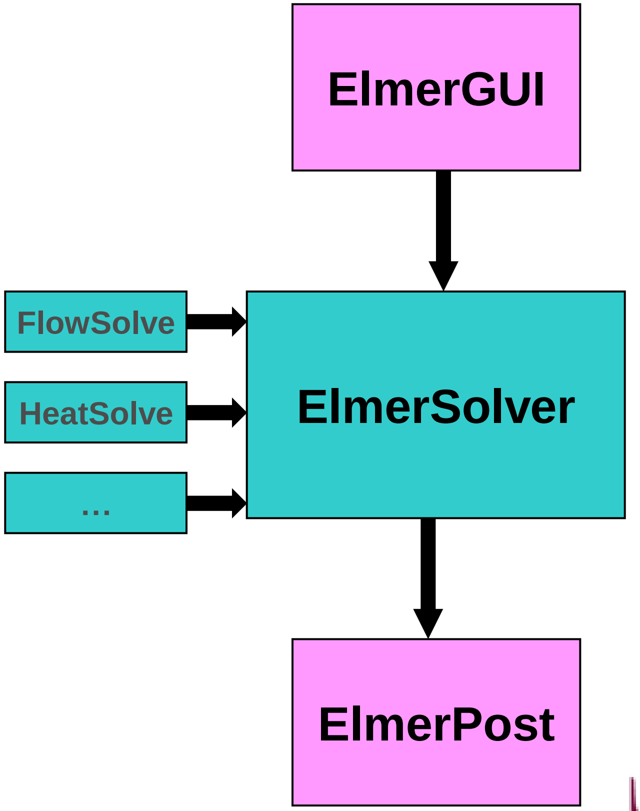


3 428 käyntiä 66 maat ja alueet

	Tietojen tarkkuustaso: Maa tai alue	Käynnit	Sivua/käyntikerta	Keskim. aika sivustossa
1.	Germany	468	5,85	00:05:19
2.	United States	419	5,36	00:04:06
3.	Finland	392	7,34	00:07:54
4.	Switzerland	290	6,83	00:07:36
5.	France	287	3,67	00:02:58
6.	United Kingdom	198	6,42	00:05:23
7.	Canada	162	6,13	00:05:22
8.	Italy	107	4,72	00:03:40
9.	Iran	101	4,04	00:03:11
10.	Russia	73	3,34	00:03:24
11.	Czech Republic	73	3,27	00:02:11
12.	Japan	70	6,54	00:05:40
13.	Netherlands	68	4,47	00:06:32
14.	Belgium	67	7,40	00:08:02
15.	Austria	64	4,73	00:07:42
16.	Poland	58	3,62	00:02:42
17.	Spain	57	4,96	00:03:01
18.	Slovakia	55	4,40	00:04:47
19.	Argentina	53	3,79	00:02:48
20.	India	37	3,62	00:03:17
21.	Australia	28	4,93	00:06:31
22.	China	26	7,81	00:09:56
23.	South Africa	25	6,76	00:10:47
24.	Sweden	25	3,32	00:01:21

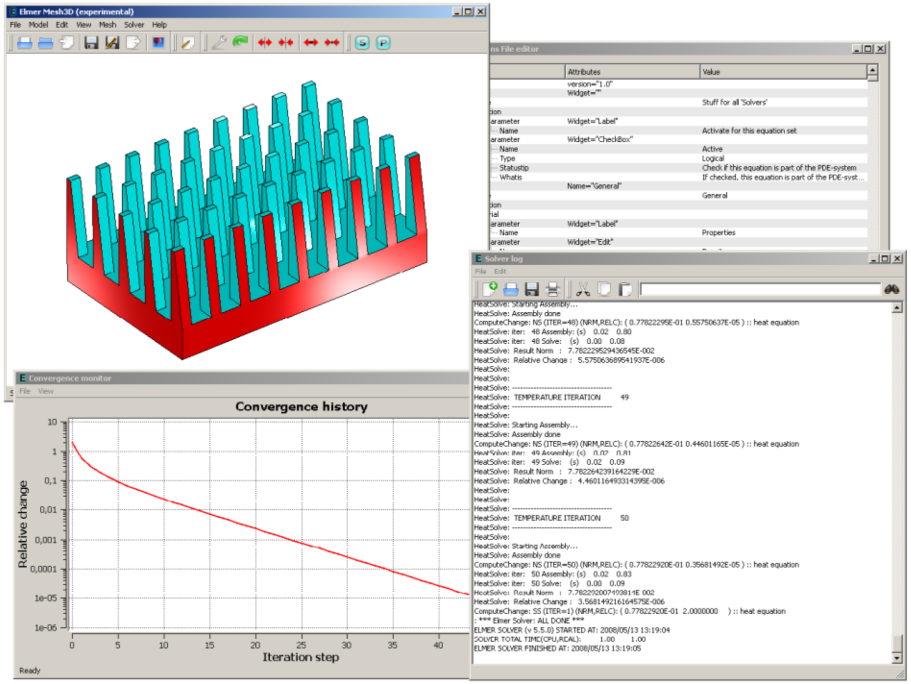
Components of Elmer software suite

- Elmer is actually a suite of several programs
- You may use many of the components independently
- ElmerGUI – Pre- and Postprocessing
- ElmerSolver - Solution
- ElmerPost - Postprocessing
- Others
  - ElmerFront: the old preprocessor
  - Mesh2D: Delaunay mesher usable through ElmerFront
  - MATC: library for on-the-fly arithmetics
  - ElmerGrid as a stand-alone tool
  - ElmerParam: black-box interfacing of ascii-file based simulations



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



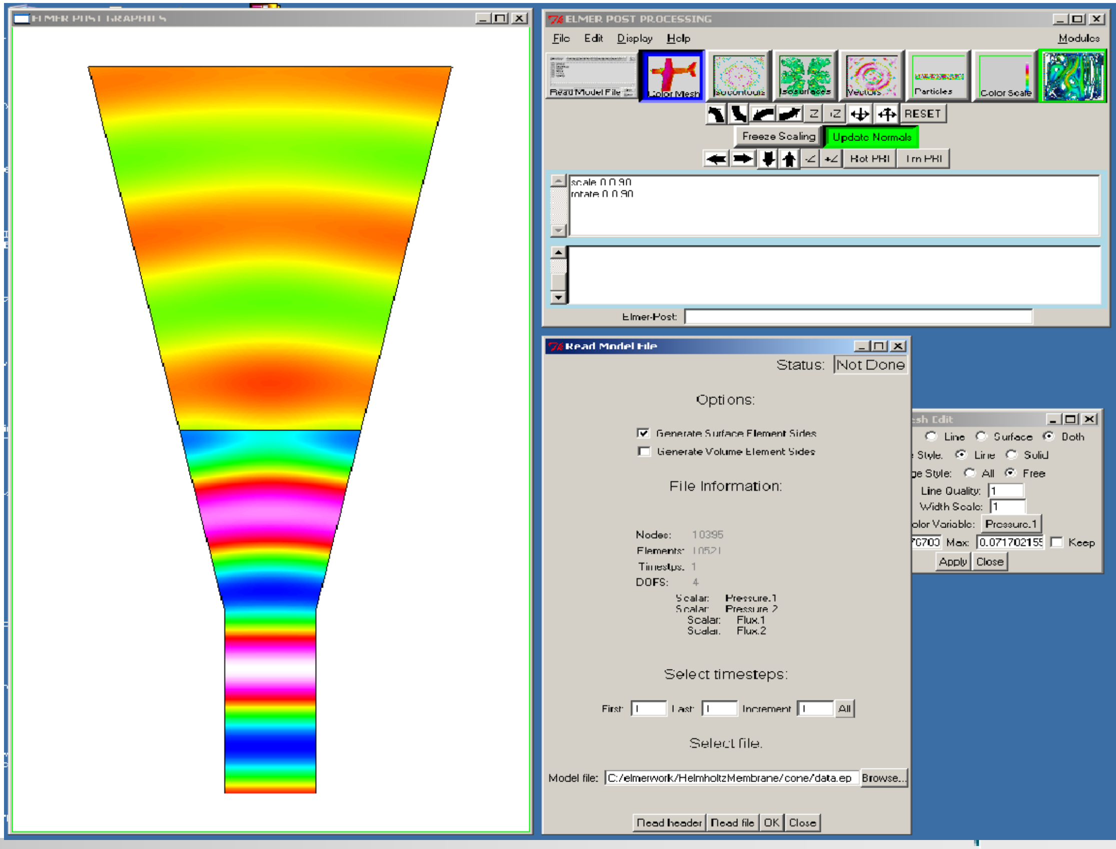
ElmerSolver

- 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
```

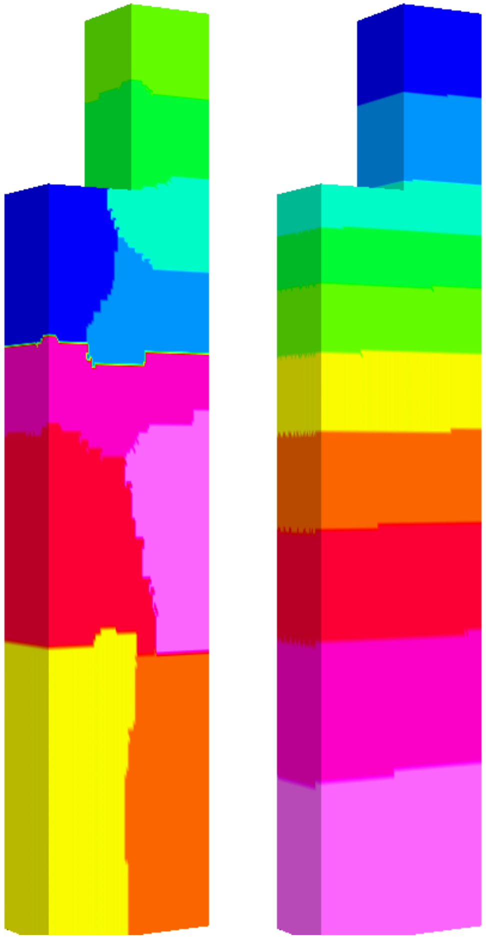
ElmerPost

- 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 - Physical Models

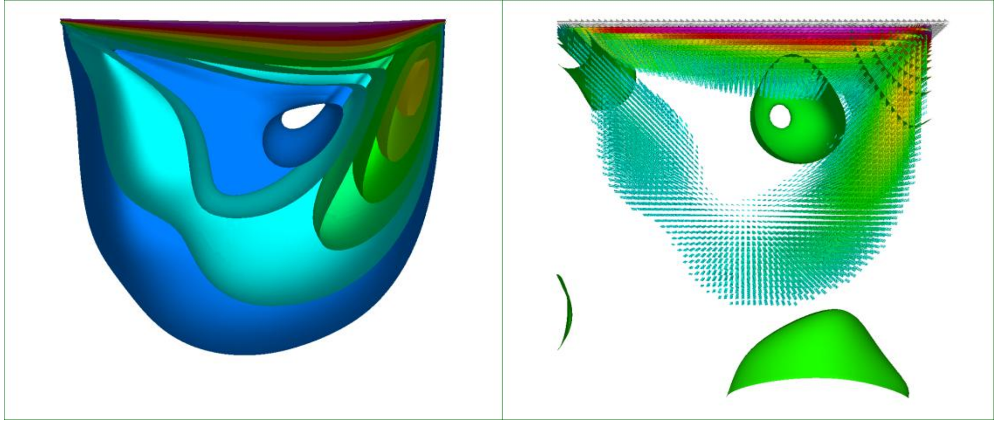
- Heat transfer
  - Heat equation
  - Radiation with view factors
  - convection and phase change
- Fluid mechanics
  - Navies-Stokes (2D & 3D)
  - Turbulence models: k-ε, v^2-f, *VMS*
  - Reynolds (2D)
- Structural mechanics
  - Elasticity (unisotropic, lin & nonlin)
  - Plate, Shell
- Free surface 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
  - Mainly steady-state and harmonic analysis
  - Edge-element formulation
- Electrokinetics
  - Poisson-Boltzmann
  - Poisson-Nernst-Planck
- Quantum mechanics
  - DFT (Kohn Scham)
- ….

Elmer – Numerical Methods

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

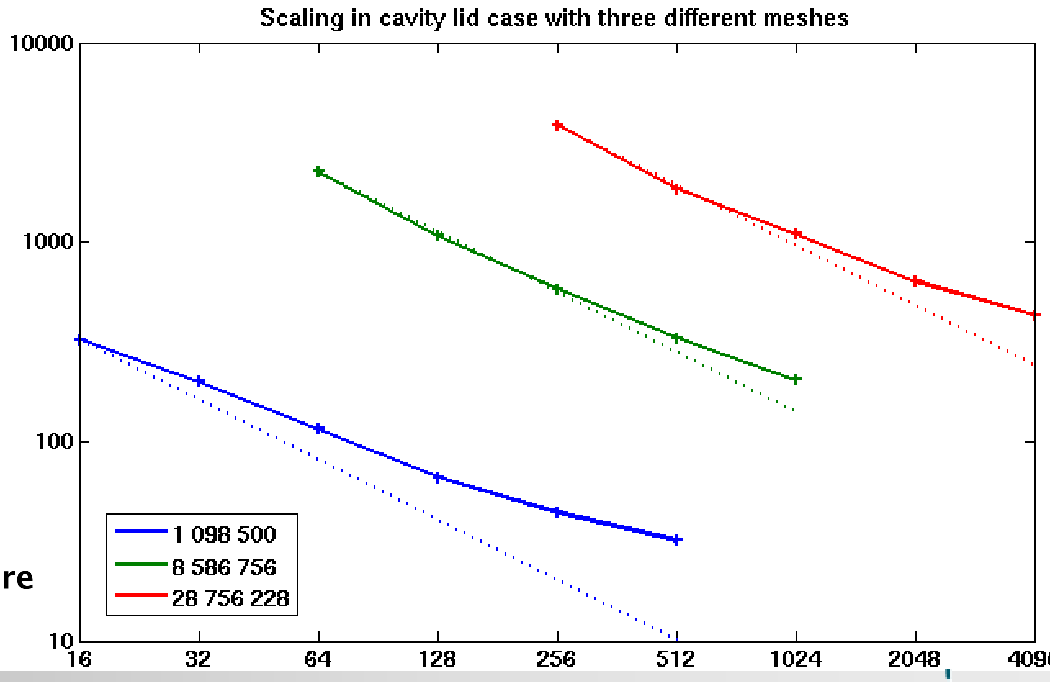
Parallel performance

- Partitioning by Metis or simple geometric division
- Parallel assembly and solution by GMG or Krylov subspace methods.
- Parallel performance may scale up to thousands of cores
- Simulation with over one billion unknowns has been performed



Scaling of wall clock time with dofs in the cavity lid case using GMRES+ILU0. Simulation Juha Ruokolainen, CSC, visualization Matti Gröhn, CSC .

Louhi: Cray XT4/XT5 with 2.3 GHz 4-core AMD Opteron. All-in-all 9424 cores and Peak power of 86.7 Tflops.



Coupling of physical phenomena

- Equations are inherently coupled and the coupling is explicitly shown in the equations
  - E and B in Maxwell's eq., p and v in Navier-Stokes eq.
- The different energy domains are coupled by a source or drain
  - viscous dissipation of kinetic energy to heat
- Coupling by material law
  - v and T by temperature dependent density
- Implicit coupling by the shape of the computational domain
  - large displacements and fluid flow
- …

Some possible multiphysical combinations

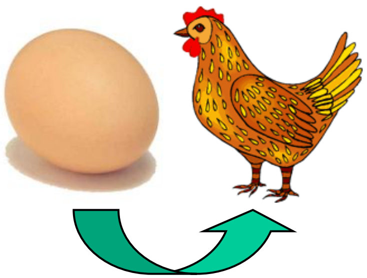
Equation	Field	*T*	*v*	*E, B*	*c*	*u*
Energy	Temperature, *T*	-				
Navier-Stokes	Velocity, *v*	1	-			
Maxwell's	Electric & magnetic, *E, B*	2	3	-		
Diffusion, Reaction	Consentration, *c*	4	5	6	-	
Elasticity	Displacement, *u*	7	8	9	10	-

1) Thermal flow: natural convection
2) Thermal-electrical: Heating by induction
3) Magnetohydrodynamics, Electrokinetics
4) Temperature dependent chemical reactions and diffusion
5) Reactive flow: CFD, combustion
6) Electrochemistry: batteries, electrodes, surface treatment
7) Thermoelasticity and –plasticity
8) Fluid-structure interaction: hemodynamics
9) Electro-mechanical: MEMS, piezoelectricity
10) Growth phenomena

Nature of coupling

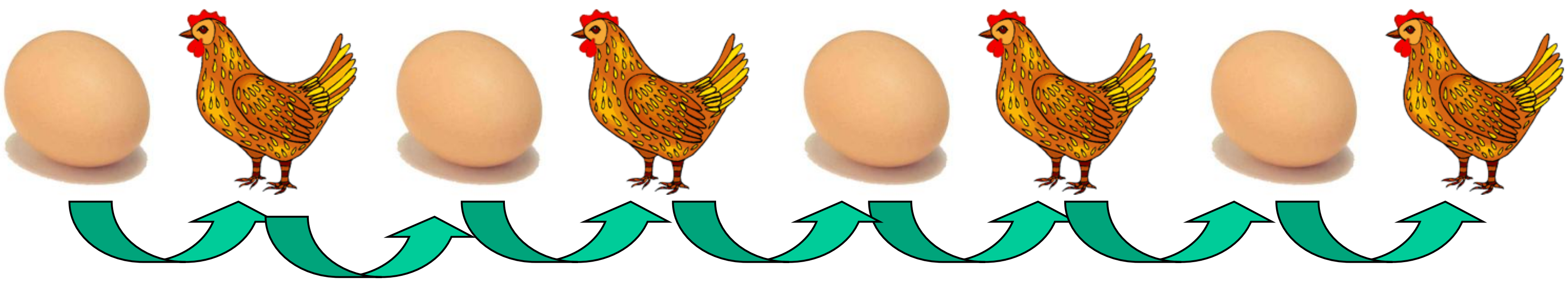
- The mathematical analysis does not give strict guidelines for the solution methods of coupled problems
  - Even uniqueness of solution is difficult to show
  - Heuristic approach: if the method works, use it
- Computational cost of coupled problems is often significantly larger than the combined solution time of individual probelms
- The strength of coupling of individual phenomena is reflected in the difficulty of solution
  - One-directional coupling -> hierarchical solution
  - Weak coupling easy -> iterative solution
  - Strong coupling difficult -> monolithic solution

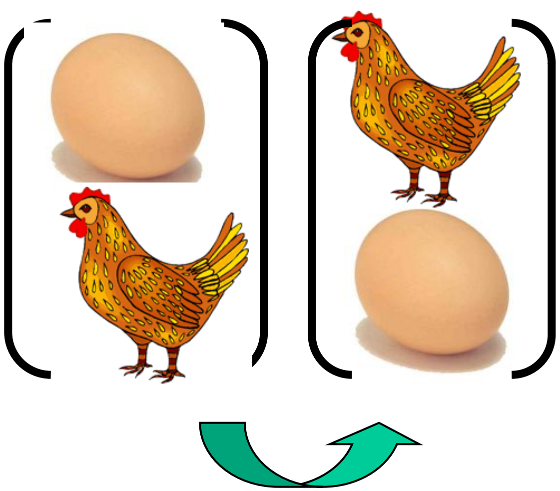
Solution strategies for coupled problems



Hierarchical solution

Iterative solution





Monolithic solution

Solution strategies for coupled problems

Assume phenomena $\mathcal{F}$ and $\mathcal{G}$ that both depend on field variables x and y. Solution is obtained from a system of equations, $f(x, y) = 0$ and $g(y, x) = 0$.

one-directional coupling $\Rightarrow$ hierarchical solution

$$\begin{aligned} & f(x_1) &= 0 \\ \Rightarrow \quad & g(y_1, x_1) &= 0 \end{aligned}$$

weak coupling $\Rightarrow$ iterative or segregated solution

$$\begin{cases} f(x_{m+1}, y_m) &= 0 \\ g(y_{m+1}, x_{m+1}) &= 0 \end{cases}$$

strong coupling $\Rightarrow$ monolithic solution

$$\begin{bmatrix} f(x_{m+1}, y_{m+1}) \\ g(y_{m+1}, x_{m+1}) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Monolithic approach requires iteration if either f or g is nonlinear.

Iterative vs. monolithic solution (analogy)

Let's assume that the equations are solved using Newton-Raphson iteration

Iterative solution

$$\begin{cases} f_x \, dx^{(m+1)} & = -f(x^{(m)}, y^{(m)}) \\ g_y \, dy^{(m+1)} & = -g(y^{(m)}, x^{(m+1)}) \end{cases}$$

Monolithic solution

$$\begin{bmatrix} f_x & f_y \\ g_x & g_y \end{bmatrix} \begin{bmatrix} dx^{(m+1)} \\ dy^{(m+1)} \end{bmatrix} = - \begin{bmatrix} f(x^{(m)}, y^{(m)}) \\ g(y^{(m)}, x^{(m)}) \end{bmatrix}$$

- If the coupling is weak ($|f_x||g_y| >> |f_y||g_x|$) the iteration method converges well
- The cross derivatives f_y and g_x may often be tricky determine. (for example, sensitivity of fluid flow to deformation)

Considerations on the iteration method

- Iteration method can easily be used when there are separate solvers for all equations
- Verification is straight-forward
  - Show consistancy (verify separate solvers) and reach convergence of coupled system
- Convergence may be poor
  - Under-relaxation may be used to improve convergence
  - Many new parameters to play with
- Often only conditionally stable (with respect to time-step)
- For simple equations it's much easier to design robust scalable methods
  - Multigrid

Considerations on the monolithic method

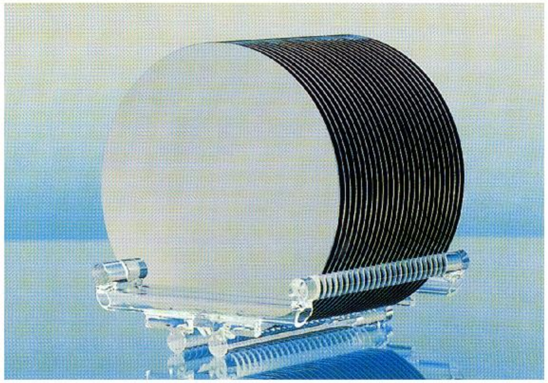
- Often difficult to implement
  - Implicit cross terms…
- Verification more tedious
- Ideal convergence
- Often real memory hogs
- Its difficult to find scalable linear algebra methods for the linear systems
  - Situation is manifested in parallel computing
  - Recent development: block preconditioners

Elmer - Multiphysics capabilities

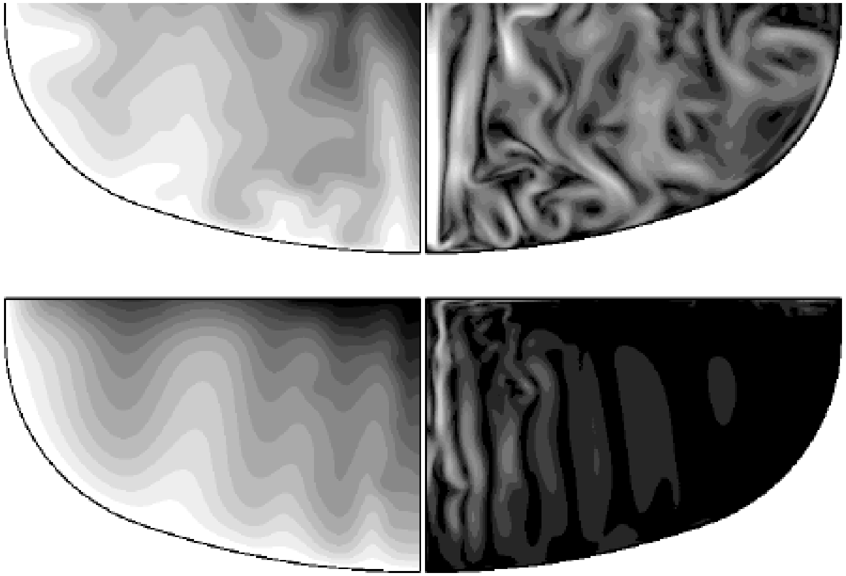
- About 20 different physical models
- Iteration method is mainly used
  - Consistancy of solution is ensured by nested iterations
- Monolithic approach is used for some inherently coupled problems
  - Linearized time-harmonic Navier-Stokes
- For some special problems using iterative coupling convergence has been improved by consistant manipulation of the equations
  - Fluid-structure interaction
  - Pull-in analysis
- High level of abstraction ensures flexibility in implementation and simulation
  - Each model is an external module with standard interfaces to the main program
  - All models may basically be coupled in any way
  - Different models may occupy different computational domains
  - Different models may use different meshes and the results are mapped between them

Czockralski Crystal Growth

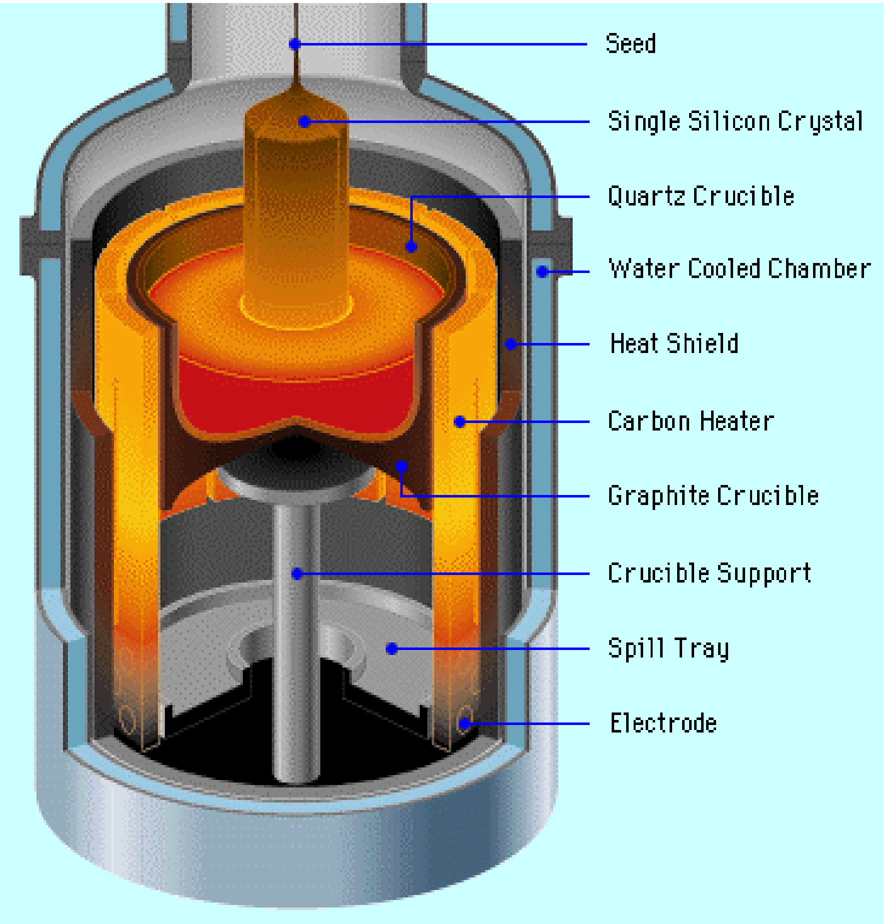
- Most crystalline silicon is grown by the Czhockralski (CZ) method
- One of the key application when Elmer development was started in 1995



Figures by Okmetic Ltd.



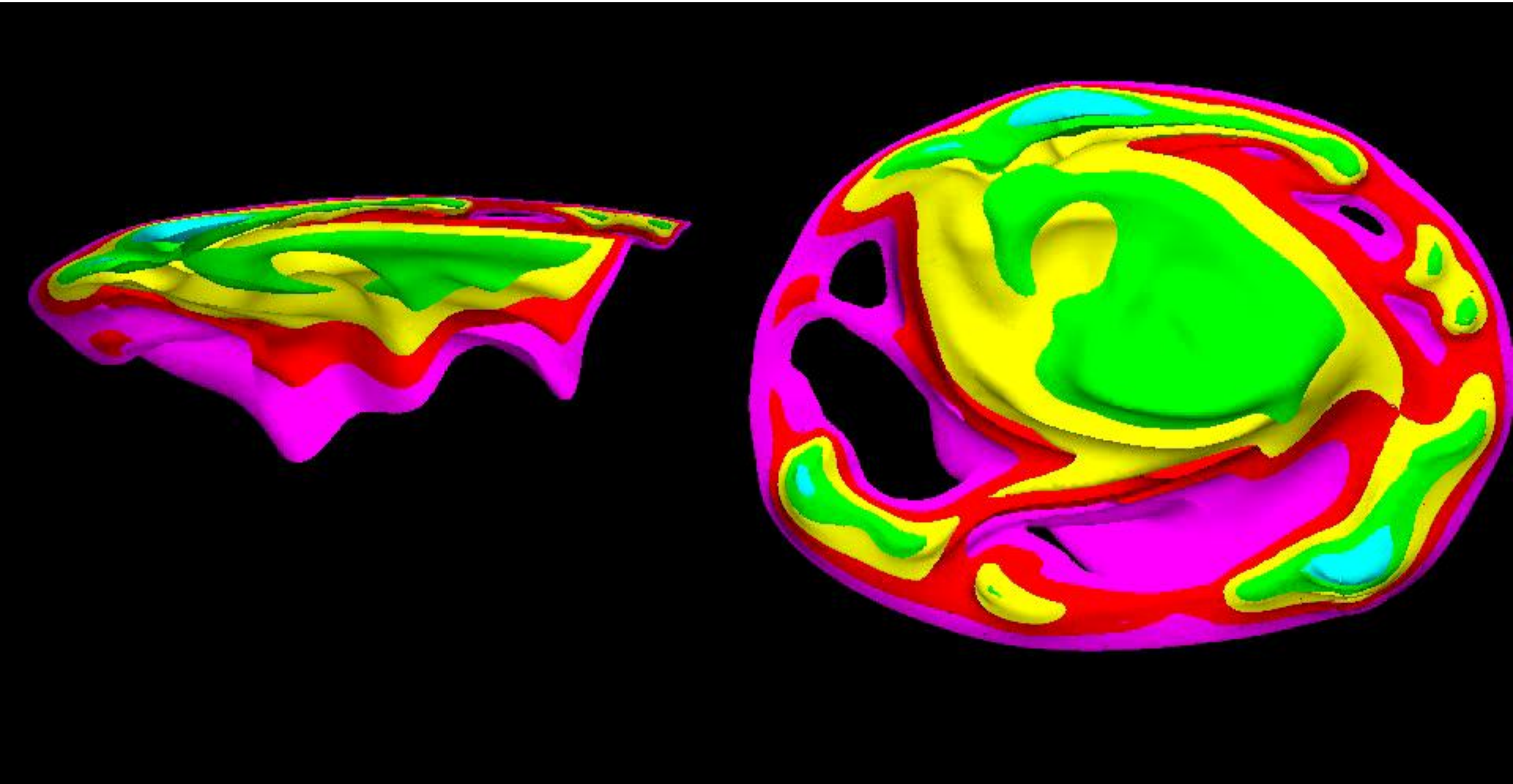
V. Savolainen et al., *Simulation of large-scale silicon melt flow in magnetic Czochralski growth,* J. Crystal Growth 243 (2002), 243-260.



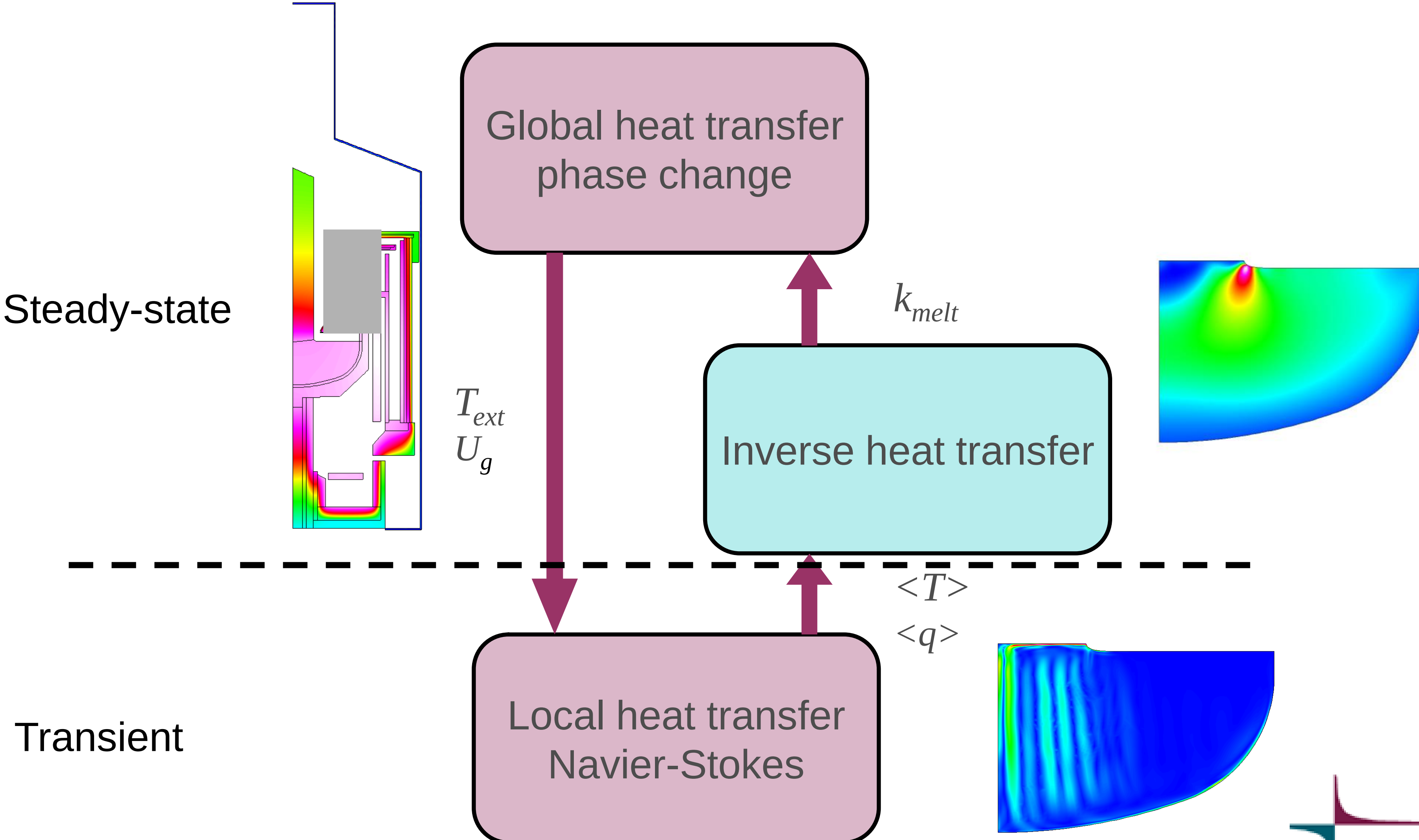
CZ-growth: Transient simulation

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

Simulation Juha Ruokolainen, animation Matti Gröhn, CSC



Multi-scale algorithm for Cz growth



Motivation for multi-scale approach

- The primary point of interest is the shape of the growth interface
  - The most relevant piece of information available
- The growth interface is a result of many time-scales
  - Global heat transfer has a time-scale of ~1h
  - Local velocity fluctuations have a stable time-scale of <1s
- Robust heating control only available in steady-state
  - In transient cases melting point is set
- Velocity fluctuations may not be accurately modeled with RANS models
  - Typically only a few convection rolls present

- We strive to combine the steady-state global heat transfer with ensamble averaged transient melt flow
  - **Multi-scale approach**

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

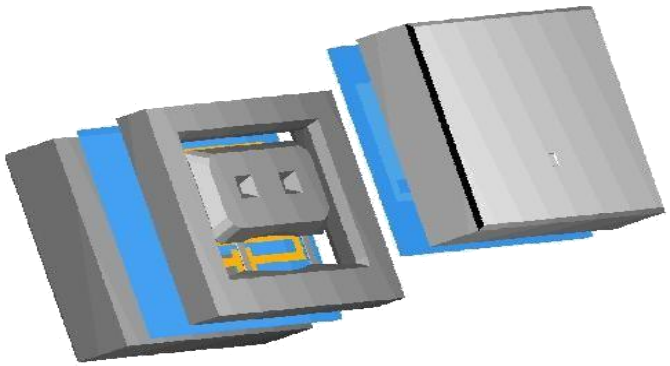
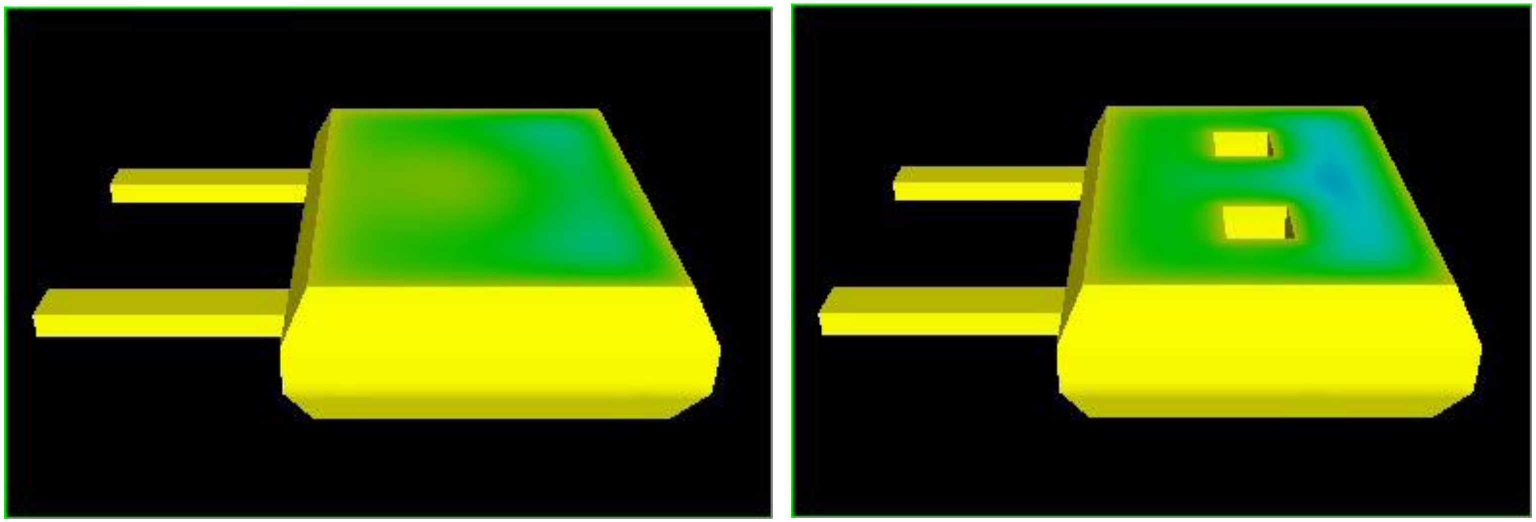


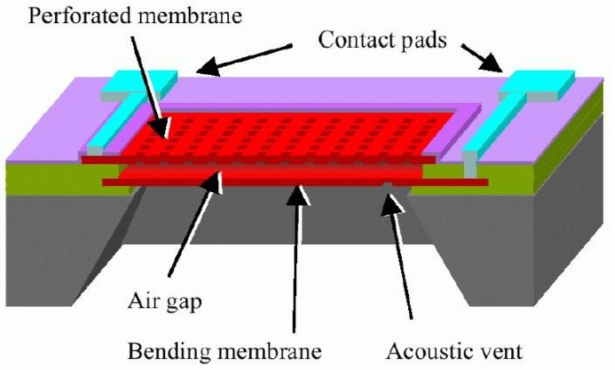
Figure by VTI Technologies

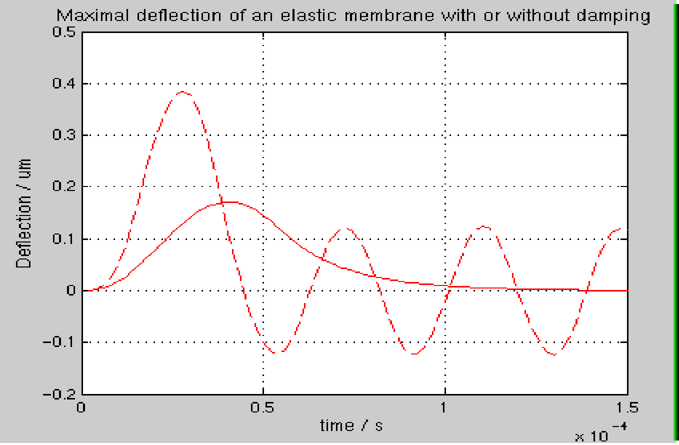


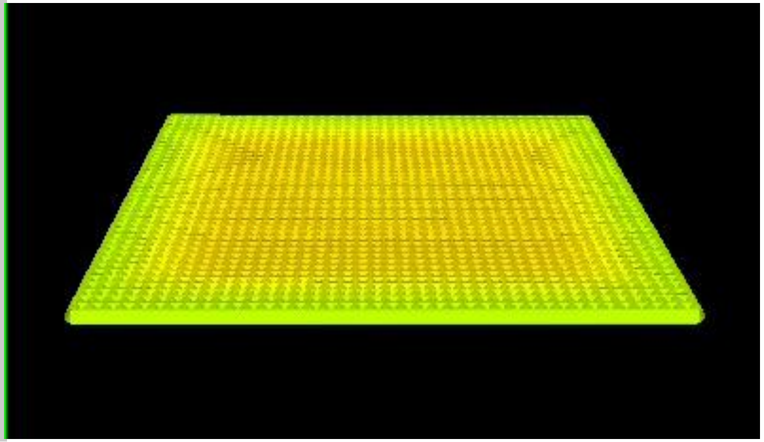
A. Pursula, P. Råback, S. Lähteenmäki and J. Lahdenperä, *Coupled FEM simulations of accelerometers including nonlinear gas damping with comparison to measurements*, J. Micromech. Microeng. **16** (2006), 2345-2354.

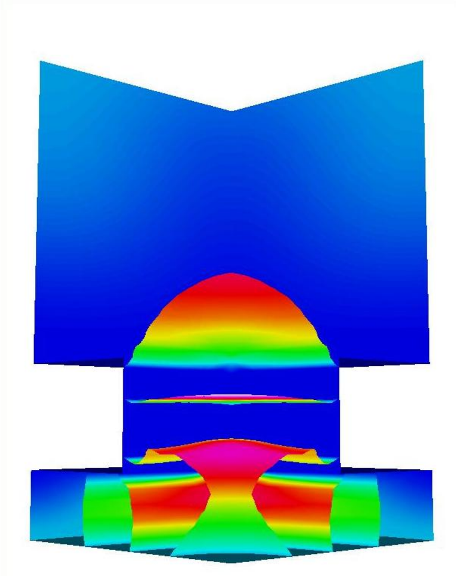
MEMS: Microphone membrane

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





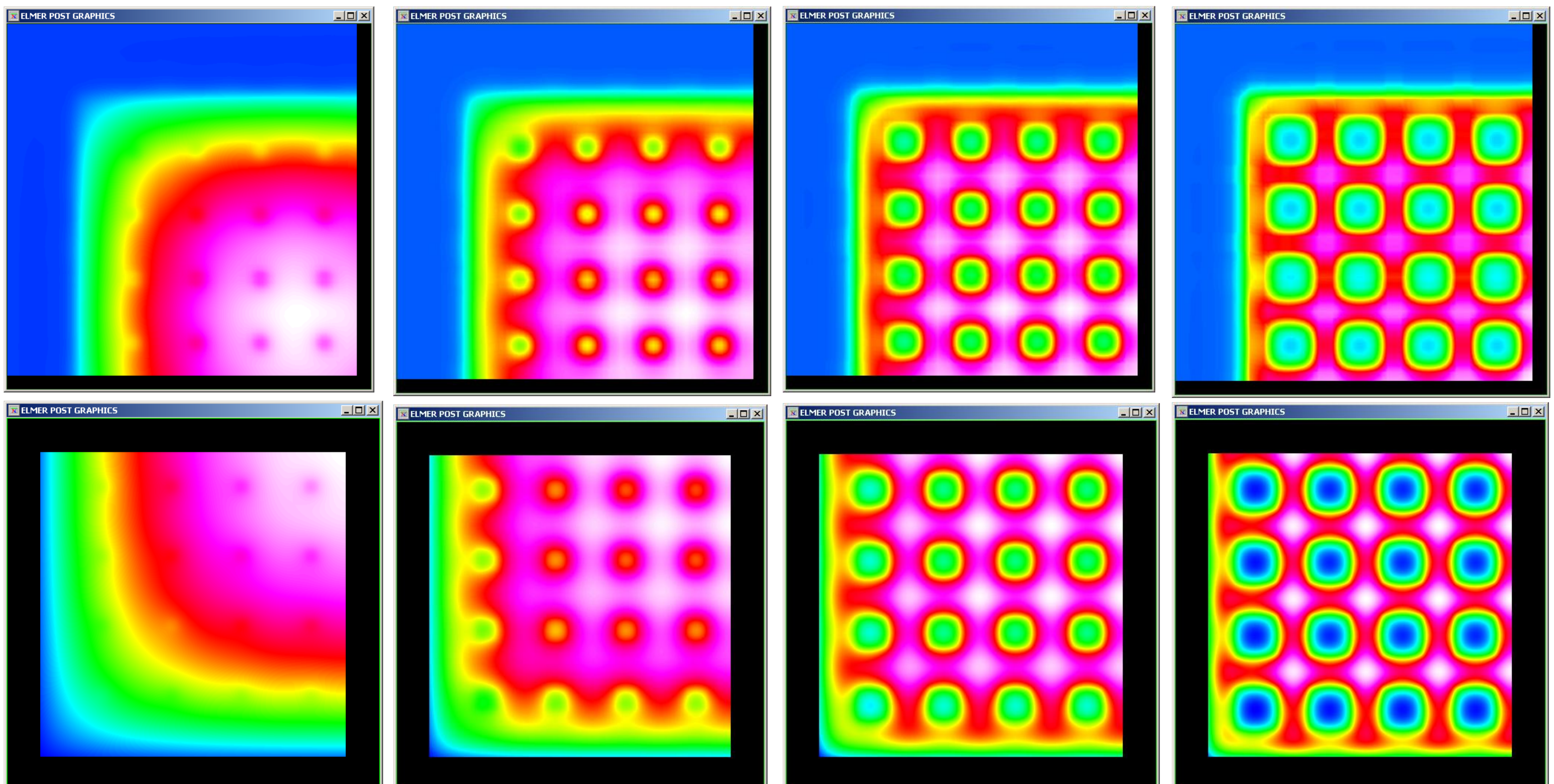




P. Råback et al., *Hierarchial finite element simulation of perforated plates with arbitrary hole geometries*, MSM 2003.

MEMS – Perforated plates

- Modified Reynolds equations may be used to model squeezed film pressure under perforated plates
- Comparison with very heavy 3D computations show good agreement (see figure)

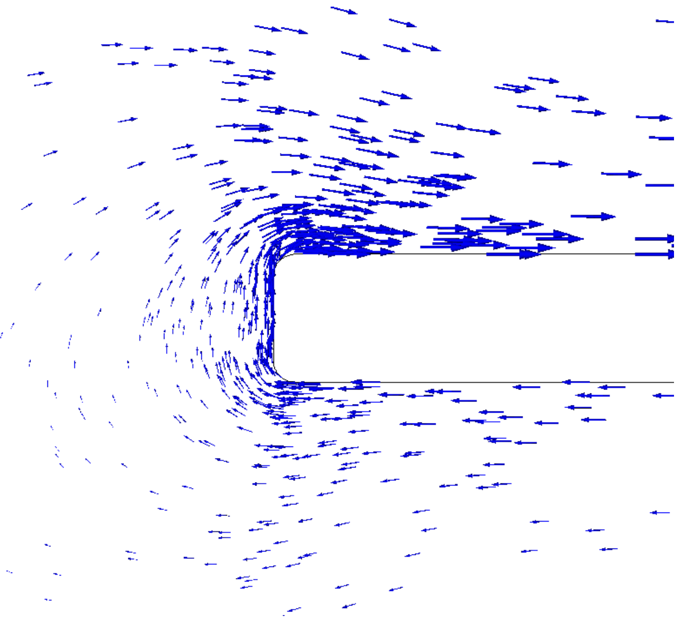


Thermal creep in light mills

- Glass container in a very low pressure < 10 Pa
- Each ving has a black and silver side
- When hit by light the light mill rotates with silver side ahead

- The physical explanation of the light mills requires consideration of rarefied gases and thermal creep
- These were studied in the thesis project of Moritz Nadler, University of Tubingen, 2008

Thermal creep in light mills



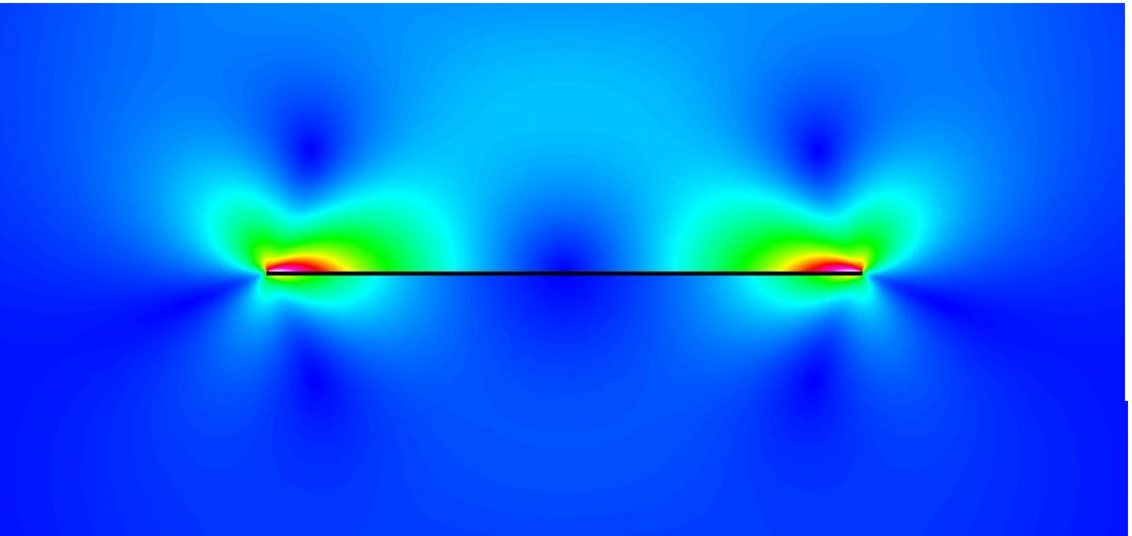
2D compressible Navier-Stokes eq. with heat eq. plus two rarefied gas effects:

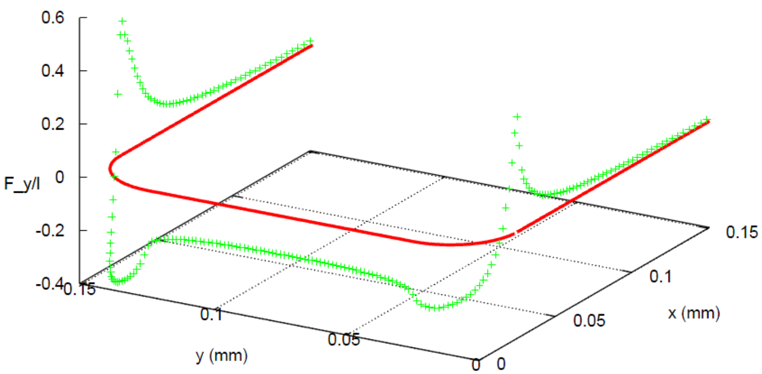
- Maxwell's wall slip and thermal transpiration

$$u_x(\Gamma) = \frac{2-\sigma}{\sigma}\lambda\left(\frac{\partial u_x}{\partial n} + \frac{\partial u_n}{\partial x}\right) + \frac{3\mu}{4\rho T}\frac{\partial T}{\partial x}$$

- Smoluchowski's temperature jump

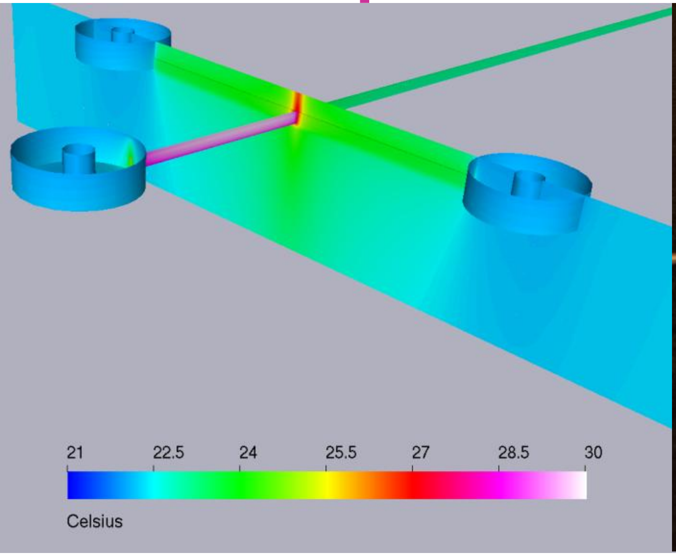
$$T_G - T_W = \frac{2-\sigma_T}{\sigma_T}\frac{2\gamma}{\gamma+1}\frac{\lambda}{Pr}\frac{\partial T}{\partial n}$$

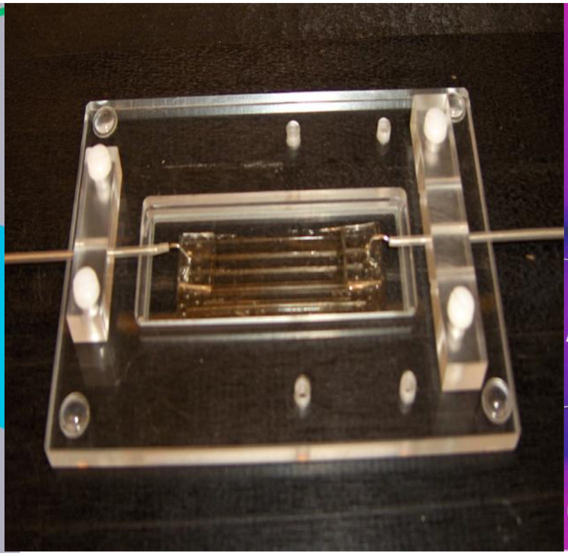


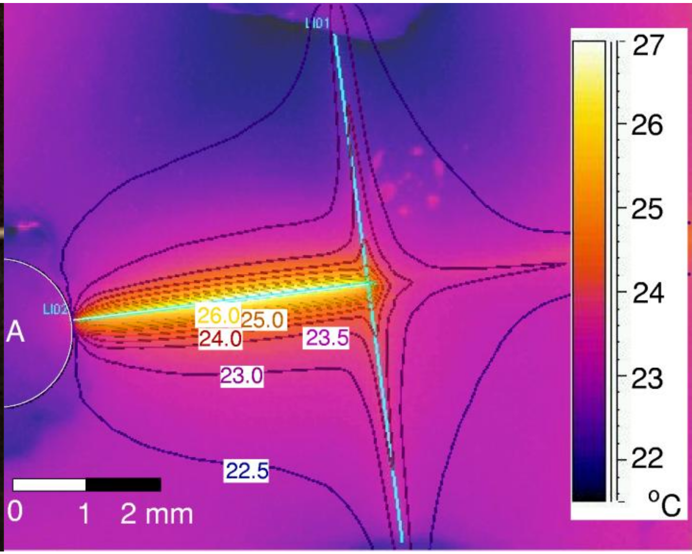


Simulation Moritz Nadler, 2008

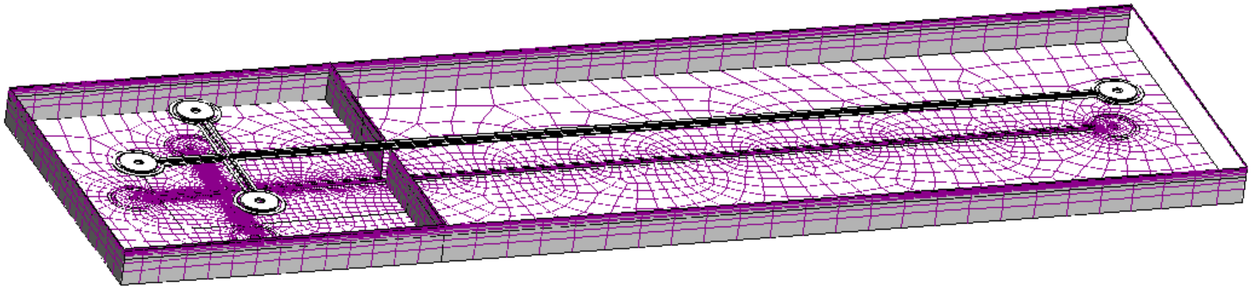
Microfluidics: Flow and heat transfer in a microchip







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

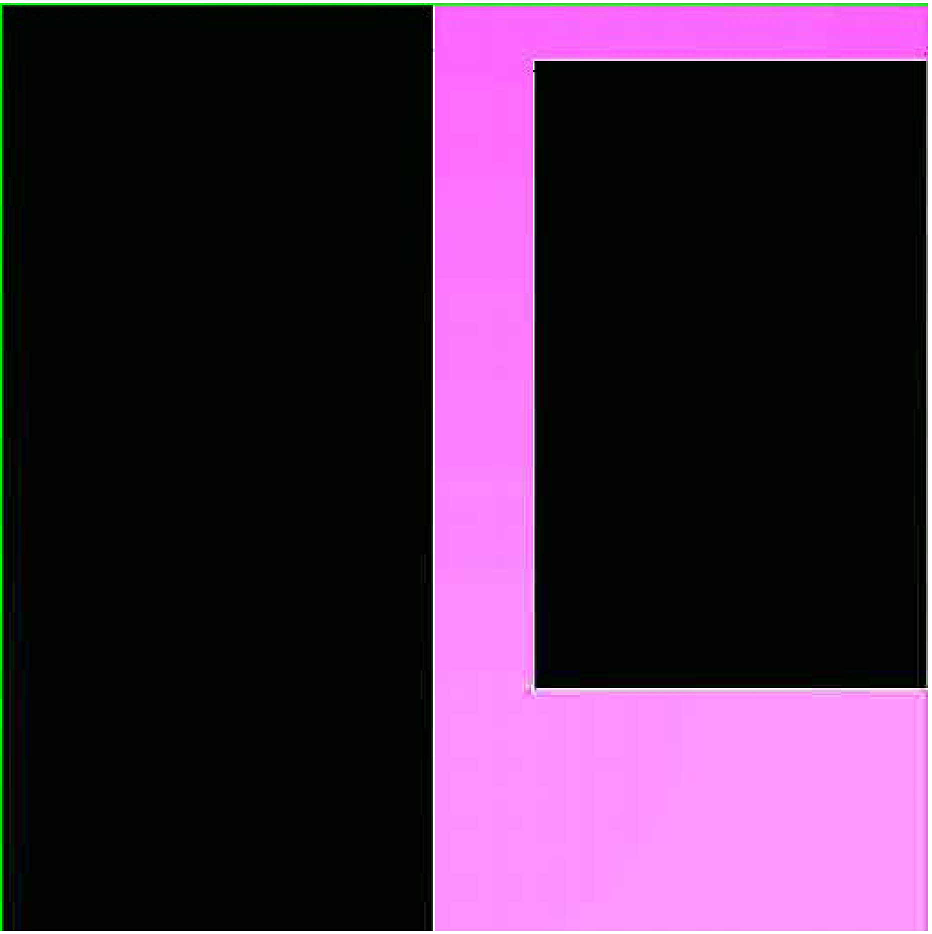


T. Sikanen, T. Zwinger, S. Tuomikoski, S. Franssila, R. Lehtiniemi, C.-M. Fager, T. Kotiaho and A. Pursula, Microfluidics and Nanofluidics (2008)

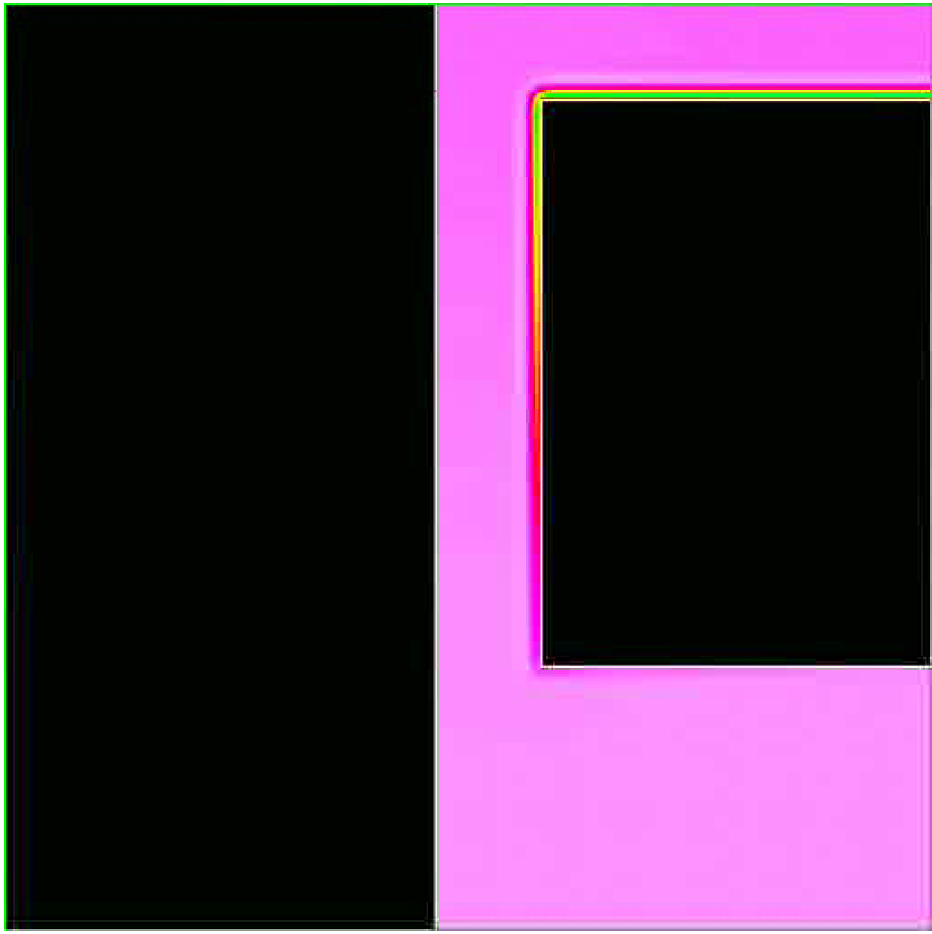
CSC

Acoustics: Losses in small cavities

Temperature waves resulting from the Helmholtz equation



Temperature waves computed from the linearized Navier-Stokes equation

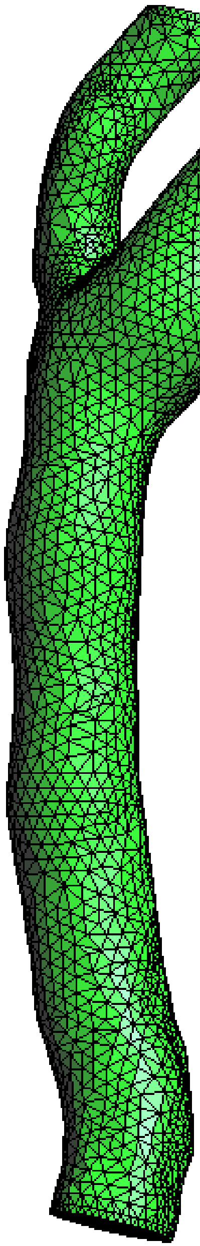


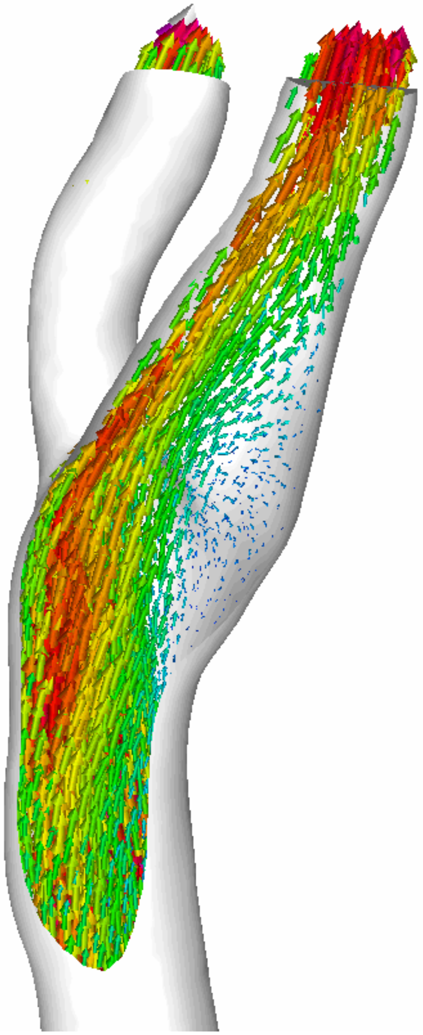
M. Malinen, *Boundary conditions in the Schur complement preconditioning of dissipative acoustic equations*, SIAM J. Sci. Comput. 29 (2007)

CSC

Computational Hemodynamics

- 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

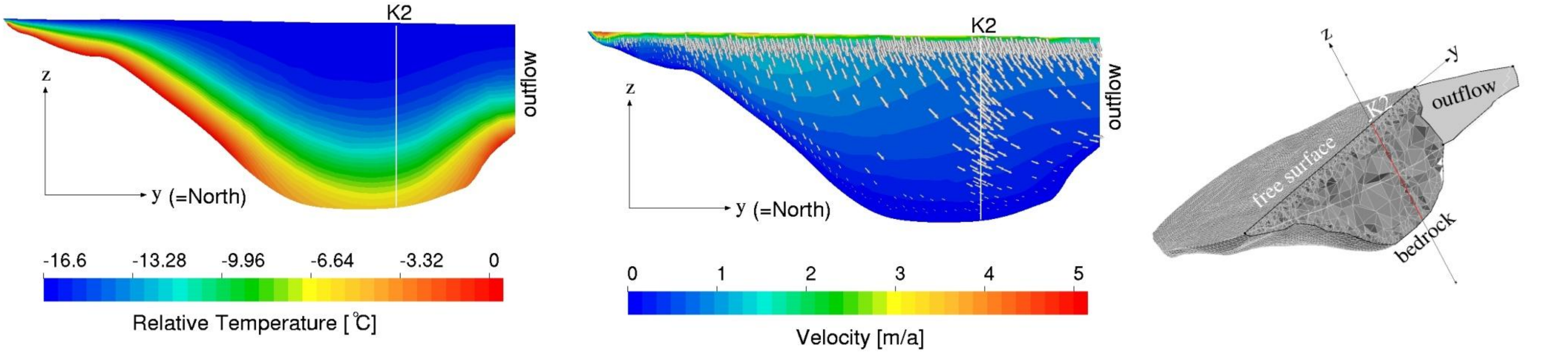


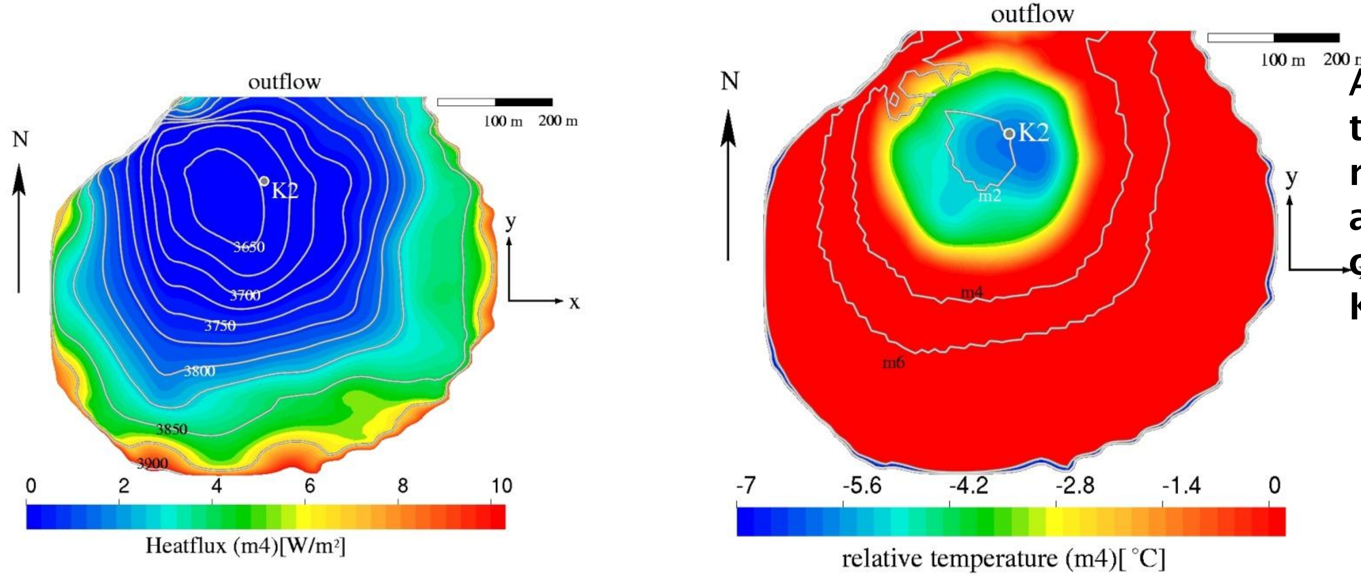


Blood flow in carotid artery accounting FSI interaction

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

Glaciology: 3D Stokes of glaciers





A full Stokes-flow thermo-mechanical model for firn and ice applied to the Gorshkov crater glacier, Kamchatka

Zwinger, Greve, Gagliardini, Shiraiwa and Lyly
Annals of Glaciology **45** (2007)

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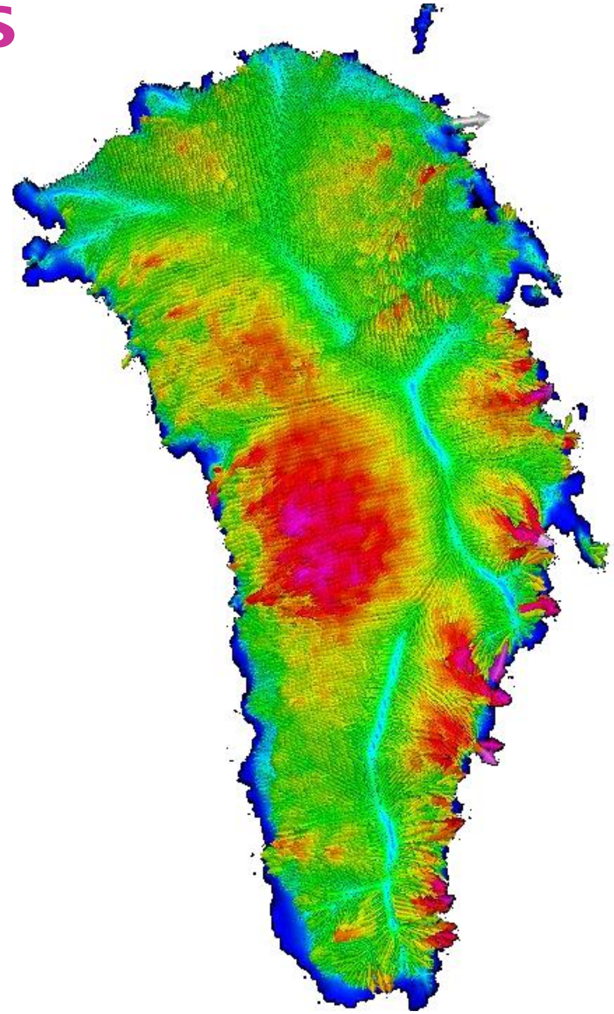
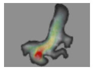
Glaciology: Grand challenges

- Elmer uses full Stokes equation to model the flow of ice
- Currently the mostly used tool in the area
  - British Antarctic Survey
  - University of Grenoble
  - University of Sapporo
- Simulations of continental ice sheets very demanding
- Global warming makes the simulations very important

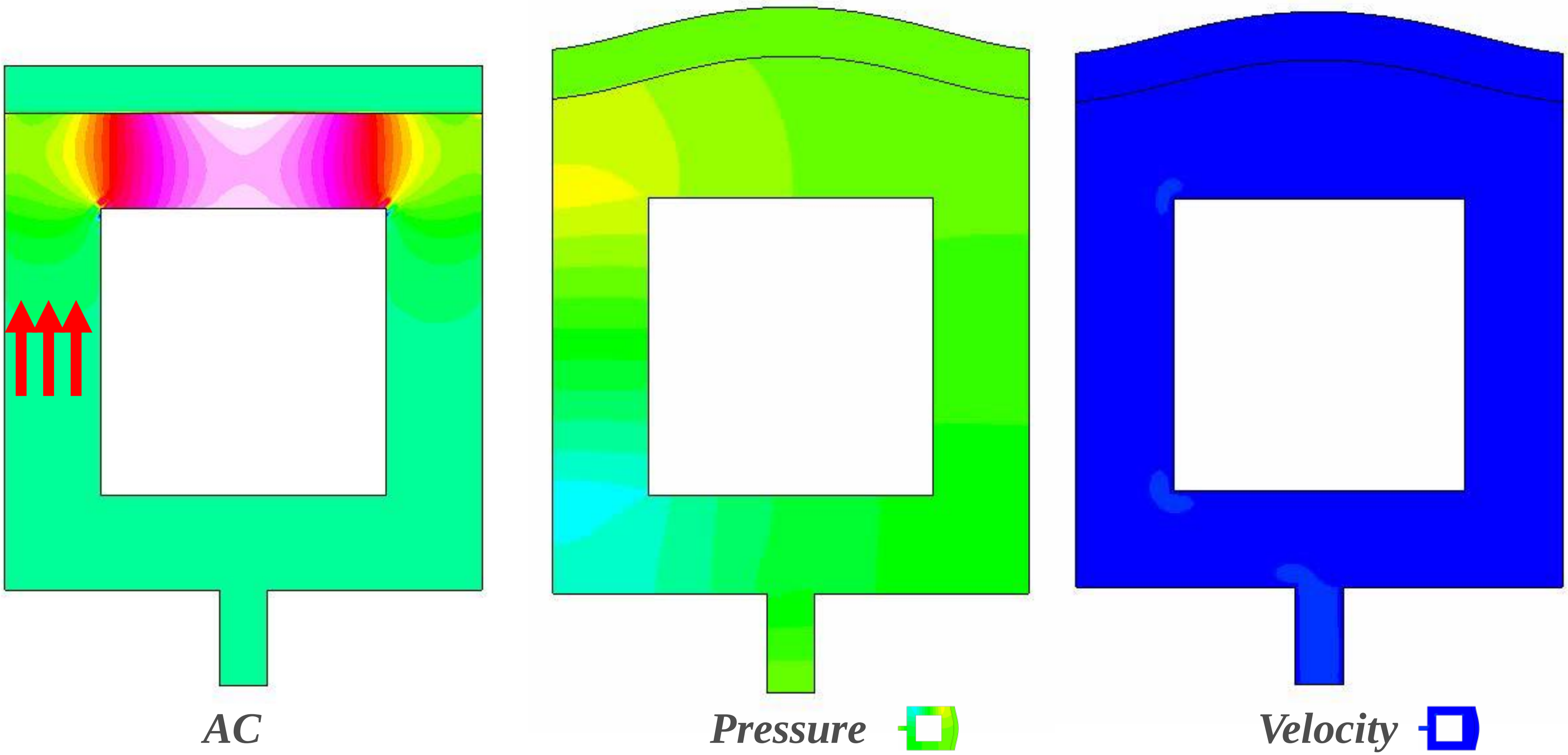




Simulation T. Zwinger, CSC

FSI with artifical compressibility

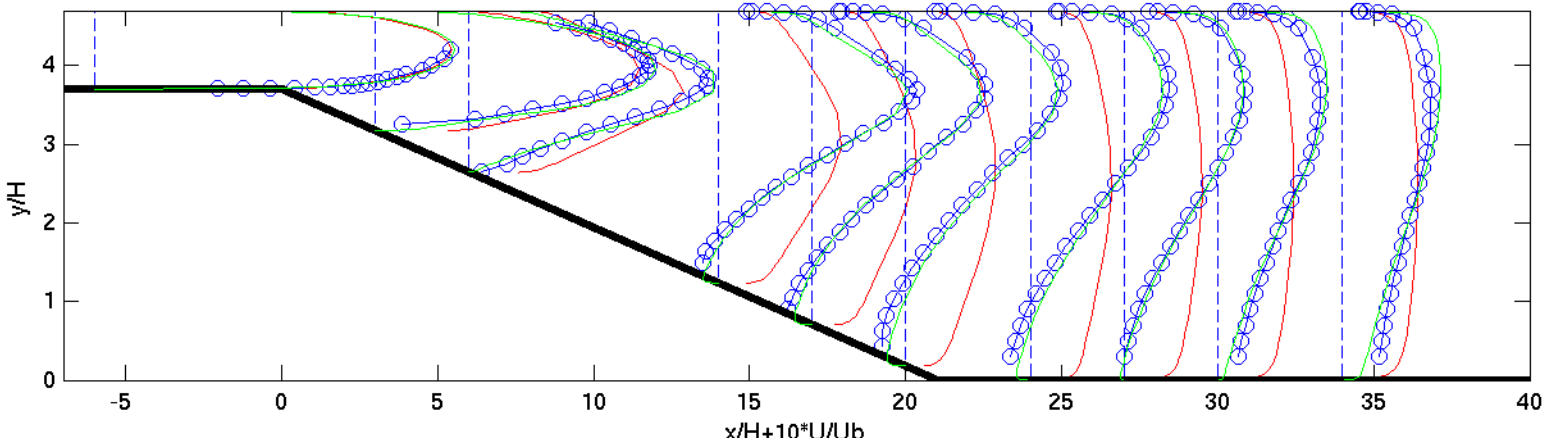
- Flow is initiated by a constant body force at the left channel
- Natural boundary condition is used to allow change in mass balance
- An optinmal artificial compressibility field is used to speed up the convergence of loosely coupled FSI iteration



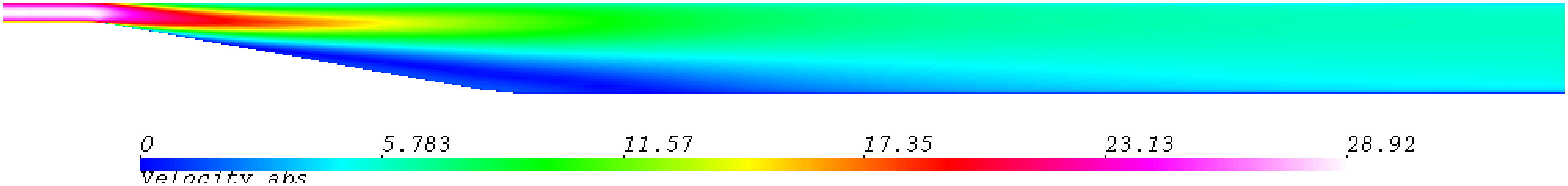
P. Råback, E. Järvinen, J. Ruokolainen, *Computing the Artificial Compressibility Field for Partitioned Fluid-Structure Interaction Simulations*, ECCOMAS 2008

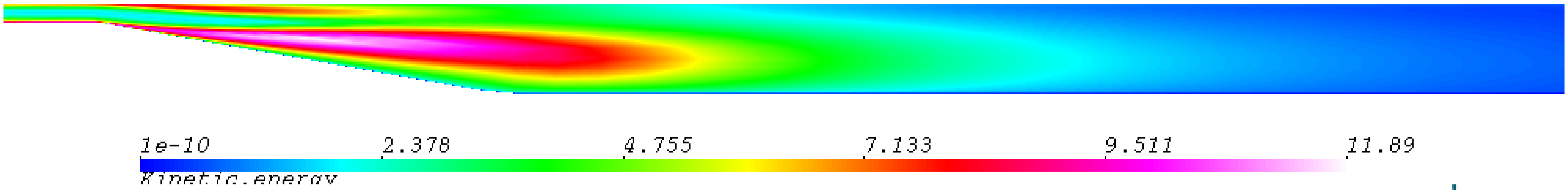
RANS turbulence modeling

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



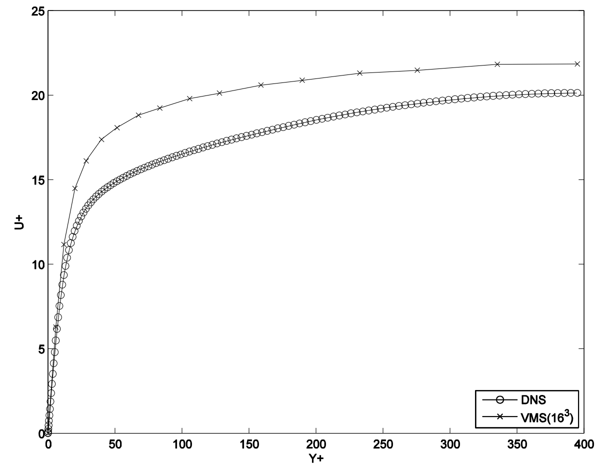
Simulation J. Ruokolainen, CSC



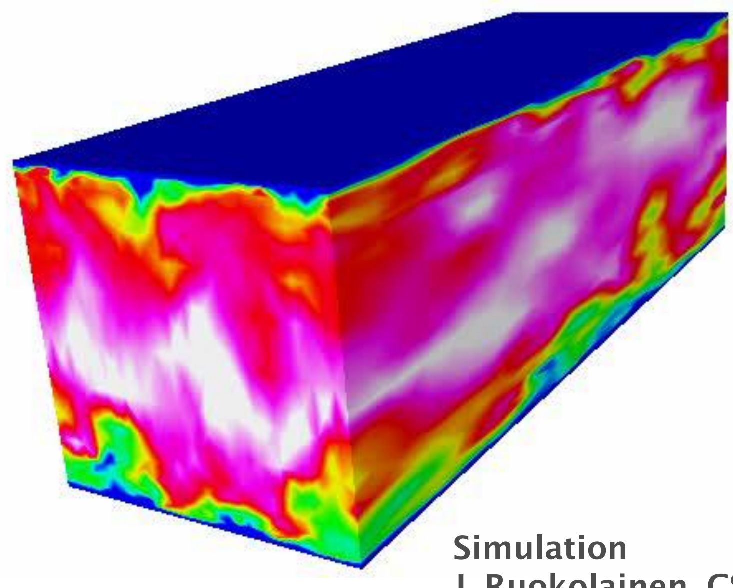


VMS turbulence modeling

- 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

VMS – Kelvin-Helmholtz instability

- Instability occuring between flow layers
- Animation shows the development of the instability
- Computations carred out with the VMS model of Elmer
- Animation with two interfaces:

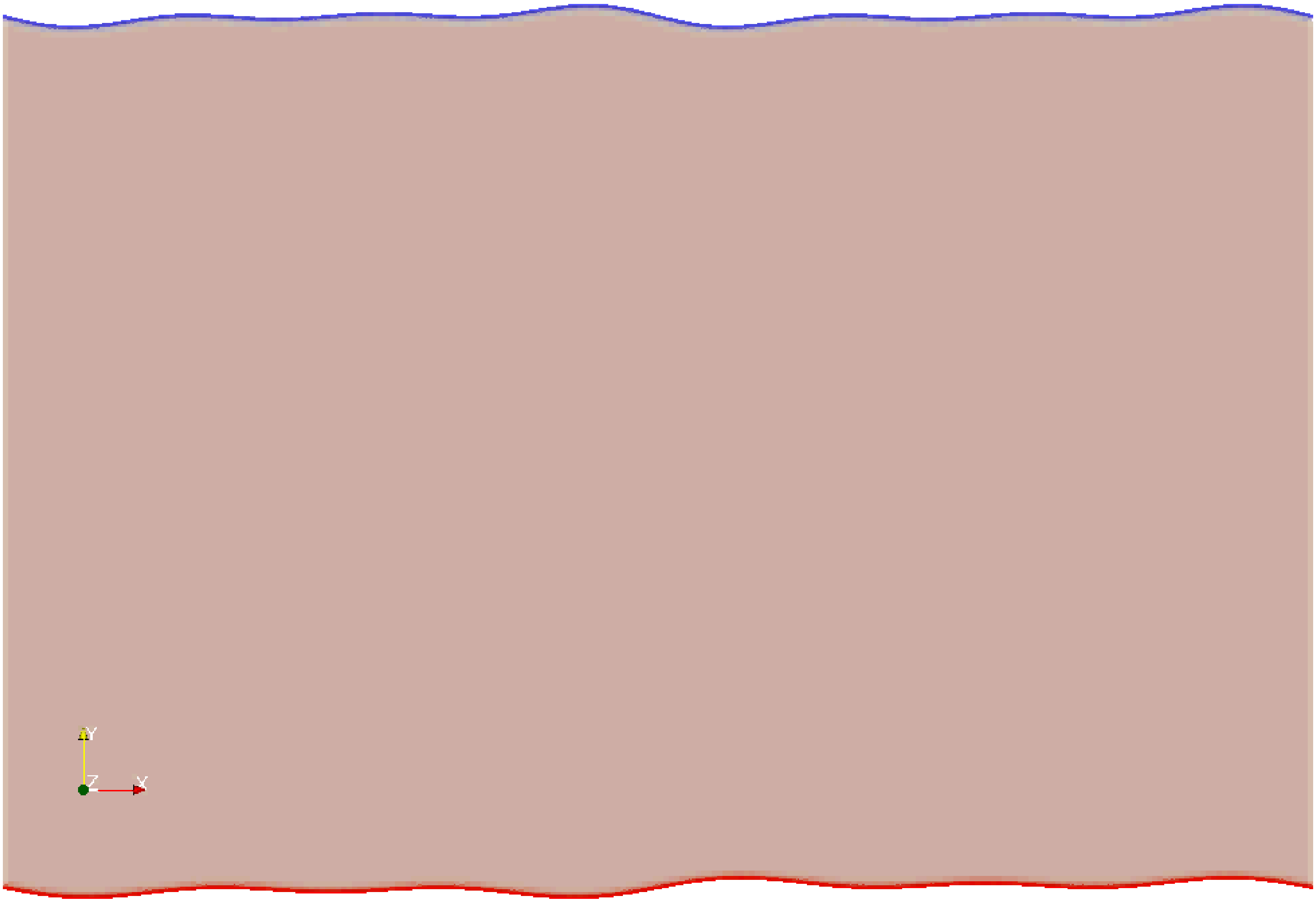
Simulation
J. Ruokolainen, CSC

CSC

VMS – Rayleigh-Benard convection

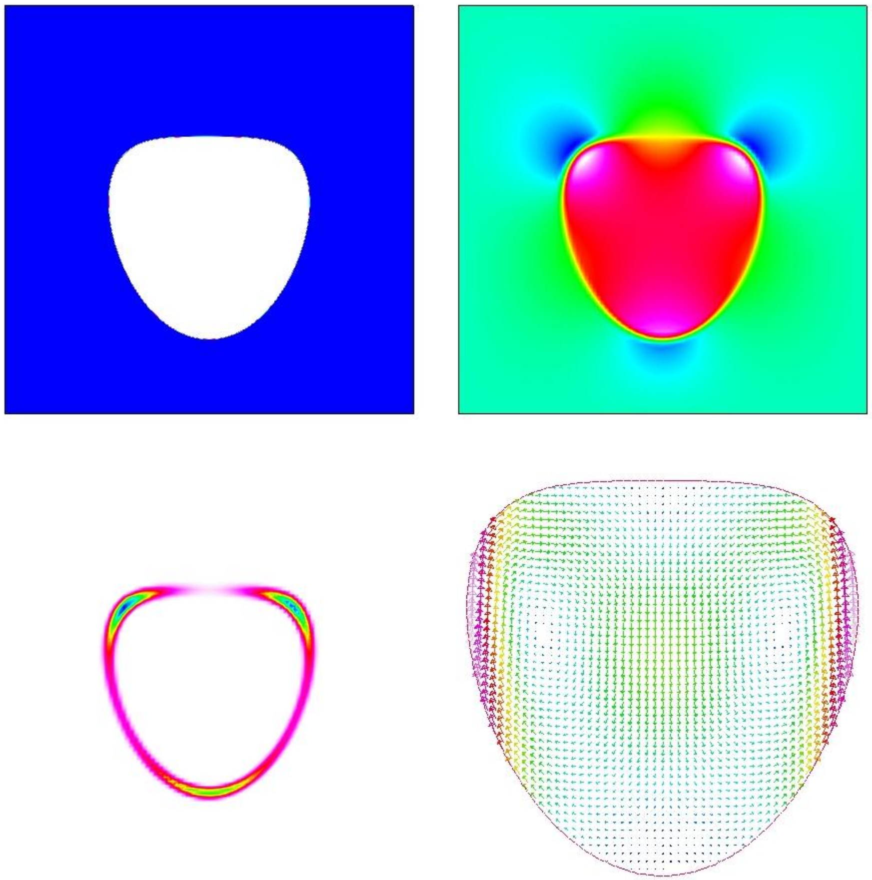
- Instability initiated by a temperature difference
- Number of convection rolls is defined by the Rayleigh number
- With high enough Rayleigh numbers the flow is fully chaotic

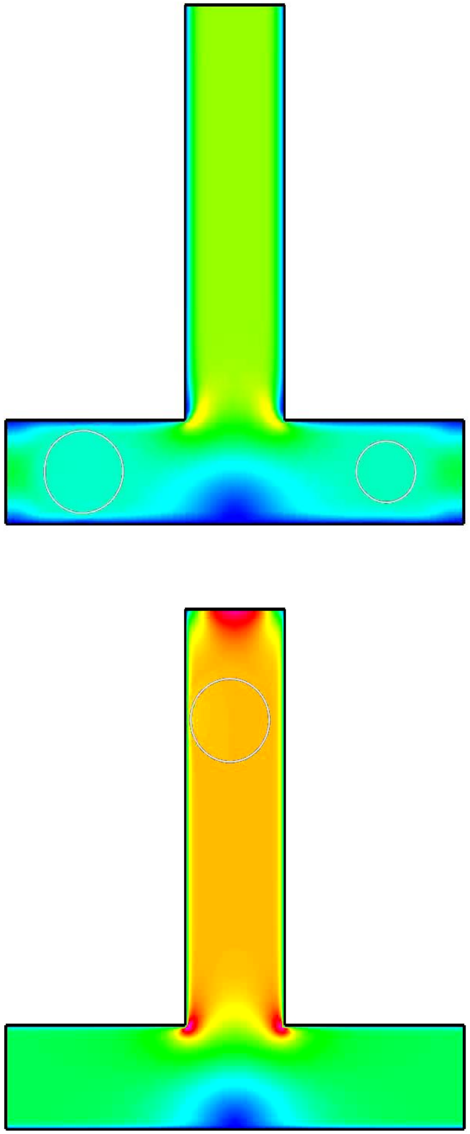
VMS - Rayleigh-Benard convection



Levelset method

- 2D levelset of a falling bubble





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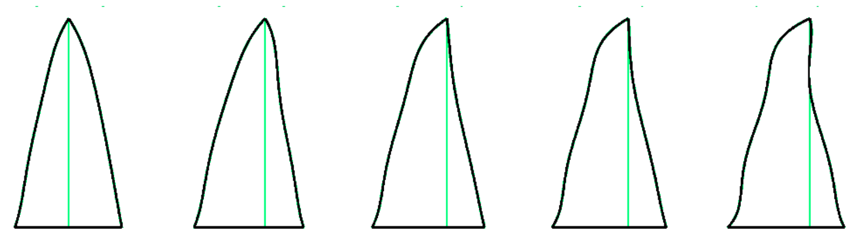
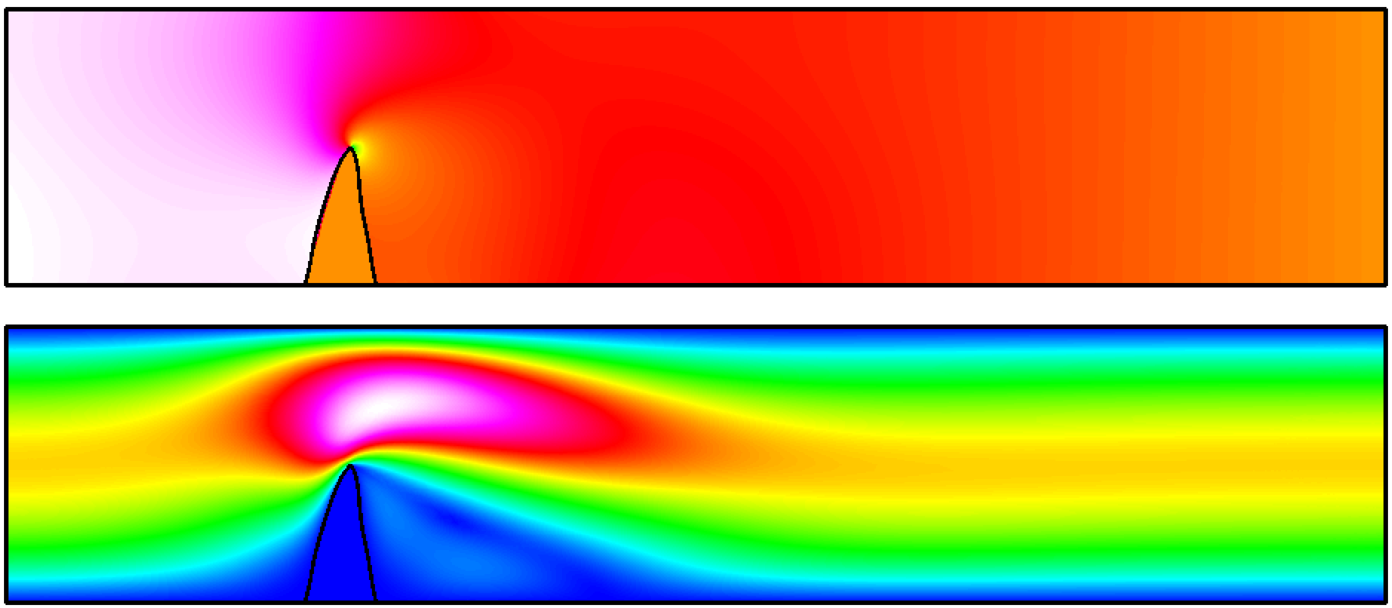
Optimization in FSI

- 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}

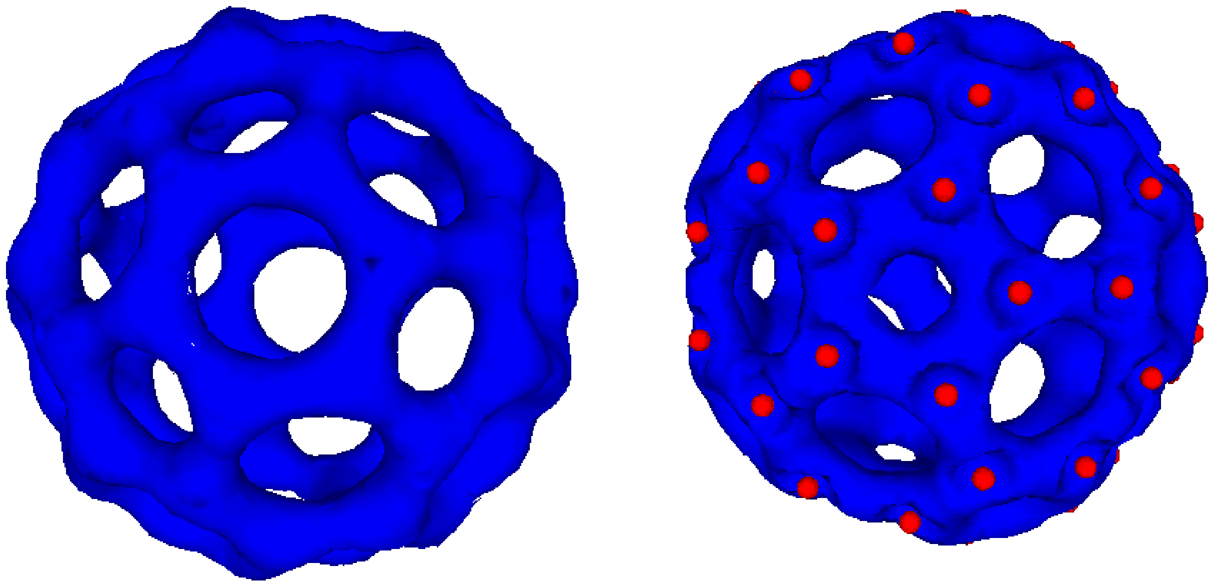


Pressure and velocity distribution with Re=10

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

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
- Mikko.Lyly@csc.fi & Peter.Raback@csc.fi
  - Finnish university customers get the best support

Thank you for your attention!