Programming Design

Variables and Arrays

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Variables and arrays

- Today we introduce **arrays**.
  - A collection of variables of the same type.
  - An array variable is of an **array type**, a **nonbasic data type**.
- There are many nonbasic data types:
  - Arrays.
  - Pointers.
  - Self-defined data types (e.g., classes).
- Before we introduce arrays, let's talk more about variables and basic data types.

Outline

- **Basic data types**
- Constants and casting
- Single-dimensional arrays
- Multi-dimensional arrays

Data types, literals, and variables

- Recall that in C++, each variable must be have its **data type**.
  - It tells the system how to **allocate** memory spaces and how to **interpret** those 0s and 1s stored there.
  - It will also determine how **operations** are performed on the variable.
- Here we introduce **basic** (or built-in or primitive) data types.
  - Those provided as part of the C++ standard.
  - We will define our own data types later in this semester.
- Before we start, let's distinguish **literals** from **variables**.
  - Literals: items whose contents are **fixed**, e.g., 3, 8.5, and "Hello world".
  - Variables: items whose values may **change**.

Basic data types

- The ten C++ basic data types (bytes information comes from the instructor's compiler):

Category	Type	Bytes	Type	Bytes
Integers	`bool`	1	`long`	4
	`char`	1	`unsigned int`	4
	`int`	4	`unsigned short`	2
	`short`	2	`unsigned long`	4
Fractional numbers	`float`	4	`double`	8

- Basic type names are all keywords.
- Number of bytes are compiler-dependent.

`int`

- `int` means an integer.
- In Dev-C++ 5.11 for Windows 10:
  - An integer uses 4 bytes to store from -2^{31} to $2^{31}-1$.
  - `unsigned` (4 bytes): from 0 to $2^{32}-1$.
  - `short` (2 bytes): from –32768 to 32767.
  - `long`: the same as **`int`**.
- The C++ standard only requires a compiler to ensure that:
  - The space for a **`long`** variable ≥ the space for an **`int`** one.
  - The space for an **`int`** variable ≥ the space for a **`short`** one.
- **`short`** and **`long`** just create integers with different "lengths".
  - In most information systems this is not an issue.

Limits of `int`

- The limits of C++ basic data types are stored in **<climits>**.

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

int main()
{
  cout << INT_MIN << " " << INT_MAX << "\n";

  return 0;
}
```

- For information, see, e.g., http://www.cplusplus.com/reference/climits/.

sizeof

- We may use the **sizeof** operator to know the size of a variable or a type.

```
cout << "int " << sizeof(int) << "\n";
cout << "char " << sizeof(char) << "\n";
cout << "bool " << sizeof(bool) << "\n";

short s = 0;
cout << "short int " << sizeof(s) << "\n";
long l = 0;
cout << "long int " << sizeof(l) << "\n";

cout << "unsigned short int " << sizeof(unsigned short) << "\n";
cout << "unsigned int " << sizeof(unsigned) << "\n";
cout << "unsigned long int " << sizeof(unsigned long) << "\n";
```

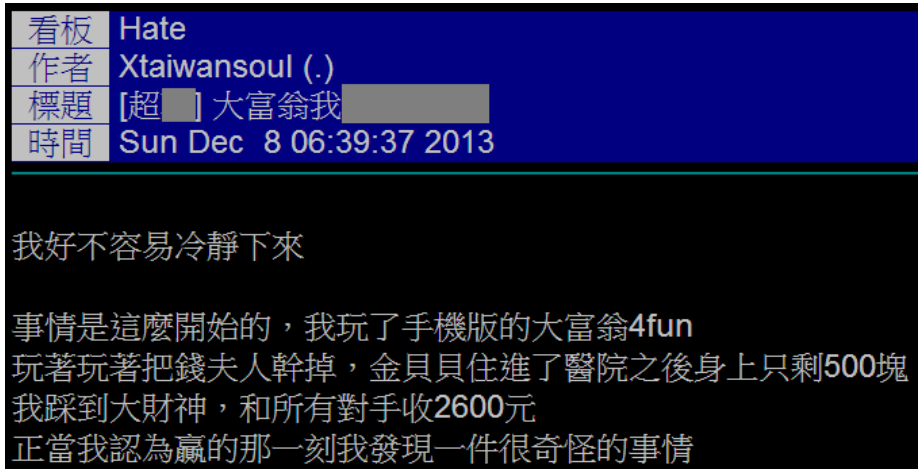
- Dev-C++ (and some other compilers) offers **long long** for 8-byte integers.

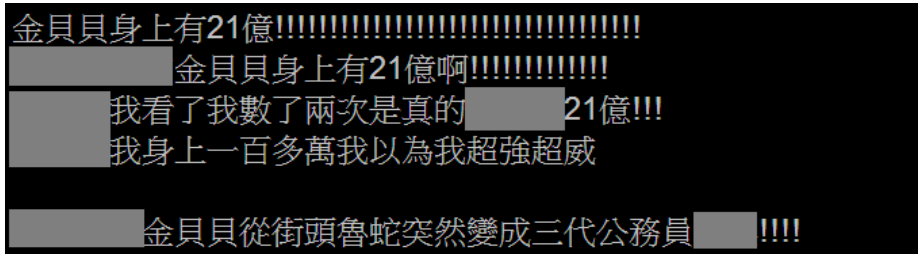
Overflow

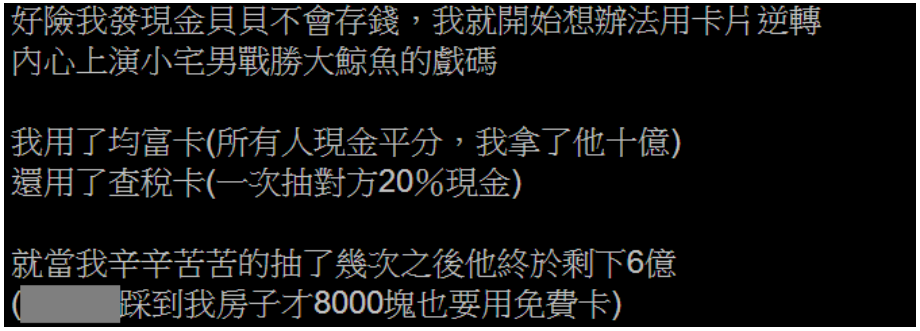
- Be aware of **overflow**!
  - Storing a value that is "too large" to a variable.

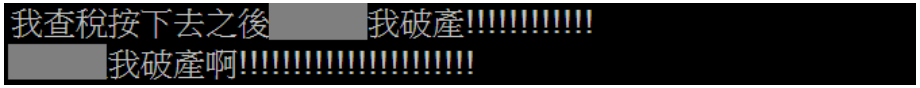
```
int i = 0;
short sGood = 32765;

while(i < 10)
{
  short sBad = sGood + i;
  cout << sGood + i << " " << sBad << "\n";
  i = i + 1;
}
```

Overflow









- Why? Why 2.1 billions?
- $2^{31} - 1 = 2147483647$.

Source: http://disp.cc/m/tread.php?id=115-70Zv

`char`

- **`char`** means a character.
  - Use **one byte** (–128 to 127) to store English letters, numbers, symbols, and special characters (e.g, the newline character).
  - Cannot store, e.g, Chinese characters.
- It is also an **integer**!
  - These characters are encoded with the **ASCII code** in most PCs.
  - ASCII = American Standard Code for Information Interchange.
  - See the ASCII code mapping in your textbook.
- Nevertheless, avoid doing arithmetic on **`char`**.

Example: ASCII code table 1

- This program prints out common symbols and their ASCII codes.

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

int main()
{
  for(int c = 33; c <= 126; c++)
  {
    cout << c << " ";
    char cAsChar = c;
    cout << cAsChar << "\n";
  }

  return 0;
}
```

Example: ASCII code table 2

- Here is another version.
- What is the difference?

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

int main()
{
  cout << "   0 1 2 3 4 5 6 7 8 9\n";
  cout << " 3      ";
  for(int c = 33; c <= 126; c++)
  {
    if(c % 10 == 0)
    {
      if(c / 10 <= 9)
        cout << " ";
      cout << c / 10;
    }
    char cAsChar = c;
    cout << " " << cAsChar;
    if(c % 10 == 9)
      cout << "\n";
  }
  return 0;
}
```

Literals in `char` type

- Use single quotation marks to make your **`char`** literal.
  - **`char c = 'c';`**
  - **`char c = 99;`**
- Some wrong ways of marking a character:
  - Wrong: **`char c = "c";`**
  - Wrong: **`char c = 'cc';`**
- More about **`char`** will be discussed when we talk about **casting** and **strings**.

bool

- A **bool** variable uses 1 byte to record one Boolean value: true or false.
  - Two literals: **true** and **false**.
  - 7 bits are wasted.
  - All non-zero values are treated as true.
- **bool** variables play an important role in control statements!

```
bool b = 0;
cout << b << "\n";

b = 1;
cout << b << "\n";

b = 10;
cout << b << "\n";

b = 0.1;
cout << b << "\n";

b = -1;
cout << b << "\n";
```

`float` and `double`

- **`float`** and **`double`** are used to declare fractional numbers.
  - Can be **`5.0`**, **`-6.2`**, etc.
  - Can be **`16.25e2`** (1.625×10^3 or 1625), **`7.33e-3`** (0.00733), etc.
- They follow the IEEE floating point standards.
  - **`float`** uses 4 bytes to store values between 1.4×10^{-45} and 3.4×10^{38}.
  - **`double`** uses 8 bytes to store values between 4.9×10^{-324} and 1.8×10^{308}.
- Dev-C++ (and some other compilers) offers **`long double`** as a 16-bytes floating point data type.

Precision can be a big issue

- Consider the following program:
- Nothing special.

```
#include<iostream>
#include<cmath> // for sqrt()
using namespace std;

int main()
{
  for(int i = 0; i < 100; i++)
  {
    float f = sqrt(i);
    cout << f << " " << f * f << " ";
    cout << "\n";
  }

  return 0;
}
```

Precision can be a big issue

- How about this:
- As modern computers store values in bits, most **decimal fractional numbers** can only be **approximated**.
  - 3

1	1	.	0	0	0	0

  - 3.375

1	1	.	0	1	1	0

  - 3.4375

1	1	.	0	1	1	1

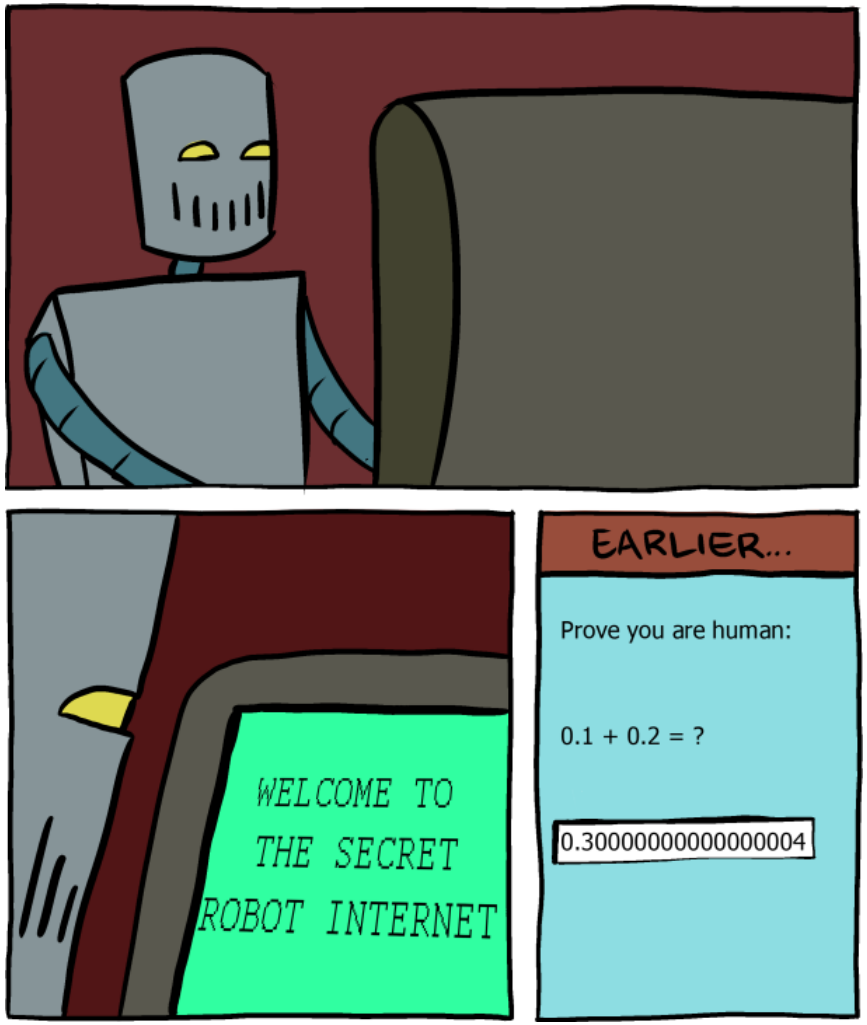
  - 3.4?

```
int bad = 0;
for(int i = 0; i < 100; i++)
{
  float f = sqrt(i);
  cout << f << " " << f * f << " ";

  if(f * f != i)
  {
    cout << "!!!";
    bad++;
  }
  cout << "\n";
}
cout << "bad precision: " << bad;
```

Precision can be a big issue

- Let's see how big the errors are:

```
#include<iostream>
#include<cmath>
#include<iomanip> // setprecision()
using namespace std;

int main()
{
  for(int i = 0; i < 100; i++)
  {
    float f = sqrt(i);
    cout << f << " "
         << setprecision(10)
         << f * f << " ";
    cout << "\n";
  }
  return 0;
}
```



(http://www.smbc-comics.com/comic/2013-06-05)

Precision can be a big issue

- Remedy: “imprecise” comparisons.

```
if(abs(f * f - i) > 0.0001)
{
  cout << "!!!";
  bad++;
}
```

- The error tolerance can be neither too large nor too small.
  - It should be set according to the property of your own problem.
- To learn more about this issue, study *Numerical Methods*, *Numerical Analysis*, *Scientific Computing*, etc.
- In this course, we will play with only integers for most of the time.

Outline

- Basic data types
- **Constants and casting**
- Single-dimensional arrays
- Multi-dimensional arrays

Constant variables

- Sometimes we want to use a variable to store a particular value.
  - In a program doing calculations regarding circles, the value of π may be used **repeatedly**.
  - We do not want to write many `3.14` throughout the program! Why?
  - We may declare `pi = 3.14` once and then use `pi` repeatedly.
- In this case, this variable is actually a **symbolic constant**.
  - We want to prevent it from being **modified**.

Constant variables

- A **constant** is one kind of variables.
- To declare a constant, use the key word **`const`**:
  - `const int a = 100;`
  - All further assignment operations on a constant generate compilation errors.
  - That is why we must **initialize** a constant.
- It is suggested to use **capital characters** and **underlines** to name constants. This distinguishes them from usual variables.
  - `const double PI = 3.1416;`
  - `const int MAX_LEVEL = 5;`
  - Some people use lowercase characters and underlines.

Casting

- Variables are **containers**.
- Variables of different types are containers of different **sizes/shapes**.
  - **`long`** ≥ **`int`** ≥ **`short`**.
  - "Shapes" of **`int`** and **`float`** are different (though sizes are identical).
- A big container may store a small item. A big item must be "cut" to be stored in a small container.
  - So are variables of different types.

```
short s = 100;
int i = s; // 100
i = 100000;
s = i; // -31072
```

```
double d = 5; // d = 5.0
int s = 5.5; // s = 5
```

Casting

- Changing the type of a variable or literal is called **casting**.
- There are two kinds of casting:
  - **Implicit casting**: from a small type to a large type.
  - **Explicit casting**: from a large type to a small type.
- When implicit casting occurs, there is no value of precision loss.
  - The system does that automatically.
  - The value of that variable or literal does not change.
  - There is no need for a programmer to indicate how to implicitly cast one small type to a large type.
- To cast a large type to a small type, a programmer is responsible for indicating **how to do it** explicitly.

Explicit casting

- Suppose we want to store 5.6 to an integer:
  - `int a = 5.6;` is not good.
  - `int a = static_cast<int>(5.6);` is better.
- To cast basic data types, we use **`static_cast`**:

```
static_cast<type>(expression)
```

  - When a float or double is cast to an integer value (and there is no value loss), the fractional part is **truncated**.
- In the example above, both statements makes **`a`** equal 5.
  - Then why bothering?

Explicit casting

- Explicit casting is to indicate the **way** of casting we want.
  - For basic types, there is only one way to cast a large type to a small type.
  - For more complicated types, however, there may be **multiple**.
- There are four different explicit casting operators.
  - **`static_cast`**, **`dynamic_cast`**, **`reindivter_cast`**, and **`const_cast`**.
  - For basic data types, **`static_cast`** is enough.
- By explicitly indicating how to cast:
  - This is to make sure that, at the run time, the program runs as we expect.
  - This is also to notify other programmers (or the future ourselves).
- Explicit casting also allows for a temporary change of types (see below).

Good programming style

- There is an old way of explicit casting:

```
(type) expression
```

  - For example, `int a = (int) 5.6;` .
- Try to avoid it!
  - This operation includes all four possibilities, and we have no idea which one will be performed at the run time.
- If possible, try to modify your variable declaration to avoid casting.

Casting for division

- Let's try this program:

```
int grade1 = 0, grade2 = 0;
cin >> grade1 >> grade2;
cout << (grade1 + grade2) / 2;
```

- The **division** operator returns an integer if both operands (numerator and denominator) are integers.
- How to get our desired results?
  - If appropriate, we may change the data types of the operands.

```
double grade1 = 0, grade2 = 0;
```

  - If not appropriate, we may cast the operands **temporarily**.

Casting for division

- Which one works?

```
int grade1 = 0, grade2 = 0;
cin >> grade1 >> grade2;
cout << static_cast<float>((grade1 + grade2) / 2);
```

```
int grade1 = 0, grade2 = 0;
cin >> grade1 >> grade2;
cout << static_cast<float>(grade1 + grade2) / 2;
```

- Casting can be a big issue when we work with nonbasic data types.
- At this moment, just be aware of fractional and integer values.

Casting a character to an integer

- Try to explain the following program:

```
char c = 254;
int a = 10;
cout << c + a; // 8. Why?
```

- Avoid doing arithmetic on **`char`**.

Outline

- Basic data types
- Constants and casting
- **Single-dimensional arrays**
- Multi-dimensional arrays

Set of similar variables

- Suppose we want to write a program to store five students' scores.
- We may declare 5 variables.
  - `int score1, score2, score3, score4, score5;`
- What if we have 500 students? How to declare 500 variables?
- Even if we have only 5, we are unable to write a loop to process them.

```
for(int i = 0; i < 5; i++)
{
  cout << score1; // and then?
  cout << scorei; // error!
}
```

Why arrays?

- An array is a collection of variables with **the same type**.
- To declare five integer variables for scores, we may write:

```
int score[5];
```

  - These variables are declared with **the same array name** (**`score`**).
  - They are distinguished by their **indices**.

```
cin >> score[2];
```

```
cout << score[2] + score[3];
```

An array is a type

- Arrays are often used with loops.
  - Quite often the loop counter is used as the array index.

```
int score[5];
for(int i = 0; i < 5; i++)
  cin >> score[i];
for(int i = 0; i < 5; i++)
  cout << score[i] << " ";
```

- An array is also a (nonbasic) **type**.
  - The type of **`score`** is an "integer array" (of length 5).
  - What is this?

```
cout << score;
```

- We will go back to this when we introduce pointers.
  - For now, just treat an array as a sequence of variables.

Array declaration

- The grammar for declaring an array is

```
data type array name[number of elements];
```

- E.g., **`int score[5];`**
  - This is an integer array with five elements (the **array length/size** is 5).
  - Each **array element** itself is a **variable**.
  - The **index** starts at **0**! They are **`score[0]`**, **`score[1]`**, …, and **`score[4]`**.
- It occupies 4 bytes × 5 = 20 **continuous** bytes.
  - Try **`cout << sizeof(score);`**!

Address	Identifier	Value
0x20c648	Score[0]	?
0x20c64c	Score[1]	?
0x20c650	Score[2]	?
0x20c654	Score[3]	?
0x20c658	Score[4]	?

Memory

An example

- We have written a program for 5 scores:

```
int score[5];
for(int i = 0; i < 5; i++)
  cin >> score[i];
for(int i = 0; i < 5; i++)
  cout << score[i] << " ";
```

- If we have 500 students:

```
int score[500];
for(int i = 0; i < 500; i++)
  cin >> score[i];
for(int i = 0; i < 500; i++)
  cout << score[i] << " ";
```

Array initialization

- Arrays are **not** initialized automatically.

```
int array[100];

for(int i = 0; i < 100; i++)
{
  cout << array[i] << " ";
  if (i % 10 == 9)
    cout << "\n";
}
```

Array initialization

- Various ways of initializing an array:

```
int daysInMonth1[12] = {31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31};
int daysInMonth2[] = {31, 28, 31, 30, 31, 30, 31, 31, 30, 31, 30, 31};
cout << sizeof(daysInMonth2); // 4 * 12 = 48
int daysInMonth3[12] = {31, 28, 31}; // nine 0s
int daysInMonth4[3] = {1, 2, 3, 4}; // error!
```

- To initialize all elements to 0:

```
int array[100] = {0};

for(int i = 0; i < 100; i++)
{
  cout << array[i] << " ";
  if (i % 10 == 9)
    cout << "\n";
}
```

Example: inner product

- This program calculates the inner product of two given 4-dimensional vectors.
- Do these exercises at home:
  - Modify the program to allow a user to decide the values of the two vectors.
  - Write a program that calculate the sum of two vectors.

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

int main()
{
  int a[4] = {1, 2, 3, 4};
  int b[4] = {4, 3, 2, 1};

  int ip = 0;
  for(int i = 0; i < 4; i++)
    ip += a[i] * b[i];
  cout << ip << "\n";

  return 0;
}
```

The boundary of an array

- In C++, it is **allowed** for one to "go outside an array".
  - No compilation error!
  - **May or may not** generate a **run time error**: If our program try to access a memory space allocated to another program, the operating system will terminate our program.
  - The result is **unpredictable**.
- A programmer must be aware of array bounds by herself/himself.

```
int array[100] = {0};

for(int i = 0; i < 500; i++)
{
  cout << array[i] << " ";
  if (i % 10 == 9)
    cout << "\n";
}
```

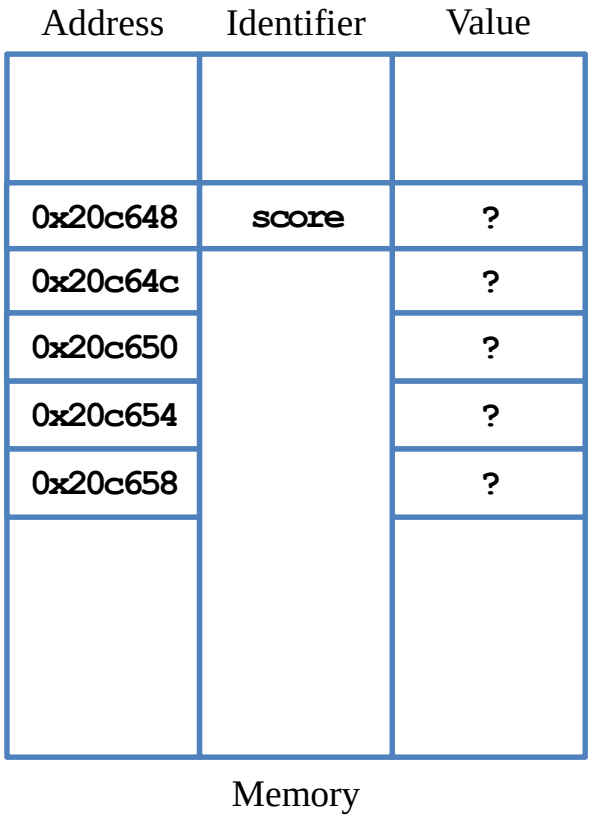
Memory allocation for arrays

- So what happens when we declare or access an array?
- When we declare an array:

```
int score[5];
```

  - The system allocates memory spaces according to the type and length.
  - The array variable indicates the **beginning address** of the space.

```
cout << score; // 0x20c648 (Hexadecimal)
```

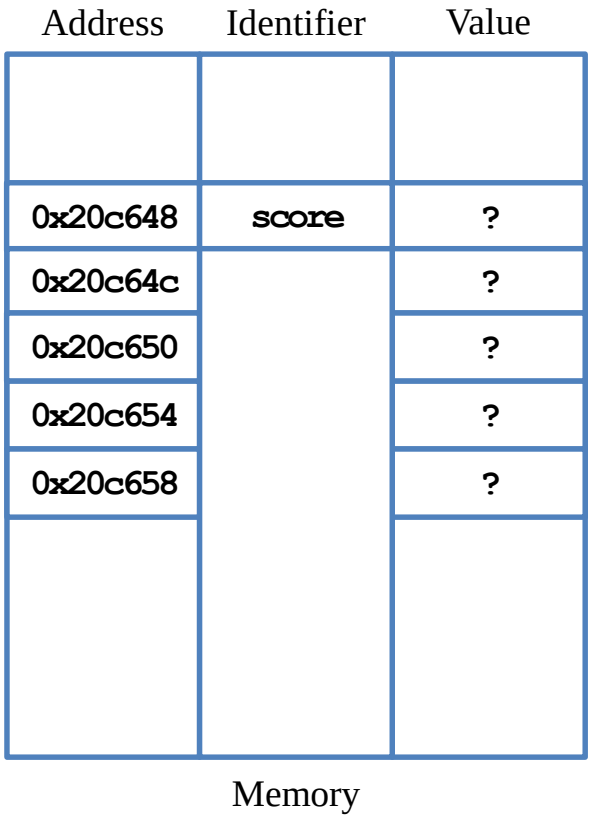


Memory indexing for arrays

- When we access an array element:
  - The array index indicates the amount of **offset** for accessing a memory space.
  - **`score[i]`** means to take the variable stored at "starting from **`score`**, offset by **`i`** units".

```
cout << score + 2; // 0x20c650
```

- So **`score[i]`** is **always accepted** by the compiler for any value of **`i`**.
  - Always be careful when using arrays!



Finding the array length

- Sometimes we are given an array whose size is not known by us.
- One way of finding the **array length** is to use **`sizeof`**.
  - It returns the total number of bytes allocated to that array.
- Suppose the array is named score, its length equals

```
sizeof(score) / sizeof(score[0]);
```

  - **`sizeof(score)`** is the total number of bytes allocated to the array.
  - **`sizeof(score[0])`** is the number of bytes allocated to the first element.

Finding the array length

- Example: Let's print out all elements in an array:

```
int array[] = {1, 2, 3};
int length = sizeof(array) / sizeof(array[0]);
for(int i = 0; i < length; i++)
  cout << array[i] << " ";
```

- When using **`sizeof`** to count the length of, e.g., an integer array:
  - Use **`sizeof(a) / sizeof(a[0])`**.
  - Do not use **`sizeof(a) / sizeof(int)`**.
- Why?

Example: finding the maximum

- How to find the **maximum** among many numbers?
- We want to write a program that:
  - Asks the user to input 10 numbers.
  - Once 10 numbers are input, prints out the maximum.

```
float value[10] = {0};
for(int i = 0; i < 10; i++)
  cin >> value[i];

// and then?
```

- How to find the maximum?
  - Compare the first two and find the larger one.
  - Use it to be compare with the third one.
  - And so on.

Example: finding the maximum

- Let's record the current maximum at **`max`**:

```
float value[10] = {0};
for (int i = 0; i < 10; i++)
  cin >> value[i];

float max = value[0];
for(int i = 1; i < 10; i++)
{
  if(value[i] > max)
    max = value[i];
}
cout << max;
```

Good programming style

- It is suggested to declare a **constant** and use it to:
  - Declare an array.
  - Control any loop that traverses the array.
- Why?

```
const int VALUE_LEN = 10;

float value[VALUE_LEN] = {0};
for (int i = 0; i < VALUE_LEN; i++)
  cin >> value[i];

float max = value[0];
for (int i = 1; i < VALUE_LEN; i++)
{
  if (value[i] > max)
    max = value[i];
}
cout << max;
```

Things you cannot (should not) do

- Suppose that you have two arrays **a1** and **a2**.
  - Even if they have the same length and their elements have the same type, you **cannot** write **a1 = a2**. This results in a syntax error.
  - You also **cannot** compare two arrays with **==**, **>**, **<**, etc.
- Why?
- **a1** and **a2** are just two **memory addresses**!
- To copy one array to another array, use a loop to copy each element **one by one**.

```
int a1[5] = {1, 2, 3, 4, 5};
int a2[5] = {0};

// a2 = a1; // error!
for(int i = 0; i < 5; i++)
{
  a2[i] = a1[i];
}
```

Things you cannot (should not) do

- Although allowed in Dev-C++, you should not declare an array whose length is **nonconstant**.
  - This creates a syntax error in some compilers.
  - In ANSI C++, the length of an array must be **fixed** when it is declared.
- To dynamically determine the array length:
  - We will talk about this a few weeks later.
- The index of an array variable should be **integer**.
  - Some compiler allows a fractional index (casting is done automatically).

```
// DO NOT do this
int x = 0;
cin >> x;
// very bad!
int array[x];
array[2] = 3; // etc.
```

```
// Do this
int x = 0;
cin >> x;
// good!
int* array = new int[x];
array[2] = 3; // etc.
```

Outline

- Basic data types
- Constants and casting
- Single-dimensional arrays
- **Multi-dimensional arrays**

Two-dimensional arrays

- While a one-dimensional array is like a **vector**, a two-dimensional array is like a **matrix** or **table**.
- Intuitively, a two-dimensional array is composed by **rows** and **columns**.
  - To declare a two-dimensional array, we should specify the numbers of rows and columns.

```
data type array name[rows][columns];
```

- As an example, let's declare an array with 3 rows and 7 columns.

```
double score[3][7];
```

Two-dimensional arrays

- **`double score[3][7];`**

	0	1	2	3	4	5	6
0	[0][0]	[0][1]	[0][2]				
1	[1][0]				[*x*][*y*]		
2	[2][0]						

  - **`score[0][0]`** is the 1st and **`score[0][1]`** is the 2nd. What are *x* and *y*?

Two-dimensional arrays

- We may initialize a two-dimensional array as follows:

```
int score1[2][3] = {{4, 5, 6}, {7, 8, 9}};
int score2[][3] = {4, 5, 6, 7, 8, 9}; // 2 can be omitted.
```

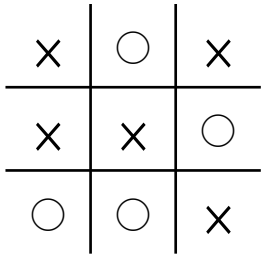
```
int score3[2][3] = {{4, 5}, {7, 8, 9}};
cout << score3[0][2]; // 0
```

```
int score4[2][3] = {4, 5, 7, 8, 9};
cout << score4[0][2]; // 7
```

Example: tic-tac-toe

- Let's write a program to detect the winner of a tic-tac-toe game:

```
int a[3][3] = {{1, 0, 1}, {1, 1, 0}, {0, 0, 1}};

for(int i = 0; i <= 2; i++)
{
  if(a[i][0] == a[i][1] && a[i][1] == a[i][2])
  {
    cout << a[i][0] << "\n";
    break;
  }
}
// then check for columns and diagonals
```



Example: matrix additions

- Let's write a program to do matrix additions.

```
int a[2][3] = {{1, 2, 3}, {1, 2, 3}};
int b[2][3] = {{4, 5, 6}, {7, 8, 9}};
int c[2][3] = {0};

for(int i = 0; i < 2; i++) // matrix addition
  for(int j = 0; j < 3; j++)
    c[i][j] = a[i][j] + b[i][j];

for(int i = 0; i < 2; i ++) // print out c
{
  for(int j = 0; j < 3; j ++)
    cout << c[i][j] << " ";
  cout << "\n";
}
```

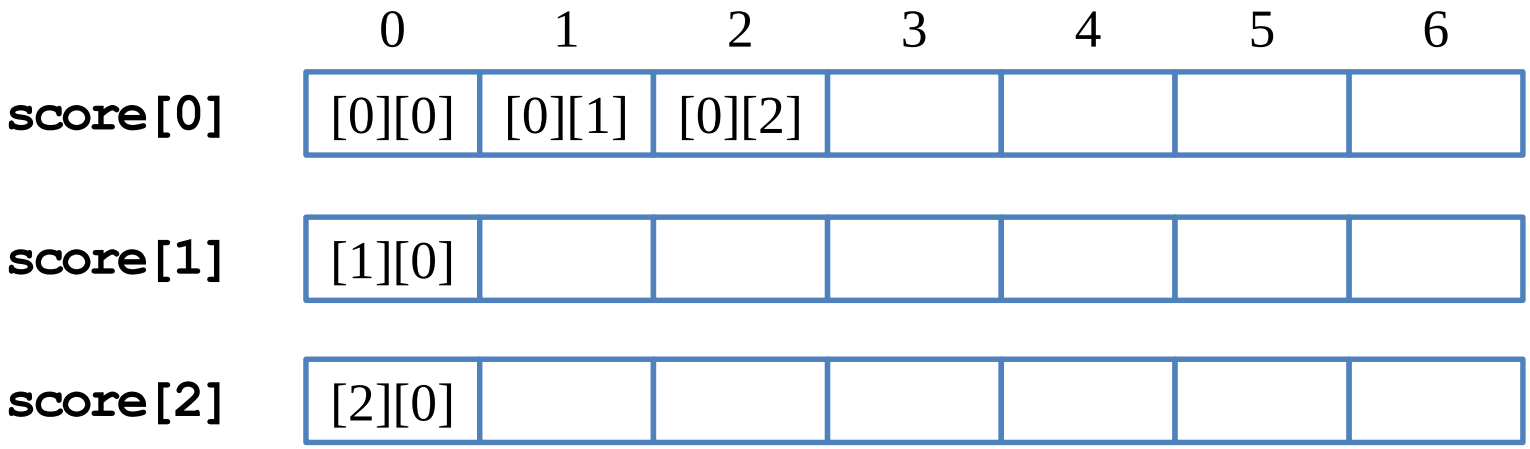
Example: matrix multiplications

- Let's write a program to do matrix multiplications.

```
int a[2][3] = {1, 1, 1, 2, 2, 2};
int b[3][4] = {1, 1, 1, 1, 2, 2, 2, 2, 3, 3, 3, 3};
int c[2][4] = {0};

for(int i = 0; i < 2; i++)
  for(int j = 0; j < 4; j++)
    for(int k = 0; k < 3; k++)
      c[i][j] += a[i][k] * b[k][j];

// print out c
```

Embedded one-dimensional arrays

- Two-dimensional arrays are not actually rows and columns.
- A two-dimensional array is actually **several** one-dimensional arrays.



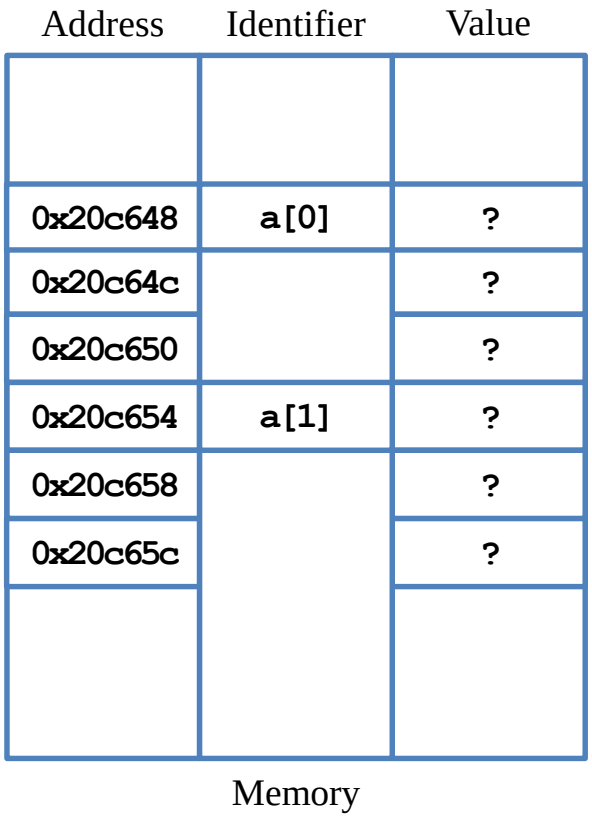
- Try this:

```
int a[2][3];
cout << a << " " << a[0] << " " << a[1] << "\n";
```

Embedded one-dimensional arrays

- `int a[2][3];`
  - `a[0][0]` is the first element.
  - `a[0][1]` is the second element.
  - `a[1][0]` is the **fourth** element.
- Two dimensional arrays are stored **linearly**.
  - And still **consecutively**.
- Try this:

```
int a[2][3];
cout << a << " " << a[0] << "\n";
cout << a[1] << " " << a + 1 << "\n";
cout << sizeof(a) << " " << sizeof(a[0]) << "\n";
```



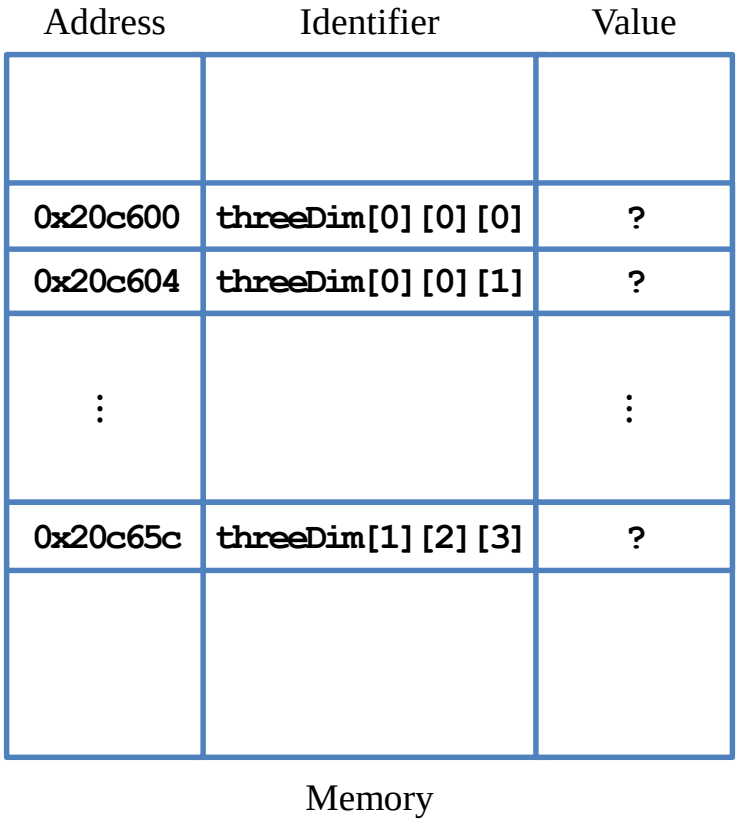
Memory

Embedded one-dimensional arrays

- So for a two dimensional array **`score`**:
  - **`score[0]`** is the ____th one-dimensional array.
  - **`score[i][j]`** is the ____th element of the ____th one-dimensional array.
  - **`score[i]`** is the ____th one-dimensional array.
- Which description is more accurate?
  - There is an array having three rows and seven columns.
  - There is an array having three rows, each having seven elements.
- All these one-dimensional arrays must be of **the same length**.
  - Two-dimensional arrays with various row lengths can be built with pointers.

Multi-dimensional arrays

- We may have arrays with even higher dimensions (but hard to use).
  - `int threeDim[2][3][4];`
  - This is an array of $2 \times 3 \times 4 = 24$ integers.
  - They together occupies $24 \times 4 = 96$ bytes (in a continuous space in the memory).
  - `threeDim` is still the address of the first element `threeDim[0][0][0]`.



Memory

Multi-dimensional arrays

`threeDim`

[0][0][0]	[0][0][1]	[0][0][2]	[0][0][3]
[0][1][0]	[0][1][1]	[0][1][2]	[0][1][3]
[0][2][0]	[0][2][1]	[0][2][2]	[0][2][3]
[1][0][0]	[1][0][1]	[1][0][2]	[1][0][3]
[1][1][0]	[1][1][1]	[1][1][2]	[1][1][3]
[1][2][0]	[1][2][1]	[1][2][2]	[1][2][3]

`threeDim[1]`

[1][0][0]	[1][0][1]	[1][0][2]	[1][0][3]
[1][1][0]	[1][1][1]	[1][1][2]	[1][1][3]
[1][2][0]	[1][2][1]	[1][2][2]	[1][2][3]

`threeDim[1][1]`

[1][1][0]	[1][1][1]	[1][1][2]	[1][1][3]