

Short Course on OpenFOAM[®] development

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UADE



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1 Object Oriented Programming: Its use in OpenFOAM[®]

- Basics on OOP
- An overview of OpenFOAM[®] class Diagram

2 Programming Solvers

3 Turbulence Model Implementation

4 Boundary Condition Implementation

5 Adding a control system to an application

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This section is based on Håkan Nilsson [course](#).

- OpenFOAM® is a C++ library, used primarily to create executables, known as applications. The applications fall into two categories:
 - ▶ solvers, that are designed to solve a specific continuum mechanics problem. Example: icoFoam.
 - ▶ utilities, that are designed to perform tasks that involve data manipulation. Example: blockMesh.
- Special applications for pre- and post-processing are included in OpenFOAM®. Converters to/from other pre- and post-processors are available.
- OpenFOAM® is distributed with a large number of applications, but soon any advanced user will start developing new applications or specific codes for his/ her special needs.
- Programming Code Style:
<http://www.openfoam.org/contrib/code-style.php>

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- The *types* (`int`, `double`) can be seen as *classes*, and the variables we assign to a *type* are *objects* of that class (`int a;`)
- Object orientation focuses on the *objects* instead of the functions.
- An *object* belongs to a *class* of objects with the same attributes. The class defines:
 - ▶ The construction of the object
 - ▶ The destruction of the object
 - ▶ Attributes of the object (member data)
 - ▶ Methods which manipulate the object (member functions)
- I.e. it is the `int` class that defines how the operator `+` should work for objects of that class, and how to convert between classes if needed (e.g. `1 + 1.0` involves a conversion).

- General description of the structure to define the class with name `myClass` and its public and private member functions and member data.

```
class myClass {  
    public:  
        //declarations of public member functions and data  
    private:  
        //declaration of hidden member functions and data  
};
```

- public attributes are visible from outside the class.
- private attributes are only visible within the class.
- If neither public nor private are specified, all attributes will be private.
- Declarations of attributes and methods are done just as functions and variables are declared outside a class.
- A standard practise is to encapsulate the attributes as private data and set and get them through the class interface provided by methods.

- Example Class definition:

```
class myClass {  
    private:  
        int a;  
    public:  
        inline void set(int a){this->a = a;};  
        int get();  
};  
inline int myClass::get(){return a;};
```

- Example usage: objects, pointers and references.

```
myClass myObj; //object declaration  
myObj.set(10);  
myClass* p = &myObj; //pointer (memory address)  
myClass& r = &myObj; //reference (alias)  
  
cout<<"a: " <<p->a<<endl; // not allowed!!  
cout<<"a: " <<p->get()<<endl; // allowed!!
```

- A good programming standard is to organize the class files in pairs, the other one with the class declarations (`.H`), and one with the class definitions (`.C`).
- The class *declaration* file must be included in the files where the class is used, i.e. the class definition file and files that inherits from, or construct objects of that class.
- The compiled *definition* file is statically or dynamically linked to the executable by the compiler.
- Inline functions must be implemented in the class *declaration* file, since they must be inlined without looking at the class *definition* file.

- A *constructor* is a special method that is called each time a new object of that class is instantiated.
- Example: Vector class from OpenFOAM®

```
// Constructors
//-- Construct null (default)
inline Vector();
//-- Construct by copy
inline Vector(const Vector<Cmpt>&);
//-- Construct given three components
inline Vector(const Cmpt& vx, const Cmpt& vy, const Cmpt& vz);
//-- Construct from Istream
inline Vector(Istream&);
```

- The Vector will be initialized differently depending on which of these constructors is chosen
- Also there is a *destructor* method: `~Vector()`...

Example:

```
Vector<scalar> a(1.0,2.0,0.0);  
Vector<scalar> b(-1.0,1.0,1.0);  
a+=b;  
Info<<a<<endl;
```

Why work += and << ? Operator overloading

```
Vector<Cmpt>& Vector<Cmpt>::operator+=(Vector<Cmpt>& v){  
    this->v_[0]+=v.x();  
    this->v_[1]+=v.y();  
    this->v_[2]+=v.z();  
    return this;  
};  
...  
Ostream& Vector<Cmpt>::operator<<(Vector<Cmpt>& v){ ... }
```

(this implementation differs from real OpenFOAM[®] implementation)

- A class can inherit members from already existing classes extending their functionality with new members.
- Syntax, when defining the new class:

```
class newClass : public oldClass { ...members... }
```

- newClass is now a sub-class to oldClass.
- Members of a class can be public, private or protected.
 - ▶ private members are never visible in a sub-class, while public and protected are. However, protected are only visible in a sub-class (not in other classes).
 - ▶ The visibility of the inherited members can be modified in the new class. It is only possible to make the members of a base-class less visible in the sub-class.
 - ▶ To combine features, a class may be a sub-class to several base-classes (multiple inheritance).

- C++ virtual functions: should be implemented by sub-classes
- C++ abstract classes: they have at least one pure virtual method.

(see \$FOAM_SRC/turbulenceModels/incompressible/LES/LESModel/LESModel.H)

```
virtual tmp<volScalarField> nuSgs() const = 0;
```

- C++ templates:

```
template<class T> Vector{ ... } //declaration  
...  
Vector<scalar> V; //usage
```

- C++ typedef:

```
typedef Vector<int> integerVector; //declaration  
...  
integerVector iV; //usage
```

- C++ namespace:

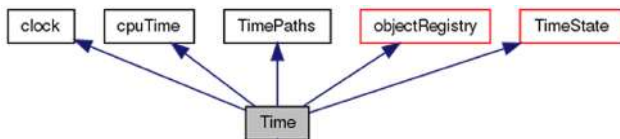
```
namespace Foam{ ... declarations ... } //declaration  
...  
Foam::member() //usage
```

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This section is based on the H. Jasak [presentation](#)

- Space and time: polyMesh, fvMesh, Time
- Field algebra: Field, DimensionedField and GeometricField
- Boundary conditions: fvPatchField and derived classes
- Sparse matrices: lduMatrix, fvMatrix and linear solvers
- Finite Volume discretisation: fvc and fvm namespace

Representation of Time



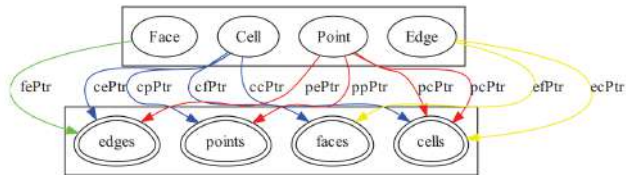
- Class `Time` manages simulation in terms of time-steps: start and end time, delta `t`
 - ▶ `deltaT()`: Return time step
 - ▶ `name()`: Return current directory name
 - ▶ `operator++()`, `operator+=(scalar)`: Time increments.
 - ▶ `write()`: Write to disk the objects.
 - ▶ `startTime()`, `endTime()`.
- Time is associated with IO functionality: what and when to write
- User main simulation control through a dictionary: `controlDict` file

objectRegistry: all IOObjects, including mesh, fields and dictionaries registered in the class Time

```
volScalarField p
(
    IOobject
    (
        "p",
        runTime.timeName(), //directory name
        mesh,
        IOobject::MUST_READ, //read controls
        IOobject::AUTO_WRITE //write controls
    ),
    mesh
);
```

Representation of Space

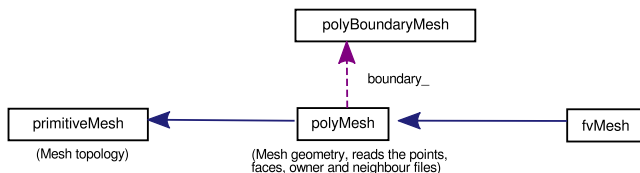
- Computational mesh consists of
 - ▶ List of points. Point index is determined from its position in the list
 - ▶ List of faces. A face is an ordered list of points (defines face normal)
 - ▶ List of cells OR owner-neighbour addressing
 - ▶ List of boundary patches, grouping external faces
- Main classes:
 - ▶ `primitiveMesh`: Cell-face mesh analysis engine (Figure from Passalacqua, Pal Singh, 2008):



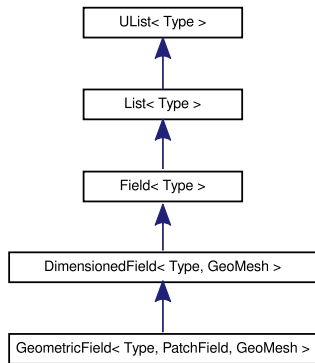
- ▶ `polyMesh`: Mesh consisting of general polyhedral cells: reads points, faces, owner and neighbor files.
- ▶ `polyBoundaryMesh` is a list of `polyPatches`. It is an attribute of `polyMesh`.

Finite Volume Method

- `polyMesh` class provides mesh data in generic manner: it is used by multiple applications and discretisation methods
- For convenience, each discretisation wraps up primitive mesh functionality to suit its needs: mesh metrics, addressing etc.
- `fvMesh`: Mesh data needed to do the Finite Volume discretisation
 - ▶ `C()`, `V()`, `Sf()`, `magSf()`, `Cf()`: geometrical information
 - ▶ `movePoints()`, `updateMesh()`: designed for dynamic meshes



- UList: unallocated array pointer and access
begin(), end(), operator[]
- List: allocation + resizing
size(), resize(), clear(), append()
- Field: algebra overloaded for scalar, vector, tensor
operator+=(), operator-=(), operator*=(), operator/=(), T()
- DimensionedField: I/O, dimension set, name, mesh reference
dimensions(), mesh(), operatorXX() with dimensions check
- GeometricField: internal field, boundary conditions, old time
internalField(), boundaryField()



- **Field**
 - ▶ Simply, a list with algebra, templated on element type
 - ▶ Assign unary and binary operators from the element, mapping functionality etc
- **DimensionedField**
 - ▶ A field associated with a mesh, with a name and mesh reference
 - ▶ Derived from IObject for input-output and database registration
- **GeometricField**
 - ▶ Consists of an internal field (derivation) and a GeometricBoundaryField
 - ▶ Boundary field is a field of fields or boundary patches
 - ▶ Geometric field can be defined on several mesh entities and element types:
volScalarField, volVectorField, surfaceScalarField,
surfaceTensorField, volSymmTensorField,
tensorAverageIOField

- Implementation of boundary conditions is a perfect example of a virtual class hierarchy
- Consider the implementation of a boundary condition
 - ▶ Evaluate function: calculate new boundary values depending on behaviour: fixed value, zero gradient etc.
 - ▶ Enforce boundary type constraint based on matrix coefficients
 - ▶ Virtual function interface: run-time polymorphic dispatch
- Base class: `fvPatchField`
 - ▶ Derived from a field container
 - ▶ Reference to `fvPatch`: easy data access
 - ▶ Reference to internal field
- Types of `fvPatchField`:
 - ▶ Basic: fixed value, zero gradient, mixed, coupled, default
 - ▶ Constraint: enforced on all fields by the patch: cyclic, empty, processor, symmetry, wedge, GGI
 - ▶ Derived: wrapping basic type for physics functionality

GeometricBoundaryField: It has a list of fvPatchFields.

- GeometricField calls its GeometricBoundaryField object

```
correctBoundaryConditions ()  
{  
    this->setUpToDate ();  
    storeOldTimes ();  
    boundaryField_.evaluate (); //method of its attribute  
}
```

- A loop over each fvPatchField is done

```
evaluate () {  
    forAll (*this , patchi )  
    {  
        this->operator [] (patchi).evaluate ();  
    }  
}
```

Sparse Matrix Class

- Addressing classes:
 - ▶ `lduAddressing`: matrix profile
`upperAddr()`, `lowerAddr()`
 - ▶ `lduInterface`: treatment of special B.C: cyclic, parallel and so on.
 - ▶ `lduMesh`, `lduPrimitiveMesh`: `lduAddressing`+`lduInterface`
- `lduMatrix`: matrix coefficients (values)
`upper()`, `lower()`, `diag()`
- Animated .gif

- Finite Volume matrix class: `fvMatrix`
- Derived from `lduMatrix`, with a reference to the solution field and to the *rhs* vector. It looks like an equation system class:
`residual()`, `source()`, `relax()`, `solve()`
- Solver technology: preconditioner, smoother, solver → out of scope
- Matrices are currently always scalar: segregated solver for vector and tensor variables
- It allows matrix assembly at equation level: adding and subtracting matrices
- *Non-standard* matrix functionality in `fvMatrix`:
 - ▶ `A()`: return matrix diagonal in FV field form
 - ▶ `H()`: vector-matrix multiply with current `psi()`, using off-diagonal coefficients and *rhs*
 - ▶ `flux()`: consistent evaluation of off-diagonal product in face form.

- Finite Volume Method implemented in 3 parts
 - ▶ Surface interpolation: cell-to-face data transfer
 - ▶ Finite Volume Calculus (fvc): given a field, create a new field
 - ▶ Finite Volume Method (fvm): create a matrix representation of an operator, using FV discretisation
- In both cases, we have static functions with no common data. Thus, `fvc` and `fvm` are implemented as namespaces
- Discretisation involves a number of choices on how to perform identical operations: eg. gradient operator. In all cases, the signature is common

```
volTensorField gradU = fvc::grad(U);
```

- Multiple algorithmic choices of gradient calculation operator: Gauss theorem, least squares fit, limiters etc. implemented to use run-time selection.
- Choice of discretisation controlled by the user on a per-operator basis: `system/fvSchemes`

$$\vec{\nabla}\psi = \frac{1}{V_P} \sum_f \psi_f \vec{S}_f$$

Example Code

```
...  
volScalarField p;  
surfaceScalarField phi;  
  
// call 1 -> fvcGrad.C -> gaussGrad.C  
fvc::grad(phi);  
  
// call 2 -> fvcGrad.C -> gradScheme.C -> gaussGrad.C  
fvc::grad(p);  
...
```



```
43 template<class Type>
44 tmp
45 <
46     GeometricField
47     <
48         typename outerProduct<vector, Type>::type, fvPatchField, volMesh
49     >
50 >
51 grad
52 (
53     const GeometricField<Type, fvsPatchField, surfaceMesh>& ssf
54 )
55 {
56     return fv::gaussGrad<Type>::gradf(ssf, "grad(" + ssf.name() + ')');
57 }
```

```
...
41 Foam::fv::gaussGrad<Type>::gradf
42 (
43     const GeometricField<Type, fvsPatchField, surfaceMesh>& ssf,
44     const word& name
45 )
46 {
...
82     forAll(owner, facei)
83     {
84         GradType Sfssf = Sf[facei]*ssf[facei];
85         igGrad[owner[facei]] += Sfssf;
86         igGrad[neighbour[facei]] -= Sfssf;
87     }
88 }
90 forAll(mesh.boundary(), patchi)
91 {
92     const labelUList& pFaceCells =
93         mesh.boundary()[patchi].faceCells();
94     const vectorField& pSf = mesh.Sf().boundaryField()[patchi];
95     const fvsPatchField<Type>& pssf = ssf.boundaryField()[patchi];
96     forAll(mesh.boundary()[patchi], facei)
97     {
98         igGrad[pFaceCells[facei]] += pSf[facei]*pssf[facei];
99     }
100 }
101 }
102 }
103 }
104 igGrad /= mesh.V();
105 gGrad.correctBoundaryConditions();
106 return tgGrad;
107 }
```

- `fvGrad.C`

```

...
97     return fv::gradScheme<Type>::New
98     (
99         vf.mesh(),
100        vf.mesh().gradScheme(name)
101    )().grad(vf, name);

```

- `gradScheme.C`

```

62     typename IstreamConstructorTable::iterator cstrIter =
63         IstreamConstructorTablePtr_>find(schemeName);
...
171     return calcGrad(vsf, name);

```

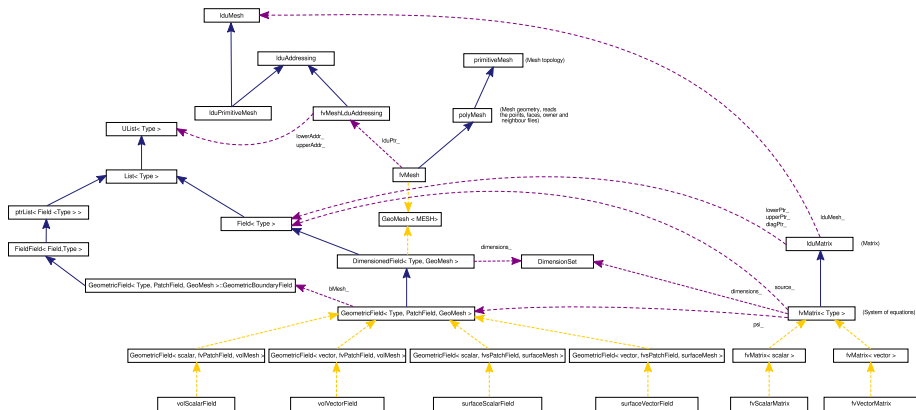
- `gaussGrad.C`

```

131     tmp<GeometricField<GradType, fvPatchField, volMesh>> tgGrad
132     (
133         gradf(tinterpScheme_().interpolate(vsf), name)
134     );

```

Brief Class Diagram



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Compiling OpenFOAM® on debug mode

- If the installation of OpenFOAM® is in a system directory, login as root (`$ sudo su`)
- Edit the file `$WM_PROJECT_DIR/etc/bashrc` and modify the environment variable `WM_COMPILE_OPTION` setting the line:

```
export WM_COMPILE_OPTION=Debug
```

- Reload environment variables (or open a new terminal instance)

```
$ . $WM_PROJECT_DIR/etc/bashrc
```

- Recompile

```
$ cd $WM_PROJECT_DIR  
$ ./Allwmake
```

- Create the host folder imitating the tree directory of OpenFOAM®

```
mkdir $WM_PROJECT_USER_DIR/applications/solvers
```

- Copy the most similar solver

```
$ cp -r \  
$WM_PROJECT_DIR/applications/solvers/incompressible/pisoFoam \  
$WM_PROJECT_USER_DIR/applications/solvers/myPisoFoam
```

- Rename and edit some files

```
$ cd $WM_PROJECT_USER_DIR/applications/solvers/myPisoFoam  
$ mv pisoFoam.C myPisoFoam.C  
$ sed -i s/pisoFoam/myPisoFoam/g myPisoFoam.C  
$ sed -i s/pisoFoam/myPisoFoam/g Make/Files  
$ sed -i s/FOAM_APPBIN/FOAM_USER_APPBIN/g Make/Files
```

- To use the IDE Qtcreator follow the guidelines in http://openfoamwiki.net/index.php/HowTo_Use_OpenFOAM_with_QtCreator
- Once done, we will be able to
 - ▶ Add new projects to the IDE (applications, solvers, tests)
 - ▶ Code-autocompletion
 - ▶ Navigate through files (definitions, declarations)
 - ▶ Compile applications and solvers
 - ▶ Execute tests
 - ▶ User-friendly debugging

gdbOF is a tool attachable to the GNU debugger (gdb) that includes macros to debug OpenFOAM[®] solvers and applications in an easier way.

- Download, installation and user-manual from:
http://openfoamwiki.net/index.php/Contrib_gdbOF
- In QTcreator activate:
Windows -> Views -> Debugger log
- Once at breakpoint, write the gdbOF command in the corresponding box.

- Starting from the turbulent incompressible flow solver `pisoFoam`, which solves ...

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot (\nu \nabla \mathbf{u})$$

- ... and a passive scalar transport equation is added

$$\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{u}T) = \nabla \cdot (\alpha \nabla T)$$

- where the viscosity and diffusivity are related by $Pr = \nu/\alpha$.

- Starting from the solver for 2 incompressible fluids using Volume of Fluid (VoF) `interFoam`, which solves ...

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u} + \nabla^T \mathbf{u}) + \rho \mathbf{g} + \sigma \kappa \nabla \alpha$$

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) = -\nabla \cdot [\alpha (1 - \alpha) \mathbf{v}]$$

- ... where $0 \leq \alpha \leq 1$ is the volume fraction (a sharp function)
- A widely used strategy is coupling VoF and LevelSet to smooth α and to improve the surface tension forces calculation.
- Level Set function ϕ properties
 - ▶ $\phi = 0$ at interface
 - ▶ $|\nabla \phi| = 1$
 - ▶ $\mathbf{n} = \nabla \phi$
 - ▶ $\kappa = -\nabla \cdot \mathbf{n}$

- Initial value of Level Set function

$$\phi^0 = (2\alpha - 1)\Gamma$$

- Reinitialization equation

$$\frac{\partial \phi^{n+1}}{\partial \tau} = S(\phi^0)(1 - |\nabla \phi^n|)$$

- Volumetric surface tension force

$$\mathbf{F}_\sigma = \sigma \kappa(\phi) \delta(\phi) \nabla \phi$$

- Heaviside smoothed Function (for physical properties)

$$H(\phi) = \begin{cases} 0 & \phi < -\epsilon \\ \frac{1}{2} \left[1 + \frac{\phi}{\epsilon} + \frac{1}{\pi} \sin \frac{\pi \phi}{\epsilon} \right] & |\phi| < \epsilon \\ 1 & \phi > \epsilon \end{cases}$$

Implementation based on the work of [Takuya Yamamoto](#)

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Run-time type selection (RTS) mechanism

With the aid of Bruno Santos and Tomislav Maric ([Turbulence models and run time selection tables](#)).

Run-time type selection is a mechanism that allows the user of a program to select different variable (object) types at a point of program execution. This mechanism is heavily used in OpenFOAM® to enable the user a high level of flexibility in choosing:

- boundary conditions,
- discretization schemes,
- models (viscosity, turbulence, two-phase property),
- function objects,

and similar elements that build up a numerical simulation –all at run-time. The type selection mechanism can be considered as a black box, that takes the input parameter, and returns a constructed object of an appropriate class (type).

Run-time type selection (RTS) mechanism

Other options to this mechanism could be:

- hard-coding,
- using multiple decision structures (f.e. `switch--case` in C++),

	Advantages	Disadvantages
Hard-coding	Speed	Not-flexible
Decision structures	Speed	Partially flexible
RTS	Highly flexible	Complex

- RTS is based on static variables and methods and the extensive use of pre-processor macros,
- the constructors of the selected objects are taken from predefined tables which are loaded at startup

Class names

defineTypeNameAndDebug(Type, DebugSwitch) (className.H)

```

142 //- Define the typeName and debug information
143 #define defineTypeNameAndDebug(Type, DebugSwitch) \
144     defineTypeName(Type); \
145     defineDebugSwitch(Type, DebugSwitch)

105 //- Define the typeName
106 #define defineTypeName(Type) \
107     defineTypeNameWithName(Type, Type::typeName_())

101 //- Define the typeName, with alternative lookup as \a Name
102 #define defineTypeNameWithName(Type, Name) \
103     const ::Foam::word Type::typeName(Name)

```


Run time selection tables creation. Allocation of table pointer.

```
defineRunTimeSelectionTable(baseType, argNames)
(runTimeSelectionTables.H)
```

```
292 // external use:
293 // -----
294 // define run-time selection table
295 #define defineRunTimeSelectionTable\
296 (baseType, argNames)
297
298     defineRunTimeSelectionTablePtr(baseType, argNames);
299     defineRunTimeSelectionTableConstructor(baseType, argNames);
300     defineRunTimeSelectionTableDestructor(baseType, argNames)
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321 // internal use:
322 // create pointer to hash-table of functions
323 #define defineRunTimeSelectionTablePtr\
324 (baseType, argNames)
325
326     /* Define the constructor function table */
327     baseType::argNames##ConstructorTable*
328     baseType::argNames##ConstructorTablePtr_ = NULL
```

Run time selection tables creation. Creation of empty table.

defineRunTimeSelectionTable(baseType, argNames)
 (runTimeSelectionTables.H)

```

237 // internal use:
238 // constructor aid
239 #define defineRunTimeSelectionTableConstructor\
240 (baseType, argNames)
241
242 /* Table constructor called from the table add function */
243 void baseType::construct##argNames##ConstructorTables()
244 {
245     static bool constructed = false;
246     if (!constructed)
247     {
248         constructed = true;
249         baseType::argNames##ConstructorTablePtr_
250             = new baseType::argNames##ConstructorTable;
251     }
252 }
  
```

RTS principal macros

Run time selection tables use. Direct calling of constructors, add of new entries.

```
declareRunTimeSelectionTable(autoPtr, baseType, argNames  
, argList, parList) (runTimeSelectionTables.H)
```

```
27 // declareRunTimeSelectionTable is used to create a run-time selection table  
28 // for a base-class which holds constructor pointers on the table.  
  
46 // external use:  
47 // -----  
48 // declare a run-time selection:  
49 #define declareRunTimeSelectionTable\  
50 (autoPtr, baseType, argNames, argList, parList)  
51  
52 /* Construct from argList function pointer type */  
53 typedef autoPtr< baseType > (*argNames##ConstructorPtr)argList;  
54  
55 /* Construct from argList function table type */  
56 typedef HashTable< argNames##ConstructorPtr, word, string::hash >  
57 argNames##ConstructorTable;  
58  
59 /* Construct from argList function pointer table pointer */  
60 static argNames##ConstructorTable* argNames##ConstructorTablePtr_;  
61  
62 /* Table constructor called from the table add function */  
63 static void construct##argNames##ConstructorTables();  
64  
65 /* Table destructor called from the table add function destructor */  
66 static void destroy##argNames##ConstructorTables();
```

```

68  /* Class to add constructor from argList to table */
69  template< class baseType##Type >
70  class add##argNames##ConstructorToTable
71  {
72  public:
73
74      static autoPtr< baseType > New argList
75      {
76          return autoPtr< baseType >(new baseType##Type parList);
77      }
78
79      add##argNames##ConstructorToTable
80      (
81          const word& lookup = baseType##Type::typeName
82      )
83      {
84          construct##argNames##ConstructorTables();
85          if (!argNames##ConstructorTablePtr_>insert(lookup, New))
86          {
87              std::cerr<< "Duplicate entry " << lookup
88                  << " in runtime selection table " << #baseType
89                  << std::endl;
90              error::safePrintStack(std::cerr);
91          }
92      }
93
94      ~add##argNames##ConstructorToTable()
95      {
96          destroy##argNames##ConstructorTables();
97      }
98  };

```

Run time selection tables use. Calling of “New” methods, add of new entries.

```
declareRunTimeNewSelectionTable(autoPtr,baseType,
argNames,argList,parList) (runTimeSelectionTables.H)
```

```
30 declareRunTimeNewSelectionTable is used to create a run-time selection
31 table for a derived-class which holds "New" pointers on the table.
```

```
137 // external use:
138 // ~~~~~
139 // declare a run-time selection for derived classes:
140 #define declareRunTimeNewSelectionTable\
141 (autoPtr,baseType,argNames,argList,parList)
142
143 /* Construct from argList function pointer type */
144 typedef autoPtr< baseType > (*argNames##ConstructorPtr)argList;
145
146 /* Construct from argList function table type */
147 typedef HashTable< argNames##ConstructorPtr, word, string::hash >
148 argNames##ConstructorTable;
149
150 /* Construct from argList function pointer table pointer */
151 static argNames##ConstructorTable* argNames##ConstructorTablePtr_;
152
153 /* Table constructor called from the table add function */
154 static void construct##argNames##ConstructorTables();
```

```

156  /* Table destructor called from the table add function destructor */
157  static void destroy##argNames##ConstructorTables();
158
159  /* Class to add constructor from argList to table */
160  template< class baseType##Type >
161  class add##argNames##ConstructorToTable
162  {
163  public:
164
165      static autoPtr< baseType > New##baseType argList
166      {
167          return autoPtr< baseType >(baseType##Type::New parList.ptr());
168      }
169
170      add##argNames##ConstructorToTable
171      (
172          const word& lookup = baseType##Type::typeName
173      )
174      {
175          construct##argNames##ConstructorTables();
176          if
177          (
178              !argNames##ConstructorTablePtr_>insert
179              (
180                  lookup,
181                  New##baseType
182              )
183          )

```

Run time selection tables use.

Adding new entries. The actual adding is performed when the `add##thisType##argNames##ConstructorTo##baseType##Table_` object is instantiated via its constructor.

```
addToRunTimeSelectionTable(baseType, thisType, argNames)
(addToRunTimeSelectionTable.H)
```

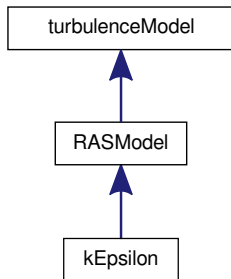
```
25 // Macros for easy insertion into run-time selection tables
35 // add to hash-table of functions with typename as the key
36 #define addToRunTimeSelectionTable\
37 (baseType, thisType, argNames)
38
39 /* Add the thisType constructor function to the table */
40 baseType::add##argNames##ConstructorToTable< thisType >
41     add##thisType##argNames##ConstructorTo##baseType##Table_
```

RTS in turbulence models

The whole mechanism is based on two tables (RAS case):

- Turbulence models = 3(LESModel, RASModel, laminar)
- RAS models = 18(LRR, LamBremhorstKE, LaunderGibsonRSTM, LaunderSharmaKE, LienCubicKE, LienCubicKELowRe, LienLeschzinerLowRe, NonlinearKEShih, RNGkEpsilon, SpalartAllmaras, kEpsilon, kOmega, kOmegaSST, kkLOmega, laminar, qZeta, realizableKE, v2f)

where their objects have the following hierarchy:



Definition of Turbulence Models table via static data (creation of empty table) at startup

```
defineRunTimeSelectionTable(turbulenceModel,  
turbulenceModel); (turbulenceModel.C)
```

```
38 // * * * * * Static Data Members * * * * * //  
39  
40 defineTypeNameAndDebug(turbulenceModel, 0);  
41 defineRunTimeSelectionTable(turbulenceModel, turbulenceModel);
```

Definition of RAS Models table via static data (creation of empty table) at startup. Adding of RASModel to Turbulence Models table.

```
defineRunTimeSelectionTable(turbulenceModel, turbulenceModel);  
addToRunTimeSelectionTable(turbulenceModel, RASModel, turbulenceModel);  
(RASModel.C)
```

```
36 // * * * * * Static Data Members * * * * * //  
37  
38 defineTypeNameAndDebug(RASModel, 0);  
39 defineRunTimeSelectionTable(RASModel, dictionary);  
40 addToRunTimeSelectionTable(turbulenceModel, RASModel, turbulenceModel);
```

Finally each RAS turbulence models adds itself to RAS Models table, f.e. `kEpsilon`

```
addToRunTimeSelectionTable(RASModel, kEpsilon, dictionary);  
(kEpsilon.C)
```

```
40 // * * * * * Static Data Members * * * * * //  
41  
42 defineTypeNameAndDebug(kEpsilon, 0);  
43 addToRunTimeSelectionTable(RASModel, kEpsilon, dictionary);
```

RTS in action, selecting kEpsilon in pimpleFoam

The selection of turbulence model requires to set first the `constant/turbulenceProperties` user dictionary to select the main type of turbulence model.

```
// * * * * * //  
simulationType RASModel;  
  
// * * * * * //
```

Then, the `constant/RASProperties` user dictionary is set to select the particular RAS turbulence model

```
// * * * * * //  
RASModel          kEpsilon;  
  
turbulence         on;  
  
printCoeffs        on;  
  
// * * * * * //
```

RTS in action, selecting kEpsilon in pimpleFoam

Once `pimpleFoam` is executed and reaches the following line of the corresponding `createFields.H`:

```
39 autoPtr<incompressible::turbulenceModel> turbulence
40 (
41     incompressible::turbulenceModel::New(U, phi, laminarTransport)
42 );
```

Here the `turbulence` auto pointer is set in order to invoke the methods required from the turbulence model such as `turbulence->correct()` to solve the turbulence models equations or `turbulence->divDevReff(U)` to evaluate the viscous terms of momentum equations.

The `turbulenceModel::New(U, phi, laminarTransport)` method is a selector which reads from `constant/turbulenceProperties` dictionary and searches in the `Turbulence Models` table, if the required main turbulence models exists continues the calling chain, if not, shows an error by the `stdout`.

RTS in action, selecting kEpsilon in pimpleFoam

turbulenceModel.C

```
76 autoPtr<turbulenceModel> turbulenceModel::New
77 (
78     const volVectorField& U,
79     const surfaceScalarField& phi,
80     transportModel& transport,
81     const word& turbulenceModelName
82 )
83 {
84     // get model name, but do not register the dictionary
85     // otherwise it is registered in the database twice
86     const word modelType
87     (
88         IOdictionary
89         (
90             IOobject
91             (
92                 "turbulenceProperties",
93                 U.time().constant(),
94                 U.db(),
95                 IOobject::MUST_READ_IF_MODIFIED,
96                 IOobject::NO_WRITE,
97                 false
98             )
99         ).lookup("simulationType")
100     );
101
102     Info<< "Selecting turbulence model type " << modelType << endl;
103
104     turbulenceModelConstructorTable::iterator cstrIter =
105         turbulenceModelConstructorTablePtr_>find(modelType);
```

RTS in action, selecting kEpsilon in pimpleFoam

```
107     if (cstrIter == turbulenceModelConstructorTablePtr_>end())
108     {
109         FatalErrorIn
110         (
111             " turbulenceModel::New(const volVectorField&, "
112             " const surfaceScalarField&, transportModel&, const word&)"
113             ) << "Unknown turbulenceModel type "
114             << modelType << nl << nl
115             << "Valid turbulenceModel types:" << endl
116             << turbulenceModelConstructorTablePtr_>sortedToc()
117             << exit(FatalError);
118     }
119
120     return autoPtr<turbulenceModel>
121     (
122         cstrIter()(U, phi, transport, turbulenceModelName)
123     );
124 }
```

The `cstrIter()` has a pointer to a **New** method of `RASModel` class as was defined using the `declareRunTimeNewSelectionTable` macro included in `turbulenceModel.H`.

RTS in action, selecting kEpsilon in pimpleFoam

RASModel.C

```
98 autoPtr<RASModel> RASModel::New
99 (
100     const volVectorField& U,
101     const surfaceScalarField& phi,
102     transportModel& transport,
103     const word& turbulenceModelName
104 )
105 {
106     // get model name, but do not register the dictionary
107     // otherwise it is registered in the database twice
108     const word modelType
109     (
110         IOdictionary
111         (
112             IOobject
113             (
114                 "RASProperties",
115                 U.time().constant(),
116                 U.db(),
117                 IOobject::MUST_READ_IF_MODIFIED,
118                 IOobject::NO_WRITE,
119                 false
120             )
121         ).lookup("RASModel")
122     );
123
124     Info<< "Selecting RAS turbulence model " << modelType << endl;
125
126     dictionaryConstructorTable::iterator cstrIter =
127         dictionaryConstructorTablePtr_>find(modelType);
```

RTS in action, selecting kEpsilon in pimpleFoam

```
129     if (cstrIter == dictionaryConstructorTablePtr_>end())
130     {
131         FatalErrorIn
132         (
133             "RASModel::New"
134             "("
135             "    const volVectorField&, "
136             "    const surfaceScalarField&, "
137             "    transportModel&, "
138             "    const word&"
139             ")"
140         ) << "Unknown RASModel type "
141           << modelType << nl << nl
142           << "Valid RASModel types:" << endl
143           << dictionaryConstructorTablePtr_>sortedToc()
144           << exit(FatalError);
145     }
146
147     return autoPtr<RASModel>
148     (
149         cstrIter()(U, phi, transport, turbulenceModelName)
150     );
151 }
```

The `cstrIter()` has a pointer to a **true constructor** for `kEpsilon` class as was defined using the `declareRunTimeSelectionTable` macro included in `RASModel.H`.

RTS in action, selecting kEpsilon in pimpleFoam

Once the `kEpsilon` model object is instantiated the calling chain returns to `createFields.H` and the turbulence model is ready to use.

UEqn.H

```
1 // Solve the Momentum equation
2
3 tmp<fvVectorMatrix> UEqn
4 (
5     fvm::ddt(U)
6     + fvm::div(phi, U)
7     + turbulence->divDevReff(U)
8     ==
9     fvOptions(U)
10 );
```

pimpleFoam.C

```
72 // — Pressure-velocity PIMPLE corrector loop
73 while (pimple.loop())
74 {
75     #include "UEqn.H"
76
77     // — Pressure corrector loop
78     while (pimple.correct())
79     {
80         #include "pEqn.H"
81     }
82
83     if (pimple.turbCorr())
84     {
85         turbulence->correct();
86     }
87 }
```

Turbulence model implementation study case

Modifications in `kEpsilon` model.

Key concepts:

- Reading parameters in the initialization list;
- implementation of the correct method;
- call the `addToRunTimeSelectionTable` macro to add the new turbulence model to the RTS table;
- set the `Make/files` and `Make/options` files.

Remember the `$WM_PROJECT_DIR` and `$WM_PROJECT_USER_DIR` environment variables.

Turbulence model implementation study case

Main steps.

- Copy the original `kEpsilon` implementation to the `$WM_PROJECT_USER_DIR`;

```
cp -r --parents src/turbulenceModels/incompressible/RAS/kEpsilon \  
  $WM_PROJECT_USER_DIR
```

(The original directory tree and naming is used.)

- rename directories;

```
cd $WM_PROJECT_USER_DIR/src/turbulenceModels/incompressible/RAS  
mv kEpsilon mykEpsilon
```

Turbulence model implementation study case

- create Make/files and Make/options files;

```
mkdir Make  
cd Make/  
nano files
```

```
mykEpsilon.C
```

```
LIB = $(FOAM_USER_LIBBIN)/libmyIncompressibleRASModels
```

```
nano options
```

```
EXE_INC = \  
-I$(LIB_SRC)/turbulenceModels \  
-I$(LIB_SRC)/transportModels \  
-I$(LIB_SRC)/finiteVolume/lnInclude \  
-I$(LIB_SRC)/meshTools/lnInclude \  
-I$(LIB_SRC)/turbulenceModels/incompressible/RAS/lnInclude
```

```
LIB_LIBS =
```

This method is intended for only one turbulence model within the library. The other way is to reproduce the `$WM_PROJECT_DIR/.../RAS/Make` directory and files, *add* the new model and generate a library for all the new turbulence models.

Turbulence model implementation study case

- edit filenames and code;

```
cd ..  
rm kEpsilon.dep  
mv kEpsilon.C mykEpsilon.C  
mv kEpsilon.H mykEpsilon.H  
sed -i s/kEpsilon/mykEpsilon/g mykEpsilon.C  
sed -i s/kEpsilon/mykEpsilon/g mykEpsilon.H
```

- make simple changes in constructor;

```
Info << "Defining my own kEpsilon model" << endl;
```

- compile;

```
wmake libso
```

Turbulence model implementation study case

- run.

```
cd $FOAM_RUN
cp -r $FOAM_TUTORIALS/incompressible/pimpleFoam/pitzDaily
cd pitzDaily
nano system/controlDict
```

```
libs ("libmyIncompressibleRASModels.so");
```

```
nano constant/RASProperties
```

```
RASModel      mykEpsilon;
```

```
pimpleFoam
```

The message included in the turbulence model constructor will be displayed by the stdout.

For further details see: “[How to implement a turbulence model](#)” slides by Håkan Nilsson.

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Boundary conditions from a FVM basis

Setting boundary conditions affects the matrix's coefficients and the source term of the linear system. For example, in case of fixed value derived BC's:

- Convective term:

$$\int_{\Gamma} \vec{v} \phi \cdot d\vec{\Gamma} = \sum_f \phi_f (\vec{v}_f \cdot \vec{S}_f)$$

The contribution to source term is given by the value $-\phi_b \vec{v}_f \cdot \vec{S}_f$ and the contribution to the matrix **is zero**.

Boundary conditions from a FVM basis

- Diffusive term:

$$\int_{\Gamma} \vec{\nabla} \cdot (\nu \vec{\nabla} \phi) d\Omega = \sum_f (\nu)_f (\vec{\nabla} \phi)_f \cdot \vec{S}_f$$

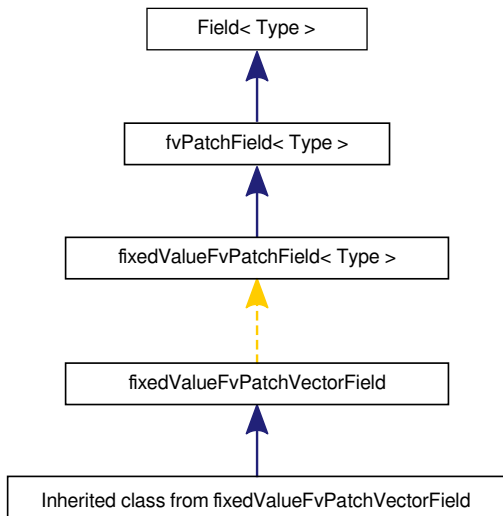
For the case of orthogonal meshes and Gauss linear laplacian scheme the contributions to the matrix and source term are given by:

$$(\nu)_f (\vec{\nabla} \phi)_b \cdot \vec{S}_f = (\nu)_f |\vec{S}_f| \frac{\phi_b - \phi_P}{|\vec{d}_n|}$$

with a contribution to the source term of $-(\nu)_f |\vec{S}_f| \frac{\phi_b}{|\vec{d}_n|}$ and to the matrix diagonal of $-(\nu)_f |\vec{S}_f| \frac{1}{|\vec{d}_n|}$.

The fixed value boundary conditions are implemented via `fixedValueFvPatchField` and related classes.

Inheritance diagram for fixedValueFvPatchField and related classes



- `fvPatchField< Type >`

Abstract base class with a fat-interface to all derived classes covering all possible ways in which they might be used.

–The first level of derivation is to basic patchFields which cover zero-gradient, fixed-gradient, fixed-value and mixed conditions.

–The next level of derivation covers all the specialised types with specific evaluation procedures, particularly with respect to specific fields.

- `fixedValueFvPatchField< Type >`

This boundary condition supplies a fixed value constraint, and is the base class for a number of other boundary conditions.

–The derived classes could not accept templating, then a series of typedef's is created automatically for scalar, vector, tensor type and so on. This is achieved by the `makePatchFields` macro

`fixedValueFvPatchFields.C`

```

35 // * * * * * Static Data Members * * * * * //
36
37 makePatchFields(fixedValue);
38
39 // * * * * * //

```

fixedValueFvPatchField and related classes

fvPatchField.H

```

668 #define makePatchFields(type)
669     makeTemplatePatchTypeField
670     (
671         fvPatchScalarField ,
672         type##FvPatchScalarField
673     );
674     makeTemplatePatchTypeField
675     (
676         fvPatchVectorField ,
677         type##FvPatchVectorField
678     );
679     makeTemplatePatchTypeField
680     (
681         fvPatchSphericalTensorField ,
682         type##FvPatchSphericalTensorField
683     );
684     makeTemplatePatchTypeField
685     (
686         fvPatchSymmTensorField ,
687         type##FvPatchSymmTensorField
688     );
689     makeTemplatePatchTypeField
690     (
691         fvPatchTensorField ,
692         type##FvPatchTensorField
693     );

```

- `fixedValueFvPatchVectorField`

From this class other vectorial fixed value boundary condition can be inherited.

Induction to some methods required in boundary condition classes

- The case of `fvm::div(phi, U)` term.

This term requires the evaluation of a divergence in weak form. The implementation for the Gauss case is presented in `gaussConvectionScheme.C` and returns a `tmp<fvMatrix<Type>>`

```
74 template<class Type>
75 tmp<fvMatrix<Type>>
76 gaussConvectionScheme<Type>::fvmDiv
77 (
78     const surfaceScalarField& faceFlux,
79     const GeometricField<Type, fvPatchField, volMesh>& vf
80 ) const
81 {
82     tmp<surfaceScalarField> tweights = tinterpScheme_().weights(vf);
83     const surfaceScalarField& weights = tweights();
84
85     tmp<fvMatrix<Type>> tfvm
86     (
87         new fvMatrix<Type>
88         (
89             vf,
90             faceFlux.dimensions()*vf.dimensions()
91         )
92     );
```

Induction to some methods required in boundary condition classes

```
93 fvMatrix<Type>& fvm = tfvm();
94
95 fvm.lower() = -weights.internalField()*faceFlux.internalField();
96 fvm.upper() = fvm.lower() + faceFlux.internalField();
97 fvm.negSumDiag();
98
99 forAll(vf.boundaryField(), patchI)
100 {
101     const fvPatchField<Type>& psf = vf.boundaryField()[patchI];
102     const fvsPatchScalarField& patchFlux = faceFlux.boundaryField()[patchI];
103     const fvsPatchScalarField& pw = weights.boundaryField()[patchI];
104
105     fvm.internalCoeffs()[patchI] = patchFlux*psf.valueInternalCoeffs(pw);
106     fvm.boundaryCoeffs()[patchI] = -patchFlux*psf.valueBoundaryCoeffs(pw);
107 }
108
109 if (tinterpScheme_.corrected())
110 {
111     fvm += fvc::surfaceIntegrate(faceFlux*tinterpScheme_.correction(vf));
112 }
113
114 return tfvm;
115 }
```

The contribution to the system matrix is stored in `fvm.internalCoeffs()` and the contribution to the source term is stored in `fvm.boundaryCoeffs()`. The `valueInternalCoeffs()` and `valueBoundaryCoeffs()` are required from the boundary condition classes.

Induction to some methods required in boundary condition classes

fixedValueFvPatchField.C

```
112 template<class Type>
113 tmp<Field<Type>> fixedValueFvPatchField<Type>::valueInternalCoeffs
114 (
115     const tmp<scalarField>&
116 ) const
117 {
118     return tmp<Field<Type>>
119     (
120         new Field<Type>(this->size(), pTraits<Type>::zero)
121     );
122 }
123
124
125 template<class Type>
126 tmp<Field<Type>> fixedValueFvPatchField<Type>::valueBoundaryCoeffs
127 (
128     const tmp<scalarField>&
129 ) const
130 {
131     return *this;
132 }
```

As was expected the contribution to the matrix will be zero and the contribution to the source term returns `*this`. Since the `fvPatch` related classes inherit from `Field`, the `this` pointer points to the BC field values. **These values are calculated following their definition equations.**

Induction to some methods required in boundary condition classes

The fixed values on each face of the boundary patch are evaluated in the boundary condition class constructor by the evaluate method.

fvPatchField.C

```
322 template<class Type>
323 void Foam::fvPatchField<Type>::evaluate(const Pstream::commsTypes)
324 {
325     if (!updated_)
326     {
327         updateCoeffs();
328     }
329
330     updated_ = false;
331     manipulatedMatrix_ = false;
332 }
```

The evaluate execution requires to have implemented the updateCoeffs method. This method is boundary condition specific and the center of the efforts in new fixed value boundary conditions implementation.

implementation study case

Parabolic inlet boundary condition from foam-extend-3.1
(parabolicVelocityFvPatchVectorField).

This boundary conditions fixes a parabolic velocity in a boundary with normal n , along direction y and with a peak velocity of `maxValue`.

Key concepts:

- Reading parameters in the initialization list;
- implementation of the `updateCoeffs` and `write` methods;
- call the `makePatchTypeField` macro to add the new boundary condition to the RTS table;
- set the `Make/files` and `Make/options` files.

fvPatchField.H

```
651 // for non-templated patch fields
652 #define makePatchTypeField(PatchTypeField, typePatchTypeField) \
653     defineTypeNameAndDebug(typePatchTypeField, 0); \
654     addToPatchFieldRunTimeSelection(PatchTypeField, typePatchTypeField)
```

Boundary condition implementation study case

Compiling and using

- Compile the new boundary condition using `wmake libso`;
- set the parameter in the O/U field;

```
type          parabolicVelocity;  
n             (1 0 0);  
y             (0 1 0);  
maxValue     1;  
value        uniform (0 0 0);
```

- load the library declaring it in the `system/controlDict` file:
`libs ("parabolicVelocity.so");`

For further details see: “[How to implement a new boundary condition](#)”
slides by Håkan Nilsson.

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Module: adding a control system to an application

- An excuse to learn how to:
 - ▶ modify fixedValue BCs during runtime, and
 - ▶ exchange information between processors.
- Base code: scalarTransportFoam
- Base case: pitzDaily

- Base case
 - ▶ Serial run
- Version 1: variable BC
 - ▶ Add code for modifying fixedValue BC
 - ▶ Serial run
- Version 2: control system (first try)
 - ▶ Add control system code
 - ▶ Create control system dictionaries
 - ▶ Serial run
 - ▶ Decompose and run in parallel
- Version 3: control system (revisited)
 - ▶ Add interprocess communication
 - ▶ Run in parallel

```
int main(int argc, char *argv[])
{
#include "setRootCase.H"
#include "createTime.H"
#include "createMesh.H"
#include "createFields.H"
// #include "CScreeSensors.H"
simpleControl simple(mesh);

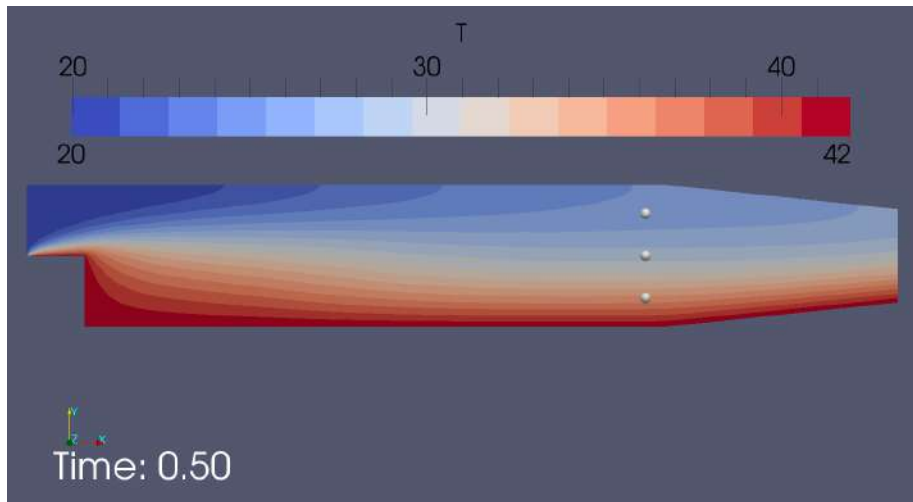
Info<< "\nCalculating scalar transport\n" << endl;

#include "CourantNo.H"
...
}
```



```
...
while (simple.loop())
{
    Info<< "Time = " << runTime.timeName() << nl << endl;
    // #include "CScontrolActions.H"
    while (simple.correctNonOrthogonal())
    {
        solve
        (
            fvm::ddt(T)
            + fvm::div(phi, T)
            - fvm::laplacian(DT, T)
        );
    }
    runTime.write();
}
Info<< "End\n" << endl;
return 0;
}
```

Base case: pitzDaily (modified)



- #include "modifyBC.H" inside the time loop to linearly increase the BC value of patch "lowerWall"

```
//file: modifyBC.H
//Identify patchID
label patchID = mesh.boundaryMesh().findPatchID("lowerWall");
//Get pointer to the field data
fixedValueFvPatchScalarField& WallTemperature =
    refCast<fixedValueFvPatchScalarField>(T.boundaryField()[patchID]);
//Copy pointer
scalarField& TemperatureValue = WallTemperature;
//for all faces in the patch, increase temperature in 0.001C
forAll (TemperatureValue, i) {
    TemperatureValue[i] += 0.001;
}
```

- Compile and run

- Remove `#include "modifyBC.H"`
- Add `#include "CScreateSensors.H"` before the time loop
- Add `#include "CScontrolActions.H"` inside the time loop
- Compile
- Create dictionary "constant/probeLocations"
- Run serial
- Decompose and run in parallel

"CScreeSensors.H"

```
IOdictionary pLocs
(
  IOobject
  (
    "probeLocations",
    runtime.constant(),
    mesh,
    IOobject::MUST_READ,
    IOobject::NO_WRITE
  )
);

. . .
```

"CScreateSensors.H"

```
. . .  
  
// Probes  
// create pointer to probes  
const pointField& probeLocations(pLocs.lookup("probeLocations"));  
// build cell ID list  
labelList probeCells(probeLocations.size(), -1);  
// create array for storing temperature readings  
List<double> Tsensor(probeLocations.size(), 0.0);  
// locate probe cells and take first reading  
forAll(probeLocations, pI)  
{  
    probeCells[pI] = mesh.findCell(probeLocations[pI]);  
    Tsensor[pI] = T[probeCells[pI]];  
}  
  
. . .
```

"CScreateSensors.H"

. . .

```
// Control system parameters
double CS_Tmed; // variable for storing measured mean temperature
dimensionedScalar CS_setPoint // set point
( pLocs.lookup("CS_setPoint") );
dimensionedScalar CS_gain // gain
( pLocs.lookup("CS_gain") );
```

"CScontrolActions.H"

```
forAll(probeLocations, pI)
{
    Tsensor[pI] = T[probeCells[pI]]; // measure temperatures
}

// Calculate mean temperature
CS_Tmed = 0;
forAll(probeLocations, pI)
{
    CS_Tmed = CS_Tmed + (Tsensor[pI]);
}
if (probeLocations.size()>0) {CS_Tmed = CS_Tmed/probeLocations.size();}
```


"CScontrolActions.H"

```
. . .  
  
// Control lowerWall temperature  
label patchID = mesh.boundaryMesh().findPatchID("lowerWall");  
fixedValueFvPatchScalarField& WallTemperature =  
    refCast<fixedValueFvPatchScalarField>(T.boundaryField()[patchID]);  
scalarField& TemperatureValue = WallTemperature;  
  
forAll (TemperatureValue, i) {  
    TemperatureValue[i] -= CS_gain.value()*(CS_Tmed-CS_setPoint.value());  
}  
  
// Output relevant information (processor 0 only)  
if( Pstream::myProcNo() == 0 )  
{  
    Pout << endl;  
    Pout << " *** Control System | mean T: " << CS_Tmed << "oC - ";  
    Pout << " target T: " << CS_setPoint.value() << "oC - ";  
    Pout << " lowerWall T: " << TemperatureValue[0] << "oC - ***" << endl << endl;  
}
```

"constant/probeDictionary"

```
// FoamFile
{
    version      2.0;
    format       ascii;
    class        dictionary;
    location     "constant";
    object       probeLocations;
}
probeLocations
(
    ( 0.2 -0.01 0)
    ( 0.2  0.0  0)
    ( 0.2  0.01 0)
);
fields
(
    T
);
CS_setPoint CS_setPoint [0 0 0 0 0 0 0] 30;
CS_gain     CS_gain     [0 0 0 0 0 0 0] 0.01;
```

- Remove `#include "modifyBC.H"`
- Add `#include "CScreateSensors.H"` before the time loop
- Add `#include "CScontrolActions.H"` inside the time loop
- Compile
- Create dictionary "constant/probeLocations"
- Run serial
- Decompose and run in parallel

"CScreeSensors.H"

```
IOdictionary pLocs
(
  IOobject
  (
    "probeLocations",
    runtime.constant(),
    mesh,
    IOobject::MUST_READ,
    IOobject::NO_WRITE
  )
);

. . .
```

"CScreateSensors.H"

```
. . .  
  
// Probes  
// create pointer to probes  
const pointField& probeLocations(pLocs.lookup("probeLocations"));  
// build cell ID list  
labelList probeCells(probeLocations.size(), -1);  
// create array for storing temperature readings  
List<double> Tsensor(probeLocations.size(), 0.0);  
// locate probe cells and take first reading  
forAll(probeLocations, pI)  
{  
    probeCells[pI] = mesh.findCell(probeLocations[pI]);  
    Tsensor[pI] = T[probeCells[pI]];  
}  
  
. . .
```

- Modify `#include "CScreeateSensors.H"` to include interprocessor communication
- Modify `#include "CScontrolActions.H"` to include interprocessor communication
- Compile
- Run in parallel

"CScreateSensors.H"

```
:  
forall(probeLocations, pI)  
{  
  probeCells[pI] = mesh.findCell(probeLocations[pI]);  
  Tsensor[pI] = T[probeCells[pI]];  
}  
reduce( Tsensor, sumOp<List<double>>() ); // *** communicate temperatures ***  
:
```

"CScontrolActions.H"

```
:  
forAll(probeLocations, pI)  
{  
  Tsensor[pI] = T[probeCells[pI]]; // measure temperatures  
}  
reduce( Tsensor, sumOp<List<double>>() ); // *** communicate temperatures ***  
:
```


Thanks for your attention...
Have a nice week and a fruitful conference!