Introduction to C++
MATH 5061: Fundamentals of Computer Programming for Scientists and Engineers

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Outline

Introduction
Your first C++ program
   Hello World
   Compilation
Basic C++ Syntax
   Statements and Comments
   Expressions
   Variable Declaration & Definition
Fundamental Data Types
   Integer Types
   Floating-Point Types
   Literals
   Characters and C-Strings
   Booleans
Basic Input/Output
Operators
Interpreted vs. Compiled Languages

Python

- Code
- Interpreter
- Machine Code
- CPU

C/C++

- Code
- Compiler
- Machine Code
- CPU

compile time

execution
Portable Code

source code → compiler → machine code

11011101... → mobile phone
01010101... → desktop
11010101... → car
The C Programming Language

- Popular systems programming language
- Implementation language of the UNIX operating systems
- Very portable and efficient
- C++ is a superset of C
What is C++?

C++ is one of the most widely used programming languages today. Many software products you use everyday are programmed in C/C++.

Popular programs implemented in C++

- Microsoft Windows
- Microsoft Office
- Adobe Photoshop
- Facebook uses C++ on the backend
- All major browsers (Firefox, Chrome, Safari)
- 3D Game Engines (Unreal Engine, Cry Engine)
Table: Most popular programming languages (September 2016)

<table>
<thead>
<tr>
<th></th>
<th>Language</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Java</td>
<td>18.236%</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>10.955%</td>
</tr>
<tr>
<td>3</td>
<td>C++</td>
<td>6.657%</td>
</tr>
<tr>
<td>4</td>
<td>C#</td>
<td>5.493%</td>
</tr>
<tr>
<td>5</td>
<td>Python</td>
<td>4.302%</td>
</tr>
<tr>
<td>6</td>
<td>JavaScript</td>
<td>2.929%</td>
</tr>
<tr>
<td>7</td>
<td>PHP</td>
<td>2.847%</td>
</tr>
<tr>
<td>8</td>
<td>Assembly language</td>
<td>2.417%</td>
</tr>
<tr>
<td>9</td>
<td>Visual Basic .NET</td>
<td>2.343%</td>
</tr>
<tr>
<td>10</td>
<td>Perl</td>
<td>2.333%</td>
</tr>
</tbody>
</table>
History

1969-1973  Development of the C Programming Language
1979     Bjarne Stroustrup started developing “C with Classes”
1984     “C with Classes” is renamed to C++
1998     First ISO C++ standard was ratified (C++98)
2001     Bugfix release of the standard (C++2001)
2011     Second ISO C++ standard (C++11) ratified. Previously known as C++0x (they were optimistic)
2014     C++14 standard
2017     Upcoming C++17 standard
ISO C++ Standard

This standard consists of two parts:

**Core language**
- Syntax Rules
- Keywords
- Statements
- Operators

**Standard library**
- General utilities
- Strings
- Data Structures
- Algorithms
- Numerics
- Input/output
Comparison to Python

Python
- architecture independent
- "batteries included"
- rich standard library
- rich ecosystem (pip)
- automatic memory management / garbage collection
- good for general purpose applications, but for expensive computations most modules fall back to "native" code (which is usually written in C/C++)

C/C++
- architecture dependent
- harder to write
- general purpose library
- starting with C++11 standard library is rapidly expanding
- libraries easily extend code, but are not as convenient and error prone in their usage
- manual memory management
- easier to write efficient and fast code
C++ Learning Resources

🌐 Online Resources

▶ http://cppreference.com
▶ http://mindview.net/Books/TICPP/ThinkingInCPP2e.html

📚 Books

▶ The C++ Programming Language, 4th Edition
▶ The C++ Standard Library: Tutorial and Reference
▶ The C Programming Language
What you need to program in C++

1. a text editor
   ▶ vim
   ▶ emacs
   ▶ gedit
   ▶ Notepad++

2. a C++ compiler
   ▶ GNU Compiler Collection (GCC)
   ▶ Clang
   ▶ Intel Compiler
   ▶ Microsoft Visual C++
“Real Programmers”

nano? REAL PROGRAMMERS USE emacs

HEY. REAL PROGRAMMERS USE vim.

WELL, REAL PROGRAMMERS USE ed.

NO, REAL PROGRAMMERS USE cat.

REAL PROGRAMMERS USE A MAGNETIZED NEEDLE AND A STEADY HAND.

EXCUSE ME, BUT REAL PROGRAMMERS USE BUTTERFLIES.

They open their hands and let the delicate wings flap once.

The disturbance ripples outward, changing the flow of the eddy currents in the upper atmosphere.

Which act as lenses that deflect incoming cosmic rays, focusing them to strike the drive platter and flip the desired bit.

NicE. ‘Course, there’s an emacs command to do that. Oh yeah! Good ol’ C-x M-c M-butterfly...

DAMMIT, EMACS.
Know your text editor and know it well

Practise makes perfect

- A tennis player will perfect using his/her tennis racket
- A music player will perfect using his/her instrument
- A artist will learn about his/her brushes and materials
- A programmer’s #1 tool is his/her text editor
Create a configuration file for vim by putting a hidden file in your home directory:

```
vim ~/.vimrc
```

Good defaults are the following contents:

```
syntax on # enables syntax highlighting
set tabstop=4 # makes tab stops 4 spaces wide
set shiftwidth=4 # shifts 4 spaces for indent
set expandtab # expands tabs to spaces
```
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Basic Input/Output

Operators
Your first C++ program

Following the tradition in most programming languages, we are going to write our first C++ program that will print out "Hello World!" to the console.

```cpp
int main() {
    puts("Hello World!");
    return 0;
}
```
Compilation

- a compiler translates C++ code (text) into machine code (binary)
- each source file corresponds to one translation unit
Compilation using the GNU C++ compiler

Before compilation

```bash
ls -la
drwxr-xr-x 2 richard richard 4096 Jun 24 12:12 .
drwxr-xr-x 4 richard richard 4096 Jun 24 12:01 ..
-rw-r--r-- 1 richard richard 104 Jun 24 12:01 hello.cpp
```

After compilation

```bash
g++ -o hello hello.cpp
```
Compilation using the GNU C++ compiler

Before compilation

```
ls -la
drwxr-xr-x 2 richard richard 4096 Jun 24 12:12 .
drwxr-xr-x 4 richard richard 4096 Jun 24 12:01 ..
-rw-r--r-- 1 richard richard 104 Jun 24 12:01 hello.cpp
```

After compilation

```
g++ -o hello hello.cpp
```

```
ls -la
drwxr-xr-x 2 richard richard 4096 Jun 24 12:12 .
drwxr-xr-x 4 richard richard 4096 Jun 24 12:01 ..
-rwxr-xr-x 1 richard richard 8488 Jun 24 12:13 hello
-rw-r--r-- 1 richard richard 104 Jun 24 12:01 hello.cpp
```
Compilation using the GNU C++ compiler

Before compilation

```
ls -la
drwxr-xr-x 2 richard richard 4096 Jun 24 12:12 .
drwxr-xr-x 4 richard richard 4096 Jun 24 12:01 ..
-rw-r--r-- 1 richard richard  104 Jun 24 12:01 hello.cpp
```

After compilation

```
g++ -o hello hello.cpp
```

```
ls -la
drwxr-xr-x 2 richard richard 4096 Jun 24 12:12 .
drwxr-xr-x 4 richard richard 4096 Jun 24 12:01 ..
-rwxr-xr-x 1 richard richard  8488 Jun 24 12:13 hello
-rw-r--r-- 1 richard richard  104 Jun 24 12:01 hello.cpp
```
Live Demo
Your first C++ compile error

g++ -o hello hello.cpp
hello.cpp: In function 'int main()':
hello.cpp:2:24: error: 'puts' was not declared in this scope
  puts("Hello World!");
     ^

int main() {
  puts("Hello World!");
  return 0;
}

Compilation

- During compilation the compiler will NOT run your code
- The compiler only reads the C++ code, line by line, word for word
- Everything used must be known to the compiler
- If you introduce new names in your program, you must tell the compiler what it is

puts example:

We have to tell the compiler what puts is. We want to use the puts function from the C standard library, defined by the POSIX standard.
Using functions from system libraries

- functions such as `puts` are declared in header files
- you have to `include` the correct header in your program in order to use its functions
- if a function is part of the POSIX standard, use `man [FUNCTION]` to learn about which header is needed.

```c
#include <stdio.h>

int main() {
    puts("Hello World!");
    return 0;
}
```

- headers are just another form of C++ code files
- their name usually ends with `.h`, but you will also find `.hh` and `.hpp`
File inclusion

- the `#include`-directive copies the contents of a given header into your source code during compilation
- so when the compiler processes the final file, it will first see the contents of `stdio.h` and *learn about* `puts`
- afterwards `puts` can be used because it is known to the compiler
Live Demo
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Basic Input/Output

Operators
Every C++ program starts in the main-function

- main contains the code which is executed
- Each statement ends with a semicolon ;
- The number returned by the main function is its exit code. By convention, 0 signifies that everything was ok. Non-zero values indicate that an error has occurred.
Simple Expressions

* Multiplication
/ Division
+ Addition
- Subtraction
% Modulus (remainder after division)

Parentheses may be used to group terms.

\[
\begin{align*}
3 & \times (4 + 4) \\
3 & + 8 \times 4 + 4 \\
3 & + (8 \times 4) + 4
\end{align*}
\]
Using Expressions

```c
int main() {
    3 + (8 * 4) + 4;
    return 0;
}
```

While this is a valid program, it doesn’t do anything with the result. We want to store the result of the computation and use it somewhere else.
Dynamic typing vs statically typing

### Python

```
a = 10
# a is an int

a = 10.0
# now it is a float

a = "text"
# now it is a string
```

The data type of variables can change at any time and is determined dynamically.

### C/C++

```
int a = 10;
// a is an int

float b = 10.0f;
// b is a float

char * s = "text";
// s is a C-String
```

Variables are declared of *one* data type which can not change.
Declaration

- Introduces a *name* to the compiler and specifies its *data type*
- A variable can only be declared once inside a scope
- Variables must be declared before being used

```c
int variableName;
```

data type  name
Definition

Copies the value on the right side to the named variable on the left

```
variableName = VALUE;
```

Both can be combined into one statement:

```
int variableName = 42;
```
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Basic Input/Output

Operators
Contents of a Computer Program

- the smallest unit of information is one **bit**, which is either 0 or 1
- any information on a computer is a sequence of bits
- a program consists of two things: data and instructions
  
  **data**  Information needed by the program to run
  **instructions**  Sequence of commands which the processor should execute. This is machine code dependent on the processor.
Recap: storing information in binary

with 1 bit, you can store 2 values

0, 1
Recap: storing information in binary

with 1 bit, you can store 2 values

0, 1

with 2 bit, you can store 4 values

00, 01, 10, 11
Recap: storing information in binary

with 1 bit, you can store 2 values

0, 1

with 2 bit, you can store 4 values

00, 01, 10, 11

with 3 bit, you can store 8 values

000, 001, 010, 011, 100, 101, 110, 111
Recap: storing information in binary

with 1 bit, you can store 2 values

0, 1

with 2 bit, you can store 4 values

00, 01, 10, 11

with 3 bit, you can store 8 values

000, 001, 010, 011, 100, 101, 110, 111

with 4 bit, you can store 16 values

0000, 0001, 0010, 0011, 0100, 0101, 0110, 0111, 1000, 1001, 1010, 1011, 1100, 1101, 1110, 1111
Storing information in binary

number of values represented by $b$ bits $= 2^b$

- 1 byte is 8 bits $\Rightarrow 2^8 = 256$
- 2 bytes are 16 bits $\Rightarrow 2^{16} = 65,536$
- 4 bytes are 32 bits $\Rightarrow 2^{32} = 4,294,967,296$
- 8 bytes are 64 bits $\Rightarrow 2^{64} = 18,446,744,073,709,551,616$
Fundamental Data Types

Processors have two different modes of doing calculations:

- integer arithmetic
- floating-point arithmetic

The operands of these calculations have to be stored in binary form. Because of this there are two groups of fundamental data types for numbers in a computer:

- integer data types
- floating-point data types
Integer Types

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>8 bit (1 byte)</td>
</tr>
<tr>
<td>short int</td>
<td>16 bit (2 byte)</td>
</tr>
<tr>
<td>int</td>
<td>32 bit (4 bytes)</td>
</tr>
<tr>
<td>long int</td>
<td>64 bit (8 bytes)</td>
</tr>
</tbody>
</table>

- `short int` can be abbreviated as `short`
- `long int` can be abbreviated as `long`
- integers are by default `signed`, and can be made `unsigned`

---

1 sizes only valid on Linux x86_64
char

unsigned char
int

unsigned int
### Integer Types - Value Ranges

<table>
<thead>
<tr>
<th>Type</th>
<th>Value Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>$[-128, 127]$</td>
</tr>
<tr>
<td>short</td>
<td>$[-32768, 32767]$</td>
</tr>
<tr>
<td>int</td>
<td>$[-2147483648, 2147483647]$</td>
</tr>
<tr>
<td>long</td>
<td>$[-9223372036854775808, 9223372036854775807]$</td>
</tr>
<tr>
<td>signed char</td>
<td>$[-128, 127]$</td>
</tr>
<tr>
<td>signed short</td>
<td>$[-32768, 32767]$</td>
</tr>
<tr>
<td>signed int</td>
<td>$[-2147483648, 2147483647]$</td>
</tr>
<tr>
<td>signed long</td>
<td>$[-9223372036854775808, 9223372036854775807]$</td>
</tr>
<tr>
<td>unsigned char</td>
<td>$[0, 255]$</td>
</tr>
<tr>
<td>unsigned short</td>
<td>$[0, 65535]$</td>
</tr>
<tr>
<td>unsigned int</td>
<td>$[0, 4294967295]$</td>
</tr>
<tr>
<td>unsigned long</td>
<td>$[0, 18446744073709551615]$</td>
</tr>
</tbody>
</table>
Type Compatibility

- **char**
- **short**
- **int**
- **long**

- **char < short < int < long**
- in words: you can store values of a **char** in a **short**. Both of them can be stored in an **int**. Finally **long** has the largest value range and can store all three smaller types.
- the similar logic applies for **unsigned** types
Floating-Point Types

**float** 32 bit (4 bytes) single precision $\approx 7$ decimal digits
**double** 64 bit (8 bytes) double precision $\approx 15$ decimal digits

- **float** numbers are between $10^{-38}$ to $10^{38}$
- **double** numbers are between $10^{-308}$ to $10^{308}$
**float**

![Float representation](image)

**double**

![Double representation](image)
**sizeof operator**

- returns the number of bytes a data type occupies in memory

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Size (Bytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>1</td>
</tr>
<tr>
<td>short</td>
<td>2</td>
</tr>
<tr>
<td>int</td>
<td>4</td>
</tr>
<tr>
<td>long</td>
<td>8</td>
</tr>
<tr>
<td>float</td>
<td>4</td>
</tr>
<tr>
<td>double</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table:** Data type sizes in Linux with GCC compiler on x86_64

- it can also return the size of a literal
Live Demo
Integer Literals

- A literal represents a fixed value in code: e.g., 42
- There are multiple ways to write integer literals in C++
- If you write just a number, the compiler will choose the smallest data type it will fit into from the following list: `int, long, long long`.

Example:

```c
sizeof(42)     // = 4 (int)
sizeof(4294967295)  // = 8 (long)
```
Integer Literals

- The data type of the literal can be changed using suffixes
-Appending `u` or `U` to an integer makes it an **unsigned** type
-Appending `l` or `L` to an integer makes it a **long** type
-Appending `ul` or `UL` makes it a **unsigned long** type

**Example:**

```plaintext
sizeof(42u)  // = 4 (unsigned int)
sizeof(42ul) // = 8 (unsigned long)
sizeof(4294967295U) // = 8 (unsigned long)
```
Floating-Point Literals

- by default a floating-point literal is a **double**
- appending `f` or `F` to a floating-point literal makes it a **float**
- leading zero is optional
- you can use scientific notation using either `e` or `E`

Examples:

```c
sizeof(42.0)  // = 8 (double)
sizeof(42.0f) // = 4 (float)
.5            // short form
42.0e10       // scientific notation
6.02214086E23
1.38064852e-23
```
Characters and Character Literals

- **char** not only represents 8 bit numbers, but is mainly used for representing text characters.
- each text character in ASCII is mapped to a 8 bit integer number.
- in other words: a character is simply an integer number *interpreted* as a text character
- a character literal is defined using single quotes

**Example:**

```c
char a = 'A';  // equal to 65
char b = 'B';  // equal to 66
char c = b + 1; // equal to 67 which is 'C'
char d = 'a';  // equal to 97
char e = 'b';  // equal to 98
char f = 'B' + ('a'-'A');
```
Special Characters

- \n  newline
- \t  tabulator
- \r  cartridge return
- \0  NUL
- \"  Escaped double quote
- \\
  Escaped backslash
C-Strings

- sequences of characters are called strings
- a string literal is defined using double quotes
- they are often called C-Strings because these are the most primitive form of text strings which existed since C

```c
printf("some text ");
printf("that will be in the same line\n");
printf("some other text on its own line\n");
```

Output

some text that will be in the same line
some other text on its own line
Booleans

- Can only have one of two values: `true` and `false`
- C didn't have Booleans. It used integers for storing such information. This is why they are compatible. You can use any integer result as Boolean expression.
- The integer value 0 is associated to `false`, while anything else is considered `true`

```c
bool b1 = true;
bool b2 = false;
bool b3 = 2; // true
bool b4 = 0; // false
bool is_odd = 5 % 2; // = 1 => true
```
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Basic Input/Output

Operators
Basic Output

- `puts` automatically starts a new line after its output
- `printf` needs the `\n` character at the end to start a new line

```ruby
puts("Hello World!");
printf("Hello World!\n");
```
Formatted Output with `printf`

- `printf` takes one or more arguments
- defined in the `stdio.h` header
- the first argument is a string which may contain placeholders

**Placeholders**

- `%d` decimal number
- `%ud` unsigned decimal number
- `%f` floating-point number
- `%s` C-string
- `%x` decimal as hexadecimal
- `%p` pointer (next week)
printf examples

```
int a = 10;
printf("the value is %d\n", a);
```

the value is 10
```c
double x = 10.0;
double y = 20.0;
printf("Point =(%f, %f)\n", x, y);
```

Point = (10.0, 20.0)
Getting user input using `scanf`

- `scanf` is the inverse of `printf`
- Instead of printing a formatting string with placeholders to a screen, it accepts user input in that format.
- The placeholders are used to save the entered data into variables.
- Variables must be given to the function using their address: `&var`

```c
int value = 0;
printf("Enter a value: ");
scanf("%d", &value);
printf("The value was %d!\n", value);
```

Enter a value:
42
The value was 42!
```c
#include <cstdio>

int main() {
    int a = 0;
    int b = 0;

    puts("Enter first number:");
    scanf("%d", &a);

    puts("Enter second number:");
    scanf("%d", &b);

    int sum = a + b;
    printf("The sum is %d\n", sum);

    return 0;
}
```
Live Demo
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  Expressions
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  Floating-Point Types
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  Booleans

Basic Input/Output

Operators
# Relational Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>&lt;=</code></td>
<td>Less than or equal to</td>
</tr>
<tr>
<td><code>&lt;</code></td>
<td>Less than</td>
</tr>
<tr>
<td><code>&gt;</code></td>
<td>Greater than</td>
</tr>
<tr>
<td><code>&gt;=</code></td>
<td>Greater than or equal to</td>
</tr>
<tr>
<td><code>==</code></td>
<td>Equal</td>
</tr>
<tr>
<td><code>!=</code></td>
<td>Not equal</td>
</tr>
</tbody>
</table>

**Examples:**

```plaintext
int a = 3;
int b = 5;
bool c = a < 4;  // true
bool d = b > 6;  // false
bool e = (b == 5); // true
```
Logical Operators

<table>
<thead>
<tr>
<th>Operator</th>
<th>Name</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp;&amp;</td>
<td>logical AND</td>
<td>(expr1) &amp;&amp; (expr2)</td>
</tr>
<tr>
<td>!</td>
<td>logical NOT</td>
<td>!(expr1)</td>
</tr>
</tbody>
</table>

Examples:

```plaintext
int a = 3;
int b = 5;
bool c = (a == 3) || (b == 5); // true
bool d = (a > 1) && (a < 5);   // true
bool e = !true;                // false
```
Short-circuit evaluation

**Logical OR**

```
exprA || exprB || exprC
```

Evaluation stops after one expression is **true**

**Logical AND**

```
exprA && exprB && exprC
```

Evaluation stops after one expression is **false**

- expressions are evaluated left to right, from inside out, stopping as soon as the result can no longer change.
implicit type conversion

- arithmetic has to be performed using the same data type
- if you mix data types in an expression, the compiler will attempt to implicitly convert towards the larger data type

Type promotion

```c
int a = 3;
double b = 3.3;

printf("%f", a+b); // implicit double+double
printf("sizeof(a+b) = ", sizeof(a+b));
```

6.3
sizeof(a+b) = 8
explicit type conversion

- the compiler will only do conversions to larger types automatically
- for smaller types you have to explicitly tell the compiler what you want by *casting* an expression to a specific data type.
- final result depends on when a cast happens

```java
double a = 3.1;
double b = 3.3;
double c = 3.6;

int result = (int)a + (int)b + (int)c;  // = 9

int result2 = (int)(a + b + c);          // = 10
```
Division

Floating-Point

double a = 1.0 / 3.0;
double b = 10.0 / 3.0;

// a = 0.33333...
// b = 3.33333...

Integer

int a = 1 / 3;
int b = 10 / 3;

// a = 0
// b = 3
operators accessing and changing the same variable can be written in a more compact notation

<table>
<thead>
<tr>
<th>long form</th>
<th>short form</th>
</tr>
</thead>
<tbody>
<tr>
<td>a = a + x</td>
<td>a += x</td>
</tr>
<tr>
<td>a = a - x</td>
<td>a -= x</td>
</tr>
<tr>
<td>a = a * x</td>
<td>a *= x</td>
</tr>
<tr>
<td>a = a / x</td>
<td>a /= x</td>
</tr>
<tr>
<td>a = a % x</td>
<td>a %= x</td>
</tr>
</tbody>
</table>
Increment operator

- incrementing an integer number by one can be done using the increment `++` operator.
- depending on whether the operator is before or after a variable name determines when the operation takes place.
- the prefix versions immediately change the value of the given variable and returns the updated value.
- the postfix version first returns the current value and then updates.

### Pre-increment

```c
int i = 1;
a = ++i;  // a = 2
b = i;    // b = 2
```

### Post-increment

```c
int i = 1;
a = i++;  // a = 1
b = i;    // b = 2
```
Decrement operator

- decrementing an integer number by one can be done using the decrement `--` operator
- depending on whether the operator is before or after a variable name determines when the operation takes place
- the prefix versions immediately change the value of the given variable and returns the updated value
- the postfix version first returns the current value and then updates

### Pre-decrement

```c
int i = 1;
a = --i;  // a = 0
b = i;    // b = 0
```

### Post-decrement

```c
int i = 1;
a = i--;  // a = 1
b = i;    // b = 0
```
Integer literals come in 3 forms: decimal, octal and hexadecimal

- **decimal**: 2016
  - **octal**: 03740 (number start with leading 0)
  - **hexadecimal**: 0x7E0 (number start with leading 0x)

- the reason for octal and hexadecimal are useful for programmer is because they both have a basis which is a power of 2
- this makes it easy to create binary numbers using either of these two notations
Digits of various number representations

Decimal (Base 10)
0, 1, 2, 3, 4, 5, 6, 7, 8, 9

Binary (Base 2)
0, 1

Octal (Base 8)
0, 1, 2, 3, 4, 5, 6, 7

Hexadecimal (Base 16)
0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F
Decimal (Base 10)

\[ 2016 = (2 \cdot 1000) + (0 \cdot 100) + (1 \cdot 10) + (6 \cdot 1) \]
Hexadecimal (Base 16)

\[0x\begin{array}{c}
7 \\
E \\
0
\end{array}\]

\[16^2 \ 16^1 \ 16^0\]

\[2016 = (7 \cdot 256) + (14 \cdot 16) + (0 \cdot 1)\]
Binary (Base 2)

2016 = (1 \cdot 1024) + (1 \cdot 512) + (1 \cdot 256) + (1 \cdot 128) + (1 \cdot 64) + (1 \cdot 32) +
(0 \cdot 16) + (0 \cdot 8) + (0 \cdot 4) + (0 \cdot 2) + (0 \cdot 1)
Recall

with 4 bit, you can store 16 values

\[
\begin{align*}
0000, & \ 0001, \ 0010, \ 0011, \ 0100, \ 0101, \ 0110, \ 0111, \\
1000, & \ 1001, \ 1010, \ 1011, \ 1100, \ 1101, \ 1110, \ 1111
\end{align*}
\]

That’s exactly how many digits we need for one hexadecimal number!

\[
\begin{array}{cccc}
0 & 1 & 0 & 1 \\
2^3 & 2^2 & 2^1 & 2^0
\end{array} \quad \Rightarrow \quad \begin{array}{cccc}
0 & 1 & 0 & 1 \\
8 & 4 & 2 & 1
\end{array}
\]

\[(0 \cdot 8) + (1 \cdot 4) + (0 \cdot 2) + (1 \cdot 1) = 5\]
### Decimal ↔ Hexadecimal ↔ Binary

<table>
<thead>
<tr>
<th>dec</th>
<th>hex</th>
<th>bin</th>
<th>dec</th>
<th>hex</th>
<th>bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0000</td>
<td>8</td>
<td>8</td>
<td>1000</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0001</td>
<td>9</td>
<td>9</td>
<td>1001</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0010</td>
<td>10</td>
<td>A</td>
<td>1010</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0011</td>
<td>11</td>
<td>B</td>
<td>1011</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0100</td>
<td>12</td>
<td>C</td>
<td>1100</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0101</td>
<td>13</td>
<td>D</td>
<td>1101</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>0110</td>
<td>14</td>
<td>E</td>
<td>1110</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>0111</td>
<td>15</td>
<td>F</td>
<td>1111</td>
</tr>
</tbody>
</table>
Binary ⇔ Hexadecimal

0 1 1 1 1 1 1 1 0 0 0 0 0 0

0111 1110 0000 = 0x7E0