Bitwise Operations

We have seen arithmetic and logical integer operations.

C also supports bitwise operations.

These operations correspond to circuit elements.

They are often related to, yet different from, logical operations.

The major operations are:
- Bitwise complement
- Bit shifts (left and right)
- Bitwise AND, OR, and XOR
Planning: Diagrams

After a once-through of the documentation, start drawing.

(See the PA2 Handout video!)

Draw the ideas:

- Data structures
  - Abstract the structure!
  - Arrows represent connections
  - Boxes represent data storage
  - …

- Program flow
  - Read args → open inputs → …
  - (This is more interesting if it’s non-linear!)
Truth Tables

You should already be familiar with truth tables.

Every bitwise operation (except shift) is defined by a truth table.

A truth table represents one or two input bits and their output bit.

For example, bitwise OR:

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>1</td>
</tr>
</tbody>
</table>
### Bitwise Operations

**OR (∨):**

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>Result</th>
</tr>
</thead>
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<tr>
<td>0</td>
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<td>0</td>
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<tr>
<td>1</td>
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<td>1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**XOR (⊕):**

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
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<td>1</td>
<td>1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

**AND (∧):**

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>1</td>
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</tr>
</tbody>
</table>

**NOT (¬):**

<table>
<thead>
<tr>
<th>x</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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Bit Operations on Words

Each of these bit operations can be applied to a word.

Each bit position will have the operation applied individually.

E.g., the application of XOR to an n-bit word is:

$$\forall_{i=0}^{n-1} \text{Result}_i = x_i \oplus y_i$$

Each operation applies to a single bit, so no carries are needed.
Bit Shifting

Bit shifts are slightly more complicated.

C can shift bits left or right.

- **Left shift** (<<): bits move toward larger bit values
- **Right shift** (>>): bits move toward smaller bit values

For **left shift**, zeroes are shifted in on the right.

Examples:

- 0111 left shift 1 bit → 1110
- 0010 left shift 2 bits → 1000
Right Shifts

Right shifts are somewhat trickier.

In particular, they may obey sign extension.

If the shifted integer is unsigned, zeroes are shifted in on the left:
- 0110 right shift 1 bit → 0011
- 1010 right shift 2 bits → 0010

If the shifted integer is signed, the sign bit may affect the shift.
- If it is zero, shifts behave as unsigned
- If it is one, it might shift in ones

If [the shifted value] is a signed type and a negative value, the resulting value is implementation-defined. — ISO C99
Operators

The C bitwise operators divide into unary and binary operators:

Unary:
- \( \sim x \): Bitwise complement of \( x \) (0 → 1, 1 → 0)

Binary:
- \( x | y \): Bitwise OR of \( x \) and \( y \)
- \( x & y \): Bitwise AND of \( x \) and \( y \)
- \( x ^ y \): Bitwise XOR of \( x \) and \( y \)
- \( x << y \): Left shift \( x \) by \( y \) bits
- \( x >> y \): Right shift \( x \) by \( y \) bits
Bit versus Logical Operators

Do not confuse the bit and logical operators!

Some of them work correctly for integers; e.g., |\texttt{\textasciitilde}|.

Some decidedly do not, e.g., &:
\[1 \& 2 \rightarrow \text{logical false!}\]

Not (~) and and (\&) are particularly pernicious because they often work.
Masking

Many bitwise operations are used to work on a portion of a word.

This typically requires masking either:
  ▪ The bits to be modified
  ▪ The bits to be ignored

Masking uses & and sometimes ~.

For example, to get the lowest 8 bits of an integer:

\[
\text{eightbits} = x \& 0xff;
\]

(You might remember this from dumpmem().)
Bit Twiddling

Setting and unsetting individual bits typically uses masking.

Assume we want to set bit zero:

```c
#define LOWBIT 0x1

x = x | LOWBIT;
```

Later, we want to unset bit zero:

```c
x = x & ~LOWBIT;
```

In this case, ~LOWBIT is a mask for all bits except 0.
Twiddling with XOR

If you always want to complement a bit, you can use XOR.

This comes from the truth table; assume $y$ is a constant 1:

<table>
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$x = x \ ^{\text{LOWBIT}}$;
Shifting and Powers of 2

Note that bit shifting left is multiplying by powers of 2!

A one-bit left shift is multiplying by 2:
- 0010 → 2
- 0100 → 4
- 0011 → 3
- 0110 → 6

Successive bit shifts continue to multiply by 2.
- \(1 \ (= 2^0)\)
- \(1 \ll k \ (= 2^k)\)
Forcing Endianness

```c
int hton1(int input) {
    int output;
    char *outb = (char *)&output;
    for (int b = 0; b < sizeof(int); b++) {
        int shift = (sizeof(int) - b - 1) * 8;
        outb[b] = (input >> shift) & 0xff;
    }
    return output;
}
```
htonsl in Action

```c
int x = 0x01020304;
int y = htons(x);

dump_mem(&x, sizeof(x));
dump_mem(&y, sizeof(y));

04 03 02 01
01 02 03 04
```
Summary

- C can manipulate individual bits in memory.
- Bit operations can be subtle and tricky!
- Signedness matters.
- Bit manipulations can force endianness or other representations.
Required Readings


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