The Design of C: A Rational Reconstruction

Goals of this Lecture

• Help you learn about:
  • The decisions that were available to the designers of C
  • The decisions that were made by the designers of C
  … and thereby…
  • C!

• Why?
  • Learning the design rationale of the C language provides a richer understanding of C itself
  • A power programmer knows both the programming language and its design rationale (helps to decide if it’s the right tool for the job)
  • A case study in system design

• But first a preliminary topic…
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
  - \( 4173 = 4 \times 10^3 + 1 \times 10^2 + 7 \times 10^1 + 3 \times 10^0 \)

- Binary (base 2)
  - Each bit represents a power of 2
  - \( 10110 = 1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 = 22 \)

Decimal to binary conversion:
Divide repeatedly by 2 and keep remainders
\[
\begin{align*}
12 / 2 &= 6 \quad R = 0 \\
6 / 2 &= 3 \quad R = 0 \\
3 / 2 &= 1 \quad R = 1 \\
1 / 2 &= 0 \quad R = 1 \\
\text{Result} &= 1100
\end{align*}
\]

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

\[
\begin{align*}
0000 &= 0 & 1000 &= 8 \\
0001 &= 1 & 1001 &= 9 \\
0010 &= 2 & 1010 &= A \\
0011 &= 3 & 1011 &= B \\
0100 &= 4 & 1100 &= C \\
0101 &= 5 & 1101 &= D \\
0110 &= 6 & 1110 &= E \\
0111 &= 7 & 1111 &= F \\
\end{align*}
\]

Thus the 16-bit binary number \( 1011 \ 0010 \ 1010 \ 1001 \) converted to hex is \( \text{B2A9} \)
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: <span style="color:#FF0000">De-Comment Assignment Due</span>
  - Blue: <span style="color:#0000FF">Reading Period</span>

- 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 $\Rightarrow$ 1
  - 0001111 $\Rightarrow$ 15
  - 00010000 $\Rightarrow$ 16
  - 0010001 $\Rightarrow$ 33
  - 11111111 $\Rightarrow$ 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

<table>
<thead>
<tr>
<th></th>
<th>Base 10</th>
<th></th>
<th>Base 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>1 9 8</td>
<td>+</td>
<td>0 1 1</td>
</tr>
<tr>
<td></td>
<td>2 6 4</td>
<td></td>
<td>0 0 1</td>
</tr>
<tr>
<td>Sum</td>
<td>4 6 2</td>
<td>Sum</td>
<td>1 0 0</td>
</tr>
<tr>
<td>Carry</td>
<td>0 1 1</td>
<td>Carry</td>
<td>0 1 1</td>
</tr>
</tbody>
</table>

Binary Sums and Carries

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>Sum</th>
<th>a</th>
<th>b</th>
<th>Carry</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>0</td>
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XOR ("exclusive OR")

<table>
<thead>
<tr>
<th>0100 0101 +0110 0111</th>
<th>1010 1100</th>
</tr>
</thead>
<tbody>
<tr>
<td>69</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>172</td>
</tr>
</tbody>
</table>
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...
  - Suppose you want to compute $a - b$
  - Note that this equals $a + (256 - 1 - b) + 1$

One’s and Two’s Complement

- One’s complement: flip every bit
  - E.g., $b$ is 01000101 (i.e., 69 in decimal)
  - One’s complement is 10111010
  - That’s simply 255-69
- Subtracting from 11111111 is easy (no carry needed!)
  \[
  \begin{array}{c}
  1111 1111 \\
  - 0100 0101 \\
  \hline
  1011 1010
  \end{array}
  \]
  \[ \text{b} \rightarrow \text{one’s complement} \]
- Two’s complement
  - Add 1 to the one’s complement
  - E.g., $(255 - 69) + 1 \rightarrow 1011 1011$
Putting it All Together

• Computing “a – b”
  • Same as “a + 256 – b”
  • 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

Signed Integers

• Sign-magnitude representation
  • Use one bit to store the sign
    • Zero for positive number
    • One for negative number
  • Examples
    • E.g., 0010 1100 \(\rightarrow\) 44
    • E.g., 1010 1100 \(\rightarrow\) -44
  • Hard to do arithmetic this way, so it is rarely used

• Complement representation
  • One’s complement
    • Flip every bit
    • E.g., 1101 0011 \(\rightarrow\) -44
  • Two’s complement
    • Flip every bit, then add 1
    • E.g., 1101 0100 \(\rightarrow\) -44
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

- Signed integers
  - Can get nonsense values
  - Example with 16-bit integers
    - Sum: 10000+20000+30000
    - Result: -5536

Bitwise Operators: AND and OR

- Bitwise AND (&)
  - 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 1 1 1 1
  ________
  5 0 0 0 0 1 0 1
Bitwise Operators: Not and XOR

- One’s complement (~)
  - Turns 0 to 1, and 1 to 0
  - E.g., set last three bits to 0
    - \( x = x \& \sim 7; \)

- XOR (^)
  - 0 if both bits are the same
  - 1 if the two bits are different

<table>
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<td>1</td>
<td>1</td>
<td>0</td>
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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

<table>
<thead>
<tr>
<th>53</th>
<th>0 0 1 1 0 1 0 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>53&lt;&lt;2</td>
<td>1 1 0 1 0 0 0 0</td>
</tr>
</tbody>
</table>

- 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!

<table>
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<th>53</th>
<th>0 0 1 1 0 1 0 1</th>
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<tbody>
<tr>
<td>53&gt;&gt;2</td>
<td>0 0 0 0 1 1 0 1</td>
</tr>
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</table>
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 \((n \& 1)\)

Counting the Number of ‘1’ Bits

```c
#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;
}
```
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

The Main Event

The Design of C
Goals of C

Designers wanted C to support:
  • **Systems programming**
    • Development of Unix OS
    • Development of Unix programming tools

But also:
  • **Applications programming**
    • Development of financial, scientific, etc. applications

*Systems* programming was the primary intended use

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The Goals of C (cont.)

The designers of wanted C to be:
  • Low-level
    • Close to assembly/machine language
    • Close to hardware

But also:
  • Portable
    • Yield systems software that is easy to port to differing hardware
The Goals of C (cont.)

The designers wanted C to be:
• Easy for *people* to handle
  • Easy to understand
• *Expressive*
  • High (functionality/sourceCodeSize) ratio

But also:
• Easy for *computers* to handle
  • Easy/fast to compile
  • Yield efficient machine language code

Commonality:
• Small/simple

Design Decisions

In light of those goals…
• What design decisions did the designers of C *have*?
• What design decisions did they *make*?

Consider programming language features, from simple to complex…
Feature 1: Data Types

- Previously in this lecture:
  - Bits can be combined into bytes
  - Our interpretation of a collection of bytes gives it meaning
    - A signed integer, an unsigned integer, a RGB color, etc.
- A data type is a well-defined interpretation of a collection of bytes
- A high-level programming language should provide primitive data types
  - Facilitates abstraction
  - Facilitates manipulation via associated well-defined operators
  - Enables compiler to check for mixed types, inappropriate use of types, etc.

Primitive Data Types

- Issue: What primitive data types should C provide?
- Thought process
  - C should handle:
    - Integers
    - Characters
    - Character strings
    - Logical (alias Boolean) data
    - Floating-point numbers
  - C should be small/simple
- Decisions
  - Provide integer, character, and floating-point data types
  - Do not provide a character string data type (More on that later)
  - Do not provide a logical data type (More on that later)
Issue: What integer data types should C provide?

Thought process:
- For flexibility, should provide integer data types of various sizes.
- For portability at application level, should specify size of each data type.
- For portability at systems level, should define integral data types in terms of natural word size of computer.
- Primary use will be systems programming.

Why?

Integer Data Types (cont.)

Decisions:
- Provide three integer data types: short, int, and long.
- Do not specify sizes; instead:
  - int is natural word size
  - 2 <= bytes in short <= bytes in int <= bytes in long.

Incidentally, on hats using gcc217:
- Natural word size: 4 bytes
  - short: 2 bytes
  - int: 4 bytes
  - long: 4 bytes
**Integer Constants**

- **Issue:** How should C represent integer constants?
- **Thought process**
  - People naturally use decimal
  - Systems programmers often use binary, octal, hexadecimal
- **Decisions**
  - Use decimal notation as default
  - Use "0" prefix to indicate octal notation
  - Use "0x" prefix to indicate hexadecimal notation
  - Do not allow binary notation; too verbose, error prone
  - Use "L" suffix to indicate `long` constant
  - Do not use a suffix to indicate `short` constant; instead must use cast
- **Examples**
  - `int`: 123, -123, 0173, 0x7B
  - `long`: 123L, -123L, 0173L, 0x7BL
  - `short`: (short)123, (short)-123, (short)0173, (short)0x7B

**Unsigned Integer Data Types**

- **Issue:** Should C have both signed and unsigned integer data types?
- **Thought process**
  - Must represent positive and negative integers
    - Signed types are essential
  - Unsigned data can be twice as large as signed data
    - Unsigned data could be useful
  - Unsigned data are good for bit-level operations
    - Bit-level operations are common in systems programming
  - Implementing both signed and unsigned data types is complex
    - Must define behavior when an expression involves both
Unsigned Integer Data Types (cont.)

• Decisions
  • Provide unsigned integer types: \texttt{unsigned short}, \texttt{unsigned int}, and \texttt{unsigned long}
  • Conversion rules in mixed-type expressions are complex
    • Generally, mixing signed and unsigned converts signed to unsigned
    • See King book Section 7.4 for details

Do you see any potential problems?

Was providing unsigned types a good decision?

What decision did the designers of Java make?

Unsigned Integer Constants

• Issue: How should C represent unsigned integer constants?

• Thought process
  • “L” suffix distinguishes \texttt{long} from \texttt{int}; also could use a suffix to distinguish signed from unsigned
  • Octal or hexadecimal probably are used with bit-level operators

• Decisions
  • Default is signed
  • Use "U" suffix to indicate unsigned
  • Integers expressed in octal or hexadecimal automatically are unsigned

• Examples
  • \texttt{unsigned int}: 123U, 0173, 0x7B
  • \texttt{unsigned long}: 123UL, 0173L, 0x7BL
  • \texttt{unsigned short}: (short)123U, (short)0173, (short)0x7B
There’s More!

To be continued next lecture!