CSC 411

Computer Organization (Fall 2024)
Lecture 3: Bitwise Operations

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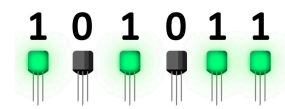
Bits

- Computers use the binary number system to represent and process data
- A **bit** (binary digit) is the <u>smallest</u> unit of data in computing
  - can have a value of 0 or 1
  - easy to implement in digital circuits
  - forms the foundation for all digital information
- Bit Representation
  - bits are typically represented by electrical voltages in computer hardware
    - high voltage corresponds to 1 and low voltage to 0



Bytes

- A **byte** is a group of 8 bits
  - commonly used to represent characters, numbers, and other data
  - <u>smallest addressable unit of memory</u> in most computer architectures

1	0	0	0	1	0	0	1
MSB							LSB
most significant bit							least significant bit

- Important calculations
  - how many different values can be stored in 1 byte?
  - ow 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 dealing with binary variables and logic operations
  - fundamental to digital circuit design and computer science
- Three basic 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

Bit vectors

- Sequences of bits that can represent various types of data
- Boolean algebra can be extended to operate on bit vectors
- Applications in Computer Science
  - efficient set representation
  - implementation of data structures
  - low-level programming and bitwise manipulation

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

Bitwise operators in C

- Operate on "integer" data types
  - long, int, short, chart, unsigned variants
- Treat arguments as bit vectors
- Corresponding logic operators are applied bitwise to operands
- Commonly used to manipulate sets and masks

~	bitwise NOT	~a	the bitwise NOT of **a**
&	bitwise AND	a & b	the bitwise AND of **a** and **b**
|	bitwise OR	a | b	the bitwise OR of **a** and **b**
^	bitwise XOR	a ^ b	the bitwise XOR of **a** and **b**
<<	bitwise left shift	a << b	**a** left shifted by **b**
>>	bitwise right shift	a >> b	**a** right shifted by **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 << y)
  - shifts each bit in **x** to the left by **y** positions
    - discards **y** bits on the left
  - fills **y** blank spaces on the right with zeros

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

Shift operations

- Right shift (x >> y)
  - shifts each bit in **x** to the right by **y** positions
    - discards **y** bits on the right

Logical shift: fill blank spaces on left with zeroes

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

```
1 0 1 1 1 0 0 1   >> 2
---------------
0 0 1 0 1 1 1 0
    logical
```

```
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 an 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

- Questions
  - 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 sequences 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 (true or false)
  - any non-zero value is considered true, zero is false
  - always return a boolean value (true or false)

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

Practice

```
!0xF3

!0x00

!!0xF3

~0xF3

0xF3 && 0xF1

0xF3 || 0xF1
```