2. Information Representation

Informática

Ingeniería en Electrónica y Automática Industrial

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Positional Representation

- Positional representation is based on the next theorem:

Theorem

Let $b > 1$ be a positive integer. Any positive integer n can be written in a unique way as

$$n = \sum_{j=0}^{k} a_j b^j = a_k b^k + a_{k-1} b^{k-1} + \cdots + a_1 b + a_0,$$

with $0 \leq a_j \leq b-1$ for $j = 0, \ldots, k$, y $a_k \neq 0$.

- So we can write the positional representation of n as

$$n = (a_k, a_{k-1}, \ldots, a_0),$$

or just $a_k a_{k-1} \ldots a_0$.

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Representation Bases

- As the theorem states, we can use any integer b as base to represent all integer numbers.
- Traditionally we use base $b = 10$, or *decimal*.
- However computers use base $b = 2$ or *binary* to make information process more efficient inside them.
- Ii is very common to use base $b = 16$ or *hexadecimal* as an easier and more compact way for humans to represent binary information

Rational numbers representation

- Rational numbers are always a ratio of two integers.
- To include the fractional part of a rational number, we can extend the positional system using the negative powers of the base:

$$n = \sum_{j=\ell}^{k} a_j b^j = a_k b^k + \cdots + a_1 b + a_0 + a_{-1} b^{-1} + \cdots + a_\ell b^\ell,$$

  with $\ell \leq 0 \leq k$.
- We can't represent exactly irrational numbers, (e.g. $\sqrt{2}, \pi, e$), so we take as an approximation the closets rational number that we can represent.

Rational numbers representation

- Let r be a rational number $r = \left[\frac{p}{q}\right]$ with $q = b^s$ where b is the base and s any positive integer. Then r can be expressed as:

$$r = \frac{p}{q} = \frac{\sum_{j=0}^{k} p_j b^j}{b^s} = \sum_{j=0}^{k} p_j b^{j-s}.$$

- If $k > s$, then r can be expressed as

$$r = \left(p_k p_{k-1} \cdots p_s, p_{s-1} \cdots p_0\right),$$

where $p_{s-1}, \ldots, p_0$ are the coefficients of the negative powers of b.

Base Change

- Let b_1 and b_2 be two different bases. Let (u, v) be a real number where u is the integer part and v is the fractional part.
- Then (u, v) can be represented with both bases:
    - With base b_1: $u = (p_{k-1}p_{k-2}\cdots p_0)_{b_1}$, $v = (,p_{-1}p_{-2}\cdots p_{-\ell})_{b_1}$, with $k, \ell > 0$.
    - With base b_2: $u = (q_{K-1}q_{K-2}\cdots q_0)_{b_2}$, $v = (,q_{-1}q_{-2}\cdots q_{-L})_{b_2}$, with $K, L > 0$.
- A very common task for computers is to pass from the representation in one base to the other (e.g. represent the decimal number 17 in binary).

Base Change

To obtain the integer part:

Divide successively $(u)_{b_1}$ by $(b_2)_{b_1}$. The remainders q_i are the digits of $(u)_{b_2}$ starting with q_0 until q_{K-1}.

To obtain the fractional part:

Multiply successively $(v)_{b_1}$ by $(b_2)_{b_1}$. After each multiplication, the integer parts q_i will form the digits of $(v)_{b_2}$ (from q_{-1} to q_{-L}). Before the next multiplication the previous integer part must be removed.

Example: Represent the decimal number 22.375 in binary (i.e. change from base 10 to base 2)

- Integer part: $u = 22$

dividend	quotient	remainder
22	11	0
11	5	1
5	2	1
2	1	0
1	0	1

- Fractional part: $v =, 375$

multiplicand	product	integer part
0,375	0,75	0
0,75	1,5	1
0,5	2	1

- Therefore the result is 10110.011

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Inverse Base Change

- Just apply the opposite procedure or the positional formula

Example: Express the binary number 10110.011 in decimal

- Integer part: $u = 10110$

$$1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 = 22.$$

- Fraccional part: $v =, 011$

$$0 \times 2^{-1} + 1 \times 2^{-2} + +1 \times 2^{-3} = 0.375.$$

Therefore the result is 22.375.

What is a *codification*?

- From chapter 1:

Definition

Codification: is a biunivocal correspondence among the elements of two sets

Observation

As it is biunivocal (i.e. one-to-one) we can identify the elements of the first set using the ones of the second set.

More formally . . .

- Let A and B be two sets and let $f : A \to B$ be a function.

Definition

We can say that B *codifies* A by f if f is *biunivocal*

- If the sets are provided with an inner operation $(A, +)$, $(B, \oplus)$:

Definition

If $f(a + b) = f(a) \oplus f(b)$ for any $a, b \in A$, then we have a *faithful representation* (or *codification*)

- Example: We obtain the same result adding two numbers in decimal or binary representations:
  $2 + 4 = 6$, $0010 + 0100 = 0110$, and $6_{10} = 0110_2$

Modulo Operation

Definition

Let $m > 0$. Then the modulo operation with two integer numbers, $b = a \pmod{m}$, is the remainder of a divided by m.
(therefore $a = q \cdot m + b$, for some integer q)

Example

- $7 \pmod{2} = 1$, as $7 = 3 \times 2 + 1$
- Clocks work modulo 12 or 24 hours.

Operations in $\mathbb{Z}$ and B

- The set of all integers is $\mathbb{Z}$
- B_w is the set of all binary numbers with w digits
  There are 2^w binary numbers with w digits (e.g. for $w = 2$ there are 2^2 binary numbers $\{00, 01, 10, 11\}$
- Codification of integers is a biunivocal correspondence $R \to B$ where R is a subset of $\mathbb{Z}$
- We want also a faithful representation, that is, that operations in R correspond to operations in B obtaining the same result (e.g. $2 + 4 = 6$, $0010 + 0100 = 0110$).

Integer Representation

- The number of bits that a computer uses to store binary numbers is the *width* or *size* of a *word*,
- Usually is 8, 16, 32, or 64 bits.
- In programming languages, each size receives a name, for instance in C language:

$$\begin{aligned} \texttt{char} &\Rightarrow \text{8 bits.}\\ \texttt{short int} &\Rightarrow \text{16 bits.}\\ \texttt{int} &\Rightarrow \text{32 bits.}\\ \texttt{long int} &\Rightarrow \text{64 bits.} \end{aligned}$$

Summary of different binary representations

Fixed point	Unsigned binary	
	Signed binary	With sign bit
		One's complement
		Two's complement
		Excess-Z
Floating point	Integer significand	
	Fractional significand	

Unsigned b¡nary

- Corresponding function is simply the formula to change to base 2:
$$\begin{array}{rcl} f: R & \rightarrow & B \\ n & \mapsto & (x_{w-1}, \dots, x_0)_2 \end{array}$$
such us $n = \sum_{i=0}^{w-1} x_i 2^i$.
- For w bits, the set $R = \{0, 1, \dots, 2^w - 1\}$ is codified as $0 \mapsto (0 \cdots 0)$, ..., $2^w - 1 \mapsto (1 \cdots 1)$ (positives and 0)
- Example: for $w = 3$, $\{0, \cdots, 2^3 - 1\} \mapsto \{000, \cdots, 111\}$
- It is a faithful representation

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Signed binary

- Add an extra bit at the left to express the sign (0 for positive, 1 for negative)
- Therefor for w bits we can represent the set $R = \{-2^{w-1} + 1, \ldots, 2^{w-1} - 1\}$.
- Example: $-3_{10} = 1011_2$
- It is NOT a faithful representation as 0 can be represented in two ways $(+0, -0)$, and therefore is not biunivocal.

Excess-Z binary representation

- Simply add a positive integer $Z > 0$: $n \mapsto n + Z$, $n \in R$. Assuming that $n + Z \geq 0$, we can represent $R = \{-Z, \ldots, Z - 1\}$.
- Use unsigned binary representation to express the result

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

- Typically for w bits we choose $Z = 2^{w-1}$
- It is used to represent the exponential in floating point representation (see below)

Excess-Z binary representation

- It is NOT a faithful representation:
  Let $n, m \in R$

$$\begin{array}{rcc} n & \mapsto & n+Z \\ + & & + \\ m & \mapsto & m+Z \\ \hline n+m & \not\mapsto & n+m+2Z, \end{array}$$

i.e. it is necessary to subtract Z to get the correct result in R

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One's Complement -1C- binary representation

- Positive 1C numbers are the same than in signed binary (SB) $+5_{10} = 0101_{SB} = 0101_{1C}$
- To get 1C representation of a negative number swap all bits $(0 \rightarrow 1, 1 \rightarrow 0)$ of the corresponding positive signed binary: $-5_{10} = 1101_{SB} = 1010_{1C}$
- Range of representation $R_{1C} = \{-2^{w-1} - 1, \ldots, 2^{w-1} - 1\}$
- It is NOT a faithful representation as it is not biunivocal because the number 0 can be represented in two ways $(+0, -0)$
- Much less used than 2C

Two's Complement -2C- binary representation

- Positive 2C numbers are the same than in SB
  $+5_{10} = 0101_{SB} = 0101_{1C} = 0101_{1C}$
- To get the 2C representation of a negative number
  - Obtain 1C
  - Add $+1$
  - $-5_{10} = 1101_{SB} = 1010_{1C} = 1011_{2C}$
- To know the magnitude of a negative 2C number, compute its 2C again to obtain the corresponding positive

Two's Complement -2C- binary representation

- Range of 2C representation $R_{2C} = \{-2^{w-1}, \ldots, 2^{w-1} - 1\}$.

$$\begin{array}{ccc} -2^{w-1} & \mapsto & (1, 0, \ldots, 0)\,, \\ & \cdots & \\ -1 & \mapsto & (1, 1, \ldots, 1)\,, \\ 0 & \mapsto & (0, 0, \ldots, 0)\,, \\ 1 & \mapsto & (0, 0, \ldots, 1)\,, \\ & \cdots & \\ 2^{w-1} - 1 & \mapsto & (0, 1, \ldots, 1)\,. \end{array}$$

- It is **UNIVERSALLY USED** by computers:
  - It is biunivocal and faithful with $\{+, -, \times, \div\}$ operations
  - To subtract is very easy: just add the 2C of the number

Floating point representation

- The idea is to save space without loosing accuracy by means of moving the coma and changing the exponent: (decimal example: $0.00027 \times 10^{-2} = 2.7 \times 10^{-6}$)
- Each number x is represented as $x = \pm m \times b^{e}$, where

m	significand or mantissa
b	base
e	exponent

Example

$$\begin{aligned} a &= (1.001)_2 \times 2^{-5} \\ b &= (1.001)_2 \times 2^{7} \end{aligned}$$

Floating point format

- The typical format to represent a floating point number is:

s	exponente	mantisa

- *Sign* 0 → positive, 1 → negative.
- *Exponent*: Integer expressed in Z-excess with $Z = 2^{w_e - 1}$, where w_e is the number of bits to store it.
- *Significand or mantissa*:
    - *Integer*: not used
    - *Fractional*: It is generally *normalized* such as the integer part is just one significant bit ($\neq 0$)

Floating point examples

Example

- $a = 1.001 \times 2^{-5}$. Exponent is $e = -5$ and the mantissa $m = 1.001$ is already normalized (1 in the integer part)
- $a = 10.01 \times 2^{-6}$. Exponent is $e = -6$ and $m = 10.01$ is not normalized (two bits in the integer part)
- $a = 0.1001 \times 2^{-4}$. Exponent is $e = -4$ and $m = 0.1001$ is not normalized (the integer part is 0)

By the way: $a = \frac{(1001)_2}{2^3} \times \frac{1}{2^5} = \frac{9}{2^8} = 0.03515625$.

ANSI/IEEE 754 Standard representation

- MOST EXTENDED standard to represent floating point numbers in computations.
- Defines the size in bits of each field.
- Normalized mantissa → just one integer bit always = 1. Therefore is never stored (*implicit bit*)
- There are two sizes::
    - Simple precision floating point, `float`, total size = 32 bits.
    - Double precision floating point, `double`, total size = 64 bits.

ANSI/IEEE 754 Standard. Special values

- **Zero** cannot be represented, so it is chosen by convention to be the number with all bits = 0 (otherwise would be 1.0×2^{-127} for `float` and 1.0×2^{-1023} for `double`.
- **Infinity**. By convention two different codes are chosen to represent $\pm\infty$ (0/1 for sign, exponent all 1's, mantissa al 0's).
- **NaN**. Not a Number. Undefined result after some operation (for instance 0/0). Represented as well by a particular code.

ANSI/IEEE 754 Standard

	simple	**doble**
Total Size	32 bits	64 bits
Mantissa	$23+1$ bits	$52+1$ bits
Exponent	8 bits	11 bits
Excess	2^7-1	$2^{10}-1$
Minimum	$2^{-126}\simeq 1.2\times 10^{-38}$	$2^{-1022}\simeq 2.2\times 10^{-308}$
Maximum	$2^{128}-2^{-127}\simeq 3.4\times 10^{38}$	$2^{1024}-2^{-1023}\simeq 1.8\times 10^{308}$
Zero	$e+exc=0\ ,\ m=0$	$e+exc=0,\ m=0$
Infinity	$e+exc=255,\ m=0$	$e+exc=2047,\ m=0$
NaN	$e+exc=255,\ m\neq 0$	$e+exc=2047,\ m\neq 0$

Alphanumeric Information Representation

- Alphanumeric Information is codified with character tables.
- Each element is represented by a binary code
- Each table defines the number of bits to represent each character.
- There are different standards:
    - ANSI/ASCII.
    - ISO8859-XX.
    - Unicode, UTF-8, UTF-16.
    - BM/EBCDIC.

ANSI/ASCII-7 table

- 7 bits are used to codify 128 alphanumeric characters.

Examples:

Character	“0”	“1”	...	“9”	“A”	...	“Z”
ASCII-7 code	48	49	...	57	65	...	90

ISO8859-15 table

- 8 bits to codify 256 alphanumeric characters
  - First 128 are the same than in ASCII-7
  - Last 128 are Western language characters

Examples:

Character	"é"	...	"è"	...	"û"	...
ISO8859-15 code	130	...	138	...	150	...

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UTF-8 table

- It uses variable lenght codes, from 8 to 16 bits.
- For codes smaller than 128 is fully compatible with ASCII-7
- It allows to codify character of many languages, including Easter ones

Character	“é”	. . .	“è”	. . .	“û”	. . .
UTF-8 code	0xC3A9	. . .	0xC3A8	. . .	0xC3BB	. . .

Character Chains

To store character chains in memory another aspect must be considered:

- How to codify the chain length. Three main methods
    - Terminator method
    - Length indicator method
    - Descriptor method

Terminator method

- A special character is used to indicate the end of the chain. Typically 0 is used.
- To access the chain it is only necessary to know the address of the first character.

Example

To represent the string `"Hola"` with ISO8859-15 table we use five bytes:

`H`	`o`	`l`	`a`	`0`

Length indicator method

- The first (or first and second) byte(s) of the chain indicate(s) its length.
- To access the chain it is only necessary to know the address of the first character.
- This method limits the maximum length of the chain.

Example

To represent the string `"Hola"` with ISO8859-15 table we use five bytes:

4	`H`	`o`	`l`	`a`

Descriptor method

- Chain characters are written alone from a memory position onwards
- To access the chain it is necessary to know the address of the first character AND its length. These two data together form the *descriptor*

Example

To represent the string `"Hola"` with ISO8859-15 table we use four bytes:

`H`	`o`	`l`	`a`