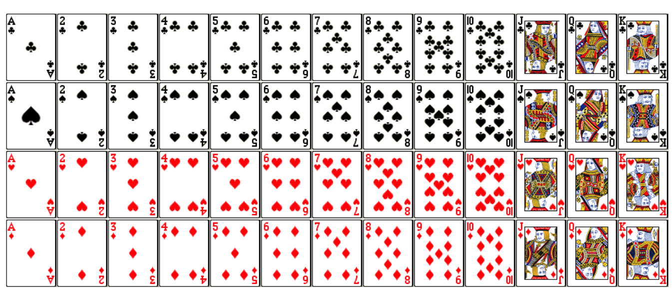
Today's Topics

- Representation of integers: unsigned and signed
- Casting
- Arithmetic and shifting
- Sign extension

But before we get to integers….

- How about encoding 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?



Some options

- **52 cards – 52 bits with bit corresponding to card set to 1**

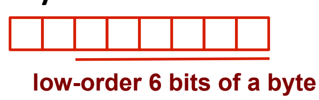
  - One-hot encoding

- **4 bits for suit, 13 bits for card value – 17 bits with 2 set to 1**

  - Two-hot(?) encoding

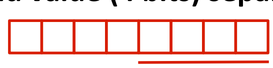
Some options

- **Binary encoding of all 52 cards – only 6 bits needed**



  - Fits in one byte

- **Binary encoding of suit (2 bits) and value (4 bits) separately**



  - Also fits in one byte, easier to do value comparisons

Some basic operations

- **Checking two cards are of the same suit**

```
char array[4];   // represents a 5 card hand
char card1, card2;  // two cards to compare
card1 = array[0];
card2 = array[1];
...
if sameSuitP(card1, card2) {
...
```

SUIT_MASK = 0x30;

```
bool sameSuitP(char card1, char card2) {
    return (! (card1 & SUIT_MASK) ^ (card2 & SUIT_MASK) );
}
```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Some basic operations

- **Greater value test**

```
char array[4];   // represents a 5 card hand
char card1, card2;  // two cards to compare
card1 = array[0];
card2 = array[1];
...
if greaterValue(card1, card2) {
...
```

VALUE_MASK = 0x0F;

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

Encoding Integers

- **The hardware (and C) supports two flavors of integers:**
  - unsigned – only the non-negatives
  - signed – both negatives and non-negatives
- **There are only 2^W distinct bit patterns of W bits, so...**
  - Can't represent all the integers
  - Unsigned values are 0 ... 2^W-1
  - Signed values are -2^{W-1} ... 2^{W-1}-1

Unsigned Integers

- **Unsigned values are just what you expect**
  - $b_7b_6b_5b_4b_3b_2b_1b_0 = b_72^7 + b_62^6 + b_52^5 + \ldots + b_12^1 + b_02^0$
    - Interesting aside: $1+2+4+8+\ldots+2^{N-1} = 2^N - 1$

```
 00111111
+00000001
 01000000
```

```
 63
+ 1
 64
```

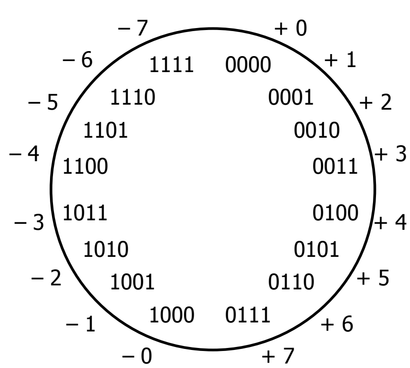
- **You add/subtract them using the normal “carry/borrow” rules, just in binary**
- **An important use of unsigned integers in C is pointers**
  - There are no negative memory addresses

Signed Integers

- **Let's do the natural thing for the positives**
  - They correspond to the unsigned integers of the same value
    - Example (8 bits): 0x00 = 0, 0x01 = 1, …, 0x7F = 127
- **But, we need to let about half of them be negative**
  - Use the high order bit to indicate 'negative'
  - Call it "the sign bit"
  - Examples (8 bits):
    - 0x00 = 00000000_2 is non-negative, because the sign bit is 0
    - 0x7F = 01111111_2 is non-negative
    - 0x80 = 10000000_2 is negative

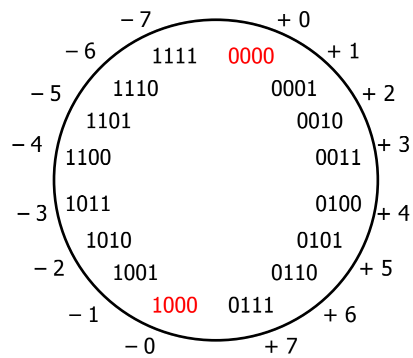
Sign-and-Magnitude Negatives

- **How should we represent -1 in binary?**
  - Possibility 1: 10000001_2
    Use the MSB for "+ or -", and the other bits to give magnitude



Sign-and-Magnitude Negatives

- **How should we represent -1 in binary?**
  - Possibility 1: 10000001_2
    Use the MSB for "+ or -", and the other bits to give magnitude
    (Unfortunate side effect: there are two representations of 0!)



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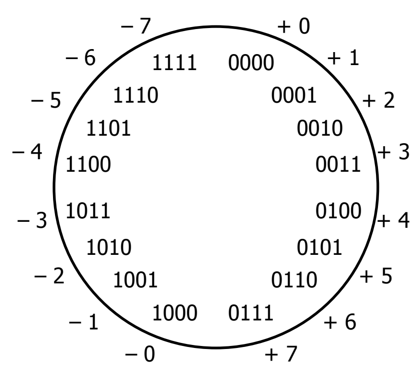
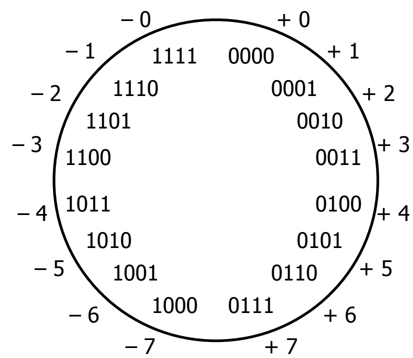
Sign-and-Magnitude Negatives

- **How should we represent -1 in binary?**
  - Possibility 1: 10000001_2
    Use the MSB for "+ or -", and the other bits to give magnitude
    Another problem: math is cumbersome
  - 4 – 3 != 4 + (-3)



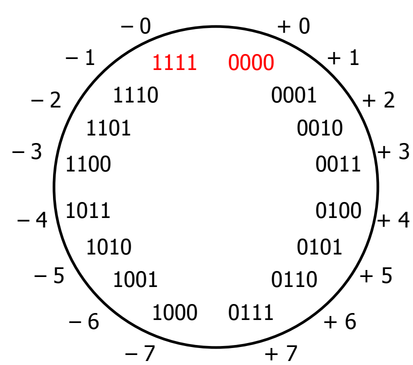
Ones' Complement Negatives

- **How should we represent -1 in binary?**
  - Possibility 2: 11111110_2
    Negative numbers: bitwise complements of positive numbers
    It would be handy if we could use the same hardware adder to add signed integers as unsigned



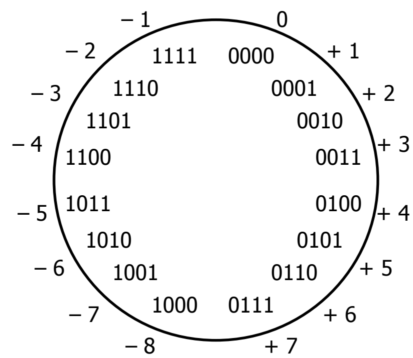
One's Complement Negatives

- **How should we represent -1 in binary?**
  - Possibility 2: 11111110_2
    Negative numbers: bitwise complements of positive numbers
    (But there are still two representations of 0!)



Two's Complement Negatives

- **How should we represent -1 in binary?**
  - Possibility 3: 11111111_2
    Bitwise complement plus one
    (Only one zero)



Two's Complement Negatives

- **How should we represent -1 in binary?**
  - Possibility 3: 11111111_2
    Bitwise complement plus one
    (Only one zero)
  - Simplifies arithmetic
    Use the same hardware adder to add signed integers as unsigned
    (simple addition; discard the highest carry bit)

Add		Invert and add		Invert and add	
4 + 3	0100 + 0011	4 – 3	0100 + 1101	– 4 + 3	1100 + 0011
= 7	= 0111	= 1 drop carry	1 0001 = 0001	– 1	1111

Two's Complement Negatives

- **How should we represent -1 in binary?**
  - Two's complement: Bitwise complement plus one
  - Why does it work?
  - Recall: The ones' complement of a b-bit positive number y is $(2^b – 1) – y$
  - Two's complement adds one to the bitwise complement, thus, -y is $2^b – y$
    - $–y$ and $2^b – y$ are equal mod 2^b (have the same remainder when divided by 2^b)
    - Ignoring carries is equivalent to doing arithmetic mod 2^b

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Two's Complement Negatives

- **How should we represent -1 in binary?**
  - Two's complement: Bitwise complement plus one
    - What should the 8-bit representation of -1 be?

```
 00000001
+????????   (want whichever bit string gives right result)
 00000000

 00000010      00000011
+????????     +????????
 00000000      00000000
```

Unsigned & Signed Numeric Values

X	Unsigned	Signed
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	–8
1001	9	–7
1010	10	–6
1011	11	–5
1100	12	–4
1101	13	–3
1110	14	–2
1111	15	–1

- Both signed and unsigned integers have limits
  - If you compute a number that is too big, you wrap: 6 + 4 = ? 15U + 2U = ?
  - If you compute a number that is too small, you wrap: -7 – 3 = ? 0U – 2U = ?
  - Answers are only correct mod 2^b
- The CPU may be capable of "throwing an exception" for overflow on signed values
  - It won't for unsigned
- But C and Java just cruise along silently when overflow occurs...

Mapping Signed ↔ Unsigned

Bits	Signed		Unsigned
0000	0		0
0001	1		1
0010	2		2
0011	3		3
0100	4	=	4
0101	5		5
0110	6		6
0111	7		7
1000	-8		8
1001	-7		9
1010	-6		10
1011	-5	+16	11
1100	-4		12
1101	-3		13
1110	-2		14
1111	-1		15

Numeric Ranges

- **Unsigned Values**
  - UMin = 0
    - 000…0
  - UMax = $2^w - 1$
    - 111…1
- **Two's Complement Values**
  - TMin = -2^{w-1}
    - 100…0
  - TMax = $2^{w-1} - 1$
    - 011…1
- **Other Values**
  - Minus 1
    - 111…1 0xFFFFFFFF (32 bits)

Values for *W* = 16

	Decimal	Hex	Binary
UMax	65535	FF FF	11111111 11111111
TMax	32767	7F FF	01111111 11111111
TMin	-32768	80 00	10000000 00000000
-1	-1	FF FF	11111111 11111111
0	0	00 00	00000000 00000000

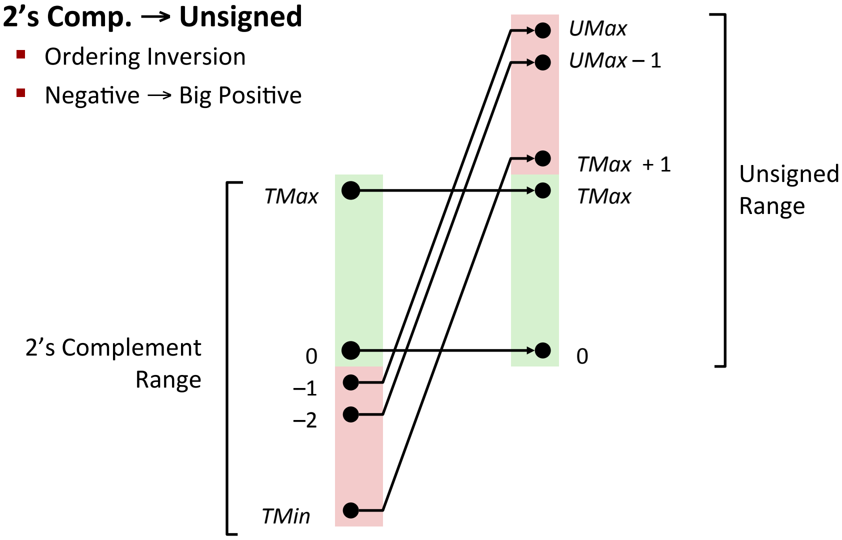
Values for Different Word Sizes

	W			
	8	16	32	64
UMax	255	65,535	4,294,967,295	18,446,744,073,709,551,615
TMax	127	32,767	2,147,483,647	9,223,372,036,854,775,807
TMin	-128	-32,768	-2,147,483,648	-9,223,372,036,854,775,808

- **Observations**
  - \| *TMin* \| = *TMax* + 1
    - Asymmetric range
  - *UMax* = 2 * *TMax* + 1
- **C Programming**
  - #include <limits.h>
  - Declares constants, e.g.,
    - ULONG_MAX
    - LONG_MAX
    - LONG_MIN
  - Values platform specific

Conversion Visualized

- **2's Comp. → Unsigned**
  - Ordering Inversion
  - Negative → Big Positive



Signed vs. Unsigned in C

- **Constants**
  - By default are considered to be signed integers
  - Unsigned if have "U" as suffix
    - `0U`, `4294967259U`
- **Casting**
    - `int tx, ty;`
    - `unsigned ux, uy;`
  - Explicit casting between signed & unsigned
    - `tx = (int) ux;`
    - `uy = (unsigned) ty;`
  - Implicit casting also occurs via assignments and procedure calls
    - `tx = ux;`
    - `uy = ty;`

Casting Surprises

- **Expression Evaluation**
  - If you mix unsigned and signed in a single expression, then ***signed values implicitly cast to unsigned***
  - Including comparison operations **<, >, ==, <=, >=**
  - Examples for *W* = 32: **TMIN = -2,147,483,648** **TMAX = 2,147,483,647**

Constant$_1$	**Constant$_2$**	**Relation**	**Evaluation**
0	0U	==	unsigned
-1	0	<	signed
-1	0U	>	unsigned
2147483647	-2147483648	>	signed
2147483647U	-2147483648	<	unsigned
-1	-2	>	signed
(unsigned)-1	-2	>	unsigned
2147483647	2147483648U	<	unsigned
2147483647	(int) 2147483648U	>	signed

Shift Operations

- **Left shift: x << y**
  - Shift bit-vector x left by y positions
    - Throw away extra bits on left
    - Fill with 0s on right
  - Multiply by 2**y
- **Right shift: x >> y**
  - Shift bit-vector x right by y positions
    - Throw away extra bits on right
  - Logical shift (for unsigned)
    - Fill with 0s on left
  - Arithmetic shift (for signed)
    - Replicate most significant bit on left
    - Maintain sign of x
  - Divide by 2**y
  - Correct truncation (towards 0) requires some care with signed numbers

Argument x	01100010
<< 3	00010*000*
Logical >> 2	*00*011000
Arithmetic >> 2	*00*011000

Argument x	10100010
<< 3	00010*000*
Logical >> 2	*00*101000
Arithmetic >> 2	*11*101000

Undefined behavior when y < 0 or y ≥ word_size

Using Shifts and Masks

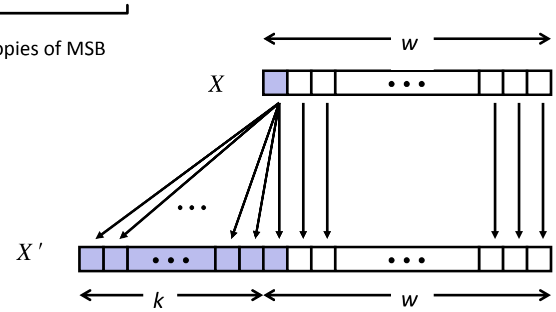
- **Extract 2nd most significant byte of an integer**
  - First shift: x >> (2 * 8)
  - Then mask: (x >> 16) & 0xFF

x	01100001 $\boxed{01100010}$ 01100011 01100100
x >> 16	00000000 00000000 01100001 $\boxed{01100010}$
(x >> 16) & 0xFF	*00000000 00000000 00000000 11111111* 00000000 00000000 00000000 01100010

- **Extracting the sign bit**
  - (x >> 31) & 1 - need the "& 1" to clear out all other bits except LSB
- **Conditionals as Boolean expressions (assuming x is 0 or 1)**
  - if (x) a=y else a=z; which is the same as a = x ? y : z;
  - Can be re-written as: a = ((x << 31) >> 31) & y + (!x << 31) >> 31) & z;

Sign Extension

- **Task:**
  - Given w-bit signed integer x
  - Convert it to w+k-bit integer with same value
- **Rule:**
  - Make k copies of sign bit:
  - $X' = \underbrace{x_{w-1},\dots,x_{w-1}}_{k \text{ copies of MSB}}, x_{w-1}, x_{w-2},\dots, x_0$



Sign Extension Example

- Converting from smaller to larger integer data type
- C automatically performs sign extension

```
short int x =  12345;
int       ix = (int) x;
short int y = -12345;
int       iy = (int) y;
```

	Decimal	Hex	Binary
x	12345	30 39	00110000 01101101
ix	12345	00 00 30 39	00000000 00000000 00110000 01101101
y	-12345	CF C7	11001111 11000111
iy	-12345	FF FF CF C7	11111111 11111111 11001111 11000111