

Information Coding

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Fall 2026

Remember...

Example: Computing the sum of all integers from 1 to 100?

```
1      int main()  
2      {  
3          int x,i;  
4          x = 0;  
5          i = 0;  
6          for (i = 1; i<100;i++)  
7              {  
8                  x = x+1;  
9              }  
10         return x;
```

The **compiler** transforms the code into a sequence of instructions

```
1    int main()
2    {
3        int x,i;
4        x = 0;
5        i = 0;
6        for (i = 1; i<100;i++)
7        {
8            x = x+1;
9        }
10    return x;
```



```
0x00000000100000f70 <+0>:    push    %rbp
0x00000000100000f71 <+1>:    mov     %rsp,%rbp
0x00000000100000f74 <+4>:    movl    $0x0,-0x4(%rbp)
0x00000000100000f7b <+11>:   movl    $0x0,-0x8(%rbp)
0x00000000100000f82 <+18>:   movl    $0x0,-0xc(%rbp)
0x00000000100000f89 <+25>:   movl    $0x1,-0xc(%rbp)
0x00000000100000f90 <+32>:   cmpl    $0x64,-0xc(%rbp)
0x00000000100000f94 <+36>:   jge     0x100000fb1 <main()+65>
0x00000000100000f9a <+42>:   mov     -0x8(%rbp),%eax
0x00000000100000f9d <+45>:   add     $0x1,%eax
0x00000000100000fa0 <+48>:   mov     %eax,-0x8(%rbp)
0x00000000100000fa3 <+51>:   mov     -0xc(%rbp),%eax
0x00000000100000fa6 <+54>:   add     $0x1,%eax
0x00000000100000fa9 <+57>:   mov     %eax,-0xc(%rbp)
0x00000000100000fac <+60>:   jmpq    0x100000f90 <main()+32>
0x00000000100000fb1 <+65>:   mov     -0x8(%rbp),%eax
0x00000000100000fb4 <+68>:   pop     %rbp
```

The **assembler** transforms the sequence of instructions into (weird) numbers

```
0x00000000100000f70 <+0>:    push    %rbp
0x00000000100000f71 <+1>:    mov     %rsp,%rbp
0x00000000100000f74 <+4>:    movl    $0x0,-0x4(%rbp)
0x00000000100000f7b <+11>:   movl    $0x0,-0x8(%rbp)
0x00000000100000f82 <+18>:   movl    $0x0,-0xc(%rbp)
0x00000000100000f89 <+25>:   movl    $0x1,-0xc(%rbp)
0x00000000100000f90 <+32>:   cmpl    $0x64,-0xc(%rbp)
0x00000000100000f94 <+36>:   jge     0x100000fb1 <main()+65>
0x00000000100000f9a <+42>:   mov     -0x8(%rbp),%eax
0x00000000100000f9d <+45>:   add     $0x1,%eax
0x00000000100000fa0 <+48>:   mov     %eax,-0x8(%rbp)
0x00000000100000fa3 <+51>:   mov     -0xc(%rbp),%eax
0x00000000100000fa6 <+54>:   add     $0x1,%eax
0x00000000100000fa9 <+57>:   mov     %eax,-0xc(%rbp)
0x00000000100000fac <+60>:   jmpq    0x100000f90 <main()+32>
0x00000000100000fb1 <+65>:   mov     -0x8(%rbp),%eax
0x00000000100000fb4 <+68>:   pop     %rbp
```



```
0000f70 55 48 89 e5 c7 45 fc 00 00 00 00 c7 45 f8 00 00
0000f80 00 00 c7 45 f4 00 00 00 00 c7 45 f4 01 00 00 00
0000f90 83 7d f4 64 0f 8d 17 00 00 00 8b 45 f8 83 c0 01
0000fa0 89 45 f8 8b 45 f4 83 c0 01 89 45 f4 e9 df ff ff
0000fb0 ff 8b 45 f8 5d c3 90 90 01 00 00 00 1c 00 00 00
0000fc0 00 00 00 00 1c 00 00 00 00 00 00 00 1c 00 00 00
0000fd0 02 00 00 00 70 0f 00 00 34 00 00 00 34 00 00 00
```

Who reads/writes what?

Programmers...

... usually manipulate complex instructions and numbers
(Integers, Reals, etc)

but at the end programs...

... are made of numbers (Integers, Reals, etc)

and machines

... only understand **binary**

⇒ We need a way to transform numbers into binary sequences
and binary sequences into numbers.

Just do it...

0100101101010010010101001010111010101001010111110111
0100010001001111110010101001101010101110101110100100
1000100010100110001010101001001000100100000100010001
0011101100100101001000101001000101111001001010010001
1111001001001010100010100111001010000001011011010001
1001000101100100101001000101100100011111001001001010
0110001010101001001000100100000001000100010011101100
1001010010001100100100101010001010011100100010000001
0110110100011001000101001001010010001011010010001111
1001001001010011000101010010101000101001110010001000
0001011011010001100100010110010010100100010110100100
01111100100100101001100010101010010010001001...

Bit vectors (aka “Words”)

Basic information: the bit $\in \{0, 1\}$ (for *binary digit*)

Example of word: 01010101110010011100001111

We work with finite words of predefined length l (why?)

l is the number of bits: in practice $l = 8 * n$

n is the number of bytes (octets in french)

When programming (on a 32 or 64 bits machine):

- ▶ $n = 1$ is called a byte or a char
- ▶ $n = 2$ is called a short
- ▶ $n = 4$ is *usually* called an int (or float if it represents a pseudo-real number)
- ▶ $n = 8$ is called long long (or double for a pseudo-real)

Beware, these are only naming conventions!

So, be always sure that you know what you are talking about!

Length conventions help

Example with 32 bits words (4 bytes)

01001011010100100101010010101110101001010111110111
0100010001001111110010101001101010101110101110100100
1000100010100110001010101001001000100100000100010001
0011101100100101001000101001000101111001001010010001
1111001001001010100010100111001010000001011011010001
1001000101100100101001000101100100011111001001001010
0110001010101001001000100100000001000100010011101100
1001010010001100100100101010001010011100100010000001
01101101000110010001010010010010001011010010001111
1001001001010011000101010010101000101001110010001000
0001011011010001100100010110010010100100010110100100
01111100100100101001100010101010010010001001...

But we still need to transform binary words into numbers...

Natural numbers in base 2 (Unsigned integers)

Let x be a vector of n bits:

$x_{n-1}, x_{n-2}, \dots, x_1, x_0$, with $x_i \in \{0, 1\}$ (in base 2).

Using positional notation¹ we can interpret the value of x as a natural number:

$$x = \sum_{i=0}^{n-1} x_i \cdot 2^i$$

2^n different values can be represented:

$$0 \leq x \leq 2^n - 1$$

¹Note that positional notation is what you use on an everyday basis when you manipulate decimal numbers. Always remember that mechanisms are similar (see the 'protopoly' for a generalization to base $\beta > 1$)

Blackboard examples

LSBit/MSBit

- ▶ Least Significant Bit (*bit de poids faible*):

LSBit (or “LSB”) is the bit position in a binary integer giving the units value, that is, determining whether the number is even or odd².

1	0	0	1	0	1	0	1
---	---	---	---	---	---	---	---

- ▶ Most Significant Bit (*bit de poids fort*):

MSBit (or “MSB”) is the bit position in a binary number having the greatest potential value³.

1	0	0	1	0	1	0	1
---	---	---	---	---	---	---	---

²https://en.wikipedia.org/wiki/Least_significant_bit

³https://en.wikipedia.org/wiki/Most_significant_bit

Warning: MSB/LSB not to be confused with “little-endian” and “big-endian”

- ▶ MSB/LSB are to be understood relatively to the **Binary code**.
- ▶ “Little-Endian” and “Big-Endian” are ways to organise the bytes of a word into the **physical memory** of a computer...

→ Comics vs. Mangas

- ▶ “Big-Endian”: The MSByte is stored first (mangas)...
- ▶ “Little-Endian”: The LSBytes is stored first (comics)...

→ When you directly look at the memory content, be careful to the “endianness” (aka “boutisme” en Français)...

→ Named after Jonathan Swift’s “Gulliver’s Travel” (1726)

WARNING

When computing with integers, computations are mathematically exact EXCEPT if the value exceeds the limits of the code (given the size of the word)...

In that case... Well, the shit hits the fan and its called an oVerflow “V” (RIP Ariane V 501 flight)



Notations and important values⁴

We write: $(x_{n-1}, x_{n-2}, \dots, x_1, x_0)_\beta$
when writing x in base β .

eg:

- ▶ $(101)_2 = (5)_{10}$
- ▶ $(1010)_2 = (10)_{10}$

for $n = 8$:

- ▶ 256 different values
- ▶ max: $2^8 - 1 = 255$

for $n = 32$:

- ▶ ≈ 4 billions different values
- ▶ max: $2^{32} - 1 \approx 4 \times 10^9$

for $n = 16$:

- ▶ 65.536 different values
- ▶ max: $2^{16} - 1 = 65.535$

for $n = 64$:

- ▶ **A lot but not a infinite number of values...**
- ▶ max: $2^{64} - 1 \approx 16 \times 10^{18}$

⁴These values are fundamental to any serious computer science work!
Probably one of the rare things to be known by heart

Fast equivalence: the trick!

$$2^{10} = 1024 \approx 10^3 = 1000$$

Example:

$$2^{32} = 2^{30} \times 2^2 = 2^{10^3} \times 4 \approx 1000^3 \times 4 = 4.000.000.000$$

Binary $\rightarrow$ Decimal Conversion

Any number $p \in \mathbb{N}$ can be represented in a unique positional form in base 2, using n bits (with $n = \lfloor \log_2(p) \rfloor + 1$):

$$(x_{n-1}x_{n-2} \cdots x_1x_0)_2 := \sum_{i=0}^{n-1} x_i 2^i.$$

$\Rightarrow$ Binary to decimal conversion is straightforward

NB: bits are numbered from 0 to $n - 1$

Binary $\leftarrow$ Decimal Conversion

The remainder of the euclidean division of x by 2 gives the right-most digit of its representation in base 2:

$$\begin{aligned}x &= \sum_{i=0}^{n-1} x_i 2^i \\x &= x_{n-1} \cdot 2^{n-1} + x_{n-2} \cdot 2^{n-2} + \cdots + x_2 \cdot 2^2 + x_1 \cdot 2^1 + x_0 \\&= \underbrace{(x_{n-1} \cdot 2^{n-2} + x_{n-2} \cdot 2^{n-3} + \cdots + x_2 \cdot 2^1 + x_1)}_{\text{quotient}} \cdot 2 + \underbrace{x_0}_{\text{remainder}}\end{aligned}$$

We get all the digits of the binary representation of a natural number x by applying euclidean divisions (by 2) to the successive quotients until we reach 0 as a quotient.

NB: This gives least-significant bits first!

Again, see “poly” for a generalization to any base $\beta > 1$

Binary $\leftarrow$ Decimal Conversion - example

To convert $n = (423)_{10}$ to binary, we

$$\begin{array}{rclcl} 423 & = & 211 & \times & 2 + 1 \\ 211 & = & 105 & \times & 2 + 1 \\ 105 & = & 52 & \times & 2 + 1 \\ 52 & = & 26 & \times & 2 + 0 \\ 26 & = & 13 & \times & 2 + 0 \\ 13 & = & 6 & \times & 2 + 1 \\ 6 & = & 3 & \times & 2 + 0 \\ 3 & = & 1 & \times & 2 + 1 \\ 1 & = & 0 & \times & 2 + 1 \end{array}$$

From this we deduce that: $(423)_{10} = (110100111)_2$

Blackboard examples

Fine, we are able to represent natural integers...
What about signed integers?

Signed Integers?

Two ways of representing $-x$:

- ▶ 1 bit for the sign, the rest for $|x|$

$$x_{n-1} = \begin{cases} 0 & \text{if } x \geq 0, \\ 1 & \text{if } x < 0. \end{cases} \quad \text{and} \quad (x_{n-2}, x_{n-3}, \dots, x_1, x_0) = |x|$$

- ▶ Pros: Simple to understand
- ▶ Cons: 2 writings for 0
- ▶ Cons: hardware implementation $\neq$ unsigned integers
- ▶ Two's complement
 - ▶ Cons: Less easy to understand
 - ▶ Pros: numbering and hardware implementation is unchanged
 - Used in 99.99% of digital circuits⁵

⁵But other solutions are also used, e.g. for floating values...

Two's Complement - math

- ▶ Let x be a vector of n bits: $x_{n-1}, x_{n-2}, \dots, x_1, x_0$, with $x_i \in 0, 1$

The value of x interpreted as a signed integer is:

$$x = -x_{n-1}2^{n-1} + \sum_{i=0}^{n-2} x_i 2^i.$$

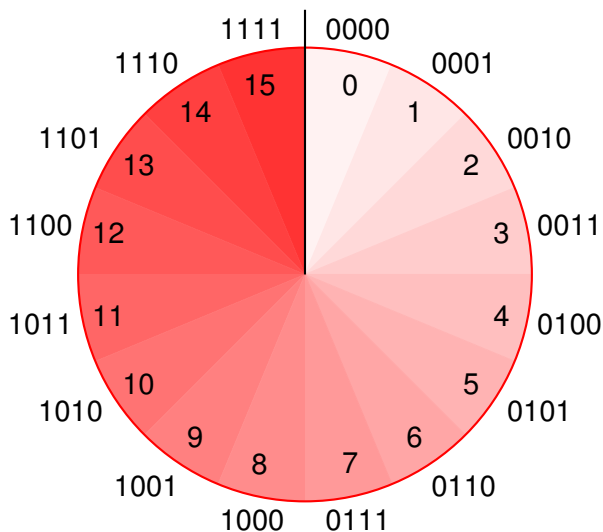
- ▶ Still only 2^n different values can be represented for a word of size n
- ▶ overflow may still happen but NOT AT THE SAME VALUE than for natural integers:

$$-2^{n-1} \leq x < 2^{n-1} - 1$$

e.g. for 32 bits,

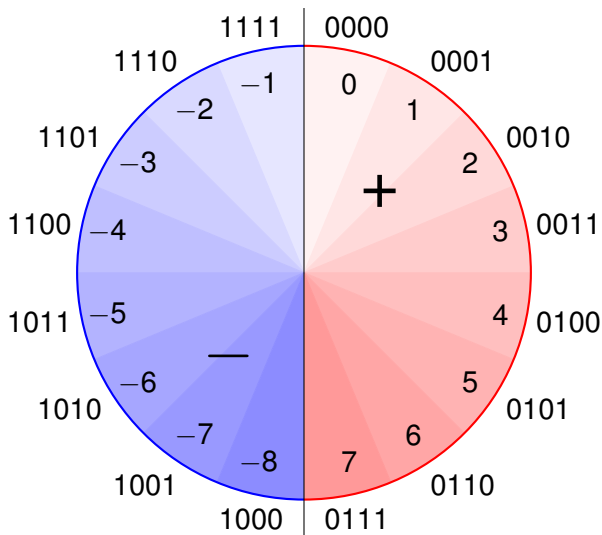
$$-2.147.483.648 \leq x < 2.147.483.647$$

Binary encoding - A graphical intuition⁶



⁶credit: Benoît Lopez

Two's Complement - a graphical intuition⁷



⁷credit: Benoît Lopez

Two's Complement - compute the opposite of x

- ▶ The opposite of a number is obtained by inverting all the bits of the word, then adding 1.
- ▶ Mathematically, if:

$$X = X_{n-1}, X_{n-2}, \dots, X_1, X_0$$

then

$$-X = (\overline{X_{n-1}}, \overline{X_{n-2}}, \dots, \overline{X_1}, \overline{X_0}) + 1$$

with $\bar{a}$ being the complement of bit a :

$$\bar{a} = \begin{cases} 1, & \text{when } a = 0 \\ 0, & \text{when } a = 1 \end{cases}$$

- ▶ This algorithm computes the opposite of a number, being it initially positive or negative!

Blackboard examples

Number Extension

How do we assign a n -bits vector to an m -bits vector?

- ▶ $n > m$, truncate $\rightarrow$ lose most significant bits
- ▶ $n < m$, requires a sign extension

Consider $(x_{n-1}, x_{n-2}, \dots, x_1, x_0)$. Let's write it as $(y_{m-1}, y_{m-2}, \dots, y_n, y_{n-1}, y_{n-2}, \dots, y_1, y_0)$. The value of x is preserved if we take:

$$y_{m-1} = x_{n-1}, y_{m-2} = x_{n-1}, \dots, y_n = x_{n-1}, y_{n-1} = x_{n-1},$$

$$y_{n-2} = x_{n-2}, \dots, y_1 = x_1, y_0 = x_0$$

Hexadecimal encoding

Decimal and binary encoding have different advantages:

- ▶ Decimal encoding: usual and easy for humans; high expressive power (numbers stay short), but not easily handled by machines (despite attempts in the 1950s).
- ▶ Binary encoding: hard to read for humans (except for very small values), but easily handled by machines.
- We would like to use both, but decimal $\Leftrightarrow$ binary conversion is difficult (at least for humans).

Hexadecimal ($\beta = 16$) encoding combines the advantages of both binary and decimal encoding:

- ▶ Easy to use for humans (high expressive power).
- ▶ Easily converted to binary for computers ($16 = 2^4$, so 1 hexadecimal digit corresponds exactly to 4 bits).
- ▶ But hexadecimal $\Leftrightarrow$ decimal conversion is still difficult :-)

The 16 symbols are: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F.

Binary $\Leftrightarrow$ Hexadecimal conversion

- ▶ One hexadecimal digit corresponds exactly to four binary digits $\rightarrow$ conversion table

$$00_{10} = 0_{16} = 0000_2$$

$$01_{10} = 1_{16} = 0001_2$$

$$02_{10} = 2_{16} = 0010_2$$

$$03_{10} = 3_{16} = 0011_2$$

$$04_{10} = 4_{16} = 0100_2$$

$$05_{10} = 5_{16} = 0101_2$$

$$06_{10} = 6_{16} = 0110_2$$

$$07_{10} = 7_{16} = 0111_2$$

$$08_{10} = 8_{16} = 1000_2$$

$$09_{10} = 9_{16} = 1001_2$$

$$10_{10} = A_{16} = 1010_2$$

$$11_{10} = B_{16} = 1011_2$$

$$12_{10} = C_{16} = 1100_2$$

$$13_{10} = D_{16} = 1101_2$$

$$14_{10} = E_{16} = 1110_2$$

$$15_{10} = F_{16} = 1111_2$$

- ▶ Binary-Hexadecimal conversion is straightforward: Group bits four by four and read the values in the table:

$$1000110111000101_2 = 1000.1101.1100.0101_2 = 8DC5_{16}$$

$$2AD7_{16} = 0010.1010.1101.0111_2 = 0010101011010111_2$$

Remember...

010010110101001001010100101011101010100101011110111
0100010001001111110010101001101010101110101110100100
1000100010100110001010101001001000100100000100010001
0011101100100101001000101001000101111001001010010001
1111001001001010100010100111001010000001011011010001
1001000101100100101001000101100100011111001001001010
0110001010101001001000100100000001000100010011101100
1001010010001100100100101010001010011100100010000001
0110110100011001000101001001010010001011010010001111
1001001001010011000101010010101000101001110010001000
0001011011010001100100010110010010100100010110100100
01111100100100101001100010101010010010001001...

Same in hexadecimal is more compact and (almost) human friendly...

4B5254AEA95F7444FCA999EBA488A62A92241113B2
5229179291F24A8A72816D19164A4591F24A62A922
40444EC948C92A29C8816D1914948B48F9253152A2
9C8816D19164A45A47C9298AA489...

Other interpretation of bit vectors

As soon as you are able to transform bit vectors into integers, you can code anything providing you have a conversion table and/or a conversion formula

→ Digital (in French “Numérique”) corresponds to this idea of transforming everything into numbers that computers are able to deal with...

- ▶ (Pseudo-)real numbers
- ▶ Characters/symbols: encodings such as ASCII or ISO or UTF-8.
- ▶ images (PNG, JPEG...), music (MP3, OGG...), video (MOV, AVI, MP4...)
- ▶ Instructions = programs in their “final” form (that which is interpreted by HW).
- ▶ ...

All this necessitates interpreting bit vectors!

Floating points

Integers have a constant precision but a very low *dynamics*...

- ▶ Difficult to represent very large values (e.g. mass of the universe in kilograms)
- ▶ Impossible to represent very small values (e.g. mass of an electron in kilograms)
- ▶ Encoding of useless (and sometimes misleading) LSB

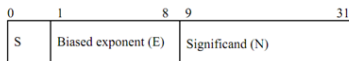
Solution: scientific notation (3×10^{52} and $9,109 \times 10^{-31}$)

⇒ Floating points are the binary analogs to scientific notation. Pseudo-real numbers are represented by a *mantissa* (or *fraction* or *significand*) and an *exponent* coded by (still finite) bit vectors.

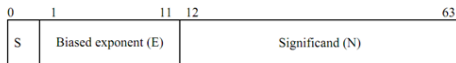
Floating-point numbers in practice

Floating-point numbers are standardised by the IEEE 754 standard. The two most commonly used formats are⁸:

- ▶ Single precision (32 bits): sign (1 bit), exponent⁹ (8 bits), fraction (23+1 bits¹⁰) → `float`
- ▶ Double precision (64 bits): sign (1 bit), exponent (11 bits), fraction (52+1 bits) → `double`



Single Precision = 32 bits



Double Precision = 64 bits

⁸Half precision (16 bits, called `half`) and quadruple precision (128 bits, sometimes called `long double`) also exist, but their use is still not as widespread and the representation may vary depending on the machines...

⁹Exponent sign is encoded using a biased representation.

¹⁰The extra bit is called the “hidden bit”. Its mere existence clearly illustrates that binary encoding is designed for machines, not humans!

Why is it important?

- ▶ Manipulating scientific notation is different from manipulating exact mathematical numbers
- ▶ It requires some *implicit* skills: you are probably already used to them, even if you don't realise it!

Example:

What is the mass of the sun plus one electron?

Example:

What is the mass of the sun plus one electron?

$$2 \times 10^{33} + 9 \times 10^{-28} = 2 \times 10^{33} \text{ g}$$

Example (continued):

What is the mass of the sun plus an electron?

$$2 \times 10^{33} + 9 \times 10^{-28} = 2 \times 10^{33} \text{g}$$

But... What is the mass of the sun plus 10^{61} electrons?

Well... it may depend on how you compute it!

$$(\dots((2 \times 10^{33} + 9 \times 10^{-28}) + 9 \times 10^{-28}) + \dots + 9 \times 10^{-28}) = 2 \times 10^{33} \text{g}$$

$$(\dots(9 \times 10^{-28} + 9 \times 10^{-28}) + \dots + 9 \times 10^{-28}) + 2 \times 10^{33} = ??? \text{g}$$

We can have $a + b = a$ even when $b \neq 0$ (absorption), and the addition is not necessarily associative ($(a + b) + c \neq a + (b + c)$) nor commutative ($a + b + c \neq c + b + a$).

Why is it important?

- ▶ The same phenomena occur with floating-point operations...
- ▶ But they are somehow *invisibilized* by the machine!
→ And this can make them even more dangerous.
- ▶ Always remember that a floating-point number can represent only a *finite set* of values:
 - ▶ a float uses 32 bits → at most 2^{32} distinct values ($\approx 4 \times 10^9$);
 - ▶ a double uses 64 bits → at most 2^{64} distinct values ($\approx 18 \times 10^{18}$);
 - Both are *much* smaller than the set of real numbers $\mathbb{R}$!
- ▶ Two important orders of magnitude: the number of bits in the significand determines the expected precision:
 - ▶ float: $23+1=24$ bits → about 7 significant decimal digits;
 - ▶ double: $52+1=53$ bits → about 15 significant decimal digits.

Example: How is π encoded in a double?

In IEEE 754 double precision, π is stored using 64 bits:

400921FB54442D18

or, in binary,

0100000000000100100100001111110110101010001000100001...

The 64 bits are divided into:

- ▶ 1 bit for the sign: 0 $\rightarrow$ positive
- ▶ 11 bits for the exponent: 10000000000 $\rightarrow$ exponent = 1
- ▶ 52 + 1 bits for the fraction (storing the significant digits):

(1)1001001000011111101101010100010001000010110100011000

But π is irrational, so it cannot be represented exactly using a finite number of bits. The stored value is therefore only an approximation:

$$\begin{aligned}\pi &= 3.141592653589793238\dots \\ \text{double}(\pi) &= 3.141592653589793116\dots \\ \text{float}(\pi) &= 3.141592741012573242\dots\end{aligned}$$

Why is it important?

These small errors can accumulate:

→ Dharan, Saudi Arabia, 1991: A Patriot system failed to intercept an Iraqi Scud because of a software rounding error.



Tiny numerical errors (28th bit of the fraction) accumulated during 100 hours, resulting in a 0.34 second timing error ($\approx 500\text{m}$ at the speed of a Scud rocket) → 28 deaths.

A last note on floating points

Floating-point formats (*i.e.* float and double) reserve some binary codes for *special values*:

- ▶ By construction of the code, the binary code of zero is $000\dots 0$. This greatly simplifies many operations.
- ▶ Positive and negative infinity are explicitly encoded such that $\frac{1}{0} = +\infty$, $\frac{-1}{0} = -\infty$.
- ▶ Floating-point arithmetic also distinguishes $+0$ and -0 . Looks mathematically absurd but is computationally very useful as it allows, for example, to distinguish $\frac{1}{+\infty} = 0$ from $\frac{1}{-\infty} = -0$.
- ▶ Some operations have no meaningful numerical result (*e.g.* $\frac{0}{0}$ and $\frac{\infty}{\infty}$) in such cases, the result is NaN (Not a Number).

Remember: these representations are not made for humans (let alone for mathematicians!)... They are designed to make computers efficient!

Character encoding — ASCII

Decimal	Hex	Char	Decimal	Hex	Char	Decimal	Hex	Char	Decimal	Hex	Char
0	0	[NULL]	32	20	[SPACE]	64	40	@	96	60	`
1	1	[START OF HEADING]	33	21	!	65	41	A	97	61	a
2	2	[START OF TEXT]	34	22	"	66	42	B	98	62	b
3	3	[END OF TEXT]	35	23	#	67	43	C	99	63	c
4	4	[END OF TRANSMISSION]	36	24	\$	68	44	D	100	64	d
5	5	[ENQUIRY]	37	25	%	69	45	E	101	65	e
6	6	[ACKNOWLEDGE]	38	26	&	70	46	F	102	66	f
7	7	[BELL]	39	27	'	71	47	G	103	67	g
8	8	[BACKSPACE]	40	28	(	72	48	H	104	68	h
9	9	[HORIZONTAL TAB]	41	29	)	73	49	I	105	69	i
10	A	[LINE FEED]	42	2A	*	74	4A	J	106	6A	j
11	B	[VERTICAL TAB]	43	2B	+	75	4B	K	107	6B	k
12	C	[FORM FEED]	44	2C	,	76	4C	L	108	6C	l
13	D	[CARRIAGE RETURN]	45	2D	-	77	4D	M	109	6D	m
14	E	[SHIFT OUT]	46	2E	.	78	4E	N	110	6E	n
15	F	[SHIFT IN]	47	2F	/	79	4F	O	111	6F	o
16	10	[DATA LINK ESCAPE]	48	30	0	80	50	P	112	70	p
17	11	[DEVICE CONTROL 1]	49	31	1	81	51	Q	113	71	q
18	12	[DEVICE CONTROL 2]	50	32	2	82	52	R	114	72	r
19	13	[DEVICE CONTROL 3]	51	33	3	83	53	S	115	73	s
20	14	[DEVICE CONTROL 4]	52	34	4	84	54	T	116	74	t
21	15	[NEGATIVE ACKNOWLEDGE]	53	35	5	85	55	U	117	75	u
22	16	[SYNCHRONOUS IDLE]	54	36	6	86	56	V	118	76	v
23	17	[ENG OF TRANS. BLOCK]	55	37	7	87	57	W	119	77	w
24	18	[CANCEL]	56	38	8	88	58	X	120	78	x
25	19	[END OF MEDIUM]	57	39	9	89	59	Y	121	79	y
26	1A	[SUBSTITUTE]	58	3A	:	90	5A	Z	122	7A	z
27	1B	[ESCAPE]	59	3B	;	91	5B	[	123	7B	{
28	1C	[FILE SEPARATOR]	60	3C	<	92	5C	\	124	7C	
29	1D	[GROUP SEPARATOR]	61	3D	=	93	5D	]	125	7D	}
30	1E	[RECORD SEPARATOR]	62	3E	>	94	5E	^	126	7E	~
31	1F	[UNIT SEPARATOR]	63	3F	?	95	5F	_	127	7F	[DEL]

Character encoding — UTF-8

UTF-8 is a variable-length encoding of UNICODE characters that uses 1 to 4 bytes per character. It allows to efficiently represent text from virtually all writing systems using sequences of 8-bit values.

Character		Binary code point	Binary UTF-8	Hexadecimal UTF-8
\$	U+0024	010 0100	00100100	24
¢	U+00A2	000 1010 0010	11000010 10100010	C2 A2
€	U+20AC	0010 0000 1010 1100	11100010 10000010 10101100	E2 82 AC
🇪🇺	U+10348	0 0001 0000 0011 0100 1000	11110000 10010000 10001101 10001000	F0 90 8D 88

Instruction encoding

```
0x00000000100000f70 <+0>:    push    %rbp
0x00000000100000f71 <+1>:    mov     %rsp,%rbp
0x00000000100000f74 <+4>:    movl    $0x0,-0x4(%rbp)
0x00000000100000f7b <+11>:   movl    $0x0,-0x8(%rbp)
0x00000000100000f82 <+18>:   movl    $0x0,-0xc(%rbp)
0x00000000100000f89 <+25>:   movl    $0x1,-0xc(%rbp)
0x00000000100000f90 <+32>:   cmpl    $0x64,-0xc(%rbp)
0x00000000100000f94 <+36>:   jge     0x100000fb1 <main()+65>
0x00000000100000f9a <+42>:   mov     -0x8(%rbp),%eax
0x00000000100000f9d <+45>:   add     $0x1,%eax
0x00000000100000fa0 <+48>:   mov     %eax,-0x8(%rbp)
0x00000000100000fa3 <+51>:   mov     -0xc(%rbp),%eax
0x00000000100000fa6 <+54>:   add     $0x1,%eax
0x00000000100000fa9 <+57>:   mov     %eax,-0xc(%rbp)
0x00000000100000fac <+60>:   jmpq    0x100000f90 <main()+32>
0x00000000100000fb1 <+65>:   mov     -0x8(%rbp),%eax
0x00000000100000fb4 <+68>:   pop     %rbp
```



```
0000f70 55 48 89 e5 c7 45 fc 00 00 00 00 c7 45 f8 00 00
0000f80 00 00 c7 45 f4 00 00 00 00 c7 45 f4 01 00 00 00
0000f90 83 7d f4 64 0f 8d 17 00 00 00 8b 45 f8 83 c0 01
0000fa0 89 45 f8 8b 45 f4 83 c0 01 89 45 f4 e9 df ff ff
0000fb0 ff 8b 45 f8 5d c3 90 90 01 00 00 00 1c 00 00 00
0000fc0 00 00 00 00 1c 00 00 00 00 00 00 00 1c 00 00 00
0000fd0 02 00 00 00 70 0f 00 00 34 00 00 00 34 00 00 00
```

Instructions can be encoded as binary vectors with two parts: The “opcode” and the “operands”

```
0x00000000100000f70 <+0>:    push    %rbp
0x00000000100000f71 <+1>:    mov     %rsp,%rbp
0x00000000100000f74 <+4>:    movl    $0x0,-0x4(%rbp)
0x00000000100000f7b <+11>:   movl    $0x0,-0x8(%rbp)
0x00000000100000f82 <+18>:   movl    $0x0,-0xc(%rbp)
0x00000000100000f89 <+25>:   movl    $0x1,-0xc(%rbp)
0x00000000100000f90 <+32>:   cmpl    $0x64,-0xc(%rbp)
0x00000000100000f94 <+36>:   jge     0x100000fb1 <main()+65>
0x00000000100000f9a <+42>:   mov     -0x8(%rbp),%eax
0x00000000100000f9d <+45>:   add     $0x1,%eax
0x00000000100000fa0 <+48>:   mov     %eax,-0x8(%rbp)
0x00000000100000fa3 <+51>:   mov     -0xc(%rbp),%eax
0x00000000100000fa6 <+54>:   add     $0x1,%eax
0x00000000100000fa9 <+57>:   mov     %eax,-0xc(%rbp)
0x00000000100000fac <+60>:   jmpq    0x100000f90 <main()+32>
0x00000000100000fb1 <+65>:   mov     -0x8(%rbp),%eax
0x00000000100000fb4 <+68>:   pop     %rbp
```



```
0000f70 55 48 89 e5 c7 45 fc 00 00 00 00 c7 45 f8 00 00
0000f80 00 00 c7 45 f4 00 00 00 00 c7 45 f4 01 00 00 00
0000f90 83 7d f4 64 0f 8d 17 00 00 00 8b 45 f8 83 c0 01
0000fa0 89 45 f8 8b 45 f4 83 c0 01 89 45 f4 e9 df ff ff
0000fb0 ff 8b 45 f8 5d c3 90 90 01 00 00 00 1c 00 00 00
0000fc0 00 00 00 00 1c 00 00 00 00 00 00 00 1c 00 00 00
0000fd0 02 00 00 00 70 0f 00 00 34 00 00 00 34 00 00 00
```

Take Home Message

1. Binary information is encoded in bit vectors which length is of utmost importance
2. Bit vectors can be interpreted as “integers”
3. Bit vectors can be interpreted as “reals” (floating points)
4. Integers can be interpreted as almost anything (“digitalization”)
5. Numbers in computers don’t behave exactly as in math!
6. Bit vectors can be interpreted as instructions

⇒ So we are able to code **data** AND **instructions**...

⇒ We’ve made a first step towards von Neumann’s machines...

Next step...

Combinatorial Logic and Circuits!!

ie, how to process information encoded in bit vectors?