Part III
Synchronization
A bit of C++ and ThreadMentor

I don’t know what the programming language of the year 2000 will look like, but I know it will be called FORTRAN.

Charles Anthony Richard Hoare
iostream and namespace

- Include `iostream` for input/output.
- Then, add `using namespace std;`

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

int main(...) {
    // other C/C++ statements
}
```
**Input with `cin` and `>`>

- Use `cin` and `>` to read from `stdin`.
- For example, `cin >> n` reads in a data item from `stdin` to variable `n`.
- One more example: `cin >> a >> b` reads in two data items from `stdin` to variables `a` and `b` in this order.
- Thus, `cin` is easier to use than `scanf`.
Output with `cout` and `<<` : 1/2

- Use `cout` and `<<` to write to `stdout`.
- For example, `cout << n` writes the content of variable `n` to `stdout`.
- One more example: `cout << a << b` writes the values of variables `a` and `b` to `stdout` in this order.
- Thus, `cout` is easier to use than `printf`.
- Formatted output with `cout` is very tedious.
Output with `cout and `\n` : 2/2

- The `\n` is `endl`: `cout `\n` prints the value of `a` and follows by a newline.
- You may want to add spaces to separate two printed values.
- `cout `\n` is better than `cout `\n`.
#include <iostream>

using namespace std;

int main(void) {
    cout << "Hello, world." << endl;
    return 0;
}
#include <iostream>
using namespace std;

int main(void)
{
    int i, n, factorial;

    cout << "A positive integer --> ";
    cin >> n;
    factorial = 1;
    for (i = 1; i <= n; i++)
        factorial *= i;
    cout << "Factorial of " << n << " = " << factorial << endl;
    return 0;
}
What Is a class?

- A class is a type similar to a struct; but, a class type normally has member functions and member variables.

```cpp
class Sum_and_Product
{
  public:
    int a, b;
    void Sum(), Product();
    void Reset(int, int), Display();
  private:
    int MySum, MyProduct;
};
```
Constructors : 1/2

- Constructors are member functions and are commonly used to initialize member variables in a class.
- A constructor is called when its class is created.
- A constructor has the same name as the class.
- A constructor definition cannot return a value, and no type, not even void, can be given at the beginning of the function or in the function header.
Constructors : 2/2

- Constructors are commonly used to initialize member variables in a class.

```cpp
class MyClass
{
    public:
        MyClass(int n); // constructor
        // ...
    }
MyClass::MyClass(int Input) // function
{
    // ...
}
```
Member Functions

- Member functions are just functions.

```cpp
class MyClass
{
    public:
        MyClass(int n);  // constructor
        void Display(...); // member function
        // ...
};
```

```cpp
MyClass::Display(...) // function
{
    // .....
```cpp
#include <iostream>

using namespace std;

class MyAccount
{
    public:
        MyAccount(int Initial_Amount); // constructor
        int Deposit(int);             // member funct
        int Withdraw(int);            // member funct
        void Display(void);          // member funct

    private:
        int Balance; // private variable

};
```
Example: 2/5

```cpp
MyAccount::MyAccount(int initial)    // constructor initialization
{
    Balance = initial;
}

int MyAccount::Deposit(int Amount)
{
    cout << "Deposit Request = " << Amount << endl;
    cout << "Previous Balance = " << Balance << endl;
    Balance += Amount;
    cout << "New Balance = " << Balance << endl;
    return Balance;
}
```
int MyAccount::Withdraw(int Amount)
{
    cout << "Withdraw Request = " << Amount << endl;
    cout << "Previous Balance = " << Balance << endl;
    Balance -= Amount;
    cout << "New Balance = " << Balance << endl;
    return Balance;
}

void MyAccount::Display(void)
{
    cout << "Current Balance = " << Balance << endl;
}
int main(void)
{
    MyAccount NewAccount(0); // initial new account

    NewAccount.Display(); // display balance
    NewAccount.Deposit(20); // deposit 20 (Bal=20)
    NewAccount.Deposit(35); // deposit 35 (Bal=55)
    NewAccount.Withdraw(40); // withdraw 40 (Bal=15)
    NewAccount.Display(); // current balance
    return 0;
}
The `new` operator creates an object and returns a pointer to it. It is similar to `malloc()` in C. Use `delete` to deallocate.
Constructors: The Initialization Section

- There is a faster way, actually maybe a preferable way, to initialize member variables.

```cpp
class Numbers
{
  public:
    int Lower, Upper;
    Numbers(int a, int b);  // constructor
    // ...
};

Numbers::Numbers(int a, int b)
    : Lower(a), Upper(b)  // init. section
{  // function body is empty
}
```
Derived Classes: 1/6

- Deriving a class from an existing one is called **inheritance** in C++.
- The newly created class is a **derived** class and the class from which the derived class is created is a **base** class.
- The constructor (and destructor) of a base class is not inherited.
A derived class is just a class with the following syntax:

```cpp
class derived-class-name : public base-class-name
{
    public:
    // public member declarations
    derived-class-constructor();
    private:
    // private member declarations
};
```
class Base
{
    public:
        int  a;
        Base(int \texttt{x=10}):a(x)  // use \texttt{x} to init \texttt{a}
            { cout \texttt{<< "Base has " << a \texttt{<< endl;} } }
};

class Derived: public Base
{
    public:
        int x;
        Derived(int \texttt{m=20}):x(m)  // use \texttt{m} to init \texttt{x}
            { cout \texttt{<< "Derived has " << x \texttt{<< endl;} } }
};
int main(void)
{
    Base    X, *XX;
    Derived Y, *YY;

    cout << "Base's value    = " << X.a << endl;
    cout << "Derived's value = " << Y.x << endl;
    cout << endl;

    XX = new Base(123);

    YY = new Derived(789);

    cout << "Base's value    = " << XX->a << endl;
    cout << "Derived's value = " << YY->x << endl;

    return 0;
}
class Base
{
    public:
    int    a;
    char  name[100];
    Base(int);
};

Base::Base(int x = 10) : a(x)
{
    char  buffer[10];
    strcpy(name, "Class");    // requires string.h
    sprintf(buffer, "%d", a); // requires stdio.h
    strcat(name, buffer);     // requires string.h
    cout << "Base has " << a << ' ' << name << endl;
}
class Derived: public Base
{
    public:
        Derived(int m=20): Base(m) {} 
};

int main(void)
{
    Base     X(23);
    Derived  Y(789);
    cout << "Base's name    = " << X.name << endl;
    cout << "Derived's name = " << Y.name << endl;
    return 0;
}
Normally, the specification part and the implementation part of a class are saved in `.h` and `.cpp` files, respectively.

```cpp
class MyAccount
{
    public:
        MyAccount(int Initial_Amount);
        int Deposit(int);
        int Withdraw(int);
        void Display(void);

    private:
        int Balance;
};
```
```cpp
#include <iostream>
#include "MyAccount.h"

using namespace std;

MyAccount::MyAccount(int initial)
    : Balance(initial)
{ /* function body is empty */ }

int MyAccount::Deposit(int Amount)
{
    cout << "Deposit Request = " << Amount << endl;
    cout << "Previous Balance = " << Balance << endl;
    Balance += Amount;
    cout << "New Balance = " << Balance << endl << endl;
    return Balance;
}
// other member functions
```
```cpp
#include <iostream>
#include "MyAccount.h"

using namespace std;

int main(void)
{
    MyAccount *NewAccount;

    NewAccount = new MyAccount(0);
    NewAccount->Display();
    NewAccount->Deposit(20);
    NewAccount->Deposit(35);
    NewAccount->Withdraw(40);
    NewAccount->Display();
    return 0;
}
```
Now we have the specification file `MyAccount.h`, the implementation file `MyAccount.cpp`, and the main program `account-3.cpp`.

Compile the whole thing this way

```
g++ MyAccount.cpp account-3.cpp -o account-3
```

Or, we may compile `MyAccount.cpp` to `MyAccount.o` and use it later:

```
g++ MyAccount.cpp -c
```

```
g++ account-3.cpp MyAccount.o -o account-3
```
ThreadMentor Basics
**ThreadMentor Architecture**

- *ThreadMentor* consists of a class library and a visualization system.

- The class library provides all mechanisms for thread management and synchronization primitives.

- The visualization system helps visualize the dynamic behavior of multithreaded programs.
ThreadMentor Architecture
Basic Thread Management

- **Thread creation**: creates a new thread
- **Thread termination**: terminates a thread
- **Thread join**: waits for the completion of another thread
- **Thread yield**: yields the execution control to another thread
- **Suspend/Resume**: suspends or resumes the execution of a thread.
How to Define a Thread?

- A thread should be declared as a derived class of `Thread`.
- All executable code must be in function `ThreadFunc()`.
- A thread may be assigned a name with a constructor.
- Method `Delay()` may be used to delay the thread execution for a random time.

```cpp
#include "ThreadClass.h"

class test : public Thread
{
   public:
      test(int i){n=i;};
   private:
      int n;
   void ThreadFunc(int);
};

void test::ThreadFunc(int n)
{
   Thread::ThreadFunc();
   for (int i=0; i<10; i++)
      cout << n << i << endl;
   // other stuffs

   // may not be thread safe!
```
Create and Run a Thread

- Declare a thread just like declaring an `int` variable.
- Then, use method `Begin()` to run a thread.

```c
int main(void)
{
    test* Run[3];
    int   i;
    for (i=0; i<3; i++) {
        Run[i] = new test(i) ;
        Run[i]->Begin() ;
    }

    // other stuffs
}
```
A Few Important Notes

- Before calling method `Begin()`, the created thread **does not** run.
- Function `ThreadFunc()` **never** returns. When it reaches the end or executes a return, it **disappears**!
- Do not use `exit()`, as it terminates the whole system. See next slide.
Terminating a Thread

- Use method `Exit()` of the thread class `Thread`.
- Do not use system call `exit()` as it terminates the whole program.

```cpp
void test::ThreadFunc(int n)
{
    Thread::ThreadFunc();

    for (int i=0; i<10; i++)
        cout << n << i << end;
    Exit();  // terminates
}
```
Thread Join

- Sometimes, a thread must wait until the completion of another thread so that the results computed by the latter can be used.

- The parent must wait until all of its child threads complete. Otherwise, when the parent exits, all of its child threads exit.
The Join() Method

- Use the `Join()` method of a thread to join with that thread.

- Suppose thread A must wait for thread B’s completion. Then, do the following in thread A:
  
  ```
  B->Join()
  ```

  or

  ```
  B.Join()
  ```
Thread Join Semantics

Suppose thread A wants to join with thread B, we have two cases:

1. If A reaches the `Join()` call before B exits, A waits until B completes.
2. If B exits before A can reach the `Join()` call, then A continues as if there is no `Join()`.
A Simple Example

```cpp
#include "ThreadClass.h"

class test : public Thread
{
    public:
        test(int i){n = i;};
    private:
        int n;
        void ThreadFunc();
};

void test::ThreadFunc(int n)
{
    Thread::ThreadFunc();
    for (int i=0; i<10; i++)
        cout << n << i << endl;
    Exit();
}

int main(void)
{
    test* Run[3];
    for (int i=0; i<3; i++)
    {
        Run[i] = new test(i);
        Run[i]->Begin();
    }
    for (i = 0; i<3; i++)
    {
        Run[i]->Join();
        Exit();
    }
    return 0;
}
```

May not be thread safe.
Why?
Threaded Quicksort: 1/3

- In each recursion step, the quicksort cuts the given array segment \( a[L:U] \) into two with a pivot element \( a[M] \) such that all elements in \( a[L:M-1] \) are less than \( a[M] \) and all elements in \( a[M+1:U] \) are greater than \( a[M] \). Then, \( a[L:M-1] \) and \( a[M+1:U] \) are sorted independently and recursively.

- Since \( a[L:M-1] \) and \( a[M+1:U] \) are sorted independently, we may use a thread for each segment!
Threaded Quicksort: 2/3

- A thread receives the array segment \( a[L:U] \) and partitions it into \( a[L:M-1] \) and \( a[M+1:U] \).
- Then, creates a thread to sort \( a[L:M-1] \) and a second thread to sort \( a[M+1:U] \).
Threaded Quicksort: 3/3

Thus, our strategy looks like the following:

1. A thread receives array \( a[L:R] \).
2. It finds the pivot element \( a[M] \).
3. Creates a child thread and provides it with \( a[L:M-1] \).
4. Creates a child thread and provides it with \( a[M+1:R] \).
5. Issues two thread \( \text{Join}() \) s waiting for both child threads.
Class Quicksort: Definition

class Quicksort : public Thread
{
public:
    Quicksort(int L, int U, int a[]);
private:
    int  low;
    int  up;
    int  *a;
    void ThreadFunc();
};

quicksort.h
Class **Quicksort**: Implementation

```cpp
Quicksort::Quicksort(int L, int U, int A[]) : low(L), up(U), a(A)
{
    ThreadName = // set a thread name;
}

Void Quicksort::ThreadFunc()
{
    Thread::ThreadFunc(); // required
    Quicksort *Left, *Right;
    int             M;
    M = // compute the pivot element;
    Left = new Quicksort(low, M-1, a); Left->Begin();
    Right = new Quicksort(M+1, up, a); Right->Begin();
    Left->Join(); Right->Join();
    Exit();
}
```

The main program is easy:

```c
int main(void)
{
    Quicksort *thread;
    int a[MAXSIZE], L, U, n;
    // read in array a[] and # of elements n
    L = 0; U = n-1;
    thread = new Quicksort(L, U, a);
    thread->Begin();
    thread->Join();
    Exit();
}
```

`quicksort-main.cpp`
What If We Have the Following?

Quicksort::Quicksort(int L, int U, int A[])
: low(L), up(U), a(A)
{
    ThreadName = // set a thread name;
}

Void Quicksort::ThreadFunc()
{
    Thread::ThreadFunc();
    Quicksort *Left, *Right;
    int M;
    M = // compute the pivot element;
    Left = new Quicksort(low, M-1, a);
    Left->Begin();  // Left->Join();
    Right = new Quicksort(M+1, up, a);
    Right->Begin();  // Right->Join();
    Exit();
}

Join() are moved to right after Begin(). Is this a correct program? Does it fulfill the maximum concurrency requirement?
Compilation with ThreadMentor

- **ThreadMentor** adds all visualization features in its class library so that you don’t have to do anything in your program to use visualization.

- But, you need to recompile your program properly so that a correct library will be used.

- There are two versions of **ThreadMentor** library: Visual and non-Visual.
Makefile for ThreadMentor: 1/4

CC = c++
CFLAGS = -g -O2
DFLAGS = -DPACKAGE="threadsystem"
RFLAGS = -I/local/eit-linux/apps/ThreadMentor/include
TMLIB = /local/eit-linux/apps/ThreadMentor/Visual/
TMLIB_NV = /local/eit-linux/apps/ThreadMentor/NoVisual/

OBJ_FILE = quicksort.o quicksort-main.o
EXE_FILE = quicksort

Define some names.
Don’t touch this portion.

visual library

This is the executable file
List the .o files here

non-visual library
Makefile for ThreadMentor: 2/4

```bash
${EXE_FILE}: ${OBJ_FILE}
${CC} ${FLAGS} -o ${EXE_FILE} ${OBJ_FILE} ${TMLIB} -lpthread

quicksort.o: quicksort.cpp
   ${CC} ${DFLAGS} ${IFLAGS} ${CFLAGS} -c quicksort.cpp

quicksort-main.o: quicksort-main.cpp
   ${CC} ${DFLAGS} ${IFLAGS} ${CFLAGS} -c quicksort-main.cpp

noVisual: ${OBJ_FILE}
   ${CC} ${FLAGS} -o ${EXE_FILE} ${OBJ_FILE} ${TMLIB_NV} -lpthread

clean:
   rm -f ${OBJ_FILE} ${EXE_FILE}
```

generate executable file with visual

open tab

generate executable file without visual

clean up
By default, the above Makefile generates executable with visual. The following generates executable quicksort:

```
make
```

If you do not want visualization, use the following:

```
make noVisual
```

To clean up the .o and executable files, use

```
make clean
```
Makefile for ThreadMentor: 4/4

- Add the following line to your .cshrc, which is in your home directory. Then, logout and login again to make it effective:

```bash
set path=($path /local/eit-linux/apps/ThreadMentor/bin)
```

- More **ThreadMentor** examples are available at the **ThreadMentor** tutorial site:

The End