COMP1521 24T3 — Integers

https://www.cse.unsw.edu.au/~cs1521/24T3/

There are only 10 types of students …

- those that understand binary
- those that don't understand binary

- Can interpret decimal number `4705` as:
$4 \times 10^3 + 7 \times 10^2 + 0 \times 10^1 + 5 \times 10^0$

- The *base* or *radix* is 10 ... digits `0` – `9`

- Place values:

...	1000	100	10	1
...	10^3	10^2	10^1	10^0

- Write number as 4705_{10}

  - Note use of subscript to denote base

- base 10 is an arbitrary choice

- can use any base

- e.g. could use base 7

- Place values:

...	343	49	7	1
...	7^3	7^2	7^1	7^0

- Write number as 1216_7 and interpret as:
  $1 \times 7^3 + 2 \times 7^2 + 1 \times 7^1 + 6 \times 7^0 == 454_{10}$

Binary Representation

- Modern computing uses binary numbers

    - because digital devices can easily produce high or low level voltages which can represent 1 or 0.

- The *base* or *radix* is 2
  Digits 0 and 1

- Place values:

...	8	4	2	1
...	2^3	2^2	2^1	2^0

- Write number as 1011_2 and interpret as:
  $1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 == 11_{10}$

- Example: Convert 1101_2 to Decimal:

- Example: Convert 29 to Binary:

Hexadecimal Representation

- Binary numbers hard for humans to read — too many digits!

- Conversion to decimal awkward and hides bit values

- Solution: write numbers in hexadecimal!

- The *base* or *radix* is 16 ... digits 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F

- Place values:

...	4096	256	16	1
...	16^3	16^2	16^1	16^0

- Write number as $3AF1_{16}$ and interpret as:
  $3 \times 16^3 + 10 \times 16^2 + 15 \times 16^1 + 1 \times 16^0 == 15089_{10}$

- in C, **0x** prefix denotes hexadecimal, e.g. **0x3AF1**

- Octal (based 8) representation used to be popular for binary numbers

- Similar advantages to hexadecimal

- in C a leading **0** denotes octal, e.g. **07563**

- binary constants were only recently added to C - some C compilers will not recognize them

```
printf("%d", 0x2A);      // prints 42
printf("%d", 052);       // prints 42
printf("%d", 0b101010);  // might compile and print 42
```

Binary Constants

In hexadecimal, each digit represents 4 bits

```
    0100 1000 1111 1010 1011 1100 1001 0111
0x    4    8    F    A    B    C    9    7
```

In octal, each digit represents 3 bits

```
    01 001 000 111 110 101 011 110 010 010 111
0    1   1   0   7   6   5   3   6   2   2   7
```

In binary, each digit represents 1 bit

```
    0b01001000111110101011110010010111
```
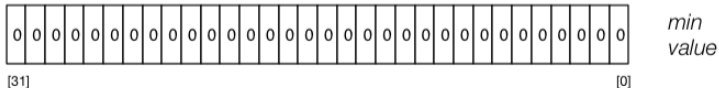
- Example: Convert 1011111000101001_2 to Hex:

- Example: Convert 10111101011100_2 to Hex:

- Reverse the previous process …

- Convert each hex digit into equivalent 4-bit binary representation

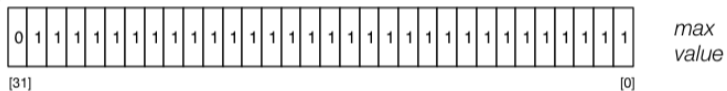- Example: Convert $AD5_{16}$ to Binary:

The `unsigned int` data type

- on cse machines is 32 bits, storing values in the range 0 .. 2^{32}-1
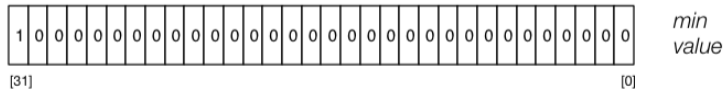
Signed integers

The `int` data type

- on cse machines is 32 bits, storing values in the range -2^{31} .. 2^{31}-1

- modern computers almost always use two's complement to represent integers

- positive integers and zero represented in obvious way

- negative integers represented in clever way to make arithmetic in silicon fast/simpler

- for an n-bit binary number the representation of $-b$ is $2^n - b$

- e.g. in 8-bit two's complement -5 is represented as $2^8 - 5$ == 11111011_2

- Some simple code to examine all 8 bit twos complement bit patterns.

```c
for (int i = -128; i < 128; i++) {
    printf("%4d ", i);
    print_bits(i, 8);
    printf("\n");
}
```

source code for 8_bit_twos_complement.c

```
$ dcc 8_bit_twos_complement.c print_bits.c -o 8_bit_twos_complement
```

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

Code example: printing all 8 bit twos complement bit patterns

```
$ ./8_bit_twos_complement
-128 10000000
-127 10000001
-126 10000010
...
  -3 11111101
  -2 11111110
  -1 11111111
   0 00000000
   1 00000001
   2 00000010
   3 00000011
...
 125 01111101
 126 01111110
 127 01111111
```

Code example: printing bits of int

```c
int a = 0;
printf("Enter an int: ");
scanf("%d", &a);
// sizeof returns number of bytes, a byte has 8 bits
int n_bits = 8 * sizeof a;
print_bits(a, n_bits);
printf("\n");
```

source code for print_bits_of_int.c

```
$ dcc print_bits_of_int.c print_bits.c -o print_bits_of_int
$ ./print_bits_of_int
Enter an int: 42
00000000000000000000000000101010
$ ./print_bits_of_int
Enter an int: -42
11111111111111111111111111010110
```

Code example: printing bits of int

```
$ ./print_bits_of_int
Enter an int: 0
00000000000000000000000000000000
$ ./print_bits_of_int
Enter an int: 1
00000000000000000000000000000001
$ ./print_bits_of_int
Enter an int: -1
11111111111111111111111111111111
$ ./print_bits_of_int
Enter an int: 2147483647
01111111111111111111111111111111
$ ./print_bits_of_int
Enter an int: -2147483648
10000000000000000000000000000000
$
```

Bits in Bytes in Words

- Many hardware operations works with bytes: 1 byte == 8 bits

- C's `sizeof` gives you number of bytes used for variable or type

- `sizeof` *variable* - returns number of bytes to store *variable*

- `sizeof (`*type*`)` - returns number of bytes to store *type*

- On CSE servers, C types have these sizes

    - `char` = 1 byte = 8 bits,   42 is 00101010
    - `short` = 2 bytes = 16 bits, 42 is 0000000000101010
    - `int` = 4 bytes = 32 bits, 42 is 00000000000000000000000000101010
    - `double` = 8 bytes = 64 bits, 42 = ?

- above are common sizes but not universal on a small embedded CPU
  `sizeof (int)` might be 2 (bytes)

Code example: `integer_types.c` - exploring integer types

We can use `sizeof` and `limits.h` to explore the range of values
which can be represented by standard C integer types **on our machine**...

```
$ dcc integer_types.c -o integer_types
$ ./integer_types
               Type Bytes Bits
               char     1    8
        signed char     1    8
      unsigned char     1    8
              short     2   16
     unsigned short     2   16
                int     4   32
       unsigned int     4   32
               long     8   64
      unsigned long     8   64
          long long     8   64
 unsigned long long     8   64
```

Code example: `integer_types.c` - exploring integer types

```
              Type                  Min                   Max
              char                 -128                   127
       signed char                 -128                   127
     unsigned char                    0                   255
             short               -32768                 32767
    unsigned short                    0                 65535
               int          -2147483648            2147483647
      unsigned int                    0            4294967295
              long -9223372036854775808   9223372036854775807
     unsigned long                    0  18446744073709551615
         long long -9223372036854775808   9223372036854775807
unsigned long long                    0  18446744073709551615
```

source code for integer_types.c

stdint.h - integer types with guaranteed sizes

`#include` <stdint.h>

- to get below integer types (and more) with guaranteed sizes

- we will use these heavily in COMP1521

```
          // range of values for type
          //                 minimum                   maximum
int8_t   i1; //                 -128                       127
uint8_t  i2; //                    0                       255
int16_t  i3; //               -32768                     32767
uint16_t i4; //                    0                     65535
int32_t  i5; //          -2147483648                2147483647
uint32_t i6; //                    0                4294967295
int64_t  i7; // -9223372036854775808       9223372036854775807
uint64_t i8; //                    0      18446744073709551615
```

source code for stdint.c

Code example: `char_bug.c`

Common C bug:

```c
char c;  // c should be declared int   (int16_t would work, int is better)
while ((c = getchar()) != EOF) {
    putchar(c);
}
```

Typically `stdio.h` contains:

```c
#define EOF -1
```

- most platforms: char is signed (-128..127)
    - loop will incorrectly exit for a byte containing 0xFF
- rare platforms: char is unsigned (0..255)
    - loop will never exit

source code for char_bug.c

Endian-ness

- The bytes of a multi-byte (2 byte, 4 byte, ...) quantity can be stored in various orders.
- *Endian-ness* is the order.
- Two common orders: big-endian & little-endian
- *big-endian* - most significant byte at the smallest memory address.
- *little-endian* - least significant byte at the smallest memory address.
- Most modern general-purpose computers little-endian
- Endian-ness configurable on some architectures e.g ARM

C

```
uint8_t b;
uint32_t u;
u = 0x03040506;
// load first byte of u
b = *(uint8_t *)&u;
// prints 6 if little-endian
// and 3 if big-endian
printf("%d\n", b);
```
source code for endian.c

MIPS

```
    lbu  $a0, u       # b = *(uint8_t *)&u;
    li   $v0, 1       # printf("%d", a0);
    syscall
    li   $a0, '\n'    # printf("%c", '\n');
    li   $v0, 11
    syscall
    li   $v0, 0       # return 0
    jr   $ra
    .data
u:
    .word 0x3040506   #u = 0x03040506;
```
source code for endian.s