High Energy Physics

Traineeships in Advanced Computing for High Energy Physics (TAC-HEP)

GPU programming module

Week 2 : Introduction to C++

Lecture 4 - September 19th 2024

Before we start!

Let’s make sure that we are able to log-in to the UW computing cluster and run some test scripts !

- Connect to a UW login machine :

```
ssh <username>@login.hep.wisc.edu
```

- It will ask for a password - please type it in.

Hopefully you will be able to connect to one of UW remote machines !

- Copy the following script in a file named **hello_world.cc**

```
#include <iostream>
int main() {
    std::cout << "Hello World!";
    return 0;
}
```

```
touch hello_world.cc
nano hello_world.cc→ Now paste the script in the file / save & close it (ctr+x then Y)
g++ hello_world.cc -o hello_world
./hello_word
```

Hopefully you will see “Hello World!” printed on the screen

- After connecting to a UW machine do :

```
ssh g38nXX (XX can be 01 - 16)
```

Hopefully you will be able to connect to one of UW remote GPUs !

- Copy the following script in a file named **hello_world.cu**

```
#include <stdio.h>

int main() {
     printf("Hello World\n");
     return 0;
}
```

```
touch hello_world.cu
nano hello_world.cu → Now paste the script in the file / save & close it (ctr+x then Y)
export LD_LIBRARY_PATH=/usr/local/cuda/lib
export PATH=$PATH:/usr/local/cuda/bin
nvcc hello_world.cu -o hello_world
./hello_word
```

Hopefully you will see “Hello World!” printed on the screen

What we learnt in the previous lecture

- History of C++
- Brushed up on :
  - Core syntax
  - Variables & Operators
  - Control instructions
  - Functions

Today

- Scopes / namespaces
- Compound data types
- Object Orientation
- The C++ compilation chain

Scopes and namespaces

Scope in C++

Scope → portion of the source code where a given variable can be accessed / declared / used etc :

- Typically
  - simple block of code, within {}
  - function, class, namespace
  - translation unit for global declarations
- Resources are allocated when a e.g variable is declared
- Resources are then freed at the end of a scope

```
{
  int a;
  {
    int b;
  } // end of b scope
} // end of a scope
```

Scope of variables in C++

Mainly two types of variable scopes :

- **Local Variables**
  - Are declared inside a block
  - Cannot be accessed or used outside that block
- **Global Variables**
  - Declared outside of all of the functions and blocks, at the top of the program.
  - Can be accessed from any portion of the program.

```
#include<iostream>
using namespace std;
int global = 1; // Global variable
int main()
{
 int local = 2; // Local variable
 cout<<"Global var : "<<global;
 cout<<" and Local var : "<<local;
 return 0;
}
```

Namespaces (1)

- declarative region that provides a scope to the identifier
- allow to segment code to avoid name clashes
- especially useful when your code base includes multiple libraries
- can be embedded to create hierarchies using the '::' separator

Syntax

```
namespace  namespace_name
{
   declarations
}
```

Usage

```
namespace_name::namespace_members
```

std namespace

- The std is a short form of standard
- the std namespace contains the built-in classes and declared functions.
- e.g. list , vector , cout etc.

Namespaces (2)

Namespaces can also be nested. Usage :

- **A::a** (outer namespace)
- **A::B::a** (inner namespace)

```
namespace A {
 int a;
 namespace B {
   int a;
 }
}
```

```
namespace A {
 int a;
 void func() {
   cout << "Namespace A" << endl;
 }
}
namespace B {
 int a;
 void func() {
   cout << "Namespace B" << endl;
 }
}
```

Exercise : Lets try this out!

- Open onlinegdb
- Copy the above two namespaces
- Let's call them from main and checkout the results!

Compound data types

What are compound data types?

A compound type is a **type that is defined in terms of another type**.

There are many compound data types in C++ :

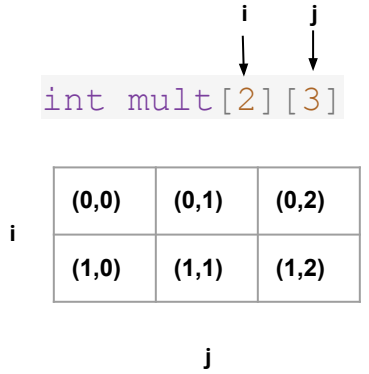
- Arrays
- Functions
- Pointers
- References
- Structs & class types
- Enumerations

Arrays

- Series of elements of the same type placed in contiguous memory locations
- Elements can be individually referenced by adding an index to a unique identifier.
- Can be **static** or **dynamic**
  - Size of static arrays is determined when the data structure is defined or allocated.
  - Dynamic arrays allows individual elements to be added or removed (e.g. std::list or std::vector)
- **Syntax** of static arrays: type name [elements]
- Arrays can also be multidimensional

```
// Defined values
int values[] = {0, 1, 2};
// Fixed-length with
undefined values
int values[3];
```

```
int mult[2][3]
```

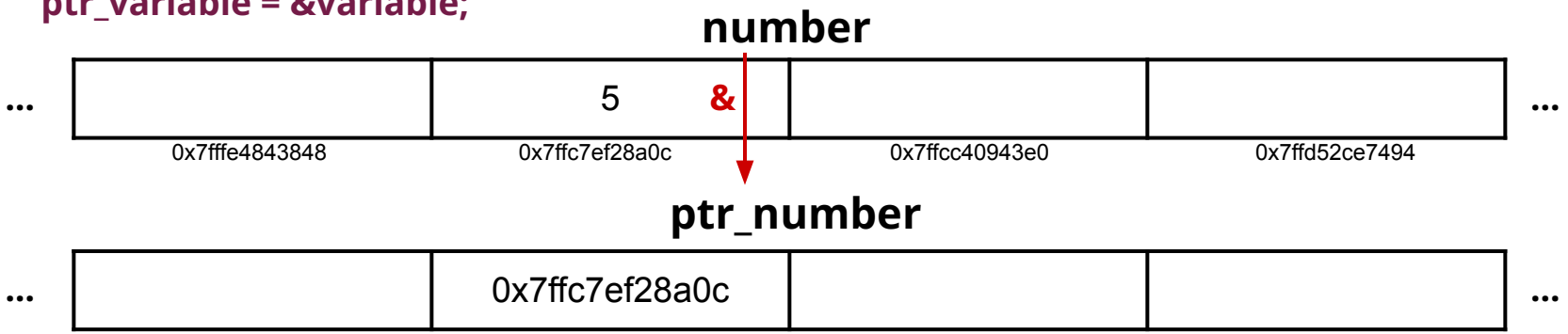


Pointers (1)

Pointer → variable that stores the memory address of a variable as its value.

- **Syntax type* pointer_variable;**
  - * → **dereference operator**
- Variable address can be obtained by preceding the name of a variable with the **Address-of** operator (&) e.g. **ptr_variable = &variable;**

```
int number = 5;
int* ptr_number = &number;
```



Pointers (2)

Pointer → variable that stores the memory address of a variable as its value.

- **Syntax type* pointer_variable;**
  - * → **dereference operator**
- Variable address can be obtained by preceding the name of a variable with the **Address-of** operator (&) e.g. **ptr_variable = &variable;**

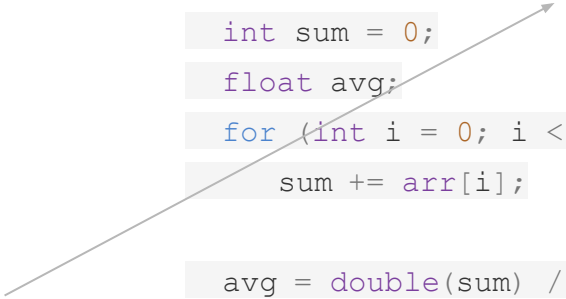
```
int number = 5;
int* ptr_number = &number;
cout << number << "\n";
cout << &number << "\n";
cout << ptr_number << "\n";
```

- Pointer should be initialized to point to a valid address
- If a pointer doesn't point to anything, set it to **nullptr** (i.e. int* ip = nullptr)

Exercise : Lets try this out!
- Open onlinegdb
- Copy the snippet
- Lets see what is printed out

Pointers (3)

A function which accepts a pointer, can also accept an array as an argument :



```
float getAverage(int *arr, int size) {
  int sum = 0;
  float avg;
  for (int i = 0; i < size; ++i)
      sum += arr[i];

  avg = double(sum) / size;
  return avg;
}

int main () {
  int balance[5] = {1, 2, 3, 4, 5};
  float avg;
  // pass pointer to the array as an argument.
  avg = getAverage( balance, 5 ) ;
  cout << "Average value is: " << avg << endl;
  return 0;
}
```

References

- References allow for direct access to another object
- They can be used as shortcuts / better readability
- References should always refer to an object and should be initialized when created
- Once a reference is initialized to an object, it cannot be changed to refer to another object.
- They can be declared const to allow only read access
- They can be used as function arguments

```
int  a;
int& ref_a = a;
```

Pointers vs References

References are preferred with respect to pointers

Pointers

- Pointers can be null
- We can change the variable that a pointer points to
- They indicate that the value of a variable can be modified
- If memory is not released, a memory leak can develop
- Prone to segfaults

References

- References can never be null & needs to be initialized during declaration.
- After initialization, cannot change the reference to reference another variable.
- Can be declared const to allow only read access

Structures

- A data structure (**struct**) is a group of data elements grouped together under one name.
- These data elements are referred to as members
- Members can have different types and different lengths.

Syntax :

```
struct type_name {
        member_type1 member_name1;
        member_type2 member_name2;
        member_type3 member_name3;
        ....
} object_names;
```

Specifying Object_names is **optional**

Declaration :

```
struct Person {
  unsigned char age;
  float weight;
};
```

Usage :

```
Person charis;
charis.age = 29;
charis.weight = 55.5;
```

Enumerations

- An enumeration (**enum**) is a distinct type whose value is restricted to a range of values
- These may include several explicitly named constants → enumerators
- An enum variable takes only one value out of many possible values

```
#include <iostream>
using namespace std;

enum month { January, February, March, April,
             May, June, July, August, September,
             October, November, December  };

int main()
{
    month thisMonth;
    thisMonth = January;
    cout << "Month " << thisMonth;
    return 0;
}
```

What do you think will be printed? Lets see :

- Open onlinegdb
- Copy the snippet & run!

Enumerations

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- An enum variable takes only one value out of many possible values

```
#include <iostream>
using namespace std;

enum month { January, February, March, April,
             May, June, July, August, September,
             October, November, December  };

int main()
{
    month thisMonth;
    thisMonth = January;
    cout << "Month " << thisMonth;
    return 0;
}
```

You can change the default value of an enum element during declaration e.g.

```
enum month { January=1, February=2, March=3, April=5,
             May=8, June=15, July=20, August=35, September=40,
             October=50, November=60, December=70
             };
```

Object Orientation

Object Oriented vs Functional programming

- **Object oriented programming** (OOP) groups related functions and their variables into objects.
- Imperative programming paradigm
  - Update the running state of the program
- Based on the following principles :
  - Encapsulation
  - Abstraction
  - Inheritance
  - Polymorphism

- **Functional programming** is paradigm where programs are constructed by composing and making use of functions
- Declarative programming paradigm
  - Maps values to other values
- Efficient
  - Code is reusable
- Allows parallel programming
- Allows for modular code

Object Oriented Programming principles

- OOP groups related functions and their variables into objects.
- Imperative programming paradigm
  - Update the running state of the program
- Based on the following principles :
  - **Encapsulation**
  - Abstraction
  - Inheritance
  - Polymorphism

- Ability to group data along with properties and methods that operate on the data in a common unit

Object Oriented Programming principles

- OOP groups related functions and their variables into objects.
- Imperative programming paradigm
  - Update the running state of the program
- Based on the following principles :
  - Encapsulation
  - **Abstraction**
  - Inheritance
  - Polymorphism

- Ability to represent data at a very conceptual level without any details.

Object Oriented Programming principles

- OOP groups related functions and their variables into objects.
- Imperative programming paradigm
  - Update the running state of the program
- Based on the following principles :
  - Encapsulation
  - Abstraction
  - **Inheritance**
  - Polymorphism

- A class can be derived from a base class with all features of base class and some of its own.
- Increases code reusability

Object Oriented Programming principles

- OOP groups related functions and their variables into objects.
- Imperative programming paradigm
  - Update the running state of the program
- Based on the following principles :
  - Encapsulation
  - Abstraction
  - Inheritance
  - **Polymorphism**

- Ability to exist in various forms
- Functions with the same name can be overloaded to perform different tasks

Classes

- Expanded concept of C structures:
  - Contain data members but also **contain functions as members → methods**
  - Access control (public/private/ protected)
  - Inheritance
- **Object** : Class instance
- A class encapsulates a concept :
  - implementation
  - properties
  - possible interactions
  - construction and destruction

- **Syntax :**

```
class class_name {
  access_specifier_1:
    member1;
  access_specifier_2:
    member2;
  ...
} object_names;
```

Access specifiers

Members : data or function declarations

Implementing methods

```
#include <iostream>
using namespace std;

class Rectangle {
   int width, height;
 public:
   void set_values (int,int);
   int area() {return width*height;}
};

void Rectangle::set_values (int x, int y) {
 width = x;
 height = y;
}

int main () {
 Rectangle rect;
 rect.set_values (3,4);
 cout << "area: " << rect.area();
 return 0;
}
```

Class **Rectangle** has 2 data members **width**, **height** and two methods **set_values** & **area**

Implementing methods

```
#include <iostream>
using namespace std;

class Rectangle {
   int width, height;
 public:
   void set_values (int,int);
   int area() {return width*height;}
};

void Rectangle::set_values (int x, int y) {
 width = x;
 height = y;
}

int main () {
 Rectangle rect;
 rect.set_values (3,4);
 cout << "area: " << rect.area();
 return 0;
}
```

Class **Rectangle** has 2 data members **width**, **height** and two methods **set_values** & **area**

Methods :

- Usually implemented outside of class declaration
- Use the class name as namespace
- When reference to the object is needed, use ***this*** keyword

Implementing methods

```
#include <iostream>
using namespace std;

class Rectangle {
   int width, height;
 public:
   void set_values (int,int);
   int area() {return width*height;}
};

void Rectangle::set_values (int x, int y) {
 width = x;
 height = y;
}

int main () {
 Rectangle rect;
 rect.set_values (3,4);
 cout << "area: " << rect.area();
 return 0;
}
```

Class **Rectangle** has 2 data members **width**, **height** and two methods **set_values** & **area**

Methods :

- Usually implemented outside of class declaration
- Use the class name as namespace
- When reference to the object is needed, use ***this*** keyword
  - `this->width = x;`

In *main*, syntax to construct a class object and access its members & methods

Overloading

- A class can have multiple functions with the same name but different parameters

Exercise : Lets try this out!

- Open onlinegdb
- Copy the snippet
- Lets see what is printed out
- Can you think of/try out another function overload?

```
#include <iostream>
using namespace std;

class Rectangle {
    int width, height;
  public:
    void set_values (int,int);
    void set_values (int);
    int area() {return width*height;}
};

void Rectangle::set_values (int x, int y) {
  width = x;
  height = y;
}
void Rectangle::set_values (int x) {
  width = x;
  height = x;
}

int main () {
  Rectangle rect;
  rect.set_values(3);
  cout << "area: " << rect.area();
  rect.set_values(3,4);
  cout << "area: " << rect.area();
  return 0;
}
```

Inheritance

- C++ classes can be extended creating new classes which retain characteristics of the original class
- **Base class**
  - Original class from which the derived class inherits the members
- **Derived class:**
  - The derived class inherits the members of the base class
  - Additionally can have its own new members
- Derived classes are defined using the following syntax :

```
class derived_class_name: public base_class_name
```

```
class Polygon {
 protected:
   int width, height;
 public:
   void set_values (int a, int b)
     { width=a; height=b;}
};
```

```
class Rectangle: public Polygon {
 public:
   int area ()
     { return width * height; }
};
```

New member

Derived class

Constructors & Destructors

- Special functions used for building/destroying an object
- A class can have several constructors
- The constructors have the same name as the class
- The constructors have the same name as the class but have a leading ~

Rectangle class has 2 constructors

Rectangle class destructor

```
class Rectangle {
   int width, height;
 public:
   Rectangle ();
   Rectangle (int,int);
   int area (void) {return (width*height);}
   ~Rectangle (){};

};

Rectangle::Rectangle () {
 width = 5;
 height = 5;
}

Rectangle::Rectangle (int a, int b) {
 width = a;
 height = b;
}
```

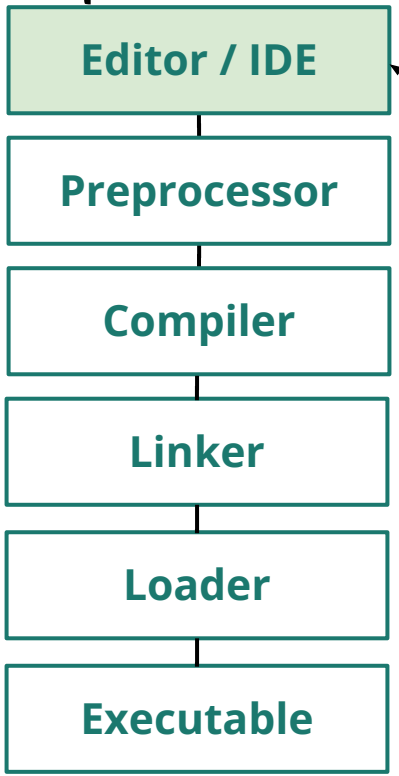
Compilation

How is a C++ code compiled

Compiler

- Utility program that translate user code into machine code
- Compilation is performed in several steps
- Simplest command :

```
g++ helloWorld.cpp -o helloWorld
```



Editor / IDE

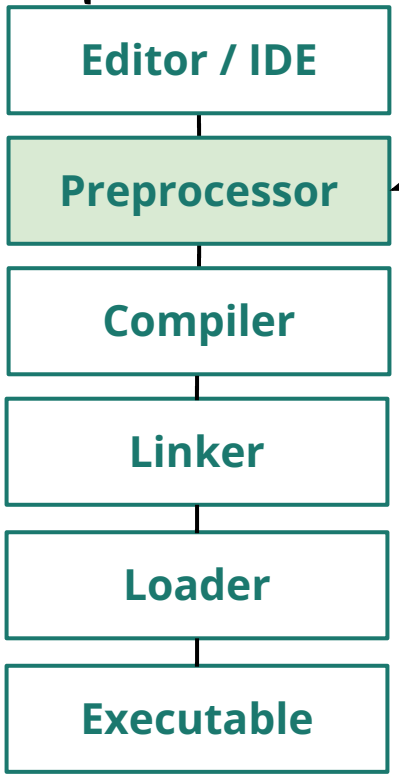
- First step is to write our C++ code
- We can use a text editor (vim, nano etc.) or an IDE (Integrated development environment i.e. vscode, eclipse etc.)

How is a C++ code compiled

Compiler

- Utility program that translate user code into machine code
- Compilation is performed in several steps
- Simplest command :

```
g++ helloWorld.cpp -o helloWorld
```



Preprocessor

- Performed before compilation
- The result of preprocessing is a single file which is then passed to the actual compiler
- The preprocessor handles the # directives (macros, includes) and creates the source code.

How is a C++ code compiled

Compiler

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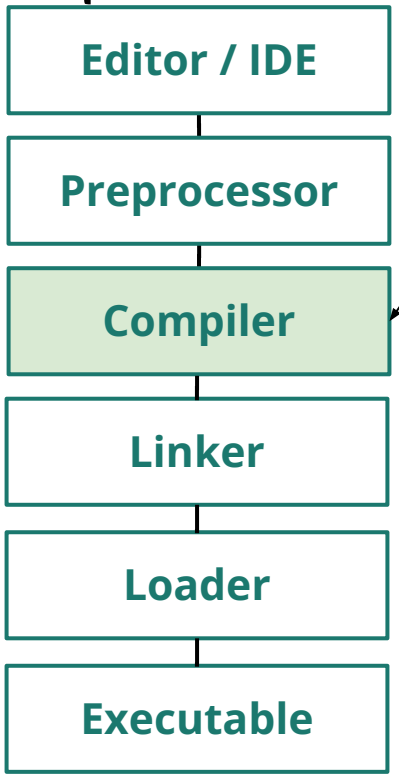
- Compilation is performed in several steps
- Simplest command :

```
g++ helloWorld.cpp -o helloWorld
```



Compiler

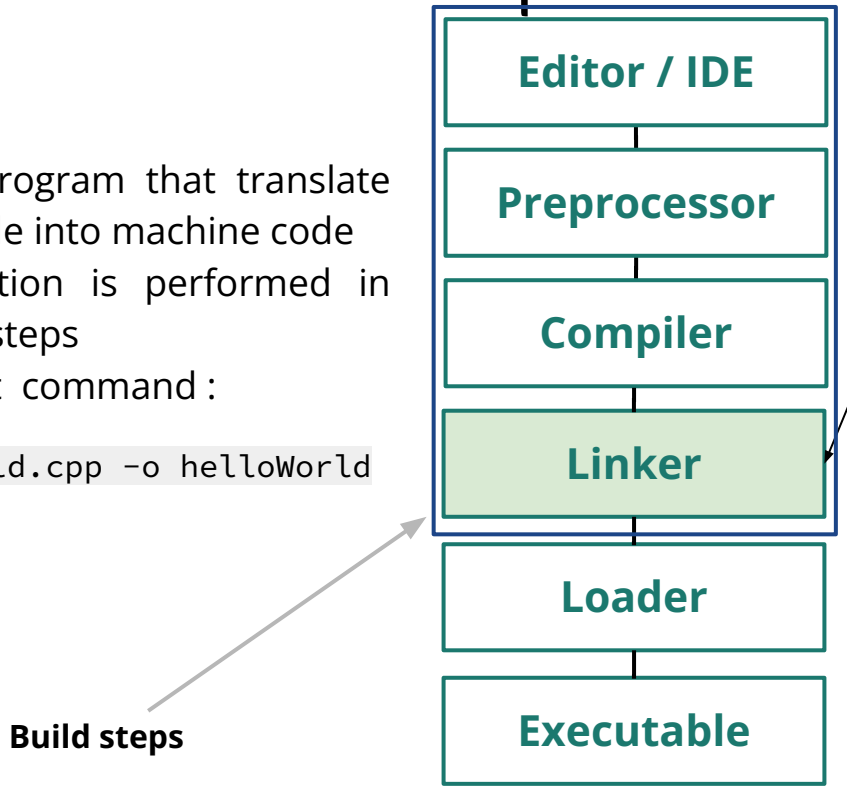
- The compilation takes place on the preprocessed files.
- The compiler parses the C++ source code and converts it into assembly & machine code.
- The produced object file contains the compiled code (in binary form)

How is a C++ code compiled

Compiler

- Utility program that translate user code into machine code
- Compilation is performed in several steps
- Simplest command :

```
g++ helloWorld.cpp -o helloWorld
```



Linker

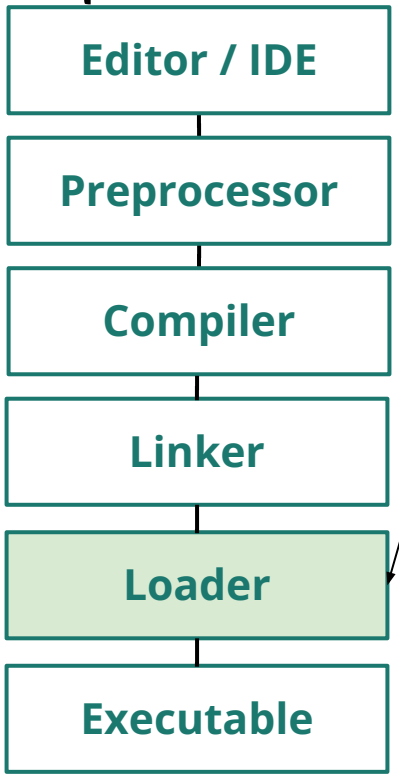
- Takes all the object files generated by the compiler and combine them into a single executable program.
- Links external library files.
- Makes sure all cross-file dependencies are properly resolved.

How is a C++ code compiled

Compiler

- Utility program that translate user code into machine code
- Compilation is performed in several steps
- Simplest command :

```
g++ helloWorld.cpp -o helloWorld
```



Loader

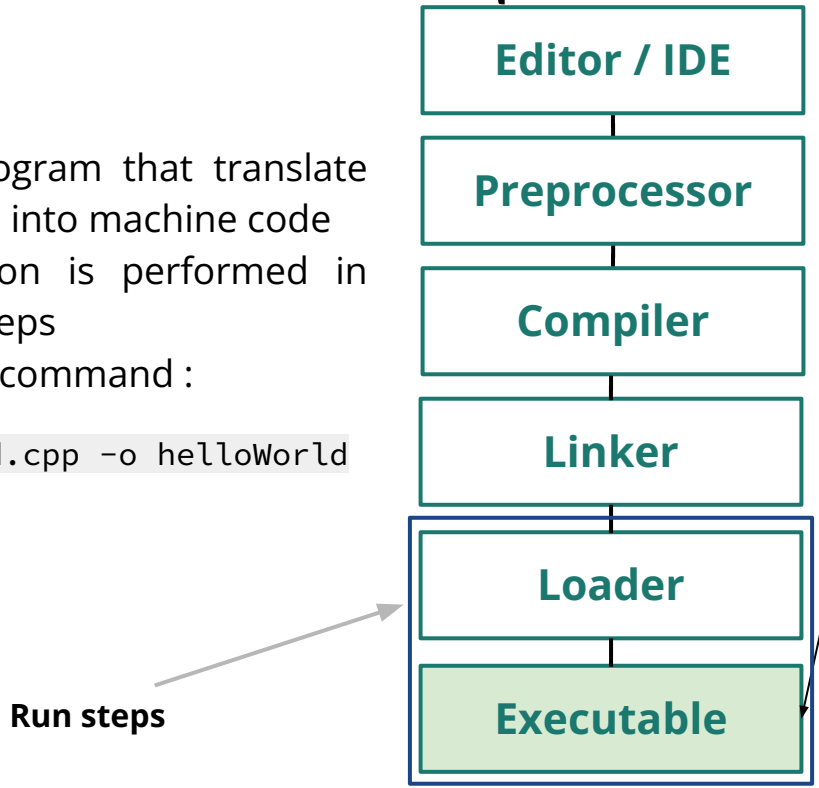
- Loader is generally part of the operating system
- Loads the executable into memory

How is a C++ code compiled

Compiler

- Utility program that translate user code into machine code
- Compilation is performed in several steps
- Simplest command :

```
g++ helloWorld.cpp -o helloWorld
```



Executable

We are now ready to run the executable!

To do so :

```
./helloWorld
```

Wrapping-up

Overview of today's lecture

- We learnt about what a scope is in C++
- We discussed about namespaces
  - std → standard library in C++ provides many facilities that can be used
- We learnt about compound data types
- We got familiar with Object Oriented programming and classes
- We got familiar with the C++ compilation chain

Assignment for next week

- Assignment can be found here :

  https://github.com/ckoraka/tac-hep-gpus

- To clone :
  - git clone git@github.com:ckoraka/tac-hep-gpus.git
- **Due Friday September 29th**
- Please upload assignment here :
  - https://pages.hep.wisc.edu/~ckoraka/assignments/TAC-HEP/
  - Upload only 1 .pdf file with all exercises
  - If you also have your code on git, please add the link to your repository in the pdf file you upload.

Next week

- We will get introduced to the CUDA programming model :
  - Concept of parallelization
  - Threads & blocks
  - CUDA core syntax
  - GPU memory hierarchy
  - Basic memory management
  - Error handling

Back-up

Resources

- cplusplus docs link
- cppreference docs link
- CERN C++ course link