COMP1521 24T1 — Bitwise Operators

https://www.cse.unsw.edu.au/~cs1521/24T1/

Bitwise Operators

- CPUs typically provide instructions which operate on individual bits of values.
  - MIPS provides 13 bit manipulation instructions
  - other CPUs can provide more
- C provides 6 operators which operate on individual bits of values

```
x & y      // bitwise and
x | y      // bitwise or
x ^ y      // bitwise exclusive-or (XOR)
~ x        //  bitwise not
x << n     // left shift
x >> n     // right shift
```

Bitwise AND: &

The **&** operator

- takes two values (1,2,4,8 bytes), treats as sequence of bits
- performs logical AND on each corresponding pair of bits
- result contains same number of bits as inputs

Example:

```
    00100111            AND | 0  1
  & 11100011            ----|------
    --------              0 | 0  0
    00100011              1 | 0  1
```

- Useful for:
  - checking whether a particular bit is set
  - setting particular bit(s) to 0

Code Example: Checking for Odd Numbers with &

- the obvious way to check for odd numbers in C

```
int is_odd(int n) {
    return n % 2 != 0;
}
```

- we *could* use **&** to achieve the same thing:

```
int is_odd(int n) {
    return n & 1;
}
```

- but should we?
  - no - write obvious readable code
  - rely on compiler to generate fastest assembler
  - if `andi` instruction is faster than `rem`, compiler will generate it

Bitwise OR: |

The **|** operator

- takes two values (1,2,4,8 bytes), treats as sequence of bits
- performs logical OR on each corresponding pair of bits
- result contains same number of bits as inputs

Example:

```
    00100111             OR | 0  1
  | 11100011            ----|------
    --------              0 | 0  1
    11100111              1 | 1  1
```

- Useful for:
  - setting particular bit(s) to 1

Bitwise NEG: ~

The ~ operator

- takes a single value (1,2,4,8 bytes), treats as sequence of bits
- performs logical negation of each bit
- result contains same number of bits as input

Example:

```
~ 00100111          NEG | 0  1
  --------          ----|------
  11011000              | 1  0
```

- Useful for:
  - creating particular bit patterns

Bitwise XOR: ^

The ^ operator

- takes two values (1,2,4,8 bytes), treats as sequence of bits
- performs logical XOR on each corresponding pair of bits
- result contains same number of bits as inputs

Example:

```
  00100111     XOR | 0  1
^ 11100011     ----|-----
  --------      0  | 0  1
  11000100      1  | 1  0
```

- Useful for:
  - generating hashes
  - cryptography
  - graphics operations

Left Shift: <<

The << operator

- takes a single value (1,2,4,8 bytes), treats as sequence of bits
- also takes a small positive integer *x*
- moves (shifts) each bit *x* positions to the left
- left-end bit vanishes; right-end bit replaced by zero

Example:

```
00100111 << 2     00100111 << 8
--------          --------
10011100          00000000
```

- Useful for:
  - creating particular bit patterns
  - multiplying by power of two

Right Shift: >>

The **>>** operator

- takes a single value (1,2,4,8 bytes), treats as sequence of bits
- also takes a small positive integer *x*
- moves (shifts) each bit *x* positions to the right
- right-end bit vanishes; left-end bit replaced by zero(*)
- shifts involving negative values are not portable (implementation defined)
- common source of bugs in COMP1521 and elsewhere
- always use unsigned values/variables to be safe/portable.

Example:

```
00100111 >> 2      00100111 >> 8
--------           --------
00001001           00000000
```

- Useful for:
  - loops which need to process one bit at a time
  - dividing by power of two

MIPS - Bit Manipulation Instructions

assembly	meaning	bit pattern
and r_d, r_s, r_t	$r_d = r_s \& r_t$	000000ssssstttttddddd00000100100
or r_d, r_s, r_t	$r_d = r_s \mid r_t$	000000ssssstttttddddd00000100101
xor r_d, r_s, r_t	$r_d = r_s \wedge r_t$	000000ssssstttttddddd00000100110
nor r_d, r_s, r_t	$r_d = \sim (r_s \mid r_t)$	000000ssssstttttddddd00000100111
andi r_t, r_s, I	$r_t = r_s$ & I	001100ssssstttttIIIIIIIIIIIIIIII
ori r_t, r_s, I	$r_t = r_s$ | I	001101ssssstttttIIIIIIIIIIIIIIII
xori r_t, r_s, I	$r_t = r_s$ ^ I	001110ssssstttttIIIIIIIIIIIIIIII
not r_d, r_s	$r_d = \sim r_s$	pseudo-instruction

- `mipsy` translates **not** r_d, r_s to **nor** r_d, r_s, $0

MIPS - Shift Instructions

assembly	meaning	bit pattern
sllv r_d, r_t, r_s	$r_d = r_t \ll r_s$	000000ssssstttttddddd00000000100
srlv r_d, r_t, r_s	$r_d = r_t \gg r_s$	000000ssssstttttddddd00000000110
srav r_d, r_t, r_s	$r_d = r_t \gg r_s$	000000ssssstttttddddd00000000111
sll r_d, r_t, I	$r_d = r_t \ll$ I	00000000000tttttdddddIIIII000000
srl r_d, r_t, I	$r_d = r_t \gg$ I	00000000000tttttdddddIIIII000010
sra r_d, r_t, I	$r_d = r_t \gg$ I	00000000000tttttdddddIIIII000011

- **`srl`** and **`srlv`** shift zeros into most-significant bit
  - this matches shift in C of **unsigned** value
- **`sra`** and **`srav`** propagate most-significant bit
  - this ensure shifting a negative number divides by 2
- `mipsy` provides **`rol`** and **`ror`** pseudo-instructions which rotate bits
  - real instructions on some MIPS versions
  - no simple C equivalent

bitwise.c: showing results of bitwise operation

```
$ dcc bitwise.c print_bits.c -o bitwise
$ ./bitwise
Enter a: 23032
Enter b: 12345
Enter c: 3
     a = 0101100111111000 = 0x59f8 = 23032
     b = 0011000000111001 = 0x3039 = 12345
    ~a = 1010011000000111 = 0xa607 = 42503
 a & b = 0001000000111000 = 0x1038 = 4152
 a | b = 0111100111111001 = 0x79f9 = 31225
 a ^ b = 0110100111000001 = 0x69c1 = 27073
a >> c = 0000101100111111 = 0x0b3f = 2879
a << c = 1100111111000000 = 0xcfc0 = 53184
```

source code for bitwise.c

source code for print_bits.c source code for print_bits.h

bitwise.c: code

```
uint16_t a = 0;
printf("Enter a: ");
scanf("%hd", &a);
uint16_t b = 0;
printf("Enter b: ");
scanf("%hd", &b);
printf("Enter c: ");
int c = 0;
scanf("%d", &c);
print_bits_hex("     a = ", a);
print_bits_hex("     b = ", b);
print_bits_hex("    ~a = ", ~a);
print_bits_hex(" a & b = ", a & b);
print_bits_hex(" a | b = ", a | b);
print_bits_hex(" a ^ b = ", a ^ b);
print_bits_hex("a >> c = ", a >> c);
print_bits_hex("a << c = ", a << c);
```

source code for bitwise.c

shift_as_multiply.c: using shift to multiply by 2^n

```
$ dcc shift_as_multiply.c print_bits.c -o shift_as_multiply
$ ./shift_as_multiply 4
2 to the power of 4 is 16
In binary it is: 00000000000000000000000000010000
$ ./shift_as_multiply 20
2 to the power of 20 is 1048576
In binary it is: 00000000000100000000000000000000
$ ./shift_as_multiply 31
2 to the power of 31 is 2147483648
In binary it is: 10000000000000000000000000000000
$
```

shift_as_multiply.c: using shift to multiply by 2^n

```c
int n = strtol(argv[1], NULL, 0);
uint32_t power_of_two;
int n_bits = 8 * sizeof power_of_two;
if (n >= n_bits) {
    fprintf(stderr, "n is too large\n");
    return 1;
}
power_of_two = 1;
power_of_two = power_of_two << n;
printf("2 to the power of %d is %u\n", n, power_of_two);
printf("In binary it is: ");
print_bits(power_of_two, n_bits);
printf("\n");
```

source code for shift_as_multiply.c

set_low_bits.c: using << and - to set low *n* bits

```
$ dcc set_low_bits.c print_bits.c -o n_ones
$ ./set_low_bits 3
The bottom 3 bits of 7 are ones:
00000000000000000000000000000111
$ ./set_low_bits 19
The bottom 19 bits of 524287 are ones:
00000000000001111111111111111111
$ ./set_low_bits 29
The bottom 29 bits of 536870911 are ones:
00011111111111111111111111111111
```


set_low_bits.c: using << and - to set low *n* bits

```c
int n = strtol(argv[1], NULL, 0);
uint32_t mask;
int n_bits = 8 * sizeof mask;
assert(n >= 0 && n < n_bits);
mask = 1;
mask = mask << n;
mask = mask - 1;
printf("The bottom %d bits of %u are ones:\n", n, mask);
print_bits(mask, n_bits);
printf("\n");
```

source code for set_low_bits.c

set_bit_range.c: using << and - to set a range of bits

```
$ dcc set_bit_range.c print_bits.c -o set_bit_range
$ ./set_bit_range 0 7
Bits 0 to 7 of 255 are ones:
00000000000000000000000011111111
$ ./set_bit_range 8 15
Bits 8 to 15 of 65280 are ones:
00000000000000001111111100000000
$ ./set_bit_range 8 23
Bits 8 to 23 of 16776960 are ones:
00000000111111111111111100000000
$ ./set_bit_range 1 30
Bits 1 to 30 of 2147483646 are ones:
01111111111111111111111111111110
```


set_bit_range.c: using << and - to set a range of bits

```c
int low_bit = strtol(argv[1], NULL, 0);
int high_bit = strtol(argv[2], NULL, 0);
uint32_t mask;
int n_bits = 8 * sizeof mask;
```

```c
int mask_size = high_bit - low_bit + 1;
mask = 1;
mask = mask << mask_size;
mask = mask - 1;
mask = mask << low_bit;
printf("Bits %d to %d of %u are ones:\n", low_bit, high_bit, mask);
print_bits(mask, n_bits);
printf("\n");
```

source code for set_bit_range.c

extract_bit_range.c: extracting a range of bits

```
$ dcc extract_bit_range.c print_bits.c -o extract_bit_range
$ ./extract_bit_range 4 7 42
Value 42 in binary is:
00000000000000000000000000101010
Bits 4 to 7 of 42 are:
0010
$ ./extract_bit_range 10 20 123456789
Value 123456789 in binary is:
00000111010110111100110100010101
Bits 10 to 20 of 123456789 are:
11011110011
```

extract_bit_range.c: extracting a range of bits

```
int mask_size = high_bit - low_bit + 1;
mask = 1;
mask = mask << mask_size;
mask = mask - 1;
mask = mask << low_bit;
// get a value with the bits outside the range low_bit..high_bit set to zero
uint32_t extracted_bits = value & mask;
// right shift the extracted_bits so low_bit becomes bit 0
extracted_bits = extracted_bits >> low_bit;
printf("Value %u in binary is:\n", value);
print_bits(value, n_bits);
printf("\n");
printf("Bits %d to %d of %u are:\n", low_bit, high_bit, value);
print_bits(extracted_bits, mask_size);
printf("\n");
```

source code for extract_bit_range.c

print_bits.c: extracting the n-th bit of a valued

```
// print the bottom how_many_bits bits of value
void print_bits(uint64_t value, int how_many_bits) {
    // print bits from most significant to least significant
    for (int i = how_many_bits - 1; i >= 0; i--) {
        int bit = get_nth_bit(value, i);
        printf("%d", bit);
    }
}
```

```
// extract the nth bit from a value
int get_nth_bit(uint64_t value, int n) {
    // shift the bit right n bits
    // this leaves the n-th bit as the least significant bit
    uint64_t shifted_value = value >> n;
    // zero all bits except the the least significant bit
    int bit = shifted_value & 1;
    return bit;
```


print_int_in_hex.c: print an integer in hexadecimal

- write C to print an integer in hexadecimal instead of using:

```
    printf("%x", n)
```

```
$ dcc print_int_in_hex.c -o print_int_in_hex
$ ./print_int_in_hex
Enter a positive int: 42
42 = 0x0000002A
$ ./print_int_in_hex
Enter a positive int: 65535
65535 = 0x0000FFFF
$ ./print_int_in_hex
Enter a positive int: 3735928559
3735928559 = 0xDEADBEEF
$
```

source code for print_int_in_hex.c

print_int_in_hex.c: main

```
int main(void) {
    uint32_t a = 0;
    printf("Enter a positive int: ");
    scanf("%u", &a);
    printf("%u = 0x", a);
    print_hex(a);
    printf("\n");
    return 0;
}
```

source code for print_int_in_hex.c

print_int_in_hex.c: print_hex - extracting digit

```
// sizeof returns number of bytes in n's representation
// each byte is 2 hexadecimal digits
int n_hex_digits = 2 * (sizeof n);
// print hex digits from most significant to least significant
for (int which_digit = n_hex_digits - 1; which_digit >= 0; which_digit--) {
    // shift value across so hex digit we want
    // is in bottom 4 bits
    int bit_shift = 4 * which_digit;
    uint32_t shifted_value = n >> bit_shift;
    // mask off (zero) all bits but the bottom 4 bites
    int hex_digit = shifted_value & 0xF;
    // hex digit will be a value 0..15
    // obtain the corresponding ASCII value
    // "0123456789ABCDEF" is a char array
    // containing the appropriate ASCII values (+ a '\0')
    int hex_digit_ascii = "0123456789ABCDEF"[hex_digit];
    putchar(hex_digit_ascii);
}
```

source code for print_int_in_hex.c

int_to_hex_string.c: convert int to a string of hex digits

- Write C to convert an integer to a string containing its hexadecimal digits.

Could use the C library function **snprintf** to do this.

```
$ dcc int_to_hex_string.c -o int_to_hex_string
$ ./int_to_hex_string
$ ./int_to_hex_string
Enter a positive int: 42
42 = 0x0000002A
$ ./int_to_hex_string
Enter a positive int: 65535
65535 = 0x0000FFFF
$ ./int_to_hex_string
Enter a positive int: 3735928559
3735928559 = 0xDEADBEEF
$
```

source code for int_to_hex_string.c

int_to_hex_string.c: main

```c
int main(void) {
    uint32_t a = 0;
    printf("Enter a positive int: ");
    scanf("%u", &a);
    char *hex_string = int_to_hex_string(a);
    // print the returned string
    printf("%u = 0x%s\n", a, hex_string);
    free(hex_string);
    return 0;
}
```

source code for int_to_hex_string.c

int_to_hex_string.c: convert int to a string of hex digits

```c
// sizeof returns number of bytes in n's representation
// each byte is 2 hexadecimal digits
int n_hex_digits = 2 * (sizeof n);
// allocate memory to hold the hex digits + a terminating 0
char *string = malloc(n_hex_digits + 1);
// print hex digits from most significant to least significant
for (int which_digit = 0; which_digit < n_hex_digits; which_digit++) {
    // shift value across so hex digit we want
    // is in bottom 4 bits
    int bit_shift = 4 * which_digit;
    uint32_t shifted_value = n >> bit_shift;
    // mask off (zero) all bits but the bottom 4 bites
    int hex_digit = shifted_value & 0xF;
    // hex digit will be a value 0..15
    // obtain the corresponding ASCII value
    // "0123456789ABCDEF" is a char array
    // containing the appropriate ASCII values
    int hex_digit_ascii = "0123456789ABCDEF"[hex_digit];
    int string_position = n_hex_digits - which_digit - 1;
    string[string_position] = hex_digit_ascii;
}
// 0 terminate the array
string[n_hex_digits] = 0;
return string;
```

source code for int_to_hex_string.c

hex_string_to_int.c: convert hex digit string to int

- As an exercise write C to convert an integer to a string containing its hexadecimal digits.

Could use the C library function **strtol** to do this.

```
$ dcc hex_string_to_int.c -o hex_string_to_int
$ dcc hex_string_to_int.c -o hex_string_to_int
$ ./hex_string_to_int  2A
2A hexadecimal is 42 base 10
$ ./hex_string_to_int FFFF
FFFF hexadecimal is 65535 base 10
$ ./hex_string_to_int DEADBEEF
DEADBEEF hexadecimal is 3735928559 base 10
$
```

source code for hex_string_to_int.c

hex_string_to_int.c: main

```
int main(int argc, char *argv[]) {
    if (argc != 2) {
        fprintf(stderr, "Usage: %s <hexadecimal-number>\n", argv[0]);
        return 1;
    }
    char *hex_string = argv[1];
    uint32_t u = hex_string_to_int(hex_string);
    printf("%s hexadecimal is %u base 10\n", hex_string, u);
    return 0;
}
```

source code for hex_string_to_int.c

hex_string_to_int.c: convert array of hex digits to int

```
uint32_t hex_string_to_int(char *hex_string) {
    uint32_t value = 0;
    for (int i = 0; hex_string[i] != 0; i++) {
        int ascii_hex_digit = hex_string[i];
        int digit_as_int = hex_digit_to_int(ascii_hex_digit);
        value = value << 4;
        value = value | digit_as_int;
    }
    return value;
}
```

source code for hex_string_to_int.c

hex_string_to_int.c: convert single hex digit to int

```
int hex_digit_to_int(int ascii_digit) {
    if (ascii_digit >= '0' && ascii_digit <= '9') {
        // the ASCII characters '0' .. '9' are contiguous
        // in other words they have consecutive values
        // so subtract the ASCII value for '0' yields the corresponding integer
        return ascii_digit - '0';
    }
    if (ascii_digit >= 'A' && ascii_digit <= 'F') {
        // for characters 'A' .. 'F' obtain the
        // corresponding integer for a hexadecimal digit
        return 10 + (ascii_digit - 'A');
    }
    fprintf(stderr, "Bad digit '%c'\n", ascii_digit);
    exit(1);
}
```

source code for hex_string_to_int.c

shift_bug.c: bugs to avoid

```c
// int16_t is a signed type (-32768..32767)
// below operations are undefined for a signed type
int16_t i;
i = -1;
i = i >> 1; // undefined -  shift of a negative value
printf("%d\n", i);
i = -1;
i = i << 1; // undefined -  shift of a negative value
printf("%d\n", i);
i = 32767;
i = i << 1; // undefined -  left shift produces a negative value
uint64_t j;
j = 1 << 33; // undefined - constant 1 is an int
j = ((uint64_t)1) << 33; // ok
```

source code for shift_bug.c

xor.c: fun with xor

```c
int xor_value = strtol(argv[1], NULL, 0);
if (xor_value < 0 || xor_value > 255) {
    fprintf(stderr, "Usage: %s <xor-value>\n", argv[0]);
    return 1;
}
int c;
while ((c = getchar()) != EOF) {
    //    exclusive-or
    //    ^  | 0  1
    //   ----|-----
    //    0  | 0  1
    //    1  | 1  0
    int xor_c = c ^ xor_value;
    putchar(xor_c);
}
```

source code for xor.c

xor.c: fun with xor

```
$ echo Hello Andrew|xor 42
bOFFE
kDNXO] $ echo Hello Andrew|xor 42|cat -A
bOFFE$
kDNXO] $
$  echo Hello |xor 42
bOFFE $ echo -n 'bOFFE '|xor 42
Hello
$ echo Hello|xor 123|xor 123
Hello
$
```

pokemon.c: using an int to represent a set of values

```c
#define FIRE_TYPE       0x0001
#define FIGHTING_TYPE   0x0002
#define WATER_TYPE      0x0004
#define FLYING_TYPE     0x0008
#define POISON_TYPE     0x0010
#define ELECTRIC_TYPE   0x0020
#define GROUND_TYPE     0x0040
#define PSYCHIC_TYPE    0x0080
#define ROCK_TYPE       0x0100
#define ICE_TYPE        0x0200
#define BUG_TYPE        0x0400
#define DRAGON_TYPE     0x0800
#define GHOST_TYPE      0x1000
#define DARK_TYPE       0x2000
#define STEEL_TYPE      0x4000
#define FAIRY_TYPE      0x8000
```

source code for pokemon.c

pokemon.c: using an int to represent a set of values

- simple example of a single integer specifying a set of values
- interacting with hardware often involves this sort of code

```c
uint16_t our_pokemon = BUG_TYPE | POISON_TYPE | FAIRY_TYPE;
```

```c
// example code to check if a pokemon is of a type:
if (our_pokemon & POISON_TYPE) {
    printf("Poisonous\n"); // prints
}
if (our_pokemon & GHOST_TYPE) {
    printf("Scary\n"); // does not print
}
```

source code for pokemon.c

pokemon.c: using an int to represent a set of values

```c
// example code to add a type to a pokemon
our_pokemon |= GHOST_TYPE;
// example code to remove a type from a pokemon
our_pokemon &= ~ POISON_TYPE;
```

```c
printf(" our_pokemon type (2)\n");
if (our_pokemon & POISON_TYPE) {
    printf("Poisonous\n"); // does not print
}
if (our_pokemon & GHOST_TYPE) {
    printf("Scary\n"); // prints
}
```

source code for pokemon.c

bitset.c: using an int to represent a set of values

```
$ dcc bitset.c print_bits.c -o bitset
$ ./bitset
Set members can be 0-63, negative number to finish
Enter set a: 1 2 4 8 16 32 -1
Enter set b: 5 4 3 33 -1
a = 0000000000000000000000000000000100000000000000010000000100010110 = 0x100010116 = 4295
b = 0000000000000000000000000000001000000000000000000000000000111000 = 0x200000038 = 8589
a = {1,2,4,8,16,32}
b = {3,4,5,33}
a union b = {1,2,3,4,5,8,16,32,33}
a intersection b = {4}
cardinality(a) = 6
is_member(42, a) = 0
```


bitset.c: main

```c
printf("Set members can be 0-%d, negative number to finish\n",
       MAX_SET_MEMBER);
set a = set_read("Enter set a: ");
set b = set_read("Enter set b: ");
print_bits_hex("a = ", a);
print_bits_hex("b = ", b);
set_print("a = ", a);
set_print("b = ", b);
set_print("a union b = ", set_union(a, b));
set_print("a intersection b = ", set_intersection(a, b));
printf("cardinality(a) = %d\n", set_cardinality(a));
printf("is_member(42, a) = %d\n", (int)set_member(42, a));
```

source code for bitset.c

bitset.c: common set operations

```c
set set_add(int x, set a) {
    return a | ((set)1 << x);
}
```

```c
set set_union(set a, set b) {
    return a | b;
}
```

```c
set set_intersection(set a, set b) {
    return a & b;
}
```

```c
// return 1 iff x is a member of a, 0 otherwise
int set_member(int x, set a) {
    assert(x >= 0 && x < MAX_SET_MEMBER);
    return (a >> x) & 1;
}
```

bitset.c: counting set members

```c
// return size of set
int set_cardinality(set a) {
    int n_members = 0;
    while (a != 0) {
        n_members += a & 1;
        a >>= 1;
    }
    return n_members;
}
```


bitset.c: set input

```c
set set_read(char *prompt) {
    printf("%s", prompt);
    set a = EMPTY_SET;
    int x;
    while (scanf("%d", &x) == 1 && x >= 0) {
        a = set_add(x, a);
    }
    return a;
}
```


bitset.c: set output

```c
// print out member of the set in increasing order
// for example {5,11,56}
void set_print(char *description, set a) {
    printf("%s", description);
    printf("{");
    int n_printed = 0;
    for (int i = 0; i < MAX_SET_MEMBER; i++) {
        if (set_member(i, a)) {
            if (n_printed > 0) {
                printf(",");
            }
            printf("%d", i);
            n_printed++;
        }
    }
    printf("}\n");
}
```

Exercise: Bitwise Operations

Given the following variable declarations:

```
// a signed 8-bit value
unsigned char x = 0x55;
unsigned char y = 0xAA;
```

What is the value of each of the following expressions:

- `(x & y)  (x ^ y)`
- `(x << 1)  (y << 1)`
- `(x >> 1)  (y >> 1)`

Exercise: Bit-manipulation

Assuming 8-bit quantities and writing answers as 8-bit bit-strings:

What are the values of the following:

- `25`, `65`, `~0`, `~~1`, `0xFF`, `~0xFF`
- `(01010101 & 10101010)`, `(01010101 | 10101010)`
- `(x & ~x)`, `(x | ~x)`

How can we achieve each of the following:

- ensure that the 3rd bit from the RHS is set to 1
- ensure that the 3rd bit from the RHS is set to 0