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Elmer FEM – Parallelisation, nonlinear and time dependent problems

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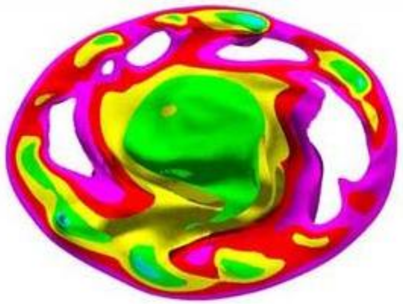
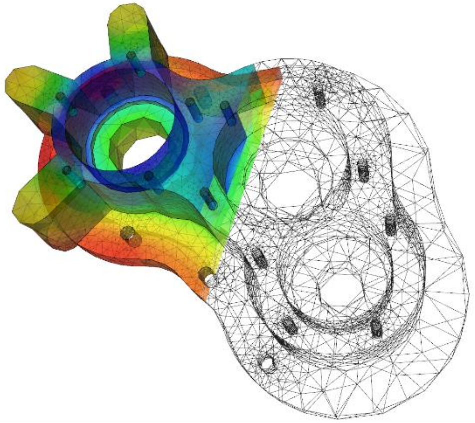
Elmer FEM

- **<u>Open source multiphysics FEM software</u>** – developed by <u>CSC – IT Center of Science</u>
- Physical models:
  - ❖ Solid mechanics
  - ❖ Fluid mechanics
  - ❖ Heat transfer
  - ❖ Acoustics
  - ❖ Electromagnetism, etc.
- Parallelization primarily based on MPI
- Suitable scalability has been shown using above 10^3 cores
- Preconditioners not always the same in parallel computations
  - ❖ Might deteriorate parallel performance

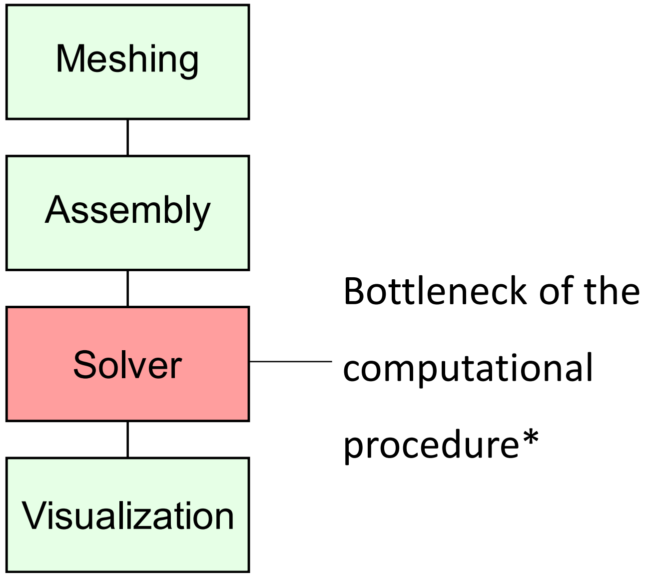




Parallelisation in Elmer FEM

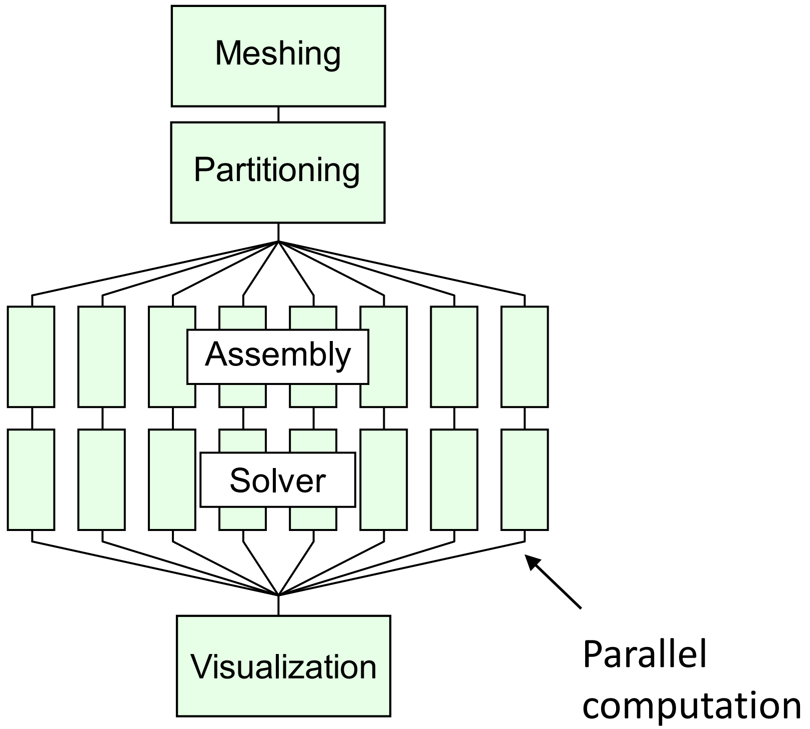
- Computational steps in typical FEM analysis:

1. Serial computation:



➢ * For large cases the other steps can also be highly time consuming – parallelization there also required

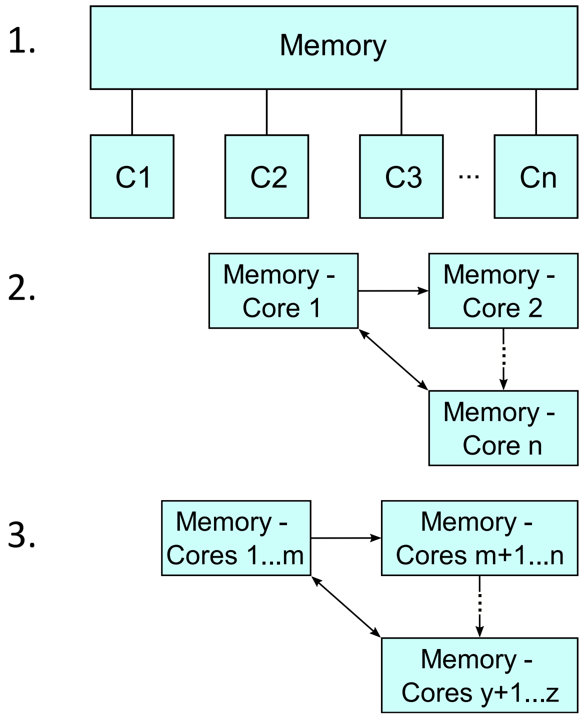
2. Parallelized computation



Parallelisation in Elmer FEM

- Data dependency – does the computation of one task require data from other tasks to proceed?
  - FEM is inherently data dependent – reflection of the physical reality of the problem

- Parallel computers:
  1. Shared memory – all cores access the whole memory
  2. Distributed memory:
     - Each core has its own memory unit
     - Communication protocol for memory access between different cores
  3. Typical HPC combines distributed and shared memory capabilities



Parallelisation in Elmer FEM

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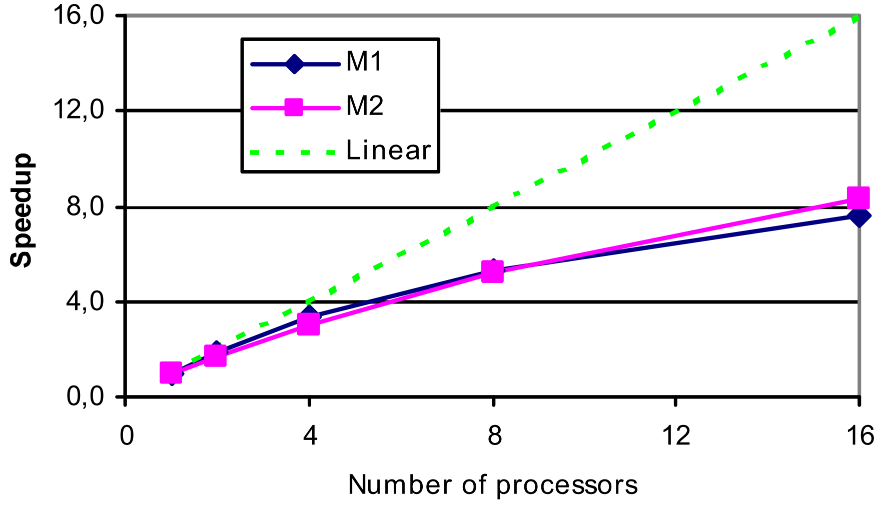
- Message passing (MPI)
  - Can be used both in distributed and shared memory computers
  - Programming model allows good parallel scalability
  - Programming is quite explicit

- Threads (pthreads, OpenMP)
  - Can be used only in shared memory computer
  - Limited parallel scalability
  - Simpler - less explicit programming

- Elmer historically uses MPI
  - Recent developments towards multithreading using OpenMP

Parallelisation in Elmer FEM

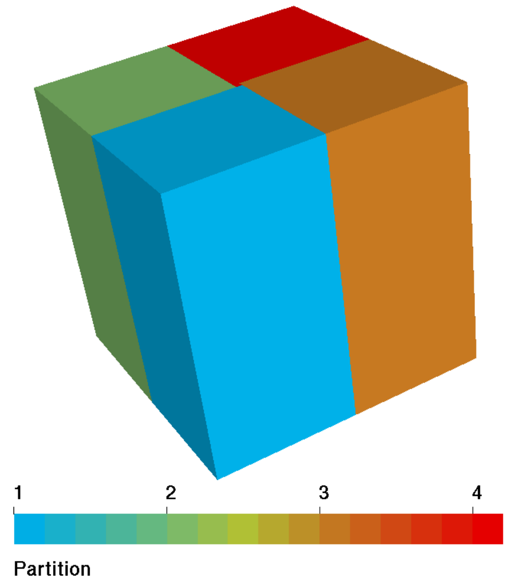
- Scalability of parallelized FEM computations:
  - *Strong scaling* – how the solution time decreases with an increased number of processors for a fixed total problem size
    - Best case scenario: $N_p \cdot T$ = const.
  - *Weak scaling* – how the solution time varies with the number of processors for a fixed problem size per processor
    - Best case scenario: T = const.
  - Typically $>10^4$ FEs needed for suitable scaling



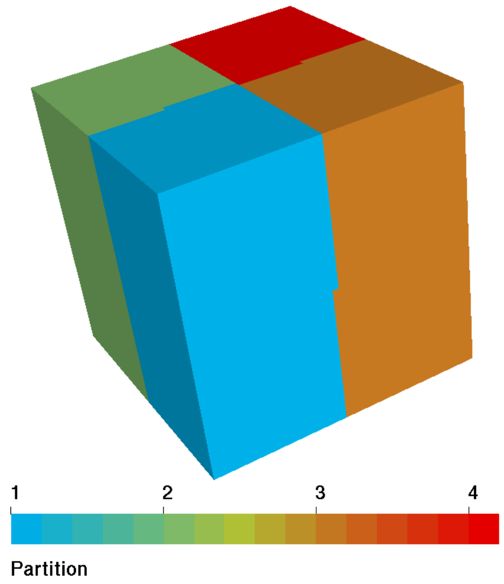
Parallelisation in Elmer FEM

Domain decomposition in Elmer FEM

- **ElmerGrid partitioning by direction**
  - Directional decomposition (*Np=Nx*Ny*Nz*)
    - `ElmerGrid 2 2 meshdir –partition Nx Ny Nz Nm`
  - Optional redefinition of major axis with a given normal vector
    - `-partorder nx ny nz`



–partition *2 2 1 0*



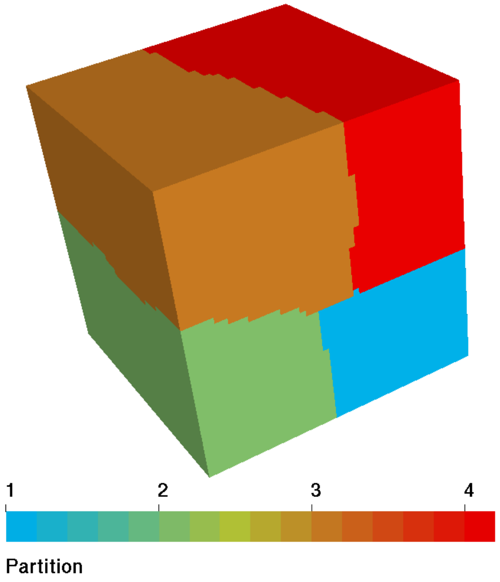
–partition *2 2 1 1*

Parallelisation in Elmer FEM

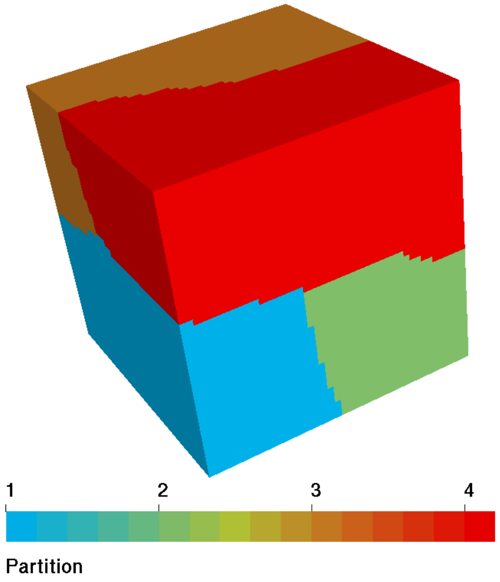
- **Using Metis library**

–ElmerGrid2 2 meshdir –metis Np Nm

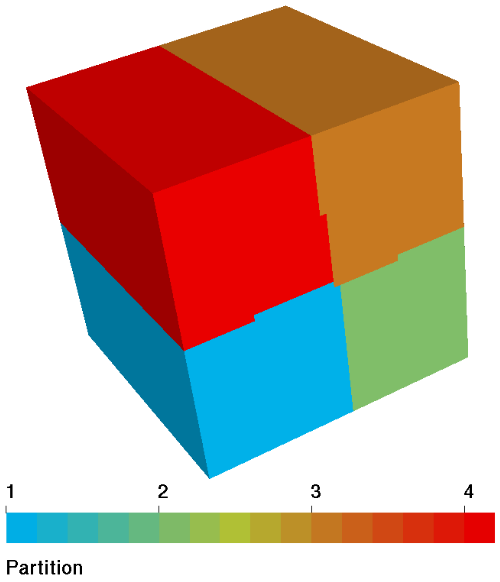
- Typically used for decomposing more complex geometric domains



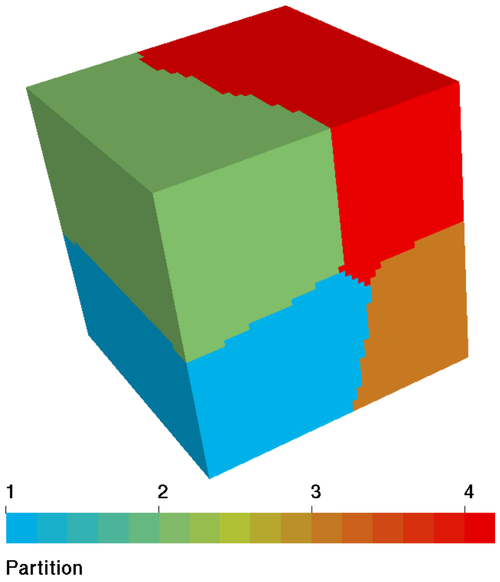
-metis *4 0*



-metis *4 1*



-metis *4 2*



-metis *4 3*

Mesh structure in Elmer models

Serial:

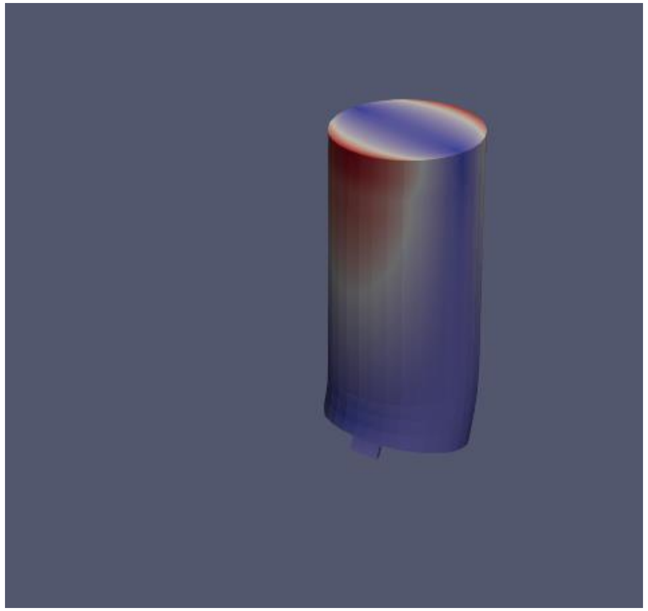
- `meshdir/`
  - `mesh.header` – size info of the mesh
  - `mesh.nodes` – node coordinates
  - `mesh.elements` – bulk element defs
  - `mesh.boundary` – boundary element defs with reference to parents

Parallel:

- `meshdir/partitioning.N/`
  - `part.n.header`
  - `part.n.nodes`
  - `part.n.elements`
  - `part.n.boundary`
  - `part.n.shared` – Information on shared nodes for each i in [0,N-1]

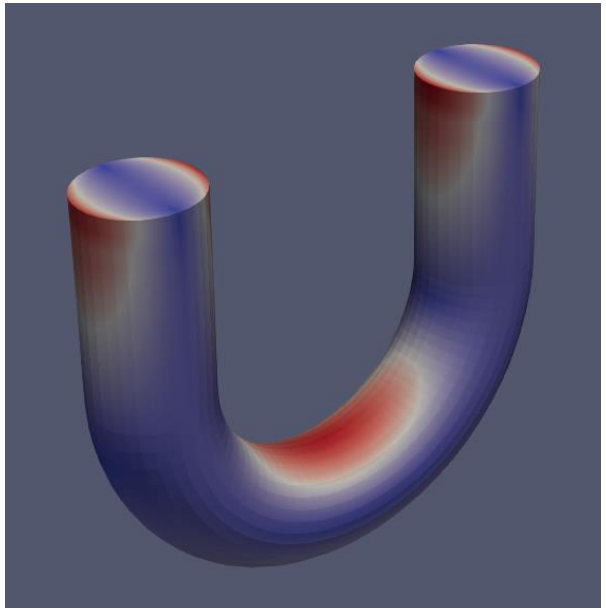
Parallel postprocessing using Paraview

- Use ResultOutputSolver to save data to `.vtu` files
- The operation is almost the same for parallel data as for serial data
- There is a extra file `.pvtu` that is a wrapper for the parallel `.vtu` data of each partition



4-core analysis

`res.1.vtu` result file



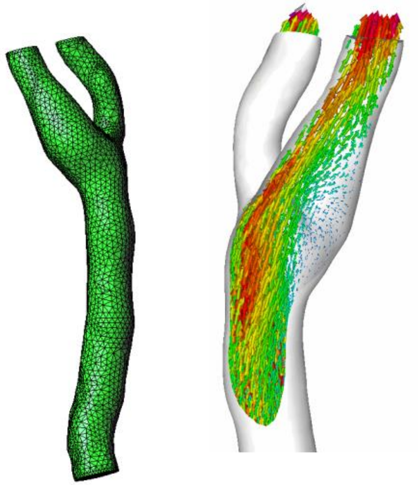
4-core analysis

`res.pvtu` wrapper file

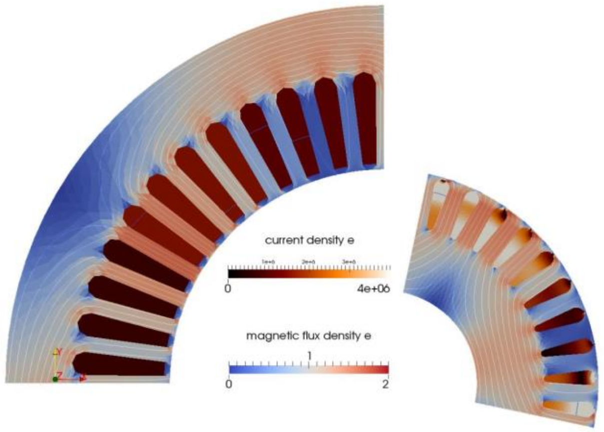
Linear v. nonlinear problems in Elmer FEM

Physical models in Elmer FEM

- Heat transfer
  - Steady state heat equation
  - Transient heat equation
- Solid mechanics
  - Linear elasticity
  - Finite elasticity
  - Shell equations
- Fluid mechanics and transport phenomena
  - Navier-Stokes equation
  - Advection-diffusion equation
  - Reynolds equation – thin film flow
- Acoustics
  - Helmholtz model
  - Linearized Navier-Stokes in the frequency domain
- Electromagnetism
  - Electrostatics
  - Circuits and dynamics solver
  - Magnetic induction equation
- Other
- User defined elements and models



Raback, PRACE 2014



Ponomarev, SEMTEC 2017

Linear v. nonlinear problems in Elmer FEM

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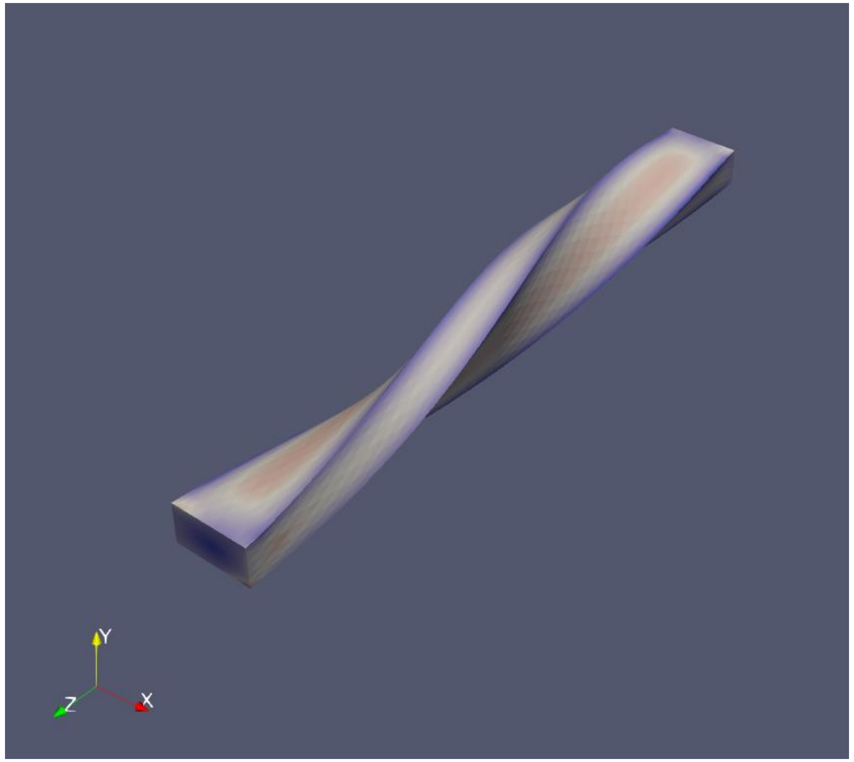
Nonlinear model examples

- Heat transfer
  - Transient heat equation with **heat radiation effect**
- Solid mechanics
  - **Finite elasticity**
  - **Non-elastic models** (e.g. hyperelasticity, viscoplasticity)
- Fluid mechanics and transport phenomena
  - **Navier-Stokes** equation with **inertial fluid force** or **convective effect**
- Acoustics
  - Large-amplitude **wave propagation**
- Electromagnetism
  - **Poisson-Boltzmann** equation – steady state electric potential law



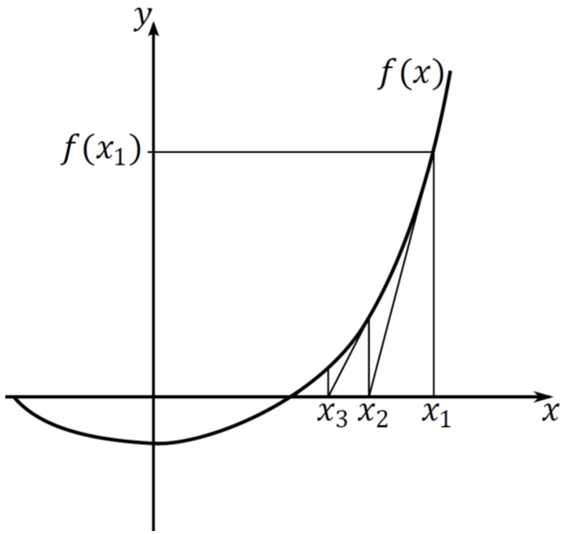
Linear v. nonlinear problems in Elmer FEM

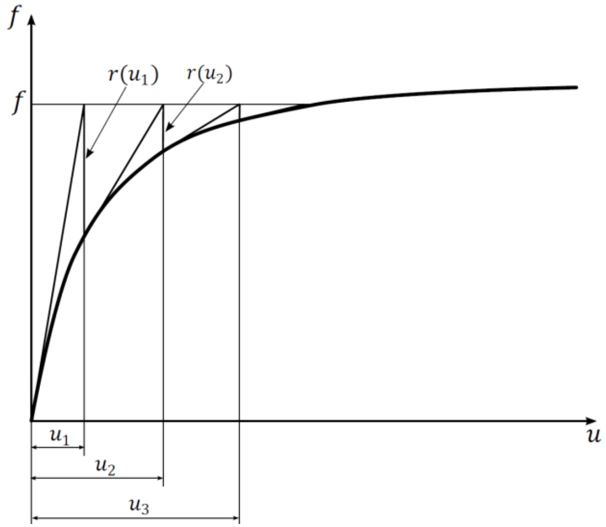
How Elmer FEM deals with nonlinear problems?

- Solver always iterative
- Problem always first linearized to the form

$$A(u_{i-1})u_i = b(u_{i-1})$$

- Two iterative algorithms available: **Newton** (aka Newton-Raphson) and **Picard** schemes
- Choice of interative solution scheme depends on used model, e.g.:
    - Solid mechanics – Newton method
    - Navier-Stokes – Picard + Netwon method combination





Neton method applied to a nonlinear solid material model

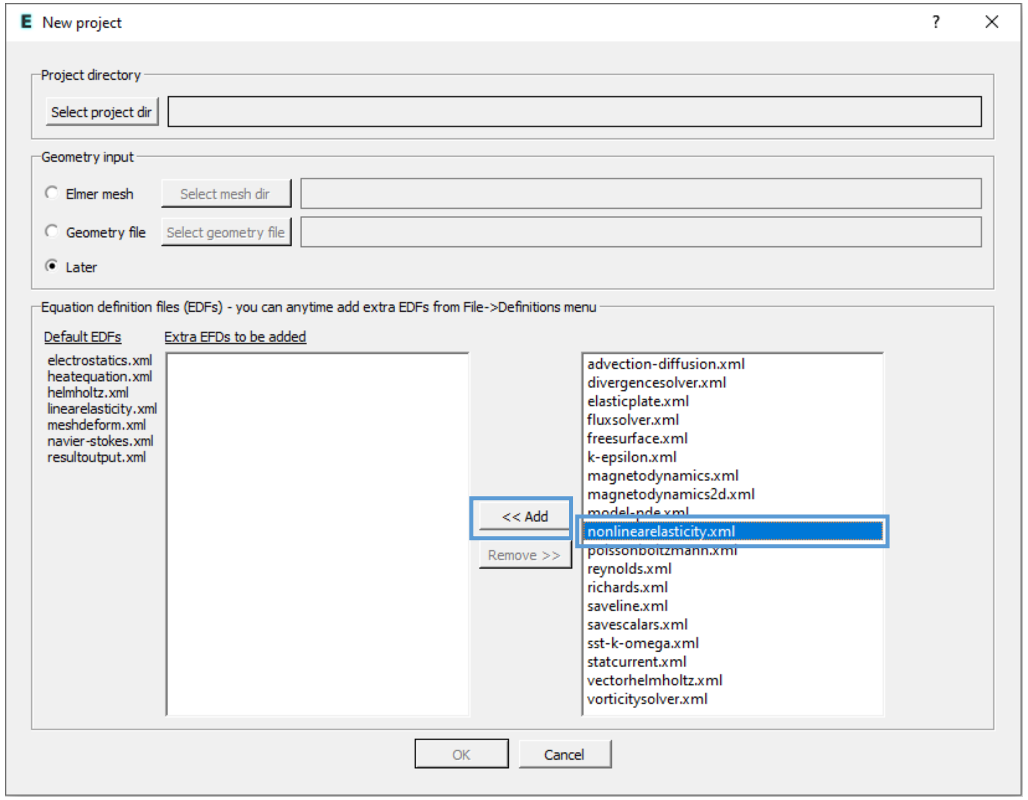
[Cerne 2014 – Master thesis]

See also: [Wikiversity – Nonlinear finite elements]

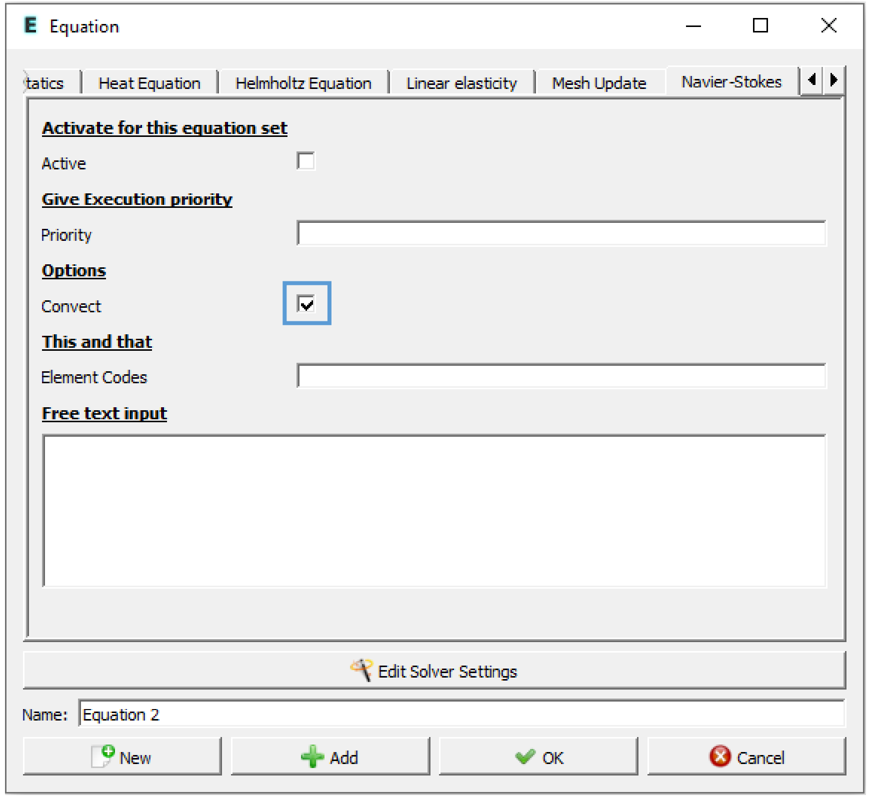
Linear v. nonlinear problems in Elmer FEM

How to enable nonlinear models in Elmer FEM

Example 1: Solid mechanics:



Example 2: Navier-Stokes – fluid mechanics



Linear v. nonlinear problems in Elmer FEM

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Time-dependent physical problems

- Can be linear or nonlinear
- General first order differential eq. (DE) problem form:

$$M\frac{\partial \Phi}{\partial t} + K\Phi = F$$

  - Example – viscoelastic solid models

- Time-dependent term can be solved numerically using various schemes:
  1. Backward Different Formula (BDF)

$$\left(\frac{1}{\Delta t}M + K\right)\Phi^{i+1} = F^{i+1} + \frac{1}{\Delta t}M\Phi^{i}$$

  - First order implicit solution

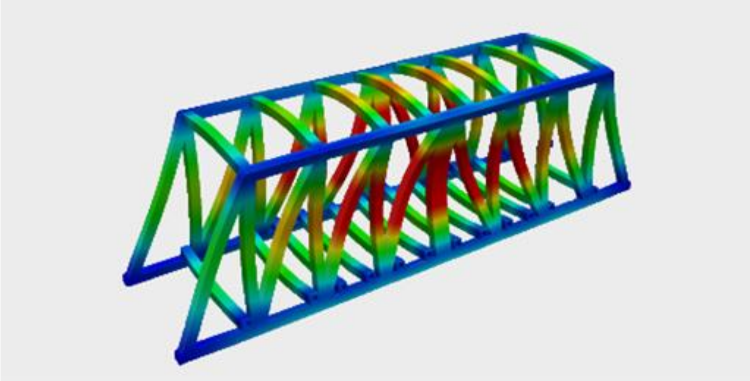
  2. Crank-Nicholson method

- Second order time derivatives:

$$M\frac{\partial^2 \Phi}{\partial t^2} + B\frac{\partial \Phi}{\partial t} + K\Phi = F$$

  - Example – structural dynamics

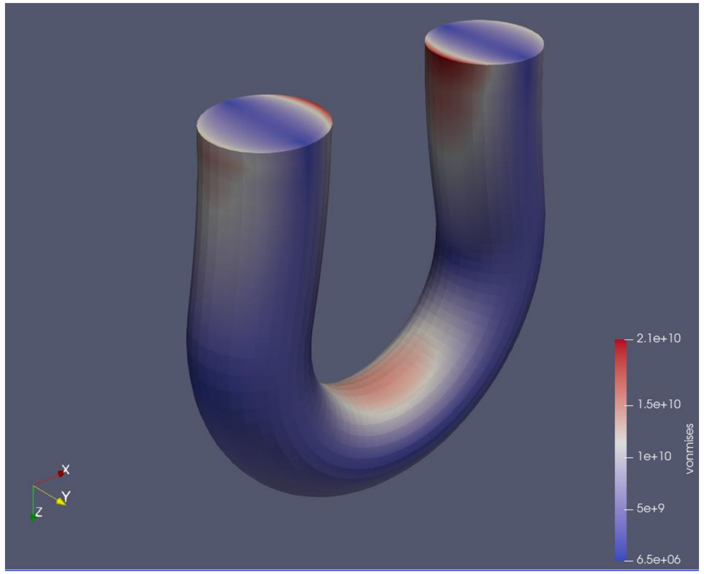
- the Bossak-Newmark method can be used to solve the DE numerically

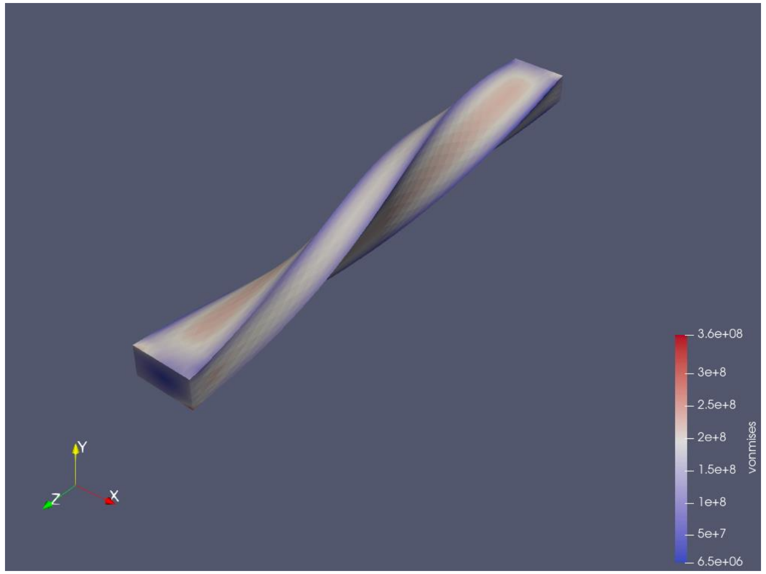


Linear v. nonlinear problems in Elmer FEM

Hands-on examples

- Finite elasticity
- Heat transfer and fluid flow





Sources

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P. Ponomarev, SEMTEC Report Elmer FEM - Induction Machine Tutorial, 2017

Thank you for your attention!

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