

Finite representation of real numbers

Fixed-point numbers

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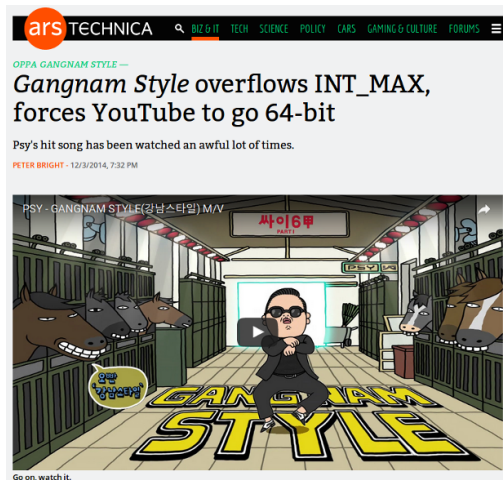
Control y Sistemas

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Resumen

- 1 Real numbers in computers
- 2 Integers
- 3 Fixed-point
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 - Dynamic range
 - How to determine the correct range
 - Addition
 - Overflow
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 - How to avoid underflow
 - Shifts
 - Accumulator

Gangnam Style problem



<https://arstechnica.com>

Patriot Missile System problem

- On February 25th, 1991, a Patriot Missile system at Dhahran, Saudi Arabia had failed to intercept a SCUD missile. The SCUD hit an Army Barracks, killing 28 Americans soldiers.
- Time is stored to an accuracy of 1/10th of a second in a 24-bit register.
- The error of representing 1/10th s in 24-bit register is 0.000000095 decimal.
- After 100 hr of operation, cumulative error gives $0.000000095 \times 100 \times 60 \times 60 \times 10 = 0.34$ s.
- A SCUD travels at about 1,676 meters per second. In 0.34 s, it travels more than half a kilometer.

<http://www-users.math.umn.edu/~arnold/disasters/patriot.html>

Integers

Unsigned integers

- An N-bit binary word can represent a total of 2^N separate values.
- Range: 0 to $2^N - 1$
- $$n_{10} = 2^{N-1}b_{N-1} + 2^{N-2}b_{N-2} + \dots + 2^1b_1 + 2^0b_0$$

2's complement signed integers

- Range: -2^{N-1} to $2^{N-1} - 1$.
- $$n_{10} = -b_{N-1}2^{N-1} + \sum_{i=0}^{N-2} b_i 2^i$$

in C:

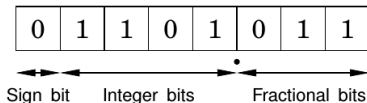
- 8 bits (`char`, `int8_t`): [-128, 127]]
- 16 bits (`short`, `int16_t`): [-32768, 32767]
- 32 bits (`int`, `long`, `int32_t`): [-2147483648, 2147483647]

Bit Pattern	Unsigned	2's Complement
0000 0000	0	0
0000 0001	1	1
0000 0010	2	2
•	•	•
•	•	•
0111 1110	126	126
0111 1111	127	127
1000 0000	128	-128
1000 0001	129	-127
•	•	•
•	•	•
1111 1110	254	-2
1111 1111	255	-1

Fixed-point representation

In fixed-point representation, a real number x is represented by an integer X with $N = m + n + 1$ bits, where

- N is the wordlength.
- m represents the number of integer bits (to the left of the binary point).
- n represents the number of fractional bits (to the right of the binary point).
- The weights of bits to the right of the binary point are negative powers of 2: $2^{-1} = \frac{1}{2}$, $2^{-2} = \frac{1}{4}$... , etc.
- Precision: 2^{-n} .
- Range: -2^m to $2^m - 2^{-n}$.
- $n_{10} = \sum_{i=0}^{m-1} b_i 2^i + \sum_{i=1}^n b_i 2^{-i}$



Qm.n notation

This naming convention does not take the MSB of the number (sign bit) into account.
For instance:

- Q0.15 (Q15)
 - 16 bits;
 - Range: -1 to 0.99996948;
 - Precision: $1/32768$ (2^{-15}).
- Q3.12
 - 16 bits;
 - Range: -8 to 7.9998;
 - Precision: $1/4096$ (2^{-12}).
- Q0.31 (Q31)
 - 32 bits;
 - Range: -1 to 0.999999999534339;
 - Precision: $4.6566129e-10$ (2^{-31}).

Conversion to and from fixed point

Conversion from real to fixed-point number:

$$X := \text{round}(x \cdot 2^n)$$

Conversion from fixed-point to real number:

$$x := X \cdot 2^{-n}$$

Example: Represent $x = 13.4$ using Q4.3 format

$$X = \text{round}(13.4 \cdot 2^3) = 107(01101011_2)$$

Example: Represent $x = 0.052246$ using Q4.11 format

$$X = \text{round}(0.052246 \cdot 2^{11}) = 107(0000000001101011_2)$$

Scale of representation

- There is no difference at the CPU level between a fractional and an integer representation.
- The difference is based on the concept of *scale*, which is almost completely in the head of the designer.
- Values represented in Qm.n notation can be seen as a signed integer simply divided by 2^n , the inverse of precision.
- In fact, the scale factor can be an arbitrary scale that is not a power of two.
- Example: 16-bit 2's complement numbers between 8000H and 7FFFH can represent decimal values between -5 and $+5$, where the scale factor is $5/32768$ ($5/2^{15}$).

Scale factor, examples

Format	Scaling factor ()	Range in Hex (fractional value)
(1.15)	$2^{15} = 32768$	0x7FFF (0.99) → 0x8000 (−1)
(2.14)	$2^{14} = 16384$	0x7FFF (1.99) → 0x8000 (−2)
(3.13)	$2^{13} = 8192$	0x7FFF (3.99) → 0x8000 (−4)
(4.12)	$2^{12} = 4096$	0x7FFF (7.99) → 0x8000 (−8)
(5.11)	$2^{11} = 2048$	0x7FFF (15.99) → 0x8000 (−16)
(6.10)	$2^{10} = 1024$	0x7FFF (31.99) → 0x8000 (−32)
(7.9)	$2^9 = 512$	0x7FFF (63.99) → 0x8000 (−64)
(8.8)	$2^8 = 256$	0x7FFF (127.99) → 0x8000 (−128)
(9.7)	$2^7 = 128$	0x7FFF (511.99) → 0x8000 (−512)
(10.6)	$2^6 = 64$	0x7FFF (1023.99) → 0x8000 (−1024)
(11.5)	$2^5 = 32$	0x7FFF (2047.99) → 0x8000 (−2048)
(12.4)	$2^4 = 16$	0x7FFF (4095.99) → 0x8000 (−4096)
(13.3)	$2^3 = 8$	0x7FFF (4095.99) → 0x8000 (−4096)
(14.2)	$2^2 = 4$	0x7FFF (8191.99) → 0x8000 (−8192)
(15.1)	$2^1 = 2$	0x7FFF (16383.99) → 0x8000 (−16384)
(16.0)	$2^0 = 1(\text{Integer})$	0x7FFF (32767) → 0x8000h (−32768)

Dynamic range

Dynamic range is defined as,

$$DR_{dB} = 20 \log_{10} \left(\frac{\text{largest possible word value}}{\text{smallest possible word value}} \right) \quad [\text{dB}]$$

For N-bit signed integers,

$$DR_{dB} = 20 \log_{10} \left[\frac{2^{(N-1)} - 1}{1} \right] \quad [\text{dB}]$$

$$DR_{dB} \approx 20 [(N-1) \log_{10}(2)]$$

$$DR_{dB} \approx 20 \log_{10}(2) \cdot (N-1)$$

$$DR_{dB} \approx 6.02 \cdot (N-1) \quad [\text{dB}]$$

Precision and Dynamic range examples

Format (N.M)		Largest positive value (0x7FFF)	Least negative value (0x8000)	Precision (0x0001)		DR(dB)
1	15	0,999969482421875	-1	3,05176E-05	2 ⁻¹⁵	90,30873362
2	14	1,99993896484375	-2	6,10352E-05	2 ⁻¹⁴	90,30873362
3	13	3,9998779296875	-4	0,00012207	2 ⁻¹³	90,30873362
4	12	7,999755859375	-8	0,000244141	2 ⁻¹²	90,30873362
5	11	15,99951171875	-16	0,000488281	2 ⁻¹¹	90,30873362
6	10	31,99902344	-32	0,000976563	2 ⁻¹⁰	90,30873362
7	9	63,99804688	-64	0,001953125	2 ⁻⁹	90,30873362
8	8	127,9960938	-128	0,00390625	2 ⁻⁸	90,30873362
9	7	255,9921875	-256	0,0078125	2 ⁻⁷	90,30873362
10	6	511,984375	-512	0,015625	2 ⁻⁶	90,30873362
11	5	1023,96875	-1024	0,03125	2 ⁻⁵	90,30873362
12	4	2047,9375	-2048	0,0625	2 ⁻⁴	90,30873362
13	3	4095,875	-4096	0,125	2 ⁻³	90,30873362
14	2	8191,75	-8192	0,25	2 ⁻²	90,30873362
15	1	16383,5	-16384	0,5	2 ⁻¹	90,30873362
16	0	32767	-32768	1	2 ⁻⁰	90,30873362

How to determine the correct range

How much bits are needed to represent $\text{INT_MIN} \leq \alpha \leq \text{INT_MAX}$?

$$N = \text{floor}(\log_2(\max([\text{INT_MIN}, \text{INT_MAX}])) + 2)$$

MATLAB

```
❶ » INT_MIN = 15; INT_MAX = 15;  
❷ » MAX = max( [ INT_MIN, INT_MAX ] );  
❸ » BITS = (log2 ( MAX ) + 2 ); % Round towards + Inf  
❹ » N = floor ( BITS );  
❺ » N = 5.00
```

Addition in 2's complement

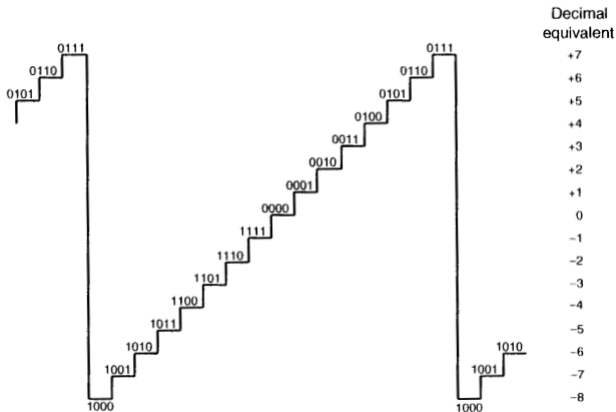
- Adding two N-bits numbers can produce a N+1 bits result.
- The result will have the same numbers of fractional bits.
- Only the integer part can grow.
- The last two bits of the carry row show if overflow occurs.

$$\begin{array}{r}
 \boxed{11}111\ 111\ (\text{carry}) \\
 0000\ 1111\ (15) \\
 +\ 1111\ 1011\ (-5) \\
 \hline
 0000\ 1010\ (10)
 \end{array}$$

$$\begin{array}{r}
 \boxed{01}11\ (\text{carry}) \\
 0111\ (7) \\
 +\ 0011\ (3) \\
 \hline
 1010\ (-6)\ \underline{\text{invalid!}}
 \end{array}$$

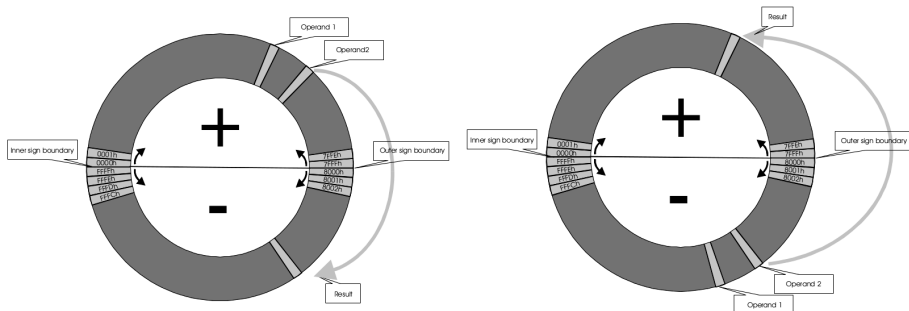
Overflow

- An **overflow** occurs in a when a result is greater than $2^{N-1} - 1$ or lesser than -2^{N-1} .
- An overflow produces a **roll-over** (wrap).



Overflow II

- A roll-over usually has catastrophic consequences on a process.
- Only happen when two very large positive operands, or two very large negative operands are added.
- It can never happen during the addition of a positive operand and a negative operand, whatever their magnitude.

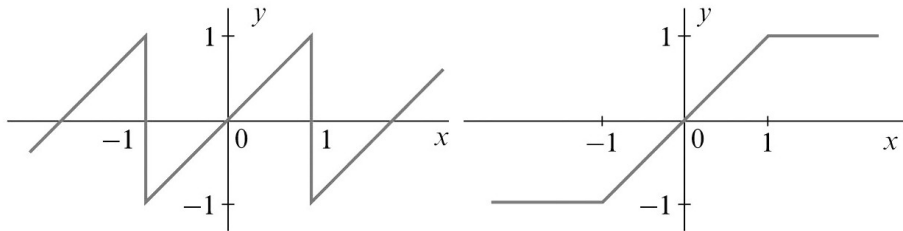


Longer word-length accumulator

- Saving the result in a $N+1$ word avoids overflows.
- The general rule is the sum of m individual b -bit can require as many as $b + \log_2(m)$.
- Example: 256 8-bits words requires an accumulator whose word length is $8 + \log_2(256) = 16$.
- DSP processors usually have 40-bit accumulators.
- ¿How many sums are supported by a 40-bits accumulator for 16-bits numbers?

Saturation

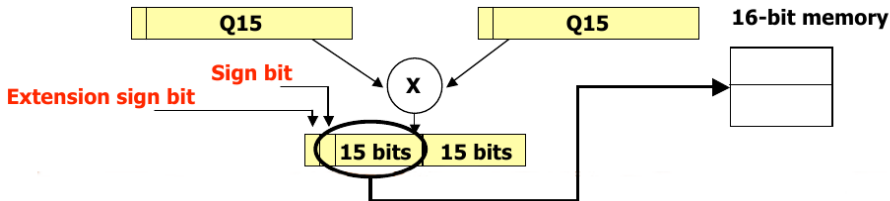
- To avoid a rollover, overflow is detected and the result is saturated to the most positive or most negative value that can be represented.
- This procedure is called **saturation arithmetic**.
- DSP processors allows the results to be saturated automatically in hardware (In TI DSP C5505, SATD Bit of ST1_55 register).



Be aware of non-linearity!

Multiplication in 2's complement

- The product of 2 N-bit numbers requires $(2m+1 + 2n)$ bits to contain all possible values.
- The 2 MSBits are always equal (extension sign bit).
- Therefore, $2N-1$ bits are enough to store the result.
- A Q15 multiplication produces Q1.30 result.
- To transform the result into Q31 notation, it must be left-shifted by one bit.
- DSP processors have a special mode that allows its ALU to automatically perform the left shift when $Q15 \times Q15$.



Four-bit signed integer multiplication

Four-Bit Integer Multiplication

	0100	4
	<u>x 1101</u>	<u>x -3</u>
	00000100	
	0000000	
	000100	
	<u>11100</u>	
	11110100	<u>-12</u>
Accumulator	<u>11110100</u>	-12
Data Memory	<u>11110100</u>	-12

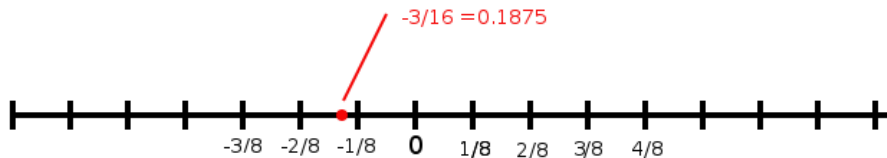
Four-bit Q0.3 multiplication

Four-Bit Multiplication

	0.100	1/2
	$\times 1.101$	$\times -3/8$
	<hr/>	<hr/>
	00000100	
	0000000	
	000100	
	11100	
	<hr/>	<hr/>
	11110100	-3/16
Accumulator	11110100	
	•	
Data Memory	1.110	-1/4

Underflow

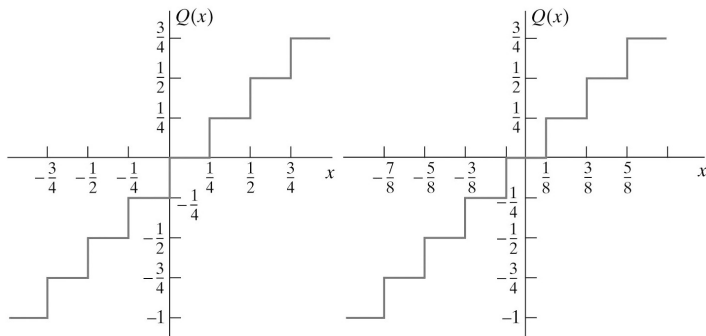
- After multiplication, $2N-1$ bits must be stored in a memory of N -bits word.
- An **underflow** occurs if a result is less than 2^{-n} .
- Q0.3 precision is $2^{-3} = \frac{1}{8}$.



- What number should the multiplication result be? $-\frac{1}{8}$ or $-\frac{2}{8}$?
- In other words, what bits should be discarded from a multiplication result?

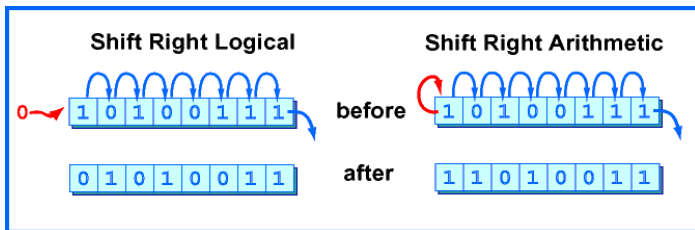
Rounding schemes, truncation and roundoff

- Truncation: $e = Q[x] - x$, $-2^{-n} \leq e < 0$, $\mu = -\frac{2^{-n}}{2}$, $\sigma^2 = \frac{2^{-n}}{12}$.
- Roundoff: $e = Q[x + 0.5] - x$, $-2^{-n}/2 < e \leq 2^{-n}/2$, $\mu = 0$, $\sigma^2 = \frac{2^{-n}}{12}$.
- DSP processors manage truncation and roundoff automatically.



Logical and Arithmetic shifts

- Multiplication: all bits are shifted left by one position.
- Division: all bits are shifted right by one position, however the sign bit must be preserved (**arithmetic shift**).
- Arithmetic shift \neq logical shift.



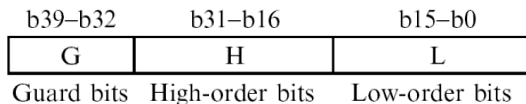
Logical and Arithmetic shifts (2)

In DSP processors:

- ALU can perform logical shifts of 32-bit operands in one cycle, from 16 bits to the right, to 15 bits to the left.
- Sign extension is performed during shifts to the right, if the Sign Extension Mode control bit (in C5505, SXM) is set.
- Result is saturated during shifts to the left if an overflow is detected, and Overflow bit (in C5505, OVM) is set.

Accumulator

- DSP processors have an accumulator with extra bits to avoid overflow during internal calculations (in C5505, 40-bits accumulator).
- Guard bits: extra bits to avoid addition overflows.
- After MAC operations, only final result is adjusted to memory data size.



Bibliography

- ① Bruno Paillard. An Introduction To Digital Signal Processors, Chapter 5 "Binary representations and fixed-point arithmetic".
- ② Richard G. Lyons. Understanding Digital Signal, Chapter 12 "Digital data formats and their effects".
- ③ Texas Instruments. C28x IQ – Math Library. [Link to document](#).
- ④ Jean-Pierre Deschamps, Gustavo D. Sutter, and Enrique Cantó. Guide to FPGA Implementation of Arithmetic Functions, Chapter 12 "Floating Point Arithmetic".