The Design of C:
A Rational Reconstruction

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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
    - … and is easier than learning rote rules
  - A systems programmer knows the language to know what's safe and what's not
- But first a preliminary topic…

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Preliminary Topic

Number Systems

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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

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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
```

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Writing Bits is Tedious for People

- Octal (base 8, 3 bits/digit)
  - Digits 0, 1, …, 7
- Hexadecimal (base 16, 4 bits/digit)
  - 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

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The Rise and Fall of Octal

- Octal (base 8, 3 bits/digit)
  - Digits 0, 1, …, 7
- Early computers often had 36 bits/word
  - Competition was high-precision (10-digit) calculators
  - 2^{36} = 68719476736, which is greater than 10^{10}
- Decimal required conversion circuitry
  - Reading and display octal numbers required much less processing than decimal
- Hexadecimal not easy with some displays (Nixie tubes)
- 36-bit octal possible in 12 octal digits

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Representing Colors: RGB

- Three primary colors
  - Red
  - Green
  - Blue
- Strength
  - 8-bit number for each color (e.g., two hex digits, 256 values)
  - So, 24 bits to specify a color (256^3 colors ~ 16M colors)
- In HTML, e.g. course "Schedule" Web page
  - Red: De-Comment Assignment Due
  - Blue: Reading Period
- Same thing in digital cameras
  - Each processed pixel is a mixture of red, green, and blue

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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…
  - Suppose you want to compute a – b
  - Note that this equals a + 256 – b, which is also 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!)

```
  1111 1111
– 0100 0101  ⟵ b
  1011 1010  ⟵ one's complement
```

- Two's complement
  - Add 1 to the one's complement
  - E.g., (255 – 69) + 1 ➔ 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

```
  1010 1100
+ 1011 1011
1 0110 0111
```

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 → 44
    - E.g., 1010 1100 → -44
  - Hard to do arithmetic this way, so it is 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
- 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

- Bitwise OR (|)

|	0	1
0	0	1
1	1	1

- Mod on the cheap for certain values!
  - 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

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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 & ~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?
    - Undefined by language spec – two common approaches

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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The Main Event

The Design of C

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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

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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

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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…

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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.

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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)

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Integer Data Types

- 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?

Why?

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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

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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" (zero) 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

Was that a good decision?

Why?

- Examples
  - `int`: `123`, `-123`, `0173`, `0x7B`
  - `long`: `123L`, `-123L`, `0173L`, `0x7BL`
  - `short`: `(short)123`, `(short)-123`, `(short)0173`, `(short)0x7B`

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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

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Unsigned Integer Data Types (cont.)

- Decisions
  - Provide unsigned integer types: **`unsigned short`**, **`unsigned int`**, and **`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?

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Unsigned Integer Constants

- Issue: How should C represent unsigned integer constants?
- Thought process
  - "L" suffix distinguishes **`long`** from **`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
  - **`unsigned int`**: **`123U`**, **`0173`**, **`0x7B`**
  - **`unsigned long`**: **`123UL`**, **`0173L`**, **`0x7BL`**
  - **`unsigned short`**: **`(short)123U`**, **`(short)0173`**, **`(short)0x7B`**

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