

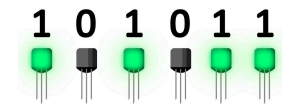
# Computer Organization (Spring 2024)

## Lecture 3: Bitwise Operations

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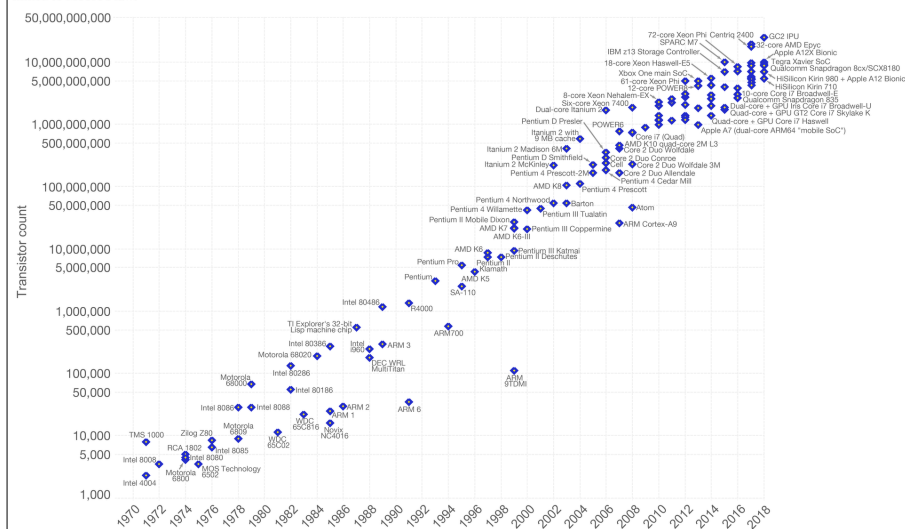
## Bits

- ▶ Computers use the binary system to represent data
- ▶ A **bit** is the smallest unit of data in computing
  - can have a value of 0 or 1, easy to embed in digital devices
  - bits are the building blocks, forming the foundation for all digital information
- ▶ Bit Representation
  - bits are often represented by electrical voltages, where high voltage corresponds to 1 and low voltage to 0



Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia ([https://en.wikipedia.org/wiki/Transistor\\_count](https://en.wikipedia.org/wiki/Transistor_count))  
The data visualization is available at [OurWorldinData.org](https://ourworldindata.org). There you find more visualizations and research on this topic.

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## Bytes

- ▶ A group of 8 bits is called a **byte**
  - bytes are commonly used to represent characters, numbers, and other data in computer systems



MSB

most significant bit

LSB

least significant bit

- ▶ How many different values can be stored in 1 byte?
- ▶ How many different values can be stored in  $n$  bits?

## Basic data types in C

The C language does not explicitly define data sizes. The actual sizes can vary depending on the compiler and the system architecture.

C declaration		Bytes	
Signed	Unsigned	32-bit	64-bit
[signed] char	unsigned char	1	1
short	unsigned short	2	2
int	unsigned	4	4
long	unsigned long	4	8
int32_t	uint32_t	4	4
int64_t	uint64_t	8	8
char *		4	8
float		4	4
double		8	8

## Boolean algebra

### Developed by George Boole in the 19th century

- branch of mathematics that deals with binary variables and logic operations
- binary values represent logical states **true** or **false**

### Three fundamental logic operations

- AND**: output is 1 only if both inputs are 1 — **conjunction**
- OR**: output is 1 if at least one input is 1 — **disjunction**
- NOT** output is the opposite of the input — **negation**

### Boolean expressions

- formed by combining variables and logic operations

## Basic boolean operations (AND, OR, NOT)

Logical operation	Operator	Notation	Alternative notations	Definition
Conjunction	AND	$x \wedge y$	$x$ AND $y$ , $Kxy$	$x \wedge y = 1$ if $x = y = 1$ , $x \wedge y = 0$ otherwise
Disjunction	OR	$x \vee y$	$x$ OR $y$ , $Axy$	$x \vee y = 0$ if $x = y = 0$ , $x \vee y = 1$ otherwise
Negation	NOT	$\neg x$	NOT $x$ , $Nx$ , $\bar{x}$ , $x'$ , $!x$	$\neg x = 0$ if $x = 1$ , $\neg x = 1$ if $x = 0$

$x$	$y$	$x \wedge y$	$x \vee y$
0	0	0	0
1	0	0	1
0	1	0	1
1	1	1	1

$x$	$\neg x$
0	1
1	0

## Bit vectors

### Bit vectors are just sequences of bits

- boolean algebra can be extended to operate on bit vectors

### Applications in Computer Science

- representing sets of elements efficiently
- implementing data structures
- performing bitwise manipulation in low-level programming

Understanding boolean algebra with bit vectors is essential for working with binary data in computer science and digital design

## Bitwise operators in C

- Used with “integer” data types
  - long, int, short, char, unsigned
  - arguments are treated as bit vectors
  - corresponding binary logic operators are applied bitwise to operands
- Bitwise operators are commonly used to manipulate sets and masks

~	bitwise NOT	~a	the bitwise NOT of <b>a</b>
&	bitwise AND	a & b	the bitwise AND of <b>a</b> and <b>b</b>
	bitwise OR	a   b	the bitwise OR of <b>a</b> and <b>b</b>
^	bitwise XOR	a ^ b	the bitwise XOR of <b>a</b> and <b>b</b>
<<	bitwise left shift	a << b	<b>a</b> left shifted by <b>b</b>
>>	bitwise right shift	a >> b	<b>a</b> right shifted by <b>b</b>

## Bitwise operators in C

bit a	bit b	a & b (a AND b)
0	0	0
0	1	0
1	0	0
1	1	1

bit a	bit b	a   b (a OR b)
0	0	0
0	1	1
1	0	1
1	1	1

bit a	bit b	a ^ b (a XOR b)
0	0	0
0	1	1
1	0	1
1	1	0

~a (NOT a) is trivial

## Examples

```

    1 0 1 1 1 0 0 1
& 0 1 1 1 0 1 1 0
-----
    0 0 1 1 0 0 0 0
    
```

```

    1 0 1 1 1 0 0 1
| 0 1 1 1 0 1 1 0
-----
    1 1 1 1 1 1 1 1
    
```

```

    1 0 1 1 1 0 0 1
^ 0 1 1 1 0 1 1 0
-----
    1 1 0 0 1 1 1 1
    
```

```

~ 0 1 1 1 0 1 1 0
-----
    1 0 0 0 1 0 0 1
    
```

## Practice

~0x102

0xABC & 0x411

## Practice

0xABC | 0x411

0x102030 & 0x00FF00

## Shift operations

### ▸ Left shift ( $x \ll y$ )

- shifts each bit in **x** to the left by the number of positions indicated by **y**
  - throw away **y** bits on left
- blank spaces on right are filled up by zeroes

1	0	1	1	1	0	0	1	<< 2
1	1	1	0	0	1	0	0	

## Shift operations

### ▸ Right shift ( $x \gg y$ )

- shifts each bit in **x** to the right by the number of positions indicated by **y**
  - throw away **y** bits on right

Logical shift: fill blank spaces on left with zeroes

1	0	1	1	1	0	0	1	>> 2
0	0	1	0	1	1	1	0	

logical

Arithmetic shift: fill blank spaces by replicating original MSB (most compilers implement it — preserves sign bit)

MSB	1	0	1	1	1	0	0	1	>> 2
	1	1	1	0	1	1	1	0	

arithmetic

## Practice

0xF3 << 2

0x9A >> 3 (logical)

0x9A >> 3 (arithmetic)

## Example: bit masking

- Assume unsigned integer `j` that stores the value `0x1A35B127`
  - define a mask to extract the most significant byte
- write C code to store the extracted value in another variable (unsigned int)

## Example: bit masking

- Assume an integer `j` that stores the value `0x1A35B127`
  - write C code to set the least significant byte of `j` to all ones leaving all other bytes unchanged

## Example: encoding sets

- Instead of using arrays, we can store information more efficiently using bits
- Example:
  - assume we are encoding sets (8 different objects)
    - we can use a `char` variable, such that each bit represents 1 object

1	0	0	0	1	0	0	1
Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune

- How to add, remove, or flip individual objects from the set?
- How to check whether an object is in the set?
- How to perform intersection, union, symmetric difference, and complement?

## Practice

- Assume 4 DNA bases: A C T G
- How many bits are necessary per base? Write a possible encoding.
- If we store bases using integers (4 bytes), how many bases can we store in a single integer?
- Write the DNA sequence stored in `0x10012001`

# Bitwise vs logical operators in C

## ▸ Logical operators

- NOT, AND, OR
- apply to boolean values operands (**true** or **false**)
  - zero is considered **false**, and any non-zero value is considered **true**
- always return a boolean value (**true** or **false**)

```
!a
a && b
a || b
```

## Practice

```
!0xF3
```

```
!0x00
```

```
!!0xF3
```

```
0xF3 && 0xF1
```

```
0xF3 || 0xF1
```