Object Oriented Programming: Polymorphism

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Polymorphism

- Polymorphism with inheritance hierarchy
- virtual and pure virtual methods
  - When and why use virtual or/and pure virtual functions
- virtual destructors
- Abstract and Pure Abstract classes
  - Providing common interface and behavior

Polymorphism

- Ability to treat objects of an inheritance hierarchy as belonging to the base class
  - Focus on common general aspects of objects instead of specifics

- Polymorphism allows programs to be general and extensible with little or no re-writing
  - resolve **different objects** of same inheritance hierarchy **at runtime**
  - Recall videogame with polymorphic objects Soldier, Engineer, Technician of same base class Unit
  - Can add new ‘types’ of Unit without rewriting application

- Base class provides interface common to all types in the hierarchy
- Application uses base class and can deal with new types not yet written when writing your application!

Examples of Polymorphism

- Application for graphic rendering
  - Base class **`Shape`** with **`draw()`** and **`move()`** methods
  - Application expects all shapes to have such functionality

- **`Function`** in Physics
  - We'll study this example in detail
  - **`Guassian`**, **`Breit-Wigner`**, **`polynomials`**, **`exponential`** are all functions
  - A **`Function`** must have
    - **`value(x)`**
    - **`integral(x1,x2)`**
    - **`primitive(x)`**
    - **`derivative(x)`**
  - Can write a fit application that can handle existing or not-yet implemented functions using a base class Function

Reminders about Inheritance

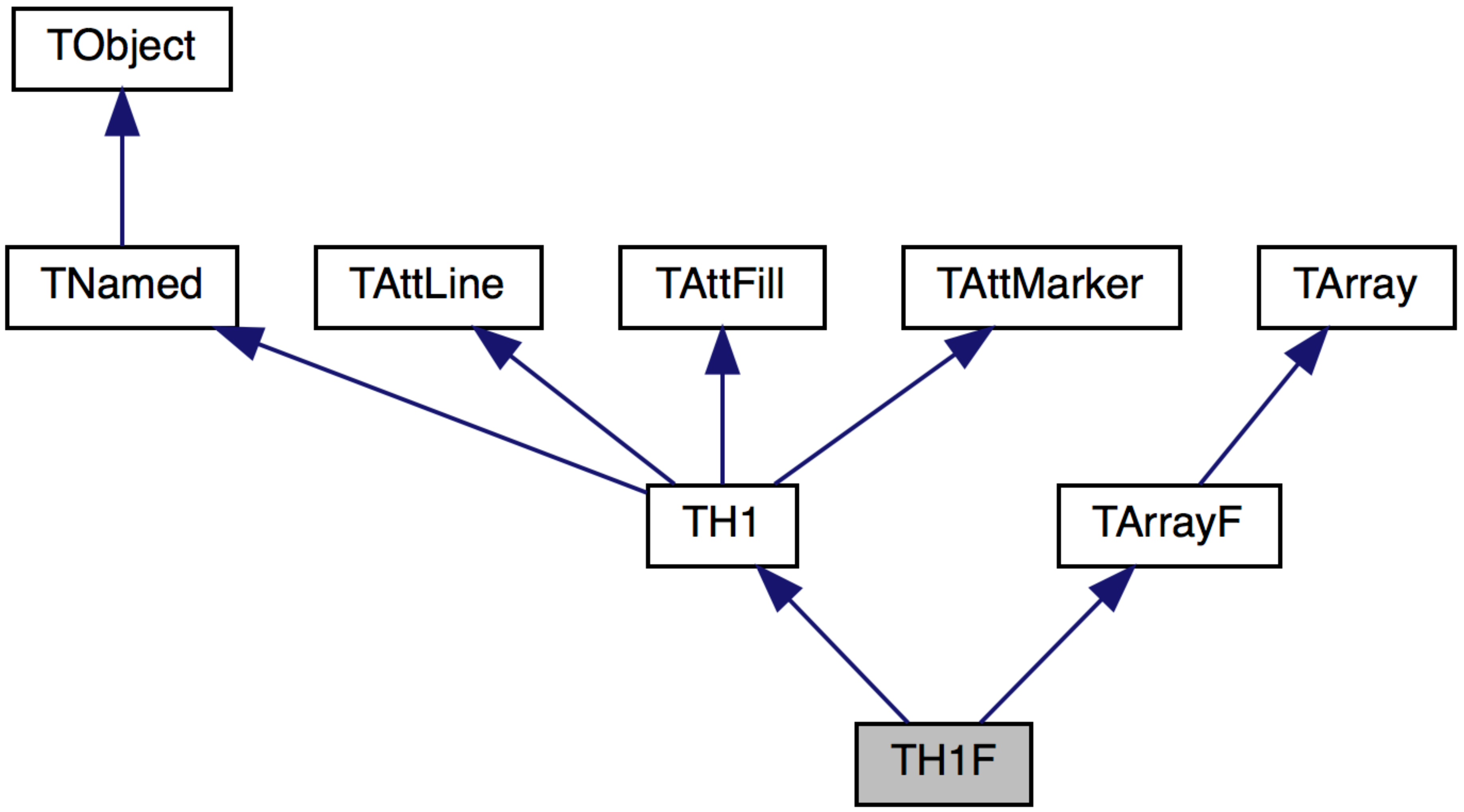
- Inheritance is a is-a relationship
  - Object of derived class ‘is a’ base class object as well
- Can treat a derived class object as a base class object
  - call methods of base class on derived class
  - can point to derived class object with pointer of type base class
- Base class does not know about its derived classes
  - Can not treat a base class object as a derived object
- Methods of base class can be redefined in derived classes
  - Same interface but different implementation for different types of object in the same hierarchy

Example from ROOT: TH1F

https://root.cern.ch/doc/master/classTH1F.html

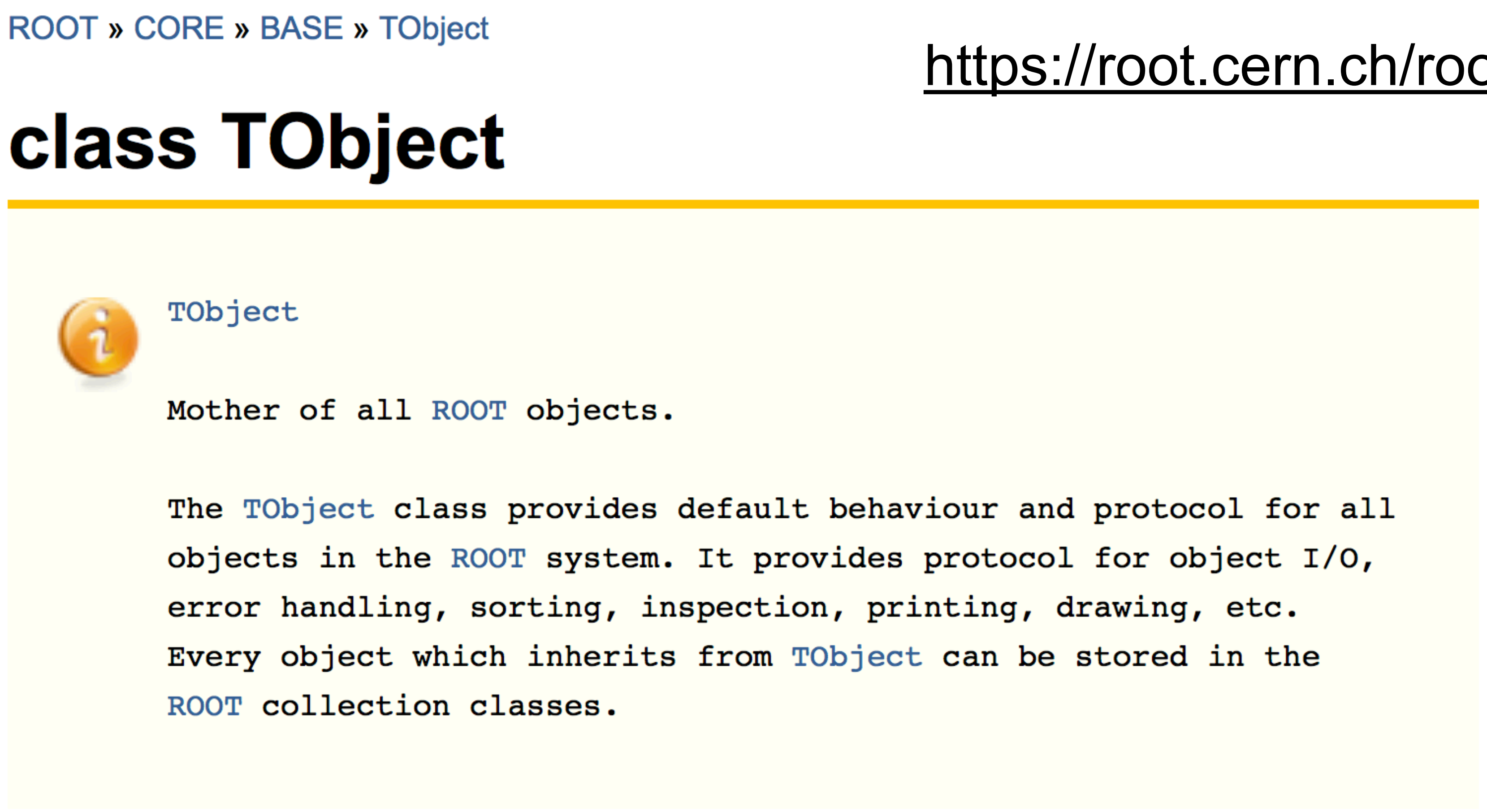
```
#include <TH1.h>
```

Inheritance diagram for TH1F:



TObject and TNamed

https://root.cern.ch/root/html526/TObject.html



ROOT » CORE » BASE » TObject

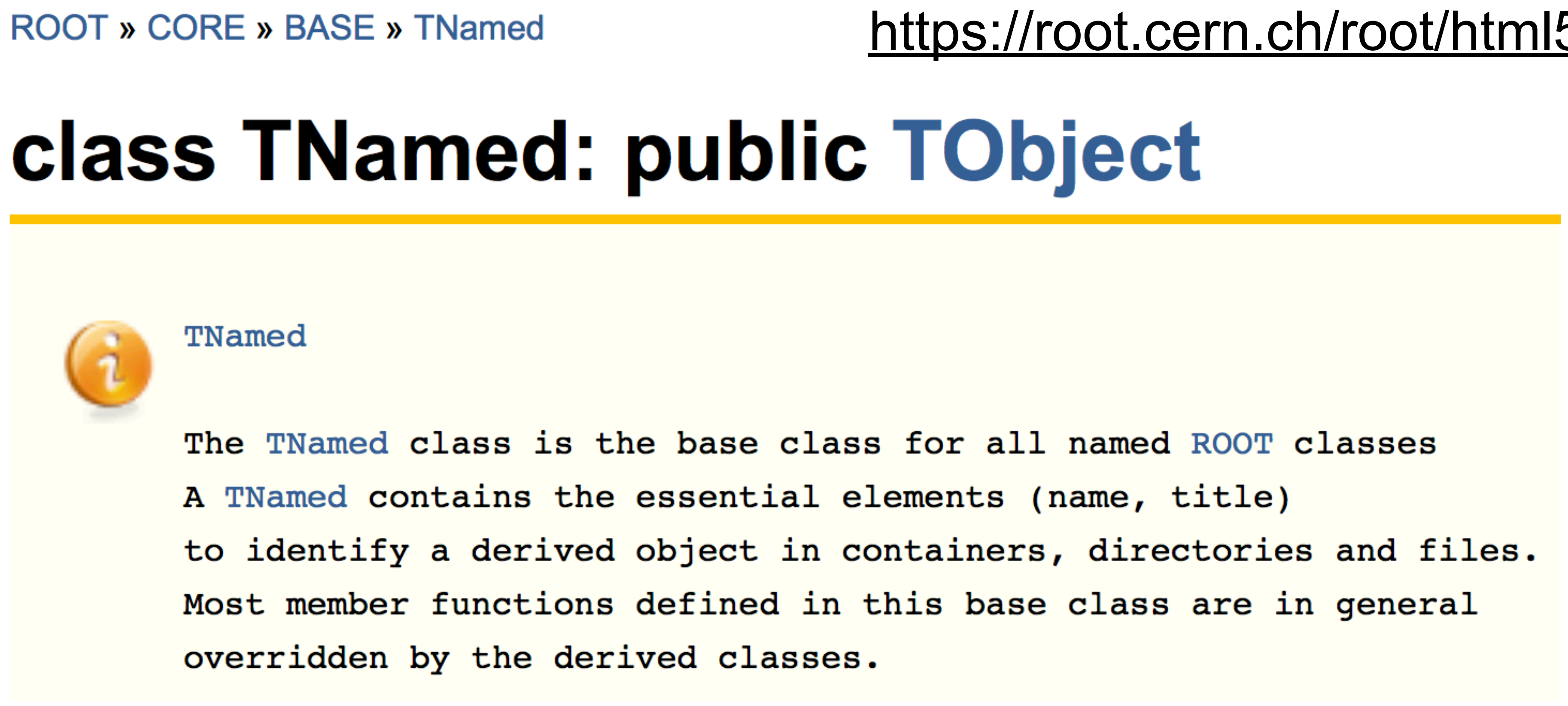
class TObject

```
TObject

Mother of all ROOT objects.

The TObject class provides default behaviour and protocol for all
objects in the ROOT system. It provides protocol for object I/O,
error handling, sorting, inspection, printing, drawing, etc.
Every object which inherits from TObject can be stored in the
ROOT collection classes.
```

https://root.cern.ch/root/html526/TNamed.html



ROOT » CORE » BASE » TNamed

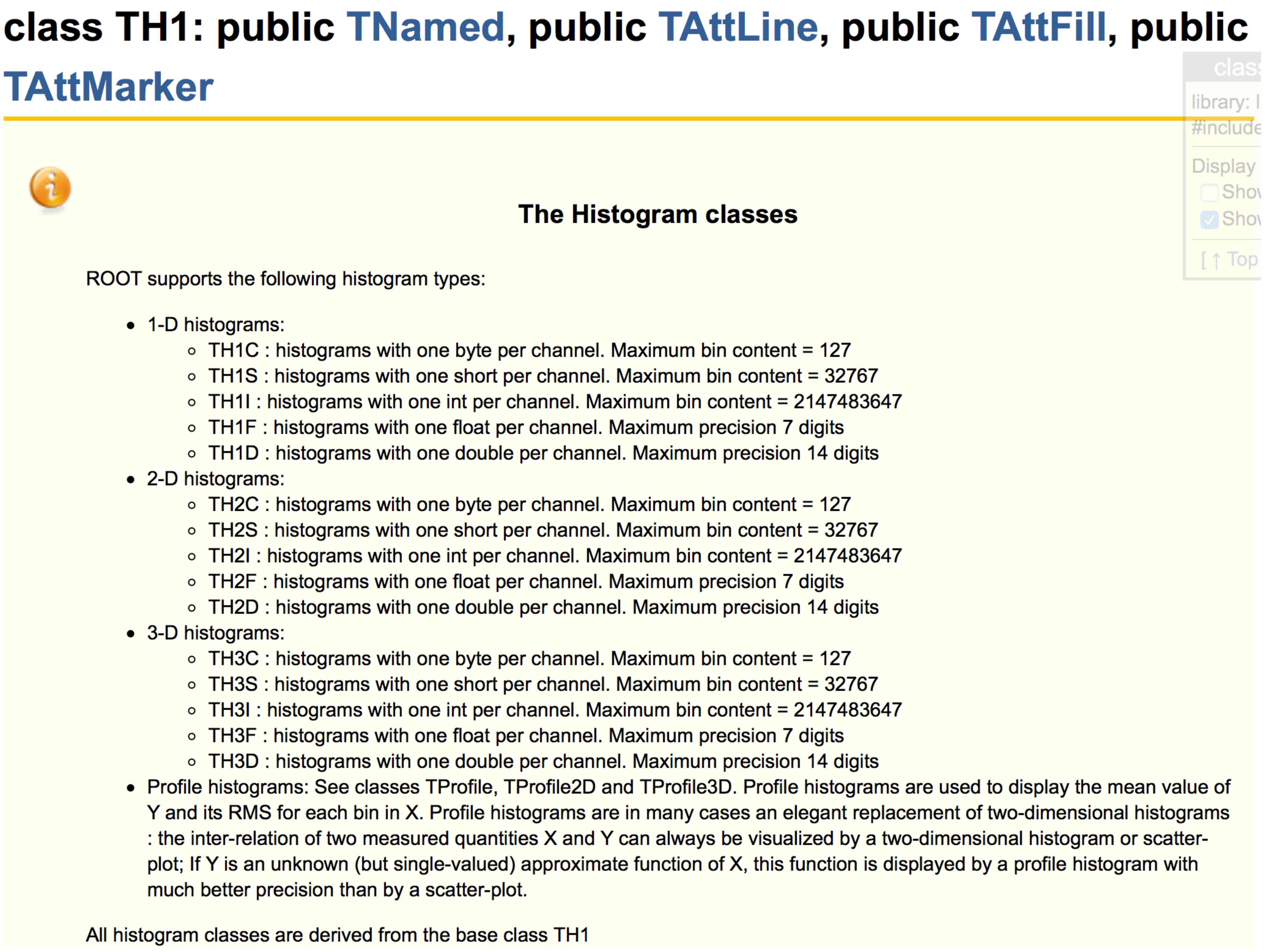
class TNamed: public TObject

```
TNamed

The TNamed class is the base class for all named ROOT classes
A TNamed contains the essential elements (name, title)
to identify a derived object in containers, directories and files.
Most member functions defined in this base class are in general
overridden by the derived classes.
```

TH1

https://root.cern.ch/root/html526/TH1.html



class TH1: public TNamed, public TAttLine, public TAttFill, public TAttMarker

class
library: l
#include
Display
Show
✓ Show
[↑ Top

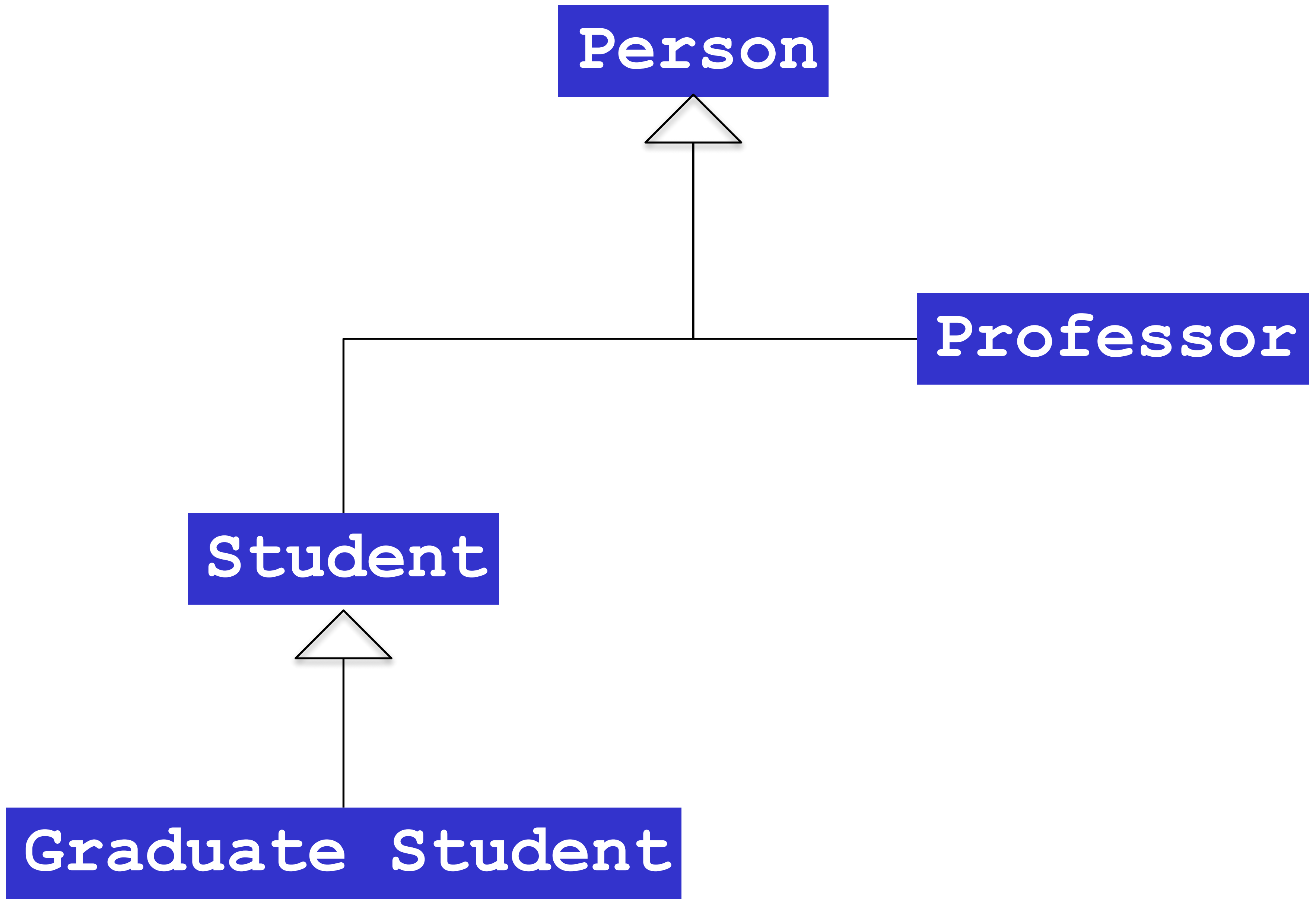
The Histogram classes

ROOT supports the following histogram types:

- 1-D histograms:
  - TH1C : histograms with one byte per channel. Maximum bin content = 127
  - TH1S : histograms with one short per channel. Maximum bin content = 32767
  - TH1I : histograms with one int per channel. Maximum bin content = 2147483647
  - TH1F : histograms with one float per channel. Maximum precision 7 digits
  - TH1D : histograms with one double per channel. Maximum precision 14 digits
- 2-D histograms:
  - TH2C : histograms with one byte per channel. Maximum bin content = 127
  - TH2S : histograms with one short per channel. Maximum bin content = 32767
  - TH2I : histograms with one int per channel. Maximum bin content = 2147483647
  - TH2F : histograms with one float per channel. Maximum precision 7 digits
  - TH2D : histograms with one double per channel. Maximum precision 14 digits
- 3-D histograms:
  - TH3C : histograms with one byte per channel. Maximum bin content = 127
  - TH3S : histograms with one short per channel. Maximum bin content = 32767
  - TH3I : histograms with one int per channel. Maximum bin content = 2147483647
  - TH3F : histograms with one float per channel. Maximum precision 7 digits
  - TH3D : histograms with one double per channel. Maximum precision 14 digits
- Profile histograms: See classes TProfile, TProfile2D and TProfile3D. Profile histograms are used to display the mean value of Y and its RMS for each bin in X. Profile histograms are in many cases an elegant replacement of two-dimensional histograms : the inter-relation of two measured quantities X and Y can always be visualized by a two-dimensional histogram or scatter-plot; If Y is an unknown (but single-valued) approximate function of X, this function is displayed by a profile histogram with much better precision than by a scatter-plot.

All histogram classes are derived from the base class TH1

`Person` Inheritance Hierarchy



Student and GraduateStudent

```
class Person {
  public:
    Person(const std::string& name);
    ~Person();
    std::string name() const { return name_; }
    void print() const;

  private:
    std::string name_;
};
```

```
class Student : public Person {
  public:
    Student(const std::string& name, int id);
    ~Student();
    int id() const { return id_; }
    void print() const;

  private:
    int id_;
};
```

```
class GraduateStudent : public Student {
  public:
    GraduateStudent(const std::string& name, int id,
                    const std::string& major);
    ~GraduateStudent();
    std::string getMajor() const { return major_; }
    void print() const;

  private:
    std::string major_;
};
```

Proper Constructor

```
// Person.cc

Person::Person(const std::string& name) {
  name_ = name;
  cout << "Person(" << name << ") called" << endl;
}
```

```
// Student.cc

Student::Student(const std::string& name, int id) : Person(name) {
  id_ = id;
  cout << "Student(" << name << ", " << id << ") called" << endl;
}
```

```
// GraduateStudent.cc

GraduateStudent::GraduateStudent(const std::string& name, int id, const std::string& major) :
  Student(name,id) {
  major_ = major;
  cout << "GraduateStudent(" << name << ", " << id << "," << major << ") called" << endl;
}
```

- **`Person::Person(name)`** assigns value to name_
- **`Student(name,id)`** assigns id_ and calls **`Person::Person(name)`**
- **`GraduateStudent(name,id,major)`** assigns major, calls **`Student::Student(name,id)`**, which calls **`Person::Person(name)`**

Example

```
// example11.cpp

int main() {

  Person* john = new Person("John");
  john->print();  // Person::print()

  Student* susan = new Student("Susan", 123456);
  susan->print(); // Student::print()
  susan->Person::print(); // Person::print()

  Person* p2 = susan;
  p2->print(); // Person::print()

  GraduateStudent* paolo =
    new GraduateStudent("Paolo", 9856, "Physics");
  paolo->print();

  Person* p3 = paolo;
  p3->print();


  delete john;
  delete susan;

  return 0;
}
```

Can point to **`Student`** or **`GraduateStudent`** object with a pointer of type **`Person`**

Can treat **`paolo`** and **`susan`** as **`Person`**

Depending on the pointer type different **`print()`** methods are called

```
$ g++  -o /tmp/app example11.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(John) called
I am a Person. My name is John
Person(Susan) called
Student(Susan, 123456) called
I am Student Susan with id 123456
I am a Person. My name is Susan
I am Student Susan with id 123456
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
I am GraduateStudent Paolo with id 9856 major in Physics
I am GraduateStudent Paolo with id 9856 major in Physics
~Person() called for John
~Student() called for name:Susan and id: 123456
~Person() called for Susan
```

No delete for **`paolo`**!!
Memory Leak!

Problem with Previous Example

```
// example11.cpp

int main() {

  Person* john = new Person("John");
  john->print();  // Person::print()

  Student* susan = new Student("Susan", 123456);
  susan->print(); // Student::print()
  susan->Person::print(); // Person::print()

  Person* p2 = susan;
  p2->print(); // Person::print()

  GraduateStudent* paolo =
    new GraduateStudent("Paolo", 9856, "Physics");
  paolo->print();

  Person* p3 = paolo;
  p3->print();


  delete john;
  delete susan;

  return 0;
}
```

```
$ g++  -o /tmp/app example11.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(John) called
I am a Person. My name is John
Person(Susan) called
Student(Susan, 123456) called
I am Student Susan with id 123456
I am a Person. My name is Susan
I am Student Susan with id 123456
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
I am GraduateStudent Paolo with id 9856 major in Physics
I am GraduateStudent Paolo with id 9856 major in Physics
~Person() called for John
~Student() called for name:Susan and id: 123456
~Person() called for Susan
```

- Call to method **`print()`** is resolved base on the type of the pointer
  - **`print()`** methods is determined by pointer not the actual type of object
- Desired feature: use generic **`Person*`** pointer but call appropriate **`print()`** method for **`paolo`** and **`susan`** based on **actual type** of these objects

Desired Feature: Resolve Different Objects at Runtime

- We would like to use the same **`Person*`** pointer but call different methods based on the type of the object being pointed to

- We **do not** want to use the scope operator to specify the function to call

```
Person* john = new Person("John");
john->print();  // Person::print()

Student* susan = new Student("Susan", 123456);
Person* p2 = susan;
p2->print(); // Person::print()

GraduateStudent* paolo =
  new GraduateStudent("Paolo", 9856, "Physics");

Person* p3 = paolo;
p3->print();
```

Same **`Person*`** pointer used for three different types of object in the same hierarchy

Same code used by types solved at runtime

```
Person(John) called
I am a Person. My name is John
Person(Susan) called
Student(Susan, 123456) called
I am Student Susan with id 123456

Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
I am GraduateStudent Paolo with id 9856 major in Physics
```

Polymorphic Behavior

```
// example12.cpp
int main() {

 vector<Person*> people;

  Person* john = new Person("John");
  people.push_back(john);

  Student* susan = new Student("Susan", 123456);
  people.push_back(susan);

  GraduateStudent* paolo = new GraduateStudent("Paolo", 9856, "Physics");
  people.push_back(paolo);

  for(int i=0;
     i< people.size(); ++i) {
    people[i]->print();
  }

  delete john;
  delete susan;
  delete paolo;

  return 0;
}
```

vector of generic type Person
No knowledge about specific types

Different derived objects stored in the vector of Person

Generic call to print()

```
$ g++ -o /tmp/app example12.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(John) called
Person(Susan) called
Student(Susan, 123456) called
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
I am GraduateStudent Paolo with id 9856 major in Physics
I am a Person. My name is John
I am Student Susan with id 123456
I am GraduateStudent Paolo with id 9856 major in Physics
~Person() called for John
~Student() called for name:Susan and id: 123456
~Person() called for Susan
~GraduateStudent() called for name:Paolo id: 9856 major: Physics
~Student() called for name:Paolo and id: 9856
~Person() called for Paolo
```

Different functions called based on the real type of objects pointed to!!

How? virtual functions!

`virtual` functions

```
class Person {
  public:
    Person(const std::string& name);
    ~Person();
    std::string name() const { return name_; }
    virtual void print() const;

  private:
    std::string name_;
};
```

```
class Student : public Person {
  public:
    Student(const std::string& name, int id);
    ~Student();
    int id() const { return id_; }
    virtual void print() const;

  private:
    int id_;
};
```

```
class GraduateStudent : public Student {
  public:
    GraduateStudent(const std::string& name, int id, const std::string& major);
    ~GraduateStudent();
    std::string getMajor() const { return major_; }
    virtual void print() const;

  private:
    std::string major_;
};
```

- Virtual methods of base class are **overridden not redefined** by derived classes
  - if not overridden, base class function called
- Type of objects pointed to determine which function is called
- Type of pointer (also called handle) has no effect on the method being executed
- `virtual` allows polymorphic behavior and generic code without relying on specific objects

Static and Dynamic (or late) binding

- Choosing the correct derived class function at run time based on the type of the object being pointed to, regardless of the pointer type, is called dynamic binding or late binding

- Dynamic binding works only with pointers and references not using dot-member operators
  - static binding: function calls resolved at compile time

```
// example13.cpp

int main() {

  Person john("John");
  Student susan("Susan", 123456);
  GraduateStudent paolo("Paolo",
      9856, "Physics");

  john.print();
  susan.print();
  paolo.print();

  return 0;
}
```

static binding

```
$ g++ -o /tmp/app example13.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(John) called
Person(Susan) called
Student(Susan, 123456) called
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
I am a Person. My name is John
I am Student Susan with id 123456
I am GraduateStudent Paolo with id 9856 major in Physics
~GraduateStudent() called for name:Paolo id: 9856 major: Physics
~Student() called for name:Paolo and id: 9856
~Person() called for Paolo
~Student() called for name:Susan and id: 123456
~Person() called for Susan
~Person() called for John
```

Example of Dynamic Binding

```
// example14.cpp

  Person* john = new Person("John");
  Person* susan = new Student("Susan", 123456);
  Person* paolo = new GraduateStudent("Paolo", 9856, "Physics");

  (*john).print();
  (*susan).print();
  (*paolo).print();

  john->print();
  susan->print();
  paolo->print();
```

```
$ g++ -o /tmp/app example14.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(John) called
Person(Susan) called
Student(Susan, 123456) called
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
I am a Person. My name is John
I am Student Susan with id 123456
I am GraduateStudent Paolo with id 9856 major in Physics
I am a Person. My name is John
I am Student Susan with id 123456
I am GraduateStudent Paolo with id 9856 major in Physics
~Person() called for John
~Person() called for Susan
~Person() called for Paolo
```

Example: **`virtual`** Function at Runtime

```
int main() {

  Person* p = 0;
  int value = 0;
  while(value<1 || value>10) {
    cout << "Give me a number [1,10]: ";
    cin >> value;
  }
  cout << flush; // write buffer to output
  cout << "make a new derived object..." << endl;
  if(value>5) p = new Student("Susan", 123456);
  else        p = new GraduateStudent("Paolo", 9856, "Physics");

  cout << "call print() method ..." << endl;

  p->print();

  delete p;
  return 0;
}
```

Type of object decided at runtime by user

Compiler does not know what object will be used

```
$ g++ -o /tmp/app example15.cpp {Person,Student,GraduateStudent,Professor}.cc
$ /tmp/app
Give me a number [1,10]: 6
make a new derived object...
Person(Susan) called
Student(Susan, 123456) called
call print() method ...
I am Student Susan with id 123456
~Person() called for Susan

$ /tmp/app
Give me a number [1,10]: 2
make a new derived object...
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
call print() method ...
I am GraduateStudent Paolo with id 9856 major in Physics
~Person() called for Paolo
```

Virtual methods allow dynamic binding at runtime

Default for Virtual Methods

```
// Professor.h
class Professor : public Person {
  public:
    Professor(const std::string& name,
              const std::string& department);
    ~Professor();
    std::string department() const { return department_; }
    //virtual void print() const; // will use Person::Print()

  private:
    std::string department_;
};
```

`print()` not overriden in `Professor`

```
// example16.cpp

int main() {

  Person john("John");
  Student susan("Susan", 123456);
  GraduateStudent
   paolo("Paolo", 9856, "Physics");
  Professor
      bob("Robert", "Biology");

  john.print();
  susan.print();
  paolo.print();
  bob.print();

  return 0;
}
```

```
$ g++ -o /tmp/app example16.cpp {Person,Student,GraduateStudent,Professor}.cc
$ /tmp/app
Person(John) called
Person(Susan) called
Student(Susan, 123456) called
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
Person(Robert) called
Professor(Robert, Biology) called
I am a Person. My name is John
I am Student Susan with id 123456
I am GraduateStudent Paolo with id 9856 major in Physics
I am a Person. My name is Robert
~Professor() called for name:Robert and department: Biology
~Person() called for Robert
~GraduateStudent() called for name:Paolo id: 9856 major: Physics
~Student() called for name:Paolo and id: 9856
~Person() called for Paolo
~Student() called for name:Susan and id: 123456
~Person() called for Susan
~Person() called for John
```

`Person::print()` used by default

Abstract Class

Pure virtual Functions

- virtual functions with no implementation
  - All derived classes ***are required*** to implement these functions
- Typically used for functions that can't be implemented (or at least in an unambiguous way) in the base case
- Class with at least one pure virtual method is called an "Abstract" class

= 0 is called pure specifier

```
class Function {
  public:
    Function(const std::string& name);
    virtual double value(double x) const = 0;
    virtual double integrate(double x1, double x2) const = 0;

  private:
    std::string name_;
};
```

```
#include "Function.h"

Function::Function(const std::string& name) {
  name_ = name;
}
```

ConstantFunction

```
#ifndef ConstantFunction_h
#define ConstantFunction_h

#include <string>
#include "Function.h"

class ConstantFunction : public Function {
  public:
    ConstantFunction(const std::string& name, double value);
    virtual double value(double x) const;
    virtual double integrate(double x1, double x2) const;

  private:
    double value_;
};
```

```
#include "ConstantFunction.h"

ConstantFunction::ConstantFunction(const std::string& name, double value) :
  Function(name) {
  value_ = value;
}

double ConstantFunction::value(double x) const {
  return value_;
}

double ConstantFunction::integrate(double x1, double x2) const {
  return (x2-x1)*value_;
}
```

Typical Error with Abstract Class

```
// func1.cpp
#include <string>
#include <iostream>
using namespace std;

#include "Function.h"

int main() {

  Function* gauss  = new Function("Gauss");

  return 0;
}
```

Cannot make an object of an Abstract class!

Pure virtual methods not implemented and the class is effectively incomplete

```
$ g++ -o /tmp/app func1.cpp Function.cc
func1.cpp:10:22: error: allocating an object of abstract class type 'Function'
  Function* gauss  = Function("Gauss");
                     ^
./Function.h:9:20: note: unimplemented pure virtual method 'value' in 'Function'
    virtual double value(double x) const = 0;
                   ^
./Function.h:10:20: note: unimplemented pure virtual method 'integrate' in 'Function'
    virtual double integrate(double x1, double x2) const = 0;
                   ^
1 error generated.
```

`virtual` and pure `virtual`

- No default implementation for pure virtual
  - Requires explicit implementation in derived classes

- Use pure virtual when
  - Need to enforce policy for derived classes
  - Need to guarantee public interface for all derived classes
  - You expect to have certain functionalities but too early to provide default implementation in base class
  - Default implementation can lead to error
    - User forgets to implement correctly a virtual function
    - Default implementation is used in a meaningless way

- Virtual allows polymorphism

- Pure virtual forces derived classes to ensure correct implementation

Abstract and Concrete Classes

- Any class with at least one pure virtual method is called an Abstract Class
  - Abstract classes are incomplete
    - At least one method not implemented
    - Compiler has no way to determine the correct size of an incomplete type
  - ***Cannot instantiate an object of Abstract class***

- Usually abstract classes are used in higher levels of hierarchy
  - Focus on defining policies and interface
  - Leave implementation to lower level of hierarchy

- Abstract classes used typically as pointers or references to achieve polymorphism
  - Point to objects of sub-classes via pointer to abstract class

Example of Bad Use of **virtual**

```
class BadFunction {
  public:
    BadFunction(const std::string& name);
    virtual double value(double x) const { return 0; }
    virtual double integrate(double x1, double x2) const { return 0; }

  private:
    std::string name_;
};
```

Default dummy implementation

```
class Gauss : public BadFunction {
  public:
    Gauss(const std::string& name, double mean, double width);

    virtual double value(double x) const;
    //virtual double integrate(double x1, double x2) const;

  private:
    double mean_;
    double width_;
};
```

Implement correctly **`value()`** but use default **`integrate()`**

We can use ill-defined **`BadFunction`** and wrongly use **`Gauss`**!

```
// func2
int main() {

  BadFunction f1  = BadFunction("bad");
  Gauss g1("g1",0.,1.);
  cout << "g1.value(2.): " << g1.value(2.) << endl;
  cout << "g1.integrate(0.,1000.): "
       << g1.integrate(0.,1000.) << endl;
  return 0;
}
```

```
$ g++ -o /tmp/app func2.cpp
        {BadFunction,Gauss,Function}.cc
$ /tmp/app
g1.value(2.): 0.0540047
g1.integrate(0.,1000.): 0
```

Function and BadFunction

```
class BadFunction {
  public:
    BadFunction(const std::string& name);
    virtual double value(double x) const { return 0; }
    virtual double integrate(double x1, double x2) const { return 0; }

  private:
    std::string name_;
};
```

```
class Function {
  public:
    Function(const std::string& name);
    virtual double value(double x) const = 0;
    virtual double integrate(double x1, double x2) const = 0;

  private:
    std::string name_;
};
```

```
// func3.cpp
int main() {

  BadFunction f1  = BadFunction("bad");
  Function f2("f2");

  return 0;
}
```

Cannot instantiate Function because abstract

Bad Function can be used

```
$ g++ -o /tmp/app func3.cpp {BadFunction,Function}.cc
func3.cpp:13:12: error: variable type 'Function' is an abstract class
  Function f2("f2");
           ^
./Function.h:9:20: note: unimplemented pure virtual method 'value' in 'Function'
    virtual double value(double x) const = 0;
                   ^
./Function.h:10:20: note: unimplemented pure virtual method 'integrate' in 'Function'
    virtual double integrate(double x1, double x2) const = 0;
                   ^
1 error generated.
```

Use of **virtual** in Abstract Class **Function**

```
class Function {
  public:
    Function(const std::string& name);
    virtual double value(double x) const = 0;
    virtual double integrate(double x1, double x2) const = 0;
    virtual void print() const;
    virtual std::string name() const { return name_; }

  private:
    std::string name_;
};
```

```
#include "Function.h"
#include <iostream>

Function::Function(const std::string& name) {
  name_ = name;
}

void
Function::print() const {
  std::cout << "Function with name "
            << name_ << std::endl;
}
```

Default implementation of name()

Unambiguous functionality: user will always want the name of the particular object regardless of its particular subclass

print() can be overriden in sub-classes to provide more details about sub-class but still a function with a name

Concrete Class **Gauss**

```cpp
#include "Gauss.h"
#include <cmath>
#include <iostream>
using std::cout;
using std::endl;

Gauss::Gauss(const std::string& name,
           double mean, double width) :
  Function(name) {
  mean_ = mean;
  width_ = width;
}

double Gauss::value(double x) const {
  double pull = (x-mean_)/width_;
  double y = (1/sqrt(2.*3.14*width_)) * exp(-pull*pull/2.);
  return y;
}

double Gauss::integrate(double x1, double x2) const {
  cout << "Sorry. Gauss::integrate(x1,x2) not implemented yet..."
       << "returning 0. for now..." << endl;
  return 0;
}

void
Gauss::print() const {
  cout << "Gaussian with name: " << name()
       << " mean: " << mean_
       << " width: " << width_
       << endl;
}
```

```cpp
#ifndef Gauss_h
#define Gauss_h

#include <string>
#include "Function.h"

class Gauss : public Function {
  public:
    Gauss(const std::string& name,
     double mean, double width);

    virtual double value(double x) const;
    virtual double integrate(double x1,
                            double x2) const;
    virtual void print() const;

  private:
    double mean_;
    double width_;
};
#endif
```

```cpp
int main() {

  Function* g1  = new Gauss("gauss",0.,1.);
  g1->print();
  double x = g1->integrate(0., 3.);

  return 0;
}
```

```
$ g++ -o /tmp/app func4.cpp {Gauss,Function}.cc
$ /tmp/app
Gaussian with name: gauss mean: 0 width: 1
Sorry. Gauss::integrate(x1,x2) not implemented yet...returning 0. for now...
```

Problem with destructors

- We now properly delete the Gauss object

```
// func5.cpp
int main() {

  Function* g1  = new Gauss("gauss",0.,1.);
  g1->print();
  double x = g1->integrate(0., 3.);

  delete g1;

  return 0;
}
```

```
$ g++ -o /tmp/app func5.cpp {Gauss,Function}.cc
$ g++ -o /tmp/app func5.cpp {Gauss,Function}.cc
func5.cpp:15:3: warning: delete called on 'Function' that is abstract but has non-virtual destructor
      [-Wdelete-non-virtual-dtor]
  delete g1;
  ^
1 warning generated.
$ /tmp/app
Gaussian with name: gauss mean: 0 width: 1
Sorry. Gauss::integrate(x1,x2) not implemented yet...returning 0. for now...
Illegal instruction
```

- In general with polymorphism and inheritance it is a VERY GOOD idea to use virtual destructors

- Particularly important when using dynamically allocated objects in constructors of polymorphic objects

Revisit Person and Student

```
// example7.cpp
int main() {

 Person* p1  = new Student("Susan", 123456);
 Person* p2  = new GraduateStudent("Paolo", 9856, "Physics");


  delete p1;
  delete p2;

  return 0;
}
```

```
$ g++ -o /tmp/app example7.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(Susan) called
Student(Susan, 123456) called
Person(Paolo) called
Student(Paolo, 9856) called
GraduateStudent(Paolo, 9856,Physics) called
~Student() called for name:Susan and id: 123456
~Person() called for Susan
~GraduateStudent() called for name:Paolo id: 9856 major: Physics
~Student() called for name:Paolo and id: 9856
~Person() called for Paolo
```

Note that ~Person() is called and
not that of the sub class!

We did not declare the destructor
to be virtual

destructor called based on the pointer
and not the object! Non-polymorphic behaviour

```
Person::~Person() {
  cout << "~Person() called for " << name_ << endl;
}
```

```
Student::~Student() {
  cout << "~Student() called for name:" << name()
<< " and id: " << id_ << endl;
}
```

```
GraduateStudent::~GraduateStudent() {
  cout << "~GraduateStudent() called for name:" << name()
       << " id: " << id()
       << " major: " << major_ << endl;
}
```

virtual destructors

- Derived classes might allocate dynamically memory
  - Derived-class destructor (if correctly written!) will take care of cleaning up memory upon destruction
- Base-class destructor will not do the proper job if called for a sub-class object
- Declaring destructor to be virtual is a simple solution to prevent memory leak using polymorphism
- virtual destructors ensure that memory leaks don’t occur when delete an object via base-class pointer

Simple Example of **virtual** Destructor

```
// noVirtualDtor.cc
#include <iostream>

using std::cout;
using std::endl;

class Base {
  public:
  Base(double x) {
    x_ = new double(x);
    cout << "Base(" << x << ") called" << endl;
  }
  ~Base() {
    cout << "~Base() called" << endl;
    delete x_;
  }
  private:
   double* x_;
};

class Derived : public Base {
  public:
  Derived(double x) : Base(x){
    cout << "Derived("<<x<<") called" << endl;
  }
  ~Derived() {
    cout << "~Derived() called" << endl;
  }
};

int main() {
  Base* a = new Derived(1.2);
  delete a;
  return 0;
}
```

Destructor Not virtual

```
$ g++ -Wall -o /tmp/noVirtualDtor noVirtualDtor.cc
$ /tmp/noVirtualDtor
Base(1.2) called
Derived(1.2) called
~Base() called
```

```
// virtualDtor.cc
#include <iostream>

using std::cout;
using std::endl;

class Base {
  public:
  Base(double x) {
    x_ = new double(x);
    cout << "Base(" << x << ") called" << endl;
  }
  virtual ~Base() {
    cout << "~Base() called" << endl;
    delete x_;
  }
  private:
   double* x_;
};

class Derived : public Base {
  public:
  Derived(double x) : Base(x){
    cout << "Derived("<<x<<") called" << endl;
  }
  virtual ~Derived() {
    cout << "~Derived() called" << endl;
  }
};

int main() {
  Base* a = new Derived(1.2);
  delete a;
  return 0;
}
```

Virtual Destructor

```
$ g++ -Wall -o /tmp/VirtualDtor VirtualDtor.cc
$ /tmp/VirtualDtor
Base(1.2) called
Derived(1.2) called
~Derived() called
~Base() called
```

Revised Class **Student**

```
class Student : public Person {
  public:
    Student(const std::string& name, int id);
    ~Student();
    void addCourse(const std::string& course);
    virtual void print() const;

    int id() const { return id_; }
    const std::vector<std::string>* getCourses() const;
    void printCourses() const;

  private:
    int id_;
    std::vector<std::string>* courses_;
};
```

```
void Student::addCourse(const std::string&
course) {
  courses_->push_back( course );
}

void
Student::printCourses() const {
  cout << "student " << name()
       << " currently enrolled in following
courses:"
       << endl;

  for(int i=0; i<courses_->size(); ++i) {
    cout << (*courses_)[i] << endl;
  }
}

const std::vector<std::string>*
Student::getCourses() const {
  return courses_;
}
```

```
Student::Student(const std::string& name,
int id) :
  Person(name) {
  id_ = id;
  courses_ = new
std::vector<std::string>();
  cout << "Student(" << name << ", " << id
<< ") called"
       << endl;
}

Student::~Student() {
  delete courses_;
  courses_ = 0; // null pointer
  cout << "~Student() called for name:" <<
name()
       << " and id: " << id_ << endl;
}

void Student::print() const {
  cout << "I am Student " << name()
       << " with id " << id_ << endl;
  cout << "I am now enrolled in "
       << courses_->size() << " courses."
<< endl;
}
```

Example of Memory Leak with **Student**

```
// example8.cpp

int main() {

  Student* p1  = new Student("Susan", 123456);
  p1->addCourse(string("algebra"));
  p1->addCourse(string("physics"));
  p1->addCourse(string("Art"));
  p1->printCourses();

  Student* paolo   = new Student("Paolo", 9856);
  paolo->addCourse("Music");
  paolo->addCourse("Chemistry");

  Person* p2 = paolo;

  p1->print();
  p2->print();

  delete p1;
  delete p2;

  return 0;
}
```

Memory leak when deleting paolo because nobody deletes courses_

Need to extend polymorphism also to destructors to ensure that object type not pointer determine correct destructor to be called

```
$ g++ -o /tmp/app example8.cpp {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(Susan) called
Student(Susan, 123456) called
student Susan currently enrolled in following courses:
algebra
physics
Art
Person(Paolo) called
Student(Paolo, 9856) called
I am Student Susan with id 123456
I am now enrolled in 3 courses.
I am Student Paolo with id 9856
I am now enrolled in 2 courses.
~Student() called for name:Susan and id: 123456
~Person() called for Susan
~Person() called for Paolo
```

virtual Destructor for **`Person`** and **`Student`**

```
class Person {
  public:
    Person(const std::string& name);
    virtual ~Person();
    std::string name() const { return name_; }
    virtual void print() const;

  private:
    std::string name_;
};
```

```
class Student : public Person {
  public:
    Student(const std::string& name, int id);
    virtual ~Student();
    void addCourse(const std::string& course);
    virtual void print() const;

    int id() const { return id_; }
    const std::vector<std::string>* getCourses() const;
    void printCourses() const;

  private:
    int id_;
    std::vector<std::string>* courses_;
};
```

Correct destructor is called using the base-class pointer to Student

```
// example9.cpp

int main() {

  Student* p1  = new Student("Susan", 123456);
  p1->addCourse(string("algebra"));
  p1->addCourse(string("physics"));
  p1->addCourse(string("Art"));
  p1->printCourses();

  Student* paolo   = new Student("Paolo", 9856);
  paolo->addCourse("Music");
  paolo->addCourse("Chemistry");
  Person* p2 = paolo;

  delete p1;
  delete p2;

  return 0;
}
```

```
$ g++ -o /tmp/app example9.cpp
                   {Person,Student,GraduateStudent}.cc
$ /tmp/app
Person(Susan) called
Student(Susan, 123456) called
student Susan currently enrolled in following courses:
algebra
physics
Art
Person(Paolo) called
Student(Paolo, 9856) called
~Student() called for name:Susan and id: 123456
~Person() called for Susan
~Student() called for name:Paolo and id: 9856
~Person() called for Paolo
```