

CSCI 2021: Binary, Integers, Arithmetic

Chris Kauffman

*Last Updated:
Tue Sep 19 03:11:15 PM EDT 2023*

Logistics

Reading

- ▶ C References
- ▶ Bryant/O'Hallaron Ch 2.1-2.3

Assignments

- ▶ Dis02 Due Mon 18-Sep
- ▶ HW01 Due Tue 19-Sep
- ▶ HW02 Due Thu 21-Sep
- ▶ Project 1 Soon

Goals

- ▶ Finish C Overview (GDB next week)
- ▶ Binary Notation and Relations
- ▶ Integers in binary
- ▶ Arithmetic operations

Announcements: None

Unsigned Integers: Decimal and Binary

- ▶ Unsigned integers are always positive:
`unsigned int i = 12345;`
- ▶ To understand binary, recall how decimal numbers “work”

Decimal: Base 10 Example

Each digit adds on a power 10

$80,345 = 5 \times 10^0 +$	5 ones
$4 \times 10^1 +$	40 tens
$3 \times 10^2 +$	300 hundreds
$0 \times 10^3 +$	0 thousands
8×10^4	80,000 ...
$5 + 40 + 300 + 80,000$	

Binary: Base 2 Example

Each digit adds on a power 2

$11001_2 = 1 \times 2^0 +$	1 ones
$0 \times 2^1 +$	0 twos
$0 \times 2^2 +$	0 fours
$1 \times 2^3 +$	8 eights
$1 \times 2^4 +$	16 sixteens
$= 1 + 8 + 16 = 25$	

So, $11001_2 = 25_{10}$

Exercise: Convert Binary to Decimal

Base 2 Example:

$$\begin{aligned} 11001 &= 1 \times 2^0 + & 1 \\ &0 \times 2^1 + & 0 \\ &0 \times 2^2 + & 0 \\ &1 \times 2^3 + & 8 \\ &1 \times 2^4 + & 16 \\ &= 1 + 8 + 16 &= 25 \end{aligned}$$

So, $11001_2 = 25_{10}$

Try With a Neighbor

Convert the following two numbers from base 2 (binary) to base 10 (decimal)

► 111

► 11010

► 01100001

Answers: Convert Binary to Decimal

$$\begin{aligned}111_2 &= 1 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 \\&= 1 \times 4 + 1 \times 2 + 1 \times 1 \\&= 7_{10}\end{aligned}$$

$$\begin{aligned}11010_2 &= 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 \\&= 1 \times 16 + 1 \times 8 + 0 \times 4 + 1 \times 2 + 0 \times 1 \\&= 26_{10}\end{aligned}$$

$$\begin{aligned}01100001_2 &= 0 \times 2^7 + 1 \times 2^6 + 1 \times 2^5 + 0 \times 2^4 \\&\quad + 0 \times 2^3 + 0 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 \\&= 0 \times 128 + 1 \times 64 + 1 \times 32 + 0 \times 16 \\&\quad + 0 \times 8 + 0 \times 4 + 0 \times 2 + 1 \times 1 \\&= 97_{10}\end{aligned}$$

Note: last example ignores leading 0's

The Other Direction: Base 10 to Base 2

Converting a number from base 10 to base 2 is easily done using repeated division by 2; keep track of **remainders**

Convert 124 to base 2:

$$124 \div 2 = 62 \qquad \text{rem } 0$$

$$62 \div 2 = 31 \qquad \text{rem } 0$$

$$31 \div 2 = 15 \qquad \text{rem } 1$$

$$15 \div 2 = 7 \qquad \text{rem } 1$$

$$7 \div 2 = 3 \qquad \text{rem } 1$$

$$3 \div 2 = 1 \qquad \text{rem } 1$$

$$1 \div 2 = 0 \qquad \text{rem } 1$$

- ▶ Last step got 0 quotient so we're done.
- ▶ Binary digits are in **remainders in reverse**
- ▶ Answer: 1111100
- ▶ Check:

$$0 + 0 + 2^2 + 2^3 + 2^4 + 2^5 + 2^6 = 4 + 8 + 16 + 32 + 64 = 124$$

Decimal, Hexadecimal, Octal, Binary

- ▶ Numbers exist independent of any writing system
- ▶ Can write the same number in a variety of bases
- ▶ C provides syntax for most common bases used in computing

	Decimal	Binary	Hexadecimal	Octal
Base	10	2	16	8
Mathematical	125	1111101 ₂	7D ₁₆	175 ₈
C Prefix	None	0b...	0x..	0...
C Example	125	0b1111101	0x7D	0175

- ▶ **Hexadecimal** often used to express long-ish byte sequences
Larger than base 10 so for 10-15 uses letters A-F
- ▶ **Examine** `number_writing.c` and `table.c` for patterns
- ▶ **Expectation:** Gain familiarity with doing conversions between bases as it will be useful in practice

Hexadecimal: Base 16

- ▶ Hex: compact way to write bit sequences

- ▶ One byte is 8 bits

- ▶ Each Hex character represents 4 bits

- ▶ **Each Byte is 2 Hex Digits**

Byte		Hex	Dec
0101 0111		$57 = 5 \cdot 16 + 7$	87
5 7			
0011 1100		$3C = 3 \cdot 16 + 12$	60
3 C=12			
1110 0010		$E2 = 14 \cdot 16 + 2$	226
E=14 2			

Hex to 4 bit equivalence

Dec	Bits	Hex
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

Exercise: Conversion Tricks for Hex and Octal

Examples shown in this week's HW, What tricks are illustrated?

Decimal	Byte = 8bits	Byte by 4	Hexadecimal
87	01010111	bin: 0101 0111 hex: 5 7	57 = $5 \cdot 16 + 7$ hex dec
60	00111100	bin: 0011 1100 hex: 3 C=12	3C = $3 \cdot 16 + 12$ hex dec
226	11100010	bin: 1110 0010 hex: E=14 2	E2 = $14 \cdot 16 + 2$ hex dec
Decimal	Byte = 8bits	Byte by 3	Octal
87	01010111	bin: 01 010 111 oct: 1 2 7	127 = $1 \cdot 8^2 + 2 \cdot 8 + 7$ oct dec
60	00111100	bin: 00 111 100 oct: 0 7 4	074 = $0 \cdot 8^2 + 7 \cdot 8 + 4$ oct dec
226	11100010	bin: 11 100 010 oct: 3 4 2	342 = $3 \cdot 8^2 + 4 \cdot 8 + 2$ oct dec

Answers: Conversion Tricks for Hex and Octal

- ▶ Converting between Binary and Hexadecimal is easiest when grouping bits by 4: each 4 bits corresponds to one hexadecimal digit

bin: 0101 0111	bin: 1110 0010
hex: 5 7	hex: E=14 2

- ▶ Converting between Binary and Octal is easiest when grouping bits by 3: each 3 bits corresponds to one octal digit

bin: 01 010 111	bin: 11 100 010
oct: 1 2 7	oct: 3 4 2

Character Coding Conventions

- ▶ Would be hard for people to share words if they interpreted bits as letters differently
- ▶ **ASCII**: American Standard Code for Information Interchange
An old standard for bit/character correspondence
- ▶ 7 bits per character, includes upper, lower case, punctuation

Dec	Hex	Binary	Char	Dec	Hex	Binary	Char
65	41	01000001	A	78	4E	01001110	N
66	42	01000010	B	79	4F	01001111	O
67	43	01000011	C	80	50	01010000	P
68	44	01000100	D	81	51	01010001	Q
69	45	01000101	E	82	52	01010010	R
70	46	01000110	F	83	53	01010011	S
71	47	01000111	G	84	54	01010100	T
72	48	01001000	H	85	55	01010101	U
73	49	01001001	I	86	56	01010110	V
74	4A	01001010	J	87	57	01010111	W
75	4B	01001011	K	88	58	01011000	X
76	4C	01001100	L	89	59	01011001	Y
77	4D	01001101	M	90	5A	01011010	Z
91	5B	01011101	[97	61	01100001	a
92	5C	01011110	\	98	62	01100010	b

Unicode

- ▶ World: Why can't I write
컴퓨터
in my code/web address/email?
- ▶ America: ASCII has 128 chars.
Deal with it.
- ▶ World: Seriously?
- ▶ America: We invented
computers. 'Merica!



- ▶ World:
- ▶ America: ... Unicode?
- ▶ World: But my language takes
more bytes than American.
- ▶ America: Deal with it. 'Merica!

- ▶ ASCII Uses 7 bits per char,
limited to 128 characters
- ▶ UTF-8 uses **1-4 bytes per
character** to represent **many**
more characters
(1,112,064 *codepoints*)
- ▶ Uses 8th bit in a byte to
indicate extension to more than
a single byte
- ▶ Requires software to understand
coding convention allowing
broader language support
- ▶ ASCII is a proper subset of
UTF-8 making UTF-8
backwards compatible and
wildly popular

Binary Integer Addition/Subtraction

Adding/subtracting in binary works the same as with decimal
EXCEPT that carries occur on values of 2 rather than 10

ADDITION #1

```
    1 11      <-carries
    0100 1010 = 74
+   0101 1001 = 89
-----
    1010 0011 = 163
```

ADDITION #2

```
    1111    1 <-carries
    0110 1101 = 109
+   0111 1001 = 121
-----
    1110 0110 = 230
```

SUBTRACTION #1

```
           ? <-carries
    0111 1001 = 121
-   0001 0011 =  19
-----
```

```
VVVVVVVVVVVVVVV
VVVVVVVVVVVVVVV
VVVVVVVVVVVVVVV
           x12 <-carries
    0111 0001 = 119
-   0001 0011 =  19
-----
    0110 0110 = 102
```

Two's Complement Integers: Representing Negative Values

- ▶ To represent negative integers, must choose a coding system
- ▶ **Two's complement** is the most common for this
- ▶ Alternatives exist
 - ▶ Signed magnitude: leading bit indicates pos (0) or neg (1)
 - ▶ One's complement: invert bits to go between positive negative
- ▶ Great advantage of two's complement: **signed and unsigned arithmetic are identical**
- ▶ Hardware folks only need to make one set of units for both unsigned and signed arithmetic

Summary of Two's Complement

Short explanation: most significant bit is associated with a negative power of two.

UNSIGNED BINARY

7654 3210 : position
ABCD EFGH : 8 bits
A: 0/1 * $+(2^7)$ *POS*
B: 0/1 * $+(2^6)$
C: 0/1 * $+(2^5)$
...
H: 0/1 * $+(2^0)$

UNSIGNED BINARY

7654 3210 : position
1000 0000 = +128
1000 0001 = +129
1000 0011 = +131
1111 1111 = +255
0000 0000 = 0
0000 0001 = +1
0000 0101 = +5
0111 1111 = +127

TWO's COMPLEMENT (signed)

7654 3210 : position
ABCD EFGH : 8-bits
A: 0/1 * $-(2^7)$ *NEG*
B: 0/1 * $+(2^6)$
C: 0/1 * $+(2^5)$
...
H: 0/1 * $+(2^0)$

TWO's COMPLEMENT (signed)

7654 3210 : position
1000 0000 = -128
1000 0001 = -127 = -128+1
1000 0011 = -125 = -128+1+2
1111 1111 = -1 = -128+1+2+4+...+64
0000 0000 = 0 [+127]
0000 0001 = +1
0000 0101 = +5
0111 1111 = +127

Two's Complement Notes

- ▶ Leading 1 indicates negative, 0 indicates positive
- ▶ All 0's = Zero
- ▶ Positive numbers are identical to unsigned

Conversion Trick

Positive → Negative

- ▶ **Invert bits, Add 1**

Negative → Positive

- ▶ **Invert bits, Add 1**

Same trick works both ways, implemented in hardware for the

unary minus operator as in

int y = -x;

~ 0110 1000 +104 : negate

1001 0111 inverted

+ 1

1001 1000 = -104

~ 1001 1000 = -104 : negate

0110 0111 = +103 inverted

+ 1

0110 1000 = +104

Add Pos/Neg should give 0

1 1111 <-carries

0110 1000 = +104

+ 1001 1000 = -104

x 0000 0000 = zero

Overflow

- ▶ Sums that exceed the representation of the bits associated with the integral type **overflow**
- ▶ Excess significant bits are **dropped**
- ▶ Addition can result in a sum smaller than the summands, even for two positive numbers (!?)
- ▶ Integer arithmetic in fixed bits is a mathematical **ring**

Examples of Overflow in 8 bits

ADDITION #3 OVERFLOW

```
1 1111 111 <-carries
  1111 1111 = 255
+ 0000 0001 =   1
```

```
1 0000 0000 = 256
x drop 9th bit
```

```
0000 0000 = 0
```

ADDITION #4 OVERFLOW

```
1           1 <-carries
  1010 1001 = 169
+ 1100 0001 = 193
```

```
1 0110 1010 = 362
x drop 9th bit
```

```
0110 1010 = 106
```

Underflow

- ▶ **Underflow** occurs in unsigned arithmetic when values go below 0 (no longer positive)
- ▶ Pretend that there is an extra significant bit to carry out subtraction
- ▶ Subtracting a positive integer from a positive integer may result in a **larger** positive integer (!!?)
- ▶ Integer arithmetic in fixed bits is a mathematical **ring**

Examples of 8-bit Underflow

SUBTRACTIION #2 UNDERFLOW

?<-carries

0000 0000 = 0

- 0000 0001 = 1

VVVVVVVVVVVVVV

?<-carries

1 0000 0000 = 256 (pretend)

- 0000 0001 = 1

VVVVVVVVVVVVVV

x 2<-carries

0 1111 1110 = 256

- 0000 0001 = 1

1111 1111 = 255

Overflow and Underflow In C Programs

- ▶ See `over_under_flow.c` for demonstrations in a C program.
- ▶ **No runtime errors** for under/overflow
- ▶ Good for hashing and cryptography
- ▶ Bad for most other applications: system critical operations should use checks for over-/under-flow
- ▶ See textbook [Ariane Rocket Crash](#) which was due to overflow of an integer converted from a floating point value
- ▶ At the assembly level, there are condition codes indicating that overflow has occurred

Endianness: Byte ordering in Memory

- ▶ Single bytes like ASCII characters lay out sequentially in memory in increasing address
- ▶ Multi-byte entities like 4-byte ints require decisions on byte ordering
- ▶ We think of a 32-bit int like this

Binary: 0000 0000 0000 0000 0001 1000 1110 1001
 0 0 0 0 1 8 E 9
Hex : 000018E9
Decimal: 6377

- ▶ But need to assign memory addresses to each byte
 - ▶ Little Endian: least significant byte early
 - ▶ Big Endian: most significant byte early
- ▶ Example: Integer starts at address #1024

	Address			
LittleEnd:	#1027	#1026	#1025	#1024
Binary:	0000 0000	0000 0000	0001 1000	1110 1001
	0 0	0 0	1 8	E 9
BigEnd:	#1024	#1025	#1026	#1027
	Address			

Little Endian vs. Big Endian

- ▶ Most modern machines use **little endian** by default
- ▶ Processor may actually support big endian
- ▶ Both Big and Little Endian have engineering trade-offs
- ▶ At one time debated hotly among hardware folks: a la *Gulliver's Travels* conflicts
- ▶ **Intel Chips** were little endian and have dominated computing for several decades, set the precedent for modern platforms
- ▶ Big endian byte order shows up in **network programming**: sending bytes over the network is done in big endian ordering
- ▶ **Examine** `show_endianness.c` : uses C code to print bytes in order, reveals whether a machine is Little or Big Endian

Output of show_endianness.c

```

1  > cat show_endianness.c
2  // Show endiannes layout of a binary number in memory. Most machines
3  // are little endian so bytes will print leas significant earlier.
4  #include <stdio.h>
5
6  int main(){
7      int bin = 0b0000000000000000000000001100011101001;    // 6377
8      //          |   |   |   |   |   |   |   |
9      //          0   0   0   0   1   8   e   9
10     printf("%d\n%x\n",bin,bin);                               // show decimal/hex of binary
11     unsigned char *ptr = (unsigned char *) &bin;             // pointer to beginning of bin
12     for(int i=0; i<4; i++){                                    // print bytes of bin from low to high
13         printf("%hhx ", ptr[i]);                              // memory address
14     }                                                         // '%hhx' : 1-byte char in hex
15     printf("\n");                                              // '%hx' : 2-byte short in hex
16     return 0;                                                  // '%x' : 4-byte int in hex
17 }
18
19 > gcc show_endianness.c
20 > ./a.out
21 6377
22 18e9
23 e9 18 0 0

```

Notice: num prints with value 18e9 but bytes appear in reverse order e9 18 when looking at memory

Integer Ops and Speed

- ▶ Along with Addition and Subtraction, **Multiplication and Division** can also be done in binary
- ▶ Algorithms are the same as base 10 but more painful to do by hand
- ▶ This pain is reflected in hardware speed of these operations
- ▶ The **Arithmetic and Logic Unit (ALU)** does integer ops in the machine
- ▶ A **clock** ticks in the machine at some rate like 3Ghz (3 billion times per second)

- ▶ Under ideal circumstances, typical ALU Op speeds are

Operation	Cycles
Addition	1
Logical	1
Shifts	1
Subtraction	1
Multiplication	3
Division	>30

- ▶ Due to disparity, it is worth knowing about **relation** between multiply/divide and **bitwise** operations
- ▶ Compiler often uses such tricks: shift rather than multiply/divide

Mangling bits Puts Muscle on Your Bones

Below illustrates difference between logical and bitwise operations.

```
int x1 = 12 || 10; // truthy (Logical OR)
int xb = 12 | 10;  // 14      (Bitwise OR)
int y1 = 12 && 10; // truthy (Logical AND)
int yb = 12 & 10;  // 8       (Bitwise AND)
int zb = 12 ^ 10;  // 6       (Bitwise XOR)
int w1 = !12;      // falsey (Logical NOT)
int wb = ~12;      // 3       (Bitwise NOT/INVERT)
```

- ▶ Bitwise ops evaluate on a per-bit level
- ▶ 32 bits for int, 4 bits shown

Bitwise OR	Bitwise AND	Bitwise XOR	Bitwise NOT
1100 = 12	1100 = 12	1100 = 12	
1010 = 10	& 1010 = 10	^ 1010 = 10	~ 1100 = 12
-----	-----	-----	-----
1110 = 14	1000 = 8	0110 = 6	0011 = 3

Bitwise Shifts

- ▶ **Shift** operations move bits within a field of bits

- ▶ Shift operations are

```
x = y << k; // left shift y by k bits, store in x
```

```
x = y >> k; // right shift y by k bits, store in x
```

- ▶ All integral types can use shifts: long, int, short, char

- ▶ **Not applicable** to pointers or floating point

- ▶ Examples in 8 bits

```
//          76543210
```

```
char x = 0b00010111; // 23
```

```
char y = x << 2;      // left shift by 2
```

```
// y = 0b01011100; // 92
```

```
// x = 0b00010111; // not changed
```

```
char z = x >> 3;      // right shift by 3
```

```
// z = 0b00000010; // 2
```

```
// x = 0b00010111; // not changed
```

```
char n = 0b10000000; // -128, signed
```

```
char s = n >> 4;      // right shift by 4
```

```
// s = 0b11111000; // -8, sign extension
```

```
// right shift >> is "arithmetic"
```

Shifty Arithmetic Tricks

- ▶ Shifts with add/subtract can be used instead of multiplication and division
- ▶ Turn on optimization: `gcc -O3 code.c`
- ▶ Compiler automatically does this if it thinks it will save cycles
- ▶ *Sometimes* programmers should do this but better to convince compiler to do it for you, **comment** if doing manually

Multiplication

```
//          76543210
char x = 0b00001010; // 10
char x2 = x << 1;      // 10*2
// x2 = 0b00010100;   // 20
char x4 = x << 2;      // 10*4
// x4 = 0b00101000;   // 40
char x7 = (x << 3)-x;  // 10*7
// x7 = (x * 8)-x;     // 10*7
// x7 = 0b01000110;   // 70
//          76543210
```

Division

```
//          76543210
char y = 0b01101110; // 110
char y2 = y >> 1;     // 110/2
// y2 = 0b00110111;  // 55
char y4 = y >> 2;     // 110/4
// y4 = 0b00011011;  // 27
char z = 0b10101100; // -84
char z2 = z >> 2;     // -84/4
// z2 = 0b11101011;  // -21
// right shift sign extension
```

Exercise: Checking / Setting Bits

Use a combination of bit shift / bitwise logic operations to...

1. Check if bit *i* of `int x` is set (has value 1)
2. Clear bit *i* (set bit at index *i* to value 0)

Show C code for this

```
{
    int x = ...;
    int i = ...;
    if( ??? ) { // ith bit of x is set
        printf("set!\n");
    }

    i = ...;
    ???;
    printf("ith bith of x now cleared to 0\n");
}
```

Answers: Checking / Setting Bits

1. Check if bit *i* of int *x* is set (has value 1)

```
int x = ...;
int mask = 1; // or 0b0001 or 0x01 ...
int shifted = mask << i; // shifted  0b00...010..00
if(x & shifted){          //          x & 0b10...010..01
    ...                  //          -----
}                        //          0b00...010..00
```

2. Clear bit *i* (set bit at index *i* to value 0)

```
int x = ...;
int mask = 1; // or 0b0001 or 0x01 ...
int shifted = mask << i; // shifted  0b00...010..00
int inverted = ~shifted; // inverted  0b11...101..11
x = x & inverted;        //          x & 0b10...010..01
    ...                  //          -----
                        //          0b10...000..01
```

Showing Bits

- ▶ `printf()` capabilities:
 - `%d` as Decimal
 - `%x` as Hexadecimal
 - `%o` as Octal
 - `%c` as Character
- ▶ No specifier for binary
- ▶ Can construct such with bitwise operations
- ▶ Code pack contains two codes to do this
 - ▶ `printbits.c`: single args printed as 32 bits
 - ▶ `showbits.c`: multiple args printed in binary, hex, decimal

- ▶ Showing bits usually involves shifting and bitwise AND &

- ▶ Example from `showbits.c`

```
#define INT_BITS 32

// print bits for x to screen
void showbits(int x){
    for(int i=INT_BITS-1; i>=0; i--){
        int mask = 1 << i;
        if(mask & x){
            printf("1");
        } else {
            printf("0");
        }
    }
}
```

Bit Masking

- ▶ Semi-common for functions to accept bit patterns which indicate true/false options
- ▶ Frequently makes use of bit **masks** which are constants associated with specific bits
- ▶ Example from earlier: Unix permissions might be...

```
#define S_IRUSR 0b100000000 // User   Read
#define S_IWUSR 0b010000000 // User   Write
#define S_IXUSR 0b001000000 // User   Execute
#define S_IRGRP 0b000100000 // Group  Read
...
#define S_IWOTH 0b000000010 // Others Write
#define S_IXOTH 0b000000001 // Others Execute
```

- ▶ Use them to create options to C functions like

```
int permissions = S_IRUSR|S_IWUSR|S_RGRP;
chmod("/home/kauffman/solution.zip",permissions);
```

Unix Permissions with Octal

- ▶ Octal arises associated with **Unix file permissions**
- ▶ Every file has 3 permissions for 3 entities
- ▶ Permissions are true/false so a single bit will suffice

- ▶ `ls -l`: long list files, shows permissions

- ▶ `chmod 665 somefile.txt`:
change permissions of
`somefile.txt` to those
shown to the right

binary	octal
110110101	= 665
rw-rw-r-x	<code>somefile.txt</code>
U G O	
S R T	
E O H	
R U E	
P R	

- ▶ `chmod 777 x.txt`: read /
write / exec for everyone

- ▶ `chmod` also honors letter
versions like `r` and `w`

Readable `chmod` version:
`chmod u=rw,g=rw,o=rx somefile.txt`

- ▶ `chmod u+x script.sh` #
make file executable