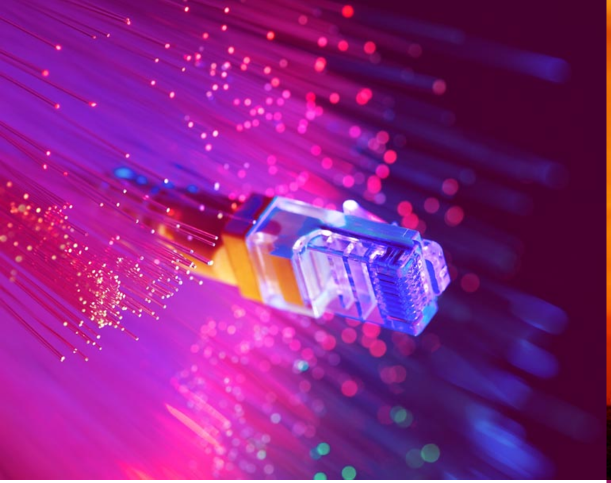

CSC

Elmer/Ice – New Generation Ice Sheet Model

Thomas Zwinger, Elmer/Ice course Stockholm, November 2017

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CSC – Finnish research, education, culture and public administration ICT knowledge center

2D GLACIER TOY MODEL

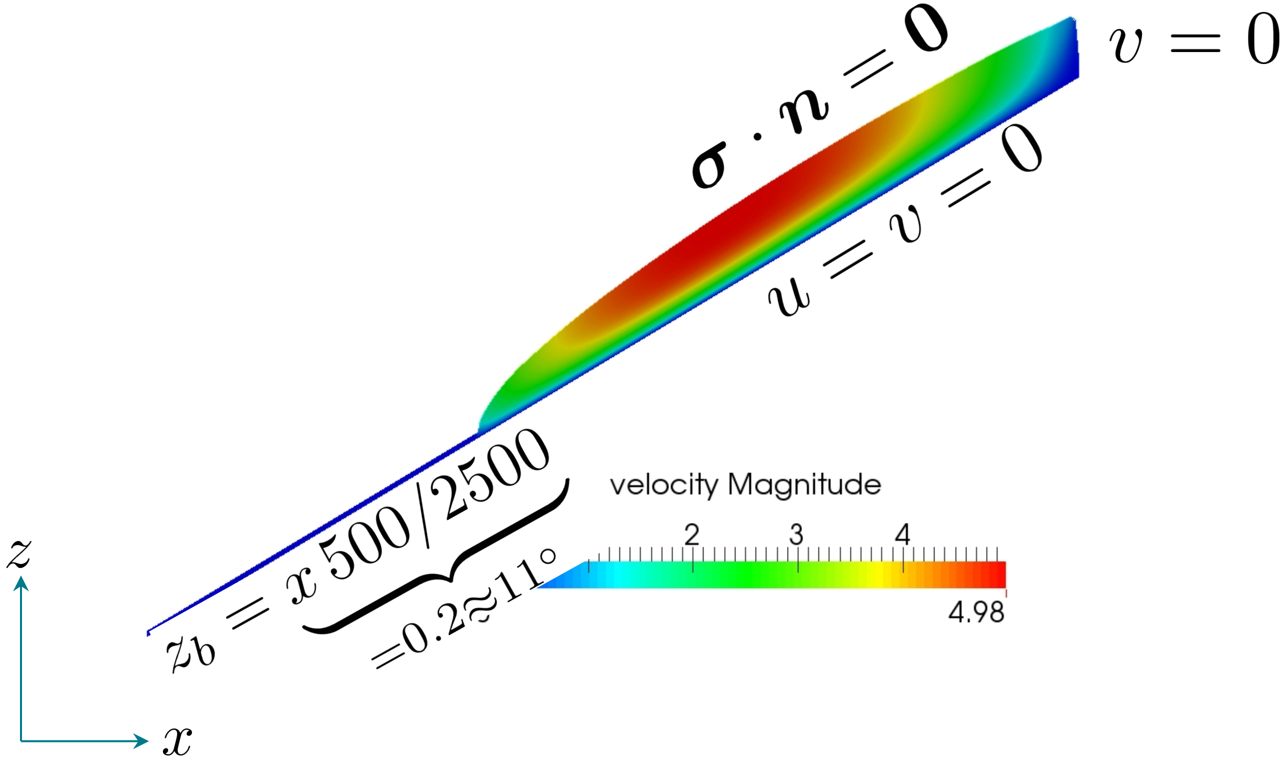
These sessions shall introduce into the **basics of Elmer/Ice**. It follows the strategy of having a possibly **simple flow-line** setup, but **containing all elements** the user needs in real world examples, such as reading in DEM's, applying temperature and accumulation distributions, etc.

DIAGNOSTIC RUN

Starting from a given point-distribution (DEM) in 2D we show how to:

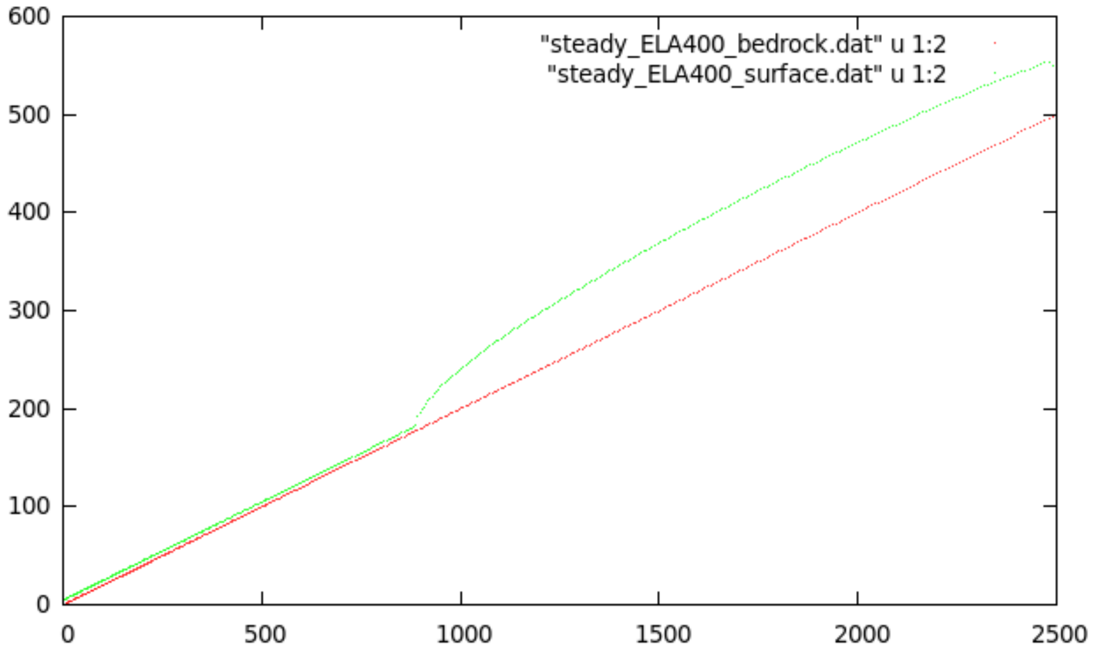
- Create the mesh
- Set up runs on fixed geometry
- Introduce sliding
- Write a simple MATC function (interpreted functions)

The diagnostic problem



The diagnostic problem

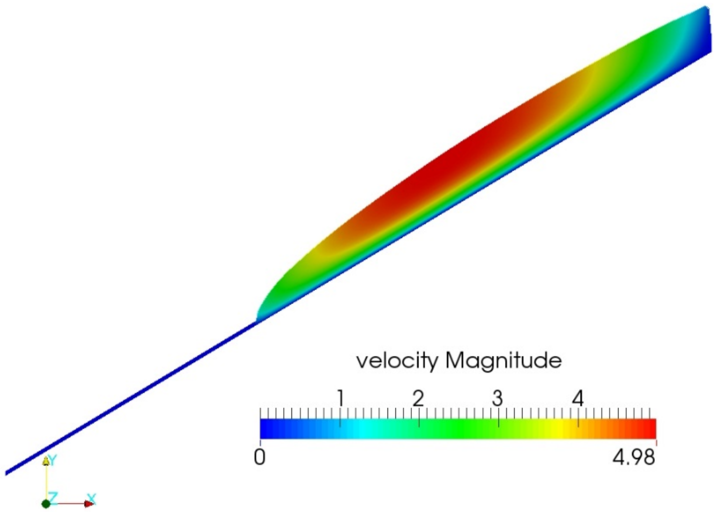
- We start from a distribution of surface and bedrock points that have been created driving a prognostic run into steady state



- The distributions are given in the files: **`steady_ELA400_bedrock.dat`** , **`steady_ELA400_surface.dat`**

The diagnostic problem

- We use a ~11 deg inclined rectangular mesh (produced with Gmsh) of unit-height (load the ready-made file



The diagnostic problem

- If you have not already saved the mesh from Gmsh, do the following (find Gmsh instructions at end of slides):

```
    $ gmsh -2 testglacier.geo
```

- Use ElmerGrid to convert the mesh:

```
> ElmerGrid 14 2 testglacier.msh\
  -autoclean -order 0.1 1.0 0.01
```

Needed to clean up geometry

Orders the numbering in x y z –directions (highest number fastest)

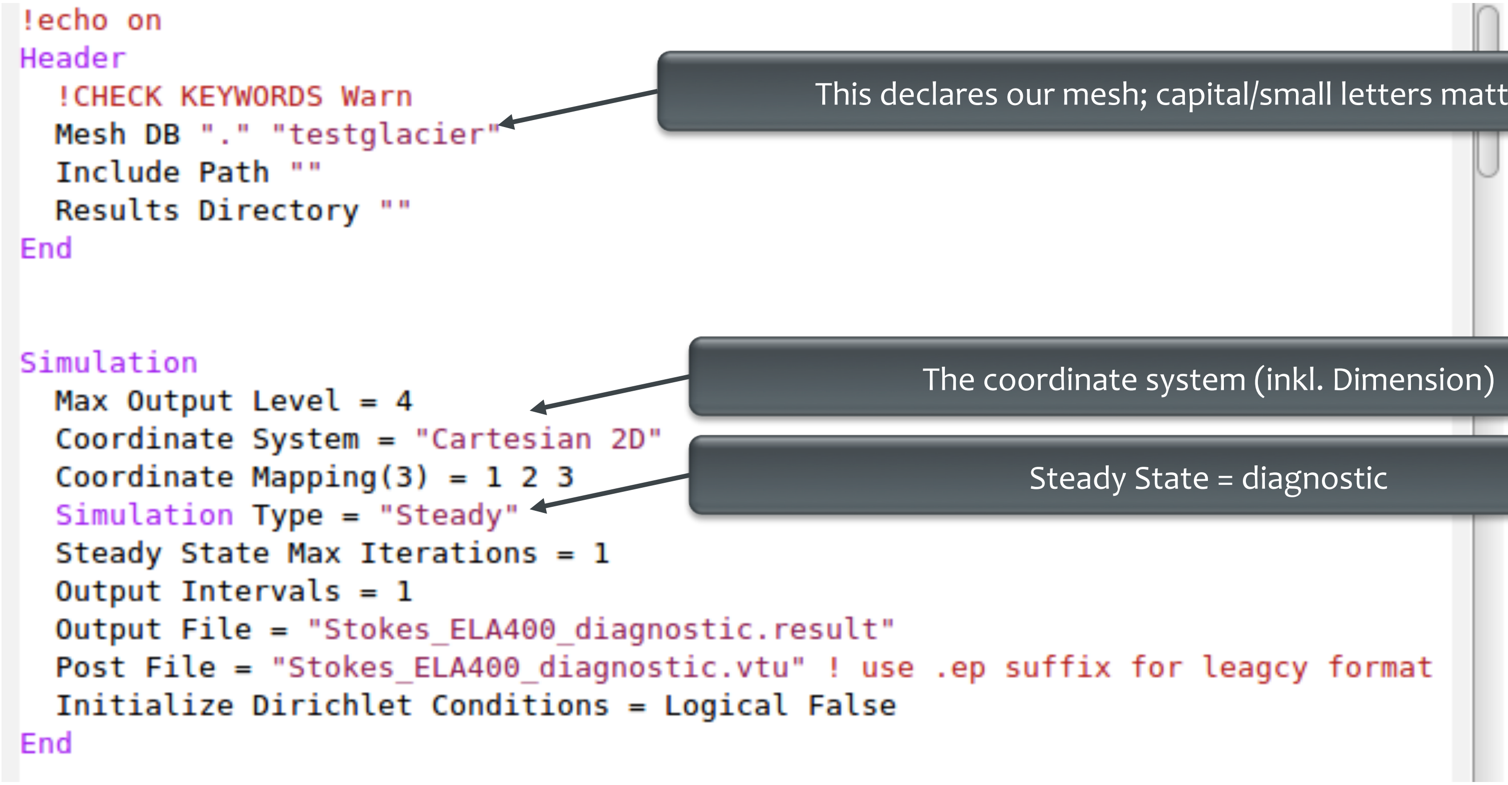
The diagnostic problem

- We will do a diagnostic simulation, i.e., we ignore the time derivative in ANY equation
  - Stokes anyhow has no explicit time dependence

    $$\nabla \cdot \boldsymbol{\sigma} + \rho \boldsymbol{g} = \mathbf{0}$$
  - That also means, that the surface velocity distribution is a result of the given geometry and cannot be prescribed (no accumulation)
- Open the Solver Input File (SIF)

```
$ emacs Stokes_diagnostic.sif &
```

The diagnostic problem



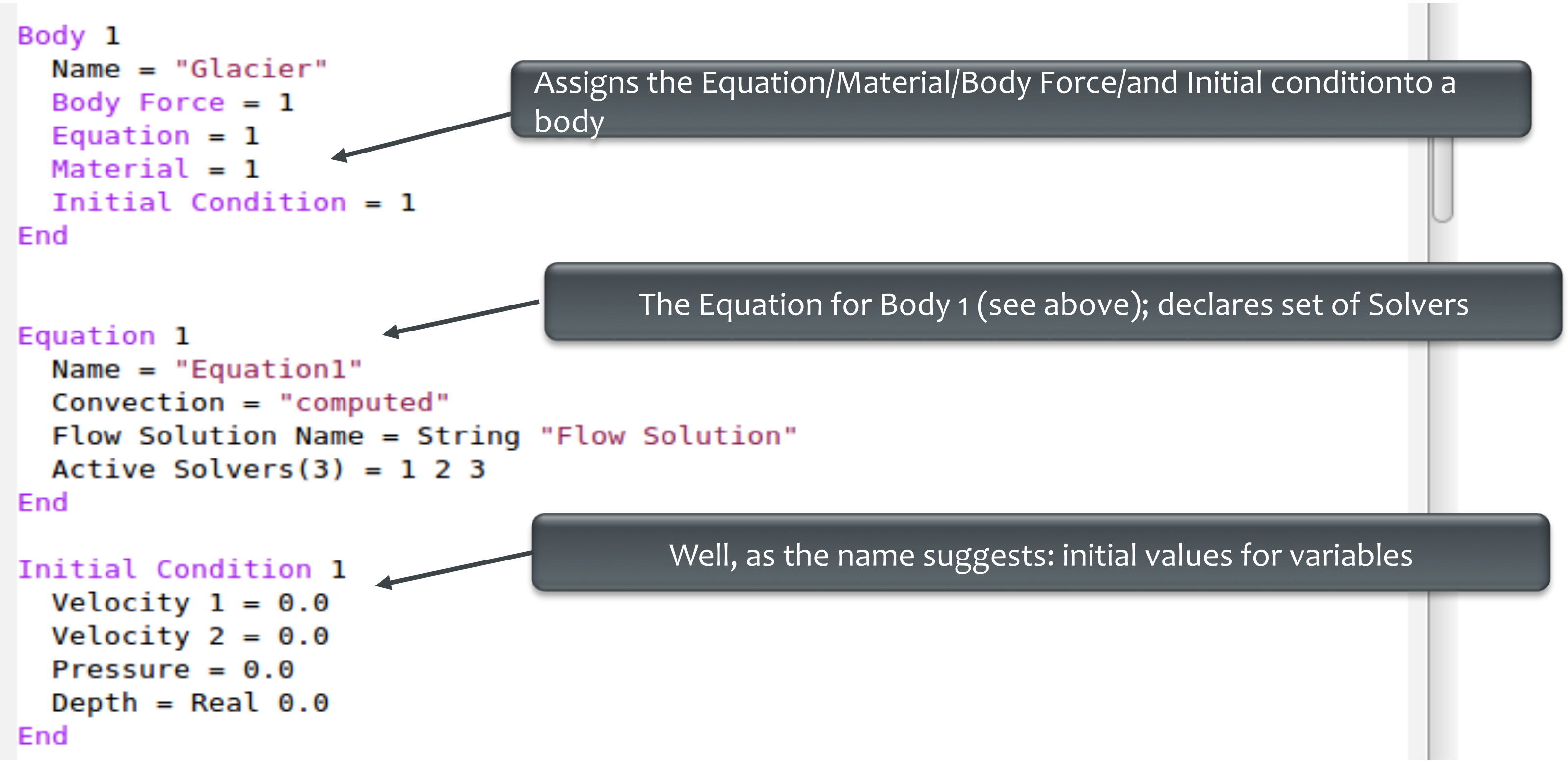
```
!echo on
Header
  !CHECK KEYWORDS Warn
  Mesh DB "." "testglacier"
  Include Path ""
  Results Directory ""
End


Simulation
  Max Output Level = 4
  Coordinate System = "Cartesian 2D"
  Coordinate Mapping(3) = 1 2 3
  Simulation Type = "Steady"
  Steady State Max Iterations = 1
  Output Intervals = 1
  Output File = "Stokes_ELA400_diagnostic.result"
  Post File = "Stokes_ELA400_diagnostic.vtu" ! use .ep suffix for leagcy format
  Initialize Dirichlet Conditions = Logical False
End
```

This declares our mesh; capital/small letters matter

The coordinate system (inkl. Dimension)

Steady State = diagnostic

The diagnostic problem



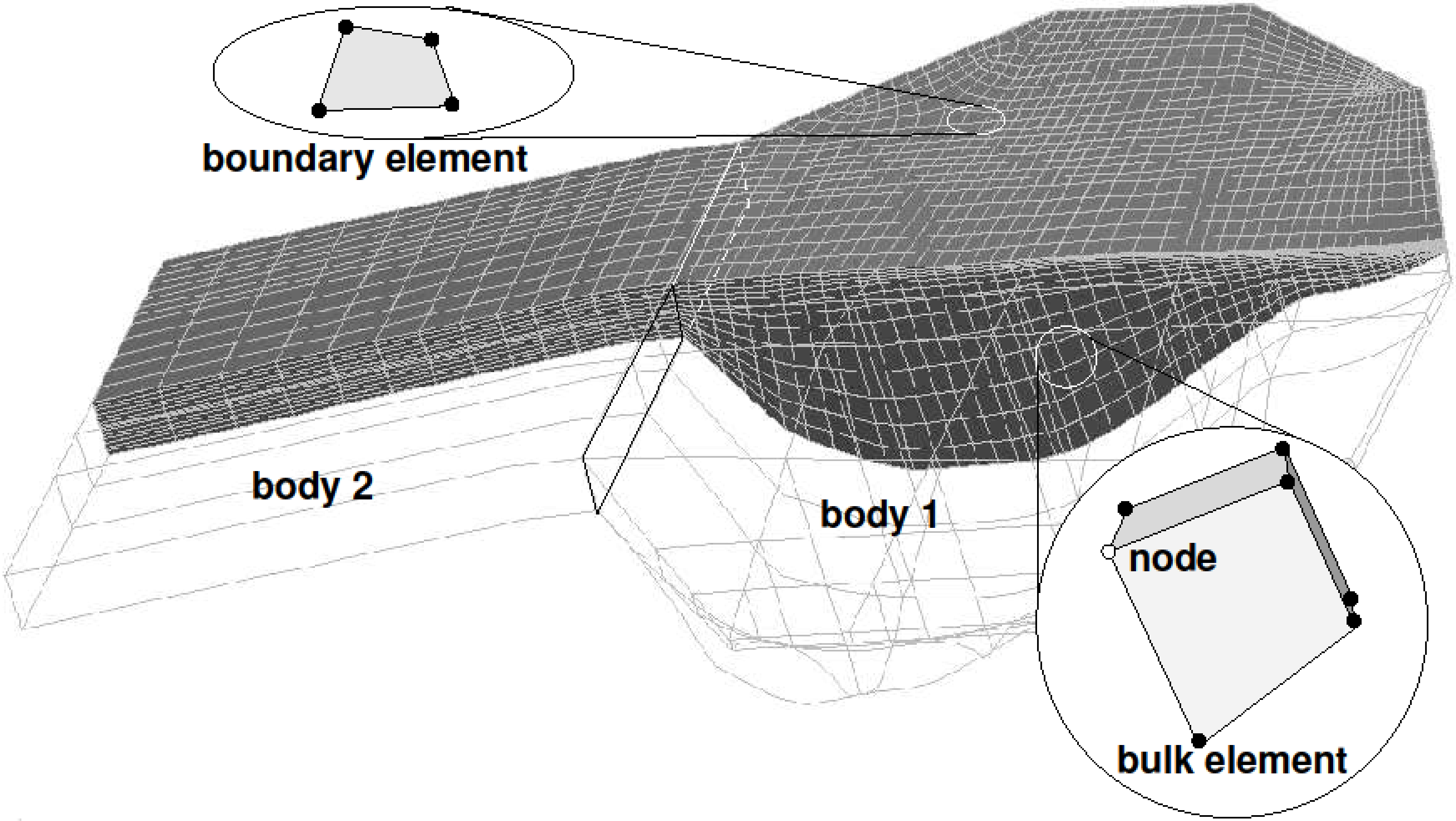
```
Body 1
  Name = "Glacier"
  Body Force = 1
  Equation = 1
  Material = 1
  Initial Condition = 1
End


Equation 1
  Name = "Equation1"
  Convection = "computed"
  Flow Solution Name = String "Flow Solution"
  Active Solvers(3) = 1 2 3
End

Initial Condition 1
  Velocity 1 = 0.0
  Velocity 2 = 0.0
  Pressure = 0.0
  Depth = Real 0.0
End
```

Assigns the Equation/Material/Body Force/and Initial conditionto a body

The Equation for Body 1 (see above); declares set of Solvers

Well, as the name suggests: initial values for variables

On Bodies and Boundaries

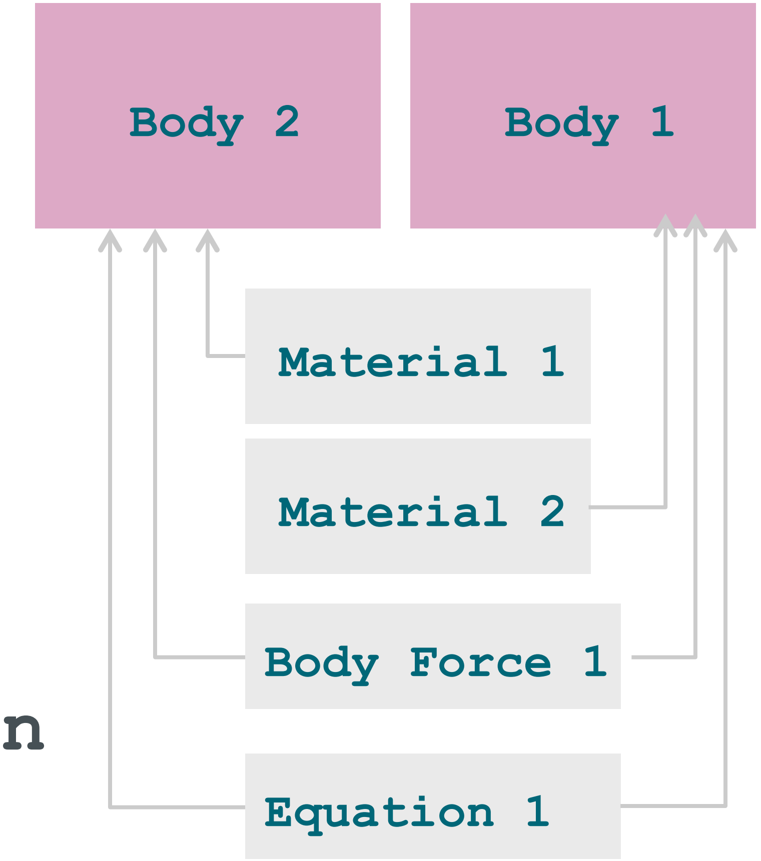


On Bodies and Boundaries

- Each **Body** has to have an **Equation** and **Material** assigned

  Body Force, **Initial Condition** optional

- Two bodies can have the same **Material/Equation/Body Force/Initial Condition** section assigned



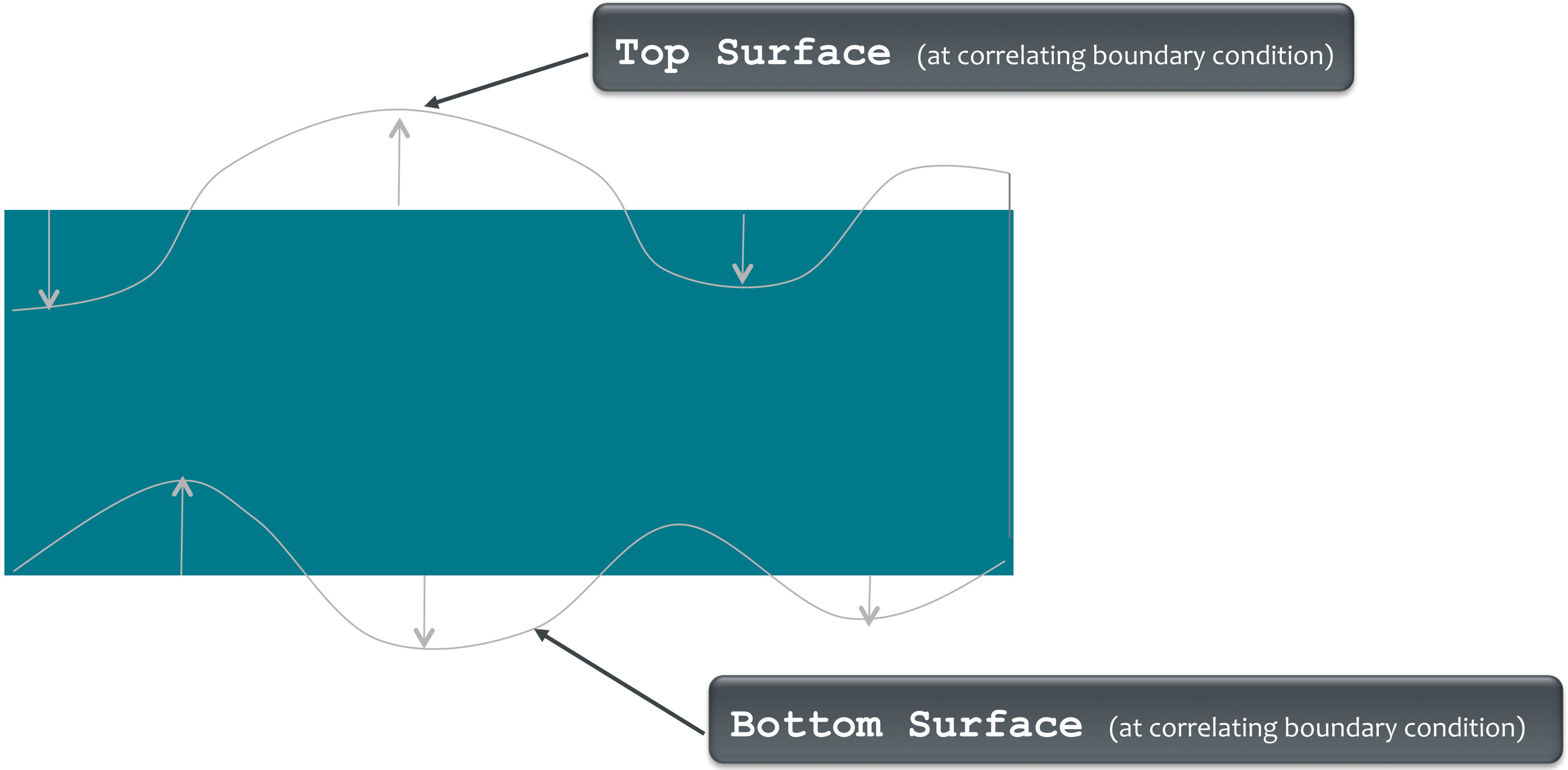
The diagnostic problem

```
! maps DEM's at the very beginning
! to originally rectangular mesh
! see Top and Bottom Surface in BC's
Solver 1
  Exec Solver = ”Before Simulation"
  Equation = "MapCoordinate"
  Procedure = "StructuredMeshMapper" "StructuredMeshMapper"
  Active Coordinate = Integer 2! the mesh-update is y-direction
! For time being this is currently externally allocated
  Mesh Velocity Variable = String "Mesh Velocity 2"
! The 1st value is special as the mesh velocity could be unrelistically high
  Mesh Velocity First Zero = Logical True
! The accuracy applied to vector-projections
  Dot Product Tolerance = Real 0.01
End
```

The primary criterion for order of execution is the **`Exec Solver`** keyword, thereafter the numbering

This solver simply projects the shape given in the input files before the run (see Exec Solver keyword) to the initially flat mesh; See **`Top Surface`** and **`Bottom Surface`** keywords later

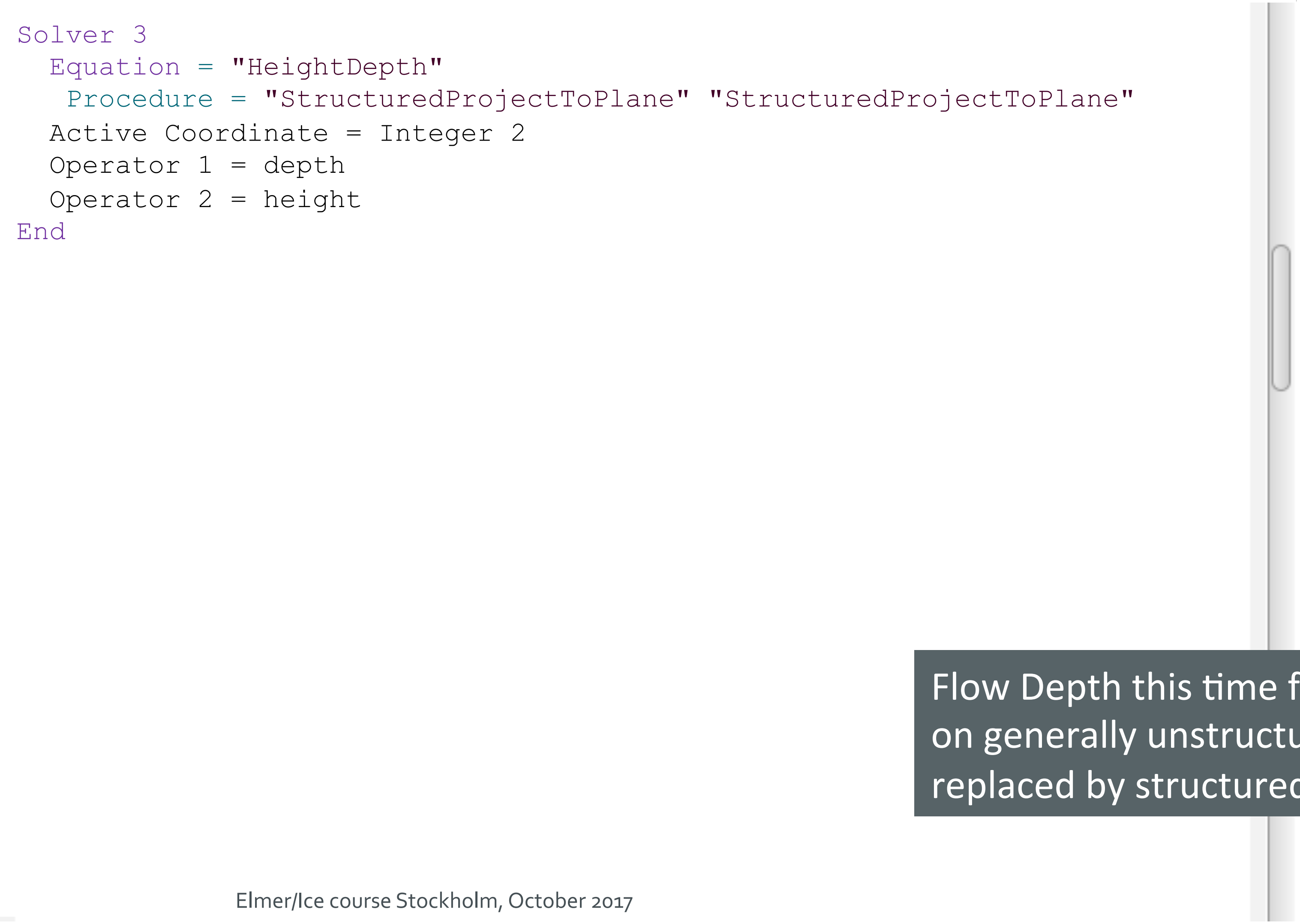
The diagnostic problem



Top Surface (at correlating boundary condition)

Bottom Surface (at correlating boundary condition)

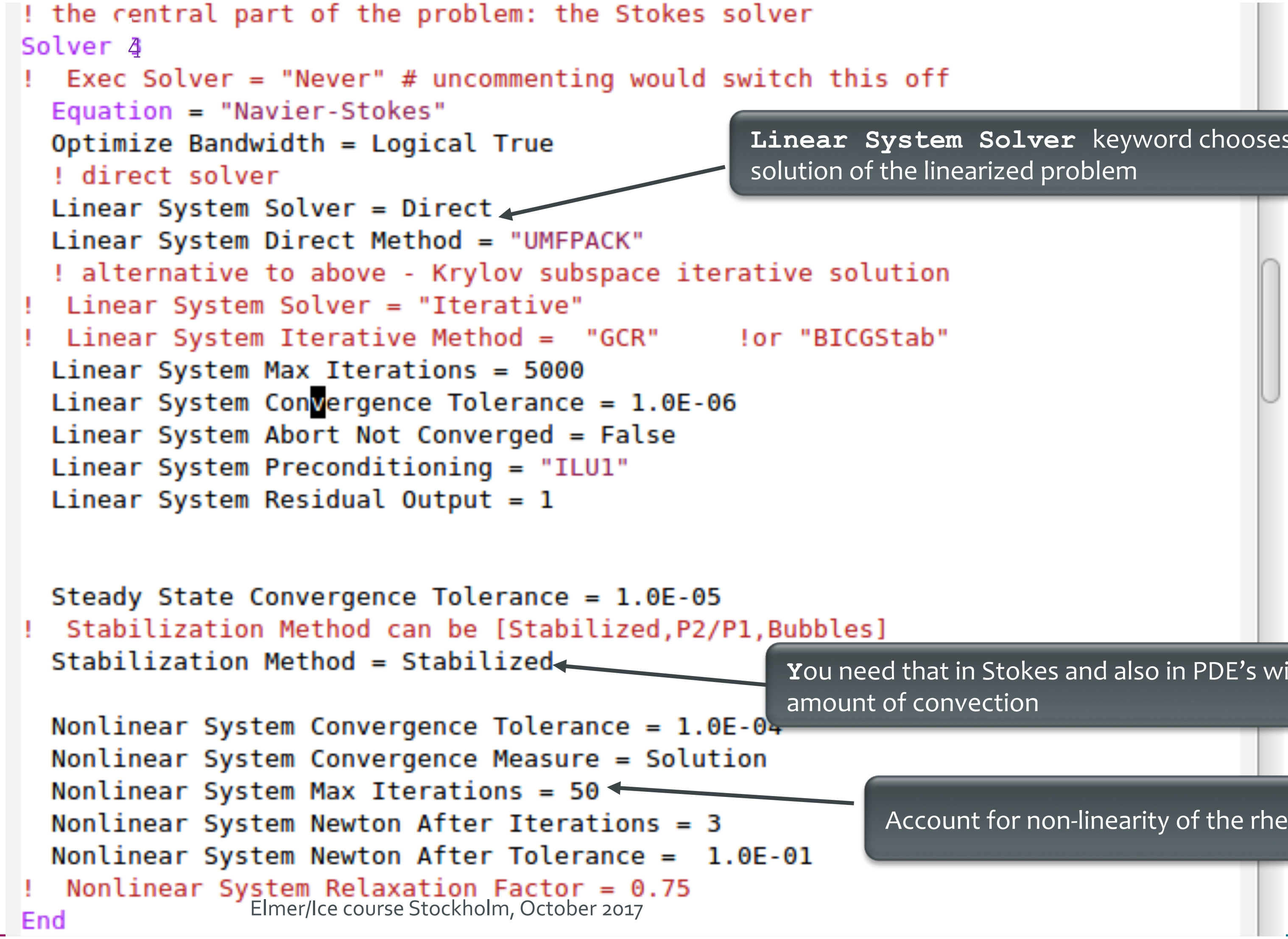
The diagnostic problem



```
Solver 3
  Equation = "HeightDepth"
   Procedure = "StructuredProjectToPlane" "StructuredProjectToPlane"
  Active Coordinate = Integer 2
  Operator 1 = depth
  Operator 2 = height
End
```

Flow Depth this time for post processing, only, on generally unstructured mesh (will be replaced by structured version)

The diagnostic problem



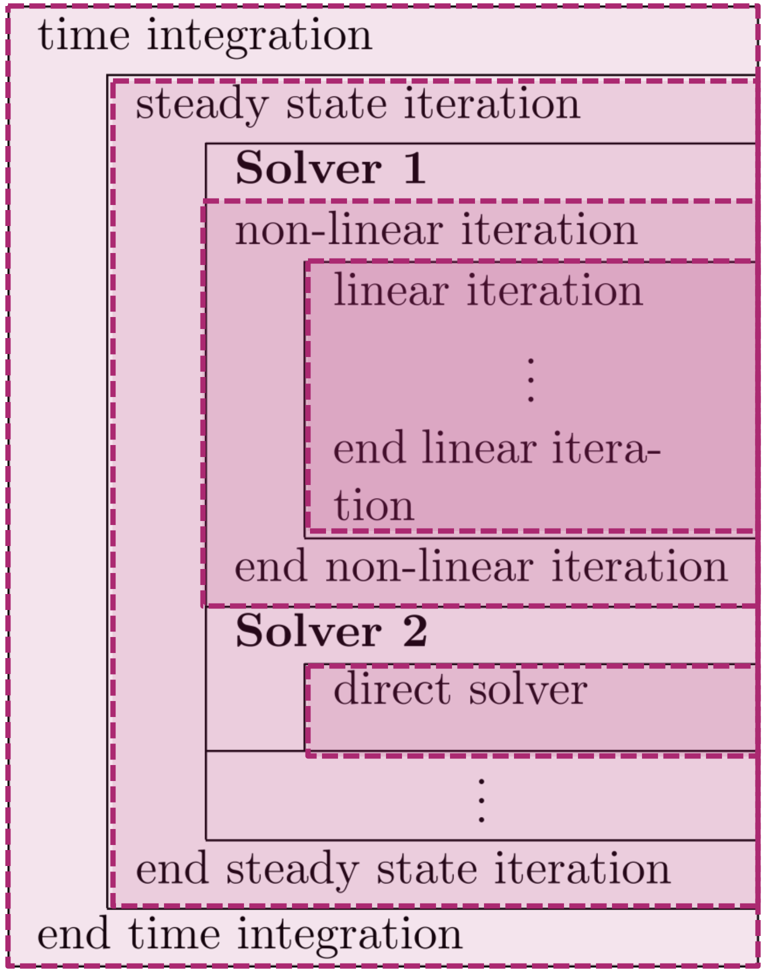
```
! the central part of the problem: the Stokes solver
Solver 4
!  Exec Solver = "Never" # uncommenting would switch this off
  Equation = "Navier-Stokes"
  Optimize Bandwidth = Logical True
  ! direct solver
  Linear System Solver = Direct
  Linear System Direct Method = "UMFPACK"
  ! alternative to above - Krylov subspace iterative solution
!  Linear System Solver = "Iterative"
!  Linear System Iterative Method =  "GCR"     !or "BICGStab"
  Linear System Max Iterations = 5000
  Linear System Convergence Tolerance = 1.0E-06
  Linear System Abort Not Converged = False
  Linear System Preconditioning = "ILU1"
  Linear System Residual Output = 1


  Steady State Convergence Tolerance = 1.0E-05
!  Stabilization Method can be [Stabilized,P2/P1,Bubbles]
  Stabilization Method = Stabilized

  Nonlinear System Convergence Tolerance = 1.0E-04
  Nonlinear System Convergence Measure = Solution
  Nonlinear System Max Iterations = 50
  Nonlinear System Newton After Iterations = 3
  Nonlinear System Newton After Tolerance =  1.0E-01
!  Nonlinear System Relaxation Factor = 0.75
End
```

`Linear System Solver` keyword chooses type of solution of the linearized problem

You need that in Stokes and also in PDE's with significant amount of convection

Account for non-linearity of the rheology

On iteration methods



time integration

steady state iteration

Solver 1

non-linear iteration

linear iteration

⋮

end linear iteration

end non-linear iteration

Solver 2

direct solver

⋮

end steady state iteration

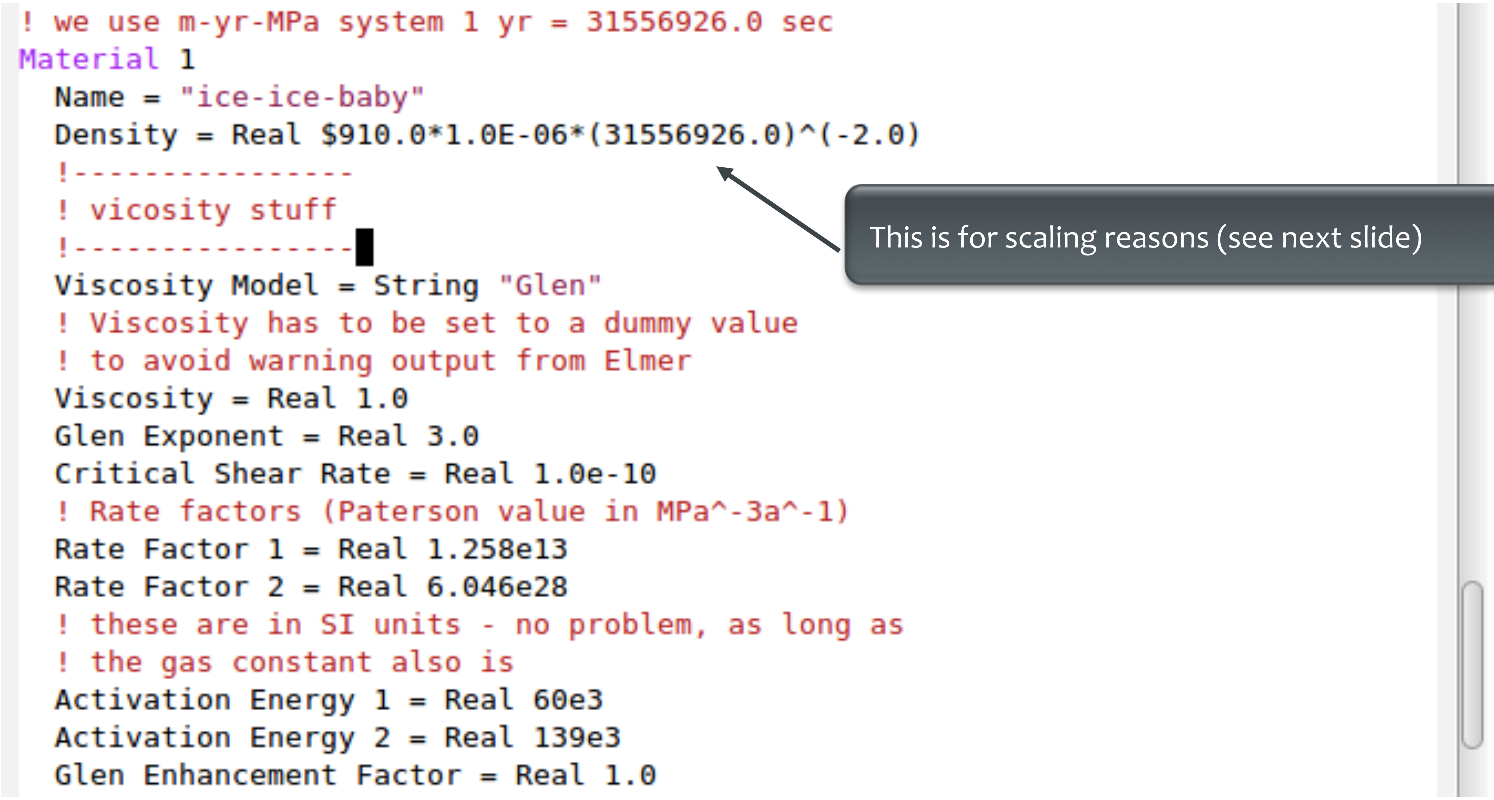
end time integration

1. Timestep Intervals
2. Steady State Max Iterations
3. Nonlinear Max Iterations
4. Linear System Max Iterations
4. Linear System Convergence Tolerance
3. Nonlinear System Convergence Tolerance

Nonlinear System Convergence Tolerance

2. Steady State Convergence Tolerance
1.

The diagnostic problem



```
! we use m-yr-MPa system 1 yr = 31556926.0 sec
Material 1
  Name = "ice-ice-baby"
  Density = Real $910.0*1.0E-06*(31556926.0)^(-2.0)
  !----------------
  ! vicosity stuff
  !----------------
  Viscosity Model = String "Glen"
  ! Viscosity has to be set to a dummy value
  ! to avoid warning output from Elmer
  Viscosity = Real 1.0
  Glen Exponent = Real 3.0
  Critical Shear Rate = Real 1.0e-10
  ! Rate factors (Paterson value in MPa^-3a^-1)
  Rate Factor 1 = Real 1.258e13
  Rate Factor 2 = Real 6.046e28
  ! these are in SI units - no problem, as long as
  ! the gas constant also is
  Activation Energy 1 = Real 60e3
  Activation Energy 2 = Real 139e3
  Glen Enhancement Factor = Real 1.0
```

This is for scaling reasons (see next slide)

$$D_{ij} = A\tau_e^{n-1} S_{ij} \quad ; \quad S_{ij} = A^{-1/n} I_{D_2}^{(1-n)/n} D_{ij}$$

where $I_{D_2}^2 = D_{ij}D_{ij}/2$ and $D_{ij} = 1/2(\partial u_i/\partial x_j + \partial u_j/\partial x_i)$

$$A = A(T^{'}) = A_0 \exp^{-Q/RT^{'}}$$

On the choice of units

Elmer(/Ice) does not assume any choice of units. This is on you, BUT, units have to be consistent amongst each other and with the mesh geometry units.

The order of magnitude in numbers do not change results, as matrix is pivoted

For the Stokes problem, one should give values for:

- the density: $\rho \quad (= 910\ \mathrm{kg/m^3})$
- the gravity: $g \quad (= 9.81\ \mathrm{m\ s^{-2}})$
- the viscosity: $\eta_0 \quad (\mathrm{Pa\ s^{1/n}}) \qquad (1\ \mathrm{Pa} = 1\ \mathrm{kg\ s^{-2}\ m^{-1}})$

kg – m – s [SI] : velocity in m/s and time-step in seconds ☹

kg – m – a : velocity in m/a and timesteps in years ☺ $1\ \mathrm{a} = 31\,557\,600\ \mathrm{s}$

MPa – m – a : velocity in m/a and Stress in MPa ☺

(What we have in our SIF)

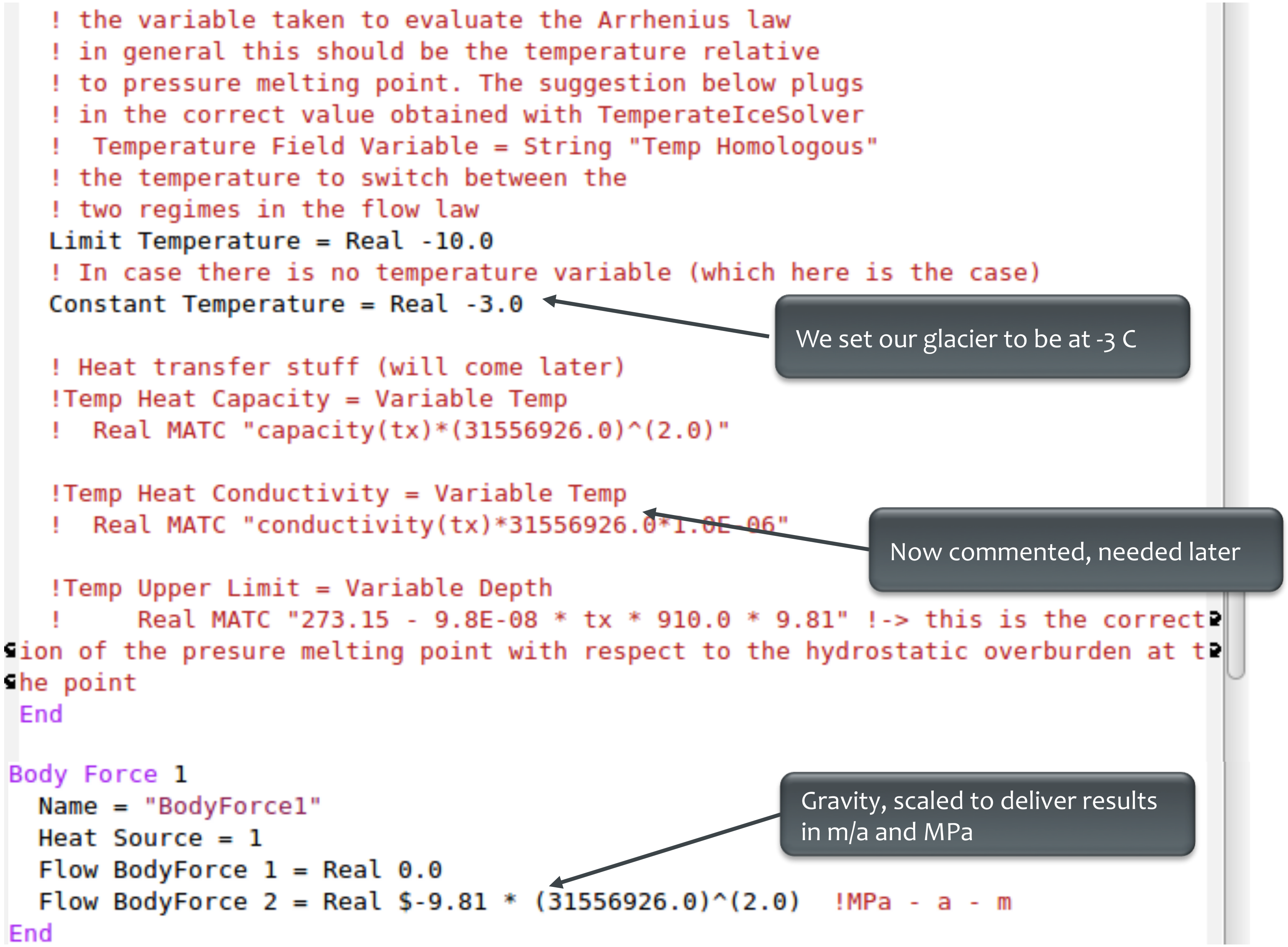
On the choice of units

To give you an example: for ISMIP tests A-D, the value for the constants would be

- the density: $\rho = 910\ \mathrm{kg/m^3}$
- the gravity: $g = 9.81\ \mathrm{m\ s^{-2}}$
- the fluidity: $A = 10^{-16}\ \mathrm{Pa^{-3}\ a^{-1}}$

	USI kg - m - s		kg - m - a		MPa - m - a	
g =	9.81	$\mathrm{m / s^2}$	9.7692E+15	$\mathrm{m / a^2}$	9.7692E+15	$\mathrm{m / a^2}$
ρ =	910	$\mathrm{kg / m^3}$	910	$\mathrm{kg / m^3}$	9.1380E-19	$\mathrm{MPa\ m^{-2}\ a^2}$
A =	3.1689E-24	$\mathrm{kg^{-3}\ m^3\ s^5}$	1.0126E-61	$\mathrm{kg^{-3}\ m^3\ a^5}$	100	$\mathrm{MPa^{-3}\ a^{-1}}$
η =	5.4037E+07	$\mathrm{kg\ m^{-1}\ s^{-5/3}}$	1.7029E+20	$\mathrm{kg\ m^{-1}\ a^{-5/3}}$	0.1710	$\mathrm{MPa\ a^{1/3}}$

The diagnostic problem



```
   ! the variable taken to evaluate the Arrhenius law
   ! in general this should be the temperature relative
   ! to pressure melting point. The suggestion below plugs
   ! in the correct value obtained with TemperateIceSolver
   !  Temperature Field Variable = String "Temp Homologous"
   ! the temperature to switch between the
   ! two regimes in the flow law
   Limit Temperature = Real -10.0
   ! In case there is no temperature variable (which here is the case)
   Constant Temperature = Real -3.0

   ! Heat transfer stuff (will come later)
   !Temp Heat Capacity = Variable Temp
   !  Real MATC "capacity(tx)*(31556926.0)^(2.0)"

   !Temp Heat Conductivity = Variable Temp
   !  Real MATC "conductivity(tx)*31556926.0*1.0E-06"

   !Temp Upper Limit = Variable Depth
   !     Real MATC "273.15 - 9.8E-08 * tx * 910.0 * 9.81" !-> this is the correct
ion of the presure melting point with respect to the hydrostatic overburden at t
he point
 End

Body Force 1
  Name = "BodyForce1"
  Heat Source = 1
  Flow BodyForce 1 = Real 0.0
  Flow BodyForce 2 = Real $-9.81 * (31556926.0)^(2.0)  !MPa - a - m
End
```

We set our glacier to be at -3 C

Now commented, needed later

Gravity, scaled to deliver results in m/a and MPa

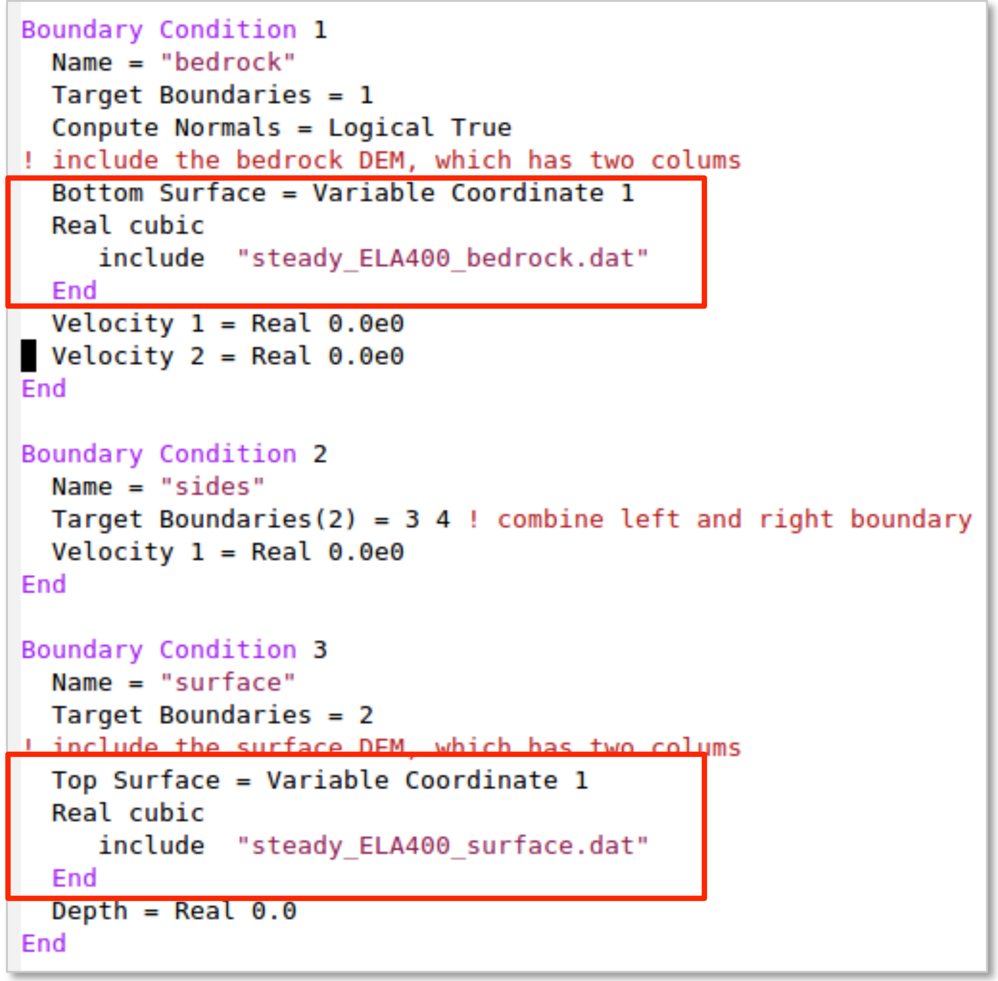
The diagnostic problem

- Boundary conditions:
  - using array function for reading surfaces
  - **`Real [cubic]`** expects two columned row:

    $x_1 \quad z_1$

    $x_2 \quad z_2$

    …
  - **`include`** just inserts external file (length)
  - Right values interpolated by matching interval of left values for input variable



```
Boundary Condition 1
  Name = "bedrock"
  Target Boundaries = 1
  Conpute Normals = Logical True
! include the bedrock DEM, which has two colums
  Bottom Surface = Variable Coordinate 1
  Real cubic
     include  "steady_ELA400_bedrock.dat"
  End
  Velocity 1 = Real 0.0e0
  Velocity 2 = Real 0.0e0
End

Boundary Condition 2
  Name = "sides"
  Target Boundaries(2) = 3 4 ! combine left and right boundary
  Velocity 1 = Real 0.0e0
End

Boundary Condition 3
  Name = "surface"
  Target Boundaries = 2
! include the surface DEM, which has two colums
  Top Surface = Variable Coordinate 1
  Real cubic
     include  "steady_ELA400_surface.dat"
  End
  Depth = Real 0.0
End
```

The diagnostic problem

- Now, run the case:

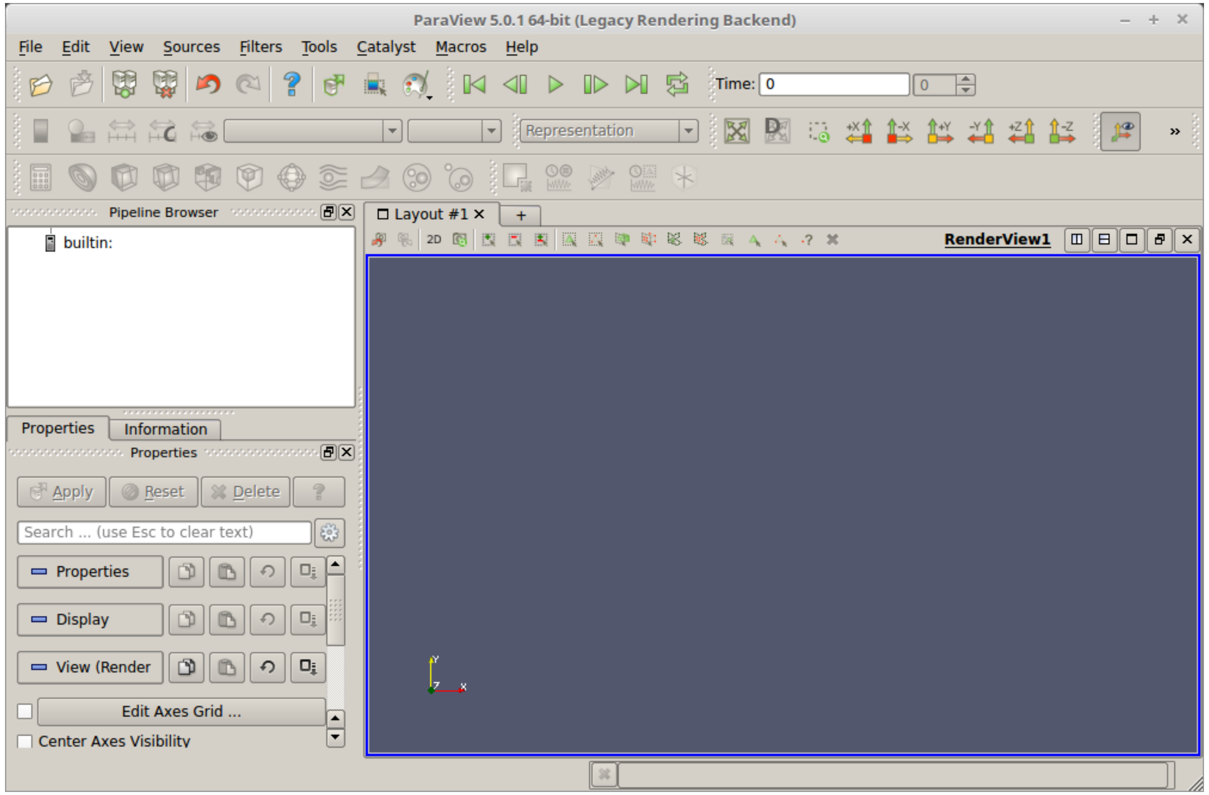
```
$ ElmerSolver Stokes_diagnostic.sif
```

  - You will see the convergence history displayed:

```
FlowSolve: -------------------------------------
FlowSolve:  NAVIER-STOKES ITERATION          23
FlowSolve: -------------------------------------
FlowSolve:
FlowSolve: Starting Assembly...
FlowSolve: Assembly done
FlowSolve: Dirichlet conditions done
ComputeChange: NS (ITER=23) (NRM,RELC): (  1.6112696
0.90361030E-03 ) :: navier-stokes
FlowSolve: iter:   23 Assembly: (s)    0.26    6.04
FlowSolve: iter:   23 Solve:    (s)    0.11    2.62
FlowSolve:  Result Norm     :    1.6112695610649261
FlowSolve:  Relative Change :    9.0361030224648782E-004
```

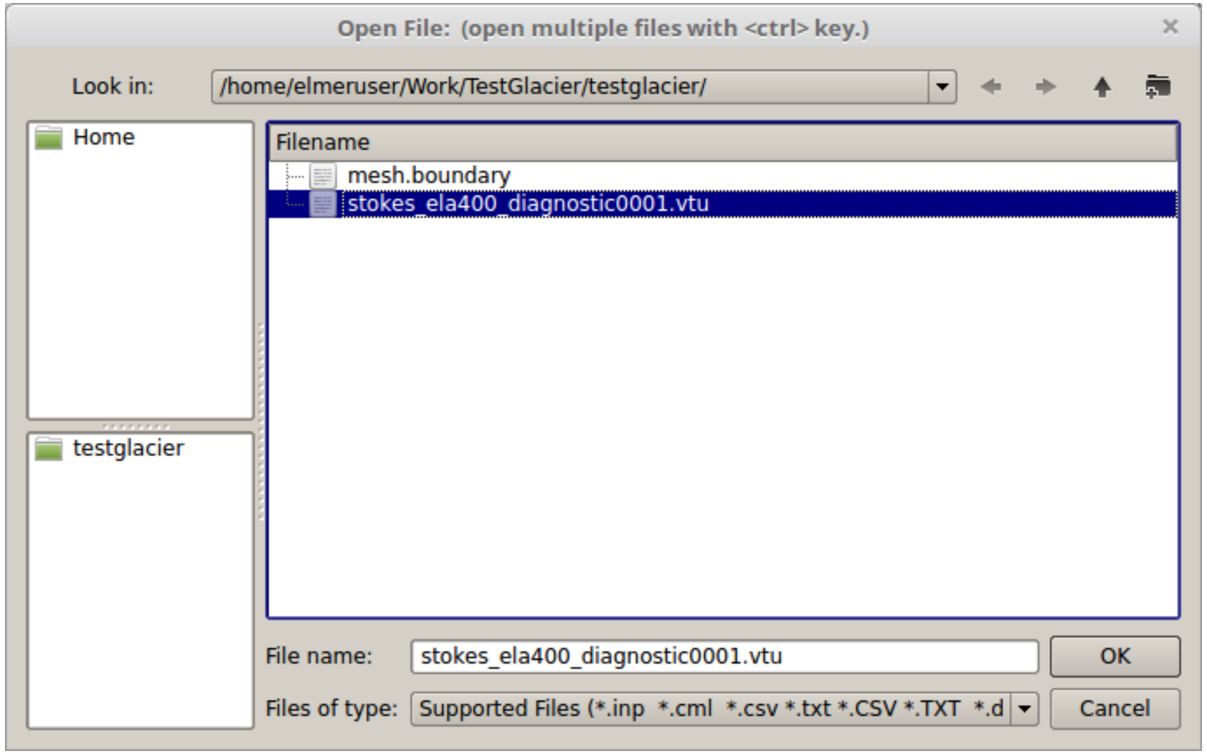
The diagnostic problem

- Post-processing using ParaView: **`$ paraview`**



The diagnostic problem

- File → Open `stokes_ela400_diagnostic0001.vtu`



Open File: (open multiple files with <ctrl> key.)
Look in:
Home
testglacier
Filename
mesh.boundary
stokes_ela400_diagnostic0001.vtu
OK
Cancel

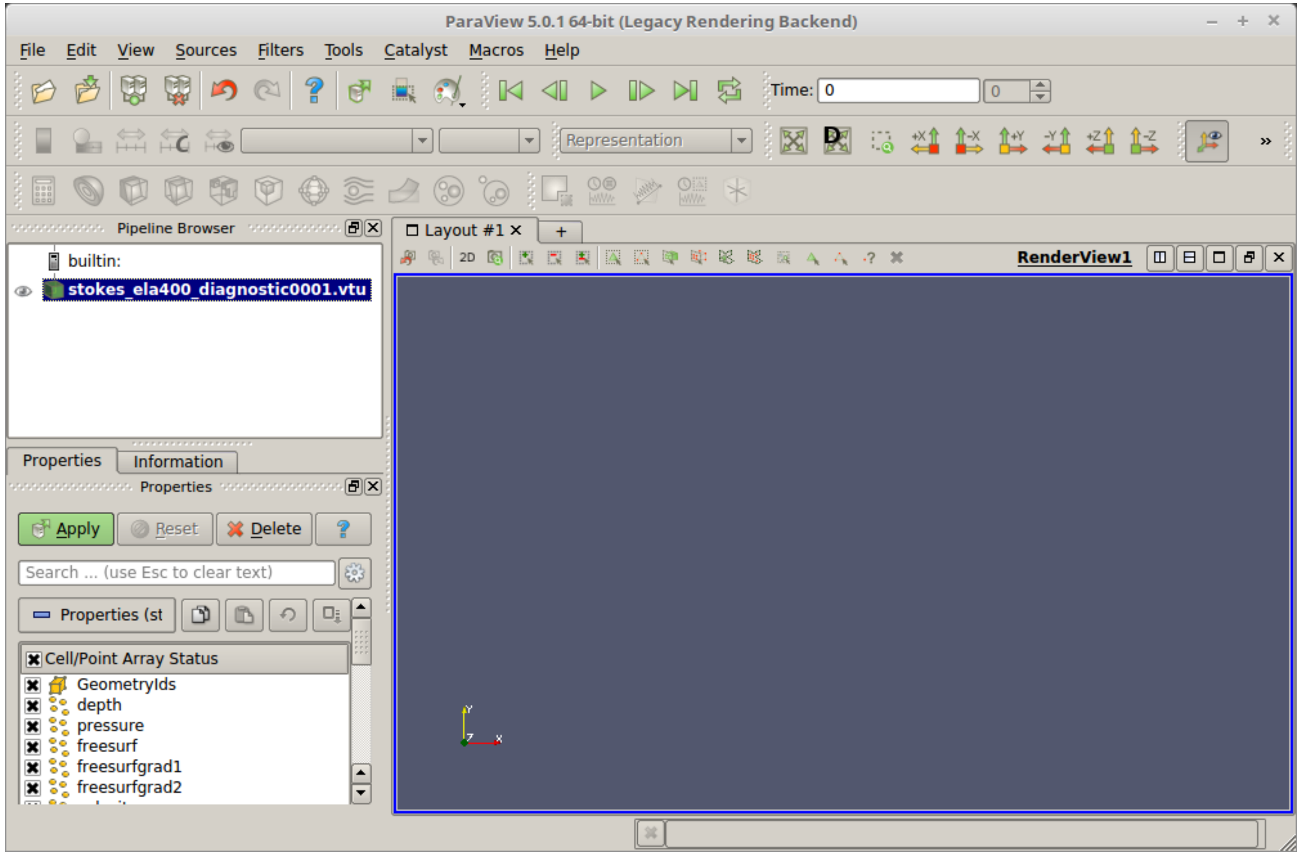
Look in: /home/elmeruser/Work/TestGlacier/testglacier/

File name: stokes_ela400_diagnostic0001.vtu

Files of type: Supported Files (*.inp *.cml *.csv *.txt *.CSV *.TXT *.d

The diagnostic problem

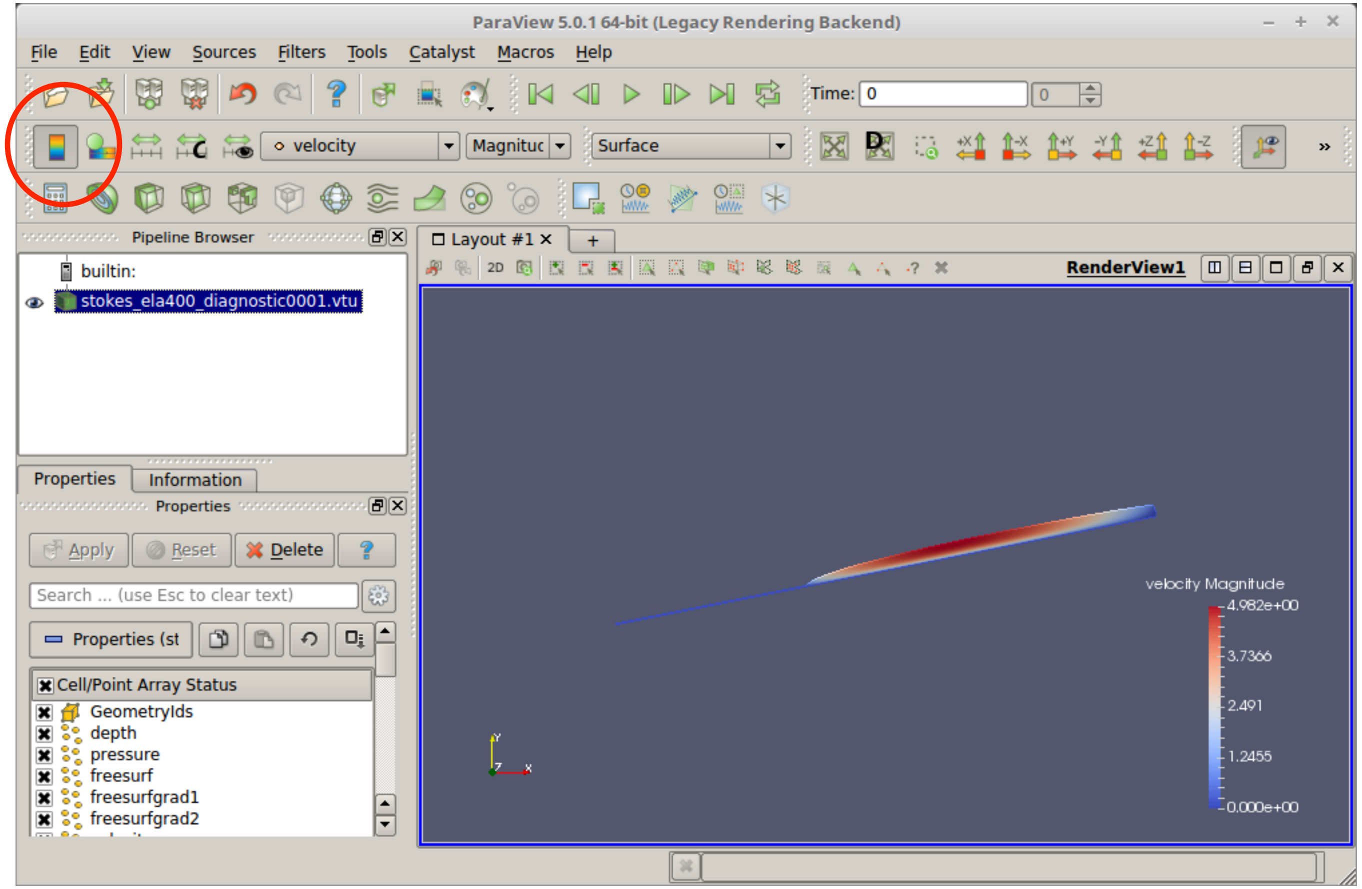
- Apply



The diagnostic problem

- Change to **velocity**

Press to activate colour bar



ParaView 5.0.1 64-bit (Legacy Rendering Backend)
File Edit View Sources Filters Tools Catalyst Macros Help
Pipeline Browser
builtin:
stokes_ela400_diagnostic0001.vtu
Layout #1
RenderView1
2D
Properties Information
Properties
Apply Reset Delete
Search ... (use Esc to clear text)
Properties (st
velocity Magnitude
4.982e+00
3.7366
2.491
1.2455
0.000e+00
Y
Z
X

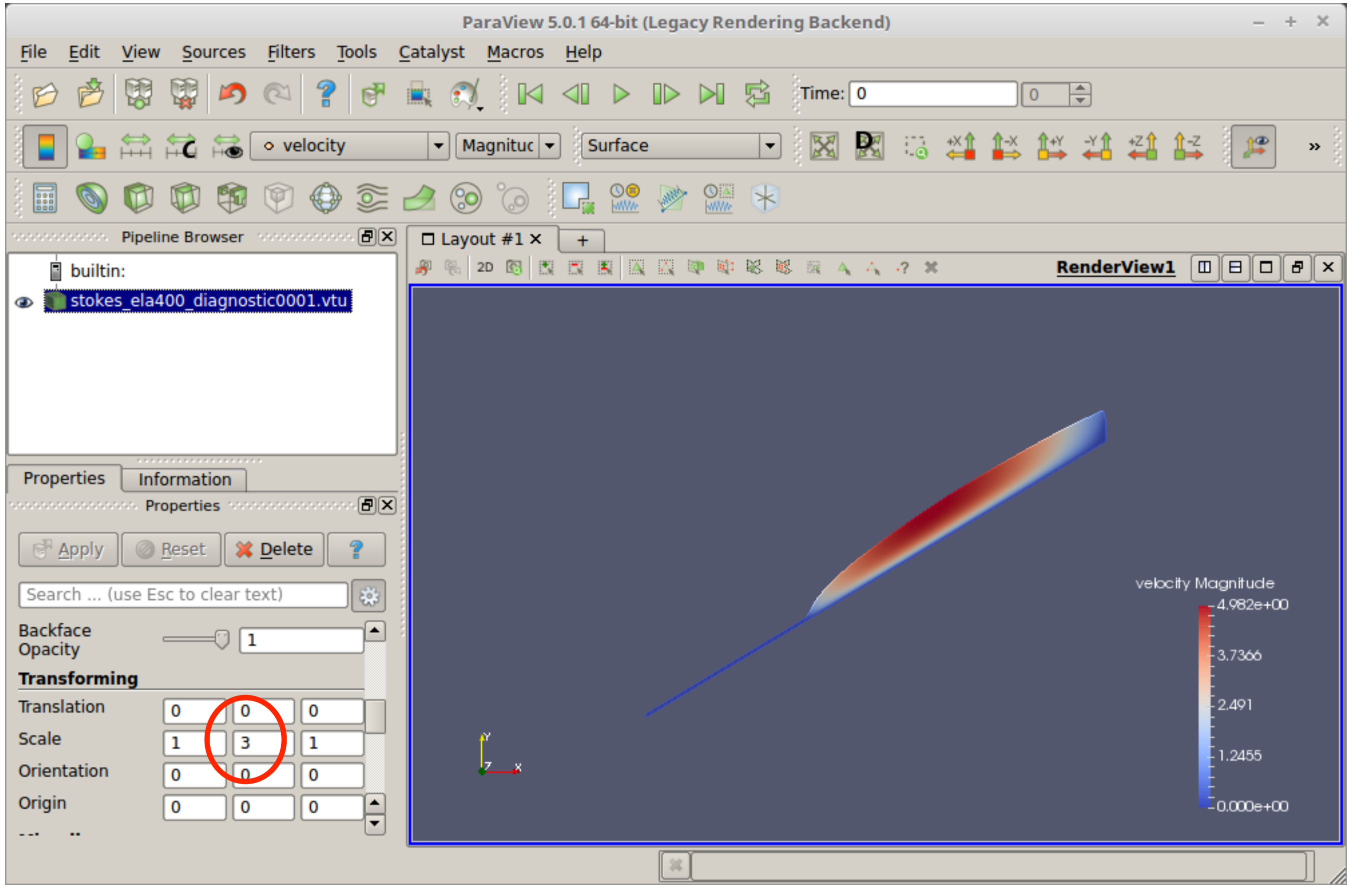
Time: 0 | 0

○ velocity | Magnituc | Surface

☒ Cell/Point Array Status
☒ GeometryIds
☒ depth
☒ pressure
☒ freesurf
☒ freesurfgrad1
☒ freesurfgrad2

The diagnostic problem

- Scale



Time: 0

velocity | Magnitude | Surface

builtin:

stokes_ela400_diagnostic0001.vtu

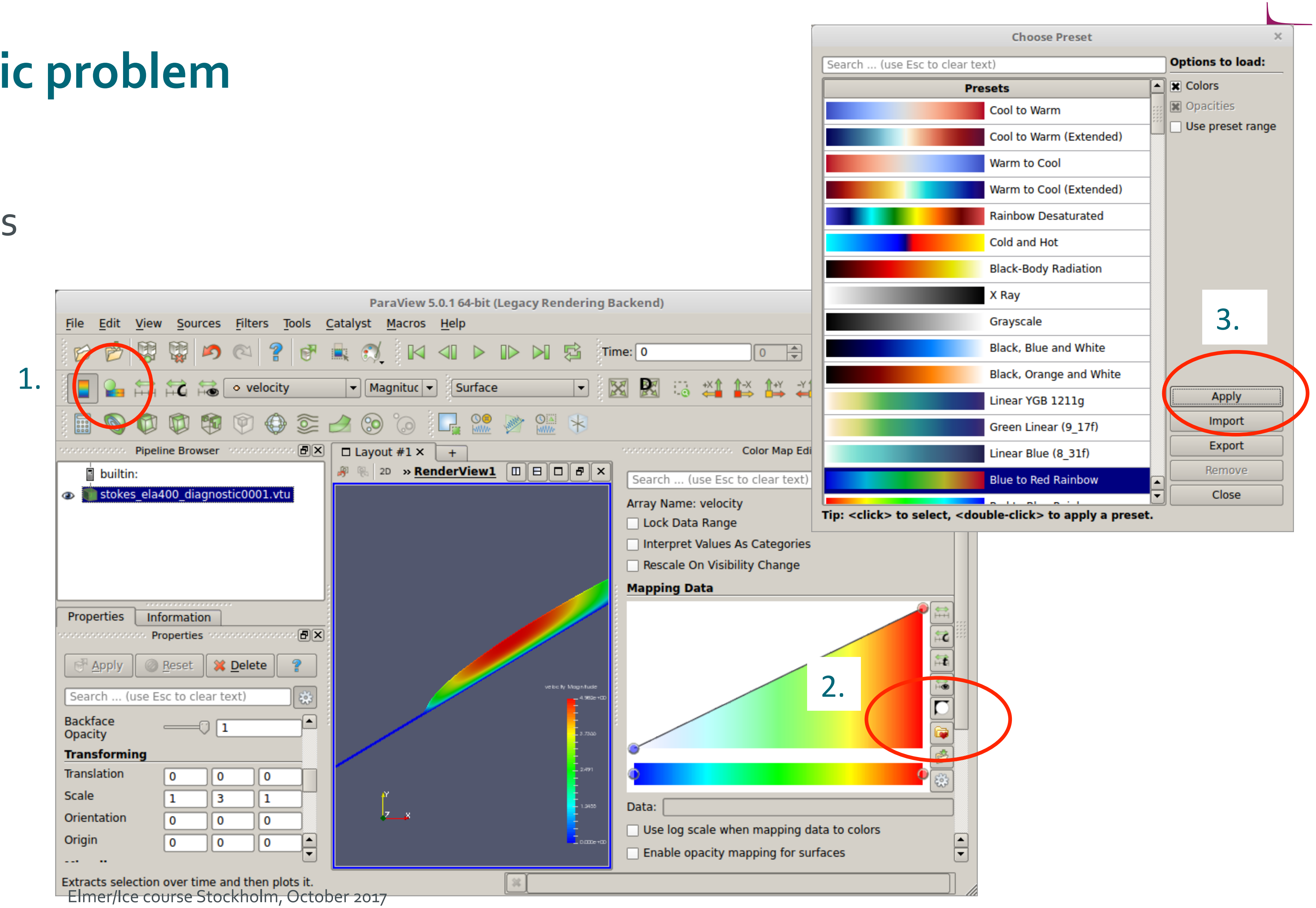
Backface Opacity 1

Transforming

Translation	0	0	0
Scale	1	3	1
Orientation	0	0	0
Origin	0	0	0

The diagnostic problem

- Change colours



ParaView 5.0.1 64-bit (Legacy Rendering Backend)

Time: 0

velocity | Magnitude | Surface

Pipeline Browser

builtin:

stokes_ela400_diagnostic0001.vtu

Backface Opacity: 1

Transforming

Translation	0	0	0
Scale	1	3	1
Orientation	0	0	0
Origin	0	0	0

Extracts selection over time and then plots it.

Color Map Editor

Array Name: velocity

☐ Lock Data Range

☐ Interpret Values As Categories

☐ Rescale On Visibility Change

Mapping Data

Data:

☐ Use log scale when mapping data to colors

☐ Enable opacity mapping for surfaces

Choose Preset

Options to load:

☒ Colors

☒ Opacities

☐ Use preset range

Presets

- Cool to Warm
- Cool to Warm (Extended)
- Warm to Cool
- Warm to Cool (Extended)
- Rainbow Desaturated
- Cold and Hot
- Black-Body Radiation
- X Ray
- Grayscale
- Black, Blue and White
- Black, Orange and White
- Linear YGB 1211g
- Green Linear (9_17f)
- Linear Blue (8_31f)
- Blue to Red Rainbow

Tip: <click> to select, <double-click> to apply a preset.

Sliding

- Different sliding laws in Elmer
- Simplest: Linear Weertman $\boldsymbol{\tau} = \beta^2 \boldsymbol{u}$
  - This is formulated for the traction $\boldsymbol{\tau}$ and velocity $\boldsymbol{u}$ in tangential plane
- In order to define properties in normal-tangential coordinates:

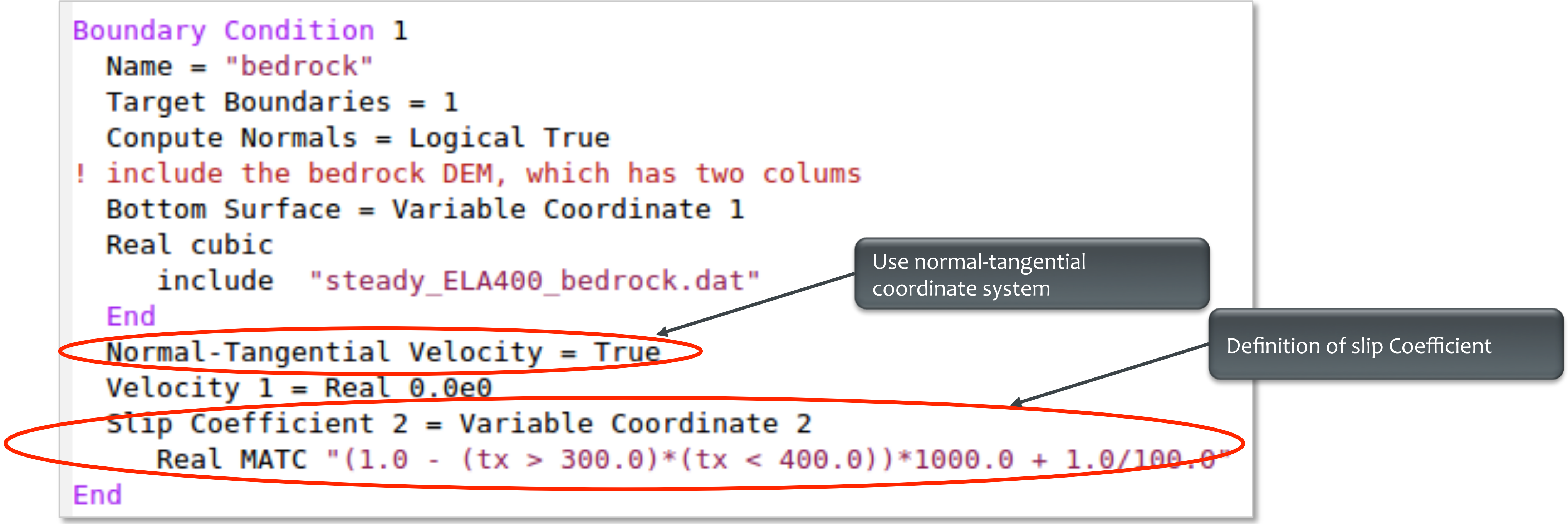
```
Normal-Tangential Velocity = True
```

- β^{-2} is the `Slip Coefficient {2,3}` (for the tangential directions 2 and 3) (for 3D, in 2d only direction 2)
- Setting normal velocity to zero (no-penetration)

```
Velocity 1 = 0.0
```

Sliding

- Now we introduce sliding
  - We deploy a sliding zone between z=300 and 400m

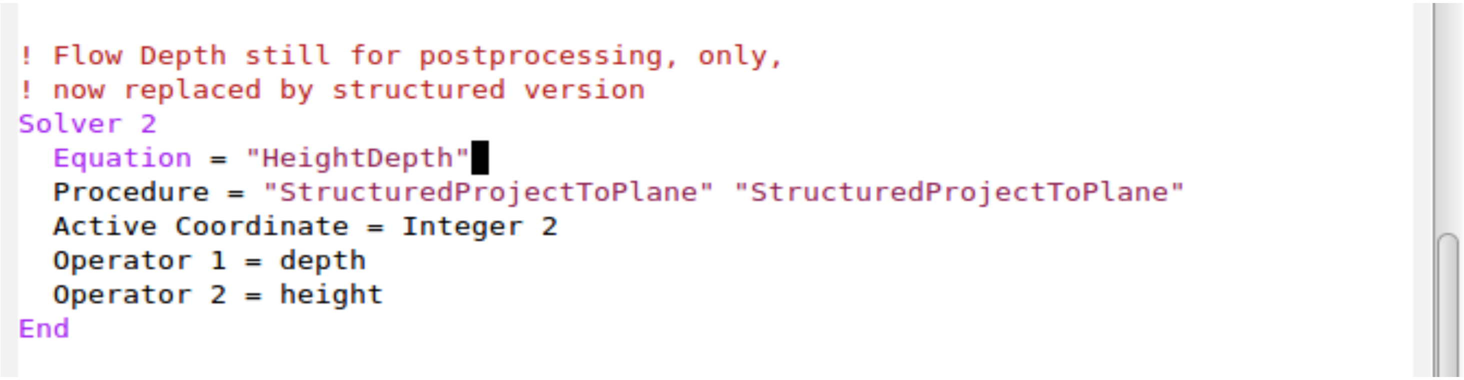


```
Boundary Condition 1
  Name = "bedrock"
  Target Boundaries = 1
  Conpute Normals = Logical True
! include the bedrock DEM, which has two colums
  Bottom Surface = Variable Coordinate 1
  Real cubic
     include  "steady_ELA400_bedrock.dat"
  End
  Normal-Tangential Velocity = True
  Velocity 1 = Real 0.0e0
  Slip Coefficient 2 = Variable Coordinate 2
     Real MATC "(1.0 - (tx > 300.0)*(tx < 400.0))*1000.0 + 1.0/100.0"
End
```

Use normal-tangential coordinate system

Definition of slip Coefficient

Sliding

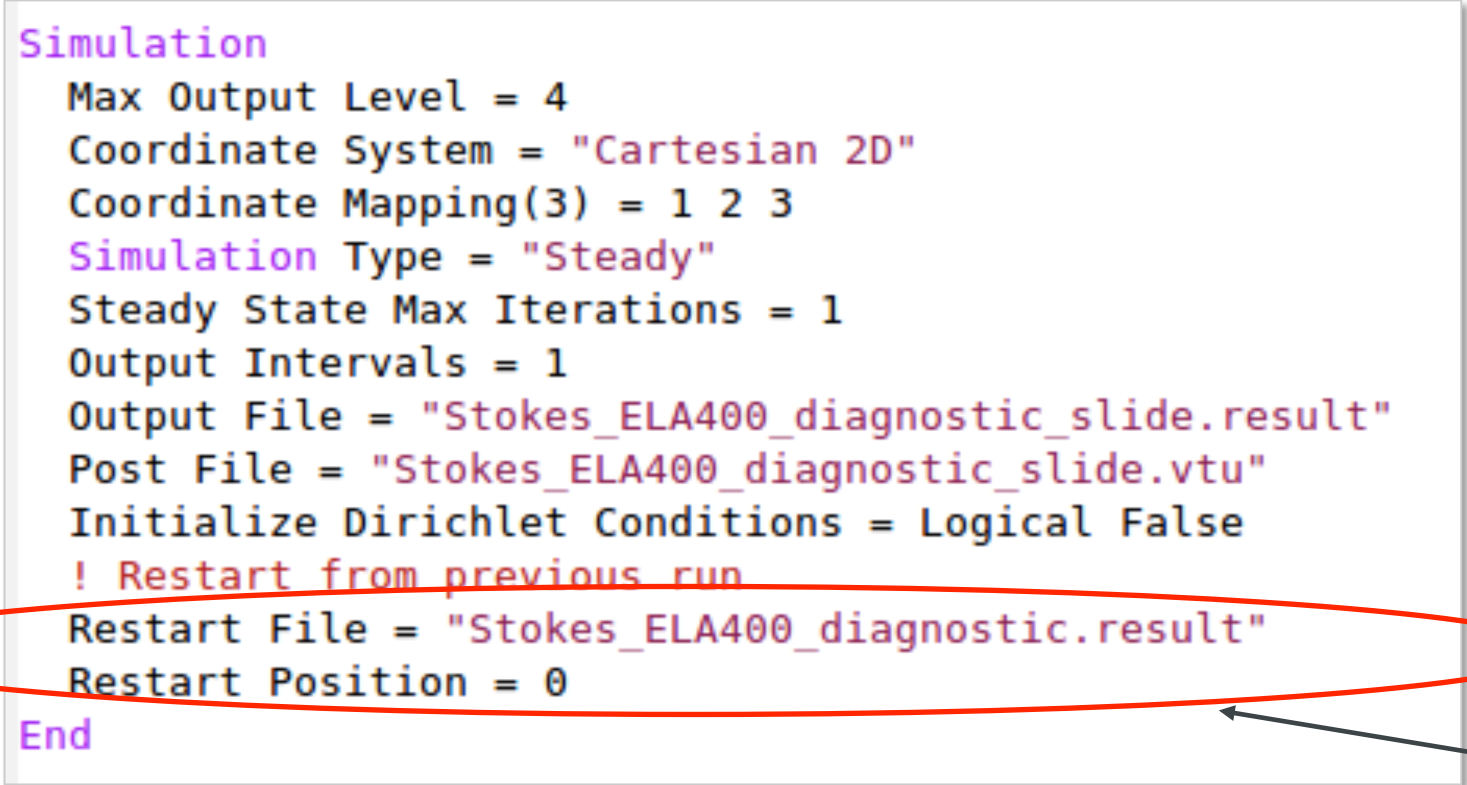


```
! Flow Depth still for postprocessing, only,
! now replaced by structured version
Solver 2
  Equation = "HeightDepth"
  Procedure = "StructuredProjectToPlane" "StructuredProjectToPlane"
  Active Coordinate = Integer 2
  Operator 1 = depth
  Operator 2 = height
End
```

Replace the `FlowDepth` Solver with this one. This solver simply uses the vertically structured mesh to inquire the Depth/Height without solving a PDE (much cheaper).

Sliding

- Restart from previous run (improved initial guess)



```
Simulation
  Max Output Level = 4
  Coordinate System = "Cartesian 2D"
  Coordinate Mapping(3) = 1 2 3
  Simulation Type = "Steady"
  Steady State Max Iterations = 1
  Output Intervals = 1
  Output File = "Stokes_ELA400_diagnostic_slide.result"
  Post File = "Stokes_ELA400_diagnostic_slide.vtu"
  Initialize Dirichlet Conditions = Logical False
  ! Restart from previous run
  Restart File = "Stokes_ELA400_diagnostic.result"
  Restart Position = 0
End
```

Load the last entry in file

Sliding

- Now, run the case:

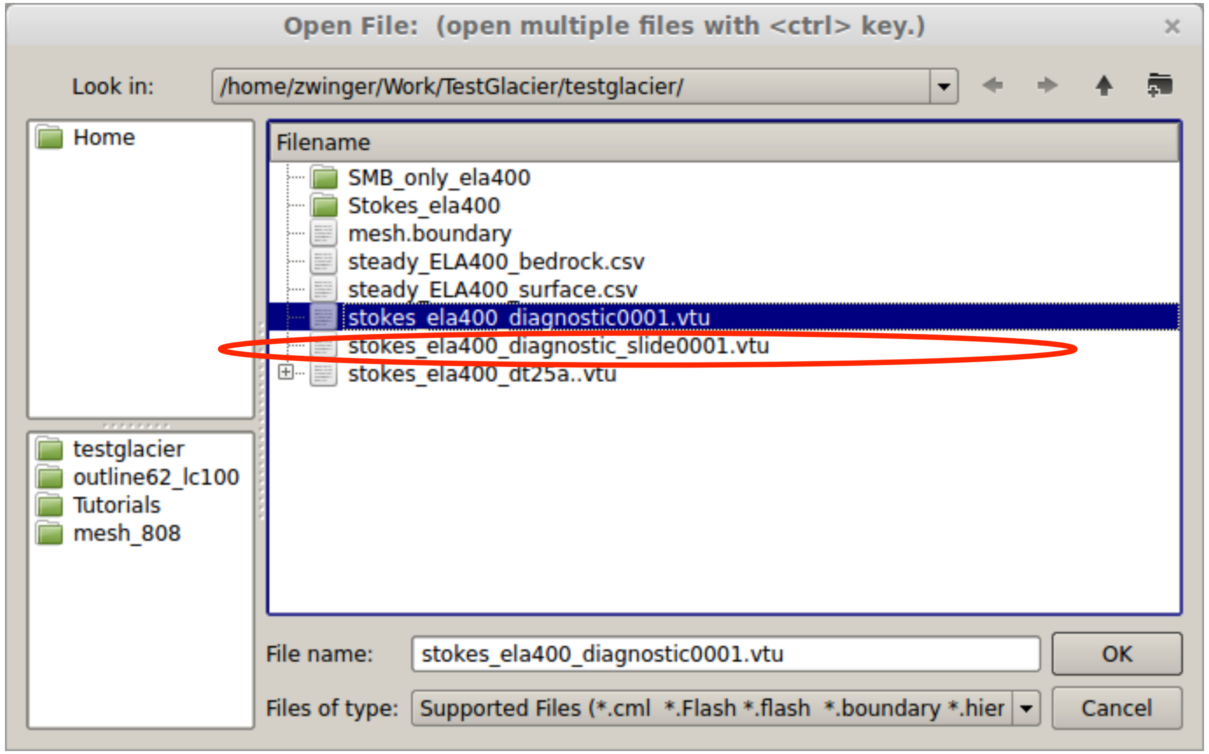
$ ElmerSolver Stokes_diagnostic_slide.sif

  - Converged much earlier:

```
FlowSolve: -------------------------------------
FlowSolve:  NAVIER-STOKES ITERATION          12
FlowSolve: -------------------------------------
FlowSolve:
FlowSolve: Starting Assembly...
FlowSolve: Assembly done
FlowSolve: Dirichlet conditions done
ComputeChange: NS (ITER=12) (NRM,RELC): (  3.4915753
0.34732117E-05 ) :: navier-stokes
FlowSolve: iter:   12 Assembly: (s)    0.32    3.53
FlowSolve: iter:   12 Solve:    (s)    0.12    1.38
FlowSolve:  Result Norm      :    3.4915753430899730
FlowSolve:  Relative Change :    3.4732116934487441E-006
ComputeChange: SS (ITER=1) (NRM,RELC): (  3.4915753
2.0000000      ) :: navier-stokes
```

Sliding

- Load parallel to previous file
- **File → Open** `stokes_ela400_diagnostic_slide0001.vtu`



Open File: (open multiple files with <ctrl> key.)

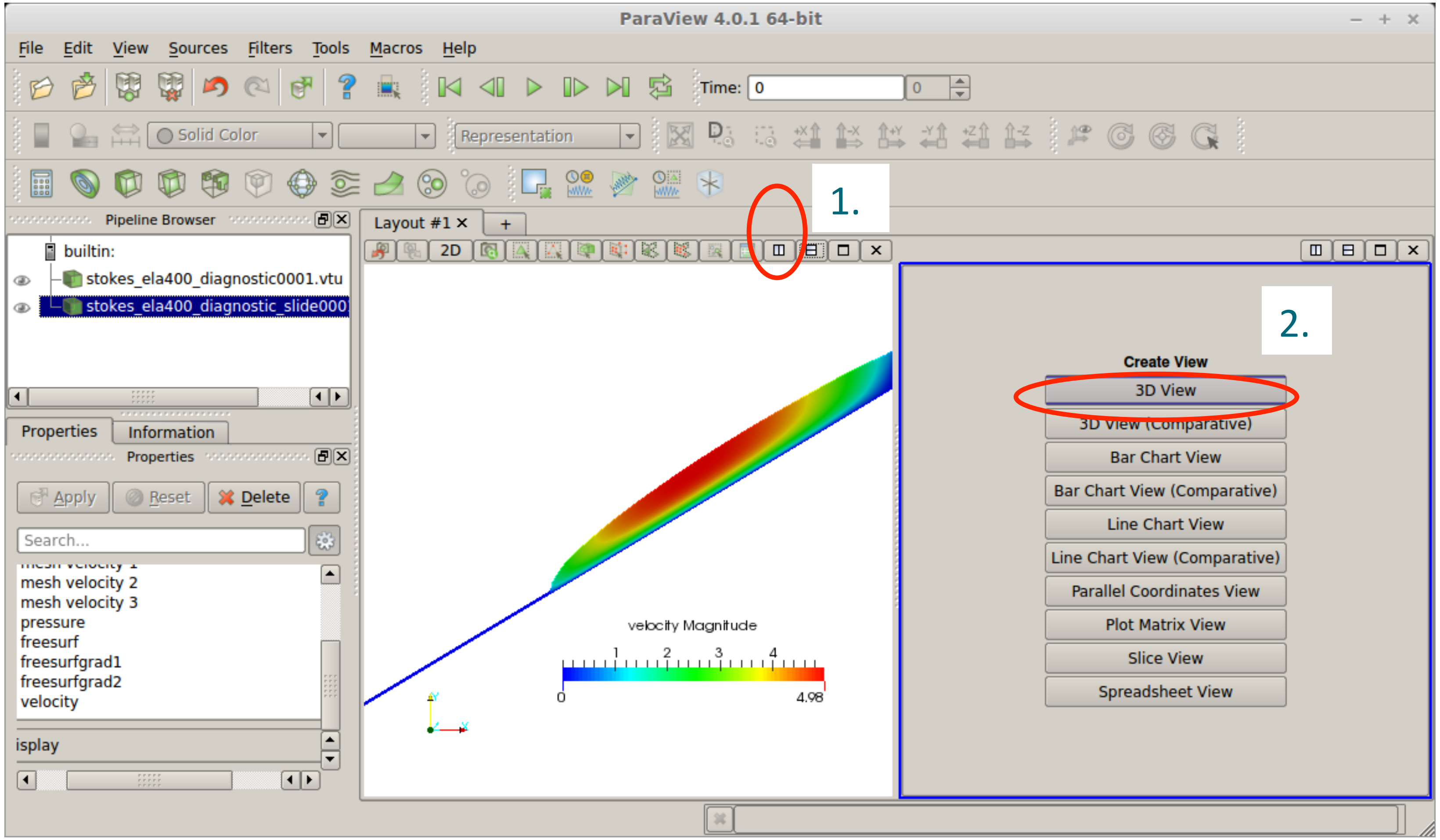
Look in: /home/zwinger/Work/TestGlacier/testglacier/

Filename
- SMB_only_ela400
- Stokes_ela400
- mesh.boundary
- steady_ELA400_bedrock.csv
- steady_ELA400_surface.csv
- stokes_ela400_diagnostic0001.vtu
- stokes_ela400_diagnostic_slide0001.vtu
- stokes_ela400_dt25a..vtu

File name: stokes_ela400_diagnostic0001.vtu

Files of type: Supported Files (*.cml *.Flash *.flash *.boundary *.hier

Sliding

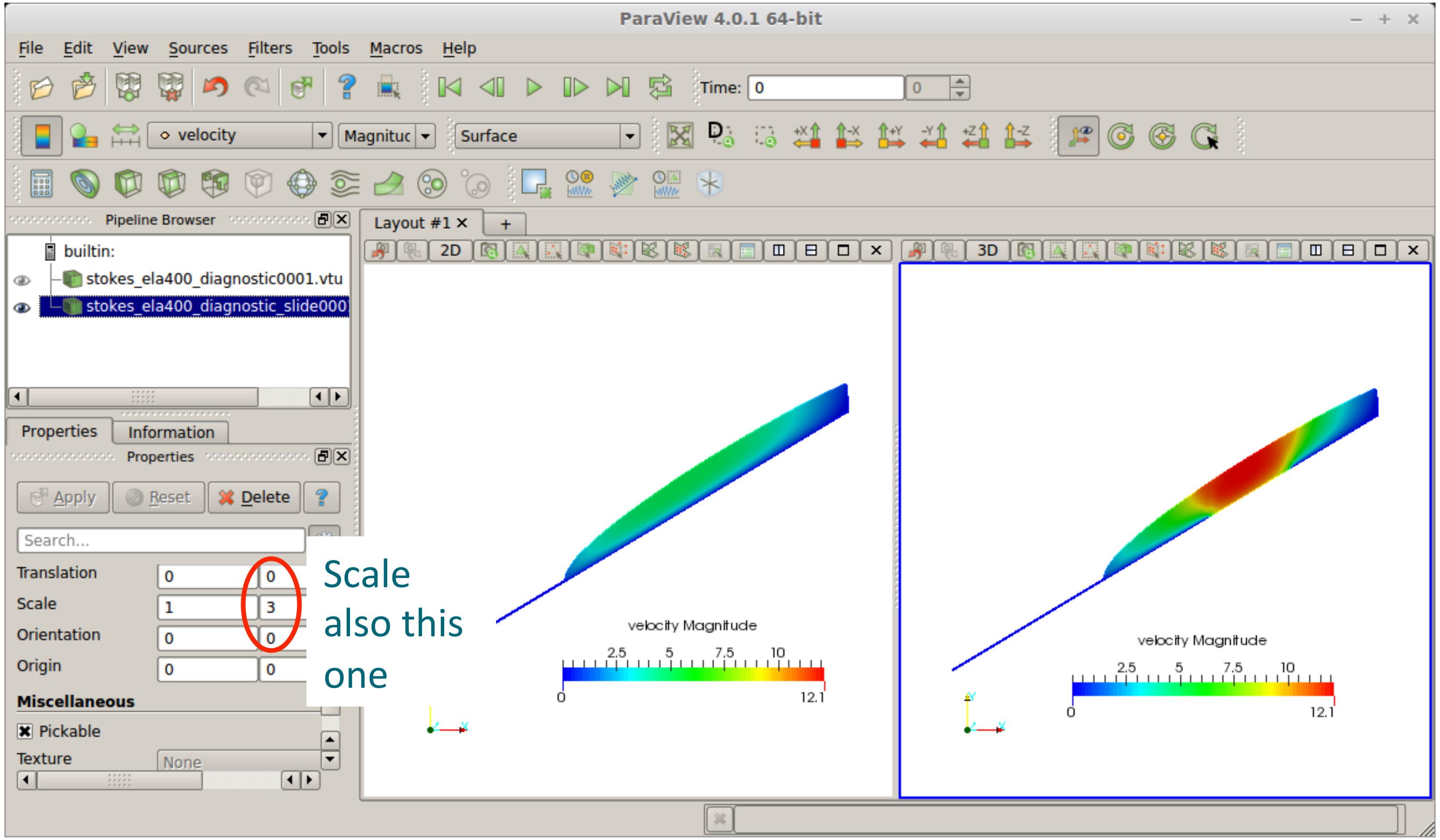


ParaView 4.0.1 64-bit
File
Edit
View
Sources
Filters
Tools
Macros
Help
Time: 0
Solid Color
Representation
Pipeline Browser
builtin:
stokes_ela400_diagnostic0001.vtu
stokes_ela400_diagnostic_slide000
Properties
Information
Apply
Reset
Delete
Search...
mesh velocity 2
mesh velocity 3
pressure
freesurf
freesurfgrad1
freesurfgrad2
velocity
isplay
Layout #1
2D
velocity Magnitude
0
1
2
3
4
4.98
Create View
3D View
3D View (Comparative)
Bar Chart View
Bar Chart View (Comparative)
Line Chart View
Line Chart View (Comparative)
Parallel Coordinates View
Plot Matrix View
Slice View
Spreadsheet View

1.

2.

Sliding



builtin:
- stokes_ela400_diagnostic0001.vtu
- stokes_ela400_diagnostic_slide000

Translation	0	0
Scale	1	3
Orientation	0	0
Origin	0	0

☒ Pickable

Texture: None

Scale also this one

End of first session

Summary in keywords:

- Basic diagnostic (= steady state with prescribed geometry) simulation
- Linear system, Non-linear system solution
- Read-in of simple DEM, manipulation of initial mesh using table interpolation in Elmer
- Introduction of interpreted MATC function

HEAT TRANSFER

Starting from the diagnostic setup of the previous session we:

- Compute the temperature for a given velocity field and boundary conditions
- Set up runs on fixed geometry
- Introduce sliding
- Introduce heat transfer (thermo-mechanical coupling)
- Write a simple MATC function (interpreted functions)

Heat transfer

- Adding heat transfer:
  - Add `ElmerIceSolvers TemperateIceSolver` with variable name `Temp` (see next slide)
  - Surface temperature distribution: linear from 273.15 K at z=0m to 263.15 K at z=1000m

```
Temp = Variable Coordinate 2
     Real
           0.0   273.15
        1000.0   263.15
     End
```

  - Geothermal heat flux of 200 mW m^{-2} at bedrock

```
 Temp Flux BC = Logical True
 Temp Heat Flux = Real $ 0.200 * (31556926.0)*1.0E-06
```

Heat transfer

```
Solver 5
  Equation = String "Homologous Temperature Equation"
  Procedure =  File "ElmerIceSolvers" "TemperateIceSolver"
  Variable = String "Temp"
  Variable DOFs = 1
  Stabilize = True
  Optimize Bandwidth = Logical True
  Linear System Solver = "Iterative"
  Linear System Direct Method = UMFPACK
  Linear System Convergence Tolerance = 1.0E-06
  Linear System Abort Not Converged = False
  Linear System Preconditioning = "ILU1"
  Linear System Residual Output = 0
  Nonlinear System Convergence Tolerance = 1.0E-05
  Nonlinear System Max Iterations = 100
  Nonlinear System Relaxation Factor = Real 9.999E-01
  Steady State Convergence Tolerance = 1.0E-04
End
```

Heat transfer

- Material parameters in Material section

```
Material 1
…
 ! Heat transfer stuff
  Temp Heat Capacity = Variable Temp
    Real MATC "capacity(tx)*(31556926.0)^(2.0)"

  Temp Heat Conductivity = Variable Temp
    Real MATC "conductivity(tx)*31556926.0*1.0E-06"
End
```

- Using defined MATC-functions for
  - Capacity: $c(T) = 146.3 + (7.253 \cdot T[\mathrm{K}])$
  - Conductivity: $\kappa(T) = 9.828 \exp\left(-5.7 \times 10^{-3} \cdot T[\mathrm{K}]\right)$

Heat transfer

- Material parameters in Material section

```
!! conductivity
$ function conductivity(T)  { _conductivity=9.828*exp(-5.7E-03*T)}
!! capacity
$ function capacity(T) { _capacity=146.3+(7.253*T)}
```

- Using defined MATC-functions for
  - Capacity: $$c(T) = 146.3 + (7.253 \cdot T[\mathrm{K}])$$
  - Conductivity: $$\kappa(T) = 9.828 \exp\left(-5.7 \times 10^{-3} \cdot T[\mathrm{K}]\right)$$

Heat transfer

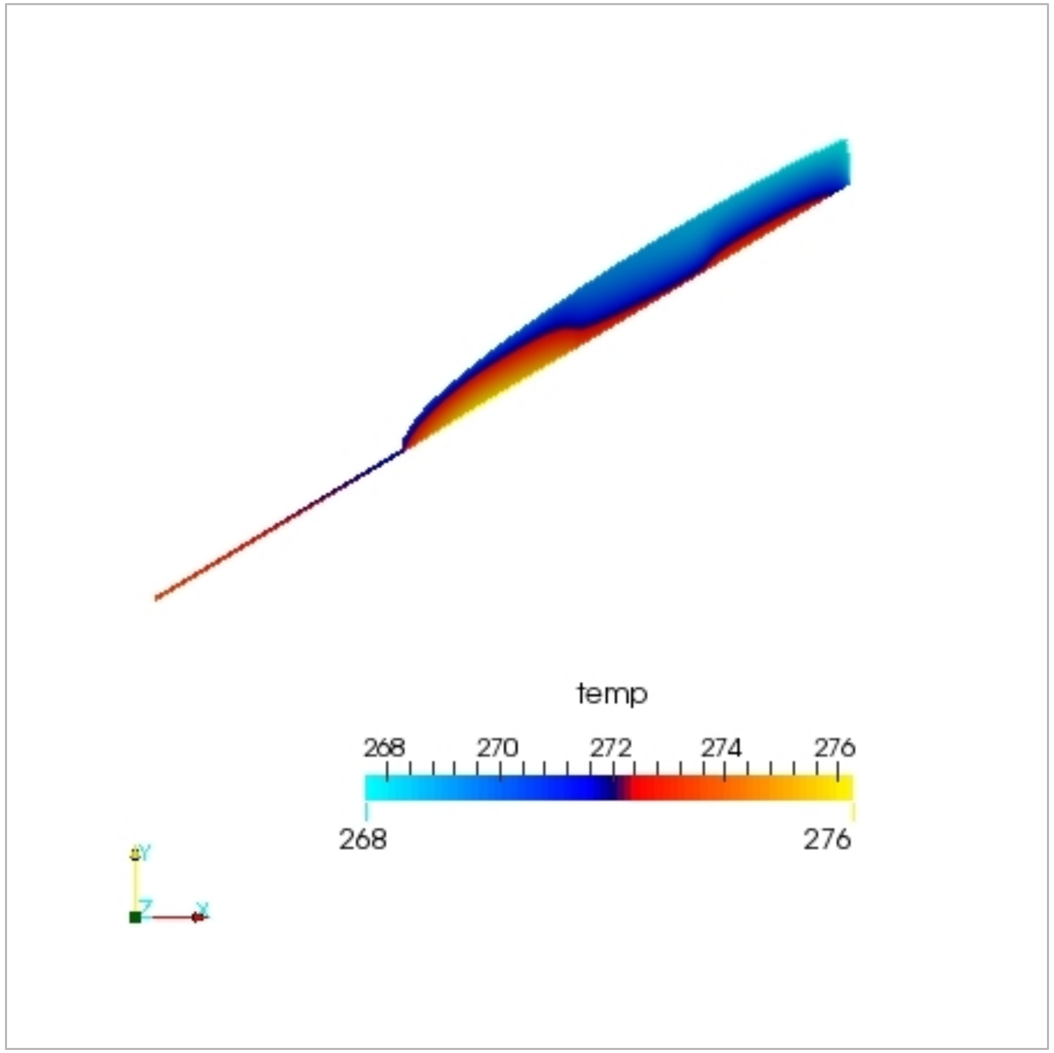
- Now, run the case:

```
$ ElmerSolver Stokes_diagnostic_temp.sif
```

- It goes pretty quick, as we only have one-way coupling and hence don’t even execute the Stokes solver

```
Solver 3
  Exec Solver = "Never" ! we have a solution from previous case
  Equation = "Navier-Stokes"
```

Heat transfer



- Due to high geothermal heatflux we have areas above pressure melting point
- We have to account for this

Heat transfer

- Constrained heat transfer:
  - Including following lines in Solver section of `TemperateIceSolver`

```
! the contact algorithm (aka Dirichlet algorithm)
!-----------------------------------------------------
 Apply Dirichlet = Logical True
! those two variables are needed in order to store
! the relative or homologous temperature as well
! as the residual
!-------------------------------------------------
Exported Variable 1 = String "Temp Homologous"
Exported Variable 1 DOFs = 1
Exported Variable 2 = String "Temp Residual"
Exported Variable 2 DOFs = 1
```

Heat transfer

- Constrained heat transfer:
  - Also introduce the upper limit for the temperature (a.k.a. pressure melting point) in the Material section

```
Temp Upper Limit = Variable Depth
       Real MATC "273.15 - 9.8E-08 * tx * 910.0 * 9.81"
```

$$T_{\mathrm{pm}} = T_0 + \beta_{\mathrm{c}} p$$

$$p \approx \rho_{\mathrm{ice}} g\, d$$

Heat transfer

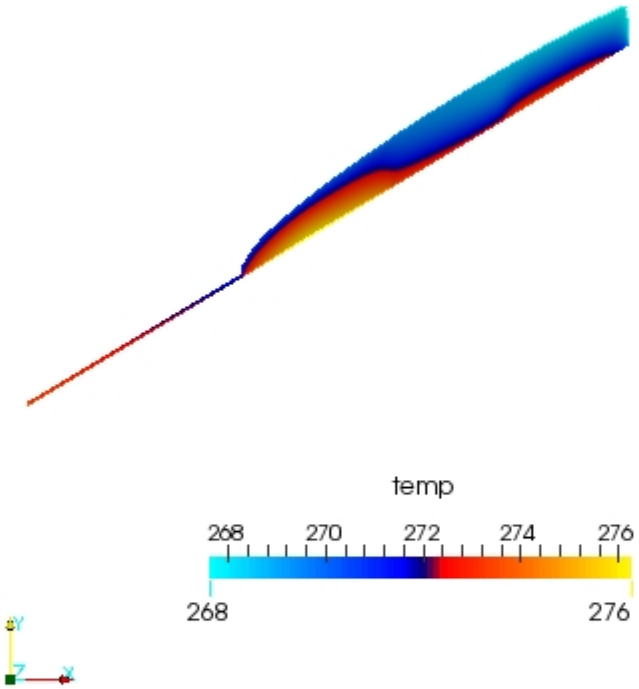
- Now, run the case:

```
$ ElmerSolver   \
  Stokes_diagnostic_temp_constrained.sif
```

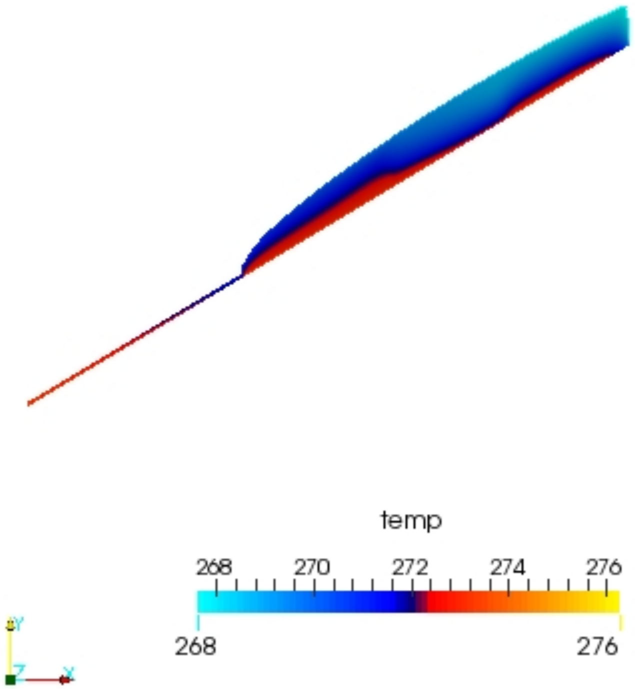
- Already from the norm (~ averaged nodal values) it comes clear that values are in general now lower

```
TemperateIceSolver (temp): iter:    5 Assembly: (s)    1.36    6.77
TemperateIceSolver (temp): iter:    5 Solve:    (s)    0.00    0.01
TemperateIceSolver (temp):  Result Norm   :    271.78121462656480
TemperateIceSolver (temp):  Relative Change :
5.0215061382786350E-006
ComputeChange: SS (ITER=1) (NRM,RELC): (  271.78121
2.0000000     ) :: homologous temperature equation
```

Heat transfer



Unconstrained



Constrained

Heat transfer

- **Thermo-mechanically coupled** simulation:
  - We have to iterate between Stokes and HTEq.

```
Steady State Max Iterations = 20
```

  - Coupling to viscosity in Material section

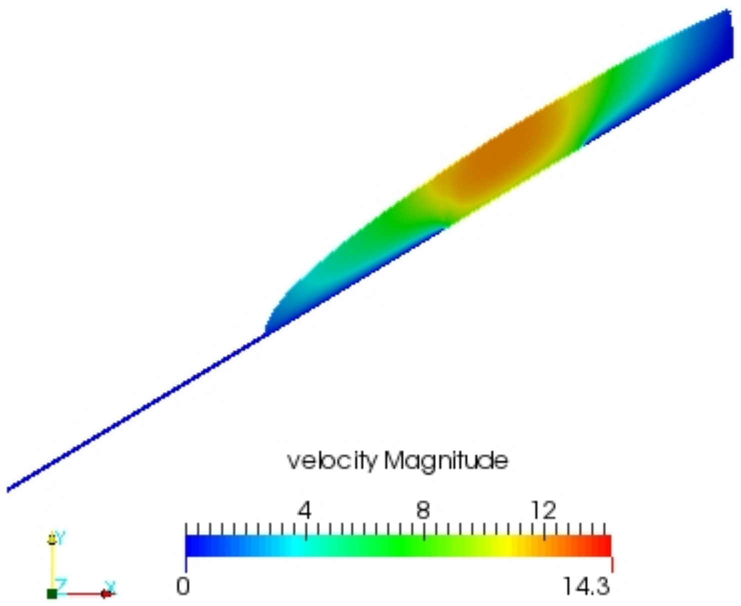
```
! the variable taken to evaluate the Arrhenius law
! in general this should be the temperature relative
! to pressure melting point. The suggestion below plugs
! in the correct value obtained with TemperateIceSolver
Temperature Field Variable = String "Temp Homologous"
```

Newton Iterations

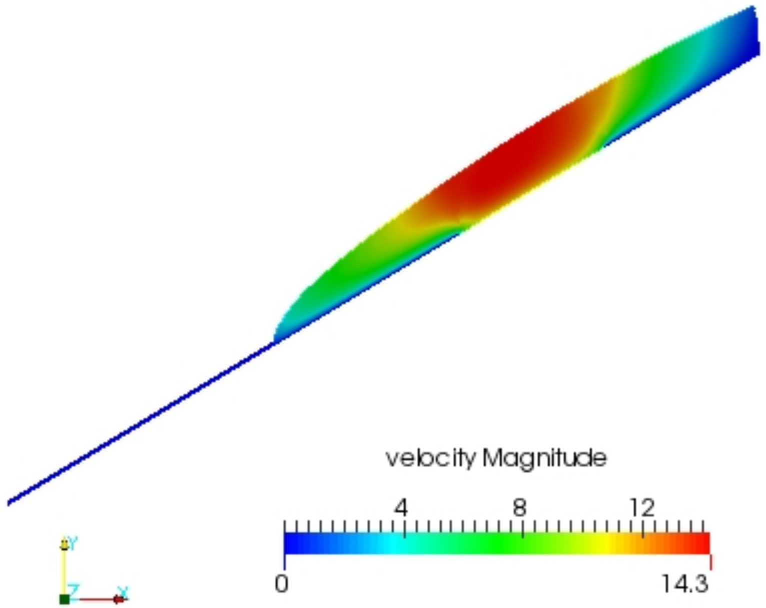
- We need Picard (=fixed-point) iterations instead of Newton iterations at the beginning of each new non-linear iteration loop

```
Solver 1
!  Exec Solver = "Never"
  Equation = "Navier-Stokes‟
…
  Nonlinear System Reset Newton = Logical True
  !Nonlinear System Relaxation Factor = 0.75
End
```

Heat transfer



Uncoupled (constant T)



Thermo-mechanically coupled

End of third session

Summary in keywords:

- Basic diagnostic (= steady state with prescribed geometry) simulation including heat transfer
- Thermo-mechanically coupled system

PROGNOSTIC RUN

- Starting from a deglaciated situation we show
- How to move to a transient run, i.e., introduce the
  - Free surface solution
  - Including coupling to climate via prescribing an accumulation/ ablation function
- How to write a less simple MATC function

The prognostic problem

- Glacier with ~11 deg constant inclination
- Standard accumulation/ablation function

$$a(z) = \lambda\, z + a(z=0)$$

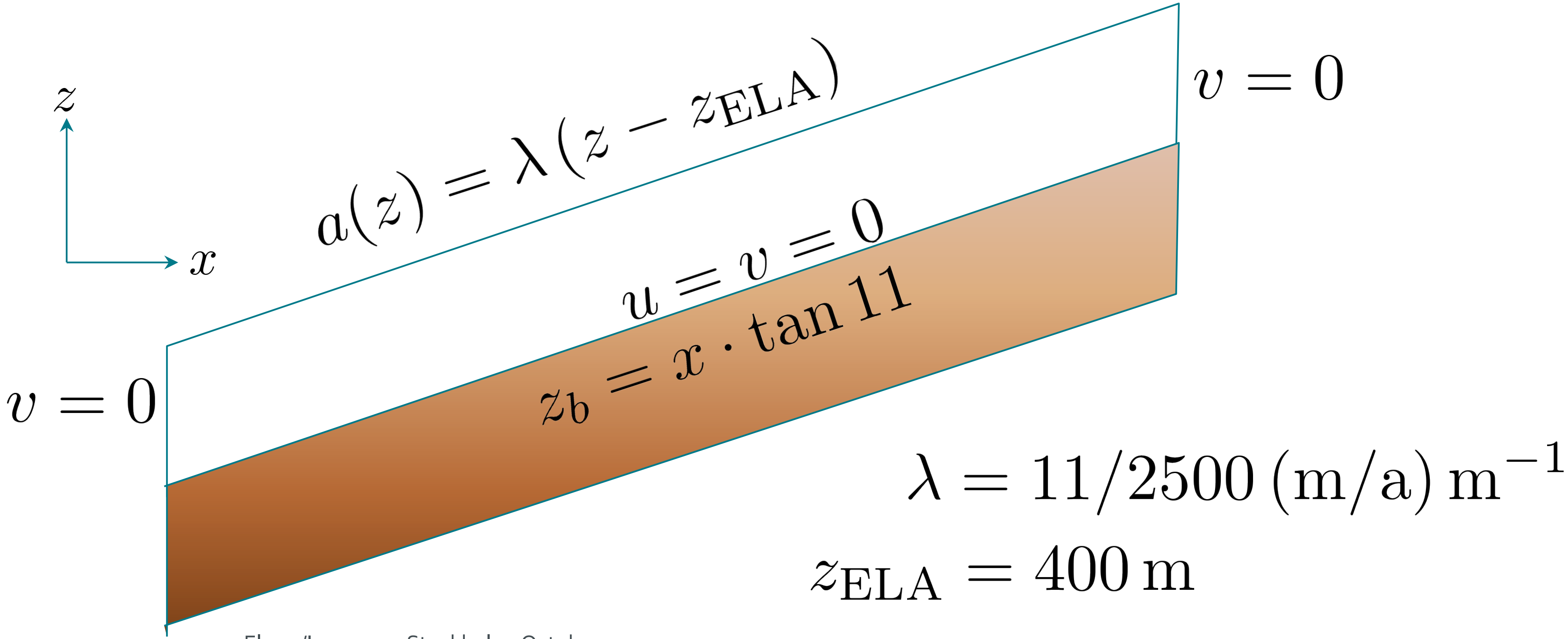
- Or in terms of ELA (equilibrium line altitude):

$$a_{\mathrm{ELA}} = \lambda\, z_{\mathrm{ELA}} + a_0 = 0$$

- We know lapserate, λ , and z_{ELA} and have to define $a_0 = -\lambda\, z_{\mathrm{ELA}}$

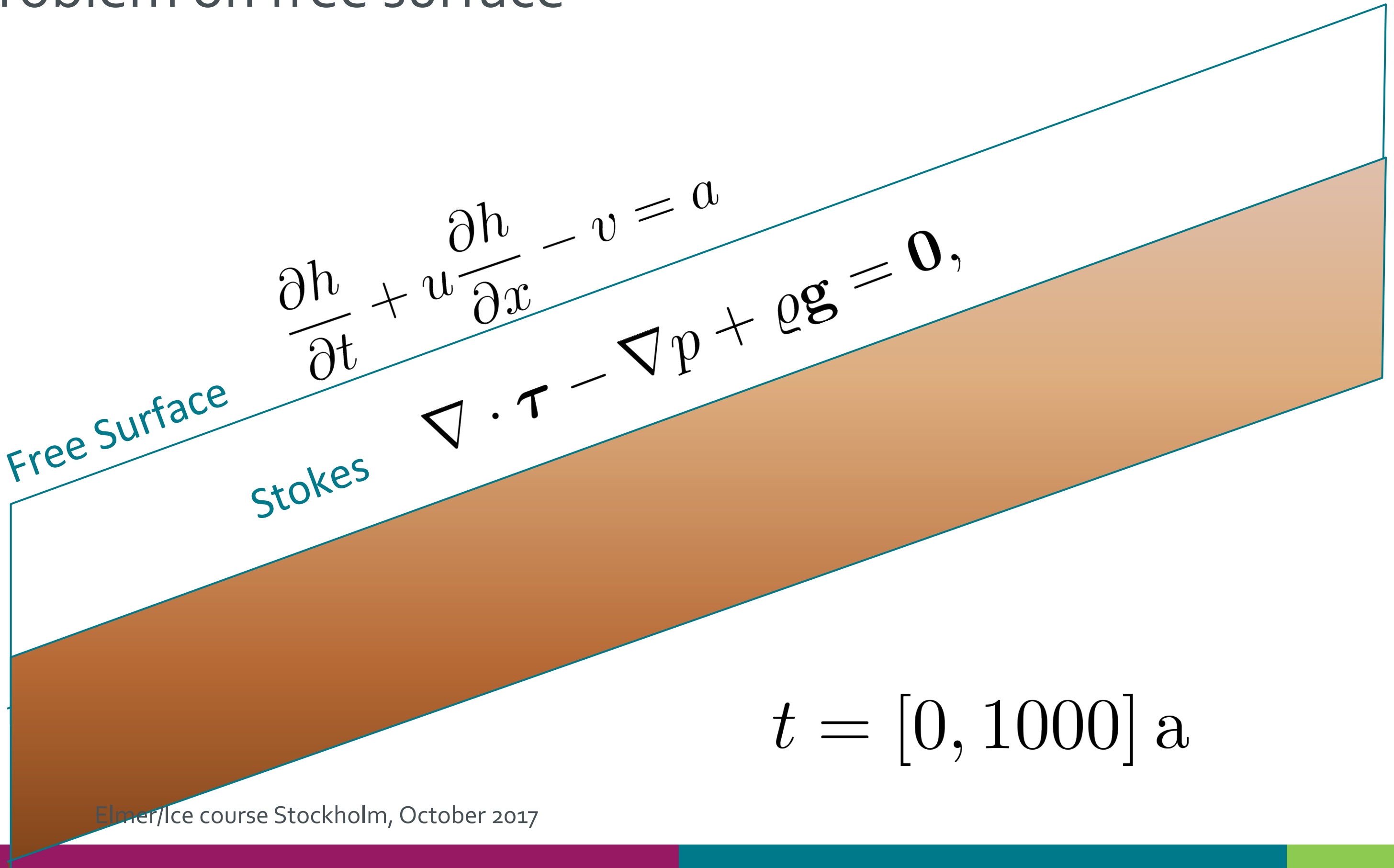
The Problem

- From x=[0 :2500], z=[0:500]
- Setting mesh with 10 vertical levels with 5m flow depth


z
x
$a(z) = \lambda\,(z - z_{\mathrm{ELA}})$
$v = 0$
$u = v = 0$
$z_{\mathrm{b}} = x \cdot \tan 11$
$v = 0$
$\lambda = 11/2500\,(\mathrm{m/a})\,\mathrm{m}^{-1}$
$z_{\mathrm{ELA}} = 400\,\mathrm{m}$

The Problem

- Flow problem (Navier-Stokes) in ice
- Free-surface problem on free surface


Free Surface
$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} - v = a$
Stokes
$\nabla \cdot \boldsymbol{\tau} - \nabla p + \varrho \mathbf{g} = \mathbf{0},$

$$t = [0, 1000]\ \mathrm{a}$$

Time Stepping

```
Simulation
  Max Output Level = 4
  Coordinate System =  File "Cartesian 2D"
  Coordinate Mapping(3) = 1 2 3
  Simulation Type = "Transient"
  Steady State Max Iterations = 1
  Timestepping Method = "BDF"
  BDF Order = 1
  Timestep Sizes = 10.0     ! Delta t (Real) of one step
  Timestep Intervals = 200 ! Amount (Integer) of steps taken
  Output Intervals = 10     ! Interval (Integer) of writing data
  Post File = "Stokes_prognostic_ELA400_SMBonly.vtu”
  Initialize Dirichlet Conditions = Logical False
End
```

Free Surface Equation

```
Solver 4
  Equation = String "Free Surface"
  Procedure =  File “FreeSrufaceSolver" “FreeSurfaceSolver"
  Exec Solver = always
  Variable = String "Zs"
  Variable DOFs =  1
  ! needed for evaluating the contact pressure
  Exported Variable 1 = -dofs 1 "Zs Residual“
  ! needed for storing the initial shape (needed for updates)
  Exported Variable 2 = -dofs 1 "RefZs"
  Procedure = "FreeSurfaceSolver" "FreeSurfaceSolver“
  ! This would take the contrained points out of solution
  ! Use in serial run, only
  ! Before Linsolve = "EliminateDirichlet" "EliminateDirichlet"
```

Free Surface Equation

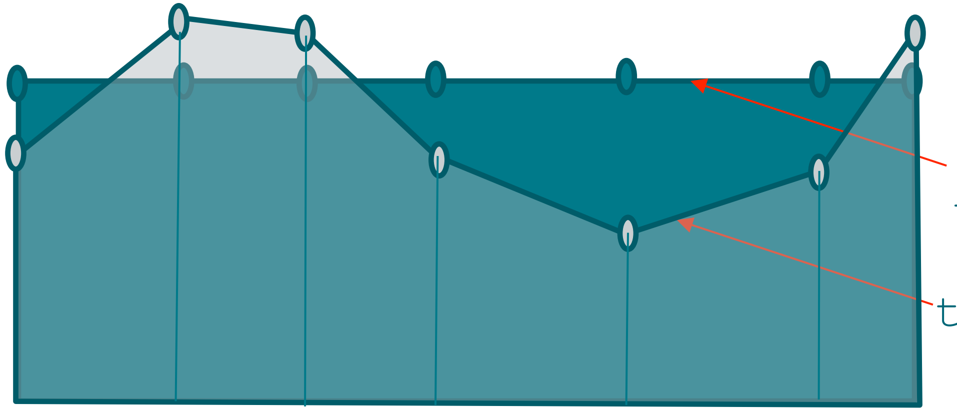
```
  Linear System Solver = Iterative
  Linear System Max Iterations = 1500
  Linear System Iterative Method = BiCGStab
  Linear System Preconditioning = ILU0
  Linear System Convergence Tolerance = Real 1.0e-7
  Linear System Abort Not Converged = False
  Linear System Residual Output = 1
  Nonlinear System Max Iterations = 100
  Nonlinear System Convergence Tolerance  = 1.0e-6
  Nonlinear System Relaxation Factor = 0.60
  Steady State Convergence Tolerance = 1.0e-03
  Stabilization Method = Bubbles
  ! Apply contact problem
  Apply Dirichlet = Logical True
End
```

Free Surface Equation

```
Body 2
  Name = "Surface"
  Body Force = 2
  Equation = 2
  Material = 2
  Initial Condition = 2
End
Equation 2
  Name = "Equation2"
  Convection = "none" !change to "computed"
  Active Solvers(1) = 3
  Flow Solution Name = String "Flow Solution"
End
```

Free Surface Equation

```
Boundary Condition 3
  Name = "surface"
  Top Surface = Equals "Zs"
  Target Boundaries = 2
  Body ID = 2
  Depth = Real 0.0
End
```



t=0: Zs = RefZs

t>0:
Top Surface = Zs

Free Surface Equation

- Starting with same values for both variables

```
Initial Condition 2
  Zs = Equals Coordinate 2
  RefZs = Equals Coordinate 2
End
```

- Using the latter to keep minimal height

```
Material 2
  Min Zs = Variable RefZs
    Real MATC "tx - 0.1"
  Max Zs = Variable RefZs
    Real MATC "tx + 600.0"
End
```

Free Surface Equation

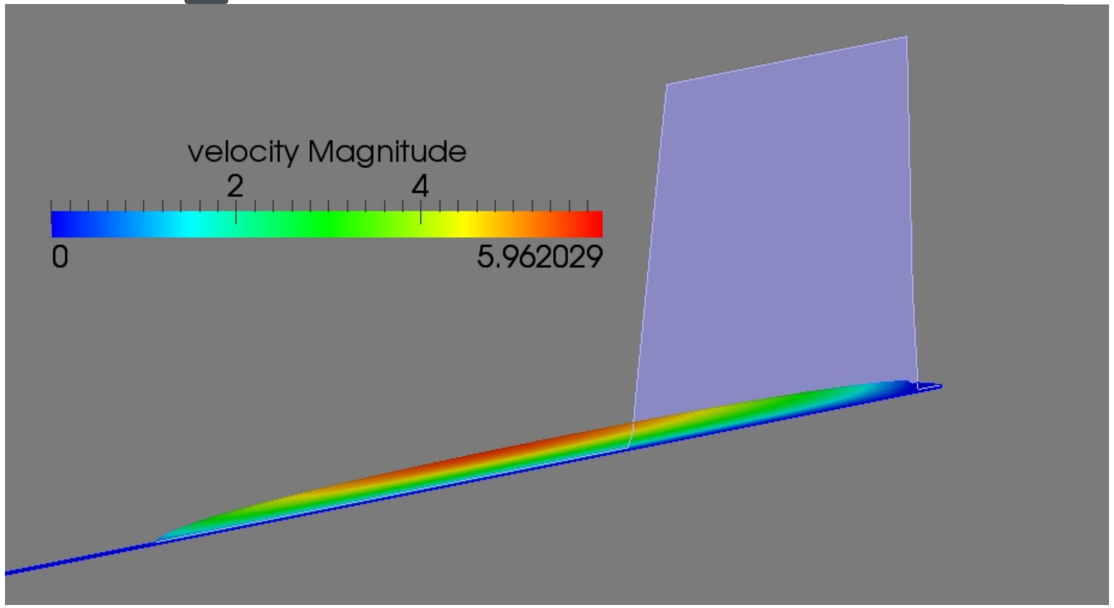
- And here comes the coupling to climate (as a general MATC function)

```
Body Force 2
  Name = "Climate"
  Zs Accumulation Flux 1 = Real 0.0e0
  Zs Accumulation Flux 2 = Variable Coordinate 1, Coordinate 2
       Real MATC "accum(tx)"
End
```

```
$ function accum(X) {\
  lapserate = (11.0/2750.0);\
  ela = 400.0;\
  atsl = -ela*lapserate;\
  if (X(0) > 2500)\
    {_accum = 0.0;}\
  else\
   { _accum = lapserate*X(1) + atsl;}\
}
```

The Solution

- Starting with no-flow problem, i.e., only surface mass balance, simply by setting Convection = “none” and (saves time) not executing Navier-Stokes, compare to run with coupled flow
- $ **ElmerSolver Stokes_prognostic.sif**



End of fourth session

Summary in keywords:

- Basic prognostic (= time dependent with prescribed surface mass balance) simulation
- Introduced general MATC function to prescribe accumulation/ablation function

USER DEFINED FUNCTION

In a follow-up session (most likely time will not allow), by changing the previous setup we show:

- How to write, compile and include a self-written user defined function
- How to introduce time changing variables

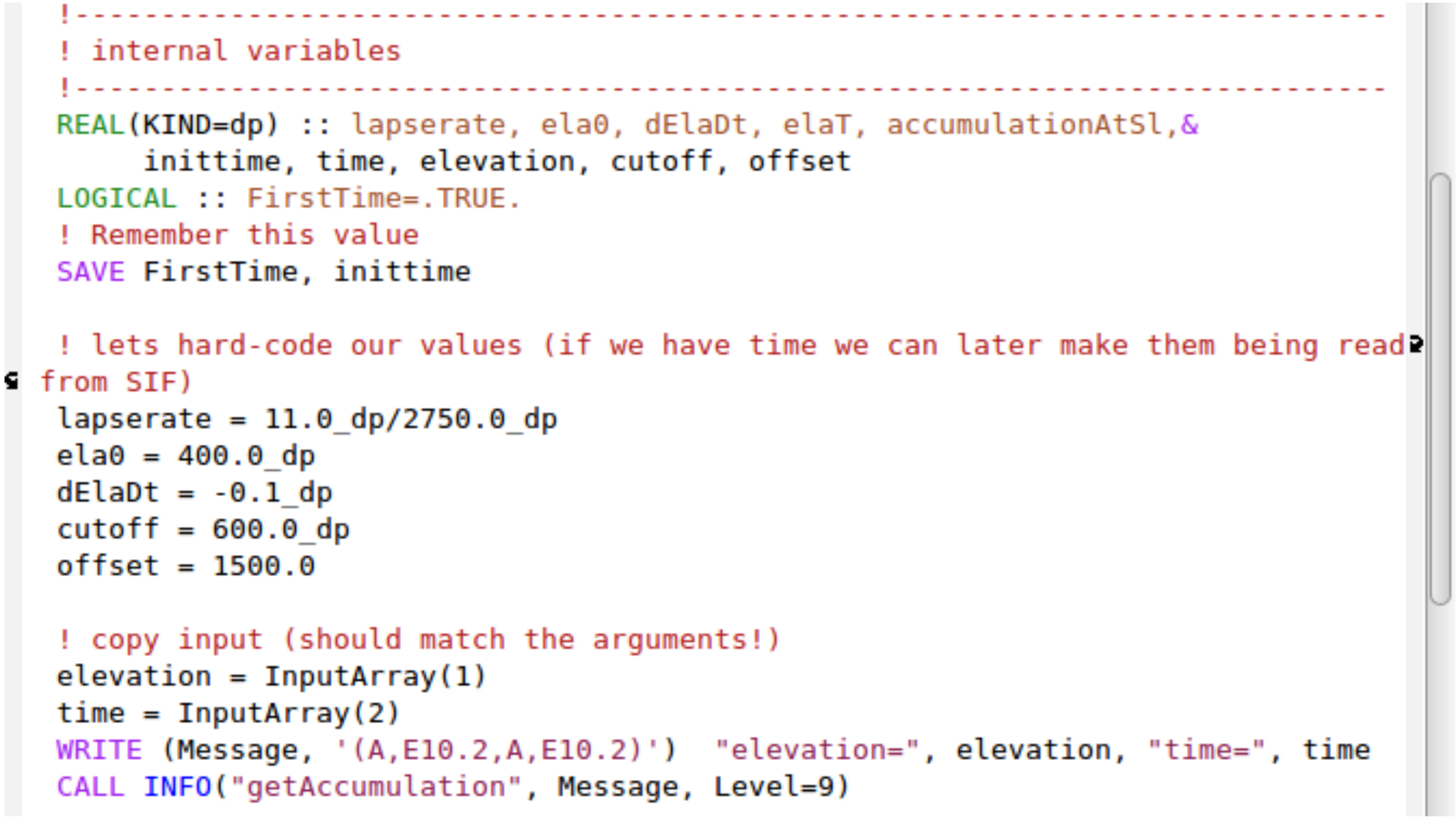
User Defined Function

- Replace the MATC function with a user defined function (UDF)

All UDF’s have the same header in Elmer(/Ice)

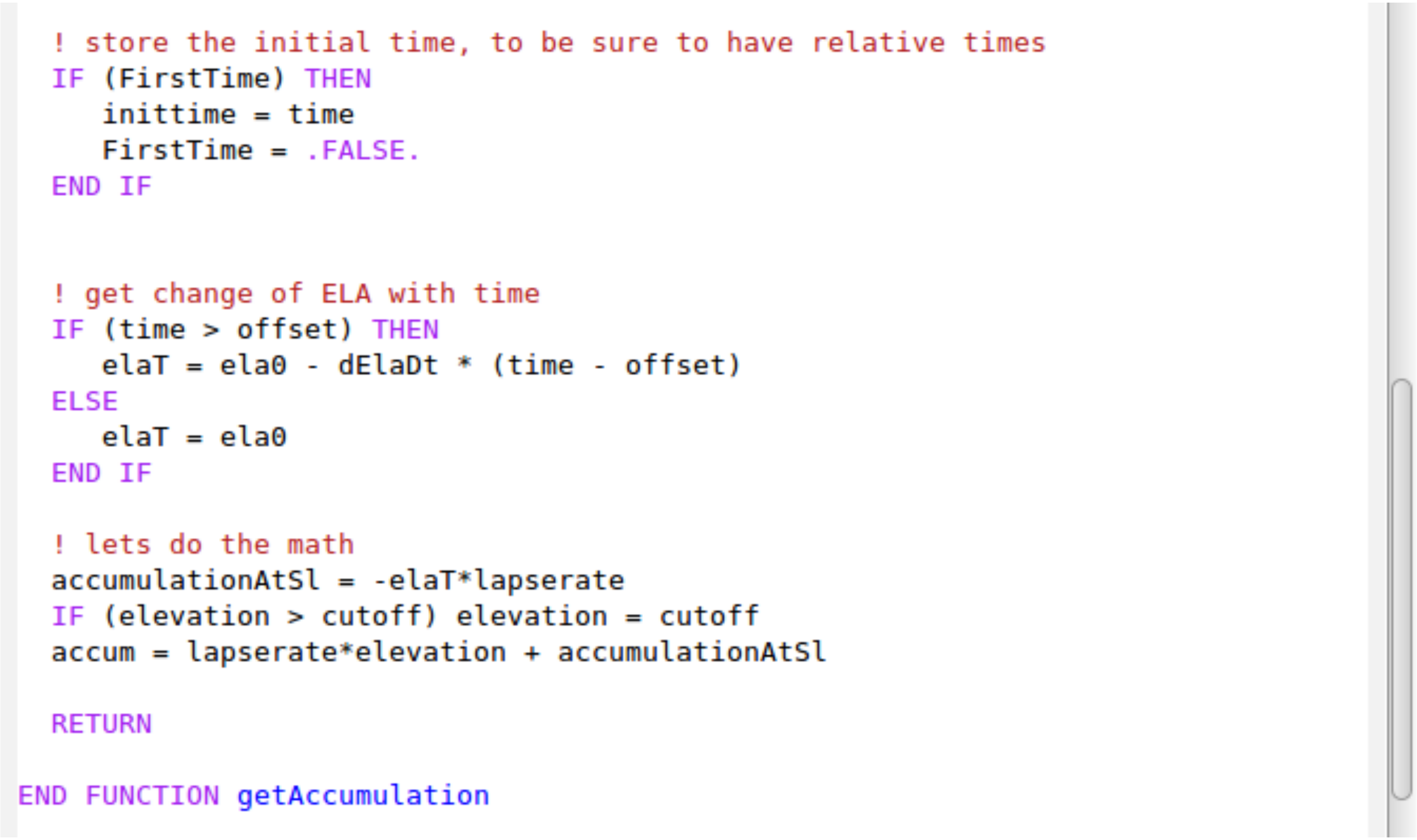
```
FUNCTION getAccumulation(  Model, Node, InputArray)RESULT(accum)
  ! provides you with most Elmer functionality
  USE DefUtils
  ! saves you from stupid errors
  IMPLICIT NONE
  ! the external variables
  !----------------------------------------------------------------
  TYPE(Model_t) :: Model      ! the access point to everything
about the model
  INTEGER :: Node             ! the current Node number
  REAL(KIND=dp) :: InputArray(2) ! Contains the arguments passed
to the function
  REAL(KIND=dp) :: accum       ! the result
  !----------------------------------------------------------------
```

User Defined Function



```fortran
  !----------------------------------------------------------------------------
  ! internal variables
  !----------------------------------------------------------------------------
  REAL(KIND=dp) :: lapserate, ela0, dElaDt, elaT, accumulationAtSl,&
       inittime, time, elevation, cutoff, offset
  LOGICAL :: FirstTime=.TRUE.
  ! Remember this value
  SAVE FirstTime, inittime

  ! lets hard-code our values (if we have time we can later make them being read
 from SIF)
  lapserate = 11.0_dp/2750.0_dp
  ela0 = 400.0_dp
  dElaDt = -0.1_dp
  cutoff = 600.0_dp
  offset = 1500.0

  ! copy input (should match the arguments!)
  elevation = InputArray(1)
  time = InputArray(2)
  WRITE (Message, '(A,E10.2,A,E10.2)')  "elevation=", elevation, "time=", time
  CALL INFO("getAccumulation", Message, Level=9)
```

User Defined Function



```
  ! store the initial time, to be sure to have relative times
  IF (FirstTime) THEN
     inittime = time
     FirstTime = .FALSE.
  END IF


  ! get change of ELA with time
  IF (time > offset) THEN
     elaT = ela0 - dElaDt * (time - offset)
  ELSE
     elaT = ela0
  END IF

  ! lets do the math
  accumulationAtSl = -elaT*lapserate
  IF (elevation > cutoff) elevation = cutoff
  accum = lapserate*elevation + accumulationAtSl

  RETURN

END FUNCTION getAccumulation
```

User Defined Function

The body-force section changes to:

```
Body Force 2
  Name = "Climate"
  Zs Accumulation Flux 1 = Real 0.0e0
  Zs Accumulation Flux 2 = Variable Coordinate 2, Time
       Real Procedure "accumulation" "getAccumulation"
End
```

Compilation is done with:

```
$ elmerf90 accumulation.f90 -o accumulation.so
```

End of second session

Summary in keywords:

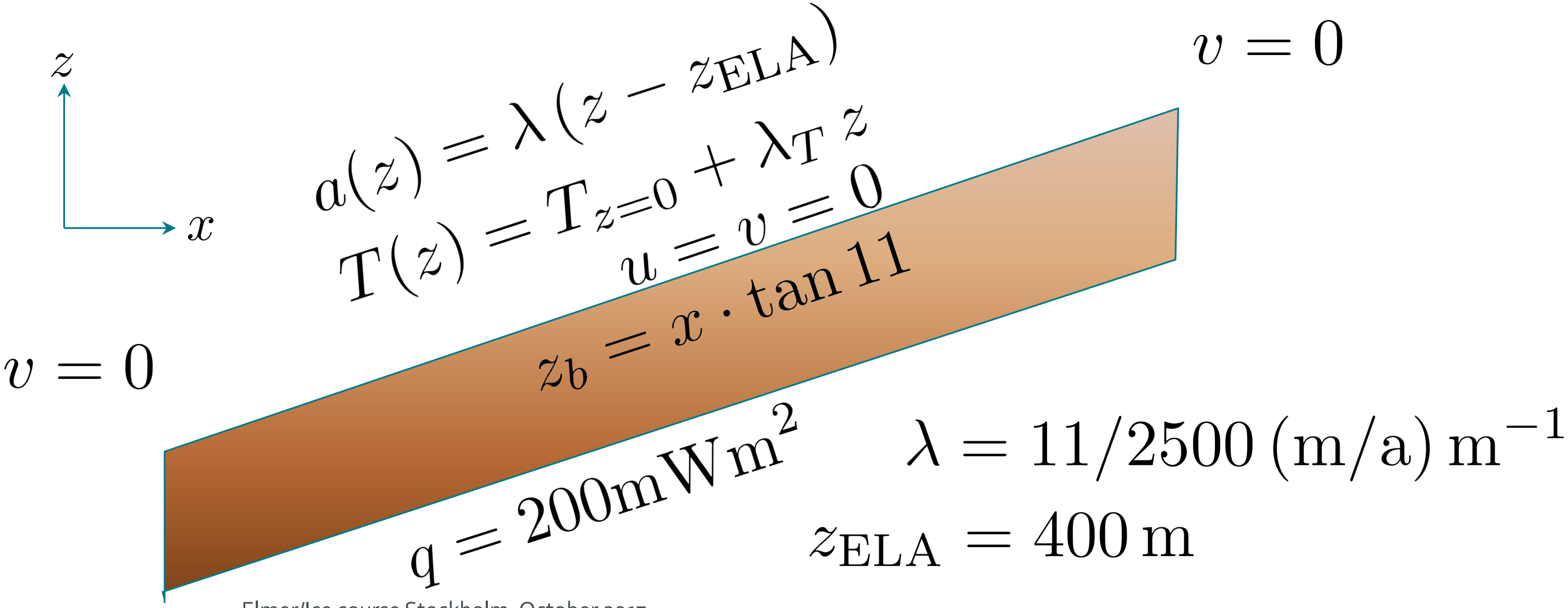
- Basic prognostic (= time dependend with prescribed surface mass balance) simulation

For those, who want to go continue …

EXERCISE

Exercise

- If time permits, lets put all things together and make a thermo-mechanically coupled prognostic run. What do we need to add?



$$a(z) = \lambda\,(z - z_{\mathrm{ELA}})$$

$$\mathrm{T}(z) = \mathrm{T}_{z=0} + \lambda_T\, z$$

$$u = v = 0$$

$$z_{\mathrm{b}} = x \cdot \tan 11$$

$$q = 200 \mathrm{m W m}^2$$

$$\lambda = 11/2500\;(\mathrm{m/a})\,\mathrm{m}^{-1}$$

$$z_{\mathrm{ELA}} = 400\,\mathrm{m}$$

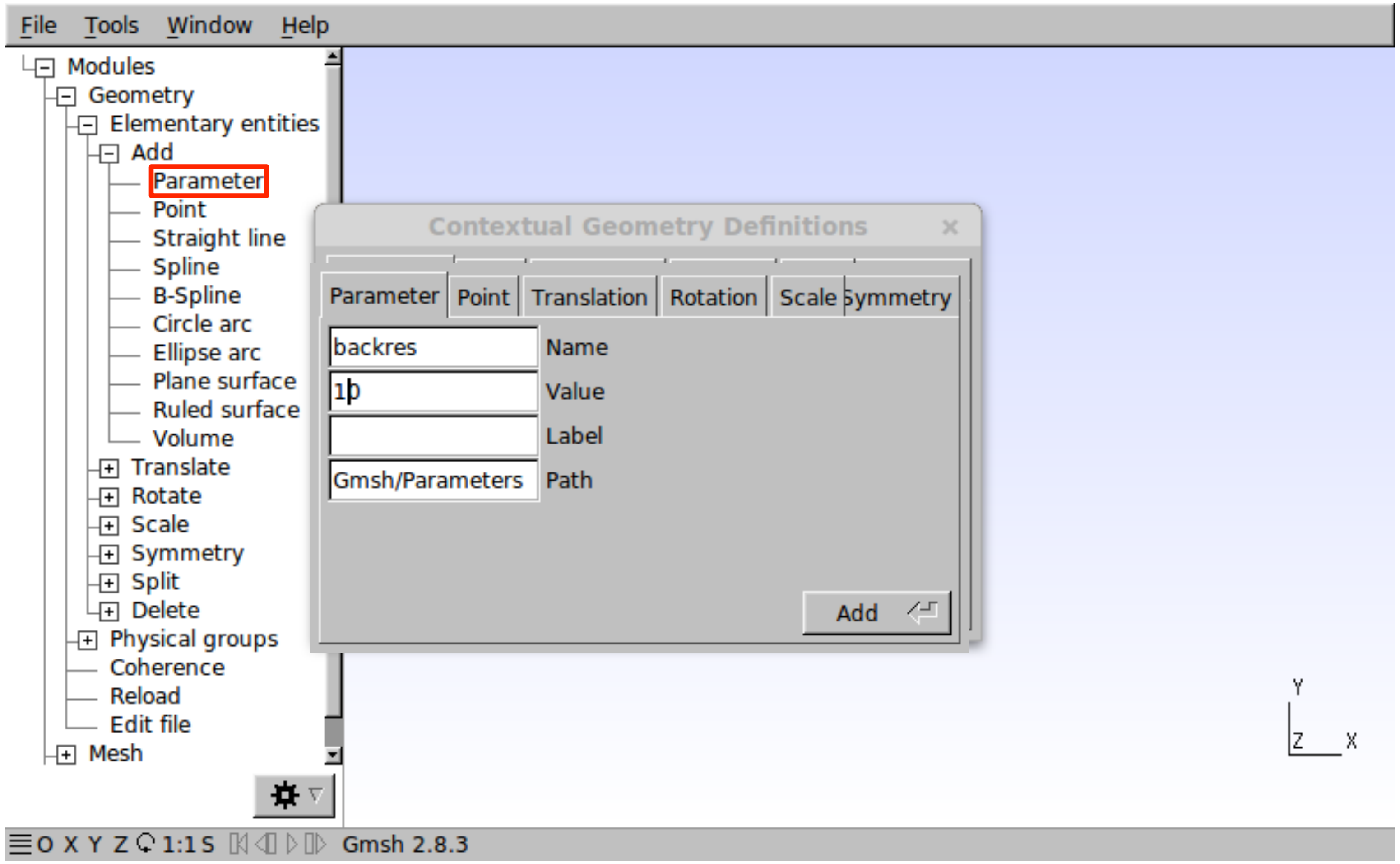
Additional information on

CREATING A MESH USING GMSH

The Mesh

- Using Gmsh
- Simply launch by:
- `$ gmsh testglacier.geo &`
  - Don’t use the existing one in the **`Solution`**-folder, since we want to keep it as a backup, should this one fail

The Mesh



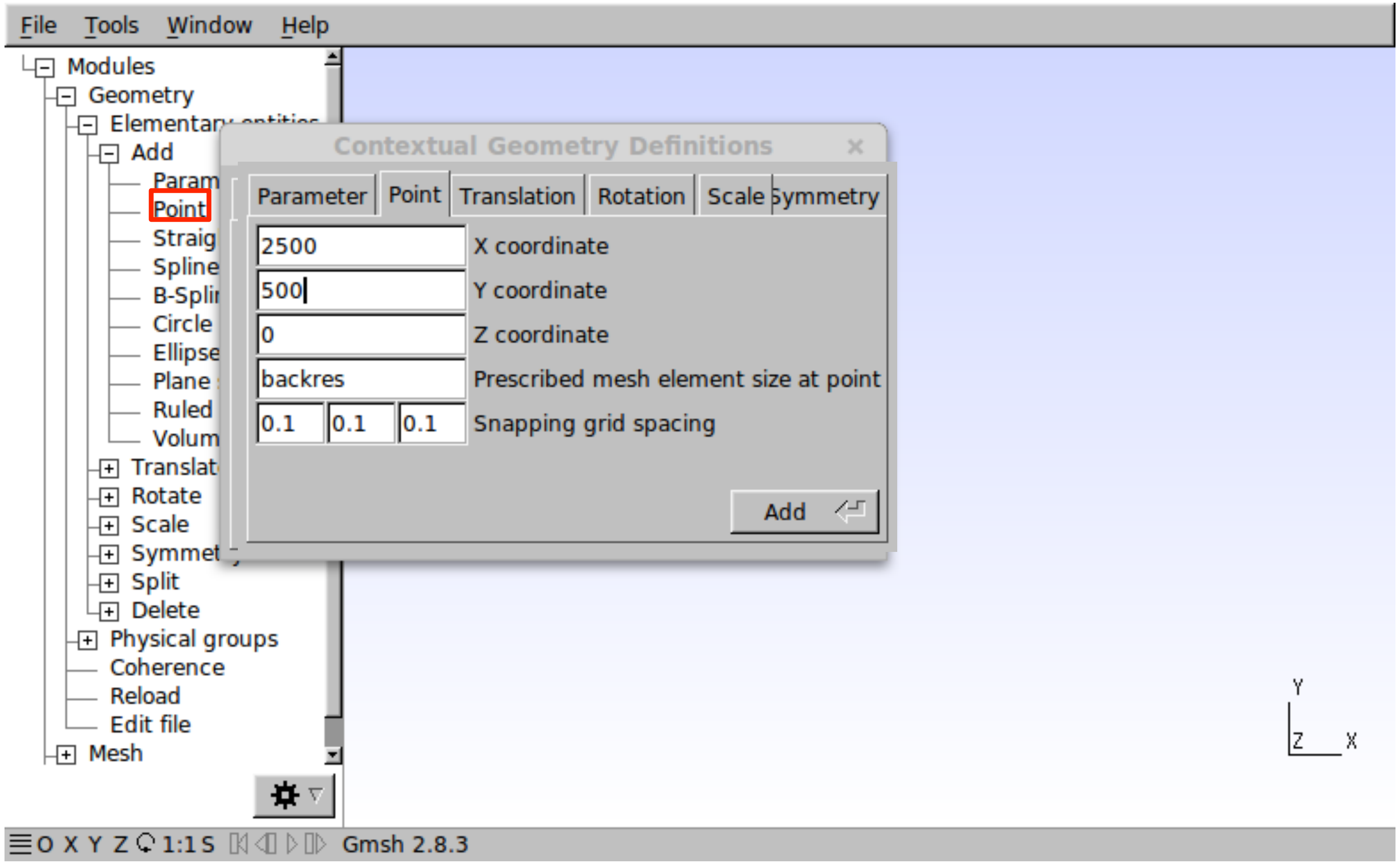
Name: backres

Value: 10

Label:

Path: Gmsh/Parameters

The Mesh



2500 X coordinate

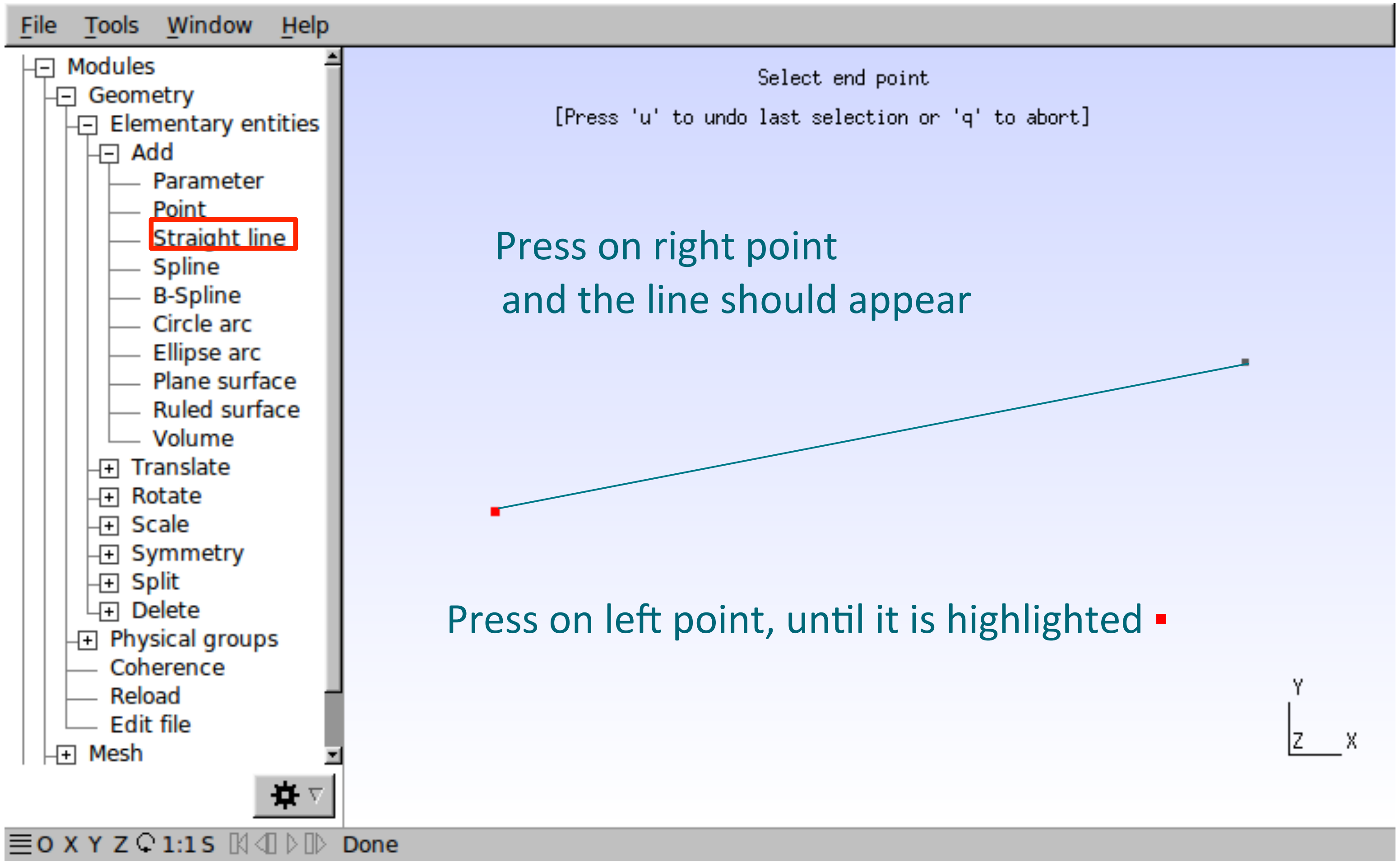
500 Y coordinate

0 Z coordinate

backres Prescribed mesh element size at point

0.1 0.1 0.1 Snapping grid spacing

The Mesh



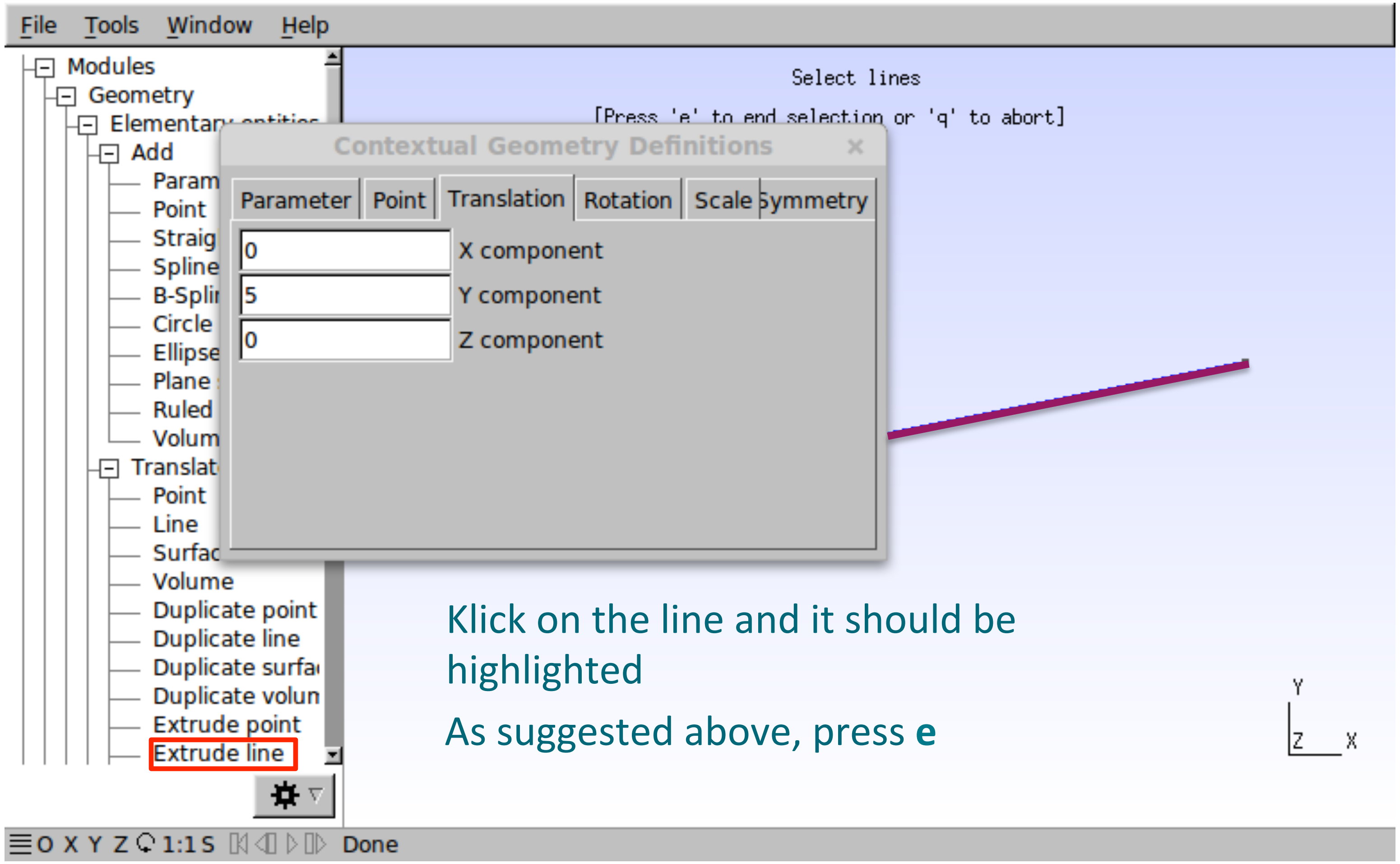
Select end point

[Press 'u' to undo last selection or 'q' to abort]

Press on right point
and the line should appear

Press on left point, until it is highlighted ▪

The Mesh



Select lines

[Press 'e' to end selection or 'q' to abort]

0	X component
5	Y component
0	Z component

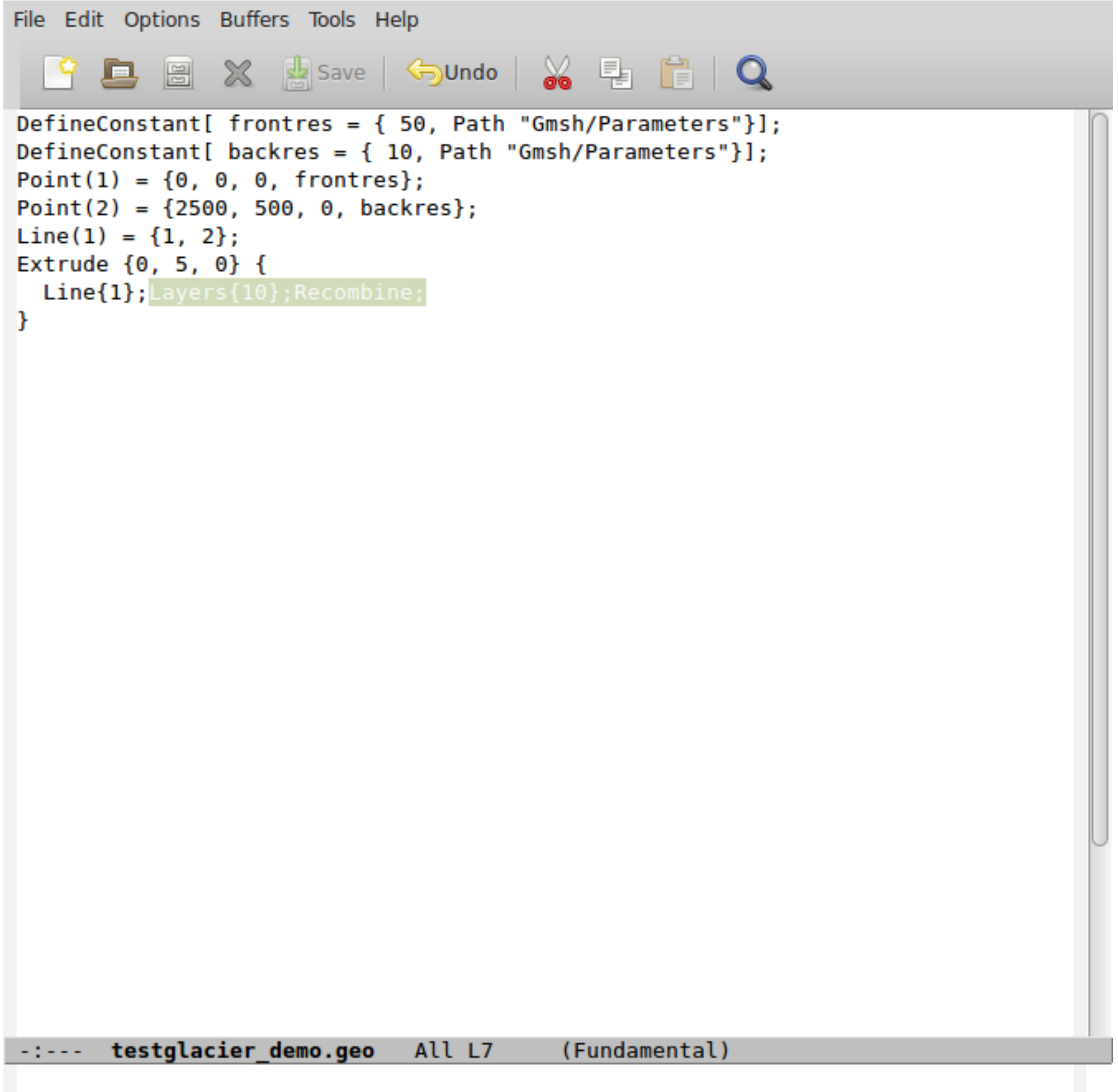
Klick on the line and it should be highlighted

As suggested above, press **e**

The Mesh

- Gmsh does journaling into the **`geo`**-file
    - it immediately writes out your entries
    - This means, that you can drive Gmsh also solely via script
    - It also means that you can make changes and reload
- Before you load:
    - **Tools** →**Options**: go to tab **Advanced**
    - Under **Text editor command: `sensible-editor`** to **`emacs`**
        - You should do a **File**→**Save Options As Default**
    - **Geometry** →**Edit file**

The Mesh



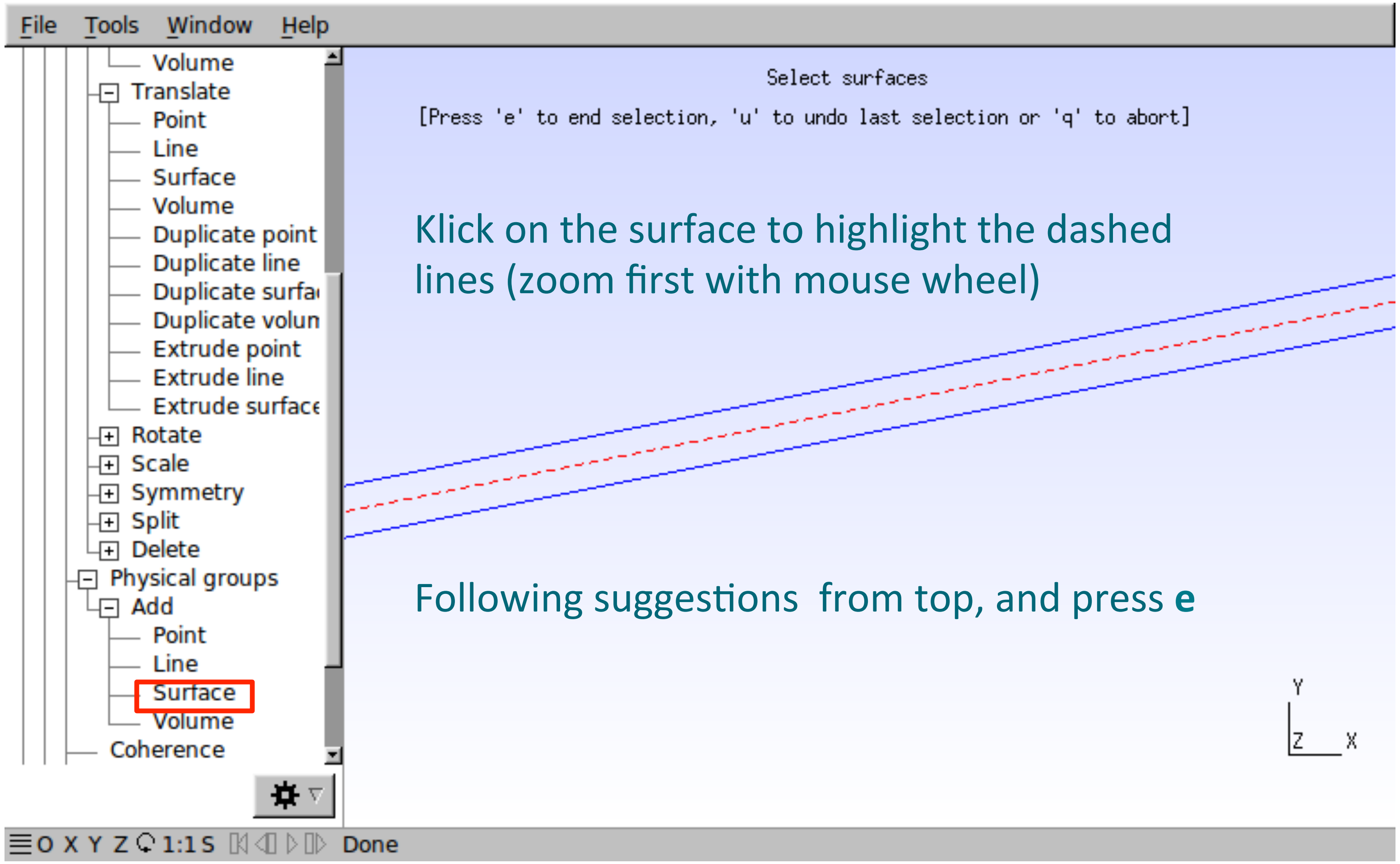
```
DefineConstant[ frontres = { 50, Path "Gmsh/Parameters"}];
DefineConstant[ backres = { 10, Path "Gmsh/Parameters"}];
Point(1) = {0, 0, 0, frontres};
Point(2) = {2500, 500, 0, backres};
Line(1) = {1, 2};
Extrude {0, 5, 0} {
  Line{1};Layers{10};Recombine;
}
```

```
-:---  testglacier_demo.geo   All L7     (Fundamental)
```

- Save the changes
- In Gmsh:

  Geometry →Reload

The Mesh

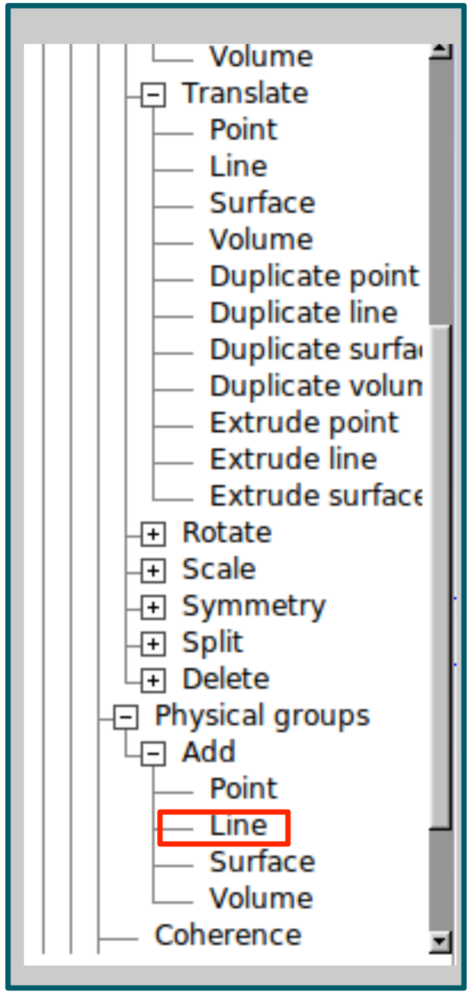


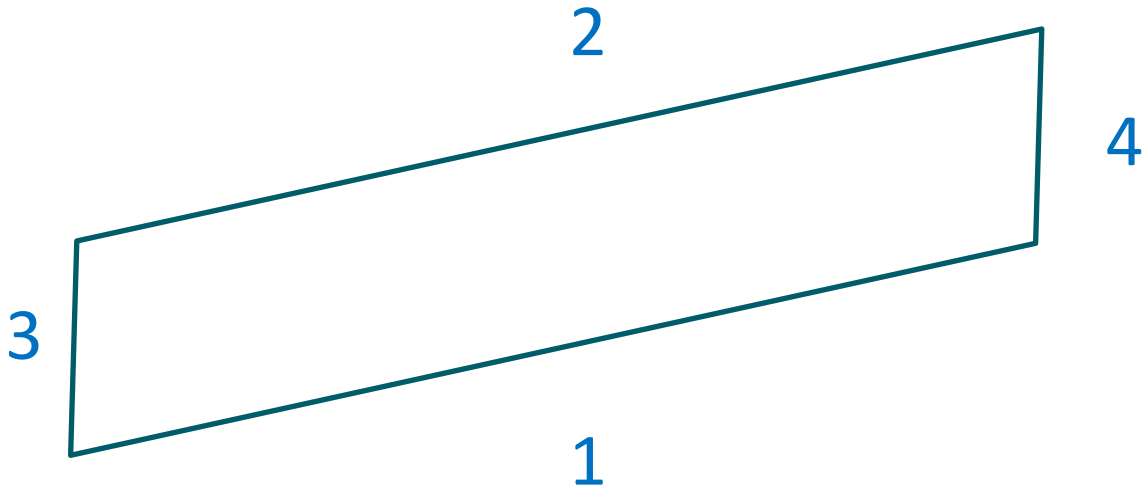
```
Select surfaces
[Press 'e' to end selection, 'u' to undo last selection or 'q' to abort]
```

Klick on the surface to highlight the dashed lines (zoom first with mouse wheel)

Following suggestions from top, and press **e**

The Mesh

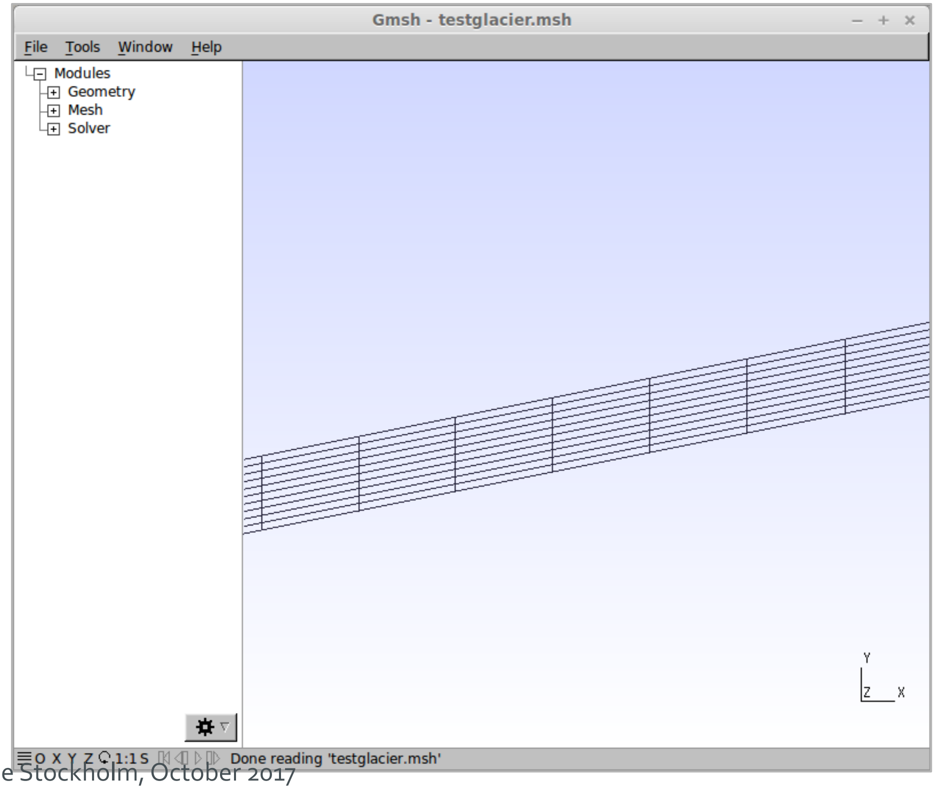




- You have to zoom (mouse wheel) in and out of the model
- and translate (right mouse button)
- Select boundary in the given order (highlights in red) and press “**e**” every time
  - If you selected the wrong boundary, use “**u**” to unselect

The Mesh

- Finally, mesh the geometry: **Mesh→2D**
- And save the mesh: **Mesh→Save**



Done reading 'testglacier.msh'