Introduction

- The advent of the digital age
  - Analog vs. digital?

- Compact Disc (CD)
  - 44.1 KHz, 16-bit, 2-channel

- MP3
  - A digital audio encoding with lossy data compression
Representing Information

- **Information = Bits + Context**
  - Computers manipulate representations of things.
  - Things are represented as binary digits.
  - What can you represent with N bits?
    - $2^N$ things
    - Numbers, characters, pixels, positions, source code, executable files, machine instructions, ...
    - Depends on what operations you do on them.

<table>
<thead>
<tr>
<th>(char)</th>
<th>‘s’</th>
<th>‘k’</th>
<th>‘k’</th>
<th>‘u’</th>
<th>‘s’</th>
<th>‘e’</th>
<th>‘m’</th>
<th>‘i’</th>
</tr>
</thead>
<tbody>
<tr>
<td>(int)</td>
<td>1969974131</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(double)</td>
<td>7.031689903291708178… x $10^{199}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

01110011 01101011 01101011 01110101 01110011 01100101 01101101 01101001
Binary Representations

- Why not base 10 representation?
  - Easy to store with bistable elements
  - Straightforward implementation of arithmetic functions
  - Reliably transmitted on noisy and inaccurate wires

- Electronic implementation
Encoding Byte Values

- **Byte = 8 bits**

  - **Binary**: \(00000000_2\) to \(11111111_2\)
  - **Octal**: \(000_8\) to \(377_8\)
    - An integer constant that begins with 0 is an octal number in C
  - **Decimal**: \(0_{10}\) to \(255_{10}\)
    - First digit must not be 0 in C
  - **Hexadecimal**: \(00_{16}\) to \(FF_{16}\)
    - Base 16 number representation
    - Use characters ‘0’ to ‘9’ and ‘A’ to ‘F’
    - Write \(FA1D37B_{16}\) in C as \(0xFA1D37B\)
      or \(0xfa1d37b\)
### Boolean Algebra (1)

- **Developed by George Boole in 1849**
  - Algebraic representation of logic
    - Encode “True” as 1 and “False” as 0

- **And**
  - $A \& B = 1$ when both $A=1$ and $B=1$
    - \[
    \begin{array}{c|cc}
    & 0 & 1 \\
    \hline
    0 & 0 & 0 \\
    1 & 0 & 1 \\
    \end{array}
    \]

- **Not**
  - $\neg A = 1$ when $A=0$
    - \[
    \begin{array}{c|c}
    \neg & 0 & 1 \\
    \hline
    0 & 1 \\
    1 & 0 \\
    \end{array}
    \]

- **Or**
  - $A \vert B = 1$ when either $A=1$ or $B=1$
    - \[
    \begin{array}{c|cc}
    & 0 & 1 \\
    \hline
    0 & 0 & 1 \\
    1 & 1 & 1 \\
    \end{array}
    \]

- **Exclusive-Or (Xor)**
  - $A \wedge B = 1$ when either $A=1$ or $B=1$, but not both
    - \[
    \begin{array}{c|cc}
    \wedge & 0 & 1 \\
    \hline
    0 & 0 & 1 \\
    1 & 1 & 0 \\
    \end{array}
    \]
Boolean Algebra (2)

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>f (X, Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Basic operations: AND(&), OR(|), NOT(~)

- \( X \land Y = (X \land \neg Y) \lor (\neg X \land Y) \)
- \( X \rightarrow Y = \neg X \lor Y \)

A complete set: \( \neg (X \land Y) \)
Unsigned Integers

- Encoding unsigned integers

\[ B = [b_{w-1}, b_{w-2}, \ldots, b_0] \]

\[ D(B) = \sum_{i=0}^{w-1} b_i \cdot 2^i \]

\[ x = 0000\ 0111\ 1101\ 0011_2 \]

\[ D(x) = 2^{10} + 2^9 + 2^8 + 2^7 + 2^6 + 2^4 + 2^1 + 2^0 = 1024 + 512 + 256 + 128 + 64 + 16 + 2 + 1 = 2003 \]

- What is the range for unsigned values with \( w \) bits?
Signed Integers (1)

- **Encoding positive numbers**
  - Same as unsigned numbers

- **Encoding negative numbers**
  - Sign-magnitude representation
  - Ones’ complement representation
  - Two’s complement representation
Signed Integers (2)

- Sign-magnitude representation

\[ S(B) = (-1)^{b_{w-1}} \cdot \sum_{i=0}^{w-2} b_i \cdot 2^i \]

- Two zeros
  - [000...00], [100...00]
- Used for floating-point numbers
Signed Integers (3)

- Ones’ complement representation

\[ O(B) = -b_{w-1}(2^{w-1} - 1) + \sum_{i=0}^{w-2} b_i \cdot 2^i \]

- Easy to find \(-n\)
- Two zeros
  - [000...00], [111...11]
- No longer used
Signed Integers (4)

- Two’s complement representation

\[ O(B) = -b_{w-1} \cdot 2^{w-1} + \left( \sum_{i=0}^{w-2} b_i \cdot 2^i \right) \]

- Unique zero
- Easy for hardware
  - leading 0 ≥ 0
  - leading 1 < 0
- Used by almost all modern machines
Signed Integers (5)

- Two’s complement representation (cont’d)
  - Following holds for two’s complement
    \[ \sim x + 1 = -x \]
  - Complement
    - Observation: \[ \sim x + x = 1111...11 = -1 \]
  - Increment
    \[ \sim x + x = -1 \]
    \[ \sim x + x + (-x + 1) = -1 + (-x + 1) \]
    \[ \sim x + 1 = -x \]
Numeric Ranges (1)

- **Unsigned values**
  - $\text{UMin} = 0\ [000...00]$
  - $\text{UMax} = 2^w - 1\ [111...11]$

- **Two’s complement values**
  - $\text{TMin} = -2^{w-1}\ [100...00]$
  - $\text{TMax} = 2^{w-1} - 1\ [011...11]$

<table>
<thead>
<tr>
<th></th>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMax</td>
<td>65535</td>
<td>FF FF</td>
<td>11111111 11111111</td>
</tr>
<tr>
<td>Tmax</td>
<td>32767</td>
<td>7F FF</td>
<td>01111111 11111111</td>
</tr>
<tr>
<td>Tmin</td>
<td>-32768</td>
<td>80 00</td>
<td>10000000 00000000</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>FF FF</td>
<td>11111111 11111111</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>00 00</td>
<td>00000000 00000000</td>
</tr>
</tbody>
</table>
Numeric Ranges (2)

- Values for different word sizes

<table>
<thead>
<tr>
<th></th>
<th>w = 8</th>
<th>w = 16</th>
<th>w = 32</th>
<th>w = 64</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMax</td>
<td>255</td>
<td>65,535</td>
<td>4,294,967,295</td>
<td>18,446,744,073,709,551,615</td>
</tr>
<tr>
<td>Tmax</td>
<td>127</td>
<td>32,767</td>
<td>2,147,483,647</td>
<td>9,223,372,036,854,775,807</td>
</tr>
<tr>
<td>Tmin</td>
<td>-128</td>
<td>-32,768</td>
<td>-2,147,483,648</td>
<td>-9,223,372,036,854,775,808</td>
</tr>
</tbody>
</table>

- Observations
  - $|\text{TMin}| = \text{TMax} + 1$ (Asymmetric range)
  - $\text{UMax} = 2 \times \text{TMax} + 1$

- In C programming
  - `#include <limits.h>`
  - `INT_MIN, INT_MAX, LONG_MIN, LONG_MAX, UINT_MAX, ...`
  - Values platform-specific
Type Conversion (1)

- **Unsigned:** $w$ bits $\rightarrow$ $w+k$ bits
  - Zero extension: just fill $k$ bits with 0’s

```c
unsigned short x = 2003;
unsigned ix = (unsigned) x;
```

![Diagram](image_url)

- $w = 16$
- $k = 16$
- $w = 16$
Type Conversion (2)

- Signed: $w$ bits $\rightarrow w+k$ bits
  - Given $w$-bit signed integer $x$
  - Convert it to $w+k$-bit integer with same value

- Sign extension
  - Make $k$ copies of sign bit
Type Conversion (3)

- **Sign extension example**
  - Converting from smaller to larger integer type
  - C automatically performs sign extension

```
short int x  = 2003;
int      ix  = (int) x;
short int y  = -2003;
int      iy  = (int) y;
```

<table>
<thead>
<tr>
<th></th>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>x</strong></td>
<td>2003</td>
<td>07 D3</td>
<td>00000111 11010011</td>
</tr>
<tr>
<td><strong>ix</strong></td>
<td>2003</td>
<td>00 07 D3</td>
<td>00000000 00000000 00000111 11010011</td>
</tr>
<tr>
<td><strong>y</strong></td>
<td>-2003</td>
<td>F8 2D</td>
<td>11111000 00101101</td>
</tr>
<tr>
<td><strong>iy</strong></td>
<td>-2003</td>
<td>FF FF F8 2D</td>
<td>11111111 11111111 11111000 00101101</td>
</tr>
</tbody>
</table>
Type Conversion (4)

- Unsigned & Signed: \( w+k \) bits \( \rightarrow \) \( w \) bits
  - Just truncate it to lower \( w \) bits
  - Equivalent to computing \( x \mod 2^w \)

\[
\begin{align*}
\text{unsigned int} & \quad x = 0x\text{cafebabe}; \\
\text{unsigned short} & \quad \text{ix} = (\text{unsigned short}) x; \\
\text{int} & \quad y = 0x\text{2003beef}; \\
\text{short} & \quad \text{iy} = (\text{short}) y;
\end{align*}
\]

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<tr>
<th></th>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x )</td>
<td>3405691582</td>
<td>CA FE BA BE</td>
<td>11001010 11111110 10111010 10111110</td>
</tr>
<tr>
<td>( \text{ix} )</td>
<td>47806</td>
<td>BA BE</td>
<td>10111010 10111110</td>
</tr>
<tr>
<td>( y )</td>
<td>537116399</td>
<td>20 03 BE EF</td>
<td>00100000 00000011 10111110 11101111</td>
</tr>
<tr>
<td>( \text{iy} )</td>
<td>-16657</td>
<td>BE EF</td>
<td>10111110 11101111</td>
</tr>
</tbody>
</table>
Type Conversion (5)

- **Unsigned → Signed**
  - The same bit pattern is interpreted as a signed number

\[ U\ 2T_w(x) = \begin{cases} 
  x, & x < 2^{w-1} \\
  x - 2^w, & x \geq 2^{w-1} 
\end{cases} \]

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<tr>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>2003</td>
<td>07 D3 00000111 11010011</td>
</tr>
<tr>
<td>ix</td>
<td>2003</td>
<td>07 D3 00000111 11010011</td>
</tr>
<tr>
<td>y</td>
<td>47806</td>
<td>BA BE 10111010 10111110</td>
</tr>
<tr>
<td>iy</td>
<td>-17730</td>
<td>BA BE 10111010 10111110</td>
</tr>
</tbody>
</table>
Type Conversion (6)

- **Signed \(\rightarrow\) Unsigned**
  - Ordering inversion
  - Negative \(\rightarrow\) Big positive

\[
T_{2U_w}(x) = \begin{cases} 
  x + 2^w, & x < 0 \\
  x, & x \geq 0
\end{cases}
\]

<table>
<thead>
<tr>
<th>Decimal</th>
<th>Hex</th>
<th>Binary</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>2003</td>
<td>07 D3 00000111 11010011</td>
</tr>
<tr>
<td>ix</td>
<td>2003</td>
<td>07 D3 00000111 11010011</td>
</tr>
<tr>
<td>y</td>
<td>-2003</td>
<td>F8 2D 11111000 00101101</td>
</tr>
<tr>
<td>iy</td>
<td>63533</td>
<td>F8 2D 11111000 00101101</td>
</tr>
</tbody>
</table>
Type Casting in C (1)

- **Constants**
  - By default, considered to be signed integers
  - Unsigned if have “U” or “u” as suffix
    - `0U`, `12345U`, `0x1A2Bu`

- **Type casting**
  - Explicit casting
    - `int tx, ty;
      unsigned ux, uy;
      tx = (int) ux;
      uy = (unsigned) ty;`
  - Implicit casting via
    - Assignments
      - `int f(unsigned);
        tx = ux;
        f(ty);`
Type Casting in C (2)

- Expression evaluation
  - If mix unsigned and signed in single expression, signed values implicitly cast to **unsigned**.
  - Including comparison operations `<`, `>`, `==`, `<=`, `>=`

<table>
<thead>
<tr>
<th>Expression</th>
<th>Type</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 == 0U</td>
<td>unsigned</td>
<td>True</td>
</tr>
<tr>
<td>-1 &lt; 0</td>
<td>signed</td>
<td>True</td>
</tr>
<tr>
<td>-1 &lt; 0U</td>
<td>unsigned</td>
<td>?</td>
</tr>
<tr>
<td>-1 &gt; -2</td>
<td>signed</td>
<td>?</td>
</tr>
<tr>
<td>(unsigned) -1 &gt; -2</td>
<td>unsigned</td>
<td>?</td>
</tr>
<tr>
<td>2147483647 &gt; -2147483647-1</td>
<td>signed</td>
<td>?</td>
</tr>
<tr>
<td>2147483647U &gt; -2147483647-1</td>
<td>unsigned</td>
<td>?</td>
</tr>
<tr>
<td>2147483647 &gt; (int) 2147483648U</td>
<td>signed</td>
<td>?</td>
</tr>
</tbody>
</table>
Type Casting in C (3)

- Example 1-1

```c
int main ()
{
    unsigned i;
    for (i = 10; i > 0; i--)
        printf (“%u\n”, i);
}
```

- Example 1-2

```c
int main ()
{
    unsigned i;
    for (i = 10; i >= 0; i--)
        printf (“%u\n”, i);
}
```
**Type Casting in C (4)**

### Example 2

```c
int sum_array (int a[], unsigned len)
{
    int i;
    int result = 0;

    for (i = 0; i <= len - 1; i++)
        result += a[i];

    return result;
}
```
Type Casting in C (5)

- Example 3-1

```c
void copy_mem1 (char *src, char *dest, unsigned len)
{
    unsigned i;
    for (i = 0; i < len; i++)
        *dest++ = *src++;
}
```

- Example 3-2

```c
void copy_mem2 (char *src, char *dest, unsigned len)
{
    int i;
    for (i = 0; i < len; i++)
        *dest++ = *src++;
}
```
Type Casting in C (6)

- Example 3-3

```c
void copy_mem3 (char *src, char *dest, unsigned len)
{
    for (; len > 0; len--)
        *dest++ = *src++;
}
```

- Example 3-4

```c
void copy_mem4 (char *src, char *dest, unsigned len)
{
    for (; (int) len > 0; len--)
        *dest++ = *src++;
}
```
Type Casting in C (7)

- Example 4

```c
#include <stdio.h>

int main ()
{
    unsigned char c;

    while ((c = getchar()) != EOF)
        putchar (c);
}
```
Lessons

- There are many tricky situations when you use unsigned integers – hard to debug
- Do not use just because numbers are nonnegative
- Use only when you need collections of bits with no numeric interpretation ("flags")
- Few languages other than C support unsigned integers