Biostatistics 615/815 - Lecture 2
Introduction to C++ Programming

Hyun Min Kang

September 6th, 2012
Last Lecture

- Algorithms are sequences of computational steps transforming inputs into outputs
  - Insertion Sort
    - ✓ An intuitive sorting algorithm
    - ✓ Loop invariant property
    - ✓ $\Theta(n^2)$ time complexity
    - ✓ Slower than default sort application in Linux.
  - A recursive algorithm for the Tower of Hanoi problem
    - ✓ Recursion makes the algorithm simple
    - ✓ Exponential time complexity
- C++ Implementation of the above algorithms.
Recap

Recursion

Data Types

Syntax

Pointers

Summary

Fill missing steps below to complete homework 0

1. ssh uniqname@scs.itd.umich.edu
2. mkdir --p ~/Private/biostat615/hw0/
3. cd ~/Private/biostat615/hw0/
4. vi helloWorld.cpp (input the code)
5. （  
6. vi towerOfHanoi.cpp (input the code)
7. （  
8. rm *.o helloWorld towerOfHanoi
9. cd ../
10. tar czvf uniqname.hw0.tar.gz hw0/
11. scp
    uniqname@scs.itd.umich.edu:Private/biostat615/uniqname.hw0.tar.gz . (After logout)
Algorithm **INSERTIONSORT**

**Data:** An unsorted list $A[1 \cdots n]$

**Result:** The list $A[1 \cdots n]$ is sorted

**for** $j = 2$ **to** $n$ **do**

\[ key = A[j]; \]
\[ i = ( ); \]

**while** $i > 0$ **and** $A[i] > key$ **do**

\[ ( ) = ( ); \]
\[ i = i - 1; \]

**end**

\[ ( ) = key; \]

**end**
Today

- Hanoi Tower Example
- Basic Data Types
- Control Structures
- Pointers and Functions
- Fisher’s Exact Test
Next few lectures

- The class does NOT focus on teaching programming language itself
- Expect to spend time to be familiar to programming languages yourself

- VERY important to practice writing code on your own.
- Utilize office hours or after-class minutes for detailed questions in practice
Tower of Hanoi

Problem

Input
- A (leftmost) tower with \( n \) disks, ordered by size, smallest to largest
- Two empty towers

Output
Move all the disks to the rightmost tower in the original order

Condition
- One disk can be moved at a time.
- A disk cannot be moved on top of a smaller disk.

How many moves are needed?
A Working Example

http://www.youtube.com/watch?v=aGl2G-DC8c
Think Recursively

Key Idea

- Suppose that we know how to move \( n - 1 \) disks from one tower to another tower.
- And concentrate on how to move the largest disk.
Think Recursively

Key Idea

- Suppose that we know how to move $n - 1$ disks from one tower to another tower.
- And concentrate on how to move the largest disk.

How to move the largest disk?

- Move the other $n - 1$ disks from the leftmost to the middle tower
- Move the largest disk to the rightmost tower
- Move the other $n - 1$ disks from the middle to the rightmost tower
A Recursive Algorithm for the Tower of Hanoi Problem

**Algorithm `TOWEROFHANOI`**

**Data:** \( n \) : # disks, \((s, i, d)\) : source, intermediate, destination towers

**Result:** \( n \) disks are moved from \( s \) to \( d \)

```plaintext
if \( n == 0 \) then
    do nothing;
else
    TOWEROFHANOI(\( n - 1 \), \( s \), \( d \), \( i \));
    move disk \( n \) from \( s \) to \( d \);
    TOWEROFHANOI(\( n - 1 \), \( i \), \( s \), \( d \));
end
```
How the Recursion Works

(3, L, M, R)
How the Recursion Works

(2, L, R, M) → (3, L, M, R)
How the Recursion Works
How the Recursion Works

(0, L, R, M) → (1, L, M, R) → (2, L, R, M) → (3, L, M, R) → ...
How the Recursion Works

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(3,L,M,R)

(2,L,R,M)

(1,L,M,R)

(0,L,R,M)

(1,R,L,M)

(0,M,L,R)

Disk1
L -> R

Disk2
L -> M

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How the Recursion Works
How the Recursion Works

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How the Recursion Works
How the Recursion Works

```
(3, L, M, R)

(2, L, R, M)

(1, L, M, R)  (1, R, L, M)

(0, L, R, M)  (0, M, L, R)  (0, R, M, L)  (0, L, R, M)

Disk1
L -> R

Disk2
L -> M

Disk1
R -> M
```
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How the Recursion Works
Analysis of \textbf{TowerOfHanoi} Algorithm

\section*{Correctness}

- Proof by induction - Skipping

\begin{itemize}
\item \textbf{Proof by induction - Skipping}
\end{itemize}

\begin{itemize}
\item \textbf{Time Complexity}
\end{itemize}

\begin{itemize}
\item \textbf{T}(n): Number of disk movements required
\end{itemize}

\begin{itemize}
\item \textbf{T}(0) = 0
\item \textbf{T}(n) = 2T(n-1) + 1
\end{itemize}

\begin{itemize}
\item \textbf{T}(n) = 2^{n+1} - 1
\end{itemize}

\begin{itemize}
\item If \textbf{n} = 64 as in the legend, it would require \textbf{T}(64) = 2^{64} - 1 = 18,446,744,073,709,551,615 turns to finish, which is equivalent to roughly 585 billion years if one move takes one second.
\end{itemize}
Analysis of **TowerOfHanoi** Algorithm

### Correctness
- Proof by induction - Skipping

### Time Complexity
- \( T(n) \) : Number of disk movements required
  - \( T(0) = 0 \)
  - \( T(n) = 2T(n-1) + 1 \)
  - \( T(n) = 2^n - 1 \)
- If \( n = 64 \) as in the legend, it would require \( 2^{64} - 1 = 18,446,744,073,709,551,615 \) turns to finish, which is equivalent to roughly 585 billion years if one move takes one second.
#include <iostream>
#include <cstdlib>

// recursive function of towerOfHanoi algorithm
void towerOfHanoi(int n, int s, int i, int d) {
    if (n > 0) {
        towerOfHanoi(n-1,s,d,i); // recursively move n-1 disks from s to i
        std::cout << "Disk " << n << " : " << s << " -> " << d << std::endl;
        towerOfHanoi(n-1,i,s,d); // recursively move n-1 disks from i to d
    }
}

// main function
int main(int argc, char** argv) {
    int nDisks = atoi(argv[1]); // convert input argument to integer
    towerOfHanoi(nDisks, 1, 2, 3); // run TowerOfHanoi(n=nDisks, s=1, i=2, d=3)
    return 0;
}
Running TowerOfHanoi Implementation

Running towerOfHanoi

user@host:~/Private/biostat615/hw0$ ./towerOfHanoi 3
Disk 1 : 1 -> 3
Disk 2 : 1 -> 2
Disk 1 : 3 -> 2
Disk 3 : 1 -> 3
Disk 1 : 2 -> 1
Disk 2 : 2 -> 3
Disk 1 : 1 -> 3
Summary: Tower of Hanoi Problem

- **Recursion**: Simple definition using induction
  - Move the other $n - 1$ disks from the leftmost to the middle tower
  - Move the largest disk to the rightmost tower
  - Move the other $n - 1$ disks from the middle to the rightmost tower

- Digesting the concept can sometimes be tricky

- Exponential time complexity: $\Theta(2^n)$
Declaring Variables

Variable Declaration and Assignment

```c
int foo;  // declare a variable
foo = 5;  // assign a value to a variable.
int foo = 5;  // declaration + assignment
```
Declaring Variables

Variable Declaration and Assignment

```
int foo; // declare a variable
foo = 5; // assign a value to a variable.
int foo = 5; // declaration + assignment
```

Variable Names

```
int poodle; // valid
int Poodle; // valid and distinct from poodle
int my_stars3; // valid to include underscores and digits
int 4ever; // invalid because it starts with a digit
int double; // invalid because double is C++ keyword
int honky-tonk; // invalid -- no hyphens allowed
```
Basic Digital Units

**bit** A single binary digit number which can represent either 0 or 1.

**byte** A collection of 8 bits which can represent $2^{256} = 2^8$ unique numbers. One character can typically be stored within one byte.

**word** An ambiguous term for the natural unit of data in each processor. Typically, a word corresponds to the number of bits to represent a memory address. In 32-bit address scheme which can represent up to 4 gigabytes, 32 bits (4 bytes) are spent to represent a memory address. In 64-bit address scheme, up to 18 exabytes can be represented by using 64 bits (8 bytes) to represent a memory address.
Data Types

Signed Integer Types

```c
char foo;  // 8 bits (1 byte): -128 <= foo <= 127
short foo; // 16 bits (2 bytes): -32,768 <= foo <= 32,767
int foo;   // Mostly 32 bits (4 bytes): -2,147,483,648 <= foo <= 2,147,483,647
long foo;  // 32 bits (4 bytes): -2,147,483,648 <= foo <= 2,147,483,647
long long foo; // 64 bits
short foo = 0; foo = foo - 1;   // foo is -1
```
## Data Types

### Signed Integer Types

```plaintext
char foo;  // 8 bits (1 byte) : -128 <= foo <= 127
short foo; // 16 bits (2 bytes) : -32,768 <= foo <= 32,767
int foo;   // Mostly 32 bits (4 bytes) : -2,147,483,648 <= foo <= 2,147,483,647
long foo;  // 32 bits (4 bytes) : -2,147,483,648 <= foo <= 2,147,483,647
long long foo; // 64 bits
short foo = 0; foo = foo - 1;  // foo is -1
```

### Unsigned Integer Types

```plaintext
unsigned char foo; 8 bits (1 byte) : 0 <= foo <= 255
unsigned short foo; // 16 bits (2 bytes) : 0 <= foo <= 65,535
unsigned int foo;   // Mostly 32 bits (4 bytes) : 0 <= foo <= 4,294,967,295
unsigned long foo;  // 32 bits (4 bytes) : 0 <= foo <= 4,294,967,295
unsigned long long foo; // 64 bits
unsigned short foo = 0; foo = foo - 1;  // foo is 65,535
```
## Floating Point Numbers

### Comparisons

<table>
<thead>
<tr>
<th>Type</th>
<th>float</th>
<th>double</th>
<th>long double</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>Single</td>
<td>Double</td>
<td>Quadruple</td>
</tr>
<tr>
<td>Size</td>
<td>32 bits</td>
<td>64 bits</td>
<td>128 bits</td>
</tr>
<tr>
<td>(in most modern OS)</td>
<td>4 bytes</td>
<td>8 bytes</td>
<td>16 bytes</td>
</tr>
<tr>
<td>Sign</td>
<td>1 bit</td>
<td>1 bit</td>
<td>1 bit</td>
</tr>
<tr>
<td>Exponent</td>
<td>8 bits</td>
<td>11 bits</td>
<td>15 bits</td>
</tr>
<tr>
<td>Fraction</td>
<td>23 bits</td>
<td>52 bits</td>
<td>112 bits</td>
</tr>
<tr>
<td>(# decimal digits)</td>
<td>7.2</td>
<td>16</td>
<td>34</td>
</tr>
<tr>
<td>Minimum (&gt;0)</td>
<td>$1.2 \times 10^{-38}$</td>
<td>$2.2 \times 10^{-308}$</td>
<td>$3.4 \times 10^{-4932}$</td>
</tr>
<tr>
<td>Maximum</td>
<td>$3.4 \times 10^{38}$</td>
<td>$1.8 \times 10^{308}$</td>
<td>$1.2 \times 10^{4932}$</td>
</tr>
</tbody>
</table>
Recap
Recursion
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Pointers
Summary

Handling Floating Point Precision Carefully

```cpp
#include <iostream>

int main(int argc, char** argv) {
    float smallFloat = 1e-8; // a small value
    float largeFloat = 1.;   // difference in 8 (>7.2) decimal figures.
    std::cout << smallFloat << std::endl; // "1e-08" is printed
    smallFloat = smallFloat + largeFloat; // smallFloat becomes exactly 1
    smallFloat = smallFloat - largeFloat; // smallFloat becomes exactly 0
    std::cout << smallFloat << std::endl; // "0" is printed
    // similar thing happens for doubles (e.g. 1e-20 vs 1).
    return 0;
}
```

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Basics of Arrays and Strings

Array

```cpp
int A[] = {3, 6, 8}; // A[] can be replaced with A[3]
std::cout << "A[0] = " << A[0] << std::endl; // prints 3
```

String as an array of characters

```cpp
char s[] = "Hello, world"; // or equivalently, char* s = "Hello, world"
std::cout << "s[0] = " << s[0] << std::endl; // prints 'H'
std::cout << "s = " << s << std::endl; // prints "Hello, world"
```
Summary - Data Types and Precisions

- Each data type consumes different amount of memory
  - For example, 1GB can store a billion characters, and 125 million double precision floating point numbers
  - To store a human genome as character types, 3GB will be consumed, but 12GB will be needed if each nucleotide is represented as an integer type
- Precision is not unlimited.
  - Unexpected results may happen if the operations require too many significant digits.
Assignment and Arithmetic Operators

```c
int a = 3, b = 2;  // valid
int c = a + b;     // addition : c == 5
int d = a - b;     // subtraction : d == 1
int e = a * b;     // multiplication : e == 6
int f = a / b;     // division (int) generates quotient : f == 1
int g = a + b * c; // precedence - add after multiply : g == 3 + 2 * 5 == 13
a = a + 2;         // a == 5
a += 2;            // a == 7
++a;               // a == 8
a = b = c = e;     // a == b == c == e == 6
```
Comparison Operators and Conditional Statements

```cpp
int a = 2, b = 2, c = 3;
std::cout << (a == b) << std::endl; // prints 1 (true)
std::cout << (a == c) << std::endl; // prints 0 (false)
std::cout << (a != c) << std::endl; // prints 1 (true)
if ( a == b ) {
    std::cout << "a and b are same" << std::endl;
}
else {
    std::cout << "a and b are different" << std::endl;
}
std::cout << "a and b are " << (a == b ? "same" : "different") << std::endl
    << "a is " << (a < b ? "less" : "not less") << " than b" << std::endl
    << "a is " << (a <= b ? "equal or less" : "greater") << " than b" << std::endl;
```
## Loops

### while loop

```cpp
int i=0;  // initialize the key value
while( i < 10 ) { // evaluate the loop condition
    std::cout << "i = " << i << std::endl; // prints i=0 ... i=9
    ++i; // update the key value
}
```

### for loop

```cpp
for(int i=0; i < 10; ++i) { // initialize, evaluate, update
    std::cout << "i = " << i << std::endl; // prints i=0 ... i=9
}
```
Pointers

```
s = 0x3fb5
```

<table>
<thead>
<tr>
<th>Address</th>
<th>0x3fb5</th>
<th>0x3fb6</th>
<th>0x3fb7</th>
<th>0x3fb8</th>
<th>0x3fb9</th>
<th>0x3fba</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>‘H’</td>
<td>‘E’</td>
<td>‘L’</td>
<td>‘L’</td>
<td>‘O’</td>
<td>‘\0’</td>
</tr>
</tbody>
</table>

Another while loop

```
char* s = "HELLO"; // array of {'H','E','L','L','O','\0'}
while ( *s != '\'0' ) { // *s access the character value pointed by s
    std::cout << *s << std::endl; // prints 'H','E','L','L','O' at each line
    ++s; // advancing the pointer by one; points to the next element
}
```
Pointers and Loops

### while loop

```cpp
char* s = "HELLO"; // array of {'H','E','L','L','O','\0'}
while ( *s != '\0' ) {
    std::cout << *s << std::endl; // prints 'H','E','L','L','O' at each line
    ++s; // advancing the pointer by one
}
```

### for loop

```cpp
// initialize array within for loop
for(char* s = "HELLO"; *s != '\0'; ++s) {
    std::cout << *s << std::endl; // prints 'H','E','L','L','O' at each line
}
```
Pointers are complicated, but important

```cpp
int A[] = {3, 6, 8}; // A is a pointer to a constant address
int* p = A;       // p and A are containing the same address
std::cout << p[0] << std::endl; // prints 3 because p[0] == A[0] == 3
std::cout << *p << std::endl; // prints 3 because *p == p[0]
std::cout << *(p+2) << std::endl; // prints 8 because *(p+2) == p[2]
int b = 3;       // regular integer value
int* q = &b;     // the value of q is the address of b
b = 4;           // the value of b is changed
std::cout << *q << std::endl; // *q == b == 4

char s[] = "Hello";
char *t = s;
std::cout << t << std::endl; // prints "Hello"
char *u = &s[3]; // &s[3] is equivalent to s + 3
std::cout << u << std::endl; // prints "lo"
```
Pointers and References

```cpp
int a = 2;
int& ra = a; // reference to a
int* pa = &a; // pointer to a
int b = a; // copy of a
++a; // increment a
std::cout << a << std::endl; // prints 3
std::cout << ra << std::endl; // prints 3
std::cout << *pa << std::endl; // prints 3
std::cout << b << std::endl; // prints 2
int* pb; // valid, but what pb points to is undefined
int* pc = NULL; // valid, pc points to nothing
std::cout << *pc << std::endl; // Run-time error : pc cannot be dereferenced.
int& rb; // invalid. reference must refer to something
int& rb = 2; // invalid. reference must refer to a variable.
```
Summary so far

- Algorithms are computational steps
- `towerOfHanoi` utilizing recursions
- `insertionSort`
  - ✓ Simple but a slow sorting algorithm.
  - ✓ Loop invariant property

- Data types and floating-point precisions
- Operators, `if`, `for`, and `while` statements
- Arrays and strings
- Pointers and References
- Fisher’s Exact Tests

- At Home: Reading material for novice C++ users: 
  
Next Lecture

- Fisher’s Exact Test
- More on C++ Programming
  - Standard Template Library
  - User-defined data types