# Data III & Integers I

CSE 351 Winter 2020

**Instructor:**

Ruth Anderson

**Teaching Assistants:**

Jonathan Chen
Justin Johnson
Porter Jones
Josie Lee
Jeffery Tian
Callum Walker
Eddy (Tianyi) Zhou


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
```

- Examples of useful operations:

$$x \wedge x = 0$$

```
  01010101
^ 01010101
  00000000
```

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

```
  01010101
| 11110000
  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           ->0x
    ```
  - ```
    a = (char) 0x69;     // 0x69->0b 0110 1001
    b = (char) 0x55;     // 0x55->0b 0101 0101
    c = a & b;           //       0b           ->0x
    ```
  - ```
    a = (char) 0x41;     // 0x41->0b 0100 0001
    b = a;               //       0b 0100 0001
    c = a ^ b;           //       0b           ->0x
    ```
    ```

# Contrast: Logic Operations

- Logical operators in C: `&&` (AND), `||` (OR), `!` (NOT)
  - **<u>0</u>** is False, **<u>anything nonzero</u>** is True
  - **<u>Always</u>** return 0 or 1
  - Early termination (a.k.a. short-circuit evaluation) of `&&`, `||`
- Examples (`char` data type)
  - `!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!

# 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();
```

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

Assembly language:

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

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

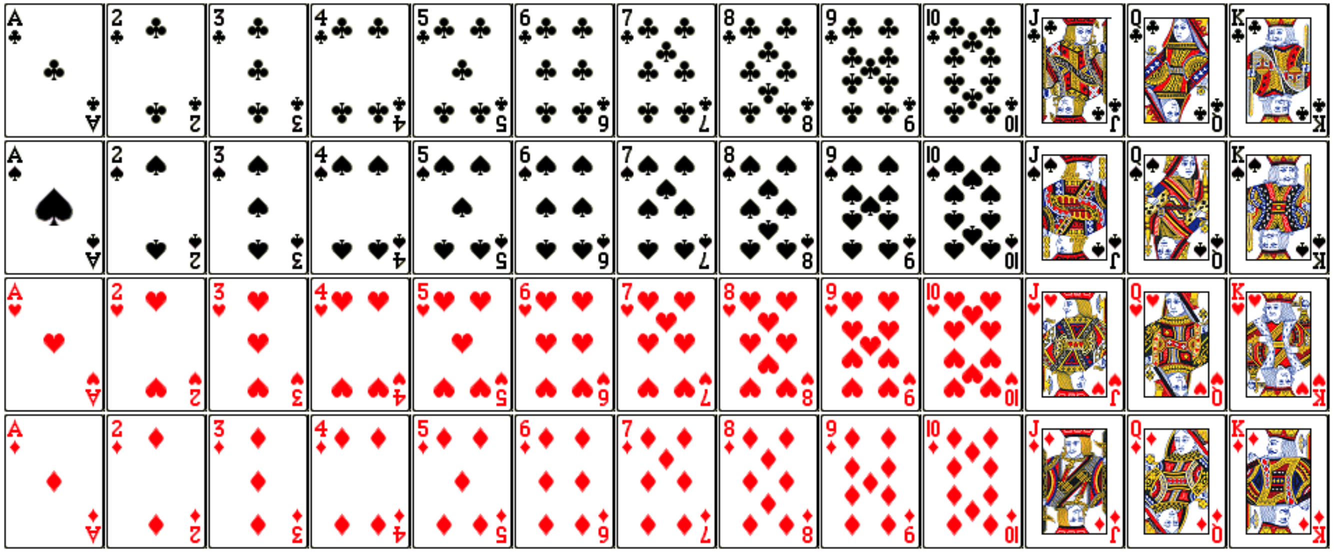
Windows 10

OS X Yosemite

Computer system:

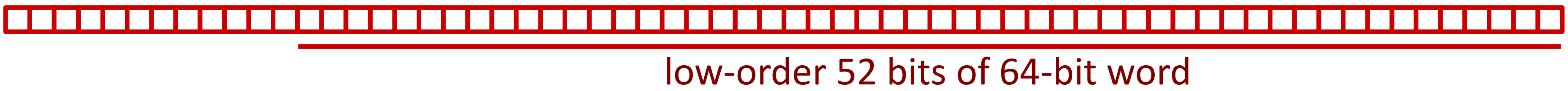

# But before we get to integers….

- 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?



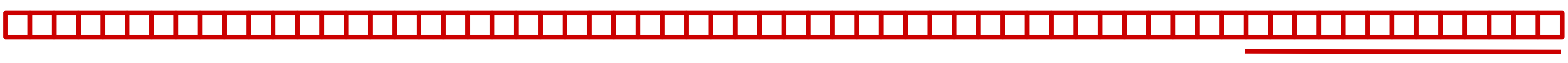
# Two possible representations

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

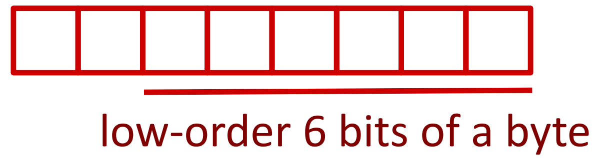
2) 1 bit per suit (4), 1 bit per number (13): 2 bits set




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

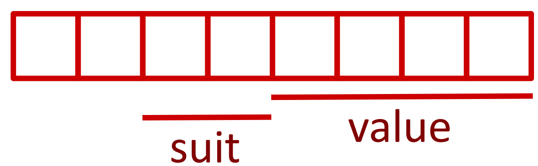
# Two better representations

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




  - 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)




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

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

| | |
|---|---|
| ♣ | 00 |
| ♦ | 01 |
| ♥ | 10 |
| ♠ | 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) ) { ... }
```

```
#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 |

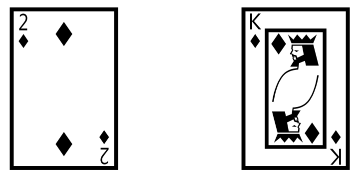
suit value

# 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);
}
```




| card1 | | SUIT_MASK | | card2 |
|---|---|---|---|---|
| 0 0 **0 1** 0 0 1 0 | | | | 0 0 **0 1** 1 1 0 1 |
| & | | | | & |
| 0 0 **1 1** 0 0 0 0 | | SUIT_MASK | | 0 0 **1 1** 0 0 0 0 |
| = | | | | = |
| 0 0 **0 1** 0 0 0 0 | | | | 0 0 **0 1** 0 0 0 0 |

^

0 0 0 0 0 0 0 0

!

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 |
|---|---|---|---|---|---|---|---|

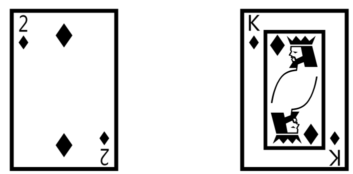
(bits 5–4: suit; bits 3–0: value)

# 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 |

&

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 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 |

&

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |

=

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |

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

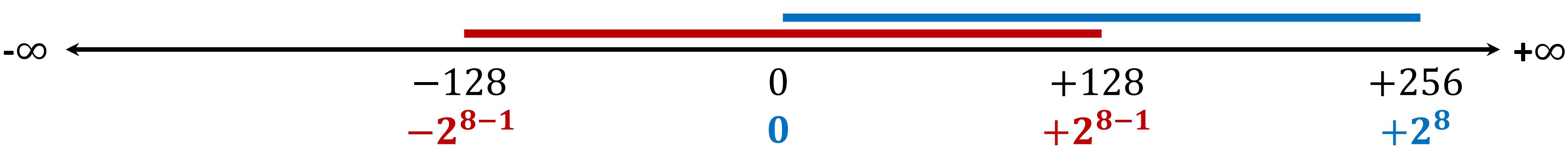
0 (false)

# 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: $-2^{w-1} \ldots 2^{w-1}-1$
- **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

```
  63
+  8
----
  71
```

```
  00111111
+ 00001000
----------
  01000111
```

- 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?

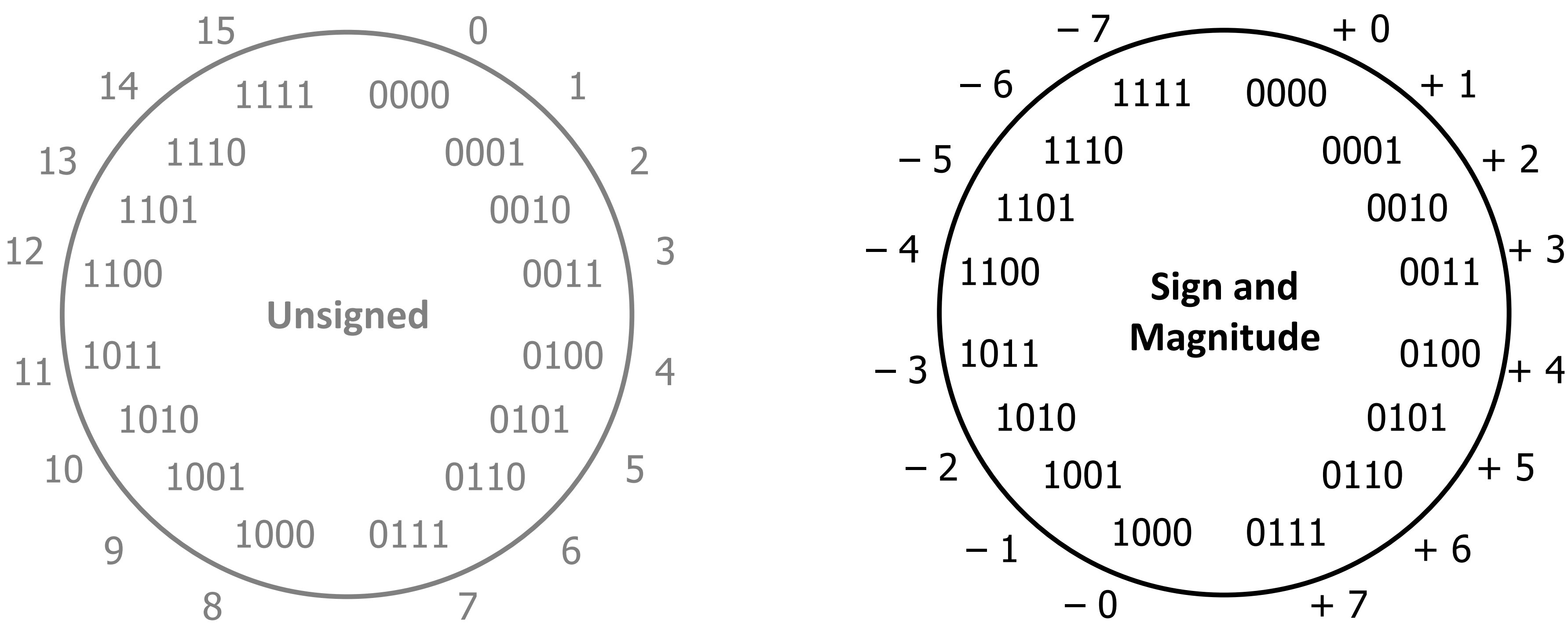
# Sign and Magnitude

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
  - 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???

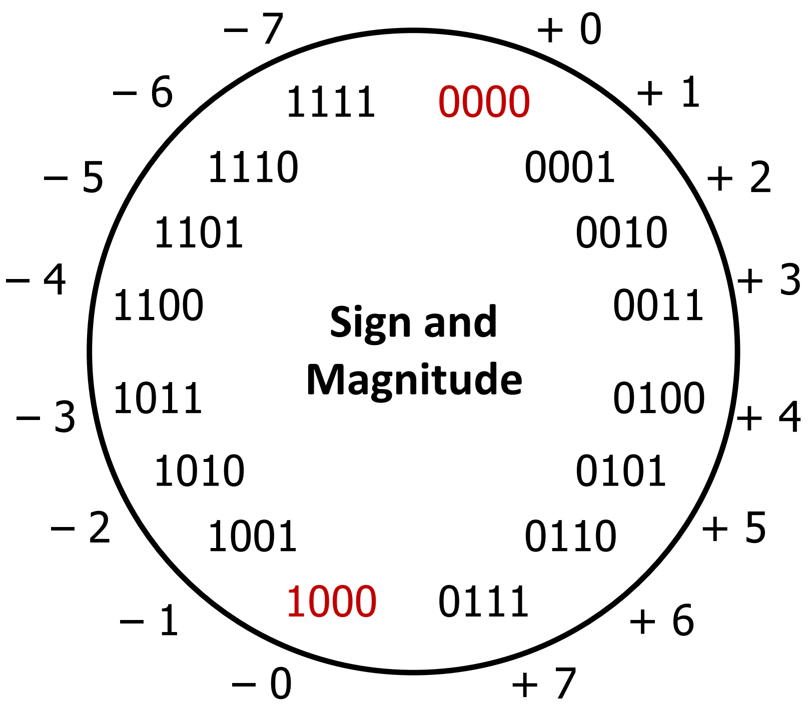
# Sign and Magnitude

- 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

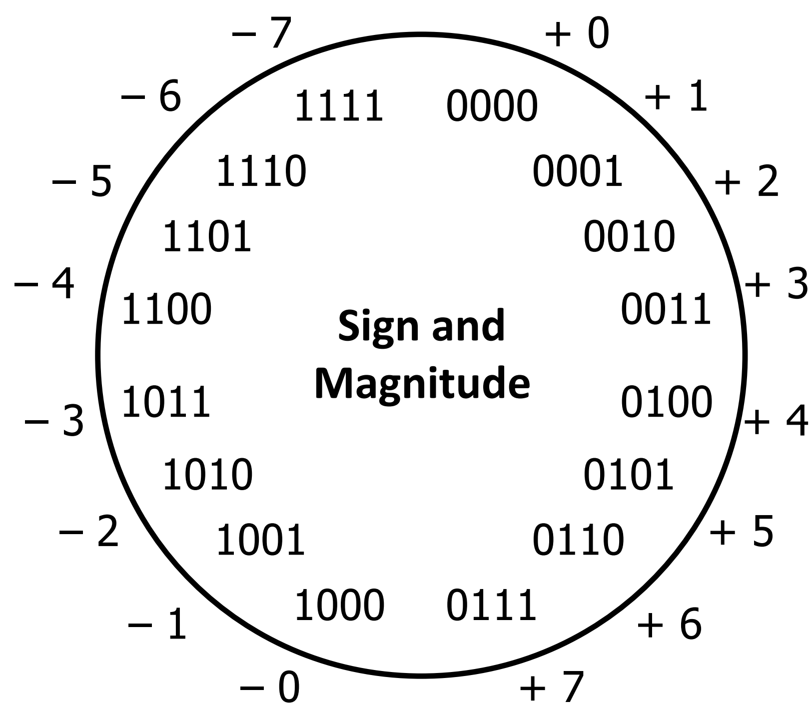
- MSB is the sign bit, rest of the bits are magnitude
- Drawbacks:
  - Two representations of 0 (bad for checking equality)
  - Arithmetic is cumbersome
    - Example: `4-3 != 4+(-3)`

| | |
|---|---|
| 4 | 0100 |
| – 3 | – 0011 |
| 1 | 0001 |

✓

| | |
|---|---|
| 4 | 0100 |
| + -3 | + 1011 |
| -7 | 1111 |

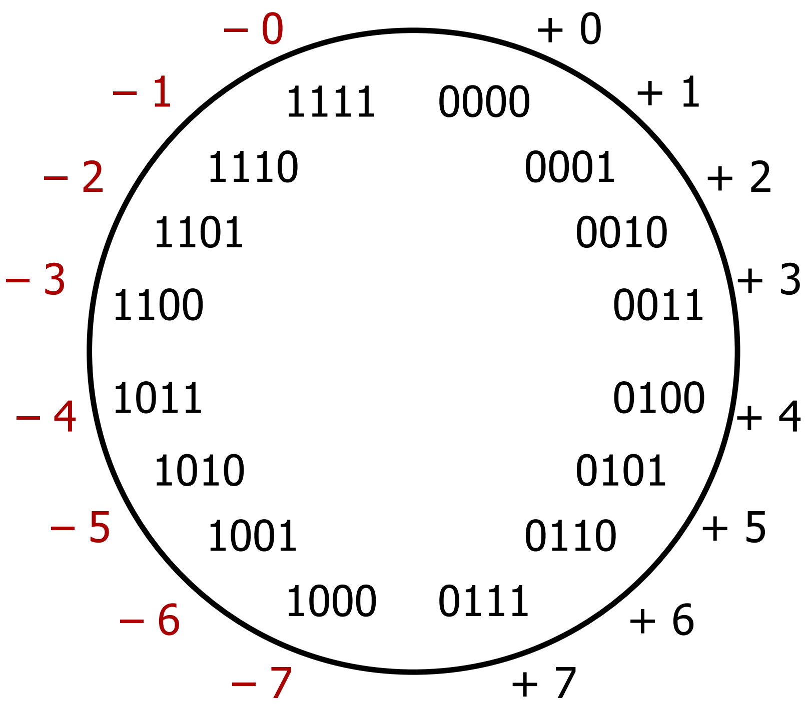
✗




- Negatives "increment" in wrong direction!

# Two's Complement

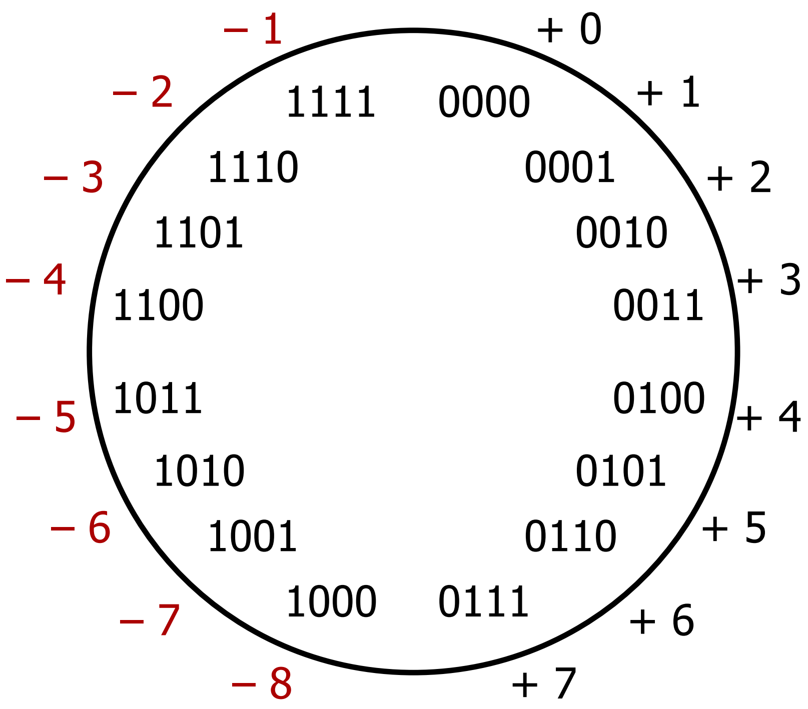
- Let's fix these problems:
  1) "Flip" negative encodings so incrementing works



# Two's Complement

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

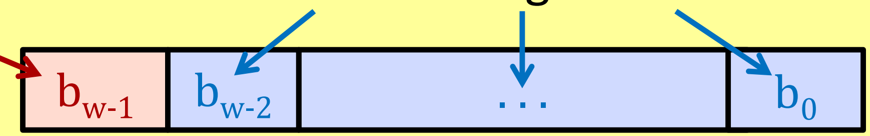
- MSB *still* indicates sign!
  - This is why we represent one more negative than positive number (-$2^{N-1}$ to $2^{N-1}-1$)



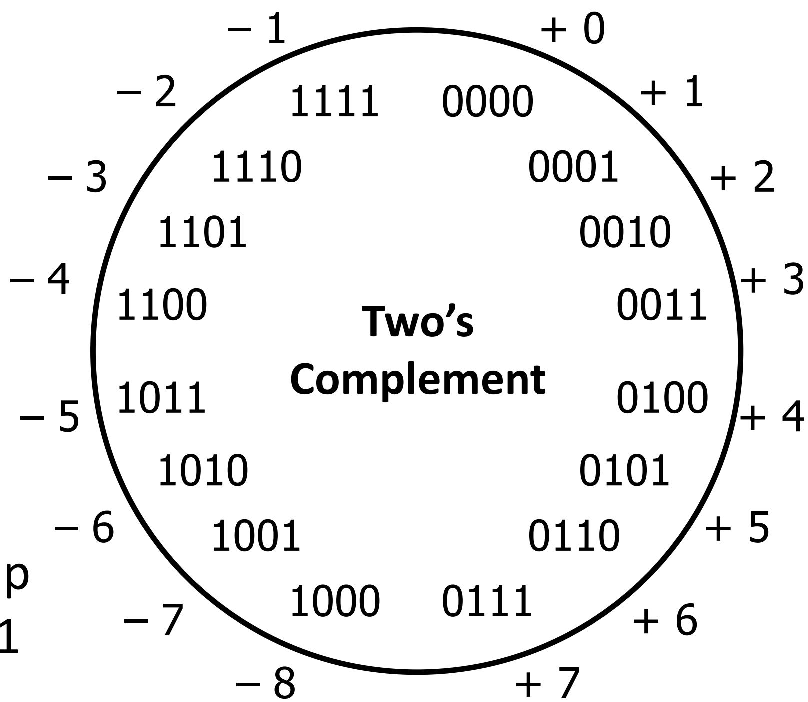
# Two's Complement Negatives

- Accomplished with one neat mathematical trick!

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



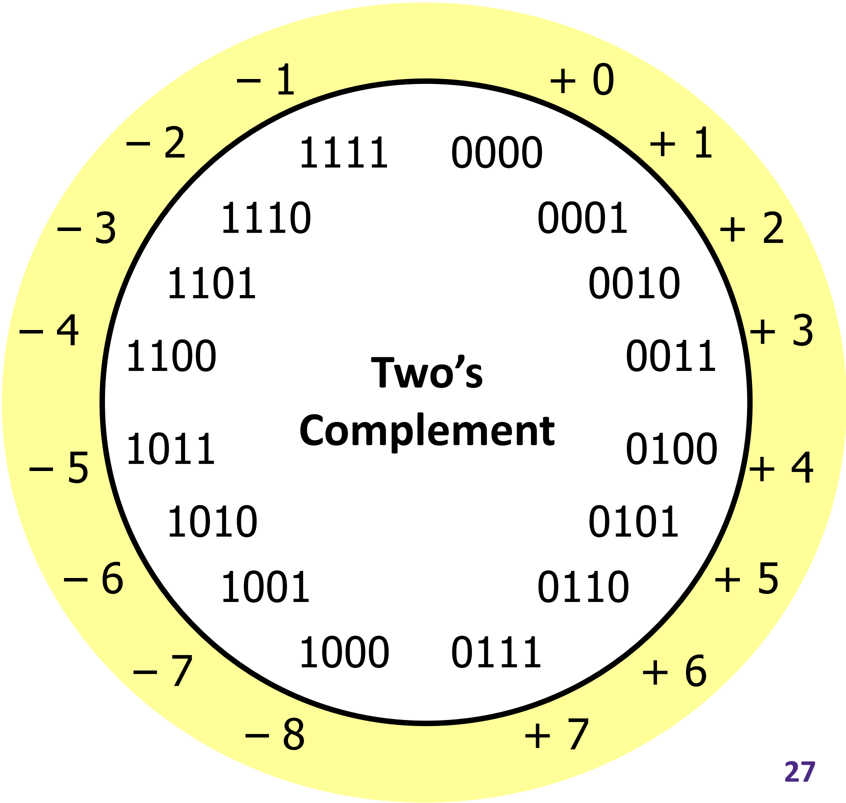

  - 4-bit Examples:
    - $1010_2$ unsigned: $1*2^3+0*2^2+1*2^1+0*2^0 =$ **10**
    - $1010_2$ two's complement: $-1*2^3+0*2^2+1*2^1+0*2^0 =$ **–6**
  - -1 represented as: $1111_2 = -2^3+(2^3-1)$
    - MSB makes it super negative, add up all the other bits to get back up to -1



# Why Two's Complement is So Great

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

- Simple negation procedure:
  - Get negative representation of any integer by taking bitwise complement and then adding one!
    `( ~x + 1 == -x )`



# Polling Question

- 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

A. -4

B. -5

C. 11

D. -3

E. We're lost...

# 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