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 tedious.
The \n is \texttt{endl}: \texttt{cout} \texttt{\lll a \lll endl} prints the value of \texttt{a} and follows by a newline.

You may want to add spaces to separate two printed values, in particular between two strings.

The formatted output depends on some default setting of a system.

\texttt{cout \lll a \lll \ \ \lll b \lll endl} is better than \texttt{cout \lll a \lll \lll b \lll endl}.
#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 \textbf{cannot} return a value, and no type, not even \texttt{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
        // ...
};
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
};
```
MyAccount::MyAccount(int initial) {
    Balance = initial;  // constructor initialization
}

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;
}
Example: 4/5

```cpp
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;
}
```
Example: 5/5

```cpp
int main(void)
{
    MyAccount *NewAccount;        // use pointer

    NewAccount = new MyAccount(0); // create account
    NewAccount->Display();         // now use ->
    NewAccount->Deposit(20);
    NewAccount->Deposit(35);
    NewAccount->Withdraw(40);
    NewAccount->Display();
    return 0;
}
```

This version uses a pointer.
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
};
```
Derived Classes: 3/6

class Base
{

    public:
    
        int a;

        Base(int x=10):a(x)  // use x to init a
        
            { cout << "Base has " << a << endl; } 

};

class Derived: public Base
{

    public:
    
        int x;

        Derived(int m=20):x(m)  // use m to init x

            { cout << "Derived has " << x << endl; } 

};
```cpp
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 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;
    }
};

This is not the best way; but, it works!
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 \texttt{.h} and \texttt{.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

- C++ User Program
- Synchronization
- Thread Kernel
  - Win32
  - Solaris
  - Pthread
  - mtuThread

Visualization
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 $\text{Join()}$ call before $B$ exits, $A$ waits until $B$ completes.
2. If $B$ exits before $A$ can reach the $\text{Join()}$ call, then $A$ continues as if there is no $\text{Join()}$. 
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();
}

test* Run[3];

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

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:

2. It finds the pivot element $a[M]$.
3. Creates a child thread and provides it with $a[L:M-1]$.
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();
};
```
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?

```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();
    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 implicitly 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.

- This **Makefile** is in the common directory.
**Makefile for ThreadMentor: 1/4**

Define some names. Don’t touch this portion.

- **CC** = `c++`
- **FLAGS** = `-no-pie`
- **CFLAGS** = `-g -O2 -Wno-write-strings -Wno-cpp -w`
- **DFLAGS** = `-DPACKAGE="threadsystem"` ......
- **IFLAGS** = `-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`

These two flags eliminate the most common warning messages related to ThreadMentor.

- Eliminate ALL warning messages.
- Add this one when you submit.

This is the executable file. List the `.o` files here.
${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}
By default, the above Makefile generates executable with visual. The following generates executable quicksort:

```make
make
```

If you do not want visualization, use the following:

```make
make noVisual
```

To clean up the .o and executable files, use

```make
make clean
```
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:

Running ThreadMentor @ Home

Windows
- Install Putty and Xming
- Install VMware Workstation
- Install RedHat Linux
- Install ThreadMentor
- Do your work locally
- Move your files to CS account
- Test your program before submission

macOS
- Install VMware Fusion
- Install RedHat Linux
- Install ThreadMentor
- Do your work locally
- Move your files to CS account
- Test your program before submission

Linux
- Install ThreadMentor
- Move your files to CS account
- Test your program before submission

See the links under the “Programming Information” section
Not applicable to Apple Silicon M1 CPU computers
The End