ESIPAP European School of Instrumentation in Particle and Astroparticle Physics

2017 edition

Supervisers: Eric Chabert, Eric Conte

Computing session 1

C++ model for the electromagnetic barrel calorimeter of the CMS (Compact Muon Solenoid) detector

Abstract:
This computing session is dedicated to the first notions of oriented-object programming. The physics topic chosen for the exercise is the electromagnetic calorimeter of the CMS experiment. In a first part, the students are invited to program a C++ model of the calorimeter from UML (Unified Modeling Language) diagrams. The developed code must describe the apparatus geometry, read data acquired by all cells and correct these data with calibration settings. The second part of the session consists in equipping the programming project with a *makefile*-based compilation and with an automatically generated documentation.

Pedagogical goals:

C++ language

- Writing new classes from UML diagrams.
- Instantiating objects from classes and initializing them.
- Reading and adapting an existing piece of code.
- Improving the robustness of the code in order to prevent abnormal termination or unexpected actions.

Collaboration work

- Respecting a given set of programming rules and conventions.
- Generating automatically the reference documentation related to the code with Doxygen.

Compiling/linking

- Creating an executable file from a simple source file.
- Compiling and linking a project made up of several source files: in a manual or automated (Makefile) way.

Requirements:

- Concept of class in C++, including constructors, destructor, mutators, accessors, ...
- Some particular C++ points: I/O access, arrays, pointers/references.

Contents

Part I
Introduction to the ESIPAP computing sessions

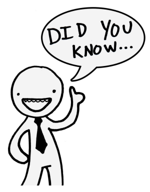
1 Foreword

Computing sessions belong to the educational program of the ESIPAP (European School in Instrumentation for Particle and Astroparticle Physics). Their goal is to teach the secrets of C++ programming through practical work in the context of high energy physics. The session is designed to be pedagogical. It is advised to read this document section-by-section. Indeed, except the *Physics context*, each section of the document is a milestone allowing to acquire computing skills and to validate them. The sections related to C++ programming are ranked in terms of complexity. In order to facilitate the reading of this document and to measure his progress, the student must **fill up the dedicated roadmap** which includes a check-list and empty fields for personal report.

In the document, some graphical tags are used for highlighting some particular points. The list of tags and their description are given below.

The student is invited to perform a pratical work by **writing a piece of code** following some instructions.

Analyzing or interpreting task is requested and the results must be reported in the roadmap.



Some **additional information** is provided for extending the main explanations. It is devoted to curious students.

A piece of **advice** is given to help the student in his task.

2 The ESIPAP framework

The practical works must be performed on devoted machines where all required software are properly installed. The user will find below all the instructions for setting the environment at each beginning of session.

2.1 Launching the `Windows` machine

You must choose a computer in the computing room, spot its name and check that no peripheral is missing (mouse, keyboard, ...). Then boot it and login to the `Windows` operator system (supervisors will provide the password access).

2.2 Accessing the `Linux` virtual machine

The practical sessions will be achieved on a `Linux` machine for pedagogical motivations. You must connect a virtual machine. First click on the "Start" button, i.e. the button with the `Windows` logo, located on the bottom left of the screen (see Figure 1).

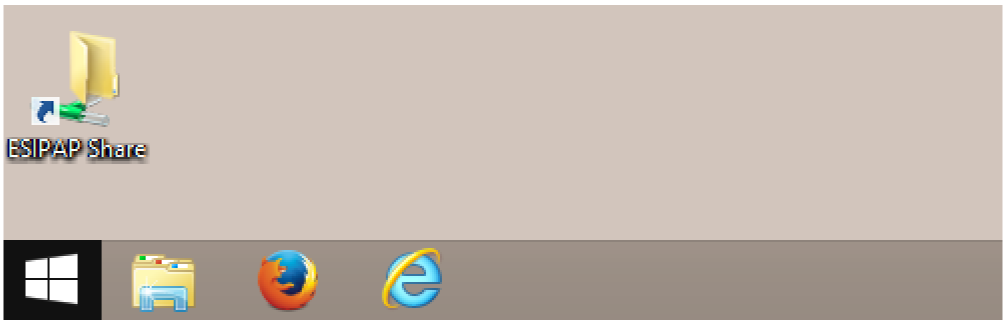


Figure 1: The `Windows` Start button

According to Figure 2, click on the virtual machine called **"ESIPAP_slc6"**. A password could be necessary and should be supplied by the supervisors.

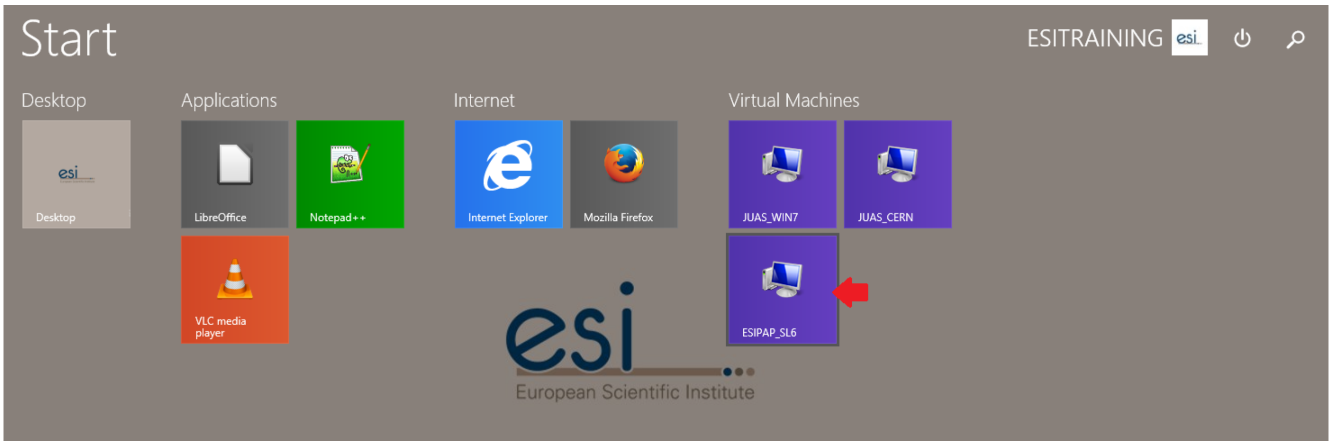


Figure 2: The screen showing the available virtual machines

2.3 Setting the environment

To load the work environment, you can issue the command below at the shell prompt.

```
bash$source␣/home/esipap/tools/setup.sh
```

If the system is properly installed, the version of each tool to study should be displayed at the screen like below. If you have an error, please call the supervisors.

```
----------------------------------------------
             ESIPAP environment
----------------------------------------------
 - GNU g++   version 4.9.1
 - ROOT      version 6.06/00
 - Geant4    version 10.2.0
----------------------------------------------
```

You must work in your local folder. Of course, it is advised to create one folder for each practical session like: `session1`, `session2`, `session3` and `session4`. Do not overwrite or remove files that you wrote in a previous session.

2.4 Saving your work on a share disk

Your work will be evaluated from the the piece of code that you wrote. At the end of each session you must save your production on a share disk. The virtual machine is equipped with one share disk called "ESIPAP-SHARE" and saved everyday. For accessing this disk, click on the `Linux` tab named **"places"** according to Figure 3 and select the disk **"ESIPAP-SHARE"**.

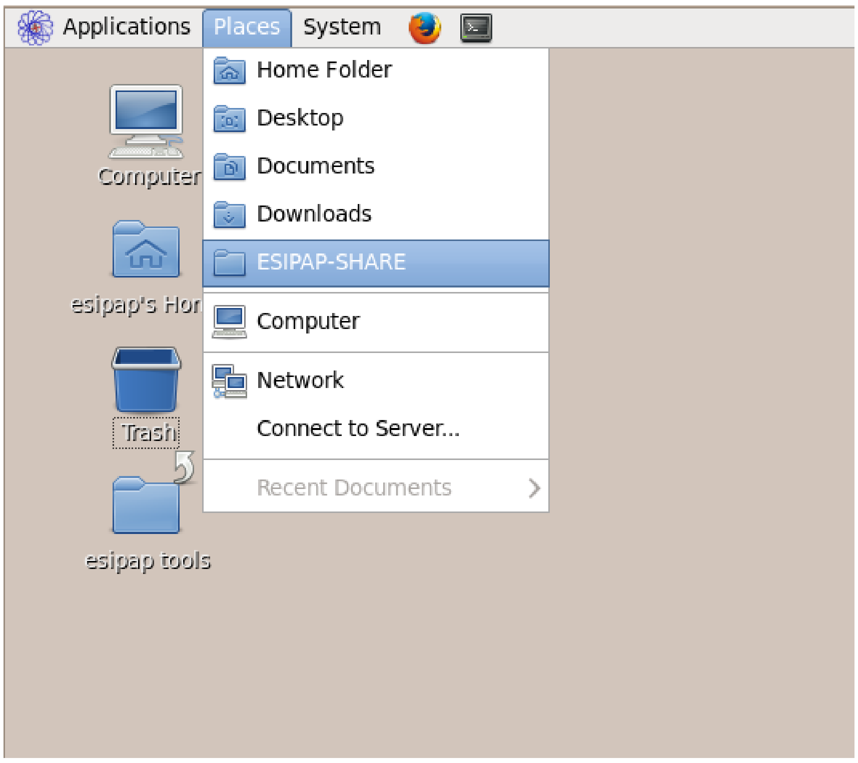


Figure 3: The `Linux` tab named "places"

After entering a password, the list of all connected machines in the room is displayed (see Figure 4). Select the folder corresponding to your machine and put there all you work. Please organize this folder by creating one folder for each practical session like: `session1`, `session2`, `session3` and `session4`.

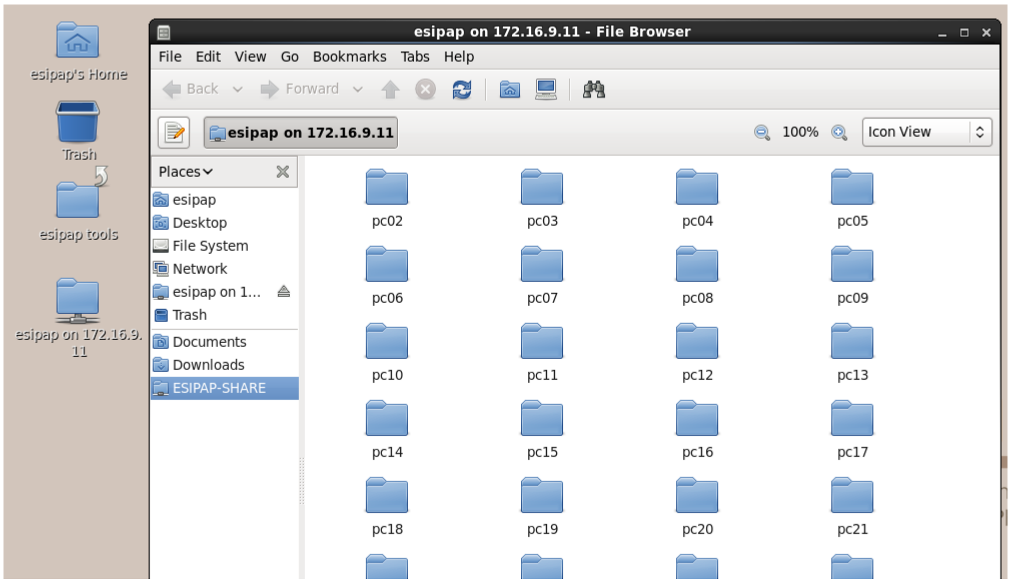


Figure 4: List of all available machines in the room

Part II

Getting started with GNU g++

3 First program

In this section, a very simple example of main program (the so-called *hello world* example) is supplied and explained in order to help beginners in C++ programming. More experimented students should be a little patient: challenging tasks are coming soon.

3.1 Programming conventions

This is a non-exhaustive list of recommendations for CMS software developpers. In the context of the exercise, the students must respect as much as possible these conventions in their source files.

- One source file and one header file per class. Naming rules: class name + suffix (.cpp or .h)
- Start method names with lower case. Use upper case initials for following words. Example: collisionPoint()
- Start data member names with lower case. User upper case initials for following words. Use "_" character at the end of the name. Example: collisionPoint_
- Do not use single character names, except for loop indices.
- Protect each header file from multiple inclusion with:

  ```
  #ifndef className_h
  #define className_h
  ...
  #endif
  ```

- Header files must not contain any implementation except for class templates and code to be inlined.
- Classes must not have public data members.
- Do not use global data.
- Use "0" not "NULL".
- Use C++ casts, not C-style casting.
- Keep the ordering of methods in the header file and in the source file identical.
- Limit line length to 120 character positions.

3.2 Main program source

The main program will be contained in a source file called `main.cpp`. A simple example respecting fully the CMS programming rules is done is. It displays at the screen the message *"Hello World!"*.

```
// STL headers
#include <iostream>
using namespace std;

// Main program
int main(int argc, char** argv)
{
  // Display messages at screen
  cout << "Hello World!" << endl;

  // Normal program termination
  return 0;
}
```

Listing 1: A first main program

3.3 Building the main program

To build with `g++` compiler an executable file from `main.cpp` file, the simpliest command to type at the shell prompt is:

```
bash$g++ main.cpp
```

If the `main.cpp` file compiles properly, an executable file with the default name `a.out` is created. Of course, we invite the students to use `g++` in more advanced way by adding three items:

- giving a proper name to the executable program
- splitting the complation step from the linking step
- specifying some compilation options

To avoid retyping several times during the session the building commands, a shell script can be written. This is an example of a such file called `mymake`:

```
gcc -W -Wall -ansi -pedantic -o main.o -c main.cpp
gcc -o main main.o
```

Listing 2: A first building script

It is necessary to make this script executable before launching it.

```
bash$chmod +x mymake
```

3.4 Work to do

- **Recopy the content of the `main.cpp` and `mymake` files.**
- **Build the program and test that the *"hellow world"* message appears properly when you launch the executable.**

- **Explain the compilation options used for generating the object file `main.o`.**

Part III
C++ model for the CMS calorimeter

4 Physics context

4.1 The CMS detector

CMS(Compact Muon Solenoid) is one of the four main detectors build for analyzing particles produced by proton-proton collisions at the LHC (Large Hadron Collider). The detector is buried under about 100m at the point 5 of LHC ring. With a weight of 12500 tons, it has cylinder volume with a diameter of 14.6 m and a length of 21.6 m. The LHC beam cross the detector in its axis and the collisions occur in its middle. CMS is made up of several detector components: a **silicon tracker** equipped with a huge **solenoid magnet**, **electromagnetic and hadronic calorimeters** and finally **ionizing chambers** devoted to muon tracking. The figure below allows to distinguish the different components.

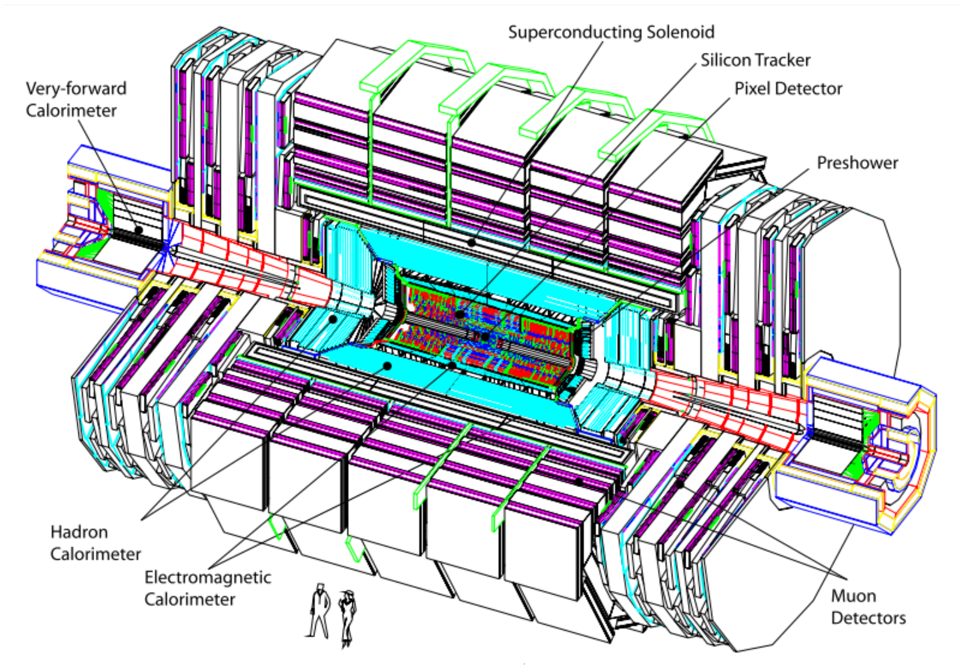


Figure 5: A perspective view of the CMS detector

The first run of data taking has begun since Fall 2008. It is designed to undergo 40 millions of proton-proton collisions per second. All collisions (we speak later in term of *events*) are not interested for the physicists and a **trigger** system selects in real-time the most relevant one. The dataflow is reduced to about 300 collisions per second.

4.2 CMS coordinates systems

It is important to remind the cartesian and cylindrical coordinates systems used in the CMS collaboration. The both coordinate systems has the origin centered at the nominal collision point inside the experiment.

- CARTESIAN. The y-axis pointing vertically upward, and the x-axis pointing radially inward toward the center of the LHC. Thus, the z-axis points along the beam direction toward the Jura mountains from LHC Point 5.
- CYLINDRICAL. The azimuthal angle ϕ is measured from the x-axis in the x-y plane and the radial coordinate in this plane is denoted by r. The polar angle θ is measured from

the z-axis. Pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$ is usually used instead of θ.

4.3 The electromagnetic calorimeter of the CMS detector

The aim of the electromagnetic calorimeter is to measure the energy of photons and electrons produced during the collisions. At high energies, electromagnetic particles induce electromagnetic shower when they interact with the calorimeter material. Loss energy is converted to light due to scintillating property of the material: lead tungstate (PbWO4) crystals with a short radiation length $X_0 = 0.89$ cm and a short Moliere radius equal to 2.2 cm. The CMS electromagnetic calorimeter is hermetic, homogeneous and compact. It covers the full range in azimuthal angle and the pseudorapidity range $|\eta| < 1.48$. The cells have a size of $22{\times}22$ mm^2 at the front face and a length of 230 mm corresponding with 25.8 X_0. The electromagnetic calorimeter is compound of two different geometries:

- the cylinder part, called *barrel*, has a radius of 1.29 cm and contains 61,200 cells.
- the two planes at each end of the cylinder (z=-1 m and z=+1 m), called *end-cap*, contain together 14,648 cells.

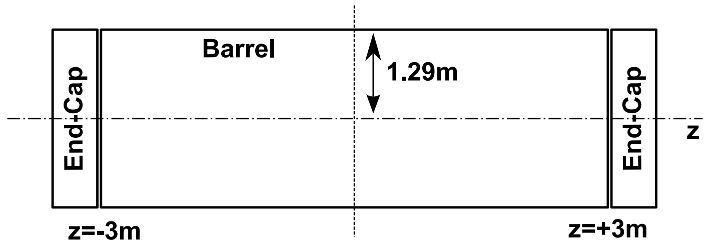


Figure 6: Barrel and End-cap part of the calorimeter in the transverse plane of the detector

Only the barrel part of the calorimeter is considered in the following.

4.4 Layout and mechanics of the barrel calorimeter

The cells are gathered in submodules; submodules are gathered in modules ; modules are gathered in supermodules. For simplifying the exercise, only the last structure is considered. There are 36 supermodules and one supermodule contains 25×68 cells. Their layout in the $\eta - \phi$ plane is shown by the figure below.

4.5 Data acquisition by a calorimeter cell

For the sake of completness, the acquisition chain of a calorimeter cell is briefly discussed. The scintillator crystals emit blue-green scintillation light which is collected by photodetectors (Avalanche PhotoDetectors). The signal is shaped by a MGPA (Multi-Gain Pre-Amplifier) and digitized by an ADC (Analogic Digital Converter). After an adaptation of the signal, the signal is sent to a Front-End electronics board which computes some information useful for the first level of trigger. If the trigger is fired, digital data are sent to the DAQ (Data AcQuisition).
The energy resolution can be parametrized as in the equation:

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

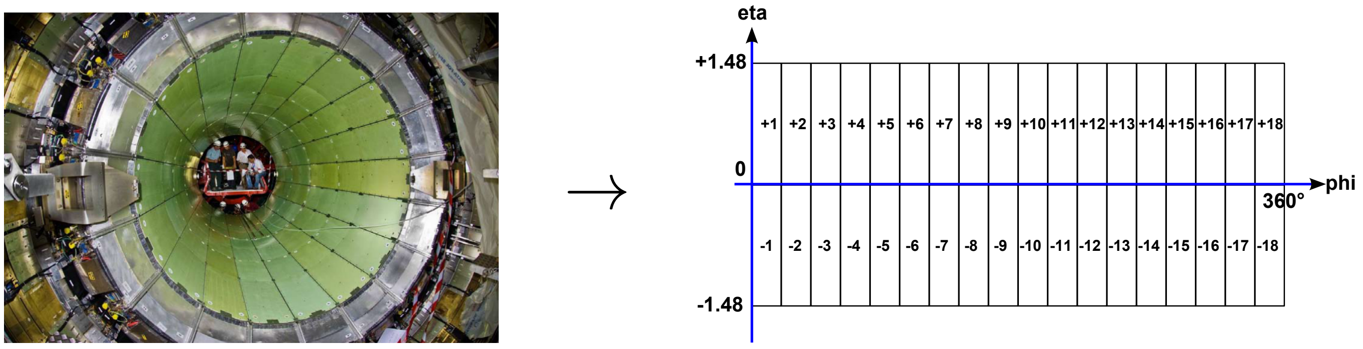


Figure 7: Subdivision of the calorimeter barrel in supermodules

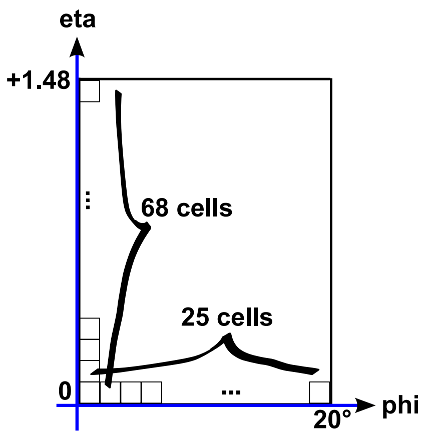


Figure 8: Subdivision of the supermodules in cells

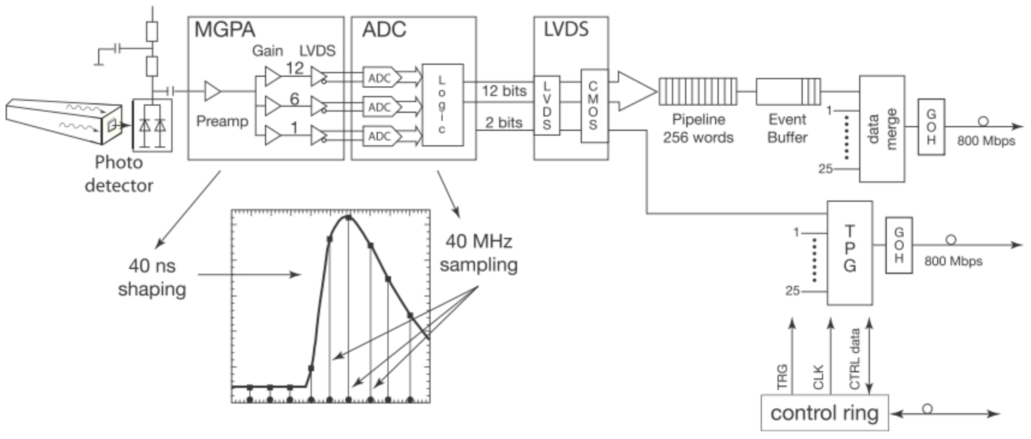


Figure 9: Simplified schematics of the calorimeter cell readout

where S is the stochastic term, N the noise term, and C the constant term. Typical values are S=2.8%, N=0.12 and C=0.30% for E in GeV.

5 Description of a calorimeter

In this section, a class called `caloCell`, corresponding to the files called `CaloClass.h` and `CaloClass.cpp`, must be written. This class must describe the status of each cell of the barrel calorimeter. Therefore 61,200 instances of this class are expected.

5.1 Specifications

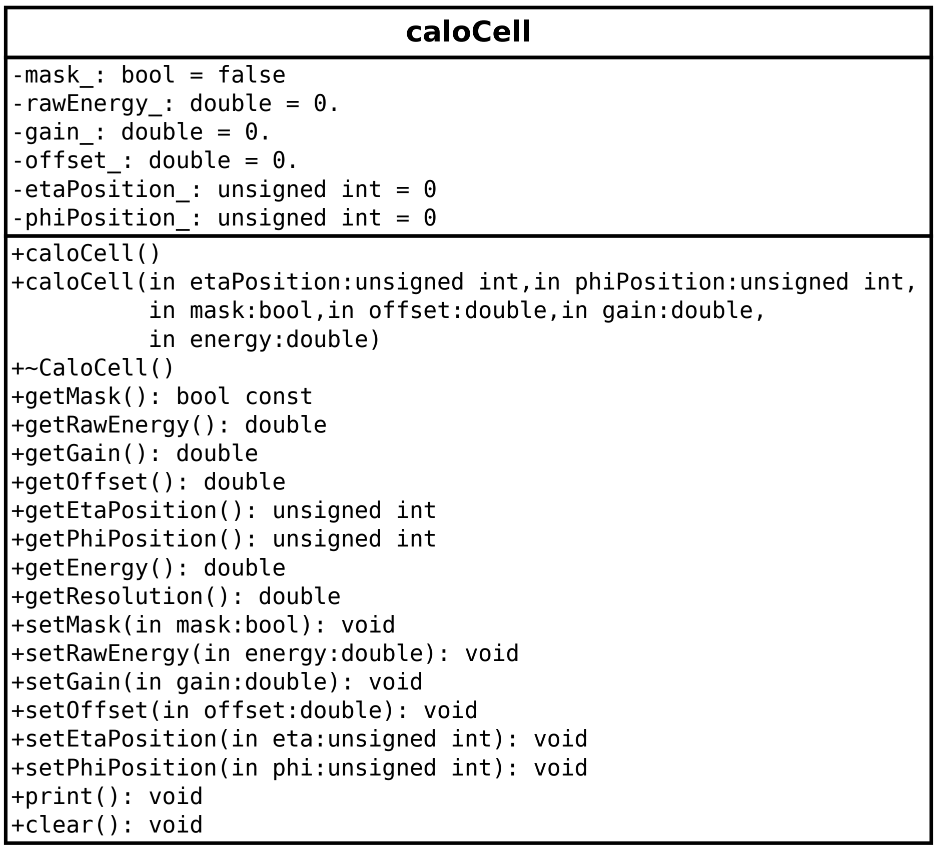
Here are enumerated the functionalities of the class `caloCell`.

- The class must contain an identification code corresponding to its relative position in the supermodule. This can be done by two positive integer called `etaPosition_` and `phiPosition_`.
- The class must store the raw energy (`rawEnergy_`) coming directly from the DAQ.
- The class must also store calibration settings:
  - offset: real value to subtract to the raw energy.
  - gain: multiplicative value (defined as a strictly positive real).
  - boolean mask: if the mask is enable, a veto is applied to the cell (describing dead cell).
- A function called `getEnergy` must return the corrected energy value following the formula:

$$\begin{cases} \text{if mask=true} & \rightarrow & \text{energy*} & = & 0. \\ \text{if mask=false} & \rightarrow & \text{energy*} & = & (\text{energy - offset}) \times \text{gain} \end{cases}$$

- A function called `getResolution` must return the resolution value expected for the current corrected energy value. The formula is given in section "Physics context".
- In order to access all data members of the class, accessor (or getter) and mutator (or setter) functions must be defined. We choose the conventions that the name of these functions begin either by `get` either by `set`.
- A function called `print` allows to display at the screen the current values of the data members of the class.
- Two constructors will be implemented for this class: one constructor with no argument where data members will be initialized to the default values and a second constructor with some arguments (etaPosition, phiPosition, mask, offset, gain, energy).
- A function called clear allows to reinitialize all the data members.

The UML diagram corresponding to the class `caloCell` is supplied below.



```
caloCell
-mask_: bool = false
-rawEnergy_: double = 0.
-gain_: double = 0.
-offset_: double = 0.
-etaPosition_: unsigned int = 0
-phiPosition_: unsigned int = 0
+caloCell()
+caloCell(in etaPosition:unsigned int,in phiPosition:unsigned int,
          in mask:bool,in offset:double,in gain:double,
          in energy:double)
+~CaloCell()
+getMask(): bool const
+getRawEnergy(): double
+getGain(): double
+getOffset(): double
+getEtaPosition(): unsigned int
+getPhiPosition(): unsigned int
+getEnergy(): double
+getResolution(): double
+setMask(in mask:bool): void
+setRawEnergy(in energy:double): void
+setGain(in gain:double): void
+setOffset(in offset:double): void
+setEtaPosition(in eta:unsigned int): void
+setPhiPosition(in phi:unsigned int): void
+print(): void
+clear(): void
```

Figure 10: UML diagram of the class `caloCell`

5.2 First work to achieve

- **Implement the class `caloCell` according to the UML diagram.**
- **Test the class definition by instantiating an object and by performing some operations.**
- **Adapt the script `mymake` for building this project.**

- **Explaining how you test the implementation of `caloCell`.**

5.3 Enriching the class `CaloCell`

We suggest to improve the implementation of the class `caloCell` by advanced functionalities. These functionalities are not crucial for the next developments. Their goal is totally pedagogical.

- **Add a copy constructor to the class.**
- **Associate the reserved word `const` to the appropriated functions.**
- **Overload the operator « to display the data member values when `std::cout` is applied directly to instance of this class.**

- **Have you other ideas (new function, optimization, ...) for improving the implementation of the class?**

6 Description of a supermodule and a barrel

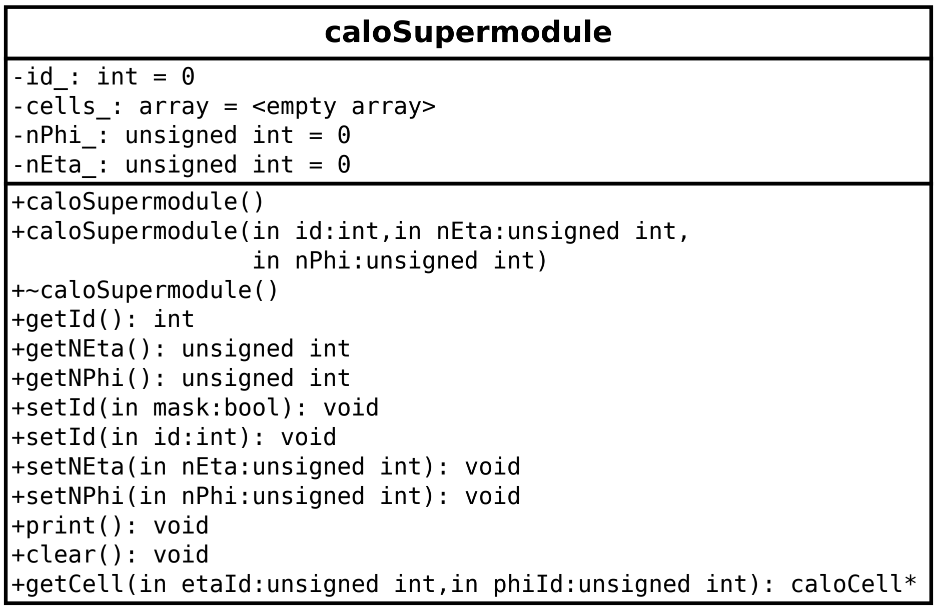
For modeling the electromagnetic barrel calorimeter, we would like to implement the two classes `caloSupermodule` and `caloBarrel`, corresponding to the files `caloSupermodule.h`, `caloSupermodule.cpp`, `caloBarrel.h` and `caloBarrel.cpp`. The implementation will be based on the supplied UML diagrams. We would like to have the most general and flexible classes as possible. For instance, the supermodule segmentation will be not fixed, but tunable by the user.

6.1 Implementation of `caloSupermodule` class

Here are enumerated the functionnalities of the class `caloSupermodule`.

- The class must contain a identification code corresponding to the supermodule position in the supermodule. This can be done by a signed integer called `Id_`.
- The class must store an array of `caloCell`. The data members `nPhi_` and `nEta_` mean the number of cells respectively in ϕ and η direction.
- In order to access all data members of the class, accessor (or getter) and mutator (or setter) functions must be defined. We choose the conventions that the name of these functions begin either by `get` either by `set`. Of course, changing `nPhi_` and `nEta_` implies changing the array dimension.
- A function called `print` allows to display at the screen the idenfication number and the array size.
- Two constructors will be implemented for this class: one constructor with no argument where data members will be initialized to the default values and a second constructor with some arguments (identification number, nEta, nPhi).
- A function called `clear` allows to reinitialize all the data members.
- A function called `getCell` allows to access, via a pointer, a `caloCell` located at *eta* and *phi* position.

The UML diagram corresponding to the class `caloSupermodule` is supplied below.



caloSupermodule

```
-id_: int = 0
-cells_: array = <empty array>
-nPhi_: unsigned int = 0
-nEta_: unsigned int = 0
```

```
+caloSupermodule()
+caloSupermodule(in id:int,in nEta:unsigned int,
                 in nPhi:unsigned int)
+~caloSupermodule()
+getId(): int
+getNEta(): unsigned int
+getNPhi(): unsigned int
+setId(in mask:bool): void
+setId(in id:int): void
+setNEta(in nEta:unsigned int): void
+setNPhi(in nPhi:unsigned int): void
+print(): void
+clear(): void
+getCell(in etaId:unsigned int,in phiId:unsigned int): caloCell*
```

6.2 Implementation of `caloBarrel` class

Here are enumerated the functionnalities of the class `CaloCell`.

- The class must store an array of `caloSupermodule`. The data member `nSupermodule_` mean the number of supermodules.

- In order to access all data members of the class, accessor (or getter) and mutator (or setter) functions must be defined. We choose the conventions that the name of these functions begin either by `get` either by `set`. Of course, changing `nSupermodule_` implies changing the array dimension.

- A function called `print` allows to display at the screen the idenfication number and the array size.

- Two constructors will be implemented for this class: one constructor with no argument where data members will be initialized to the default values and a second constructor with one argument (number of supermodules).

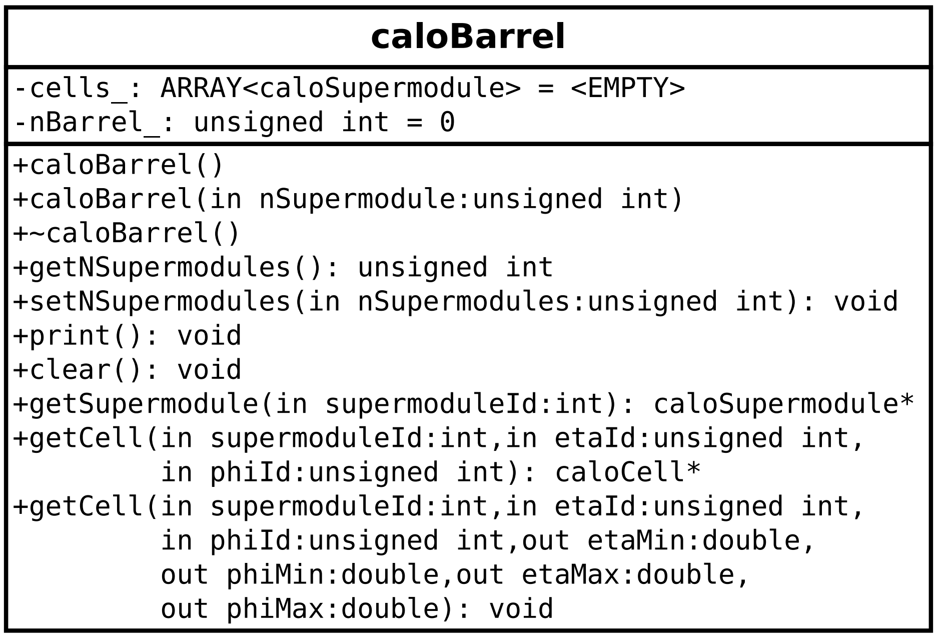
- A function called `clear` allows to reinitialize all the data members.

- A function called `getSupermodule` allows to access, via a pointer, a `caloSupermodule` with a given identification number. If no `caloSupermodule` is found, a null pointer is returned.

- A function called `getCell` allows to access, via a pointer, a `caloCell` located in a given supermodule, at relative $\eta - id$ and $\phi - id$. If no `caloCell` is found, a null pointer is returned.

- A function called `getCellDim` will give the absolute coordinate in the $\eta - \phi$ plane (η_{min}, ϕ_{min}, η_{max} and ϕ_{max}) of a `caloCell` located in a given supermodule, at relative $\eta - id$ and $\phi - id$.

The UML diagram corresponding to the class `caloBarrel` is supplied below.



```
caloBarrel
-cells_: ARRAY<caloSupermodule> = <EMPTY>
-nBarrel_: unsigned int = 0
+caloBarrel()
+caloBarrel(in nSupermodule:unsigned int)
+~caloBarrel()
+getNSupermodules(): unsigned int
+setNSupermodules(in nSupermodules:unsigned int): void
+print(): void
+clear(): void
+getSupermodule(in supermoduleId:int): caloSupermodule*
+getCell(in supermoduleId:int,in etaId:unsigned int,
         in phiId:unsigned int): caloCell*
+getCell(in supermoduleId:int,in etaId:unsigned int,
         in phiId:unsigned int,out etaMin:double,
         out phiMin:double,out etaMax:double,
         out phiMax:double): void
```

6.3 First work to achieve

- **Implement the two classes according to the UML diagrams.**
- **Test the class definition by instantiating an object and by performing some operations.**
- **Adapt the script `mymake` for building this project.**

- **Explaining how you test theses implementations.**

6.4 Enriching the classes

Like the class `CaloCell`, we suggest to improve the implementation of the classes by advanced functionnalities. These functionnalities are not crucial for the next developments. Their goal is totally pedagogical.

- **Add a copy constructor to the class.**
- **Associate the reserved word `const` to the appropriated functions. Advice: the methods `getCell` and `getSupermodule` will be duplicated in order to have a non-const version and a const version.**
- **Overload the operator << to display the data member values when `std::cout` is applied directly to instance of this class.**

- **Have you others ideas (new function, optimization, ...) for improving the implementation of the class?**

7 Setting the calorimeter cells with input files

In the existed implementation, users can only specify the calibration settings and the raw energy via the use of mutator (setter) functions. Initializing all the cells by this way will be very exhaustive. That's why we suggest that the cells can be initialized directly from (already existed) input text files. These new functions involve some addings in the `CaloBarrel` class.

7.1 Reading an input text file

In order to facilitate the life of developers, only one simple format is used for the input text files. The format is made up of lines and columns. The first line is special: it indicates the number of rows following by the number of columns in the files. Below a small example can be found.

```
3     5
0.4   0.67   0.545   675.4   70
3.4   1.00   4.505   456     56
2.8   8.00   1.800   654     123.4
```

The C++ source file `~econte/ESIPAP/TP1/read.cpp` is an example of reading the file.

The students must implement a **private** function in the class `CaloBarrel` called `ReadInputFile` which allows to read any file respecting the described format. This function must take in input argument the name of the file and in output argument a 2-dimensionnal array filling with the content of the file. It must return a boolean value which specifies if the file has been properly read (true=success, false=failure).

- **Analyze the C++ example and be sure you understand this piece of code.**
- **Implement the function `ReadInputFile` in `CaloBarrel` class by copy/paste/adapt the small C++ example given.**

7.2 Input file related to calibration settings

The input file for calibration can be found here: `~econte/public/ESIPAP/TP1/calibration.dat`.

Except the first special line, each line corresponds with a calorimeter cell. The columns have the following meaning:

column 1	column 2	column 3	column 4	column 5	column 6
supermodule id	eta id	phi id	mask	offset	gain

The students must implement a **public** function in the class `CaloBarrel` called `ReadCalibration` which allows to read any file respecting the described format and to fill the calibration settings of the calorimeter cells. The function takes in argument the name of the input file and must return a boolean value which specifies if the file has been properly read (true=success, false=failure). Of course, this function will call the private function `ReadInputFile`.

- **Implement the function `ReadCalibration` in `CaloBarrel` class.**
- **Check manually on few cases that the function runs properly.**

7.3 Input file related to events

The input file for one event can be found here: `ẽconte/public/ESIPAP/TP1/event.dat`.

Except the first special row, each row corresponds with a calorimeter cell. The columns have the following meaning:

column 1	column 2	column 3	column 4
supermodule id	eta id	phi id	raw energy

The students must implement a **public** function in the class `CaloBarrel` called `ReadEvent` which allows to read any file respecting the described format and to fill the raw energy of the calorimeter cells. The function takes in argument the name of the input file and must return a boolean value which specifies if the file has been properly read (true=success, false=failure). Of course, this function will call the private function `ReadInputFile`.

- **Implement the function `ReadEvent` in `CaloBarrel` class.**
- **Check manually on few cases that the function runs properly.**