Topic 2

C++ Review Part II:
More on Functions, Variables, Classes

資料結構與程式設計

Data Structure and Programming

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Part I: Understanding "Functions"

- Global vs. member functions
- Function signature, prototype , definition
- Function parameters, arguments

Key Concept #1: Global vs. Member Functions

- Global functions are defined in global scope
  - void f(…) { … }
  - There is no so-called local functions
    - i.e. A function can't be embedded in another function
- Member functions are defined in class scope
  - void A::f(…) { … }
  - A member function is called by an object of its class type

Key Concept #2: Function Signature

- To define the identity of a function
- 4 things to define "function signature"
  1. Function name
  2. Number of parameters
  3. Types of parameters
  4. Order of parameters

  ➔ No "return type" (why?)
- There cannot be functions with the same function signature, unless ---
  1. Separated by different name spaces
  2. Defined as "static" in different file scopes
- However, functions can have the same name, but different signature (overloading, covered later)

Key Concept #3: Function Prototype vs. Function Definition

- Think, which one is better?

1.
```
void f() {
   …
}
int main() {
   …
   f();
}
```

2.
```
void f();  ← function prototype
int main() {
   …
   f();
}
void f() {
   …        ← function definition
}
```


Key Concept #4: Default Argument

- Note:
  - void f(int x) { … } // x is f's parameter
  - f(10); f(a); // 10, a as arguments to f()
- Parameters with default assignments ➔ function with default arguments
  - Can be skipped when calling the function
  - e.g.
    void f(int x, int y = 0);
    …
    f(10);
  - Can only appear towards the end of parameter list
  - (Not OK) void f(int x = 0, int y);
- Given a function, its default argument can only be defined ONCE (even if with the same value)
  - void f(int x = 0);
    …
    void f(int x = 0) { ... } ➔ Compilation ERROR

Practice #1

- Define a function, say "`void f(int a)`"
  - Write the code in the following order:
    - The function prototype (i.e. forward declaration)
    - main(), and call f() inside main()
    - Definition of function f().
  - Make sure the code can be compiled. Then remove the function prototype. Compile again. What error do you see?
  - Put the function prototype back. Define the default argument in both function prototype and function definition. Compile again. What error do you see?
  - Change the values of the default arguments. Can the compilation error be fixed?

Key Concept #5: Parameters in a function

- When a function is called, the caller performs "=" operations on its arguments to the corresponding parameters in the function
  - ```
    void f(int a, char c, int *p) { ... }
    ...
    int main() {
       f(i, cc, pp); // int a = i;
                     // char c = cc;
                     // int *p = pp;
    }
    ```
    ```

Key Concept #6: Passed by Object, Pointer, and Reference

- // passed by object
  void f(int a) { …}
  int main() { int b; ...; f(b); }
- // passed by object
  void h(A a) { …}
  int main() { A aa; ...; f(aa); }
- // passed by pointer
  void g(int *p) { ... }
  int main() { int *q = …; f(q); }
- // passed by reference
  void k(A& a) { …}
  int main() { A aa; ...; k(aa); }

Passed by Object, Pointer, and Reference

[Rule of thumb] Making an '=' (i.e. copy) from the passed argument in the caller, to the parameter of the called function.

```
void f1(int a)
 { a = 20; }
void f2(int& a)
 { a = 30; }
void f3(int* p)
 { *p = 40; }
void f4(int* p)
 { p = new int(50); }
void f5(int* & p)
 { p = new int(60); }
```

```
main()
{
   int a = 10;
   int* p = &a;
   int a1,a2,a3,a4,a5;
   f1(a); a1 = a;
   f2(a); a2 = a;
   f3(p); a3 = *p;
   f4(p); a4 = *p;
   f5(p); a5 = *p;
}
```

What are the values of a1, a2, a3, a4, and a5 at the end?

Summary #1: Passed by pointer or passed by reference

1. If you have some data to share among functions, and you don't want to copy (by '=') them during function calling, you can use "passed by pointers"

```
class A {
   int _i; char _c; int *_p; ...
};
void f(A *a) { ... }
...
int main() {
   A *a = ...;
   f(a);
}
```


Summary #1: Passed by pointer or passed by reference

2. However, if originally the data is not a pointer type, "passed by pointers" is kind of awkward. You should use "passed by references"

```
class A {
   int _i; char _c; int *_p; ...
};
void f(A *a) { ... }
void g(A& a) { ... }
...
int main() {
   A a = ...; // an object, not a pointer
   f(&a);     // Awkward!! C style ☹
   g(a);      // Better!!
}
```

Summary #1: Passed by pointer or passed by reference

3. But, sometimes we just want to share the data to another function, but don't want it to modify the data.

```
int main() {
   A a = ...;
   g(a);
}
void g(A& a) { ... }
```

// "a" may get modified by g()

➔ Using "const" to constrain !!

Part II: More on "Variables"

- "const" keyword
- Array vs. pointers
- Pointer arithmetic
- Memory sizes of variables
- Return value of a function
- Compilation issues
- Compiler preprocessors

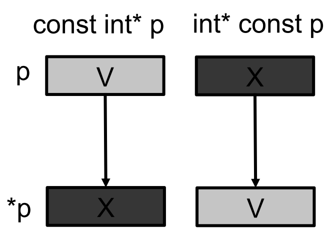
Key Concept #1: Const

- Const is an adjective
  - When a variable is declared “const”, it means it is “READ-ONLY” in that scope.
    ➔ Cannot be modified
- Const must be initialized
  - const int a = 10; // OK
  - const int b;   // NOT OK
  - int i;   // Not initialized…
    const int j = i;   // Is this OK?
    const int& k = i; // Is this OK?
    f(j);   // f(int m) { … }; Is this OK?
    i = 10;   // will j, k be changed? Is this OK?
- “const int” and “int const” are the same
- “const int *” and “int * const” are different !!

What? const *& #$&@%#q

- Rule of thumb
  - Read from right to left

1. f(int* p)
   - Pointer to an int (integer pointer)
2. f(int*& p)
   - Reference to an integer pointer
3. f(int*const p)
   - Constant pointer to an integer
4. f(const int* p) = f(int const * p)
   - Pointer to a constant integer
5. f(const int*& p)
   - Reference to a pointer of a constant int
6. f(const int*const& p)
   - Reference to a constant pointer address, which points to a constant integer



Practice #2

- Define two variables as follows
  `const int a = 10;`
  `int b = 10;`
  Add the following codes, and compile the program to see it there is any error. If no error, execute to see the results.
  - `a = 20;`
  - `a = 10;`
  - `a = b;`
  - `int& c = a; c = 20; cout << a;`
  - `const int& c = b; c = 20;`
  - `const int& c = b; b = 20; cout << c;`

Key Concept #2: Const Object

- Const object ➔ Object that is read-only
- Two cases:
  - Declare a const object: const A a;
  - Calling a const method:
    - A::constMethod() const {…}
      a.constMethod();
- When an object is declared "const", it can not call any method that may modify its data members, nor can be operated by any operator that may change its value
- When an object is calling a const method, no matter it is declared const or not, it becomes a const object during this function call

Passed in a reference to a constant object 'c'
➔ 'c' cannot be modified in the function

const A& B::blah (const C&   c) const {...}

Return a reference to a constant object
➔ The returned object can then only call constant methods

This is a constant method, meaning this object is treated as a constant during this function
➔ None of its data members can be modified

Key concept #3: The Impact of const

- Supposed "_data" is a data member of class MyClass

```
void MyClass::f() const
{
   _data->g();
}
```

  - Because this object is treated as a constant, its data field "_data" is also treated as a constant in this function
    ➔ "g()" must be a constant method too!!
  - Compiler will signal out an error if g() is NOT a const method

- [Coding tip] If we really want a member function to be a read-only one (e.g. getXX()), putting a "const" can help ensure it

Const vs. non-const??

- Passing a non-const argument to a const parameter in a function

```
void f(const A& i) { ... }
void g(const A j) { ... }
int main() {
   A a; ...
   f(a); // a reference of "a" is treated const in f()
   g(a); // a copy of "a" is treated const in g()
}
```


Const vs. non-const??

- Passing a const argument to a non-const parameter in a function

```
void f(A& i) { ... }
void g(A j) { ... }
int main() {
   const A a(...);
   f(a); // Error → No backdoor for const
   g(a); // a copy of "a" is treated non-const in g()
}
```

Const vs. non-const??

- Non-const object calling a const method

```
T a;
a.constMethod();  // OK
```

  - "a" will be treated as a const object within "constMethod()"

- Const object calling non-const method

```
const T a;
a.nonConstMethod();   // not OK
```

  - A const object cannot call a non-const method ➔ compilation error

Casting "const" to "non-const"

```
const T a;
a.nonConstMethod();   // not OK
```

Trying...

1. T(a).nonConstMethod();
   - Static cast; OK, but may not be safe (why?)
   - Who is calling nonConstMethod()?
2. const_cast<T>(a).nonConstMethod();
   - Compilation error!!
   - "const_cast" can only be used for pointer, reference, or a pointer-to-data-member type
3. const_cast<T *>(&a)->nonConstMethod();
   - OK, but kind of awkward

Practice #3

- Define a `class T` with a data member ”`int _d`”, a non-const method `f()` in which `_d` is incremented by 10, and a const method `p()` that prints out the value of `_d`. Declare a const object of `T` as “`const T a(10)`”, in which `_d` is initialized to 10. Add the following codes, and compile the program to see it there is any error. If no error, execute to see the results.
  - `a.f();`
  - `T(a).f().p(); a.p();`
  - `const_cast<T *>(&a)->f()->p(); a.p();`

const_cast<T>() for pointer-to-const object

```
const T* p;
p->nonConstMethod(); // not OK
```

➔ const_cast<T*>(p)->nonConstMethod();
A const object can now call non-const method

const class object (revisited)

- Remember:
  const A& B::blah (const C&   c) const {...}
  - When an object of class B calls this member function, this object will become a “const class object”.
  - That is, the B’s data members will be treated as const (i.e. can’t be modified) in this function.
  - Also, “this” cannot call non-const functions in “blah()”, nor can the data members call non-const functions.

Key Concept #4: “mutable” --- a back door for const method

- However, sometimes we MUST modify the data member in a const method
  - void MyClass::f() const
    {
      _flags |= 0x1; // setting a bit of the _flags
    }
  - In such case, declare “_flag” with “mutable” keyword
    - e.g.

```
mutable unsigned  _flag;
```

Key Concept #5: Array vs. Pointer

- An array variable represents a “const pointer”
  - int a[10]; ← treating “a” as an “int * const”
    a = anotherArr; // Error; can’t reassign “a”
  - int *p = new int[10];
    p = anotherPointer; // Compile OK, but memory leak !
    p = new int(20); // also compile OK, but memory leak !
- An array variable (the const pointer) must be initialized
  - Recall: “const” variable must be initialized
  - Key: the size of the array must be known in declaration
  - int a[10]; // OK, as the memory address is assigned.
    int a[10] = { 0 }; // Initialize array variable and its content
    int a[ ]; // NOT OK; array size unknown
    int a[ ] = { 1, 2, 3 }; // OK array size determined by RHS

Const pointer vs. pointer to a const

- ```
  int a = 10;
  const int c = 10;
  a = c;  // OK
  c = a;  // NOT OK; even though 10 = 10
  ```
- ```
  int a[10] = { 0 };
  int b[10];
  int *c;
  const int *d; // This is OK!
  int *const e; // Error: uninitialized
  b = a;  // Error
  c = a; d = a; // OK
  e = a;  // Error
  ```
- ```
  void f(const int* i) { ... }
  int main() {
     int * const a = new int(10);
     f(a);  // Any problem?
  }
  ```
  ```

The Address of 'a' in int a[10]

- Try this:
  - ```
    int arr[10];
    cout << arr << endl;
    cout << &arr << endl;
    cout << &arr[0] << endl;
    int *p = new int[10];
    cout << p << endl;
    cout << &p << endl;
    ```
  - Both the content and the address of "arr" are the same!
    ➔ Point to the memory location of arr[0]
- Different from "int *p", there is no separate variable to store the address of the array.
  ➔ Resolved in symbol table

More about int [] and int*

- ```
  int a[10] = { 0 }; // type of a: "int *const"
  int *p = new int[10];
  *a = 10;
  *p = 20;  // OK
  *(a + 1) = 20;
  *(a++) = 30; // Compile error; explained later
  a = p; // Compile error; non-const to const
  p = a; // OK, but memory leak...
  *(p++) = 40; // OK, but what about "delete [] p"?
  int *q = a;
  q[2] = 20;
  *(q+3) = 30;
  *(q++) = 40;  // OK
  delete a; // compile error/warning; runtime crash...
  delete []p; // compile OK, but runtime crash (p = a)
  delete []q; // compile OK, but may get fishy result
  ```
- What about:
  ```
  int a = 10; int *p = &a; ... delete p;
  ```

Key Concept #6: Pointer Arithmetic

- '+' / '-' operator on a pointer variable points to the memory location of the next / previous element (as in an array)
  - int *p = new int(10);
    int *q = p + 1; // memory addr += sizeof(int)
  - A *r = new A;
    r -= 2; // memory addr -= sizeof(A) * 2
- For an array variable "arr", "arr + i" points to the memory location of arr[i]
  - int arr[10];
    *(arr + 2) = 5; // equivalent to "arr[2] = 5"

(Recapped) Memory Sizes

- Basic "memory size" unit ➔ Byte (B)
  - 1 Byte = 8 bit
- 1 memory address ➔ 1 Byte
  - Like same sized apartments
- Remember: the variable type determines the size of its memory
  - char, bool: 1 Byte (addr += 1)
  - short, unsigned short: 2 Bytes (addr += 2)
  - int, unsigned, float: 4 Bytes (addr += 4)
  - double: 8 Bytes (addr += 8)
  - long long: 8 Bytes (addr += 8)

Key Concept #7: Size of a Pointer

- Remember:
  A pointer variable stores a memory address
  - What is the memory size of a memory address?
- The memory size of a memory address depends on the machine architecture
  - 32-bit machine: 4 Bytes
  - 64-bit machine: 8 Bytes
- Remember: 1 memory address ➔ 1 Byte
  ➔ The memory content of the pointer variables
  : For 32-bit machine, the last 2 bits are 0's
  : For 64-bit machine, the last 3 bits are 0's

Key Concept #8: Memory Alignment

- What are the addresses of these variables?

```
int *p = new int(10);   // let addr(p) = 0x7fffe84ff0e0
char c = 'a';
int i = 20;
int *pp = new int(30);
char cc = 'b';
int *ppp = pp;
int ii = 40;
char ccc = 'c';
char cccc = 'd';
int iii = 30;
```

➔ Given a variable of predefined type with memory size S (Bytes), its address must be aligned to a multiple of S

Practice #4

- Declare a char array and a void* as:
`char c[33] =`
`“0123456789abcdefghijklmnopqrstu”;`
`void *p = c;`
  - Define “`char *p1`”, “`short *p2`”, and “`int *p3`” and initialize them to `p`.
  - Print out `p1`, `p2`, `p3` and (`p1+1`), (`p2+1`) and (`p3+1`). See how they diff.
  - Define “`short *q = p2+1`”. Try to define “`int *s`” whose is equal to `q`. Note `s` is now NOT multiple of `sizeof(int)`.
  - Do “`*s = 0`”. Print out `p1, p1+2, p1+4, p1+6` to see what are affected.
  - Note that in the above practices, you may encounter type-casting errors. Try to make use of “void *”.

Key Concept #9: Return value of a function

- Every function has a return type. At the end of the function execution, it must return a value or a variable of the return type.
  - “void f()” means no return value is needed

1. Return by object
   - ```
     MyClass f(...) {
        MyClass a;...; return a; }
     MyClass b = f(...);
     MyClass& c = f(...);
     // What's the diff? Is it OK?
     // The referenced object must have a
     // valid memory addr outside f()
     ```
     ```

Return by Object, Pointer, and Reference

2. Return by pointer
   - `MyClass* f(...) { MyClass* p;...; return p; }`
     ```
     MyClass* q = f(...);
     // Should we "delete q" later?
     ```
3. Return by reference (reference to whom?)
   - ```
     MyClass& f(...) {...; return r; }
     //  r cannot be local (why?)
     MyClass& s = f(...); // <------------|
     MyClass t = f(...);  // What's the diff?
                          // Is it OK?
     ```
   - [NOTE] Should NOT return the reference of a local variable
     ```
     ➔ int& f() { int a; ...; return a; }
     ➔ compilation warning
     ```
   - ```
     MyClass& MyClass::f(...)
     {...; return (*this); }
     MyClass s;
     MyClass& t = s.f(...);  // <------------|
     MyClass v = s.f(...); // What's the diff?
     ```


When is "return by reference" useful?

- ```
  template<class T>      class Array
  {
    public:
       Array(size_t i = 0) { _data = new T[i]; }
       T& operator[] (size_t i) { return _data[i]; }
       const T& operator[] (size_t i) const {
          return _data[i]; }
       Array<T>& operator= (const Array& arr) {
       ... return (*this); }
    private:
       T  *_data;
  };
  int main()
  {
     Array<int> arr(10);  // declare an array of size 10
     int t = arr[5];   // <---------|
     arr[0] = 20;      // Which one will be called?
     Array<int> arr2; arr2 = arr;
  }  // Why not "Array<int> arr2 = arr;"?
  ```
  ```

Remember in a software project...

- Your program may have many classes...
- You should create multiple files for different class definitions ---
  - .h (header) files
    ➔ class declaration/definition, function prototype
  - .cpp (source) files
    ➔ class and function implementation
  - Makefiles
    ➔ scripts to build the project

Key Concept #10: Define classes in header files

```
// a.h
class A
{
public:
   void f();
};
```

```
// b.h
class B
{
public:
   void g();
};
```

```
// a.cpp
#include "a.h"
#include "b.h"
void A::f() {
   B b;
   b.g();
   ...
}
```

Why should we include "a.h" and "b.h"?

```
// b.cpp
#include "b.h"
void B::g() {
   ...
}
```

```
// main.cpp
#include "a.h"
int main()
{
   A a;
   a.f();
}
```

Why don't we include both "a.h" and "b.h"?

Key Concept #11: "#include"

- A compiler preprocessor
  - Process before compilation
  - Perform copy-and-paste
- This is NOT OK
  - ```
    // no #include "b.h"
    class A {
       B   _b;
    };
    ```
- This is OK
  - ```
    // no #include "b.h"
    class B; // forward declaration
    class A {
       B   *_b;
    };
    ```

➔ The rule of thumb is "need to know the size of the class"!!

Key Concept #12: #include " " or <> ?

- Standard C/C++ header files
  - Stored in a compiler-specified directory
    - e.g. /usr/local/include/c++/8.2.0/
- #include <> will search it in the standard header files
- #include "" will search it in the current directory ('.'), or the directories specified by "-I" in g++ command line.

Key Concept #13: Undefined or Redefined Issues

- Undefined errors for variable/class/type/function
  - The following will cause errors in compiling a source file ---
    `int i = j;` // If j is not declared before this point
    `A a;` // If class A is not defined before this point
    `A *a;` // If class A is not declared before this point
    `goo();` // If no function prototype for goo() before this point
  - The following is OK when compiling each source file, but will cause error during linking if goo() is NOT defined in any other source file --
    ```
    int goo(); // forward declaration
    ...
    int b = goo();
    ```
- Redefined errors
  - Variable/class/function is defined in multiple places
  - May be due to multiple inclusions of a header file
  - That's one of the major reasons why we shouldn't include ".cpp" files

Declare, Define, Instantiate, Initialize, Use

1. Declare a class identifier / function prototype
   - class MyClass;
   - void goo(int, char);
2. Define a class / function / member function
   - class MyClass { ... };
   - void goo() { ... }
   - void MyClass::goo2() { ... }
3. Instantiation (= Declaration + definition) (variable / object)
   - int a;
   - MyClass b;
4. Initialization (during instantiation) (variable / object)
   - int a = 10;
   - MyClass b(10);
5. Used (variable / object / function)
   - a = ...; or ... = a;
   - goo();
   - b.goo2();

Key Concept #14: “extern” in C++

- Remember, static variables and functions can only be seen in the file scope ➔ cannot be seen in other file
- What if we want to access (global) variables or functions across other .cpp files?

  e.g.

```
// file1.cpp
int a = 0;
void f(int i) { ... }
------------------------------
// file2.cpp
int a;   // Error: multiple definition during linking
void g()
{
  f(a); // Error: f(int) not defined
}
```


Using External Variables and Functions

e.g.

```
// file1.cpp
int a = 0;
void f(int i) { ... }
-------------------------------
// file2.cpp
extern int a; // a is an external variable
void f(int);  // f() is an external function
              // "extern" can be omitted here
void g()
{
  f(a);
}
```

Key Concept #15: Forward Declaration

[Bottom line]

Sometimes we just want to include part of the header file, or refer to some declarations

➔ We don't want to include the whole header file

➔ To reduce:

1. Executable file size
2. Compilation time due to dependency

e.g.

```
// MyClass.h
class HisClass;  // forward declaration
class HerClass;  // forward declaration
class MyClass
{
   HisClass*   _hisData;  // OK
   HerClass    _herData;  // NOT OK; why?
};
```


Key Concept #16: Namespace

- e.g.

```
namespace MyNameSpace {
   int a;
   void f();
   class MyClass;
}   // Note: no ';'
```

- namespace MyNS = MyNameSpace; // alias
- Must declare in global scope
  - ```
    int main()
    {
       namespace XYZ { ... }   // Error!!
    }
    ```
    ```

Using namespace

1.
```
void g() {
   MyNameSpace::a = 10;
}  // "::" is the scope operator
```

2.
```
using MyNameSpace::a;
void g() {
   a = 10;
}
```

3.
```
using namespace MyNameSpace;
void g() {
   a = 10;
   f();
}
```


More about namespace declaration

◆
```
namespace P {
   namespace A { void f(); }
   void A::f() { } // ok
   void A::g() { } // Error!! g() is not
                   //    yet a member of A
   namespace A { void g(){ ... } }
}
```

➔

1. Can be nested...
2. The definition of a namespace can be split over several parts (e.g. ‘A’ above)
3. Order matters!! (e.g. A::g())
4. Functions or classes can be defined either inside (e.g. g()) or outside (e.g. f()) “namespace {...}.

Summary #2: Declare, Define, & Use

- If something is declared, but not defined or used, that is fine. (Compilation warning)
- If something is used before it is defined or declared ➔ compile (undefined) error.
- If something is defined in other file, you can use it only if you forward declare it in this file. BUT you cannot define it again in this file ➔ compile (redefined) error.
  - Variable ➔ "extern"
  - Function ➔ prototype, with or without "extern"
- If something is declared, but not defined, in this file, you can use it and the compilation is OK. BUT if it is not defined in any other file ➔ linking (undefined) error.

Key Concept #17: #define

- #define is another compiler preprocessor
  - All the compiler preprocessors start with "#"
- "#define" performs pre-compilation inline string substitution
- "#define" has multiple uses in C++
  1. Define an identifier (e.g. #define NDEBUG)
  2. Define a constant (e.g. #define SIZE 1024), or substitute a string
  3. Define a function (Macro)

Practice #5

- Define two header files as:
  [a.h]
  ```
  class A { };
  ```
  [b.h]
  ```
  #include "a.h"
  class B { A _a; };
  ```
- Define p5.cpp as:
  ```
  #include "a.h"
  #include "b.h"
  int main() { A a; B b; }
  ```
  - Any compilation error? Why? How to fix it?

"#define" for an Identifier

1. To avoid repeated definition of a header file in multiple C/C++ inclusions
   - ```
     #ifndef MY_HEADER_H
     #define MY_HEADER_H
     // header file body...
     // ...
     #endif
     ```
2. Conditional compilation
   - ```
     #ifndef NDEBUG
     // Some code you want to compile by default
     // (i.e. debug mode)
     // For optimized mode,
     // define "NDEBUG" in Makefile.
     #endif
     ```

“#define” for a Constant or a String

- #define <identifier> [tokenString]
  - e.g.

```
#define SIZE          1024
#define CS_DEFAULT    true
#define HOME_DIR      "/home/ric"
            (why not /home/ric?)
```

- Advantage of using “#define”
  - Correct once, fix all
- What’s the difference from “const int xxx”, etc?
  - Remember: “#define” performs pre-compilation inline string substitution
  - “const int xxx” is a global variable
    ➔ Fixed memory space
    ➔ Better for debugging!!

“#define” for a MACRO function

- #define <identifier>(<argList>) [tokenString]
  - e.g.
    #define MAX(a, b) ((a > b)? a: b)
    // Why not “((a > b)? a: b)” ?
  - e.g.
    // Syntax error below!! Why??
    #define MAX(int a, int b) ((a > b)? a: b)
- Disadvantage
  - “#define” MACRO function is difficult to debug!!
    ➔ Cannot step in the definition (Why??)
  - Use inline function (i.e. inline int max(int a, int b)) instead

Part III: More on "Classes"

- Class, struct, union, enum
- Bit-slicing
- Class wrapper
- "static" keyword

Key Concept #1: "struct" in C++

- [Note] "struct" is a C construct used for "record type" data
  - Very similar to "class" in C++, but in C, there is no private/public, nor member function, etc.
- However, "struct" in C++ inherits all the features of the "class" construct
  - Can have private/public, member functions, and can be used with polymorphism
  - The only difference is: the default access privilege for "struct" is public

Key Concept #2: "union" in C++

- At any given time, contains only one of its data members
  - To avoid useless memory occupation
  - i.e. data members are mutual exclusive
    - Use "union" to save memory
  - size = *max(size of its data members)*
- A limited form of "class" type
  - Can have private/public/protected, data members, member functions
    - default = public
  - Can NOT have inheritance or static data member

Example of "union"

```
union U
{
 private:
   int  _a;
   char _b;
 public:
   U() { _a = 0; }
   int getA() const
       { return _a; }
   void setA(int i)
       { _a = i; }
   char getB() const
       { return _b; }
   void setB(char c)
       { _b = c; }
};
```

```
int
main()
{
   U u;
   u.setB('a');
   cout << u.getA()
        << endl;
   return 0;
}
```

- What is the output???

Anonymous union

- Union can be declared anonymously
  - i.e. Omit the type specifier
- `main()`

```
main()
{
   union {
      int    _a;
      char   _b;
   };
   int  i = _a;
   char j = _b;
}
```

➔ used as non-union variables
➔ What if it is NOT anonymous?

```
class A {
   union T {
      int    _a;
      double _b;
   };
   T _t;
   void f() {
      if (_t._a >
   10)...
   }
};
```


Key Concept #3: Another ways to save memory: memory alignment and bit slicing

- Note: in 64-bit machine, data are 8-byte aligned
  What are "sizeof(A)" below ?
  - class A { char _a; };
  - class A { int _i; bool _j; int* _k; }
  - class A { int _i; bool _j; int* _k; char _l; }
- Recommendation
  - Pack the data in groups of "sizeof(void*)", or ---
  - Use bit-slicing to save memory

```
class A {
   int _id: 30;
   int _gender: 1;
   int _isMember: 1;
   void f() { if (_isMember) _id += ...; }
};
```

How about bit-slicing for pointers?

- No, size of pointers is fixed. You cannot bit slice them.
- One "tricky" way to save memory is to use the fact that pointer addresses are multiple of 8's (for 64-bit machines)

```
#define BDD_EDGE_BITS     3
#define BDD_NODE_PTR_MASK
       ((~(size_t(0)) >>
         BDD_EDGE_BITS) <<
         BDD_EDGE_BITS)
class BddNode {
private:
   size_t       _nodeV;
   // Private functions
   BddNodeInt* getBddNodeInt()
   const {    return
      (BddNodeInt*)(_nodeV &
       BDD_NODE_PTR_MASK); }
```

```
   bool isNegEdge() const {
      return (_nodeV &
              BDD_NEG_EDGE); }
};

class BddNodeInt
{
   BddNode        _left;
   BddNode        _right;
   size_t         _level    : 32;
   size_t         _refCount : 31;
   size_t         _visited  : 1;
};
```


Practice #6

- Define a `class N` as:
  [a.h]
  ```
  class N {
     void *_p;
  public:
     N(void*p): _p(p) {}
  };
  ```
  - Instantiate two objects `n1, n2` of `class N` with some pointers.
  - Define a function "`void setMark()`" that uses the LSB of `N::_p` to record the object is "marked".
  - Define a function "`bool checkMark() const`" that check whether this object is marked.
  - Define a function "`void* getPtr() const`" that returns a valid pointer for `N::_p` (that is, a pointer address without the mark bit).
  - Use `n1, n2` to play around the above functions.

A Closer Look at the Previous Example

```
class BddNode {  // wrapper class for BddNodeInt
private:
   size_t       _nodeV;
};
class BddNodeInt {  // as pointer variables
   …
};
```

- Important concepts:
  - No extra memory usage when wrapping a pointer variable with a class
  - However, you gain the advantages in using constructor/destructor, operator overloading, etc, which are not applicable for pointer type variables.
    ➔ BddNode a, b, c;… ; c = a & b;
  - The LSBs can be used as flags or stored other information.

Summary #2: "class", "struct", & "union"

- In C++, data members are encapsulated by the keywords "private" and "protected"
  - Make the interface between objects clean
    - Reduce direct data access
  - Using member functions: correct once, fix all
- Struct and class are basically the same, except for their default access privilege
- Union: no *inheritance* nor *static* data member

	class	struct	union
Default access	private	public	public

- Enum: user-defined type for named constants

Key Concept #4: Enum

- A user-defined type consisting of a set of named constants called enumerators
  - e.g.

```
class T {
   enum COLOR {
      RED,        // value = 0
      BLUE,       // value = 1
      GREED = 5,
      YELLOW      // value = 6
   };
};
```

- By default, first enumerator's value = 0
- Each successive enumerator is one larger than the value of the previous one, unless explicitly specified (using "=") with a value

Scope of "enum"

- Enumerators are only valid within the scope it is defined
  - e.g.

```
class T {
  enum COLOR { RED, BLUE };
};
```

    ➔ RED/BLUE is only seen within T
  - To access enumerator outside of the class, use explicit class name qualification
    - e.g. void f() { int i = T::RED; }

    ➔ But in this case, the enum must be defined as *public*

Common usage of "enum"

1. Used in function return type
   - Color getSignal() { ... }
2. Used as "status" and controlled by "switch-case"
   - ```
     ProcState f() { ...; return ...; }
     ...
     ProcState state = f();
     switch (state) {
        case IDLE   : ...; break;
        case ACTIVE: ...; break;
     }  // What's the advantage??
     ```
3. Used as "bit-wise" mask

Bitwise Masks

- To manipulate multiple control "flags" in a single integer
- ```
  enum ErrState {
     NO_ERROR  = 0,
     DIV_ZERO  = 0x1, // 001
     OVERFLOAT = 0x2, // 010
     INTERRUPT = 0x4, // 100
     BAD_STATUS= DIV_ZERO | OVERFLOAT |
  INTERRUPT
  };
  int ~~ErrState~~ status = NO_ERROR; // This line is OK
  // To set the error status
  status |= OVERFLOAT;
  // To unset the error status
  status &= ~DIV_ZERO;
  // To test the error status
  if ((status & INTERRUPT) != 0)
     ...
  ```
  ➔ Compilation error... WHY???

Key Concept #5: “#define” vs. “enum”

```
1. #define RED    0
   #define BLUE   1
   #define GREEN  5
2. enum COLOR {
      RED,       // value = 0
      BLUE,      // value = 1
      GREED = 5
   };
```

- What’s the difference in terms of debugging?
  - Using “#define” ➔ Can only display “values”
  - Using “enum” ➔ Can display “names”

  Recommendation: using “enum”

Practice #7

- Write a .cpp file and compile it with “-g” flag (debugging)

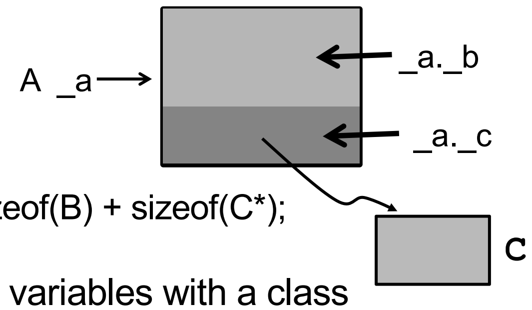
```
#define RED    0
#define BLUE   1
#define GREEN  5
int main() {
   int color = RED;
   cout << color << endl;
}
```

- Use debugger (gdb/lldb) to debug this file
  - r(run), b(set break point), p(print)
  - What’s the value of “color” you see?
- Change the #define to enum. Try again. What’s the difference?

Recall: Size of a Class

◆ The size of a class (object) is equivalent to the summation of the sizes of its data members

```
class A {
   B   _b;
   C  *_c;
};
```



➔ sizeof(A) = sizeof(B) + sizeof(C*);

◆ Wrapping some variables with a class definition DOES NOT introduce any memory overhead!!

Key Concept #6: Class Wrapper

1. To create a “record” type with a cleaner <u>interface</u>
   - e.g. When passing too many parameters to a function, creating a class to wrap them up.
   - ➔ Making sure data integrity (checked in constructor)
   - ➔ Creating member functions to enact assumptions, constraints, etc.

Key Concept #6: Class Wrapper

2. To manage the memory allocation/deletion of pointer variables
   - Recap: pointer data member will not be explicitly constructed in class constructor
   - Memory allocation/deletion problems for pointer variables
     - There may be many pointer variables pointing to the same piece of heap memory
     - The memory should NOT be freed until the "last" pointer variable become useless (HOW DO WE KNOW!!?)
     - What about the pointer (re-)assignment?
   - Recap: The memory of an object variable is allocated when entering the scope, and released when getting out.
   - Recap: The heap memory must be explicitly allocated and deleted.

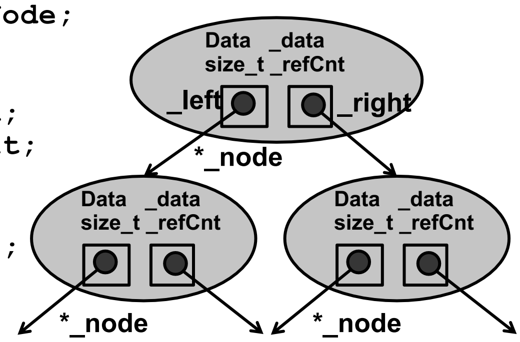
Object-Wrapped Pointer Variables

If your program contains pointer-pointed memory that is highly shared among different variables

◆Keep the reference count

◆Pointer → internal class (e.g. class NodeInt)
Object → user interface (e.g. class Node)

```
class NodeInt {     // a private class
   friend class Node;
   Data     _data;
   Node     _left;
   Node     _right;
   size_t   _refCnt;
};
class Node {
   NodeInt *_node;
};
```



Object-Wrapped Pointer Variables

```
Node::Node(...) {
   ...
   if (!_node) _node = newNode(...);
   _node->increaseRefCnt();
}
Node::~Node() { resetNode(); }
Node::resetNode() {
   if (_node) {
      _node->decreaseRefCnt();
      if (_node->getRefCnt() == 0) delete _node;
   }
}
Node& Node::operator = (const Node& n) {
   resetNode();
   _node = n._node;
   _node->increaseRefCnt();
}
```


Key Concept #6: Class Wrapper

3. To keep track of certain data/flag changes and handle complicated exiting/exception conditions

```
void f() {
   x1.doSomething();
   if (...) x2.doSomething();
   else { x1.undo(); return; }
   ...
   x2.undo(); x1.undo();
}
➔Very easy to miss some actions...
void f() {
   XKeeper xkeeper; // keep a list in xkeeper
   xkeeper.doSomething(x1);
   if (...) xkeeper.doSomething(x2);
   else return;
}  // ~XKeeper() will be called
```

Key Concept #7: “static” in C++

- As the word “static” suggests, “static xxx” should be allocated, initialized and stay unchanged throughout the program
  ➔ Resides in the “fixed” memory

However,

- The keyword “static” is kind of overloaded in C++

1. Static variable in a file
2. Static variable in a function
3. Static function
4. Static data member of a class
5. Static member function of a class

So, what does “static” mean anyway?

- “static” here,
  refers to “memory allocation” (storage class)
  - The memory of “static xxx” is allocated before the program starts (i.e. in fixed memory), and stays unchanged throughout the program

  [cf] “auto” storage class
    - Memory allocated is controlled by the execution process (e.g. local variables in the stack memory)

Key Concept #8: Visibility of “static” variable and function

1. Static variable in a file
   - It is a file-scope global variable
   - Can be seen throughout this file (only)
   - Variable (storage) remained valid in the entire execution
2. Static variable in a function
   - It is a local variable (in terms of scope)
   - Can be seen only in this function
   - Variable (storage) remained valid in the entire execution
3. Static function
   - Can only be seen in this file

◆ Static variables and functions can only be seen in the defined scope
   - Cannot be seen by other files
   - No effect by using “extern”

[Note] Storage class vs. visible scope

◆ Remember, “static” refers to static “memory allocation” (storage class)
   - We’re NOT talking about the “scope” of a variable

◆ The scope of a variable is determined by where and how it is declared
   - File scope (global variable)
   - Block scope (local variable)

➔ However, the “static” keyword does constrains the maximum visible scope of a variable or function to be the file it is defined

Key Concept #9:
"static" Data Member in a Class

- Only one copy of this data member is maintained for all objects of this class
  - All the objects of this class see the same copy of the data member (in fixed memory)
  - (Common usage) Used as a counter

```
class T
{
   static int _count;
public:
   T() { _count++; }
   ~T() { _count--; }
};
------------------------------------------------
int T::_count=0;
// Static data member must be initialized in some
//     cpp file ==> NOT by constructor!!!  (why?)
```


Key Concept #10:
"static" Member Function in a Class

- Useful when you want to access the "static" data member but do not have a class object
  - Calling static member function without an object
    - e.g. T::setGlobalRef();
  - No implicit "this" argument (no corresponding object)
  - Can only see and use "static" data members , enum, or nested types in this class
    - Cannot access other non-static data members
- Usage
  - T::staticFunction(); // OK
  - object.staticFunction(); // OK
  - T::staticFunction() { ... staticMember... } // OK
  - T::staticFunction() { ... this... } // Not OK
  - T::staticFunction() { ... nonStaticMember... } // Not OK
  - T::nonstaticFunction() { ... staticMember... } // OK

Example of using “static” in a class

```
class T
{
   static unsigned    _globalRef;
   unsigned           _ref;

public:
   T() : _ref(0) {}
   bool isGlobalRef(){ return (_ref == _GlobalRef); }
   void setToGlobalRef(){ _ref = _global Ref; }
   static void setGlobalRef() { _globalRef++; }
}
```

- Use this method to replace “setMark()” functions in graph traversal problems
(How??)

Practice #8

- Define a `class N` and N_ as:

```
class N {
   N_  *_n;
public:
   N(): _n(0) {}
   void gen();
   void statistics() const;
};
class N_ {
   friend class N;
   size_t    _d[1 << 17];  // 1MB
   unsigned  _refCnt;
   N         _child1;
   N         _child2;
   N_(): _refCnt(0) {}
};
```

- Define a global variable:

```
N_* nList[1 << MAX_DEPTH] = {0};
```

- In `main()`, do:

```
srandom(getpid());
N root;
root.gen();
root.statistics();
```

Practice #8 (cont'd)

- The behavior of `N::gen()` is as follows:
  - Assert `_n == 0`.
  - Generate a random number "`i`" in [0, 1 << MAX_DEPTH)
  - If (`nList[i] == 0`)
    - Create a new `N_*` and assign it to `_n`.
    - Increase its `_refCnt` and assign it to `nList[i]`.
    - For each of its children, recursive call `_child.gen()`.
  - Else // if (`nList[i] != 0`)
    - Let `_n = nList[i]`.
    - Increase its `_refCnt`.
- The behavior of `N::statistics()` is as follows:
  - Define `maxRef` to be the maximum number of `_refCnf` for all the nodes in `nList[]`.
  - For `i = 0 to maxRef`, print out the number of nodes in `nList[]` whose `_refCnf == i`.
  - The sample output is as:

```
Ref[0] = 52830     (20.2%)
Ref[1] = 85249     (32.5%)
Ref[2] = 67460     (25.7%)
...
```


Key Concept #11: static_cast<T>(a)... Cast away static?? ☹

- Convert object "a" to the type "T"
  - No consistency check (i.e. sizeof(T))
    - ➔ static implies "compile time"
    - ➔ May not be safe
    - ➔ cf. dynamic_cast<T>(a)
  - (Common use) // more safer use
    // Parent-class pointer object wants to
    //   call the child-only method

```
class Child : public Dad { ... };
----------------------------------
void f()
{
   Dad* p = new Child;
   ...
   static_cast<Child *>(p)->childOnlyMethod();
};
```