# Bits, Bytes, Ints

Jinyang Li

Some are based on Tiger Wang's slides

# The language of electronics has evolved from analog signals…

Analog signals: smooth and continuous

**Problems**

1. **Difficult to design**
2. **Susceptible to noise**

Analog components: resistors, capacitors, inductors, diodes, etc.

# … to digital

Digital signals: discrete (encode sequence of 0s and 1s)

## Advantages

1. **Easier to design**
2. **Robust to noise**

Digital components: transistors, logic gates …

# Using bits to represent everything

Bit = Binary digit,  0 or 1

- A bit is too small to be useful
  - A bit has 2 values; the English alphabet has 26 values (characters)
- Use a group of bits instead of bit
  - different bit patterns represent different “values”

# Question

- How many bit patterns can a group of 2 bits have?

Can be
either 0 or 1

$b_1 \; b_0$

All patterns of 2-bits: 00, 01, 10, 11

- How many bit patterns does a group of n bits have?

$$\underbrace{b_{n-1}b_{n-2}\ldots b_1b_0}_{\text{n bits}}$$

# of patterns of n-bits: $2^n$

# A digression: you must memorize common powers of 2

$2^0 = 1$
$2^1 = 2$

$2^2 = 4$

$2^3 = 8$
$2^4 = 16$
$2^5 = 32$

$2^6 = 64$
$2^7 = 128$

$2^8 = 256$

$2^9 = 512$
$2^{10} = 1024$

# A digression: you must memorize common powers of 2 and beyond

$2^{10} = 1024 \approx 10^3$ (Kilo)

$2^{20} \approx 10^{3*2} = 10^6$ (Mega)

$2^{30} \approx 10^{3*3} = 10^9$ (Giga)

$2^{40} \approx 10^{3*4} = 10^{12}$ (Tera)

$2^{50} \approx 10^{3*5} = 10^{15}$ (Peta)

# Represent non-negative integer

bits: $b_{n-1}b_{n-2}...b_2b_1b_0$

Goal: map each bit pattern to an integer in [0, ??]

[0, $2^n$ -1]

Solution: Base-2 representation

$$b_{n-1}b_{n-2}...b_2b_1b_0 = \sum_{i=0}^{n-1} b_i * 2^i$$

$b_i$ is bit at i-th position (from right to left, starting i=0)

# Most significant bit (MSB)

The bit position has the greatest value

```
Bits    01010
MSB      ?

Bits    11011010
MSB      ?
```

# Most significant bit (MSB)

The bit position has the greatest value

- The leftmost bit

```
Bits    01010010
MSB      0

Bits    11011010
MSB      1
```

# Least significant bit (LSB)

The bit position has the least value

- The rightmost bit

```
Bits    01010010
MSB      0

Bits    11011010
MSB      0
```

# Examples

Bits 0110

Value $0*2^3 + 1*2^2 + 1*2^1 + 0*2^0 = 6$

Bits 1110

Value ?

$1*2^3+1*2^2+1*2^1+0*2^0 = 14$

# Byte

Byte: Basic unit of computation and storage

- The term is coined by Werner Buchholz (IBM).
- Byte sizes from 1 bit to 48 bits have been used in the history

# Byte

Memory is a continuous array.
Each unit is a byte.

1 Byte is the smallest information CPU can fetch from memory
(One cannot fetch just 1 bit)

# Byte – 8 bits chunk

IBM System/360, 1964

Introduced

Intel 8080, 1974

Widely adopted

Modern processors

Standardized

# Your mental model

Each byte has 8 bits

# Range of a single byte as non-negative integers

Maximum

$11111111_2 \rightarrow 255$

Minimum

$00000000_2 \rightarrow 0$

# Range of 4-byte as non-negative integers

Maximum

$11111111\ldots1_2 \rightarrow 2^{32}-1$

Minimum

$00000000\ldots0_2 \rightarrow 0$

# Describing a bit pattern – intuitive way

How to make a bit pattern human readable?

– Use base-2 notation?

```
Bits 10101110 11001010 00001110 00011010
```

4 bytes

15 cm on my laptop

# Describing a bit pattern – strawman

How to make a bit pattern human readable?

- Use base-2 notation? Too verbose
- Use base-10 notation?

How many decimal digits needed to represent 1 byte? 3

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |

Conversion from base-2 to base-10 (and vice versa) is mentally difficult for humans

# Describing a bit pattern- Hex Notation

Use base-16 (hexadecimal) notation

- Hex "digit" is one of 16 symbols: 0-9, a,b,c,d,e,f
- How many bits needed to represent a hex digit?

4

# Hexadecimal "digit"

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

# Hex Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| Bits | 10101110 | 11001010 | 00001110 | 00011010 |
| Decimal | 174 | 202 | 014 | 026 |
| Hex | | | | |
| Hex(C) | | | | |

1010 =

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| Bits | 10101110 | 11001010 | 00001110 | 00011010 |
| Decimal | 174 | 202 | 014 | 026 |
| Hex | A | | | |
| Hex(C) | | | | |

$1010 = 1 * 2^3 + 0 * 2^2 + 1 * 2 + 0 = 10 = A_{16}$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A** | | | |
| **Hex(C)** | | | | |

**1110 =**

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | | | |
| **Hex(C)** | | | | |

$$1110 = 1 * 2^3 + 1 * 2^2 + 1 * 2 + 0 = 14 = E_{16}$$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | | | |
| **Hex(C)** | | | | |

**1100 =**

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| Bits | 10101110 | 11001010 | 00001110 | 00011010 |
| Decimal | 174 | 202 | 014 | 026 |
| Hex | A E | C | | |
| Hex(C) | | | | |

$1100 = 1 * 2^3 + 1 * 2^2 + 0 * 2 + 0 = 12 = C_{16}$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | **C** | | |
| **Hex(C)** | | | | |

**1010 =**

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | **C A** | | |
| **Hex(C)** | | | | |

$$1010 = 1 * 2^3 + 0 * 2^2 + 1 * 2 + 0 = 10 = A_{16}$$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| Bits | 10101110 | 11001010 | 00001110 | 00011010 |
| Decimal | 174 | 202 | 014 | 026 |
| Hex | A E | C A | 0 | |
| Hex(C) | | | | |

$0000 = 0 * 2^3 + 0 * 2^2 + 0 * 2 + 0 = 0 = 0_{16}$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | **C A** | **0 E** | |
| **Hex(C)** | | | | |

$$1110 = 1 * 2^3 + 1 * 2^2 + 1 * 2 + 0 = 14 = E_{16}$$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | **C A** | **0 E** | **1** |
| **Hex(C)** | | | | |

$$0001 = 0 * 2^3 + 0 * 2^2 + 0 * 2 + 1 = 1 = 1_{16}$$

# Hexadecimal Notation

- 1 byte = 8 bits = 2 hex digits

| | | | | |
|---|---|---|---|---|
| **Bits** | **10101110** | **11001010** | **00001110** | **00011010** |
| **Decimal** | **174** | **202** | **014** | **026** |
| **Hex** | **A E** | **C A** | **0 E** | **1 A** |
| **Hex(C)** | | | | |

$$1010 = 1 * 2^3 + 0 * 2^2 + 1 * 2 + 0 = 10 = A_{16}$$

# Hexadecimal Notation

- Each byte is represented with 2 hex numbers ($00_{16}$ -- $FF_{16}$)

| | | | | |
|---|---|---|---|---|
| Bits | 10101110 | 11001010 | 00001110 | 00011010 |
| Decimal | 174 | 202 | 014 | 026 |
| Hex | A E | C A | 0 E | 1 A |
| Hex(C) | 0xAECA0E1A | | | |

# Exercises Time

| Hexadecimal | Decimal | Binary |
|---|---|---|
| | | 1010 0111 |
| | | 0011 1110 |
| 0xBC | | |
| | 55 | |
| 0xF3 | | |

# Answers

| Hexadecimal | Decimal | Binary |
|---|---|---|
| 0xA7 | 10*16 + 7 = 167 | 1010 0111 |
| 0x3E | 3*16 + 14 = 62 | 0011 1110 |
| 0xBC | 11*16 + 12 = 188 | 1011 1100 |
| 0x37 | 3*16+7=55 | 0011 0111 |
| 0xF3 | 15*16+3=243 | 1111 0011 |

# Unsigned addition

$11 + 10$

$00001011_2 + 00001010_2$

# Unsigned addition

11 + 10

$00001011_2 + 00001010_2$

$$
\begin{array}{r}
0\ 0\ 0\ 0\ 1\ 0\ 1\ 1 \\
+\quad 0\ 0\ 0\ 0\ 1\ 0\ 1\ 0 \\
\hline
\end{array}
$$

# Unsigned addition

11 + 10

$00001011_2 + 00001010_2$

$$
\begin{array}{r}
0\,0\,0\,0\,1\,0\,1\,1 \\
+\quad 0\,0\,0\,0\,1\,0\,1\,0 \\
\hline
1\phantom{\,0\,0\,0\,0\,1\,0\,1\,0}
\end{array}
$$

# Unsigned addition

11 + 10

$00001011_2 + 00001010_2$

$$
\begin{array}{r}
0\ 0\ 0\ 0\ 1\ 0\ 1\ 1 \\
+\quad 0\ 0\ 0\ 0\ 1\ 0\ 1\ 0 \\
\hline
2\ 1
\end{array}
$$

# Unsigned addition

11 + 10

$00001011_2 + 00001010_2$

$$
\begin{array}{r}
1\phantom{0000101} \\
0\,0\,0\,0\,1\,0\,1\,1 \\
+\quad 0\,0\,0\,0\,1\,0\,1\,0 \\
\hline
0\,1
\end{array}
$$

# Unsigned addition

11 + 10

$00001011_2 + 00001010_2$

```
                1
    0 0 0 0 1 0 1 1
+   0 0 0 0 1 0 1 0
-----------------------
              1 0 1
```

# Unsigned addition

11 + 10

$00001011_2 + 00001010_2$

$$
\begin{array}{r}
0\ 0\ 0\ 0\ 1\ 0\ 1\ 1 \\
+\quad 0\ 0\ 0\ 0\ 1\ 0\ 1\ 0 \\
\hline
0\ 0\ 0\ 1\ 0\ 1\ 0\ 1
\end{array}
$$

# Unsigned subtraction

11 - 10

$00001011_2 - 00001010_2$

```
    0 0 0 0 1 0 1 1
-   0 0 0 0 1 0 1 0
-----------------------
```

# Unsigned subtraction

11 - 10

$00001011_2 - 00001010_2$

$$
\begin{array}{r}
0\ 0\ 0\ 0\ 1\ 0\ 1\ 1 \\
-\quad 0\ 0\ 0\ 0\ 1\ 0\ 1\ 0 \\
\hline
0\ 0\ 0\ 0\ 0\ 0\ 0\ 1
\end{array}
$$

# Unsigned subtraction

10-11

$00001010_2$ - $00001011_2$

```
    0 0 0 0 1 0 1 0
-   0 0 0 0 1 0 1 1
-----------------
    ? ? ?
```

**Question:**

How to represent negative numbers?

# Strawman

Most significant bit (MSB) represents the sign

$0\ 0\ 0\ 0\ 0\ 0\ 0\ 1_2 \longrightarrow 1$

$1\ 0\ 0\ 0\ 0\ 0\ 0\ 1_2 \longrightarrow -1$

$$
\begin{array}{rcccccccc}
 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
+ & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\hline
\end{array}
$$

# Strawman

Most significant bit (MSB) represents the sign

$0\ 0\ 0\ 0\ 0\ 0\ 0\ 1_2 \longrightarrow 1$

$1\ 0\ 0\ 0\ 0\ 0\ 0\ 1_2 \longrightarrow -1$

$$
\begin{array}{rr}
 & 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1 \\
+ & 1\ 0\ 0\ 0\ 0\ 0\ 0\ 1 \\
\hline
 & 1\ 0\ 0\ 0\ 0\ 0\ 1\ 0
\end{array}
$$

# Strawman

Most significant bit (MSB) represents the sign

$0\ 0\ 0\ 0\ 0\ 0\ 0\ 1_2 \longrightarrow 1$

$1\ 0\ 0\ 0\ 0\ 0\ 0\ 1_2 \longrightarrow -1$

$$
\begin{array}{r}
0\ 0\ 0\ 0\ 0\ 0\ 0\ 1 \\
+\quad 1\ 0\ 0\ 0\ 0\ 0\ 0\ 1 \\
\hline
1\ 0\ 0\ 0\ 0\ 0\ 1\ 0
\end{array}
$$

-2 ???

# Two's complement

Byte 10010110

Unsigned number

$1 * 2^7 + 0 * 2^6 + 0 * 2^5 + 1 * 2^4 + 0 * 2^3 + 1 * 2^2 + 1 * 2 + 0 * 2^0$

# Two's complement

Byte 10010110

Unsigned number

$1 * 2^7 + 0 * 2^6 + 0 * 2^5 + 1 * 2^4 + 0 * 2^3 + 1 * 2^2 + 1 * 2 + 0 * 2^0$

Signed number

$-1 * 2^7 + 0 * 2^6 + 0 * 2^5 + 1 * 2^4 + 0 * 2^3 + 1 * 2^2 + 1 * 2 + 0 * 2^0$

# Two's complement

$$\vec{b} = \left[ b_w, b_{w-1}, \ldots, b_0 \right] \qquad val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

MSB: val( $b_w$ ) = $-b_w * 2^w$

Other: val ( $b_i$ ) = $b_i * 2^i$, $0 <= i < w$

# Two's complement

$$\vec{b} = \left[ b_w, b_{w-1}, \ldots, b_0 \right]$$

$$val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

| Binary | Value |
|---|---|
| 1000 0001 | |
| 1010 0101 | |
| 0101 0101 | |

# Two's complement

$$\vec{b} = \left[ b_w, b_{w-1}, \ldots, b_0 \right]$$

$$val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

| Binary | | Value |
|---|---|---|
| 1000 0001 | $-1 * 2^7 + 1$ | -127 |
| 1010 0101 | | |
| 0101 0101 | | |

# Two's complement

$$\vec{b} = \left[ b_w, b_{w-1}, \ldots, b_0 \right] \qquad val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

| Binary | | Value |
|---|---|---|
| 1000 0001 | $-1 * 2^7 + 1$ | -127 |
| 1010 0101 | $-1 * 2^7 + 2^5 + 2^2 + 2^0$ | -91 |
| 0101 0101 | | |

# Two's complement

$$\vec{b} = \left[ b_w, b_{w-1}, \ldots, b_0 \right]$$

$$val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

| Binary | | Value |
|---|---|---|
| 1000 0001 | $-1 * 2^7 + 1$ | -127 |
| 1010 0101 | $-1 * 2^7 + 2^5 + 2^2 + 2^0$ | -91 |
| 0101 0101 | $2^6 + 2^4 + 2^2 + 2$ | 85 |

# Two's complement

$$\vec{b} = \left[ b_w, b_{w-1}, \ldots, b_0 \right]$$

$$val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

```
    0 0 0 0 0 0 0 1
+   1 0 0 0 0 0 0 1
-----------------------
    1 0 0 0 0 0 1 0
```

# Two's complement

$$\vec{b} = \left[b_w, b_{w-1}, \ldots, b_0\right] \qquad val\left(\vec{b}\right) = -b_w 2^w + \sum_{i=0}^{w-1} b_i 2^i$$

| | | | |
|---|---|---|---|
| | 0 0 0 0 0 0 0 1 | $2^0$ | 1 |
| + | 1 0 0 0 0 0 0 1 | $-1 * 2^7 + 2^0$ | -127 |
| | 1 0 0 0 0 0 1 0 | $-1 * 2^7 + 2^1$ | -126 |

# Find 2's complement quickly

With a negative number, how to give its binary representation?  e.g. -40

# Find 2's complement quickly

With a negative number, how to give its binary representation? e.g. -40

Step 1. represent 40 in binary

0010 1000

# Find 2's complement quickly

With a negative number, how to give its binary representation? e.g. -40

Step 2. flip all bits

0010 1000 $\longrightarrow$ 1101 0111

# Find 2's complement quickly

With a negative number, how to give its binary representation? e.g. -40

Step 3. add 1

0010 1000 → 1101 0111 → 1101 1000

# Find 2's complement quickly

With a negative number, how to give its binary representation? e.g. -40

Step 3. add 1

0010 1000 → 1101 0111 → 1101 1000

# Find 2's complement quickly

With a negative number, how to give its binary representation? e.g. -40

Step 3. add 1

0010 1000 → 1101 0111 → 1101 1000

# Why does this trick work

- What is $1111\ldots11_2$ in 2's complement?

- $$\vec{b} + (\sim \vec{b}) = 11\ldots11_2 = -1$$

b with bits flipped

$$-\vec{b} = (\sim \vec{b}) + 1$$

# Exercise Time II

| Hexadecimal | Decimal | Binary |
| --- | --- | --- |
| 0xce | | |
| | | 1001 1100 |
| | 127 | |
| | -128 | |
| | -90 | |

# Answers

| Hexadecimal | Decimal | Binary |
|---|---|---|
| 0xce | -50 | 1100 1110 |
| 0x9c | -100 | 1001 1100 |
| 0x7f | 127 | 0111 1111 |
| 0x80 | -128 | 1000 0000 |
| 0xa6 | -90 | 1010 0110 |

# Ranges

| | Range | Min | Max |
|---|---|---|---|
| 1 byte unsigned | $[0, 2^8 - 1]$ | 0 | 255 |
| 1 byte signed | | | |

# Ranges

| | Range | Min | Max |
|---|---|---|---|
| 1 byte unsigned | $[0, 2^8 - 1]$ | 0 | 255 |
| 1 byte signed | $[-2^7, 2^7 - 1]$ | -128 | 127 |

Min: 1000 0000

Max: 0111 1111

# Overflow

| | | |
|---|---|---|
| | 1 0 0 0 0 0 0 1 | -127 |
| + | 1 0 0 0 0 0 0 1 | -127 |

| | Range | Min | Max |
|---|---|---|---|
| 1 byte unsigned | $[0, 2^8 - 1]$ | 0 | 255 |
| 1 byte signed | $[-2^7, 2^7 - 1]$ | -128 | 127 |

# Overflow

| | | |
|---|---|---|
| | 1 0 0 0 0 0 0 1 | -127 |
| + | 1 0 0 0 0 0 0 1 | -127 |
| 1 | 0 0 0 0 0 0 1 0 | 2 ??? |

carry bit discarded

| | Range | Min | Max |
|---|---|---|---|
| 1 byte unsigned | $[0, 2^8 - 1]$ | 0 | 255 |
| 1 byte signed | $[-2^7, 2^7 - 1]$ | -128 | 127 |

# Intel 8080

0xb0
0x0f
0xa9
0xaf
0xa8
0x1e
0xa7
0x4c
0xa6
0xea
0xa5
0xcb
0xa4
0xba
0xa3
0x00
0xa2
0xff
0xa1
0x8c
...
.....
Memory
0x4c
CPU
Arithmetic Logic Unit
registers
0x4c

# Intel 8080 (1974)

**8 bits machine – 8 bits length of**

- Memory – processor transfer
- CPU Register
- Memory Address

# Intel 386 (1985)

**32 bits machine – 32 bits length of**

- Memory – processor transfer
- CPU Register
- Memory Address

# AMD K8 (2000), Intel Pentium 4 and later

**64 bits machine – 64 bits length of**

- Memory – processor transfer
- CPU Register
- Memory Address

# Intel Opteron → i7

**Word**

- Memory – processor transfer
- CPU Register
- Memory Address

# Word

Definition

- Fixed size of data handled as a unit by the instruction set or processor

Length

- 8 for 8 bits machine
- 32 for 32 bits machine
- 64 for 64 bits machine

# Wrapping up last lecture

- What you have learnt:
  - information as bits
  - byte: 8-bit
  - how to represent unsigned/signed integer
    - Computers use fixed-width representation (1, 2, 4, 8 bytes)
    - overflow
  - 32-bit vs. 64-bit computer architecture
- Wrapping up:
  - C's integer data types
  - How multi-byte integers are stored in memory

# C's integral data types on 64 bits machine

| | Length | Min | Max |
|---|---|---|---|
| [signed] char | 1 byte | $-2^7$ | $2^7 - 1$ |
| unsigned char | 1 byte | 0 | $2^8 - 1$ |
| short | 2 bytes | | |
| unsigned short | 2 bytes | | |
| int | 4 bytes | | |
| unsigned int | 4 bytes | | |
| long | 8 bytes | | |
| unsigned long | 8 bytes | | |

# Integral data types on 64 bits machine

| | Length | Min | Max |
|---|---|---|---|
| [signed] char | 1 byte | $-2^7$ | $2^7 - 1$ |
| unsigned char | 1 byte | 0 | $2^8 - 1$ |
| short | 2 bytes | $-2^{15}$ | $2^{15} - 1$ |
| unsigned short | 2 bytes | 0 | $2^{16} - 1$ |
| int | 4 bytes | | |
| unsigned int | 4 bytes | | |
| long | 8 bytes | | |
| unsigned long | 8 bytes | | |

# Integral data types on 64 bits machine

| | Length | Min | Max |
|---|---|---|---|
| [signed] char | 1 byte | $-2^{7}$ | $2^{7} - 1$ |
| unsigned char | 1 byte | 0 | $2^{8} - 1$ |
| short | 2 bytes | $-2^{15}$ | $2^{15} - 1$ |
| unsigned short | 2 bytes | 0 | $2^{16} - 1$ |
| int | 4 bytes | $-2^{31}$ | $2^{31} - 1$ |
| unsigned int | 4 bytes | 0 | $2^{32} - 1$ |
| long | 8 bytes | | |
| unsigned long | 8 bytes | | |

# Integral data types on 64 bits machine

| | Length | Min | Max |
|---|---|---|---|
| [signed] char | 1 byte | $-2^{7}$ | $2^{7} - 1$ |
| unsigned char | 1 byte | 0 | $2^{8} - 1$ |
| short | 2 bytes | $-2^{15}$ | $2^{15} - 1$ |
| unsigned short | 2 bytes | 0 | $2^{16} - 1$ |
| int | 4 bytes | $-2^{31}$ | $2^{31} - 1$ |
| unsigned int | 4 bytes | 0 | $2^{32} - 1$ |
| long | 8 bytes | $-2^{63}$ | $2^{63} - 1$ |
| unsigned long | 8 bytes | 0 | $2^{64} - 1$ |

# Your first C program

```
#include <stdio.h>

int
main()
{
     char x = -127;
     char y = 0x81;
     char z = x + y;
     printf("hello world sum is %d\n", z);
}
```

```
$ gcc helloworld.c
$ ./a.out
```

| | | |
|---|---|---|
| | 1 0 0 0 0 0 0 1 | -127 |
| + | 1 0 0 0 0 0 0 1 | -127 |
| 1 | 0 0 0 0 0 0 1 0 | 2 |

# Memory layout for multi-byte integers

*int a = 0x12345678*

address: *0x00…00a2*

# Memory layout for multi-byte integers: 2 ways

*int a = 0x12345678*

address: *0x00…00a2*

# Memory layout for multi-byte integers: 2 ways

*int a = 0x12345678*

address: *0x00…00a2*

# Memory layout – Little Endian

*int a = 0x12345678*

address: *0x00…00a2*

Least significant byte in smallest address,

e.g, laptops, and server machines

# Advantages of Little Endian

0x12345678

\+ 0x12131415

Processor performs the calculation from the least significant bit

Processor can simultaneously perform memory transfer and calculation.

# Advantages of Little Endian

*int a = 0x12345678*

address of variable a: *0x00…00a2*

# Advantages of Little Endian

*int a = 0x12345678*

address: *0x00…00a2*

# Advantages of Little Endian

*int a = 0x12345678*

address: *0x00…00a2*

**short b = (short)a**

Directly get the data from 0x00…00a2

# Memory layout – Big Endian

*int a = 0x12345678*

address: *0x00…00a2*

Most significant byte in smallest address,

e.g, ARM architecture >v3 (cellphones, ipads)

# Advantages of Big Endian

Test whether the number is positive or negative by looking at the byte at offset zero.