Chapter 20

Low-Level Programming

Introduction

- Previous chapters have described C's ***high-level*** machine-independent features
- However, some kinds of programs need to perform operations at the bit level (***low-level***) , e.g.,
  - System programs (including compilers and operating systems)
  - Programs for which fast execution and/or efficient use of space is critical
    - Encryption programs
    - Graphics programs

Bitwise Operators

- `C` provides six ***bitwise operators***, which operate on ***integer data*** at the bit level
- Two of these operators perform
  - *Shift left*, and
  - *Shift right* operations
- The other four perform
  - bitwise *complement*,
  - bitwise *and*,
  - bitwise *exclusive or*, and
  - bitwise *inclusive or* operations

Bitwise Shift Operators

- The bitwise *shift operators* shift the bits in an integer to the left or to the right

  `<<` ***left shift***

  `>>` ***right shift***
- The operands for `<<` and `>>` may be of any integer type (including `char`)
- The integer promotions are performed on both operands
- The result has the type of the left operand after promotion

Bitwise Shift Operators

- The value of `i << j` is the result when the bits in `i` are shifted left by `j` places
  - For each bit that is *"shifted off"* the left end of `i`,
    - zeros are added at the right as needed
- The value of `i >> j` is the result when `i` is shifted right by `j` places.
  - If `i` is of an unsigned type or if the value of `i` is nonnegative,
    - zeros are added at the left as needed
  - If `i` is negative,
    - the result is implementation-defined

Bitwise Shift Operators

- Examples illustrating the effect of applying the shift operators to the number 13

```
unsigned short i, j;

i = 13;
  /* i is now 13 (binary 0000000000001101) */
j = i << 2;
  /* j is now 52 (binary 0000000000110100) */
j = i >> 2;
  /* j is now  3 (binary 0000000000000011) */
```

Bitwise Shift Operators

- To modify a variable by shifting its bits, use the compound assignment operators `<<=` and `>>=`

```
i = 13;
  /* i is now 13 (binary 0000000000001101) */
i <<= 2;
  /* i is now 52 (binary 0000000000110100) */
i >>= 2;
  /* i is now 13 (binary 0000000000001101) */
```

Bitwise Shift Operators

- The *bitwise shift* operators have *lower precedence* than the arithmetic operators, which can cause surprises

  `i << 2 + 1` means `i << (2 + 1)`, not `(i << 2) + 1`

Bitwise Complement, *And*, Exclusive *Or*, and Inclusive *Or*

- There are four additional bitwise operators

`~`	bitwise *complement*
`&`	bitwise *and*
`^`	bitwise *exclusive or*
`|`	bitwise *inclusive or*

- The `~` operator is unary
- The other operators are binary
- The integer promotions are performed on operands
- The usual arithmetic conversions are performed on operands

Bitwise Complement, *And*, Exclusive *Or*, and Inclusive *Or*

- The `~`, `&`, `^`, and `|` operators perform *Boolean operations* on all bits in their operands
- The `^` operator produces `0` whenever both operands have a `1` bit, whereas `|` produces `1`

Bitwise Complement, *And*, Exclusive *Or*, and Inclusive *Or*

- Examples of the `~`, `&`, `^`, and `|` operators

```
unsigned short i, j, k;
i = 21;
  /* i is now    21 (binary 0000000000010101) */
j = 56;
  /* j is now    56 (binary 0000000000111000) */
k = ~i;
  /* k is now 65514 (binary 1111111111101010) */
k = i & j;
  /* k is now    16 (binary 0000000000010000) */
k = i ^ j;
  /* k is now    45 (binary 0000000000101101) */
k = i | j;
  /* k is now    61 (binary 0000000000111101) */
```

Bitwise Complement, *And*, Exclusive *Or*, and Inclusive *Or*

- The `~` operator can be used to help make low-level programs more portable
  - An integer whose bits are all 1's: `~0`
  - An integer whose bits are all 1's except for the last five: `~0x1f`
  - An integer whose bits are all 1's except for the last n: `(~0<<n)`

Bitwise Complement, *And*, Exclusive *Or*, and Inclusive *Or*

- Each of the `~`, `&`, `^`, and `|` operators has a different precedence

```
Highest:  ~
          &
          ^
Lowest:   |
```

- Examples

`i & ~j | k` means `(i & (~j)) | k`

`i ^ j & ~k` means `i ^ (j & (~k))`

- Using parentheses helps avoid confusion

Bitwise Complement, *And*, Exclusive *Or*, and Inclusive *Or*

- The compound assignment operators `&=`, `^=`, and `|=` correspond to the bitwise operators `&`, `^`, and `|`

```
i = 21;
  /* i is now 21 (binary 0000000000010101) */
j = 56;
  /* j is now 56 (binary 0000000000111000) */
i &= j;
  /* i is now 16 (binary 0000000000010000) */
i ^= j;
  /* i is now 40 (binary 0000000000101000) */
i |= j;
  /* i is now 56 (binary 0000000000111000) */
```

Using the Bitwise Operators to Access Bits

- The bitwise operators can be used to extract or modify data stored in a small number of bits
- Common single-bit operations
  - Setting a bit
  - Clearing a bit
  - Testing a bit
- Assumptions
  - `i` is a 16-bit `unsigned short` variable
  - The leftmost—or ***most significant***—bit is numbered 15
  - The rightmost—or ***least significant***—bit is numbered 0

Using the Bitwise Operators to Access Bits

- ***Setting a bit:*** The easiest way to set bit 4 of `i` is to *or* the value of `i` with the constant `0x10`

```
i = 0xFF00;
  /* i is now 1111111100000000 */
i |= 0x10;
  /* i is now 1111111100010000 */
```

- If the position of the bit is stored in the variable `j`, a shift operator can be used to create the mask

```
i |= 1 << j;        /* sets bit j */
```

- Example
  If `j` has the value `3`, then `1 << j` is `0x8`

Using the Bitwise Operators to Access Bits

- ***Clearing a bit:*** Clearing bit 4 of `i` requires a mask with a 0 bit in position 4 and 1 bits everywhere else

```
i = 0x00FF;
  /* i is now 0000000011111111 */
i &= ~0x10;
  /* i is now 0000000011101111 */
```

- A statement that clears a bit whose position is stored in a variable

```
i &= ~(1 << j);     /* clears bit j */
```

Using the Bitwise Operators to Access Bits

- ***Testing a bit:*** An `if` statement that tests whether bit 4 of `i` is set

```
if (i & 0x10) …    /* tests bit 4 */
```

- A statement that tests whether bit `j` is set

```
if (i & 1 << j) …    /* tests bit j */
```

Using the Bitwise Operators to Access Bits

- Working with bits is easier if they are given names
- Suppose that bits 0, 1, and 2 of a number correspond to the colors blue, green, and red, respectively
- Names that represent the three *bit positions*

```
#define BLUE   1
#define GREEN  2
#define RED    4
```

Using the Bitwise Operators to Access Bits

- Examples of setting, clearing, and testing the `BLUE` bit

```
i |= BLUE;          /* sets BLUE bit    */
i &= ~BLUE;         /* clears BLUE bit */
if (i & BLUE) …     /* tests BLUE bit   */
```

Using the Bitwise Operators to Access Bits

- It's also easy to set, clear, or test several bits at time

```
i |= BLUE | GREEN;
  /* sets BLUE and GREEN bits   */
i &= ~(BLUE | GREEN);
  /* clears BLUE and GREEN bits */
if (i & (BLUE | GREEN)) …
  /* tests BLUE and GREEN bits  */
```

- The `if` statement tests whether *either* the `BLUE` bit *or* the `GREEN` bit is set

Using the Bitwise Operators to Access Bit-Fields

- Dealing with a *group of several consecutive bits* (a ***bit-field***) is slightly more complicated than working with single bits
- Common *bit-field* operations
  - *Modifying* a bit-field
  - *Retrieving* a bit-field

Using the Bitwise Operators to Access Bit-Fields

- ***Modifying a bit-field***
  Requires two operations
  – A bitwise *and* (to clear the bit-field)
  – A bitwise *or* (to store new bits in the bit-field)
- Example

```
i = i & ~0x70 | 0x50;
  /* stores 101 in bits 4-6 */
```

  – The `&` operator clears bits 4–6 of `i`
  – The `|` operator then sets bits 4 and 6, but not 5

Using the Bitwise Operators to Access Bit-Fields

- To generalize the example, assume that `j` contains the value to be stored in bits 4–6 of `i`
- `j` will need to be shifted into position before the bitwise *or* is performed

```
i = (i & ~0x70) | (j << 4);
  /* stores j in bits 4-6 */
```

- The `|` operator has lower precedence than `&` and `<<`, so the parentheses can be dropped

```
i = i & ~0x70 | j << 4;
```

Using the Bitwise Operators to Access Bit-Fields

- ***Retrieving a bit-field*:**
  Fetching a bit-field at the right end of a number (in the least significant bits) is easy

```
j = i & 0x7;
  /* retrieves bits 0-2 */
```

- If the bit-field isn't at the right end of `i`, we can first shift the bit-field to the end before extracting the field using the `&` operator

```
j = (i >> 4) & 0x7;
  /* retrieves bits 4-6 */
```

Program: XOR Encryption

- One of the simplest ways to encrypt data is to exclusive-*or* (XOR) each character with a *secret key*
- Suppose that the key is the ASCII code of the `&` character
- XORing this key with the character `z` yields the `\` character

```
     00100110  (ASCII code for &)
XOR  01111010  (ASCII code for z)
     01011100  (ASCII code for \)
```

- Decrypting a message is done by applying the same algorithm

```
     00100110  (ASCII code for &)
XOR  01011100  (ASCII code for \)
     01111010  (ASCII code for z)
```

Program: XOR Encryption

- The `xor.c` program encrypts a message by XORing each character with the `&` character
- The original message can be entered by the user or read from a file using input redirection
- The encrypted message can be viewed on the screen or saved in a file using output redirection

Program: XOR Encryption

- A sample file named `msg`

```
Trust not him with your secrets, who, when left
alone in your room, turns over your papers.
            --Johann Kaspar Lavater (1741-1801)
```

- A command that encrypts `msg`, saving the encrypted message in `newmsg`

```
xor < msg > newmsg
```

- Contents of `newmsg`

```
rTSUR HIR NOK QORN _IST UCETCRU, QNI, QNCH JC@R
GJIHC OH _IST TIIK, RSTHU IPCT _IST VGVCTU.
            --lINGHH mGUVGT jGPGRCT (1741-1801)
```

Program: XOR Encryption

- A command that recovers the original message and displays it on the screen

```
xor < newmsg

Trust not him with your secrets, who, when left
alone in your room, turns over your papers.
            --Johann Kaspar Lavater (1741-1801)
```

Program: XOR Encryption

- The `xor.c` program will not change some characters, including digits
- XORing these characters with `&` would produce invisible control characters, which could cause problems with some operating systems
- The program checks whether both the original character and the new (encrypted) character are printable characters
- If not, the program will write the original character instead of the new character

xor.c

```
/* Performs XOR encryption */

#include <ctype.h>
#include <stdio.h>

#define KEY '&'

int main(void)
{
  int orig_char, new_char;

  while ((orig_char = getchar()) != EOF)
  { new_char = orig_char ^ KEY;
    if (isprint(orig_char) && isprint(new_char))
      putchar(new_char);
    else
      putchar(orig_char);
  }

  return 0;
}
```

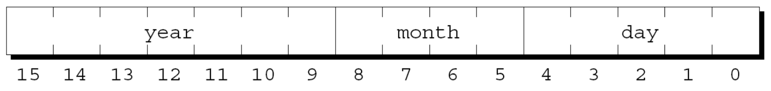
Bit-Fields in Structures

- The bit-field techniques discussed previously can be tricky to use and potentially confusing
- Fortunately, **C** provides an alternative:
  - declaring structures whose members represent *bit-fields*

Bit-Fields in Structures

Example:

- How **DOS** stores the date at which a file was created or last modified
- Since days, months, and years are small numbers, storing them as normal integers would waste space
- Instead, **DOS** allocates only 16 bits for a date, with 5 bits for the day, 4 bits for the month, and 7 bits for the year



Bit-Fields in Structures

- A **C** structure that uses bit-fields to create an identical layout

```
struct file_date {
  unsigned int day: 5;
  unsigned int month: 4;
  unsigned int year: 7;
};
```

- A condensed version

```
struct file_date {
  unsigned int day: 5, month: 4, year: 7;
};
```

Bit-Fields in Structures

- The type of a *bit-field* must be either
  - `int`
  - `unsigned int`
- Using `int` is ambiguous, as some compilers treat the field's high-order bit as a sign bit, but others don't
- In **C99**, *bit-fields* may also have type `_Bool`

Bit-Fields in Structures

- A *bit-field* can be used in the same way as any other member of a structure

```
struct file_date fd;

fd.day = 28;
fd.month = 12;
fd.year = 8;      /* represents 1988 */
```

- Appearance of the `fd` variable after these assignments

0	0	0	1	0	0	0	1	1	0	0	1	1	1	0	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

Bit-Fields in Structures

- When a data item consists of more than one byte, there are two logical ways to store it in memory
  - ***Big-endian:*** Bytes are stored in *natural* order (the leftmost byte comes first)
  - ***Little-endian:*** Bytes are stored in *reverse* order (the leftmost byte comes last)
- x86 Intel processors use little-endian order
- Motorola processors use big-endian

0	0	0	1	0	0	0	1	1	0	0	1	1	1	0	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

Bit-Fields in Structures

- The address operator (`&`) ***can't*** be applied to a bit-field
- Because of this rule, functions such as `scanf` can't store data directly in a bit-field

```
scanf("%d", &fd.day);    /*** WRONG ***/
```

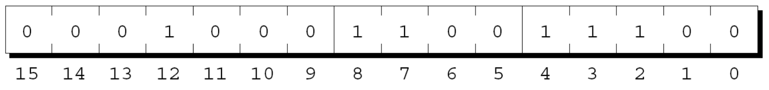
- We can still use `scanf` to read input into an ordinary variable and then assign it to `fd.day`

How Bit-Fields Are Stored

- The C standard allows the compiler considerable latitude in choosing how it stores bit-fields
- The rules for handling bit-fields depend on the notion of "*storage units*"
- The *size of a storage unit* is implementation-defined
  - Typical values are 8 bits, 16 bits, and 32 bits
- ***Obelix*** storage unit is 32 bits

How Bit-Fields Are Stored

- The compiler packs bit-fields one by one into a storage unit, with no gaps between the fields, until there's not enough room for the next field
- At that point,
  - Some compilers skip to the beginning of the next storage unit,
  - Other compilers split the bit-field across the storage units
- The *order in which bit-fields are allocated* is also implementation-defined (*left-to-right* or *right-to-left*)



How Bit-Fields Are Stored

- Assumptions in the `file_date` example
  - Storage units are 16 bits long
  - Bit-fields are allocated from right to left (the first bit-field occupies the low-order bits)
- An 8-bit storage unit is also acceptable if the compiler splits the `month` field across two storage units

0	0	0	1	0	0	0	1	1	0	0	1	1	1	0	0
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0

How Bit-Fields Are Stored

- The name of a bit-field can be omitted
- Unnamed bit-fields are useful as "*padding*" to ensure that other bit-fields are properly positioned
- A structure that stores the time associated with a **DOS** file

```
struct file_time {
  unsigned int seconds: 5;
  unsigned int minutes: 6;
  unsigned int hours: 5;
};
```

How Bit-Fields Are Stored

- The same structure with the name of the `seconds` field omitted

```
struct file_time {
  unsigned int : 5;       /* not used */
  unsigned int minutes: 6;
  unsigned int hours: 5;
};
```

- The remaining bit-fields will be aligned as if `seconds` were still present

How Bit-Fields Are Stored

- The length of an unnamed bit-field *can be* 0

```
struct s {
  unsigned int a: 4;
  unsigned int  : 0;     /* 0-length bit-field */
  unsigned int b: 8;
};
```

- A 0-length bit-field tells the compiler to *align* the following bit-field at the beginning of a storage unit
  - If storage units are 8 bits long, the compiler will allocate 4 bits for `a`, skip 4 bits to the next storage unit, and then allocate 8 bits for `b`
  - If storage units are 16 bits long, the compiler will allocate 4 bits for `a`, skip 12 bits, and then allocate 8 bits for `b`

Other Low-Level Techniques

- Some features covered in previous chapters are used often in low-level programming
- Examples
  - Defining types that represent units of storage
  - Using unions to bypass normal type-checking
  - Using pointers as addresses

Defining Machine-Dependent Types

- The `char` type occupies one byte, so characters can be treated as bytes
- It's a good idea to define a `BYTE` type

```
typedef unsigned char BYTE;
```

- Depending on the machine, additional types may be needed

Using Unions to Provide Multiple Views of Data

- `union` can be used to view a block of memory in two or more different ways
- Consider the `file_date` structure described earlier

```
struct file_time {
  unsigned int seconds: 5;
  unsigned int minutes: 6;
  unsigned int hours: 5;
};
```

- A `file_date` structure fits into two bytes, so any two-byte value can be thought of as a `file_date` structure

Using Unions to Provide Multiple Views of Data

- In particular, an `unsigned short` value can be viewed as a `file_date` structure
- A `union` that can be used to convert a `short integer` to a `file_date` or vice versa

```
union int_date {
  unsigned short i;
  struct file_date fd;
};
```

Using Unions to Provide Multiple Views of Data

- A function that *decodes* and *prints* an `unsigned short` argument as a `file_date`

```
void print_date(unsigned short n)
{
  union int_date
  { unsigned short i;
    struct file_date fd;
  } u;

  u.i = n;
  printf("%d/%d/%d\n", u.fd.month,
         u.fd.day, u.fd.year + 1980);
}
```

Using Pointers as Addresses

- An address often has the same number of bits as an `int` (or `long int`)
- Creating a pointer that represents a *specific memory address* is done by *casting an integer to a pointer*

```
BYTE *p;

p = (BYTE *) 0x1000;
  /* p contains address 0x1000 */
```

Program: Viewing Memory Locations

- The `viewmemory.c` program allows the user to view segments of computer memory
- The program first displays the address of its own `main` function as well as the address of one of its variables
- The program next prompts the user to enter an address (as a hexadecimal integer) plus the number of bytes to view
- The program then displays a block of bytes of the chosen length, starting at the specified address

Program: Viewing Memory Locations

- Bytes are displayed in groups of 10 (except for the last group)
- Bytes are shown both as hexadecimal numbers and as characters
- Only printable characters are displayed;
  other characters are shown as periods
- The program assumes that `int` values and addresses are stored using 32 bits
- Addresses are displayed in hexadecimal

viewmemory.c

```
/* Allows the user to view regions of computer memory */

#include <ctype.h> //isprint() prototype is defined in ctype.c
#include <stdio.h>

typedef unsigned char BYTE;

int main(void)
{
  unsigned int addr;
  int i, n;
  BYTE *ptr;

  printf("Address of main function: %x\n", (unsigned int) main);
  printf("Address of addr variable: %x\n", (unsigned int) &addr);
```

```
  printf("\nEnter a (hex) address: ");
  scanf("%x", &addr);
  printf("Enter number of bytes to view: ");
  scanf("%d", &n);

  printf("\n");
  printf(" Address              Bytes              Characters\n");
  printf(" -------  -----------------------------  ----------\n");
  ptr = (BYTE *) addr;
  for (; n > 0; n -= 10) {
    printf("%8X  ", (unsigned int) ptr);
    for (i = 0; i < 10 && i < n; i++)
      printf("%.2X ", *(ptr + i));
    for (; i < 10; i++)
      printf("   ");
    printf(" ");
    for (i = 0;  i < 10 && i < n; i++)
    { BYTE ch = *(ptr + i);
      if (!isprint(ch))
        ch = '.';
      printf("%c", ch);
    }
    printf("\n");
    ptr += 10;
  }

  return 0;
}
```

Program: Viewing Memory Locations

- Sample output using GCC on an `x86` system running Linux

```
Address of main function: 804847c
Address of addr variable: bff41154

Enter a (hex) address: 8048000
Enter number of bytes to view: 40

 Address               Bytes                Characters
 -------  -----------------------------     ----------
 8048000  7F 45 4C 46 01 01 01 00 00 00     .ELF......
 804800A  00 00 00 00 00 00 02 00 03 00     ..........
 8048014  01 00 00 00 C0 83 04 08 34 00     ........4.
 804801E  00 00 C0 0A 00 00 00 00 00 00     ..........
```

- The 7F byte followed by the letters E, L, and F identify the *Executable Linking Format*, which is widely used by Unix systems, including Linux (`8048000` is the default address at which ELF executables are loaded on x86 platforms)

Program: Viewing Memory Locations

- A sample that displays bytes starting at the address of `addr`

```
Address of main function: 804847c
Address of addr variable: bfec5484

Enter a (hex) address: bfec5484
Enter number of bytes to view: 64

 Address               Bytes              Characters
 -------  -----------------------------   ----------
BFEC5484  84 54 EC BF B0 54 EC BF F4 6F   .T...T...o
BFEC548E  68 00 34 55 EC BF C0 54 EC BF   h.4U...T..
BFEC5498  08 55 EC BF E3 3D 57 00 00 00   .U...=W...
BFEC54A2  00 00 A0 BC 55 00 08 55 EC BF   ....U..U..
BFEC54AC  E3 3D 57 00 01 00 00 00 34 55   .=W.....4U
BFEC54B6  EC BF 3C 55 EC BF 56 11 55 00   ..<U..V.U.
BFEC54C0  F4 6F 68 00                     .oh.
```

- When reversed, the first four bytes form the number `BFEC5484`, the address entered by the user