Data III & Integers I

CSE 351 Winter 2020

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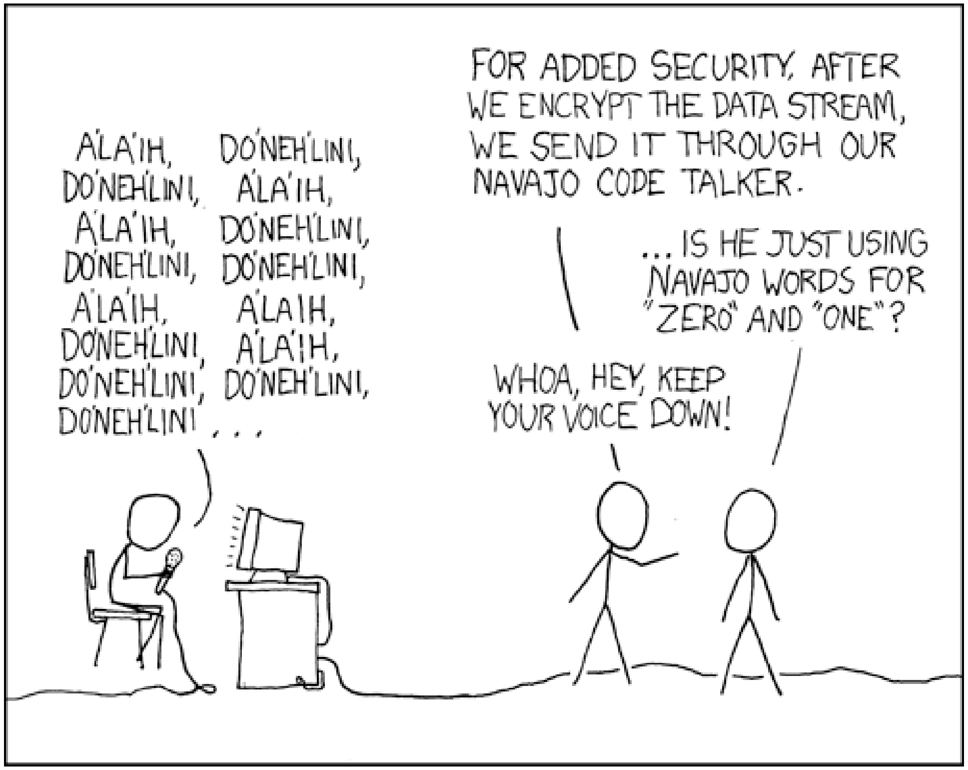


http://xkcd.com/257/

Administrivia

- hw3 due Wednesday, hw4 due Friday

- Lab 1a released
  - Workflow:
    1) Edit `pointer.c`
    2) Run the Makefile (`make`) and check for compiler errors & warnings
    3) Run ptest (`./ptest`) and check for correct behavior
    4) Run rule/syntax checker (`python dlc.py`) and check output
  - Due Friday 1/17, will overlap a bit with Lab 1b
    - We grade just your *last* submission

Lab Reflections

- All subsequent labs (after Lab 0) have a "reflection" portion
  - The Reflection questions can be found on the lab specs and are intended to be done *after* you finish the lab
  - You will type up your responses in a `.txt` file for submission on Canvas
  - These will be graded "by hand" (read by TAs)
- Intended to check your understand of what you should have learned from the lab
  - Also great practice for short answer questions on the exams

Memory, Data, and Addressing

- Representing information as bits and bytes
  - Binary, hexadecimal, fixed-widths
- Organizing and addressing data in memory
  - Memory is a byte-addressable array
  - Machine “word” size = address size = register size
  - Endianness – ordering bytes in memory
- Manipulating data in memory using C
  - Assignment
  - Pointers, pointer arithmetic, and arrays
- **Boolean algebra and bit-level manipulations**

Boolean Algebra

- Developed by George Boole in 19th Century
  - Algebraic representation of logic (True → 1, False → 0)
  - AND: A&B=1 when both A is 1 and B is 1
  - OR: A|B=1 when either A is 1 or B is 1
  - XOR: A^B=1 when either A is 1 or B is 1, but not both
  - NOT: ~A=1 when A is 0 and vice-versa
  - DeMorgan's Law: ~(A|B) = ~A & ~B
    ~(A&B) = ~A | ~B

AND

&	0	1
0	**0**	**0**
1	**0**	**1**

OR

|	0	1
0	**0**	**1**
1	**1**	**1**

XOR

^	0	1
0	**0**	**1**
1	**1**	**0**

NOT

~	
0	**1**
1	**0**

General Boolean Algebras

- Operate on bit vectors
  - Operations applied bitwise
  - All of the properties of Boolean algebra apply

```
  01101001     01101001     01101001
& 01010101   | 01010101   ^ 01010101   ~ 01010101
  01000001     01111101     00111100     10101010
```

- Examples of useful operations:

$$x \,\hat{}\, x = 0$$

```
  01010101
^ 01010101
  00000000
```

"sets to 1" "leaves as is"

$$x \mid 1 = 1, \quad x \mid 0 = x$$

$0 \mid 1 = 1$ $\quad 0 \mid 0 = 0$

$1 \mid 1 = 1$ $\quad 1 \mid 0 = 1$

```
  01010101  ← x
| 11110000  ← bit mask
  11110101
```

Bit-Level Operations in C

- & (AND), | (OR), ^ (XOR), ~ (NOT)
  - View arguments as bit vectors, apply operations bitwise
  - Apply to any "integral" data type
    - `long`, `int`, `short`, `char`, `unsigned`
- Examples with `char a, b, c;`
  - ```
    a = (char) 0x41;    // 0x41->0b 0100 0001
    b = ~a;             //       0b 1011 1110 ->0x BE
    ```
  - ```
    a = (char) 0x69;    // 0x69->0b 0110 1001
    b = (char) 0x55;    // 0x55->0b 0101 0101
    c = a & b;          //       0b 0100 0001 ->0x 41
    ```
  - ```
    a = (char) 0x41;    // 0x41->0b 0100 0001
    b = a;              //       0b 0100 0001
    c = a ^ b;          //       0b 0000 0000 ->0x 00
    ```
    ```

Contrast: Logic Operations

- Logical operators in C: && (AND), || (OR), ! (NOT)
  - **0** is False, **anything nonzero** is True
  - **Always** return 0 or 1
  - Early termination (a.k.a. short-circuit evaluation) of &&, ||

0xCC = 0b 1100 1100
0x33 = 0b 0011 0011

- Examples (`char` data type)

0xCC & 0x33 -> 0x00

  - `!0x41 -> 0x00`
  - `!0x00 -> 0x01`
  - `!!0x41 -> 0x01`
  - `0xCC && 0x33 -> 0x01`
  - `0x00 || 0x33 -> 0x01`
  - `p && *p`
    - If p is the null pointer (0x0), then p is never dereferenced!

If ① determines output of logical operator, then ② is never evaluated

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

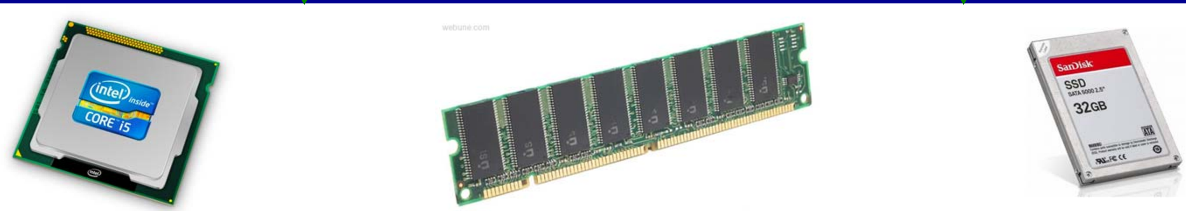
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

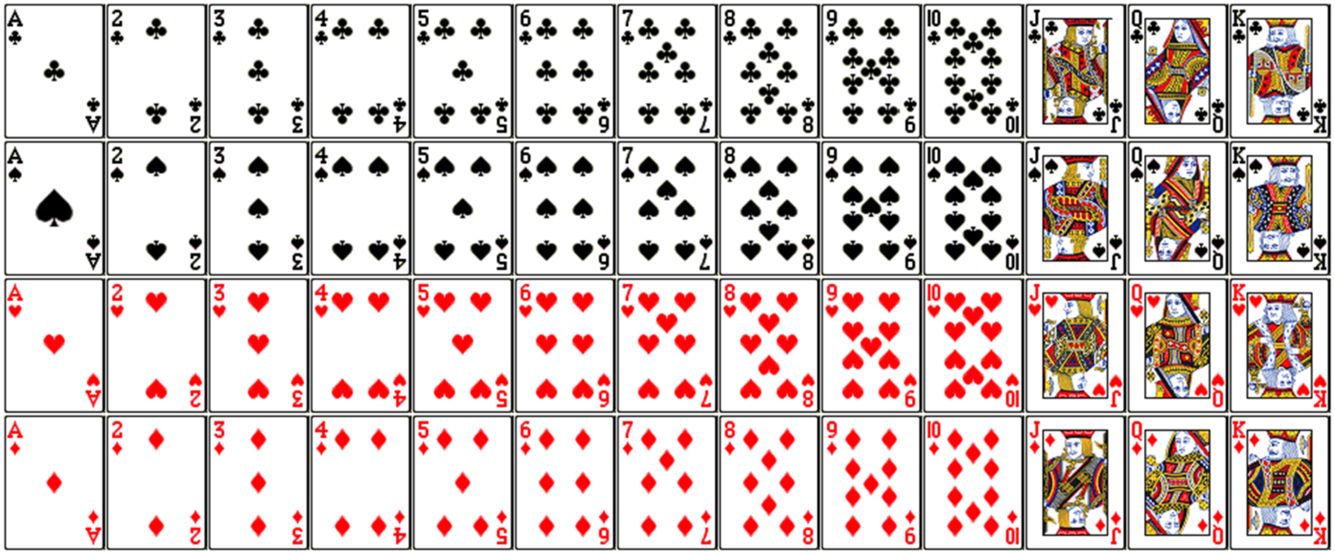
Computer system:



- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

But before we get to integers….

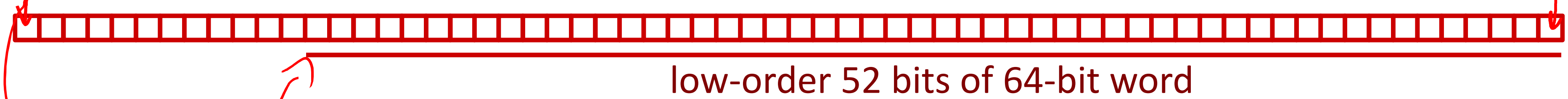
- Encode a standard deck of playing cards
- 52 cards in 4 suits
  - How do we encode suits, face cards?
- What operations do we want to make easy to implement?
  - Which is the higher value card?
  - Are they the same suit?



Two possible representations

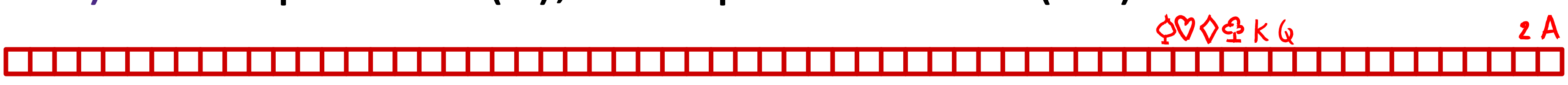
K♠ A♣

1) 1 bit per card (52): bit corresponding to card set to 1



- "One-hot" encoding (similar to set notation)
- Drawbacks:
  - Hard to compare values and suits
  - Large number of bits required 52 bits $\xrightarrow{\text{fits in}}$ 7 bytes (56 bits)

2) 1 bit per suit (4), 1 bit per number (13): 2 bits set



4 suits 13 numbers

17 bits → 3 bytes

- Pair of one-hot encoded values
- Easier to compare suits and values, but still lots of bits used

Two better representations

3) Binary encoding of all 52 cards – only 6 bits needed
   - $2^6 = 64 \geq 52$
     $2^5 = 32 < 52$

low-order 6 bits of a byte

   - Fits in one byte (smaller than one-hot encodings)
   - How can we make value and suit comparisons easier?

4) Separate binary encodings of suit (2 bits) and value (4 bits)

4 suits   13 values

suit   value

   - Also fits in one byte, and easy to do comparisons

K	Q	J	. . .	3	2	A
1101	1100	1011	. . .	0011	0010	0001

13 . . . 1

C	♣	00
D	♦	01
H	♥	10
S	♠	11

Compare Card Suits

mask: a bit vector designed to achieve a desired behavior when used with a bitwise operator on another bit vector *v*.
Here we turn all *but* the bits of interest in *v* to 0.

```
char hand[5];        // represents a 5-card hand
char card1, card2;   // two cards to compare
card1 = hand[0];
card2 = hand[1];
...
if ( sameSuitP(card1, card2) ) { ... }
```

text substitution

```
#define SUIT_MASK  0x30

int sameSuitP(char card1, char card2) {
  return (!((card1 & SUIT_MASK) ^ (card2 & SUIT_MASK)));
  //return (card1 & SUIT_MASK) == (card2 & SUIT_MASK);
}
```

returns **int**

equivalent

SUIT_MASK = 0x30 =

0	0	1	1	0	0	0	0

suit (keep)   value (discard)

x & 0 = 0

x & 1 = x

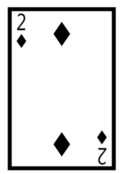
Compare Card **Suits**

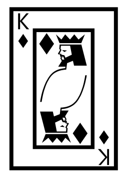
mask: a bit vector designed to achieve a desired behavior when used with a bitwise operator on another bit vector *v*.
Here we turn all *but* the bits of interest in *v* to 0.

```
#define SUIT_MASK  0x30

int sameSuitP(char card1, char card2) {
  return (!((card1 & SUIT_MASK) ^ (card2 & SUIT_MASK)));
  //return (card1 & SUIT_MASK) == (card2 & SUIT_MASK);
}
```

3 1 2 1





		card1										card2
card1	0	~~0~~	**0**	**1**	0	~~0~~	~~1~~	0				
			1 &									
	0	0	**1**	**1**	0	0	0	0				
			=									
	0	0	**0**	**1**	0	0	0	0				

card2: ~~0~~ 0 **0** **1** ~~1 1 0~~ 1

& 1

0 0 **1** **1** 0 0 0 0

=

0 0 **0** **1** 0 0 0 0

SUIT_MASK

x & 0 = 0

x & 1 = x

2 ^

0 0 0 0 0 0 0 0

3 ! ← logical

0 0 0 0 0 0 0 1

! (x^y) equivalent to x==y

Compare Card Values

mask: a bit vector designed to achieve a desired behavior when used with a bitwise operator on another bit vector *v*.

```
char hand[5];         // represents a 5-card hand
char card1, card2;    // two cards to compare
card1 = hand[0];
card2 = hand[1];
...
if ( greaterValue(card1, card2) ) { ... }
```

```
#define VALUE_MASK  0x0F

int greaterValue(char card1, char card2) {
  return ((unsigned int)(card1 & VALUE_MASK) >
          (unsigned int)(card2 & VALUE_MASK));
}
```

VALUE_MASK = 0x0F =

0	0	0	0	1	1	1	1

suit (discard) value (keep)

Compare Card **Values**

mask: a bit vector designed to achieve a desired behavior when used with a bitwise operator on another bit vector *v*.

```
#define VALUE_MASK  0x0F

int greaterValue(char card1, char card2) {
  return ((unsigned int)(card1 & VALUE_MASK) >
          (unsigned int)(card2 & VALUE_MASK));
}
```

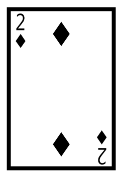
~~0~~	~~0~~	~~1~~	~~0~~	0	0	1	0

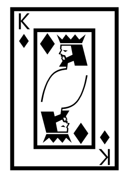
1 &

0	0	0	0	1	1	1	1

=

0	0	0	0	0	0	1	0





VALUE_MASK

~~0~~	~~0~~	~~1~~	~~0~~	1	1	0	1

& 1

0	0	0	0	1	1	1	1

=

0	0	0	0	1	1	0	1

2

$2_{10} > 13_{10}$

0 (false)

Integers

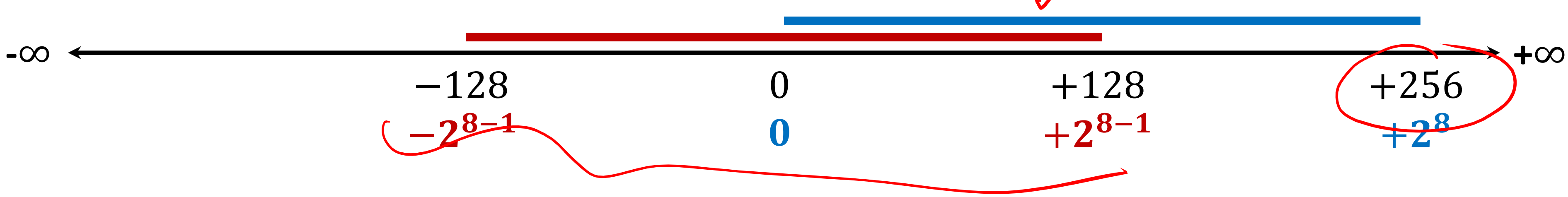
- **Binary representation of integers**
  - **Unsigned and signed**
  - Casting in C
- Consequences of finite width representation
  - Overflow, sign extension
- Shifting and arithmetic operations

Encoding Integers

- The hardware (and C) supports two flavors of integers
  - *unsigned* – only the non-negatives
  - *signed* – both negatives and non-negatives
- Cannot represent all integers with w bits
  - Only 2^w distinct bit patterns
  - Unsigned values: $0 \ldots 2^w-1$
  - Signed values: $-2^{w-1} \ldots 2^{w-1}-1$

same widths, just shifted

- **Example:** 8-bit integers (*e.g.* `char`)



Unsigned Integers

- Unsigned values follow the standard base 2 system
  - $b_7b_6b_5b_4b_3b_2b_1b_0 = b_7 2^7 + b_6 2^6 + \cdots + b_1 2^1 + b_0 2^0$
- Add and subtract using the normal "carry" and "borrow" rules, just in binary

$\begin{array}{r} \scriptstyle 1 \\ 63 \\ +\ \ 8 \\ \hline 71 \end{array}$	$\begin{array}{r} \scriptstyle 1\,1\,1 \\ 00111111 \\ +00001000 \\ \hline 01000111 \end{array}$

← x, 6 1's in a row

$x+1 = 0b1000000$
$= 2^6$

$x = 2^6 - 1$

- Useful formula: $2^{N-1} + 2^{N-2} + \ldots + 2 + 1 = 2^N - 1$
  - *i.e.* N ones in a row $= 2^N - 1$
- How would you make *signed* integers?

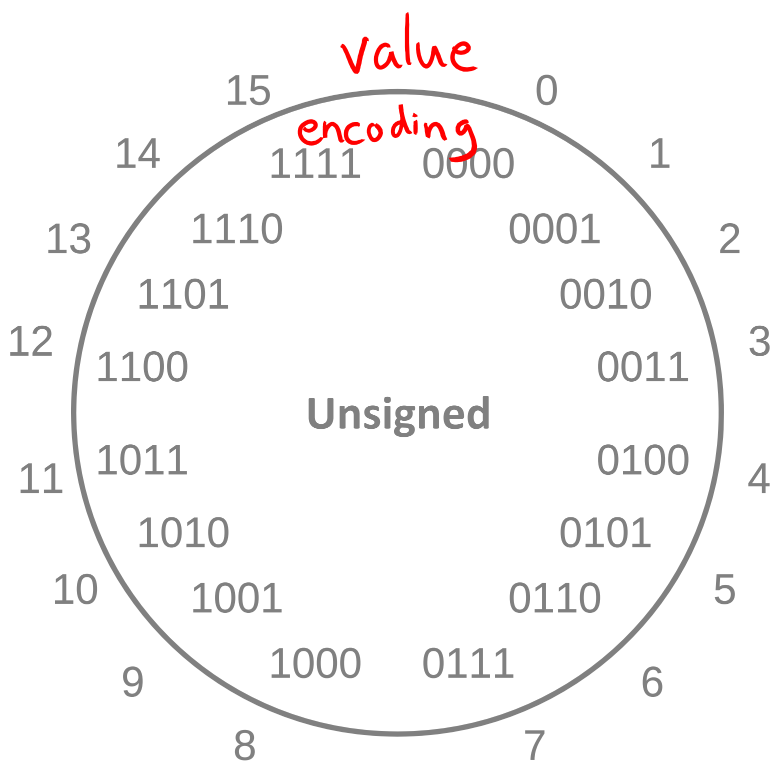
Sign and Magnitude

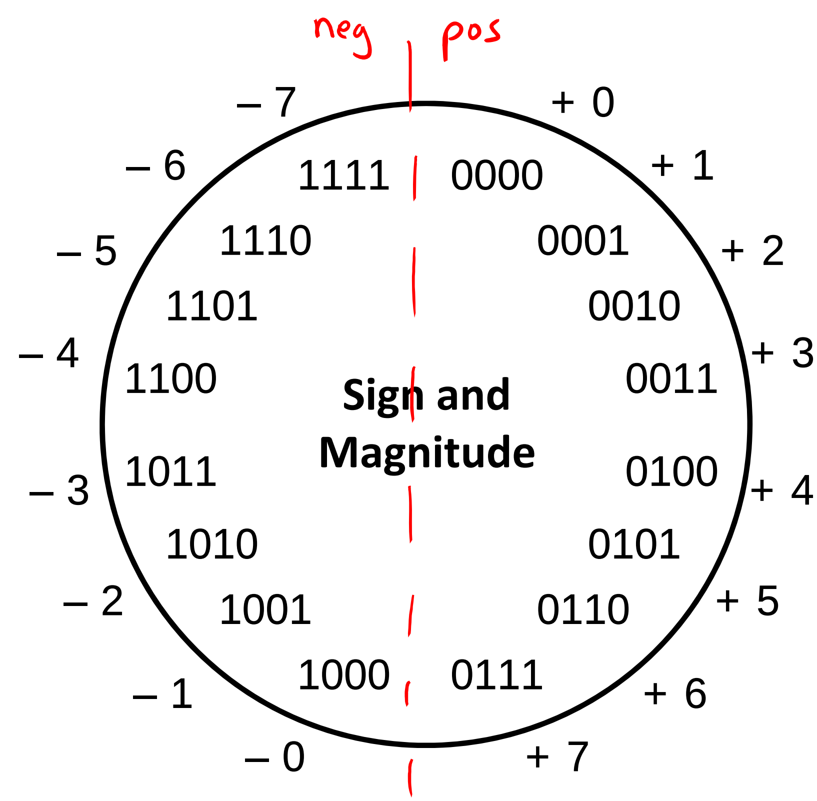
Most Significant Bit

- Designate the high-order bit (MSB) as the "sign bit"
  - `sign=0`: positive numbers; `sign=1`: negative numbers
- Benefits:
  - Using MSB as sign bit matches positive numbers with unsigned unsigned: 0b 0010 = 2^1 = 2 ; sign + mag: 0b 0010 = $+2^1$ = 2 ☑
  - All zeros encoding is still = 0
- Examples (8 bits):
  - 0x00 = 00000000_2 is non-negative, because the sign bit is 0
  - 0x7F = 01111111_2 is non-negative ($+127_{10}$)
  - 0x85 = 10000101_2 is negative (-5_{10})
  - 0x80 = 10000000_2 is negative... zero???

Sign and Magnitude

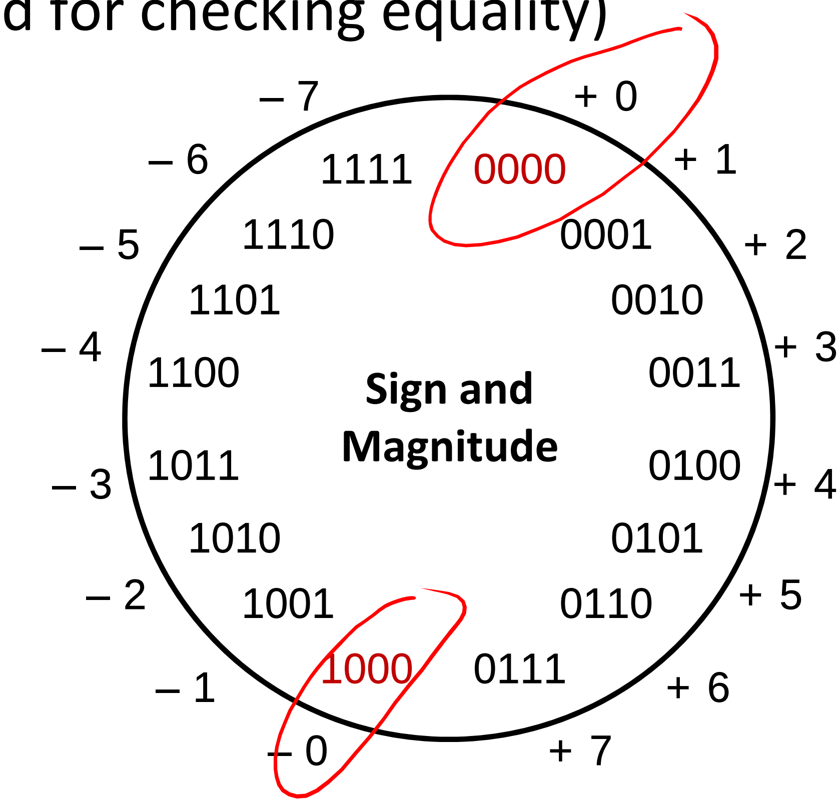
- MSB is the sign bit, rest of the bits are magnitude
- Drawbacks?





Sign and Magnitude

- MSB is the sign bit, rest of the bits are magnitude
- Drawbacks:
  - Two representations of 0 (bad for checking equality)



Sign and Magnitude

- MSB is the sign bit, rest of the bits are magnitude
- Drawbacks:
  - Two representations of 0 (bad for checking equality)
  - Arithmetic is cumbersome
    - Example: `4-3 != 4+(-3)`

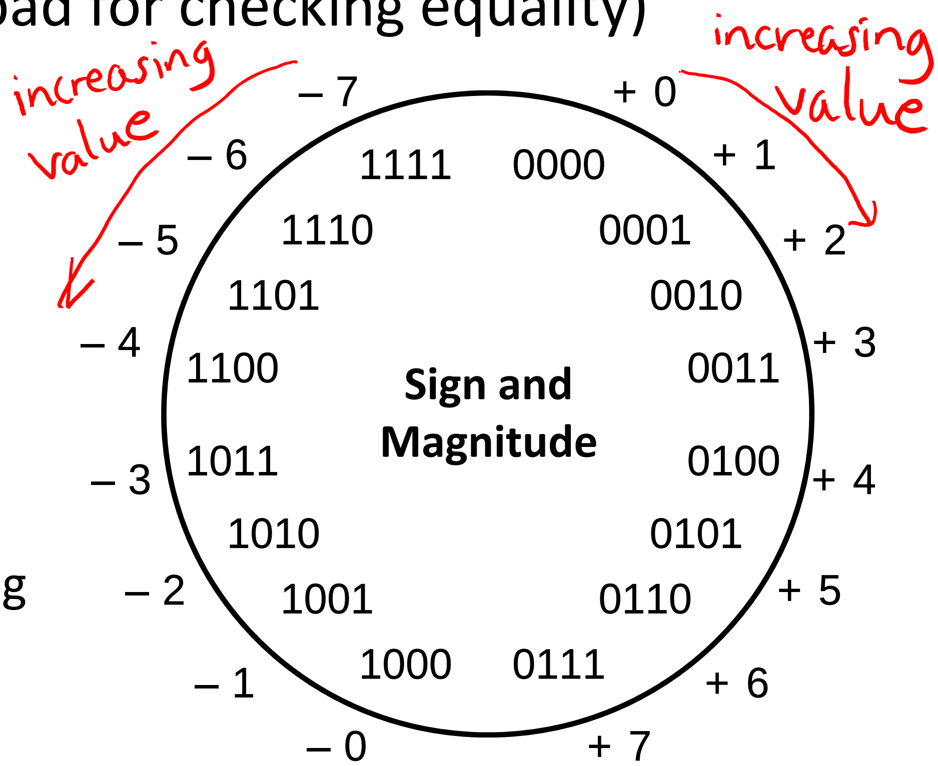
4	0100
- 3	- 0011
1	0001

✓

4	0100
+ -3	+ 1011
-7	1111

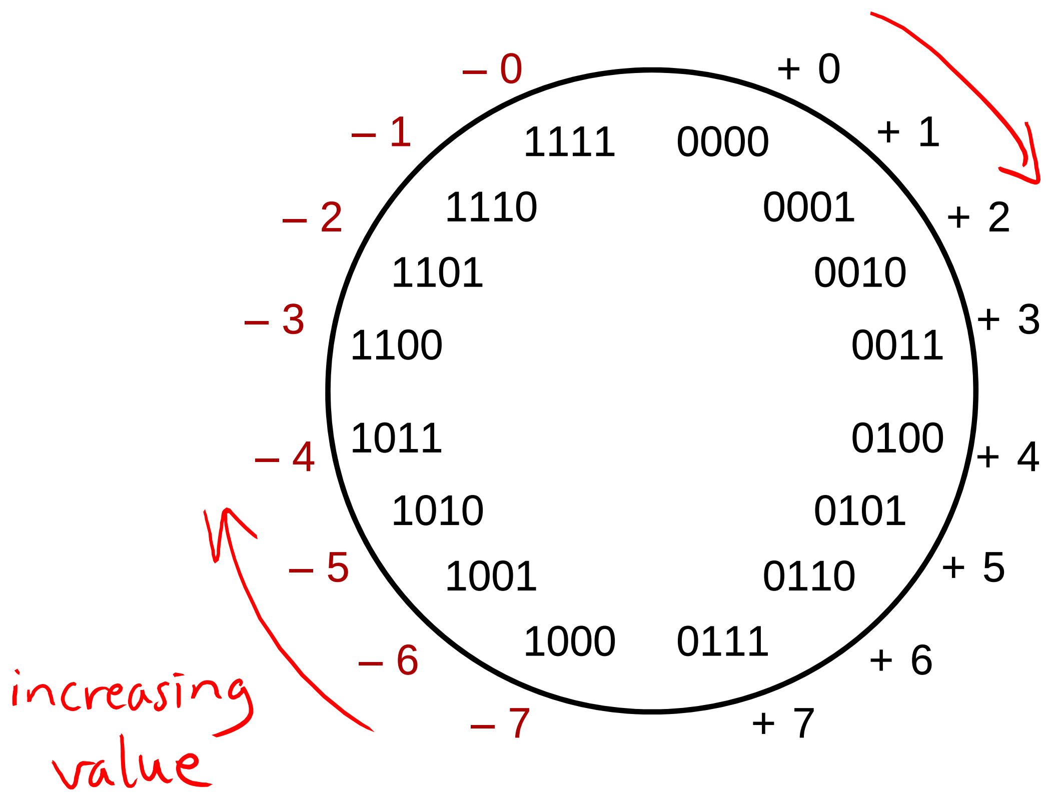
✗

    - Negatives "increment" in wrong direction!



Two's Complement

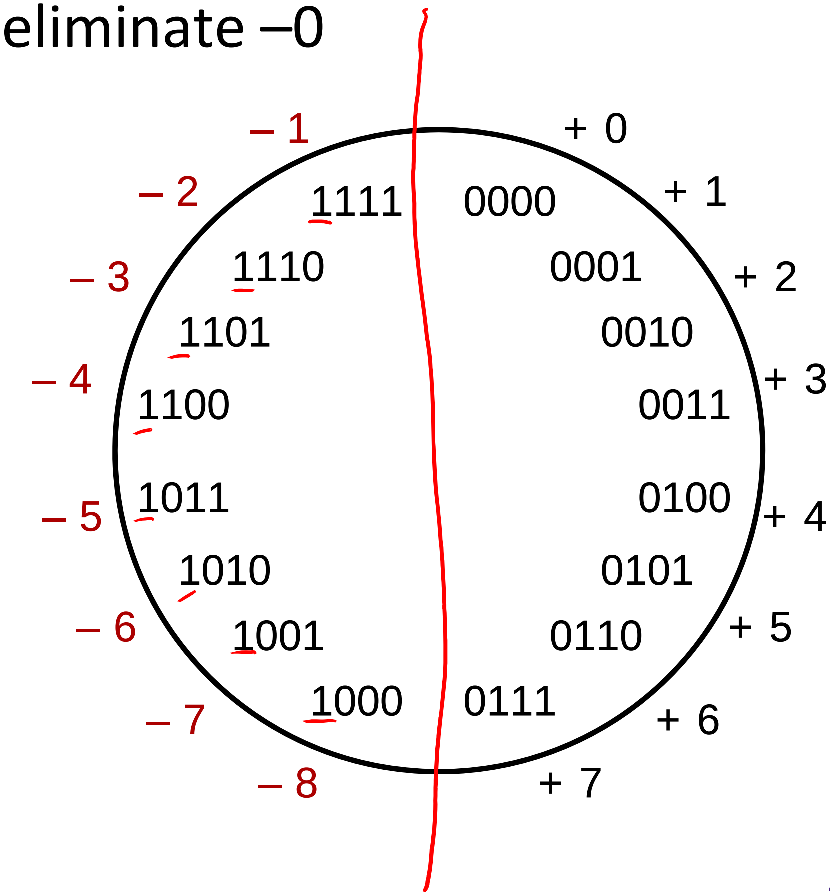
- Let's fix these problems:
  1) "Flip" negative encodings so incrementing works



Two's Complement

- Let's fix these problems:
  1) "Flip" negative encodings so incrementing works
  2) "Shift" negative numbers to eliminate –0

- MSB *still* indicates sign!
  - This is why we represent one more negative than positive number (-2^{N-1} to 2^{N-1} –1)



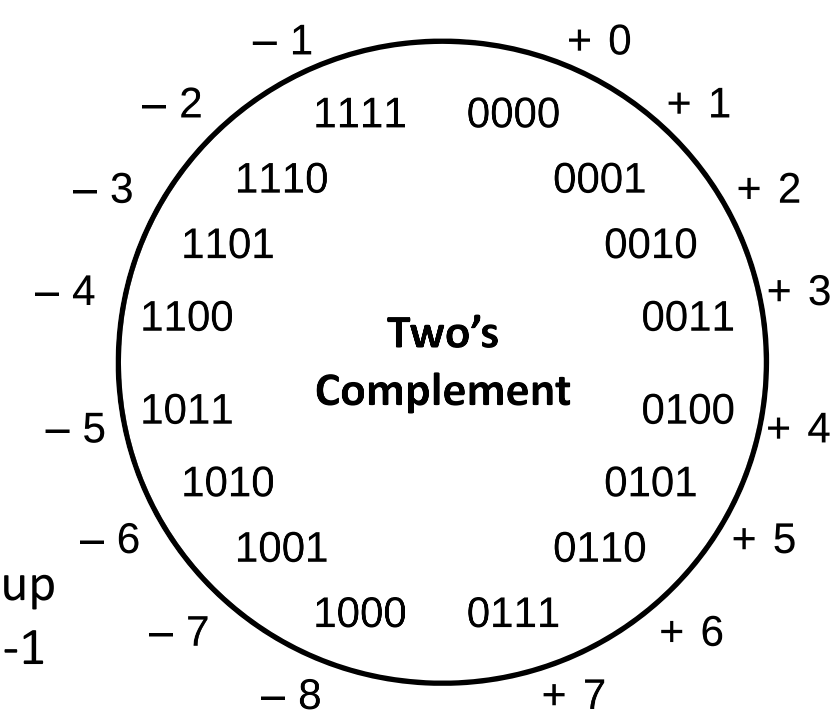
Two’s Complement Negatives

- Accomplished with one neat mathematical trick!

b_{w-1} has weight -2^{w-1}, other bits have usual weights $+2^i$

b_{w-1}	b_{w-2}	. . .	b_0

- 4-bit Examples:
  - 1010_2 unsigned: 2
    8 — $1*2^3+0*2^2+1*2^1+0*2^0$ = **10** 2
  - 1010_2 two’s complement:
    −8 $\boxed{-1*2^3}+0*2^2+1*2^1+0*2^0$ = **–6** 2
- -1 represented as: 7
  - 8 $1111_2 = -2^3+(2^3 – 1)$
    3 one's in a row
  - MSB makes it super negative, add up all the other bits to get back up to -1



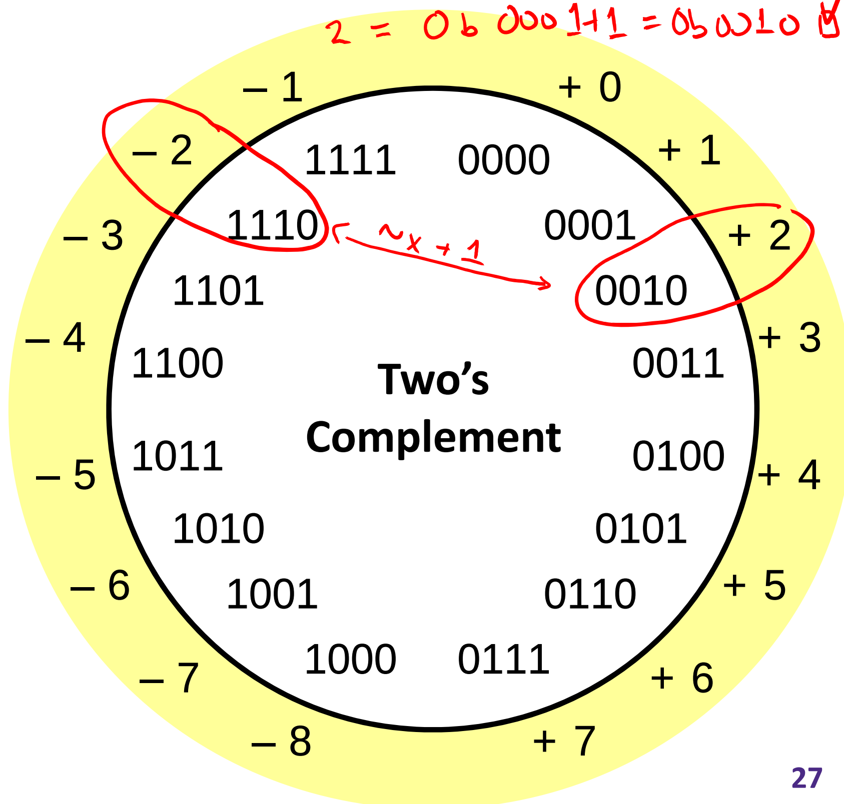
Why Two's Complement is So Great

- Roughly same number of (+) and (–) numbers
- Positive number encodings match unsigned
- Single zero
- All zeros encoding = 0

2 = 0b0010
−2 = 0b1101 +1 = 0b1110 ✓
2 = 0b0001+1 = 0b0010 ✓

- Simple negation procedure:
  - Get negative representation of any integer by taking bitwise complement and then adding one!

`( ~x + 1 == -x )`



Polling Question

MSB

- Take the 4-bit number encoding **x = 0b1011**
- Which of the following numbers is NOT a valid interpretation of x using any of the number representation schemes discussed today?
  - Unsigned, Sign and Magnitude, Two's Complement
  - Vote at http://pollev.com/rea

$\boxed{\text{A. } -4}$

~~B. -5~~

~~C. 11~~

~~D. -3~~

E. We're lost…

unsigned: $8 + 2 + 1 = 11$

sign + mag: $1011 \rightarrow -(2+1) = -3$

two's: $-8 + 2 + 1 = -5$

$-x = 0b\ 0100 + 1 = 5 \rightarrow x = -5$

Summary

- Bit-level operators allow for fine-grained manipulations of data
  - Bitwise AND (&), OR (|), and NOT (~) different than logical AND (&&), OR (| |), and NOT (!)
  - Especially useful with bit masks
- Choice of *encoding scheme* is important
  - Tradeoffs based on size requirements and desired operations
- Integers represented using unsigned and two's complement representations
  - Limited by fixed bit width
  - We'll examine arithmetic operations next lecture