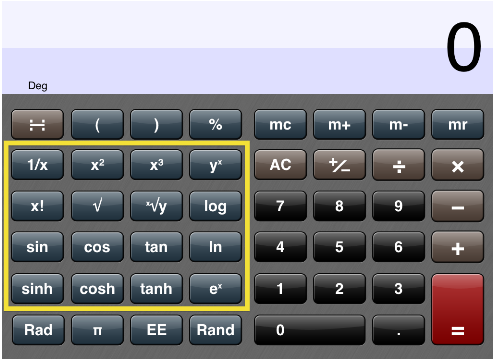
Programming with C++

COMP2011: Function I

Cecia Chan
Cindy Li
Brian Mak

Department of Computer Science & Engineering
The Hong Kong University of Science and Technology
Hong Kong SAR, China

Scientific Functions



$$z = f(u, v, w, x, y, \cdots)$$

- Example: sin(x), cos(x), log(x), sqrt(x), etc.
- We would like to generalize the notion of functions in programming languages.

Motivation Example: x! + y! + z!

```
#include <iostream>       /* File: factorial-sum.cpp */
using namespace std;

int main()                /* To compute x! + y! + z! */
{
    int x, y, z;
    int fx = 1, fy = 1, fz = 1;

    cout << "Enter x, y, z: "; cin >> x >> y >> z;

    for (int j = 2; j <= x; ++j) { fx *= j; } // Compute x!

    for (int j = 2; j <= y; ++j) { fy *= j; } // Compute y!

    for (int j = 2; j <= z; ++j) { fz *= j; } // Compute z!

    cout << x << "! + " << y << "! + " << z << "! = "
         << fx + fy + fz << endl;

    return 0;
}
```

Motivation Example: x! + y! + z! ..

- There are 3 for-loops for computing x!, y! and z!.
- Won't it be good if we can, instead, write something like:

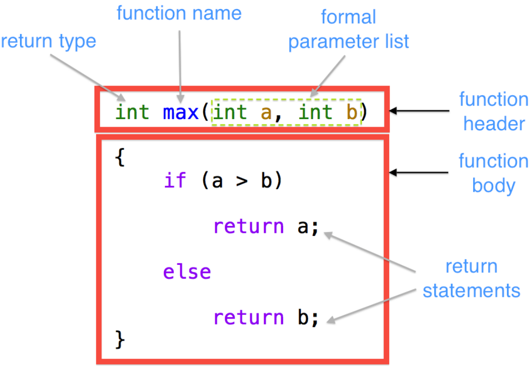
```
int main()                  /* To compute x! + y! + z! */
{
    int x, y, z;
    cout << "Enter x, y, z: "; cin >> x >> y >> z;

    cout << x << "! + " << y << "! + " << z << "! = "
         << factorial(x) + factorial(y) + factorial(z) << endl;
    return 0;
}
```

where factorial(x) is a function that takes an integer x and returns the integer value x!.

- The code is more readable and is easier to understand.
- You also don't need to repeat writing 3 very similar while loops.

Part I

Function Basics



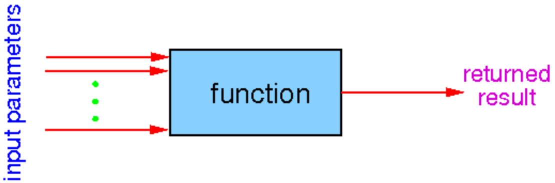
Basic Function Syntax

Syntax: Function Definition

<return-type> <function-name> (<formal-parameter-list>)
{ <function-body> }

Syntax: Function Call

<function-name> (<actual-parameter-list>)



Function Name

- Any legal C++ identifier can be used for <function-name>.
- Just like naming variables and constants, you should use meaningful names for function names.
  - The name should describe what the function does.
- The function name "main" is reserved; you must define it, and define it exactly once.
  - Recall that each program can only have one "main( )" function.
  - When a program is run, the shell — command interpreter of the operating system — looks for the main( ) function and starts execution from there.

Formal Parameter List & Actual Parameter List

```
/* max function definition */
int max(int a, int b) { return (a > b) ? a : b; }
/* max function call */
cout << max(5, 8) << endl;
```

- <formal-parameter-list> appears in the function definition: it is a list of variable declarations separated by commas.

Syntax: <formal-parameter-list>

$< type_1 \ \ variable_1 >, < type_2 \ \ variable_2 >, \cdots, < type_N \ \ variable_N >$

- <actual-parameter-list> appears in a function call: it is a list of comma-separated objects passed to the called function.

Syntax: <actual-parameter-list>

$< object_1 >, < object_2 >, \cdots, < object_N >$

- There is a one-to-one correspondence between the actual parameters (aka arguments) and the formal parameters.

Formal Parameter List & Actual Parameter List ..

- During the function call, the following initializations are performed,

$$\boxed{\begin{array}{l} < type_1 \;\; variable_1 >= object_1, \\ < type_2 \;\; variable_2 >= object_2, \\ \vdots \\ < type_N \;\; variable_N >= object_N \end{array}}$$

- Since C++ is a strongly typed programming language, the data type of an actual parameter and its corresponding formal parameter must be the same or "matched".
- A C++ compiler will perform type checking to make sure that their types match with each other.
- Exception: unless an automatic type conversion — coercion — can be done, like normal initialization or assignment of an object to a variable of a different type. (More about that later.)

Function Header & Function Body

- In the function syntax, the first line

  <return-type> <function-name> (<formal-parameter-list>)

  is also called the function header, and the rest is the function body enclosed in curly braces.

- The <function-body> usually consists of the following parts:
  - constant declarations
  - variable declarations and definitions
  - other C++ statements
  - return statement

- It is legal to have an empty function body!

- The curly braces must be there, even if there is zero or only one single statement inside the function body! (That is different from the if-statement or while-statement, etc.)

Return Type

- Usually a function returns something — in C++, we call it an object.
- The returned object may be
  - a signal to tell the caller about the status of the function: does it run successfully? does it fail?
  - the result of some computation. e.g., factorial, sum, etc.
  - a new object created by the function. e.g., a new window.
- <return-type> specifies the data type of the single returned object.
- <return-type> can be any of the C++ built-in data types (e.g., char, int, etc.) or user-defined types, except the array type. (Array type will be talked later.)

Question: Since only a single object is returned by a function, how can you return multiple objects back to the caller?

return Statement

Syntax: return Statement

return $<$ *expression* $>$;

- The return statement generally returns "2" things to the caller:
  - program control: it stops running the called function, and the function caller takes back the control and continue its execution.
  - an object: the object (or value) represented by the $<$ *expression* $>$ is returned to the caller.
- The value of $<$ *expression* $>$ in the return statement should have the same type as the $<$return-type$>$. Or, if it can be converted to the $<$return-type$>$ by coercion, otherwise it will be a compilation error.
- If a function has a return value, the function body must have at least one return statement.

Example: max

```
#include <iostream>        /* File: max.cpp */
using namespace std;       /* To find the greater value between x and y */

int max(int a, int b)
{
    if (a > b)
        return a;
    else
        return b;
}   // Question: can you write with only 1 return statement?

int main()
{
    int x, y;
    cout << "Enter 2 numbers: ";
    cin >> x >> y;

    cout << "The bigger number is " << max(x, y) << endl;
    return 0;
}
```

Example: Euclidean Distance

Example: Euclidean Distance ..

```
#include <iostream>      /* File: distance-fcn.cpp */
#include <cmath>         // Math library info
using namespace std;

/* To find the Euclidean distance between 2 points */
double euclidean_distance(double x1, double y1, double x2, double y2)
{
    double x_diff = x1 - x2;
    double y_diff = y1 - y2;
    return sqrt(x_diff*x_diff + y_diff*y_diff);
}

int main()   /* To find the length of the sides of a triangle */
{
    double xA, yA, xB, yB, xC, yC;
    cout << "Enter the co-ordinates of point A: "; cin >> xA >> yA;
    cout << "Enter the co-ordinates of point B: "; cin >> xB >> yB;
    cout << "Enter the co-ordinates of point C: "; cin >> xC >> yC;

    cout << " AB = " << euclidean_distance(xA, yA, xB, yB) << endl;
    cout << " BC = " << euclidean_distance(xB, yB, xC, yC) << endl;
    cout << " CA = " << euclidean_distance(xC, yC, xA, yA) << endl;
    return 0;
}
```

void: a New Type

- "void" means *nothing*, *emptiness*.
- A function that returns nothing back to the caller has a return type of void.
- A function that does not take any arguments from the caller may
  - leave the <formal-parameter-list> empty.

    ```
    int fcn_example( ) { ... }
    ```

  - put the <formal-parameter-list> as void.

    ```
    void print_hkust(void) { cout << "hkust" << endl; }
    ```

Example: Rock/Paper/Scissors Game

Example: Rock/Paper/Scissors Game — main( )

```
#include <iostream>  /* File: rps-game.cpp */
#include <cstdlib>   // Info about random number generator rand()
using namespace std; //rps-game2.cpp: another solution with error messages

// 0/1/2 is used to represent ROCK/PAPER/SCISSORS
const int ROCK = 0, PAPER = 1, SCISSORS = 2;

// Define the game functions here
int print_choice(char player, int choice) { ... }
void print_game_result(int computer_choice, int user_choice) { ... }

int main()
{
    int seed;               // To seed the random number generator
    cout << "Enter an integer: "; cin >> seed;
    srand(seed);            // Initialize random number generator

    int computer_choice = rand()%3; // rand() produces an integer which is
    int user_choice = rand()%3;     // then converted to ROCK/PAPER/SCISSORS

    if (print_choice('C', computer_choice) != 0) return -1; // -1 ⇒ an error
    if (print_choice('U', user_choice) != 0) return -1; // -1 signals an error
    print_game_result(computer_choice, user_choice);
    return 0;
}
```

Example: Rock/Paper/Scissors Game — other Functions

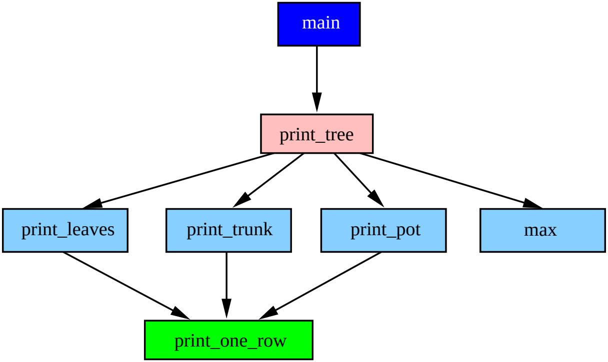
```
/* To print out the choice picked by the computer or the user */
int print_choice(char player, int choice) // 'C' for computer and 'U' for user
{
    if (player == 'C')
        cout << "Computer";
    else if (player == 'U')
        cout << "User";
    else
        return -1;      // Better also print an error message

    cout << " picks ";

    if (choice == ROCK)
        cout << "rock" << endl;
    else if (choice == PAPER)
        cout << "paper" << endl;
    else if (choice == SCISSORS)
        cout << "scissors" << endl;
    else
        return -1;      // Better also print an error message

    return 0;
}
```

Example: Rock/Paper/Scissors Game — other Functions ..

```
/* To print game result: "DRAW!", "COMPUTER WINS!", or "PLAYER WINS!" */

void print_game_result(int computer_choice, int user_choice)
{
    if (computer_choice == user_choice)
        cout << "\tDRAW!" << endl;

    else if (computer_choice == ROCK && user_choice == SCISSORS
        || computer_choice == SCISSORS && user_choice == PAPER
        || computer_choice == PAPER && user_choice == ROCK)
        cout << "\tCOMPUTER WINS!" << endl;

    else
        cout << "\tUSER WINS!" << endl;
}
```

Part II

Modular Programming



Why Modular Programming?

- In reality, many application software contains hundreds of thousands, or even million lines of code.
- A common approach to solve complex problems is "divide-and-conquer": divide the problem into smaller parts, and then solve each part in turn.
- In programming, we divide a large program into modules, each of which is implemented by a function.
- This is called modular programming, or top-down programming.

Example: Draw a Tree — Problem Statement

```
        *
       ***
      *****
     *******
    *********
   ***********
  *************
 ***************
*****************
       &&&
       &&&
       &&&
  ^^^^^^^^^^^^^
   ^^^^^^^^^^^
    ^^^^^^^^^
```

- Task: To draw a tree; the drawing consists of
  - a triangular top (the leaves)
  - a rectangular trunk
  - a trapezium pot
- Requirements: A user may define
  - the drawing symbols of the 3 parts.
  - the height of the tree.
- For simplicity, other dimensions (width/height of leaves, trunk, pot) are computed from the tree height using pre-determined formulas.

Example: Draw a Tree — main( )

```cpp
#include <iostream>      /* File: draw-tree.cpp */
using namespace std;

// Definition of other functions go here ...

int main()
{
    char tree_symbol, trunk_symbol, pot_symbol;
    int tree_height;

    cout << "Enter the character symbols for tree, trunk, and pot: ";
    cin >> tree_symbol >> trunk_symbol >> pot_symbol;

    cout << "Enter height of the tree (an odd integer, please): ";
    cin >> tree_height;

    cout << endl << endl << endl;
    print_tree(tree_height, tree_symbol, trunk_symbol, pot_symbol);

    return 0;
}
```

Example: Draw a Tree — other Functions

```
int max(int a, int b) { return (a > b) ? a : b; }


void print_one_row(int num_leading_spaces, int num_symbols, char symbol)
{
    for (int j = 0; j < num_leading_spaces; ++j)
        cout << ' ';

    for (int j = 0; j < num_symbols; ++j)
        cout << symbol;

    cout << endl;
}


void print_leaves(int tree_height, char tree_symbol)
{
    for (int row = 0, num_leading_spaces = tree_height;
         row < tree_height;
         ++row, --num_leading_spaces)
        print_one_row(num_leading_spaces, 2*row+1, tree_symbol);
}
```

Example: Draw a Tree — other Functions ..

```
void print_trunk(int tree_width, int trunk_height,
                 int trunk_width, char trunk_symbol)
{
    int num_leading_spaces = (tree_width - trunk_width)/2;

    for (int row = 0; row < trunk_height; ++row)
        print_one_row(num_leading_spaces, trunk_width, trunk_symbol);
}


void print_pot(int tree_width, int pot_height,
               int pot_base_width, char pot_symbol)
{
    int num_leading_spaces = (tree_width - pot_base_width)/2;
    int row = pot_height, width = pot_base_width;

    while (row > 0)
    {
        print_one_row(num_leading_spaces, width, pot_symbol);
        --row;
        ++num_leading_spaces;
        width -= 2;
    }
}
```

Example: Draw a Tree — other Functions ..

```
/************* The exact formulas are not important! ************
 * The leaves have 2n+1 symbols on the n-th row.
 * The trunk is just a rectangle: width = height = 2/3 of tree's height.
 * pot's height = 1/3 of tree's. pot's width = 2/3 of tree's.
 */
void print_tree(int tree_height,
                char tree_symbol, char trunk_symbol, char pot_symbol)
{
    int tree_width = 2*tree_height + 1;
    int trunk_width = max(1, tree_width/6);
    int trunk_height = max(1, tree_height/3);
    int pot_width = tree_width * 2/3;
    int pot_base_width = (pot_width % 2) ? pot_width : pot_width + 1;
    int pot_height = max(2, tree_height/3);

    print_leaves(tree_height, tree_symbol);
    print_trunk(tree_width, trunk_height, trunk_width, trunk_symbol);
    print_pot(tree_width, pot_height, pot_base_width, pot_symbol);
}
```

Remarks: Why Function?

- When you have several segments of codes doing similar things, then they are good candidates for a function.
- A function allows "write-once-call-many": you only write it once they can be called many times in the same program with the same or different arguments.
- Functions make programs easier to understand.
- Functions make programs easier to modify.
- Functions allow reusable code. (e.g., log, sqrt, sin, etc.)
- Functions separate the concept (what is done) from the implementation (how it is done).
- The last two remarks lead to the creation of binary libraries which are a set of compiled functions. These libraries can be shared, yet the users do not know their implementation. (You'll learn how to do this later.)

Part III

Parameter Passing Methods

How Actual Parameters are Passed to Formal Parameters

Actual Parameter		Formal Parameter
$object_1$	$\longrightarrow$	$variable_1$
$object_2$	$\longrightarrow$	$variable_2$
$\vdots$	$\vdots$	$\vdots$
$object_N$	$\longrightarrow$	$variable_N$

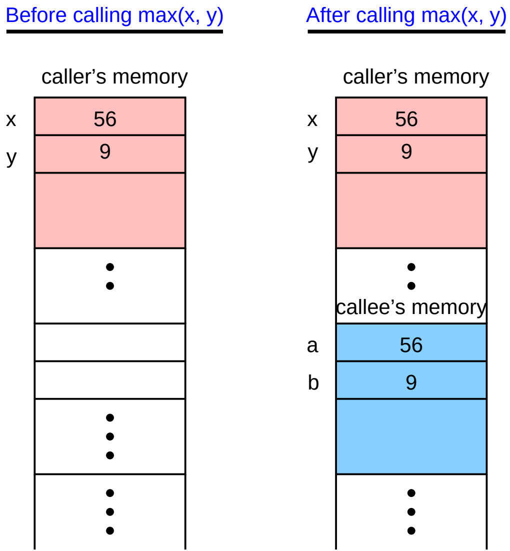
- C++ supports 2 ways to pass arguments to a function:
  1. pass-by-value (PBV), or call-by-value (CBV)
  2. pass-by-reference (PBR), or call-by-reference (CBR)
- Notice that if you call a function with an expression, the expression is first evaluated, and the result is then passed to the function.
  e.g., $\boxed{\text{max}(3 + 5,\ 2 + 9)} \rightarrow \boxed{\text{max}(8,\ 11)}$ before calling the max function.

Pass-by-Value

- In pass-by-value, the value of an actual parameter is copied into the formal parameters of the function.
- If the actual parameter is a literal constant (e.g., calling $\boxed{\text{max(2, 3)}}$), obviously it won't change.
- If the actual parameter is a variable (e.g., calling $\boxed{\text{max(x, y)}}$), only its value is copied to the function, otherwise it has nothing to do with the operation of the function. In particular, its value cannot be modified by the function.
- All the function examples presented so far use pass-by-value to pass the arguments.

Question: What happens if the argument is a big object (e.g. of several MB)?

Pass-by-Value Illustration



Reference Variable

Syntax: Reference Variable Definition

$$\langle\text{type}\rangle\&\ \langle\text{variable}_1\rangle = \langle\text{variable}_2\rangle;$$
$$\langle\text{type}\rangle\ \&\langle\text{variable}_1\rangle = \langle\text{variable}_2\rangle;$$
$$\ldots$$

- A reference variable is an alias of another variable.
- A reference variable must always be bound to an object. Therefore, it must be initialized when they are defined.
- Once a reference variable is defined and bound with a variable, you cannot "re-bind" it to another object.

In the example,

- Variables a, x, w all refer to the same integer object; similarly, variables b, y, z also all refer to the same integer object.
- Variables a, x, w share the same memory space, so that you may modify the value in that memory space through any of them! (Same for b, y, z.)
- In the line $\boxed{\text{z = a;}}$, the reference variable z is not re-bound to a, but the value of a is assigned to z.

Example: Reference Variables

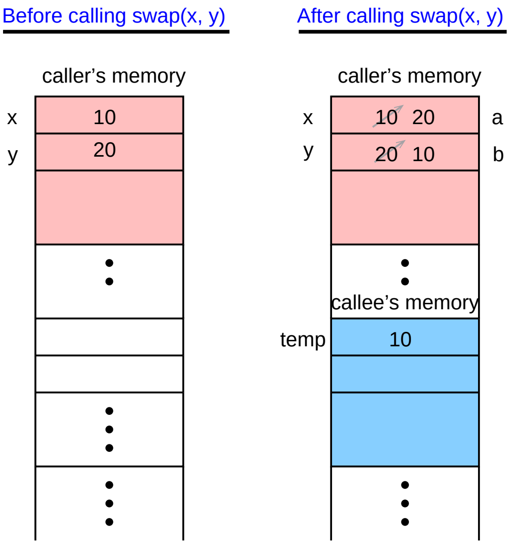
```
#include <iostream>      /* File: ref-declaration.cpp */
using namespace std;

int main()
{
    int a = 1, b = 2;
    int& x = a;          // now x = a = 1
    int &y = b;          // now y = b = 2
    int &w = a, &z = y; // now w = a = x = 1, z = b = y = 2

    a++;        cout << a << '\t' << x << '\t' << w << endl;
    x += 5;     cout << a << '\t' << x << '\t' << w << endl;
    a = w - x; cout << a << '\t' << x << '\t' << w << endl;

    y *= 10; cout << b << '\t' << y << '\t' << z << endl;
    b--;      cout << b << '\t' << y << '\t' << z << endl;
    z = 999; cout << b << '\t' << y << '\t' << z << endl;

    z = a;               // that is not re-binding z to a
    cout << b << '\t' << y << '\t' << z << endl;
    return 0;
}
```

Pass-by-Reference Example: swap

```cpp
/* File: pbr-swap.cpp */
#include <iostream>
using namespace std;

void swap(int& a, int& b)
{
    int temp = a;
    a = b;
    b = temp;
}

int main()
{
    int x = 10, y = 20;
    swap(x, y);
    cout << "(x , y) = " << '(' << x
         << " , " << y << ')' << endl;
    return 0;
}
```

```cpp
// execution of swap is
// equivalent to running
// the following codes
int& a = x;
int& b = y;
int temp = a;
a = b;
b = temp;

// OR, equivalently
int temp = x;
x = y;
y = temp;
```

Pass-by-Reference Illustration



Pass-by-Reference

- Pass-by-reference does not copy the value of actual parameters to the formal parameters of the function.
- When an actual parameter is passed by reference, its corresponding formal parameter becomes its reference variable (alias).
- In the swap example, on entering the swap function, the following codes are run: `int& a = x;    int& b = y;`
  That is, the formal parameters *a* and *b* are declared as reference variables and are initialized or bound to their corresponding actual parameters *x* and *y*, respectively.
- You must add the symbol "&" after the type name of the formal parameter if you want pass-by-reference.
- When an actual parameter is passed by reference to its formal parameter, since they share the same memory, any modification made to the formal parameter also changes the value of the corresponding actual parameter.

Example: Sort 3 Numbers

```cpp
#include <iostream>       /* File: sort3.cpp */
using namespace std;

void swap(int& x, int& y) /* To swap 2 numbers */
{
    int temp = x;
    x = y;
    y = temp;
}

int main()                /* To sort 3 numbers in ascending order */
{
    int x, y, z;
    cout << "Enter 3 numbers, x, y, z: ";
    cin >> x >> y >> z;

    if (x > y) swap(x, y);
    if (x > z) swap(x, z);
    if (y > z) swap(y, z);

    cout << "x , y , z = " << x << " , " << y << " , " << z << endl;
    return 0;
}
```

Remarks

- Function call has higher precedence than other operators. e.g., in the rock/paper/scissors game example, the 2 statements:

```
if (print_choice('C', computer_choice) != 0) return -1;
if (print_choice('U', user_choice) != 0) return -1;
```

may be shortened as

```
if (print_choice('C', computer_choice) != 0
    || print_choice('U', user_choice) != 0)
    return -1;
```

The function call print_choice('C', computer_choice) is executed first, and the returned value is then compared with 0 by the logical != operator. Same thing happens to the 2nd function call. Finally, the logical || operator combines the 2 comparison results.

- Before C++11, you cannot define a function inside another function. In other words, all C++ functions, except private class member functions (more about them in *C++ Classes*), are global — that is, any C++ function can be called by any other C++ functions if they are properly declared (more about that in *Scope*).
- After C++11, you can define local functions inside another function by the lambda expression.
- For a function with more than 1 formal parameter, some of them may get their values using pass-by-value, while others using pass-by-reference. There is no restriction on their number and order.

Example: Some PBV, Some PBR

```
#include <iostream>      /* File: sum-and-difference.cpp */
using namespace std;

// To find the sum and difference of 2 given numbers
void sum_and_difference(int x, int y, int& sum, int& difference)
{
    sum = x + y;
    difference = x - y;
}

int main()
{
    int x, y, sum, difference;
    cout << "Enter 2 numbers: ";
    cin >> x >> y;

    sum_and_difference(x, y, sum, difference);
    cout << "The sum of " << x << " and " << y << " is " << sum << endl;
    cout << "The difference between " << x << " and " << y << " is "
         << difference << endl;
    return 0;
}
```

Remarks ...

- All the local variables defined inside a function, including the formal parameters, are destroyed on return of the function call.
  - These local variables are created every time the function is called.
  - These local variables created on the current call are different from those created in the previous calls.
  - However, if a formal parameter is a reference variable, only itself is destroyed when the function returns, the variable (actual parameter) bound to it still exists afterwards.
- Pass-by-reference is more efficient when a large object has to be passed to a function as no copying takes place. However, there is a risk that you may accidentally modify the object.

Question: Is there a way to pass a large object to a function such that the function cannot modify its value?

const References as Function Arguments

- You can (and should!) express your intention to keep a reference argument (that is passed to a function) unchanged by making it const.
- There are 2 advantages:

1. If you accidentally try to modify the argument in your function, the compiler will catch the error.

```
// Fine
void call_by_ref(int& x) { x += 10; }

// Error!
void call_by_const_ref(const int& x) { x += 10; }
```

2. You may pass both const and non-const arguments to a function that requires a const reference parameter.

   Conversely, you may pass only non-const arguments to a function that requires a non-const reference parameter.

Passing Object	const Function Argument	non-const Function Argument
literal constant	$\surd$	X
const Object	$\surd$	X
non-const Object	$\surd$	$\surd$

Examples: const vs. non-const Reference Arguments

```cpp
#include <iostream>      /* File: const-ref-arg.cpp */
using namespace std;

void call_by_ref(int& a) { cout << a << endl; }
void call_by_const_ref(const int& a) { cout << a << endl; }

int main()
{
    int x = 50;
    const int y = 100;
    // Which of the following give(s) compilation error?
    /* passing const literals */
    call_by_ref(1234);
    call_by_const_ref(1234);

    /* passing const objects */
    call_by_ref(y);
    call_by_const_ref(y);

    /* passing non-const objects */
    call_by_ref(x);
    call_by_const_ref(x);
    return 0;
}
```

Return-by-Value (RBV) and Return-by-Reference (RBR)

Examples

```
int max(int a, int b) { return (a > b) ? a : b; }

int factorial(int x)
{
    int fx = 1;
    for (int j = 2; j <= x; ++j) fx *= j;
    return fx;
}

/* Function calls */
cout << max(5, 8) << endl;
int result = factorial(10);
```

- Just like you may PBV or PBR, you may also return objects from a function to its caller by value or reference.
- All the function examples you see so far return by value.
- During RBV, the returned ‘object’ is copied to the caller.
- If the returned object is big, the return is slow due to copying. RBR may solve the problem; more about this later.