Elmer
Open Source Finite Element Software for Multiphysical Problems

ElmerTeam
CSC – IT Center for Science

Elmer course
CSC, 1.-2.6.2017
What is CSC?

- Founded in 1971 as a technical support unit for Univac 1108
- Connected Finland to the Internet in 1988
- Owned by the Universities and Ministry of Education and Culture of Finland
- Offers IT resources for research, education, culture and administration
- Operates on a non-profit principle
- Facilities in Espoo, close to Otaniemi campus and Kajaani
- Staff ~300
- Currently official name is: "CSC – IT Center for Science"
CSC’s Services

Scientific Computing and Software

FUNET Network Services

Identity and Access Management

Training services

Research Information Management

Education Management and Student Administration Services

Datacenter and Capacity Services

Consultation and Tailored Solutions
Support in All Phases of Research Process

Plan
- Customer
- Portal
- Experts
- Guides
- Websites
- Training
- Service Desk

Produce & Collect
- Data
- International resources
- Modelling
- Software
- Supercomputers

Analyse
- Cloud Services
- Training
- Data science
- Computing
- Software

Store
- B2SAFE
- B2SHARE
- HPC Archive
- IDA
- Databases
- Research long-term preservation (LTP)

Share & Publish
- AVAA
- B2DROP
- B2SHARE
- Databank
- Etsin
- Funet FileSender
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</table>

>4PB, ~ 100GB/s

Storage services
In 2015: About 2700 active users
Elmer finite element software for multiphysical problems

Figures by Esko Järvinen, Mikko Lyly, Peter Råback, Timo Veijola (TKK) & Thomas Zwinger
Some Pros and Cons of Finite Element Method

- Applicable to **arbitrary shapes**
  - #1 method in engineering
- Non-uniform mesh refinement
- Based on variational principle
  - Approaches functional to be minimized from above
  - **Monotonic convergence** with mesh size parameter
- Suited for all kinds of PDEs
  - Elliptic, hyperbolic, parabolic
- Natural treatment of BCs
- Vast mathematical literature supports the method

- For problems without "shape" and uniform meshes the additional cost of FEM may not be well motivated
  - Indirect memory addressing of sparse matrices
- More complex machinery may take focus from the real problem
  - Mesh generation, involved mathematics, bigger codes, more complex data structures etc.
Short history of Elmer

- 1995 Elmer development was started as part of a national CFD program
  - Collaboration of CSC, TKK, VTT, JyU, and Okmetic Ltd.
- 2000 After the initial phase the development driven by number of application projects
  - MEMS, Microfluidics, Acoustics, Crystal Growth, Hemodynamics, Glaciology, Electromagnetics,...
- 2005 Elmer published under GPL-license
- 2007 Elmer version control put under sourceforge.net
  - Resulted to a rapid increase in the number of users
- 2010 Elmer became one of the central codes in PRACE project
- 2012 ElmerSolver library published under LGPL
  - More freedom for serious developers
Developers of Elmer

Current developers at CSC

- Core Elmer team: Mika Malinen, Juha Ruokolainen, Peter Råback, Thomas Zwinger, Juhani Kataja

Other/past developers & contributors

- CSC: Mikko Lyly, Mikko Byckling, Sampo Sillanpää, Jussi Heikonen, Esko Järvinen, Jari Järvinen, Antti Pursula, Ville Savolainen, Sami Ilvonen, Erik Edelmann
- VTT: Pavel Ponomarev, Janne Keränen, Paul Klinge, Martti Verho
- TKK: Jouni Malinen, Harri Hakula, Mika Juntunen
- Trafotek: Eelis Takala
- LGGE: Olivier Gagliardini, Fabien Gillet-Chaulet,
- University of Uppsala: Jonas Thies, Josefin Ahlkrona
- etc... (if your name is missing, please ask it to be added)
Elmer in numbers (11/2015)

Software
- ~400,000 lines of active code
  - ~3/4 in Fortran, 1/4 in C/C++
- ~540 consistency tests
- ~750 pages of documentation
- ~1000 code commits yearly

Community
- ~20,000 downloads for Windows binary yearly
- ~2000 forum postings yearly
- ~100 people participate on Elmer courses in yearly
- Several Elmer related scientific visits to CSC yearly
Elmer is published under (L)GPL

- Used worldwide by thousands of researchers (?)
- One of the most popular open source multiphysical software
~20k Windows downloads at sf.net in a year

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Elmer finite element software

- **Elmer** is actually a suite of several programs
- Some components may also be used independently
- **ElmerGUI** – Preprocessing
- **ElmerSolver** – FEM Solution
  - Each physical equation is a *dynamically loaded* library to the main program
- **ElmerGrid** – structured meshing, mesh import & partitioning
- **ElmerPost** - Postprocessing
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 built-in postprocessing with ElmerVTK
**ElmerGrid**

- Creation of 2D and 3D structured meshes
  - Rectangular basic topology
  - Extrusion, rotation
  - Simple mapping algorithms

- Mesh Import
  - About ten different formats:
    - Ansys, Abaqus, Fidap, Comsol, Gmsh,...
  - Gmsh import example:
    ```
    >ElmerGrid 14 2 mesh.msh -autoclean
    ```

- Mesh manipulation
  - Increase/decrease order
  - Scale, rotate, translate

- Partitioning
  - Simple geometry based partitioning
  - Metis partitioning example:
    ```
    >ElmerGrid 1 2 step.grd -metis 10
    ```

- Usable via ElmerGUI
  - All features not accessible (e.g. partitioning)
Assembly and solution of the finite element equations and beyond

Large number of auxiliary routines

Note: When we talk of Elmer we mainly mean ElmerSolver

\rm raback@hippu4:/fs/elmer/elmerfem/fem/tests/heateq> \texttt{ElmerSolver}

\texttt{ELMER SOLVER (v 7.0) STARTED AT: 2014/10/15 18:44:51}

\texttt{MAIN:}
\texttt{MAIN: ElmerSolver finite element software, Welcome!}
\texttt{MAIN: This program is free software licensed under (L)GPL}
\texttt{MAIN: Copyright 1st April 1995 , CSC - IT Center for Science Ltd.}
\texttt{MAIN: Webpage http://www.csc.fi/elmer, Email elmeradm@csc.fi}
\texttt{MAIN: Library version: 7.0 (Rev: 6927M)}

\texttt{ELMER SOLVER FINISHED AT: 2014/10/15 18:44:52}
SERIAL WORKFLOW: VISUALIZATION
ElmerSolver – Finite element shapes

- 0D: vertex
- 1D: edge
- 2D: triangles, quadrilateral
- 3D: tetrahedrons, prisms, pyramids, hexahedrons
ElmerSolver – Finite element basis functions

- Element families
  - Nodal (up to 2-4th degree)
  - p-elements (up to 10th degree)
  - Edge & face –elements
    - $H(\text{div})$ - often associated with "face" elements
    - $H(\text{curl})$ - often associated with "edge" elements

- Formulations
  - Galerkin, Discontinuous Galerkin
  - Stabilization
  - Residual free bubbles
Mapping & Projectors

- For conforming and nonconforming meshes
- For boundary and bulk meshes
- On-the-fly interpolation (no matrix created)
  - Mapping of finite element data
    - from mesh to mesh
    - From boundary to boundary
  - Mapping of data between particles and finite elements
    - Finite element fields at particle locations
    - Particle data to nodal field values

Creation of interpolation and projection matrices

- Strong continuity, interpolation: $x_l = P x_r$
- Weak continuity, Mortar projector: $Q x_l - P x_r = 0$
ElmerSolver – Time dependency modes

- Steady-state simulation
- Transient simulation
  - 1st order PDEs:
    - Backward differences formulae (BDF) up to 6th degree
    - Newmark Beta (Cranck-Nicolsen with $\beta=0.5$)
    - 2nd order Runge-Kutta
    - Adaptive timestepping
  - 2nd order PDEs:
    - Bossak
- Harmonic simulation
- Eigenmode simulation
  - Utilizes (P)Arpack library
- Scanning
  - Special mode for parametric studies etc.
ElmerSolver – Linear solvers

- Iterative Krylov subspace methods
  - HUTiter library (part of Elmer)
  - Optional: Trilinos (Belos) & Hypre
- Multigrid methods
  - AMG (serial only) and GMG included in Elmer
  - Optional: Hypre/BoomerAMG and Trilinos/ML
- Preconditioners
  - ILU, BILU, multigrid, SGS, Jacobi, ...
  - Generic block preconditioning
  - Optional: Hypre (Parasails, ILU), Trilinos
- FETI
  - PCG+MUMPS
- Direct solvers
  - Lapack (banded), Umfpack
  - Optional: SuperLU, MUMPS, Pardiso
Application examples of Elmer
Poll on application fields (status 5/2017)

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<tr>
<th>Application Field</th>
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Total votes: 246
Elmer – Heat Transfer

- Heat equation
  - convection
  - diffusion
  - Phase change
  - Temperature control feedback
  - Thermal slip BCs for small Kn number

- Radiation with view factors
  - 2D, axisymmetric use numerical integration
  - 3D based on ray tracing
  - Stand-alone program

- Strongly coupled thermoelectric equation

- Associated numerical features
  - Steady state, transient
  - Stabilization, VMS
  - ALE

- Typical couplings
  - Mesh movement
  - Electricity - Joule heating
  - Fluid - convection

- Known limitations
  - Turbulence modeling not extensively validated
  - ViewFactor computation not possible in parallel
Microfluidics: Flow and heat transfer in a microchip

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

Elmer – Fluid Mechanics

- Navier-Stokes (2D & 3D)
  - Nonnewtonian models
  - Slip coefficients
- RANS turbulence models
  - SST $k-\Omega$
  - $k-\varepsilon$
  - $\nabla^2 f$
- Large eddy simulation (LES)
  - Variational multiscale method (VMS)
- Reynolds equation
  - Dimensionally reduced N-S equations for small gaps (1D & 2D)

Associated numerical features
- Steady-state, transient
- Stabilization
- ALE formulation

Typical couplings
- FSI
- Thermal flows (natural convection)
- Transport
- Free surface
- Particle tracker

Known limitations
- Only experimental segregated solvers, default solvers monolithic
- Stronger in the elliptic regime of N-S i.e. low Re numbers
- RANS models have often convergence issues
Czockralski Crystal Growth

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

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
Elmer in Crystal Growth Simulations

- Elmer has been used extensively in crystal growth simulations: These include crystal and tube growth for silicon, silicon-carbide, NiMnGa and sapphire in Czochralski, HTCVD, sublimation, Bridgman, Vertical Gradient Freeze and Heat Exchanger Methods.
- Numerical results have been successfully verified with experiments.
- Elmer is a part of open-source chain from CAD to visualization, and offers an access to parallelism and a number of simultaneous simulations important for industrial R&D.

Simulations Jari Järvinen, Silicom Oy, 2014
**Glaceology**

- **Elmer/Ice** is the leading software used in 3D computational glaciology
- Full 3D Stokes equation to model the flow
- Large number of tailored models to deal with the special problems
- Motivated by climate change and sea level rise
- Dedicated community portal [elmerice.elmerfem.org](http://elmerice.elmerfem.org)

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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

\[ T_G - T_W = \frac{2 - \sigma_T}{\sigma_T} \frac{2\gamma}{\gamma + 1} \frac{\lambda}{Pr} \frac{\partial T}{\partial n} \]
VMS turbulence modeling

- Variational multiscale method (VMS) by Hughes et al. is a variant of LES particularly suitable for FEM
Elmer – Solid mechanics

- Linear elasticity (2D & 3D)
  - Linear & orthotropic material law
  - Thermal and residual stresses
- Non-linear Elasticity (in geometry)
  (unisotropic, lin & nonlin)
  - Neo hookean material law
- Plate equation
  - Spring, damping
- Shell equation
  - Undocumented facet shell solver
  - new solver under development
- Some capabilities for contact mechanics

Associated numerical features
- Steady-state, harmonic, eigenmode
- Contact mechanics

Typical physical coupling
- Fluid-Structure interaction (FSI)
- Thermal stresses
- Source for acoustics

Known limitations
- Limited selection of material laws
- Generality of the contact mechanics
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

EHDL of patterned surfaces

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

Elmer – Electromagnetics

- **StatElecSolve for insulators**
  - Computation of capacitance matrix
  - Dielectric surfaces

- **StatCurrentSolve for conductors**
  - Computation of Joule heating
  - Feedback for desired heating power

- **Magnetic induction**
  - Induced magnetic field by moving conducting media (silicon)

- **MagnetoDynamics2D**
  - Applicable also to rotating machines

- **MagnetoDynamics3D**
  - Modern AV formulation utilizing edge-elements (1st and 2nd order)
  - Steady-state, harmonic, transient

- **VectorHelmholtzSolver**
  - Solver for the electromagnetics wave equation

- **Associated numerical features**
  - Mainly formulations based on scalar and vector potential
  - Lagrange elements except mixed nodal-edge elements for AV solver

- **Typical physical couplings**
  - Thermal (Joule heating)
  - Flow (plasma)
  - Electromechanics

- **Known limitations**
  - One needs to be weary with the Coulomb gauge in some solvers
Simulation of electrical machines

- New developments enable simulation of electrical machines
- Partners: ABB, CSC, Ingersoll-Rand, Kone, Konecranes, Skanveir, Sulzer, Trafotek, Aalto University, LUT, TUT, VTT, (Kuava)
Modeling of magnetic losses in transformers

Simulation by Eelis Takala, Trafotek, Finland, 2014
Elmer – Acoustics

- Helmholtz Solver
  - Possibility to account for convection
- Linearized time-harmonic Navier-Stokes
  - Special equation for the dissipative acoustics
- Thermal Navier-Stokes
  - Ideal gas law
  - Propagation of large amplitude acoustic signals

- Associated numerical features
  - Bubble stabilization
- Typical physical couplings
  - Structural (vibroacoustics)

- Known limitations
  - Limited to small wave numbers
  - N-S equations are quite computationally intensive
Acoustics: Losses in small cavities

Temperature waves resulting from the Helmholtz equation

Temperature waves computed from the linearized Navier-Stokes equation

Richard’s equation

- Richards equations describes the flow of water in the ground
- Porous flow of variably saturated flow
- Modeled with the van Genuchten material models
- Picture show isolines for pressure head and magnitude of the Darcy flux
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 fullerene C60
- All electron computations using 300,000 quadratic tets and 400,000 dofs

Simulation Mikko Lyly, CSC, 2006
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, CSC
Elmer – Selected multiphysics features

Solver is an abstract dynamically loaded object
- Solver may be developed and compiled without touching the main library
- No upper limit to the number of Solvers (Currently ~50)

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)
Solution strategies for coupled problems

Hierarchical solution

Iterative solution

Monolithic solution
Reasons to use open source software in CE free as in "beer" vs. free as in "speech"
Elmer – Infrastructure for Open Research

Elmer As Infrastructure

- Elmer Courses
- Elmer Support
- GPL modules
- propriety modules
- University D
- Institute C
- Company B
- User/Developer/Customer
- HPC

Elmer Library

Company

Institute
Most important Elmer resources

- [https://github.com/elmercsc/elmerfem](https://github.com/elmercsc/elmerfem) – GIT version control (the future)
- [http://www.elmerfem.org](http://www.elmerfem.org) – Discussion forum, wiki & doxygen
- [http://youtube.com/elmerfem](http://youtube.com/elmerfem) – Youtube channel for Elmer animations

Further information: elmeradm@csc.fi