# Programming with C++

# COMP2011: Array — a Collection of Homogeneous Objects

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# What is an Array?

- Array is a collection of homogeneous objects: objects of the same type. e.g., a collection of int, char, double, ..., or user-defined types.
- Exception: The array elements cannot be reference variables.

# Motivation from Programming Point of View

- A function to sort 3 integers can be:

```
void sort_3_int(int& x, int& y, int& z);
```

- A function to sort 6 integers can be:

```
void sort_6_int(int& u, int& v, int& w, int& x, int& y, int& z);
```

- How about a function to sort 10,000 integers? Are you going to create variable names for the 10,000 different integers?
- Array is designed to solve this problem: you only need one identifier name to address all the 10,000 integers, and there is a way to refer to each of them.
- It can solve problems like: read a list of student names, and sort them in alphabetical order.
- In an Excel file, each column/row is basically an array so that you can do some common operations (like average, max, min, count) on it.

# Part I

## 1-Dimensional Array

# C++ 1-Dimensional Array

## Syntax: Definition of a 1D Array

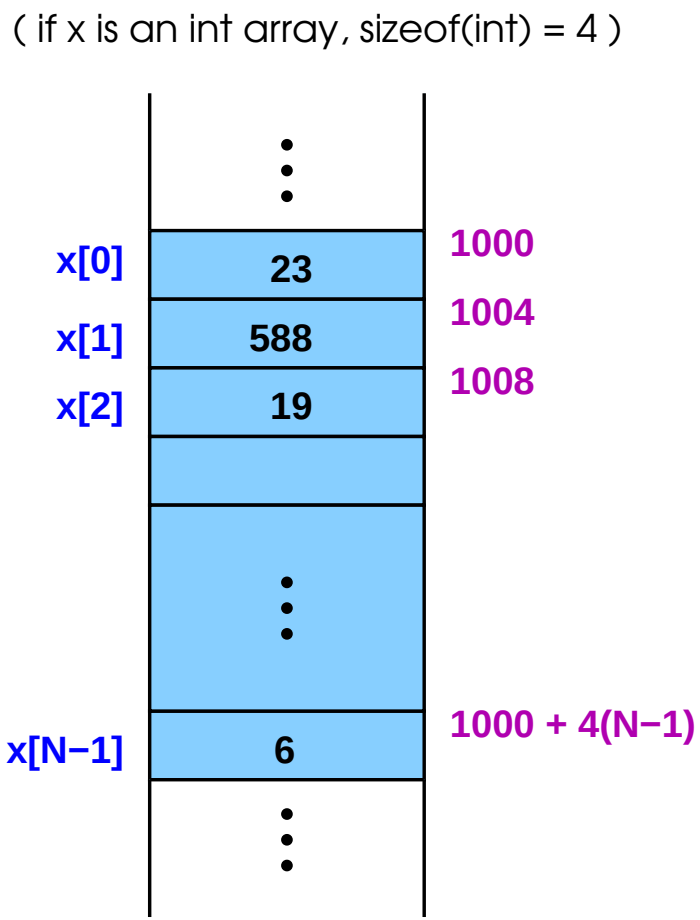
<data-type> <array-name> [ <size> ] ;

- <size> should be a positive constant. It can be a constant expression too.

## Examples

```
int number[10000]; // An array of 10,000 uninitialized integers

const int NUM_STUDENTS = 335;
char gender[NUM_STUDENTS];     // An array of 335 char
float score[NUM_STUDENTS + 1]; // An extra element to hold the mean

int n = 3;
double x[n];       // Compilation error on VC++: size is NOT a constant

int value[-4];     // Compilation error: array size cannot be -ve
```

# Subscripting: Access to Each Array Element




- A 1D array is an ordered list of elements.
- Successive elements are stored in contiguous memory.
- To access an element, use the subscript operator [] with an array index.
- For an array of size $N$, the indices run from $0, 1, 2, \ldots, N-1$.
- Each array element is treated like a regular variable:
  - you may assign a value to it
  - you may assign its value to another variable
  - you may pass it by value or reference to a function

# Array and Control

- Array works particularly well with loops: e.g., use a for-loop to access and manipulate each array element in turn.
- This is not a coincidence, but part of the C++ language design.

## Examples

```
int y;                      // A regular int variable
int x[3];                   // An array of 3 int numbers

x[0] = 34;                  // Array indices start from zero in C++
x[1] = 289;
x[2] = 75;                  // Index of the last element is 2 NOT 3!

y = x[2];                   // Now both y and x[2] are 75
max(x[2], x[0]);            // Pass array elements by value
swap(x[1], x[0]);           // Pass array elements by reference

for (int j = 0; j < 3; j++)
    x[j] *= 3;              // Triple each element of an array
```

# Example: Manipulate an Array of Scores using for Loop

```
#include <iostream>     /* array-mean.cpp */
using namespace std;

int main()
{
    const int NUM_STUDENTS = 5;
    float score[NUM_STUDENTS];
    float sum_score = 0.0;      // Don't forget initializing the sum

    for (int j = 0; j < NUM_STUDENTS; ++j)
    {
        cin >> score[j];
        sum_score += score[j]; // Accumulate the scores
    }

    cout << "mean score = " << sum_score/NUM_STUDENTS << endl;
    return 0;
}
```

# Example: Manipulate an Array of Scores using for Loop ..

```
#include <iostream>     /* array-max.cpp */
using namespace std;

int main()
{
    const int NUM_STUDENTS = 5;
    float score[NUM_STUDENTS];
    // Read in the first student's score. Assume #students >= 1
    cin >> score[0];
    float max_score = score[0]; // A good way to initialize max score

    for (int j = 1; j < NUM_STUDENTS; ++j)
    {
        cin >> score[j];
        if (max_score < score[j])
            max_score = score[j];
    }

    cout << "max score = "  << max_score << endl;
    return 0;
}
```

# Wrong Subscript: Common Reason for Segmentation Fault

- C++ compiler does not automatically check that an array index is out of bound.
- That is, for an array of size $N$, the compiler won't check if it is subscripted with an index between 0 and $N-1$, neither at compile-time nor run-time.
- There is no compilation error for the following codes:

```
int x[10]; x[-2] = 5; x[100] = 9;
```

- When the codes are run, `x[-2] = 5;` will put the value 5 to the memory space which is $2 \times 4$ bytes (size of 2 int) before the array $x$. Similarly, `x[100] = 9;` will put the value 9 to the memory space which is $90 \times 4$ bytes beyond the array.
- This is a common cause of the run-time error called segmentation fault — your program trespasses into memory locations that may not belong to it.

# Array Initialization

- Just like any local variable, when an array is defined, its elements are not initialized automatically.

**Syntax: Define and Initialize a 1D Array Simultaneously**

<data-type> <array-name> [<size>]
= { <value$_0$>, <value$_1$>, . . . , <value$_{<size>-1}$> } ;

- If there are fewer values than the array size, the unspecified values will be zeros.
- It is a compilation error if there are more values than the array size.
- If you leave out the array size in the array initialization, the compiler will count the number of initializing values and uses that as the array size.
- Once defined, you cannot assign values to an array using the initialization syntax.

# Example: Array Initialization

```
int a[5] = {1, 2, 3, 4, 5};
/* Same as

   int a[5];
   a[0] = 1; a[1] = 2; a[2] = 3; a[3] = 4; a[4] = 5;
*/

int b[5] = {1, 2};     // => 1, 2, 0, 0, 0
int c[5] = {};         // => 0, 0, 0, 0, 0
int d[] = {1, 2, 3};   // Compiler determines the size=3 automatically
int e[3];

// Compilation error:
//     can't assign values to an array using the { } syntax
e = {5, 6, 7};

// Compilation error: can't declare an array of references
double x = 1.5, y = 2.5, z = 3.5;
double& s[] = {x, y, z};
```

# Common Mis-uses of an Array

While each array element can be treated as a simple variable, the whole array, as represented by the array identifier, cannot.

## Examples: Correct and Incorrect Uses of Arrays

```
int x[] = {1, 2, 3, 4, 5 };
int y[] = {6, 7, 8, 9, 0 };
int z[5];

/* Incorrect way */
// Cannot assign to array elements using the initialization syntax
x = {5, 4, 3, 2, 1};

x = 8;       // x is not an integer! Its elements are.
x += 2;      // x is not an integer! Its elements are.
x = y;       // No assignment between 2 arrays
z = x + y;   // Cannot +, -, *, / on the array, but only its elements

/* Correct way; what does each for-statement do? */
for (int j = 0; j < 5; ++j) x[j] = 5 - j;
for (int j = 0; j < 5; ++j) x[j] = 8;
for (int j = 0; j < 5; ++j) x[j] += 2;
for (int j = 0; j < 5; ++j) x[j] = y[j];
for (int j = 0; j < 5; ++j) z[j] = x[j] + y[j];
```

# Pass a 1D Array to a Function

## Examples: Arrays as Function Arguments

```
/* function header */
float mean_score(float score[], int size) { ... }
float max_score(float score[], int size) { ... }


/* inside the main() */
float score[NUM_STUDENTS];
mean_score(score, NUM_STUDENTS);
max_score(score, NUM_STUDENTS);
```

- Since the array identifier alone does *not* tell us about its size, a function that operates on an array needs at least 2 input arguments:
  - the array identifier
  - the array size (of type int)

# Example: Pass an Array to a Function I

```
#include <iostream>     /* array-mean-max-fcn.cpp */
using namespace std;

float mean_score(float score[], int size)
{
    float sum_score = 0.0; // Don't forget initializing the sum to 0
    for (int j = 0; j < size; j++)
        sum_score += score[j]; // Accumulate the scores
    return sum_score/size;
}

float max_score(float score[], int size)
{
    // Initialize the max score to that of the first student
    float max_score = score[0];
    for (int j = 1; j < size; j++)
        if (max_score < score[j])
            max_score = score[j];
    return max_score;
}
```

# Example: Pass an Array to a Function II

```
int main()
{
    const int NUM_STUDENTS = 5;
    float score[NUM_STUDENTS];

    for (int j = 0; j < NUM_STUDENTS; j++)
        if (!(cin >> score[j]))
            return -1;

    cout << "mean score = " << mean_score(score, NUM_STUDENTS) << endl;
    cout << "max score = "  << max_score(score, NUM_STUDENTS) << endl;
    return 0;
}
```

---

Notice how we may check if the input operation is successful:

```
if (!(cin >> score[j]))
```

It returns `true`/`false` if it succeeds/fails, respectively.

# 1D Array as a Function's Formal Parameter

- While a regular variable may be passed to a function by value or reference, an array variable is always passed by value.
- However, although the array variable is passed by value, its elements are *effectively* passed by reference!
- Any change to an array element inside the function will persist even after the function returns.
- Just like a regular variable, you pass an array to a function simply by its variable name. e.g.,

```
max_score(score, NUM_STUDENTS);
```

# Example: Modifying Array's Elements by a Function I

```
#include <iostream>     /* array-add-rotate.cpp */
using namespace std;

void array_add(int x[], int y[], int z[], int size)
{
    for (int j = 0; j < size; j++)
        z[j] = x[j] + y[j];
}

void circular_rotation(int x[], int size)
{
    int item_0 = x[0];    // Save the first element before rotation
    for (int j = 1; j < size; j++)
        x[j-1] = x[j];    // Rotate up
    x[size - 1] = item_0; // Fix the last element
}

void array_print(int x[], int size)
{
    for (int j = 0; j < size; j++)
        cout << x[j] << '\t';
    cout << endl;
}
```

# Example: Modifying Array's Elements by a Function II

```
int main()
{
    int a[] = {1, 2, 3, 4};
    int b[] = {11, 12, 13, 14};
    int c[4];

    array_add(a, b, c, 4);
    array_print(c, 4);
    cout << endl;

    for (int k = 0; k < 4; k++)
    {
        circular_rotation(a, 4);
        array_print(a, 4);
    }

    return 0;
}
```

# Example: Return-by-Value vs. Return-by-Reference

```
#include <iostream>     /* random-element.cpp */
#include <cstdlib>
using namespace std;    /* To return a random array element */

int  element_rbv(int x[], int size) { return x[rand() % size]; }
int& element_rbr(int x[], int size) { return x[rand() % size]; }

void print_array(int x[], int size)
{
    for (int j = 0; j < size; j++) cout << x[j] << ' ';
    cout << endl;
}

int main()
{
    srand(time(0));     // Seed the random num generator
    int data[6] = {10, 20, 30, 40, 50, 60};

    cout << element_rbv(data, 6) << endl; // Same as: cout << data[?]
    cout << element_rbr(data, 6) << endl; // Same as: cout << data[?]
    print_array(data, 6);
    element_rbr(data, 6) += 8;            // Same as: data[?] += 8
    print_array(data, 6);
}
```

# Constant Array

- Just like simple constants, an array of constants can be made using the keyword "const".

```
const int x[] = { 1, 2, 3, 4 };
```

  It defines 4 integer constants: x[0], x[1], x[2], and x[3] are all of the type const int.

- Like simple constants, a constant array
  - must be initialized when it is defined.
  - once defined, its elements cannot be modified.
- One main use of constant array is in the definition of the formal parameters of a function: to disallow modification of the elements of an array passed to a function, declare that array constant using const.
  - inside the function, the array is read-only.
  - however, the original array in the caller is still writable.

# Example: Prevent Modification by Constant Array I

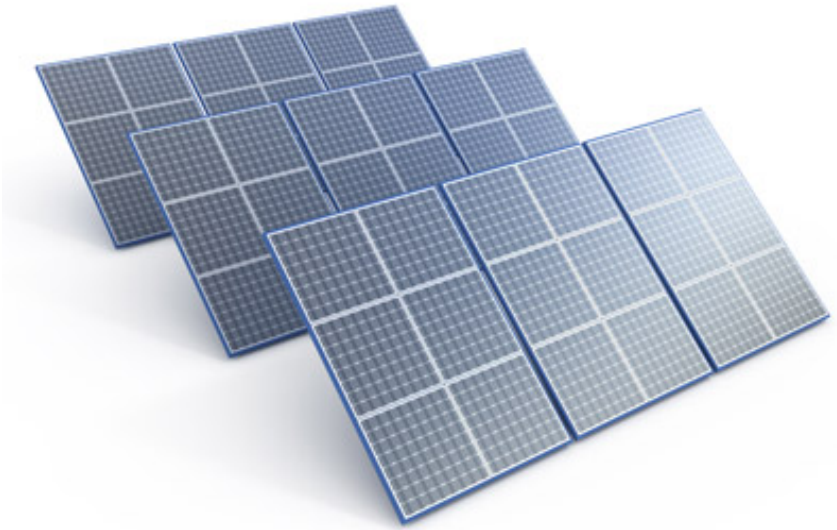
```
#include <iostream>     /* const-array-mean-max-fcn.cpp */
using namespace std;

float mean_score(const float score[], int size)
{
    float sum_score = 0.0;  // Don't forget initializing the sum to 0
    for (int j = 0; j < size; j++)
        sum_score += score[j]; // Accumulate the scores
    return sum_score/size;
}

float max_score(const float score[], int size)
{
    // Initialize the max score to that of the first student
    float max_score = score[0];
    for (int j = 1; j < size; j++)
        if (max_score < score[j])
            max_score = score[j];
    return max_score;
}
```

# Example: Prevent Modification by Constant Array II

```
int main()
{
    const int NUM_STUDENTS = 5;
    float score[NUM_STUDENTS];

    for (int j = 0; j < NUM_STUDENTS; j++)
        if (!(cin >> score[j]))
            return -1;

    cout << "mean score = " << mean_score(score, NUM_STUDENTS) << endl;
    cout << "max score = "  << max_score(score, NUM_STUDENTS) << endl;
    return 0;
}
```

# Part II

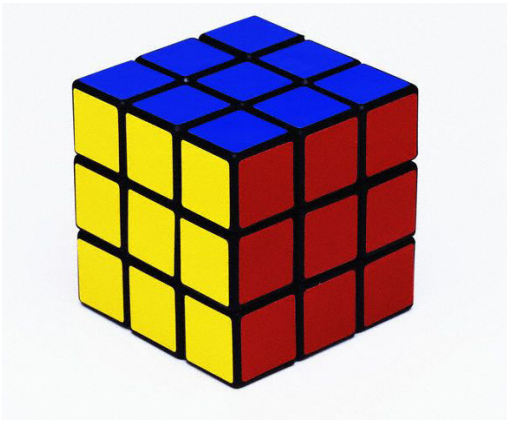
## Multi-dimensional Array



# Array of any Dimensions

In general, an array can be multi-dimensional.



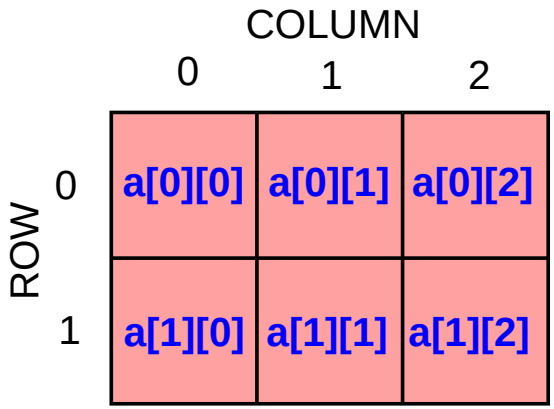


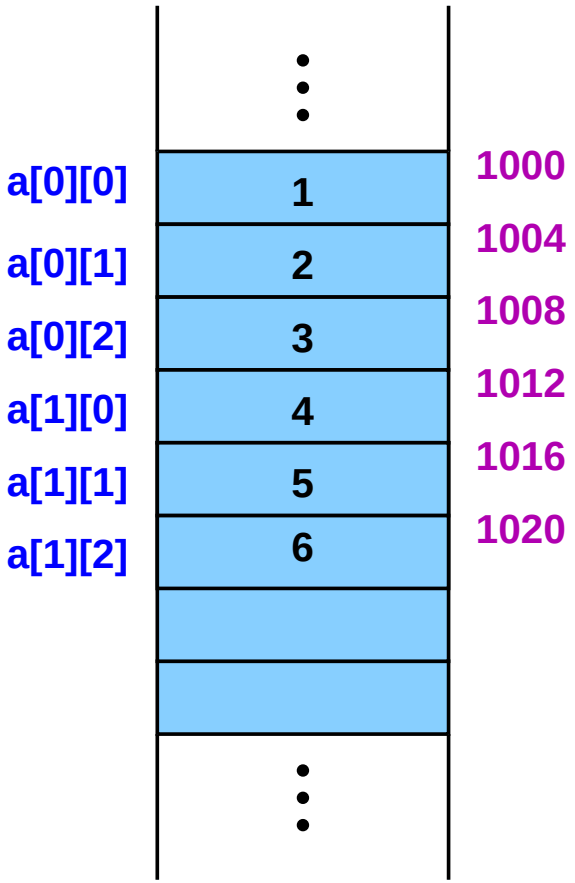
# C++ 2-dimensional Array

## Syntax: Definition of a 2D Array

<data-type> <array-name> [ <size$_1$> ] [ <size$_2$> ] ;

```
int a[2][3] = {1,2,3,4,5,6}; // sizeof(int) = 4
```



# Initialization of 2D Array

- A 2D array can be initialized in 2 ways:
  - row by row, or
  - like a 1D array since the array cells are actually stored linearly in the memory.

## Examples

```
/* Initialize row by row */
int point[5][2] = {  // An int array with 5 rows and 2 columns
    {1, 1},
    {2, 4},
    {3, 9},
    {4, 16},
    {5, 25}
};

/*
 * Initialize using the fact that the cells of a 2D
 * array actually are stored linearly in the memory
 */
int point[5][2] = { 1,1, 2,4, 3,9, 4,16, 5,25 };
```

# Example: Functions with 2D Array I

```
#include <iostream>     /* File: 2d-array-fcn.cpp */
#include <cmath>
using namespace std;

float euclidean_distance(float x1, float y1, float x2, float y2)
{
    float x_diff = x1 - x2, y_diff = y1 - y2;
    return sqrt(x_diff*x_diff + y_diff*y_diff);
}

void print_2d_array(const float a[][3], int num_rows, int num_columns)
{
    for (int i = 0; i < num_rows; i++)
    {
        for (int j = 0; j < num_columns; j++)
            cout << a[i][j] << '\t';
        cout << endl;
    }
}
```

# Example: Functions with 2D Array II

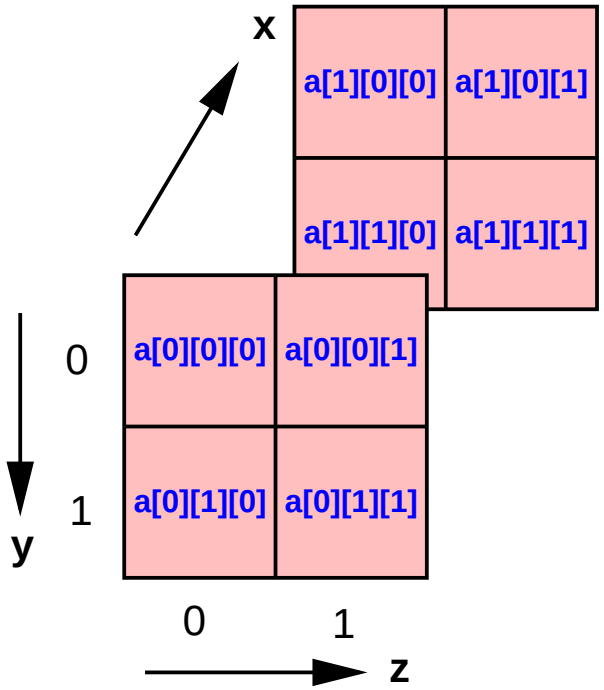
```
void compute_all_distances(
    const float point[][2], float dist[][3], int num_points)
{
    for (int i = 0; i < num_points; i++)
        for (int j = 0; j < num_points; j++)
            dist[i][j]
                = euclidean_distance(point[i][0], point[i][1],
                                     point[j][0], point[j][1]);
}

int main()
{
    float dist[3][3];   // Distances between any pairs of points
    float point[3][2]   // (x, y) coordinates of 3 points
        = { {1.0, 1.0} , {2.0, 2.0} , {4.0, 3.0} };

    compute_all_distances(point, dist, 3);
    print_2d_array(dist, 3, 3);
    return 0;
}
```

# C++ N-dimensional Array

## Syntax: Definition of an N-dimensional Array

<data-type> <array-name> [<size$_1$>] [<size$_2$>] $\cdots$ [<size$_N$>] ;

```
int a[2][2][2] = {1,2,3,4,5,6,7,8}; // sizeof(int) = 4
```

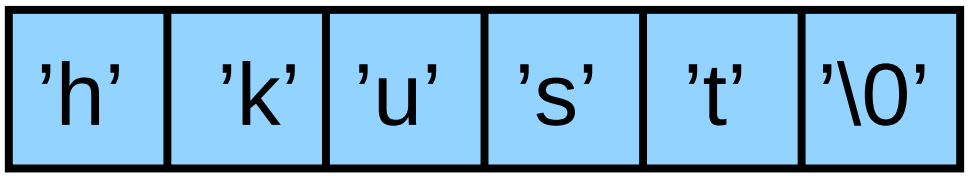



# Remarks on Multi-dimensional Array

- Although conceptually a 2D array is like a matrix, and a 3D array is like a cube, the elements of a multi-dimensional array are stored linearly in the memory (just like a 1D array).
- In C++, the elements of a multi-dimensional array are stored in row-major order: row by row.
- There are programming languages (e.g., FORTRAN) that store multi-dimensional array elements in column-major order: column by column.
- In row-major order, the last dimension index runs fastest, while the first dimension index runs slowest.
- If a multi-dimensional array is used in a C++ function, all dimensions other than the first dimension must be specified in its declaration in the function header.

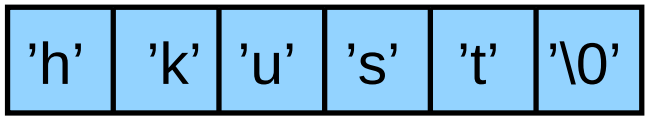
# Part III

## C String: Special 1D Character Array



# C String

- In general, one cannot deal with the whole array at once, but has to deal with each array element, one at a time because a sequence of, e.g., integers, do not represent a new object.
- A char array is different: a sequence of chars may be interpreted as a word or sentence or paragraph or even a novel!
- C++ follows C's trick of representing a character string by a 1D character array with the end-marker '\0'.
- Just add the null character '\0' (ASCII code = 0) after the last character of the string you need.



# C String ..

- For a string of length $N$, add '\0' as the $(N+1)$th element of its char array.
- Now if everyone writes functions of char arrays that represents strings with the above understanding, then one doesn't need to pass the size of such char arrays to their functions!
- C++ allows another notation using the double quotes. e.g.,

$$\text{“hkust”} = \text{'h' 'k' 'u' 's' 't' '\ 0'}$$

# Example: C String

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

int main()
{
    char s1[6] = {'h', 'k','u','s','t', 'z'};

    // At this point, s1 is still a simple char array
    for (int j = 0; j < 5; j++)
        cout << s1[j];
    cout << endl;

    s1[5] = '\0';        // Now, s1 is a C string
    cout << s1 << endl;

    // Another notation for initializing literal constant strings
    char s2[20] = {'h', 'k','u','s','t', '\0'};
    cout << "s2 = " << s2 << endl;
    char s3[20] = "hkust"; cout << "s3 = " << s3 << endl;
    return 0;
}
```

# Example: Some C String Functions I

```
#include <iostream>     /* File: c-string-fcn.cpp */
using namespace std;
const char NULL_CHAR = '\0';

int str_len(const char s[])
{
    int j;
    for (j = 0; s[j] != NULL_CHAR; j++)
        ;
    return j;
}

int str_concatenate(const char s1[], const char s2[], char s[])
{
    int j;
    for (j = 0; s1[j] != NULL_CHAR; j++)
        s[j] = s1[j];   // Copy s1 to s

    for (int k = 0 ; s2[k] != NULL_CHAR; k++, j++)
        s[j] = s2[k];   // Copy s2 after s1

    s[j] = NULL_CHAR;   // Make s a C String
    return j;
}
```

# Example: Some C String Functions II

```
int main()
{
    char a[20] = "Albert";
    char b[20] = "Einstein";
    char c[20];
    int length;

    cout << "length of string a = " << str_len(a) << endl;
    cout << "length of string b = " << str_len(b) << endl;

    length = str_concatenate(a, b, c);
    cout << "After concatenation: "
         << c << " of length " << length << endl;

    return 0;
} // Read Appendix B of the textbook for more C string library functions.
```

# Example: Functions with 2D Character Array

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

void print_strings(const char s[][16], int num_of_strings)
{
    for (int j = 0; j < num_of_strings; j++)
        cout << s[j] << " ";
    cout << endl;
}

int main()
{
    // 5 C-strings, each having a max. length of 15 char
    const char word[5][16] = {
        "hong kong",
        "university",
        "of",
        "science",
        "technology"
    };

    print_strings(word, 5);
    return 0;
}
```

# Reading C Strings with cin

- cin will skip all white spaces before reading data of the required type until it sees the next white space.
- White spaces are any sequence of ' ', '\t' and '\n'.
- For `char x; cin ≫ x;`, if the input is "  hkust ", cin will skip all the leading white spaces, and gives 'h' to x.
- The same is true for reading a C string.
- For `char x[20]; cin ≫ x;`, if the input is "  hkust ", cin will skip all the leading white spaces, and gives "hkust" to x.
- Thus, cin ≫ is not good at reading multiple words or even a paragraph including possibly the newline. Instead, use:

```
cin.getline(char s[], int max-num-char, char terminator);
```

- cin.getline( ) will stop when either (*max-num-char* - 1) characters are read, OR, the terminating character *terminator* is seen. The terminating character is removed from the input stream but is not read into the string.
- The C-string terminating null character is automatically inserted at the end of the read string.

# Example: cin.getline( ) from "hacker.txt"

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

int main()
{
    const int MAX_LINE_LEN = 255;
    char s[MAX_LINE_LEN+1];

    // Read until the newline character (default)
    cin.getline(s, MAX_LINE_LEN+1, '\n');
    cout << s << endl;

    // Read until the character 'W'
    cin.clear(); // Clear the failbit if max #chars are read
    cin.getline(s, sizeof(s), 'W');
    cout << s << endl;

    return 0;
}
```

# Example: Palindrome

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

bool palindrome(const char x[]) {
    int j = 0;              // An index reading the array from top (left)
    int k = strlen(x) - 1; // An index reading the array from bottom (right)

    for ( ; j < k; ++j, --k)
        if (x[j] != x[k])
            return false;
    return true;
}

int main() {
    const int MAX_LINE_LEN = 255; char whole_line[MAX_LINE_LEN+1];

    while (cin.getline(whole_line, MAX_LINE_LEN+1, '\n')// Input ends in newline
           || cin.gcount() == MAX_LINE_LEN) // Input ends with max #chars
    {
        cout << whole_line << endl
             << boolalpha << palindrome(whole_line) << endl;
        cin.clear();    // Clear the failbit if max #chars are read
    }
    return 0;
}
```