Number Systems

Why Bits (Binary Digits)?

- Computers are built using digital circuits
  - Inputs and outputs can have only two values
  - True (high voltage) or false (low voltage)
  - Represented as 1 and 0
- Can represent many kinds of information
  - Boolean (true or false)
  - Numbers (23, 79, …)
  - Characters ('a', 'z', …)
  - Pixels, sounds
  - Internet addresses
- Can manipulate in many ways
  - Read and write
  - Logical operations
  - Arithmetic

Base 10 and Base 2

- Decimal (base 10)
  - Each digit represents a power of 10
  - **4173** = **4** x 10^3 + **1** x 10^2 + **7** x 10^1 + **3** x 10^0
- Binary (base 2)
  - Each bit represents a power of 2
  - **10110** = **1** x 2^4 + **0** x 2^3 + **1** x 2^2 + **1** x 2^1 + **0** x 2^0 = 22

Decimal to binary conversion:
Divide repeatedly by 2 and keep remainders

```
12/2  = 6    R = 0
6/2   = 3    R = 0
3/2   = 1    R = 1
1/2   = 0    R = 1
Result = 1100
```


Writing Bits is Tedious for People

- Octal (base 8)
  - Digits 0, 1, …, 7
- Hexadecimal (base 16)
  - Digits 0, 1, …, 9, A, B, C, D, E, F

0000 = 0	**1000 = 8**
0001 = 1	**1001 = 9**
0010 = 2	**1010 = A**
0011 = 3	**1011 = B**
0100 = 4	**1100 = C**
0101 = 5	**1101 = D**
0110 = 6	**1110 = E**
0111 = 7	**1111 = F**

Thus the 16-bit binary number

1011 0010 1010 1001

converted to hex is

B2A9

Representing Colors: RGB

- Three primary colors
  - Red
  - Green
  - Blue
- Strength
  - 8-bit number for each color (e.g., two hex digits)
  - So, 24 bits to specify a color
- In HTML, e.g. course "Schedule" Web page
  - Red: De-Comment Assignment Due
  - Blue: Reading Period
- Same thing in digital cameras
  - Each pixel is a mixture of red, green, and blue

Finite Representation of Integers

- Fixed number of bits in memory
  - Usually 8, 16, or 32 bits
  - (1, 2, or 4 bytes)
- Unsigned integer
  - No sign bit
  - Always 0 or a positive number
  - All arithmetic is modulo 2^n
- Examples of unsigned integers
  - 00000001 ➔ 1
  - 00001111 ➔ 15
  - 00010000 ➔ 16
  - 00100001 ➔ 33
  - 11111111 ➔ 255

Adding Two Integers

- From right to left, we add each pair of digits
- We write the sum, and add the carry to the next column

Base 10

	1	9	8
+	2	6	4
Sum	4	6	2
Carry	0	1	1

Base 2

	0	1	1
+	0	0	1
Sum	1	0	0
Carry	0	1	1

Binary Sums and Carries

a	b	Sum
0	0	0
0	1	1
1	0	1
1	1	0

XOR
("exclusive OR")

a	b	Carry
0	0	0
0	1	0
1	0	0
1	1	1

AND

```
  0100 0101  ←  69
+ 0110 0111  ←  103
  1010 1100  ←  172
```

Modulo Arithmetic

- Consider only numbers in a range
  - E.g., five-digit car odometer: 0, 1, …, 99999
  - E.g., eight-bit numbers 0, 1, …, 255
- Roll-over when you run out of space
  - E.g., car odometer goes from 99999 to 0, 1, …
  - E.g., eight-bit number goes from 255 to 0, 1, …
- Adding 2^n doesn't change the answer
  - For eight-bit number, n=8 and 2^n=256
  - E.g., (37 + 256) mod 256 is simply 37
- This can help us do subtraction by changing it to addition…
  - Suppose you want to compute a – b
  - Note that this equals a – b + 256 = a + (256 – b)
  - How to compute 256 – b?

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One's and Two's Complement

- What's easy is computing 255 – b (in 8 bits)
- Because it's 11111111 – b, so just flip every bit of b
  - E.g., if b is 01000101 (i.e., 69 in decimal)
  - 255 – b

```
  1111 1111
- 0100 0101  ←— b

  1011 1010  ←— 255 – b = 88
```

  - This is called the one's complement of b; just flip all the bits of b
- Two's complement
  - Add 1 to the one's complement
  - E.g., 256 – 69 = (255 – 69) + 1 → 1011 1011

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Putting it All Together

- Computing "a – b"
  - Same as "a + 256 – b" (in 8-bit representation)
  - Same as "a + (255 – b) + 1"
  - Same as "a + onesComplement(b) + 1"
  - Same as "a + twosComplement(b)"
- Example: 172 – 69
  - The original number 69: 0100 0101
  - One's complement of 69: 1011 1010
  - Two's complement of 69: 1011 1011
  - Add to the number 172: 1010 1100
  - The sum comes to: 0110 0111
  - Equals: 103 in decimal

```
   1010 1100
 + 1011 1011
  10110 0111
```

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Signed Integers

How to represent negative as well as positive numbers

- Sign-magnitude representation
  - Use one bit to store the sign, (n-1) for magnitude
    - Sign bit is 0 for positive number, 1 for negative number
  - Examples
    - E.g., 0010 1100 → 44
    - E.g., 1010 1100 → -44
  - Hard to do arithmetic this way, so rarely used
- Complement representation
  - One's complement
    - Flip every bit: E.g., 1101 0011 → -44
  - Two's complement
    - Flip every bit, then add 1: E.g., 1101 0100 → -44

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Overflow: Running Out of Room

- Adding two large integers together
  - Sum might be too large to store in the number of bits available
  - What happens?
- Unsigned integers
  - All arithmetic is "modulo" arithmetic
  - Sum would just wrap around
  - End up with sum modulo 2^n
- Signed integers
  - Can get nonsense values
  - Example with 16-bit integers
    - Sum: 10000+20000+30000
    - Result: -5536

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Bitwise Operators: AND and OR

- Bitwise AND (&)

&	0	1
0	0	0
1	0	1

  - Mod on the cheap!
    - E.g., 53 % 16
    - … is same as 53 & 15;

53	0	0	1	1	0	1	0	1
& 15	0	0	0	0	1	1	1	1
5	0	0	0	0	0	1	0	1

- Bitwise OR (|)

|	0	1
0	0	1
1	1	1

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Bitwise Operators: Not and XOR

- Not or One's complement (~)
  - Turns 0s to 1s, and 1s to 0s
  - E.g., set last three bits to 0
    - x = x & ~7;
- XOR (^)
  - 0 if both bits are the same
  - 1 if the two bits are different

^	0	1
0	0	1
1	1	0

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Bitwise Operators: Shift Left/Right

- Shift left (<<): Multiply by powers of 2
  - Shift some # of bits to the left, filling the blanks with 0

53	0	0	1	1	0	1	0	1
53<<2	1	1	0	1	0	0	0	0

- Shift right (>>): Divide by powers of 2
  - Shift some # of bits to the right
  - For unsigned integer, fill in blanks with 0
  - What about signed negative integers?
    - Can vary from one machine to another!

53	0	0	1	1	0	1	0	1
53>>2	0	0	0	0	1	1	0	1

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Example: Counting the 1's

- How many 1 bits in a number?
  - E.g., how many 1 bits in the binary representation of 53?

0	0	1	1	0	1	0	1

  - Four 1 bits
- How to count them?
  - Look at one bit at a time
  - Check if that bit is a 1
  - Increment counter
- How to look at one bit at a time?
  - Look at the last bit: n & 1
  - Check if it is a 1: (n & 1) == 1, or simply (n & 1)

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Counting the Number of '1' Bits

```
#include <stdio.h>
#include <stdlib.h>
int main(void) {
   unsigned int n;
   unsigned int count;
   printf("Number: ");
   if (scanf("%u", &n) != 1) {
      fprintf(stderr, "Error: Expect unsigned int.\n");
      exit(EXIT_FAILURE);
   }
   for (count = 0; n > 0; n >>= 1)
       count += (n & 1);
   printf("Number of 1 bits: %u\n", count);
   return 0;
}
```

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Summary

- Computer represents everything in binary
  - Integers, floating-point numbers, characters, addresses, …
  - Pixels, sounds, colors, etc.
- Binary arithmetic through logic operations
  - Sum (XOR) and Carry (AND)
  - Two's complement for subtraction
- Bitwise operators
  - AND, OR, NOT, and XOR
  - Shift left and shift right
  - Useful for efficient and concise code, though sometimes cryptic

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