A First Tutorial to OpenFOAM

Feng Chen
IT Analyst 3
Louisiana State University

Things to be covered today

- Introduction to OpenFOAM
- Pre-processing OpenFOAM cases/OpenFOAM case configuration
- Running OpenFOAM case
- Post-processing OpenFOAM cases
- Create your own solver/Develop with OpenFOAM

Introduction to OpenFOAM

- Open Field of Operation And Manipulation
- Free, open source CFD software package
- C++ programming language
- A set of libraries for continuum mechanics based on Finite Volume Method (FVM)

Why consider OpenFOAM

- Open architecture—will be detailed later
- Low(Zero)-cost CFD
- Problem-independent numerics and discretization
- Efficient environment for complex physics problems

OpenFOAM features overview

- Physical Modeling Capability:
  - Basic: Laplace, potential flow, passive scalar/vector/tensor transport
  - Incompressible and compressible flow: segregated pressure-based algorithms
  - Heat transfer: buoyancy-driven flows, conjugate heat transfer
  - Multiphase: Euler-Euler, VOF free surface capturing and surface tracking
  - Pre-mixed and Diesel combustion, spray and in-cylinder flows
  - Stress analysis, fluid-structure interaction, electromagnetics, MHD, etc.

OpenFOAM features overview

- Straightforward representation of partial differential equations (PDEs):

$$\frac{\partial \rho U}{\partial t} + \nabla \bullet \rho U U - \nabla \bullet \mu \nabla U = -\nabla p$$

```
solve
    (
        fvm::ddt(rho, U)
      + fvm::div(phi, U)
      - fvm::laplacian(mu, U)
        ==
      - fvc::grad(p)
    );
```

Introduction to OpenFOAM

- History of OpenFOAM:
  - Original development started in the late 1980s at Imperial College, London (FORTRAN)
  - Later changed to C++
  - OpenFOAM 1.0 released on 10/12/2004
  - Major releases: 1.4, 1.5, 1.6, 1.7.x, 2.0.x, 2.1.x, ***2.2.x***
  - Wikki Ltd. Extend-Project: 1.4-dev, 1.5-dev, ***1.6-ext***

Introduction to OpenFOAM

- Theoretical background
  - Finite Volume Method (FVM)
  - Unstructured grid
  - Pressure correction methods (SIMPLE, PISO, and their combination PIMPLE),
    - for more information about CFD (FVM), see:

      Partankar, S. V. (1980) Numerical heat transfer and fluid flow, McGraw-Hill.

      H. Versteeg and W. Malalasekra, (2007) An Introduction to Computational Fluid Dynamics: The Finite Volume Method Approach

OpenFOAM toolbox overview

- Applications:
  - ***Utilities***: functional tools for pre- and post-processing, e.g. blockMesh, sampling tool
  - ***Solvers***: calculate the numerical solution of PDEs
- Standard libraries
  - ***General libraries***: those that provide general classes and associated functions;
  - ***Model libraries***: those that specify models used in computational continuum mechanics;

OpenFOAM toolbox overview

- Standard Solvers
  - ‘Basic’ CFD codes: e.g. laplacianFoam
  - Incompressible flow: e.g. icoFoam, simpleFoam
  - Compressible flow: e.g. rhoSimpleFoam, sonicFoam
  - Multiphase flow: e.g. interFoam
  - Direct numerical simulation (DNS) and large eddy simulation (LES)
  - Combustion
  - Particle-tracking flows

Changes to your .soft file

- Add the following keys to ~/.soft and then resoft
  - On Super Mike:

    +Intel-13.0.0

    +openmpi-1.6.3-Intel-13.0.0

    +OpenFOAM-2.2.1-Intel-13.0-openmpi-1.6.3
  - On QueenBee:

    +gcc-4.7.0

    +openmpi-1.6.3-gcc-4.7.0

    +OpenFOAM-2.2.2-gcc-4.7.0-openmpi-1.6.3
- Start an interactive session:

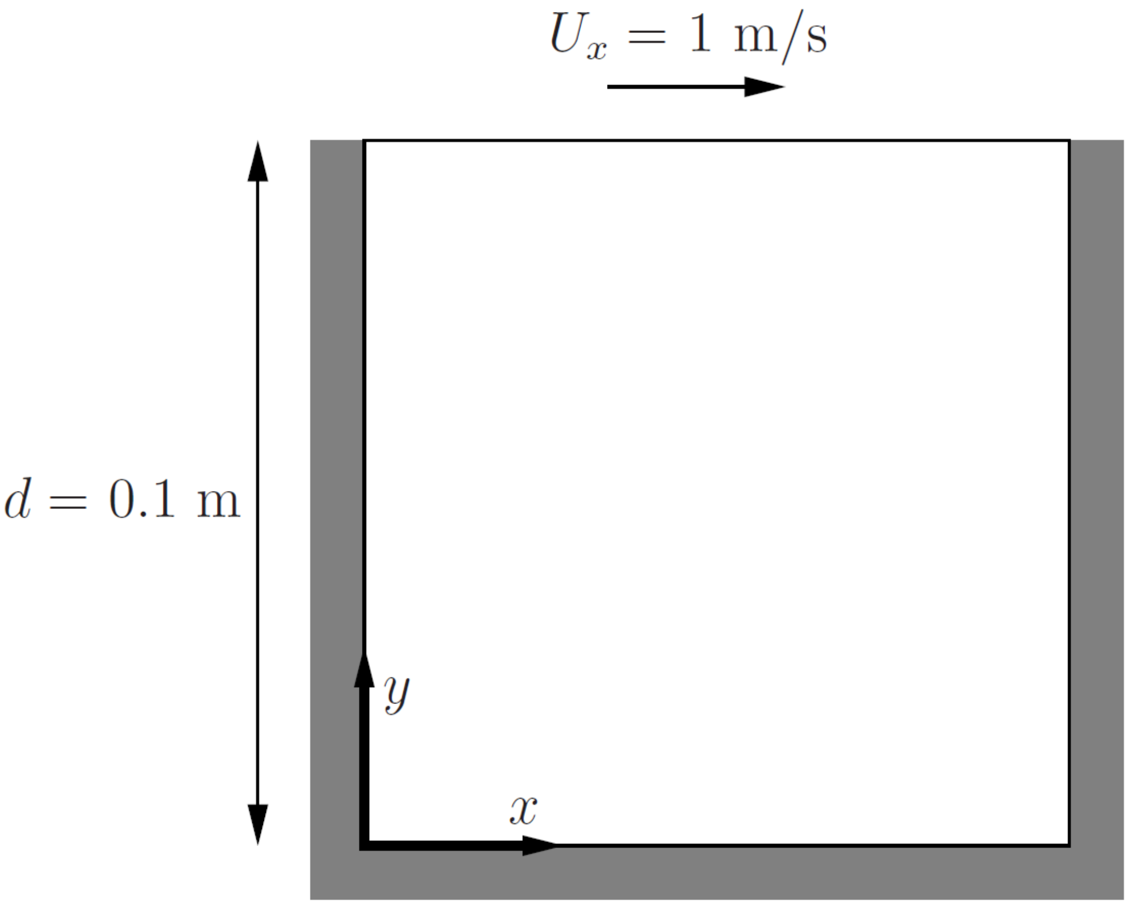
```
qsub –I -X -l nodes=1:ppn=16 -l walltime=02:00:00
```

Run First OpenFOAM case

- Steps of running first OF case on Mike:
  - $ mkdir -p /work/$USER/foam_run
  - $ cd /work/$USER/foam_run
  - $ wget https://tigerbytes2.lsu.edu/users/hpctraining/web/Downloads/intro_of.tar.gz
  - $ tar zxf intro_of.tar.gz
  - $ cd /work/$USER/foam_run/intro_of/cavity
  - $ blockMesh (generate mesh information)
  - $ icoFoam (running the PISO solver)
  - $ foamToVTK (convert to VTK format, optional)
  - $ paraFoam (post-processing)

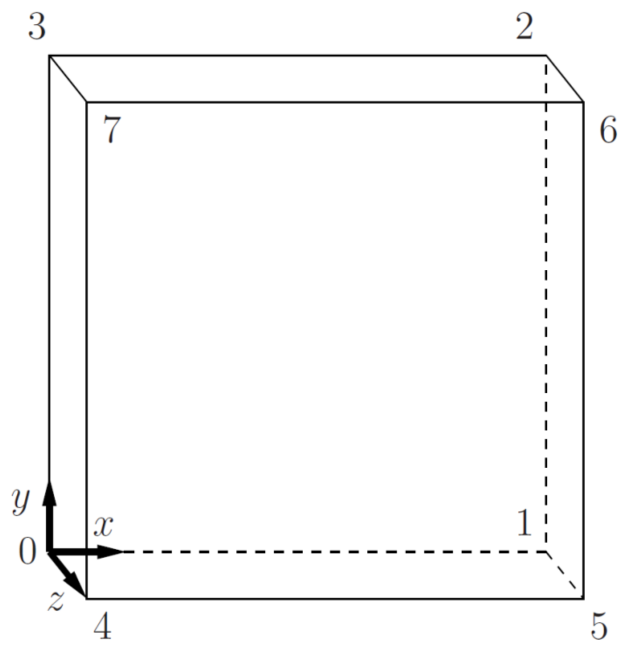
Run First OpenFOAM case

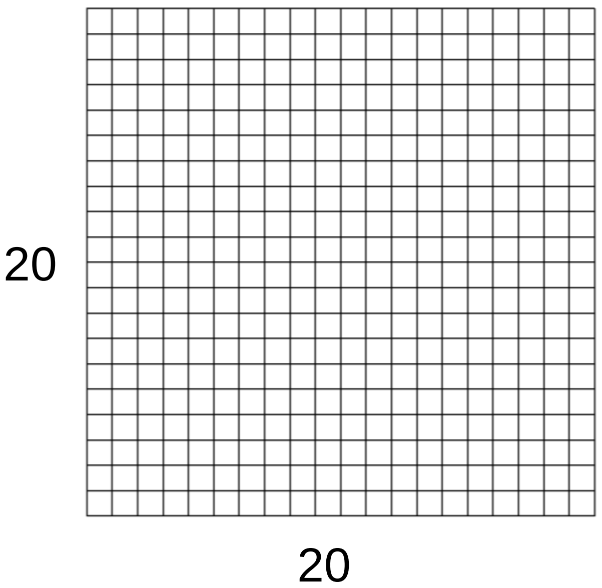
- Lid-driven cavity flow



Lid-driven cavity flow

- The cavity domain consists of a square of side length *d=0.1m* in the *x-y* plane. A uniform mesh of 20x20 cells will be used initially.

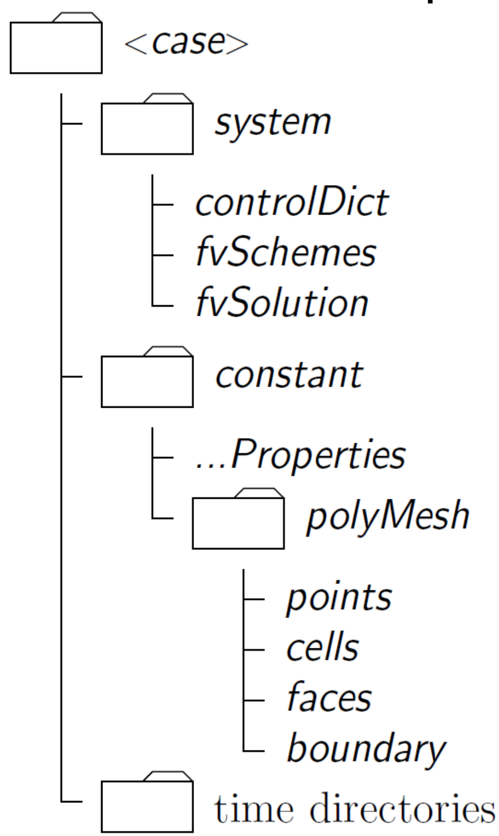




Inside case configuration

- File structure of OpenFOAM cases

$ ls -R $FOAM_RUN/tutorials/incompressible/icoFoam/cavity



Inside case configuration

- The minimum set of files required to run an OpenFOAM case
  - constant directory:
    - description of the case mesh (geometry): e.g. ***polyMesh***
    - physical properties files: e.g. ***transportProperties***
  - system directory: solution procedure settings
    - ***controlDict***
    - ***fvSchemes***
    - ***fvSolution***
  - "time" directories: ***U, p***
    - initial conditions (I.C.)
    - boundary conditions (B.C.)
    - Future result files (typically determined by controlDict)

Inside case configuration

- constant directory:
  - polyMesh
    - ***blockMeshDict: mesh description, will be detailed later***
    - boundary: list of patches with BCs definition
    - faces: list of mesh faces (list of points)
    - neighbour: list of neighboring cell labels
    - owner: list of owning cell labels
    - points: list of mesh points with their coordinates
  - transportProperties

Edit blockMeshDict file (0)

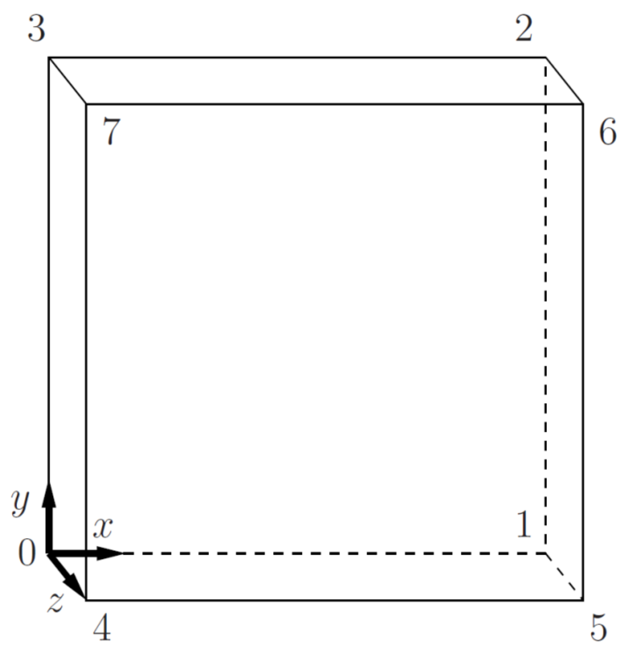
- OpenFOAM file header:

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  2.2.1                                 |
|   \\  /    A nd           | Web:      www.OpenFOAM.org                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    object      blockMeshDict;
}
```

Edit blockMeshDict file (1)

```
convertToMeters 0.1;

vertices
(
    (0 0 0)   //0
    (1 0 0)   //1
    (1 1 0)   //2
    (0 1 0)   //3
    (0 0 0.1) //4
    (1 0 0.1) //5
    (1 1 0.1) //6
    (0 1 0.1) //7
);
```



LSU INFORMATION TECHNOLOGY SERVICES

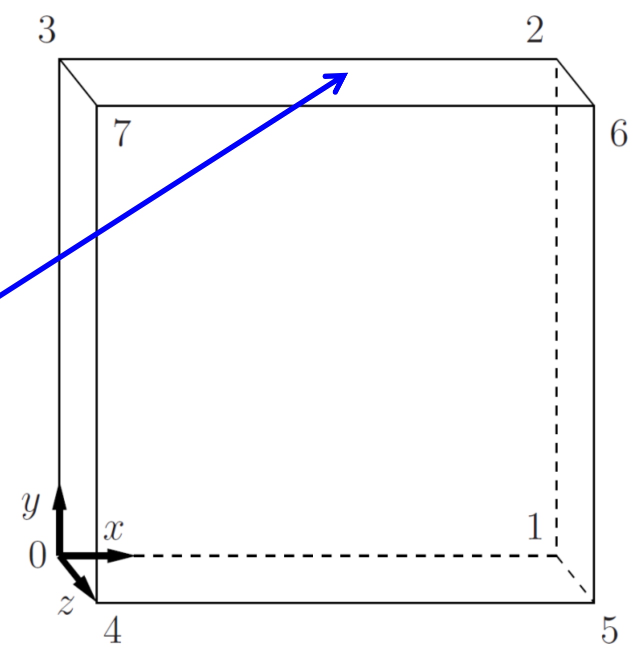
Edit blockMeshDict file (2)

```
blocks
(
    hex (0 1 2 3 4 5 6 7) (20 20 1) simpleGrading (1 1 1)
);

edges
(
);
```

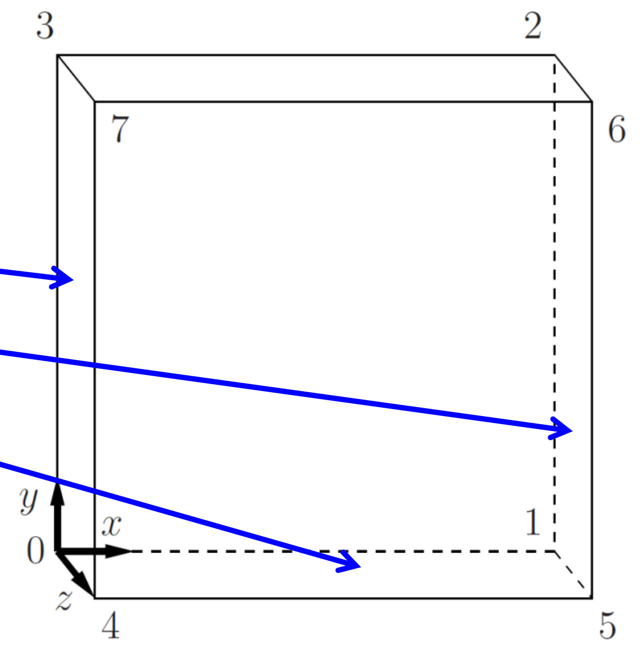
Edit blockMeshDict file (3)

```
boundary
(
    movingWall
    {
        type wall;
        faces
        (
            (3 7 6 2)
        );
    }
```



Edit blockMeshDict file (4)

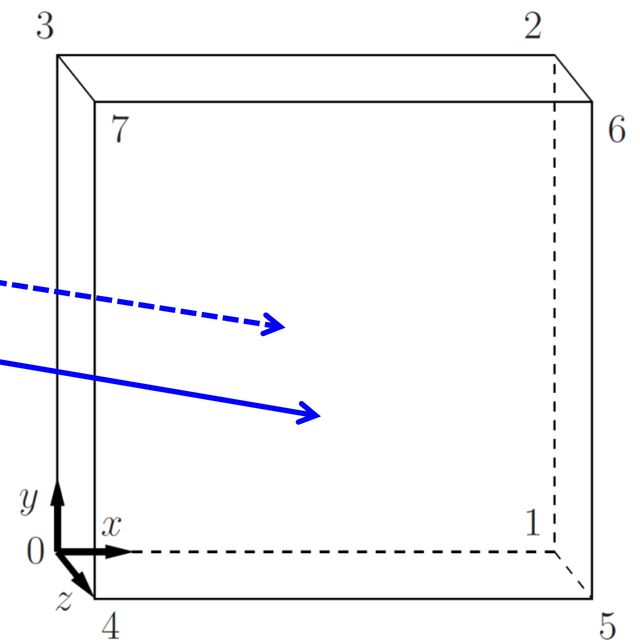
```
fixedWalls
{
    type wall;
    faces
    (
        (0 4 7 3)
        (2 6 5 1)
        (1 5 4 0)
    );
}
```



Edit blockMeshDict file (5)

```
frontAndBack
{
    type empty;
    faces
    (
        (0 3 2 1)
        (4 5 6 7)
    );
}
);

mergePatchPairs
(
);
```



Solver settings

- constant directory also contains:
  - File which defines physical/material properties, transportProperties
  - Files which define some mesh properties, e.g. dynamicMeshDict
  - Files which defines turbulent properties RASProperties

Solver settings

- dimensions/units in OpenFOAM
  - Representation of SI system
    - //dimensions [kg m sec K mol A cd];
    - dimensions [0 2 -1 0 0 0 0];
- Note: for incompressible solvers it is not needed to specify density. Pressure is then represented as p/ρ

Solver settings

- transportProperties-representation of SI system
  - transportModel Newtonian; // viscosity options: newtonian/non-newtonian
  - nu nu [0 2 -1 0 0 0 0] 0.01; // kinematic viscosity

Solver settings

- system directory contains:
  - Files concerning solver parameters, as well as definition files for utility tools e.g. decomposeParDict
  - controlDict – simulation control and parameters, additional libraries to load and extra functions
  - fvSchemes – definition of discretization schemes
  - fvSolution – definitions of solver type, tolerances, relaxation factors

Solver settings-controlDict

- controlDict: (how your results are written)

```
application       icoFoam;
startFrom         startTime;
startTime         0;
stopAt            endTime;
endTime           0.5;
deltaT            0.005;
writeControl      timeStep;
writeInterval     20;
purgeWrite        0;
writeFormat       ascii;
writePrecision    6;
writeCompression  off;
timeFormat        general;
timePrecision     6;
runTimeModifiable true;
```

Solver settings-fvSchemes

- fvSchemes:

```
// time schemes (Euler , CrankNicholson, backward,
steadyState )
ddtSchemes
{
    default         Euler;
}
// gradient schemes (Gauss , leastSquares, fourth,
cellLimited, faceLimited )
gradSchemes
{
    default         Gauss linear;
    grad(p)         Gauss linear;
}
// convection and divergence schemes ( interpolation
schemes used: linear, skewLinear,  cubicCorrected,
upwind, linearUpwind, QUICK, TVD, SFCD, NVD)
divSchemes
{
    default         none;
    div(phi,U)      Gauss linear;
}
laplacianSchemes
{
    default         none;
    laplacian(nu,U) Gauss linear orthogonal;
    laplacian((1|A(U)),p) Gauss linear orthogonal;
}
```

Solver settings-fvSchemes

- fvSchemes:

```
// interpolation schemes to calculate values on the
faces (linear, cubicCorrection, midPoint , upwind,
linearUpwind, skewLinear , QUICK, TVD,
limitedLinear , vanLeer , MUSCL, limitedCubic, NVD,
SFCD, Gamma )
interpolationSchemes
{
    default         linear;
    interpolate(HbyA) linear;
}
// schemes for surface normal gradient on the faces (
corrected, uncorrected, limited, bounded, fourth )
snGradSchemes
{
    default         orthogonal;
}
// lists the fields for which the flux is generated in the
application
fluxRequired
{
    default         no;
    p;
}
```

Solver settings-solution control

- fvSolution:

```
solvers
{
   p
   {
      solver          PCG;
      preconditioner  DIC;
      tolerance       1e-06;
      relTol          0;
   }

   U
   {
      solver          PBiCG;
      preconditioner  DILU;
      tolerance       1e-05;
      relTol          0;
   }
}
// pressure - velocity coupling
// SIMPLE (Semi - Implicit Method for Pressure - Linked Equations )
// PISO ( Pressure Implicit with Splitting of Operators )
// PIMPLE ( Combination of SIMPLE and PISO )
PISO
{
   nCorrectors     2;
   nNonOrthogonalCorrectors 0;
   pRefCell        0;
   pRefValue       0;
}
```

http://www.openfoam.org/docs/user/fvSolution.php

Solver settings-time directory

- Time directories contain field files (e.g. U, p, k, epsilon, omega, T etc.)
- Fields files store field solution values on all cells and boundary conditions on the computational domain
- 0 time directory is initial directory containing field files with initial field values and boundary conditions
- Common parts for all field files are:
  - header
  - dimensions
  - internalField
  - boundaryField

Solver settings

- U

```
dimensions      [0 1 -1 0 0 0 0];
internalField   uniform (0 0 0);
boundaryField
{
    movingWall
    {
        type            fixedValue;
        value           uniform (1 0 0);
    }

    fixedWalls
    {
        type            fixedValue;
        value           uniform (0 0 0);
    }

    frontAndBack
    {
        type            empty;
    }
}
```

Solver settings

- p

```
dimensions      [0 2 -2 0 0 0 0];

internalField   uniform 0;

boundaryField
{
    movingWall
    {
        type            zeroGradient;
    }

    fixedWalls
    {
        type            zeroGradient;
    }

    frontAndBack
    {
        type            empty;
    }
}
```

Boundary Conditions (BCs) in OpenFOAM

- base type (described purely in terms of geometry):
  - patch, wall, empty, symmetry, cyclic
- primitive type (base numerical patch condition assigned to a field variable on the patch):
  - fixedValue, fixedGradient, zeroGradient, mixed, directionMixed, calculated
- derived type (complex patch condition, derived from the primitive type, assigned to a field variable on the patch):
  - inletOutlet

Running cavity in parallel

- decomposePar //specify the parallel run params
- mpirun --hostfile <machines> -np <nProcs>

  <foamExec> <otherArgs> -parallel > log &
  - Examples on Mike:
    - mpirun --hostfile $PBS_NODEFILE -np 16 icoFoam -parallel > log &
  - Examples on QueenBee:
    - mpirun --hostfile $PBS_NODEFILE -np 8 icoFoam -parallel > log &
- reconstructPar //merge the sets of time directories from each processor
- See:

  /work/$USER/foam_run/intro_of/cavity_parallel_is
  /work/$USER/foam_run/intro_of/cavity_parallel

Running cavity in parallel

- On interactive session:

$ cd /work/$USER/foam_run/intro_of/cavity_parallel_is

$ blockMesh

$ vi system/decomposeParDict

$ decomposePar

$ mpirun --hostfile $PBS_NODEFILE -np 16 icoFoam -parallel

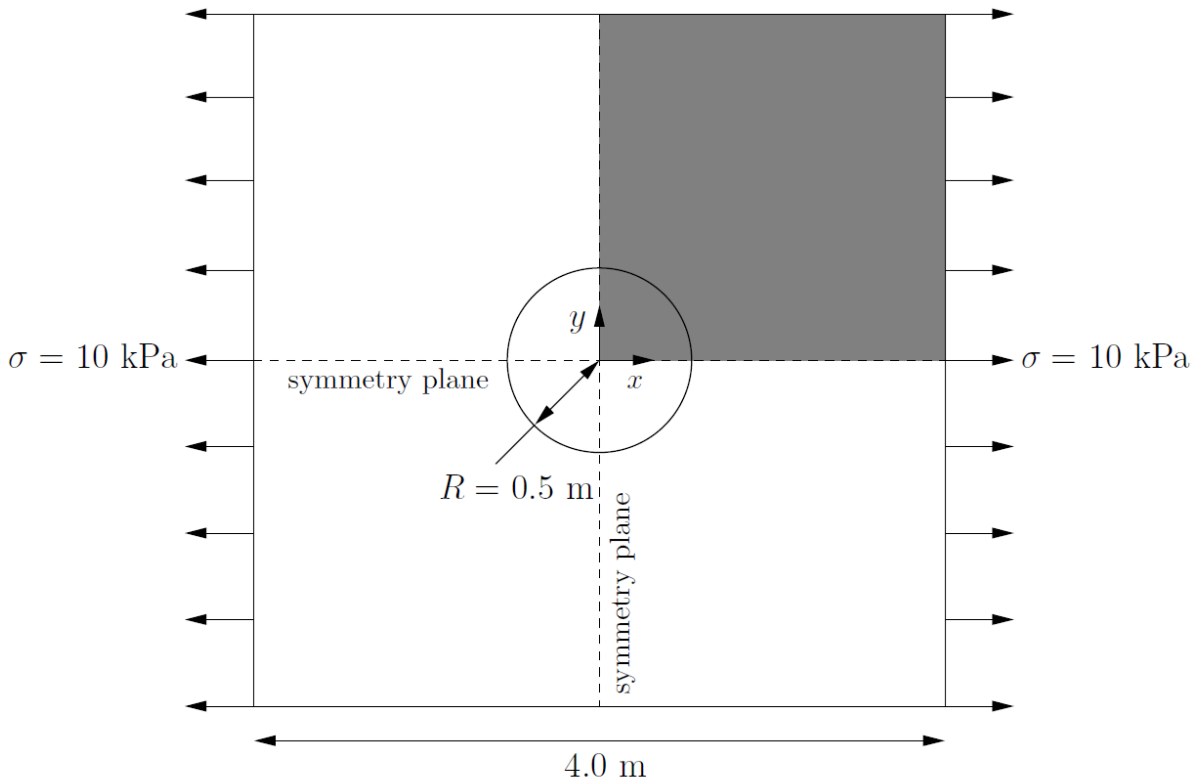
$ reconstructPar

- Via pbs script submission:

$ cd /work/$USER/foam_run/intro_of

$ ./cavity_parallel_run.sh

Stress analysis of plateHole



Analytical Solution:

$$(\sigma_{xx})_{x=0} = \begin{cases} \sigma\left(1 + \dfrac{R^2}{2y^2} + \dfrac{3R^4}{2y^4}\right) & \text{for } |y| \geq R \\ 0 & \text{for } |y| < R \end{cases}$$

Run stress analysis case

- Steps of running plateHole on Mike:
  - $ cd /work/$USER/foam_run/intro_of/plateHole
  - $ blockMesh (generate geometry)
  - $ checkMesh (tool for checking the mesh quality)
  - $ solidDisplacementFoam (running the stress analysis solver)
  - $ foamToVTK (convert VTK format, optional)
  - $ paraFoam (post-processing)

Post-processing

- Most used post-processing software for OpenFOAM data visualization is ***Paraview***
- paraFoam – script for automatic import of OpenFOAM results into Paraview
- OpenFOAM Data transformation in other formats: e.g. foamToVTK (also used by Paraview)

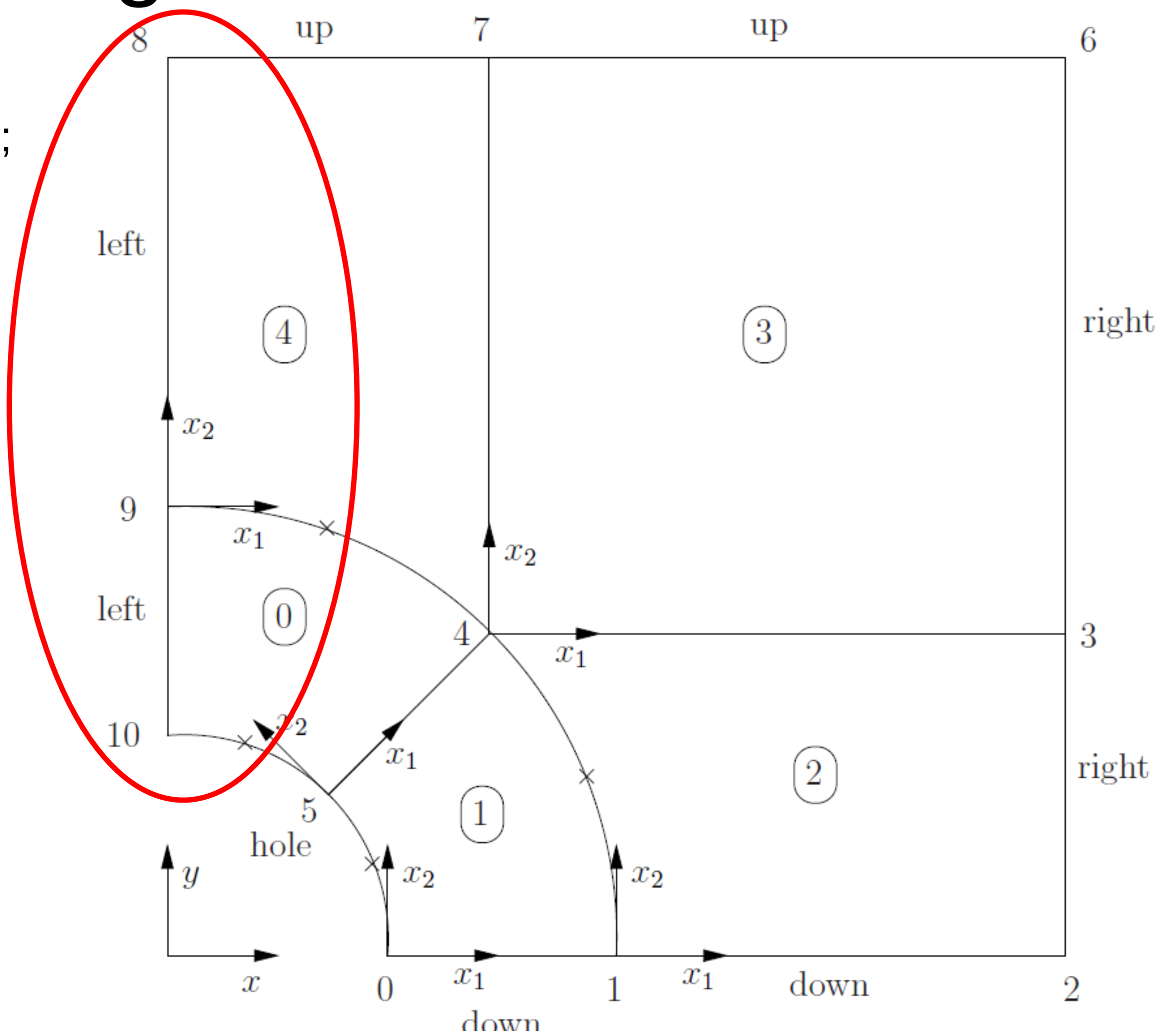
Post-processing

- ***sample*** – utility used for sampling
- Sample setups are defined in system/sampleDict
- Sample data are stored in the new (automatically) created subdirectory sets
- Example:

```
$ cd /work/$USER/foam_run/intro_of/plateHole
$ foamCalc components sigma
$ sample
```

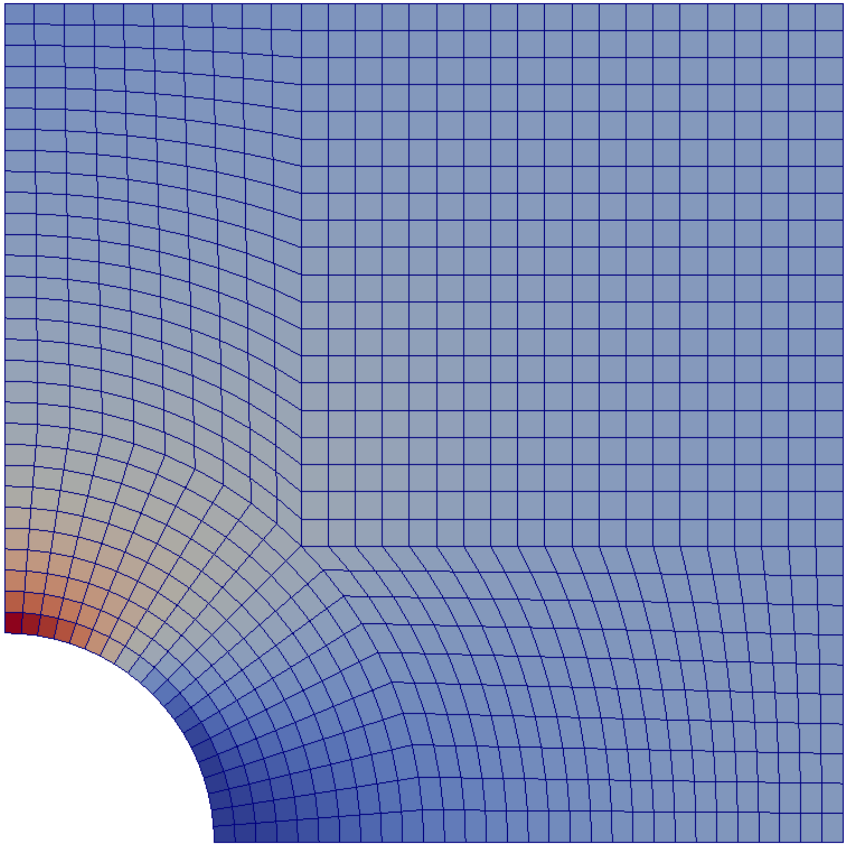
sampleDict for the plateHole case along the left line

```
/*OpenFOAM file header*/
interpolationScheme cellPoint;
setFormat       raw;
sets
(
    leftPatch
    {
        type    uniform;
        axis    y;
        start   ( 0 0.5 0.25 );
        end     ( 0 2 0.25 );
        nPoints 100;
    }
);
fields          ( sigmaxx );
```



sampleDict for the plateHole case for the entire surface

```
/*OpenFOAM file header*/
interpolationScheme cellPoint;
surfaceFormat   vtk;
surfaces
(
    sigmaxx
    {
        type plane;
        basePoint ( 0 0 0.25 );
        normalVector ( 0 0 1 );
    }
);
fields          ( sigmaxx );
```



Exercise

- Run the cavity case and sample:
  1. along middle-y axis
  2. surface

Develop your own solver

- A simple overview of the icoFoam PISO solver, see http://openfoamwiki.net/index.php/IcoFoam
- Create your own solver by copy: /usr/local/packages/OpenFOAM/2.2.1/Intel-13.0-openmpi-1.6.3/OpenFOAM-2.2.1/applications/solvers/incompressible/icoFoam

Documentation and Help

- Documentation and instructions:
  - www.openfoam.org
  - www.openfoamwiki.net
- User forum:
  - http://www.cfd-online.com/Forums/openfoam/

Thank you for your attention!

Any questions?