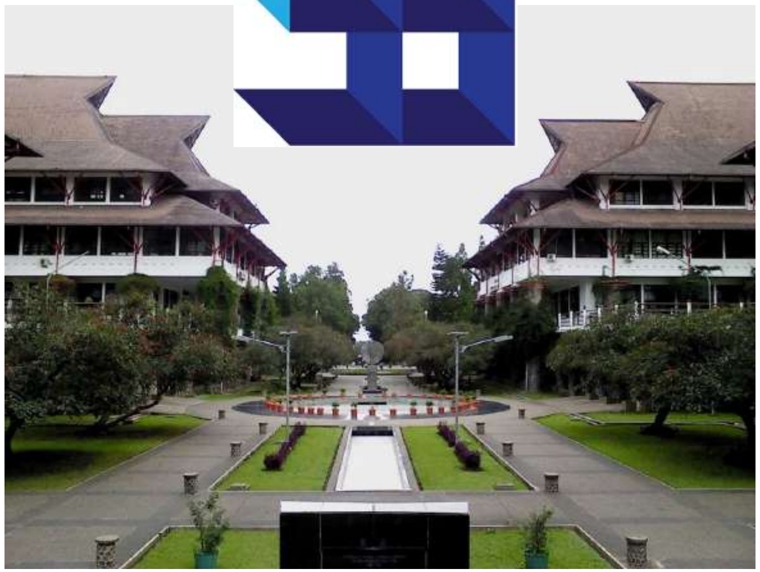


Modul 4

Floating Point

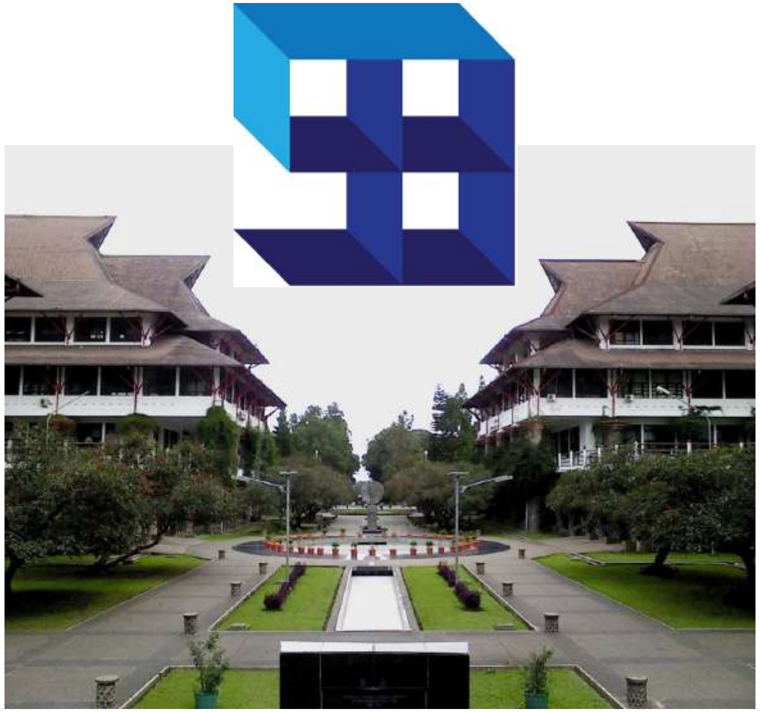
IEEE Standard

EL3011 Arsitektur Sistem Komputer

STEI - Institut Teknologi Bandung

Contents

This module adopted from 15-213 Introduction to Computer Systems Lecture, Carnegie Mellon University, 2020



STEI - Institut Teknologi Bandung

Modul 4. Floating Point

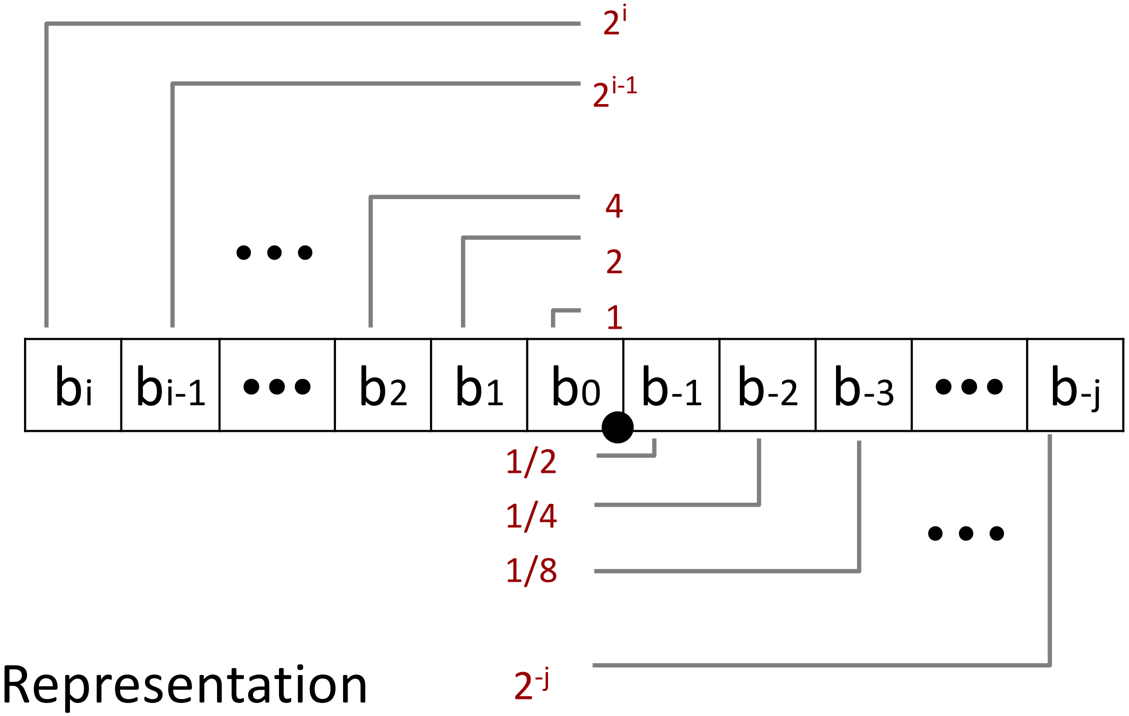
4.1. Fractional Binary Numbers

EL3011 Arsitektur Sistem Komputer

Fractional binary numbers

- What is 1011.101_2?

Fractional Binary Numbers



- Representation
  - Bits to right of "binary point" represent fractional powers of 2
  - Represents rational number: $\sum_{k=-j}^{i} b_k \times 2^k$

Fractional Binary Numbers: Examples

- Value / Representation

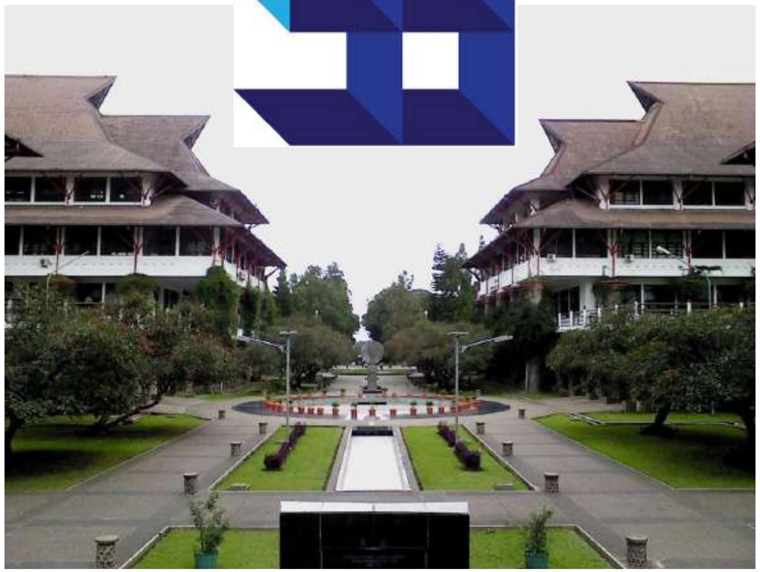
Value		Representation	
5 3/4	= 23/4	101.11_2	= 4 + 1 + 1/2 + 1/4
2 7/8	= 23/8	10.111_2	= 2 + 1/2 + 1/4 + 1/8
1 7/16	= 23/16	1.0111_2	= 1 + 1/4 + 1/8 + 1/16

- Observations
  - Divide by 2 by shifting right (unsigned)
  - Multiply by 2 by shifting left
  - Numbers of form $0.111111\ldots_2$ are just below 1.0
    - $1/2 + 1/4 + 1/8 + \ldots + 1/2^i + \ldots \rightarrow 1.0$
    - Use notation $1.0 - \varepsilon$

Representable Numbers

- Limitation #1
  - Can only exactly represent numbers of the form $x/2^k$
    - Other rational numbers have repeating bit representations
  - Value Representation
    - 1/3 `0.0101010101[01]`...$_2$
    - 1/5 `0.001100110011[0011]`...$_2$
    - 1/10 `0.0001100110011[0011]`...$_2$

- Limitation #2
  - Just one setting of binary point within the *w* bits
    - Limited range of numbers (very small values? very large?)



STEI - Institut Teknologi Bandung

Modul 4. Floating Point

4.2. IEEE Floating Point Standard

EL3011 Arsitektur Sistem Komputer

IEEE Floating Point

- IEEE Standard 754
  - Established in 1985 as uniform standard for floating point arithmetic
    - Before that, many idiosyncratic formats
  - Supported by all major CPUs
  - Some CPUs don't implement IEEE 754 in full
    e.g., early GPUs, Cell BE processor

- Driven by numerical concerns
  - Nice standards for rounding, overflow, underflow
  - Hard to make fast in hardware
    - Numerical analysts predominated over hardware designers in defining standard

10

Floating Point's Disaster

- **Ariane 5 explodes on maiden voyage: $500 MILLION dollars lost (June 4th, 1996)**
  - 64-bit floating point number assigned to 16-bit integer
  - Causes rocket to get incorrect value of horizontal velocity and crash

- **Patriot Missile defense system misses scud – 28 people die**
  - System tracks time in tenths of second
  - Converted from integer to floating point number.
  - Accumulated rounding error causes drift. 20% drift over 8 hours.
  - Eventually (on 2/25/1991 system was on for 100 hours) causes range mis-estimation sufficiently large to miss incoming missiles.

Floating Point Representation

Example:
$15213_{10} = (-1)^0 \times 1.1101101101101_2 \times 2^{13}$

- Numerical Form:

$$(-1)^s \; M \; 2^E$$

  - Sign bit s determines whether number is negative or positive
  - Significand M normally a fractional value in range [1.0,2.0).
  - Exponent E weights value by power of two

- Encoding
  - MSB s is sign bit s
  - exp field encodes E (but is not equal to E)
  - frac field encodes M (but is not equal to M)

Precision options

- Single precision: 32 bits
  ≈ 7 decimal digits, $10^{\pm 38}$

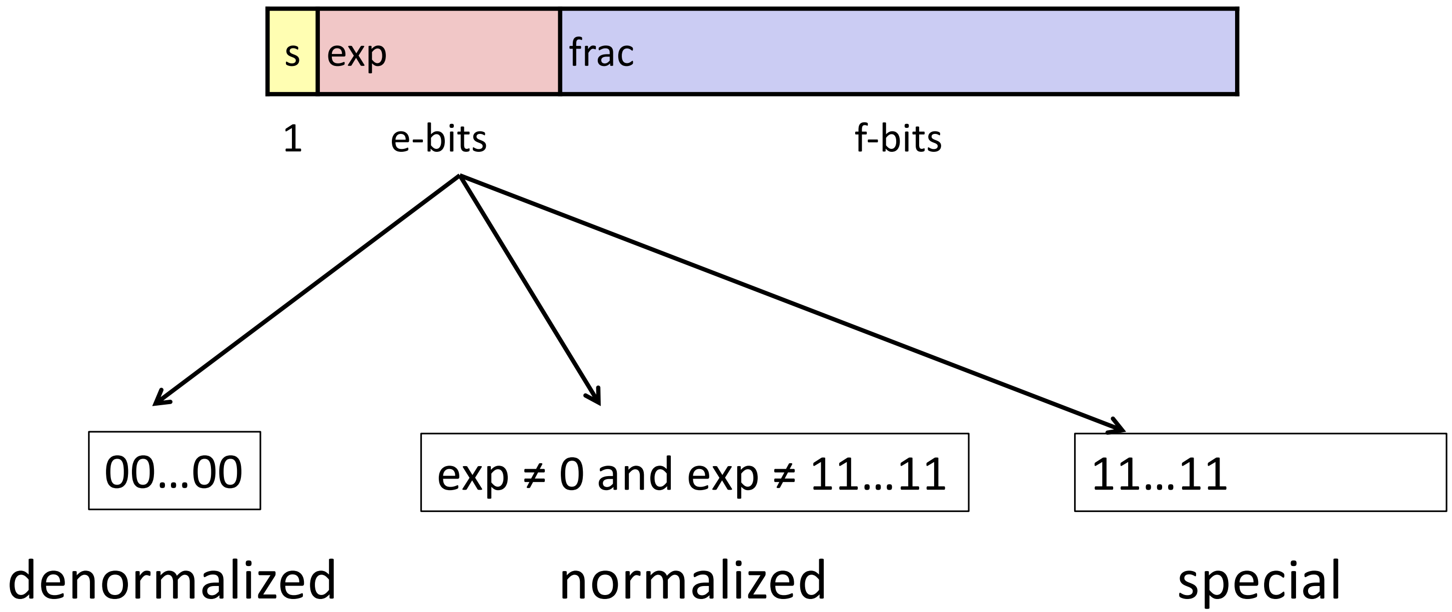
s	exp	frac
1	8-bits	23-bits

- Double precision: 64 bits
  ≈ 16 decimal digits, $10^{\pm 308}$

s	exp	frac
1	11-bits	52-bits

- Other formats: half precision, quad precision

Three “kinds” of floating point numbers



“Normalized” Values

$v = (-1)^s M 2^E$

- When: **exp** ≠ 000…0 and **exp** ≠ 111…1

- Exponent coded as a biased value: E = **exp** – Bias
  - exp: unsigned value of exp field
  - Bias = 2^{k-1} - 1, where k is number of exponent bits
    - Single precision: 127 (**exp**: 1…254, E: -126…127)
    - Double precision: 1023 (**exp**: 1…2046, E: -1022…1023)

- Significand coded with implied leading 1: M = $1.xxx\ldots x_2$
  - xxx…x: bits of frac field
  - Minimum when **frac**=000…0 (M = 1.0)
  - Maximum when **frac**=111…1 (M = 2.0 – ε)
  - Get extra leading bit for “free”

Normalized Encoding Example

- Value: `float F = 15213.0;`
  - $15213_{10} = 11101101101101_2$
    $= 1.1101101101101_2 \times 2^{13}$

$$v = (-1)^s\, M\, 2^E$$
$$E = \text{exp} - \text{Bias}$$

- Significand
  M = $1.\underline{1101101101101}_2$
  frac= $\underline{1101101101101}0000000000_2$

- Exponent
  E = 13
  Bias = 127
  exp = 140 = 10001100_2

- Result:

0	10001100	11011011011010000000000
s	**exp**	**frac**

Denormalized Values

$v = (-1)^s M\, 2^E$
$E = 1 - \text{Bias}$

- Condition: exp = 000…0
- Exponent value: E = 1 – Bias (instead of **`exp`** – Bias) (why?)
- Significand coded with implied leading 0: M = $0.xxx…x_2$
  - **`xxx…x`**: bits of **`frac`**
- Cases
  - **`exp`** = 000…0, **`frac`** = 000…0
    - Represents zero value
    - Note distinct values: +0 and –0 (why?)
  - **`exp`** = 000…0, **`frac`** ≠ 000…0
    - Numbers closest to 0.0
    - Equispaced

Special Values

- Condition: **`exp`** = **`111…1`**

- Case: **`exp`** = **`111…1`**, **`frac`** = **`000…0`**
  - **Represents value ∞ (infinity)**
  - Operation that overflows
  - Both positive and negative
  - E.g., $1.0/0.0 = -1.0/-0.0 = +\infty$, $1.0/-0.0 = -\infty$

- Case: **`exp`** = **`111…1`**, **`frac`** ≠ **`000…0`**
  - **Not-a-Number (NaN)**
  - Represents case when no numeric value can be determined
  - E.g., sqrt(–1), $\infty - \infty$, $\infty \times 0$

C float Decoding Example

$v = (-1)^s M\ 2^E$

$E = \exp - \text{Bias}$

Bias = $2^{k-1} - 1 = 127$

float: **0xC0A00000**

binary: ____ ____ ____ ____ ____ ____ ____ ____

E =

S =

M =

$v = (-1)^s M\ 2^E =$

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

C float Decoding Example #1

$v = (-1)^s M 2^E$
$E = \mathbf{exp} - \text{Bias}$

float: **0xC0A00000**

binary: **1100 0000 1010 0000 0000 0000 0000 0000**

1	1000 0001	010 0000 0000 0000 0000 0000
1	8-bits	23-bits

E =

S =

M = **1 .**

v = $(-1)^s M 2^E$ =

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

C float Decoding Example #1

$v = (-1)^s M\, 2^E$
$E = \mathbf{exp} - \text{Bias}$

$\text{Bias} = 2^{k-1} - 1 = 127$

float: **0xC0A00000**

binary: 1100 0000 1010 0000 0000 0000 0000 0000

1	1000 0001	010 0000 0000 0000 0000 0000
1	8-bits	23-bits

$E = \mathbf{exp} - \text{Bias} = 129 - 127 = 2$ (decimal)

S = 1 -> negative number

M = 1.010 0000 0000 0000 0000 0000

= 1 + 1/4 = 1.25

$v = (-1)^s M\, 2^E = (-1)^1 * 1.25 * 2^2 = -5$

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

C float Decoding Example #2

$v = (-1)^s\, M\, 2^E$
$E = \mathbf{1} - \text{Bias}$

float: **0x001C0000**

binary: 0000 0000 0001 1100 0000 0000 0000 0000

0	0000 0000	001 1100 0000 0000 0000 0000
1	8-bits	23-bits

E =

S =

M = **0 .**

$v = (-1)^s\, M\, 2^E =$

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

C float Decoding Example #2

float: **0x001C0000**

binary: 0000 0000 0001 1100 0000 0000 0000 0000

0	0000 0000	001 1100 0000 0000 0000 0000
1	8-bits	23-bits

$v = (-1)^s M\ 2^E$
$E = \mathbf{1} - \text{Bias}$

$\text{Bias} = 2^{k-1} - 1 = 127$

$E = \mathbf{1} - \text{Bias} = 1 - 127 = -126$ (decimal)

S = 0 -> positive number

M = **0.001 1100 0000 0000 0000 0000**

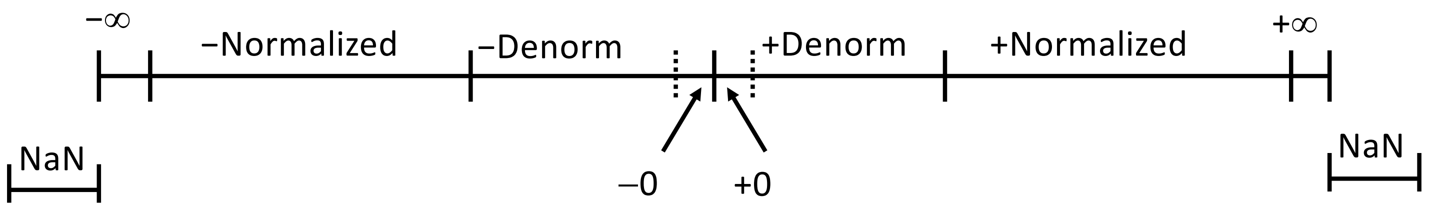
$= 1/8 + 1/16 + 1/32 = 7/32 = 7*2^{-5}$

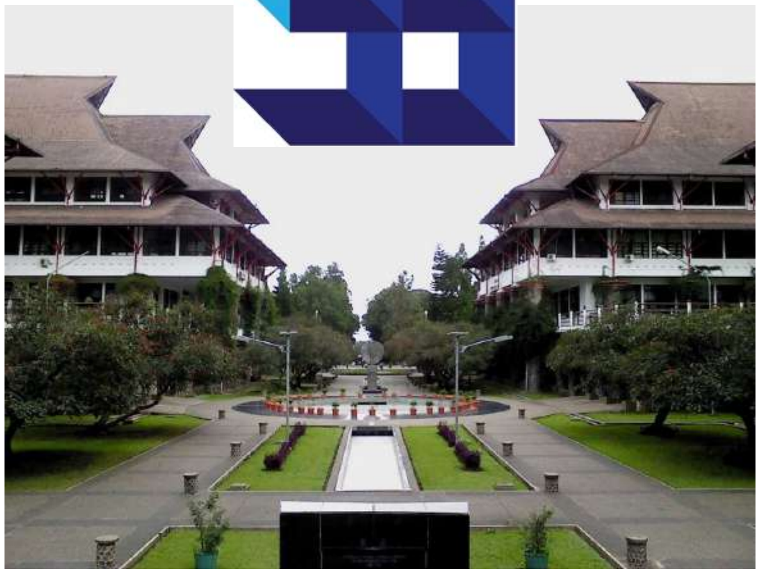
$\mathbf{v = (-1)^s M\ 2^E = (-1)^0 * 7*2^{-5} * 2^{-126} = 7*2^{-131}}$

$\approx \mathbf{2.571393892 \times 10^{-39}}$

Hex	Decimal	Binary
0	0	0000
1	1	0001
2	2	0010
3	3	0011
4	4	0100
5	5	0101
6	6	0110
7	7	0111
8	8	1000
9	9	1001
A	10	1010
B	11	1011
C	12	1100
D	13	1101
E	14	1110
F	15	1111

Visualization: Floating Point Encodings





STEI - Institut Teknologi Bandung

Modul 4. Floating Point

4.3. Example and Properties

EL3011 Arsitektur Sistem Komputer

Tiny Floating Point Example

s	exp	frac
1	4-bits	3-bits

- 8-bit Floating Point Representation
  - the sign bit is in the most significant bit
  - the next four bits are the **`exp`**, with a bias of 7
  - the last three bits are the **`frac`**

- Same general form as IEEE Format
  - normalized, denormalized
  - representation of 0, NaN, infinity

8-bit float = 0x00 = 0000 0000

8-bit float = 0x01 = 0000 0001

8-bit float = 0x02 = 0000 0010

8-bit float = 0x38 = 0011 1000

8-bit float = 0x78 = 0111 1000

8-bit float = 0x79 = 0111 1001

8-bit float = 0x80 = 1000 0000

Suatu 8-bit float dengan nilai real v = 7/512.
Tentukan kode float

Suatu 8-bit float dengan nilai real v = 9/512.
Tentukan kode float

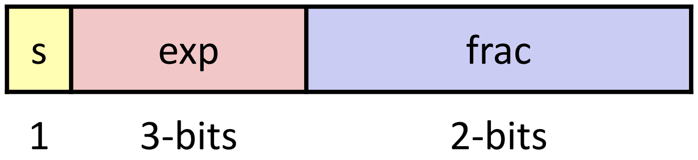
Dynamic Range (s=0 only)

$v = (-1)^s \, M \, 2^E$
norm: E = **exp** – Bias
denorm: E = 1 – Bias

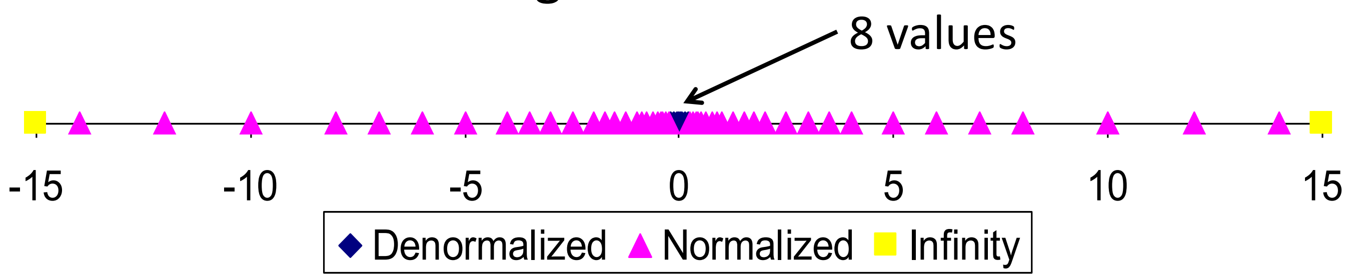
	s	exp	frac	E	Value	
Denormalized numbers	0	0000	000	-6	0	
	0	0000	001	-6	1/8*1/64 = 1/512	**closest to zero**
	0	0000	010	-6	2/8*1/64 = 2/512	$(-1)^0(0+1/4)*2^{-6}$
	…					
	0	0000	110	-6	6/8*1/64 = 6/512	
	0	0000	111	-6	7/8*1/64 = 7/512	**largest denorm**
Normalized numbers	0	0001	000	-6	8/8*1/64 = 8/512	**smallest norm**
	0	0001	001	-6	9/8*1/64 = 9/512	$(-1)^0(1+1/8)*2^{-6}$
	…					
	0	0110	110	-1	14/8*1/2 = 14/16	
	0	0110	111	-1	15/8*1/2 = 15/16	**closest to 1 below**
	0	0111	000	0	8/8*1 = 1	
	0	0111	001	0	9/8*1 = 9/8	**closest to 1 above**
	0	0111	010	0	10/8*1 = 10/8	
	…					
	0	1110	110	7	14/8*128 = 224	
	0	1110	111	7	15/8*128 = 240	**largest norm**
	0	1111	000	n/a	inf	

Distribution of Values

- 6-bit IEEE-like format
  - e = 3 exponent bits
  - f = 2 fraction bits
  - Bias is $2^{3-1}-1 = 3$

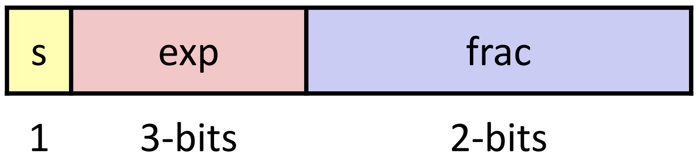


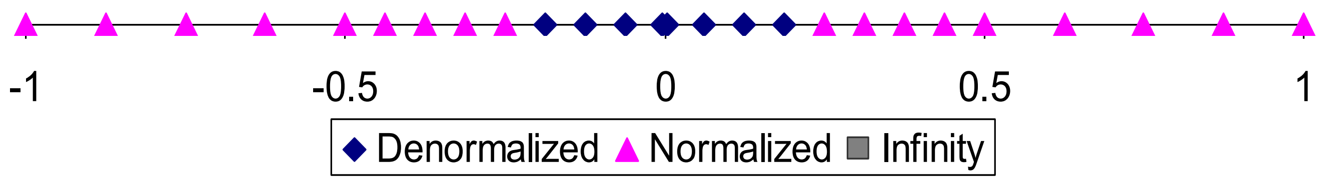
- Notice how the distribution gets denser toward zero.



Distribution of Values (close-up view)

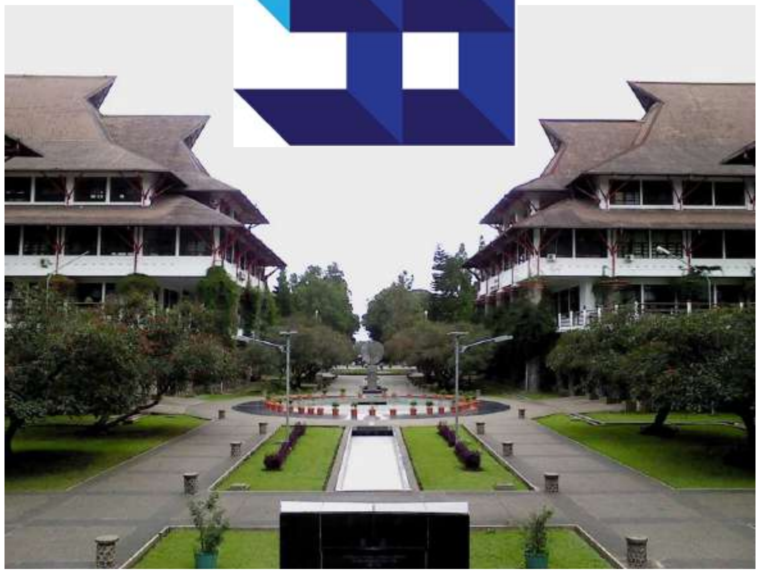
- 6-bit IEEE-like format
  - e = 3 exponent bits
  - f = 2 fraction bits
  - Bias is 3





Special Properties of the IEEE Encoding

- FP Zero Same as Integer Zero
  - All bits = 0
- Can (Almost) Use Unsigned Integer Comparison
  - Must first compare sign bits
  - Must consider −0 = 0
  - NaNs problematic
    - Will be greater than any other values
    - What should comparison yield? The answer is complicated.
  - Otherwise OK
    - Denorm vs. normalized
    - Normalized vs. infinity



Modul 4. Floating Point

4.4. Rounding, Addition, Multiplication

EL3011 Arsitektur Sistem Komputer

STEI - Institut Teknologi Bandung

Floating Point Operations: Basic Idea

- **`x +f y = Round(x + y)`**

- **`x ×f y = Round(x × y)`**

- Basic idea
  - First compute exact result
  - Make it fit into desired precision
    - Possibly overflow if exponent too large
    - Possibly round to fit into **`frac`**

Rounding

- Rounding Modes (illustrate with $ rounding)

	$1.40	$1.60	$1.50	$2.50	–$1.50
• Towards zero	$1 ↓	$1 ↓	$1 ↓	$2 ↓	–$1 ↑
• Round down (−∞)	$1 ↓	$1 ↓	$1 ↓	$2 ↓	–$2 ↓
• Round up (+∞)	$2 ↑	$2 ↑	$2 ↑	$3 ↑	–$1 ↑
• Nearest Even* (default)	$1 ↓	$2 ↑	$2 ↑	$2 ↓	–$2 ↓

*Round to nearest, but if half-way in-between then round to nearest even

Closer Look at Round-To-Even

- Default Rounding Mode
  - Hard to get any other kind without dropping into assembly
    - C99 has support for rounding mode management
  - All others are statistically biased
    - Sum of set of positive numbers will consistently be over- or under-estimated
- Applying to Other Decimal Places / Bit Positions
  - When exactly halfway between two possible values
    - Round so that least significant digit is even
  - E.g., round to nearest hundredth

7.8949999	7.89	(Less than half way)
7.8950001	7.90	(Greater than half way)
7.8950000	7.90	(Half way—round up)
7.8850000	7.88	(Half way—round down)

Rounding Binary Numbers

- Binary Fractional Numbers
  - "Even" when least significant bit is 0
  - "Half way" when bits to right of rounding position = $100\ldots_2$

- Examples
  - Round to nearest 1/4 (2 bits right of binary point)

Value	Binary	Rounded	Action	Rounded Value
2 3/32	10.00011_2	10.00_2	(<1/2—down)	2
2 3/16	10.00110_2	10.01_2	(>1/2—up)	2 1/4
2 7/8	10.11100_2	11.00_2	(1/2—up)	3
2 5/8	10.10100_2	10.10_2	(1/2—down)	2 1/2

Rounding

1.BBGRXXX

Guard bit: LSB of result

Round bit: 1st bit removed

Sticky bit: OR of remaining bits

- Round up conditions
  - Round = 1, Sticky = 1 → > 0.5
  - Guard = 1, Round = 1, Sticky = 0 → Round to even

Fraction	GRS	Incr?	Rounded
1.0000000	000	N	1.000
1.1010000	100	N	1.101
1.0001000	010	N	1.000
1.0011000	110	Y	1.010
1.0001010	011	Y	1.001
1.1111100	111	Y	10.000

FP Multiplication

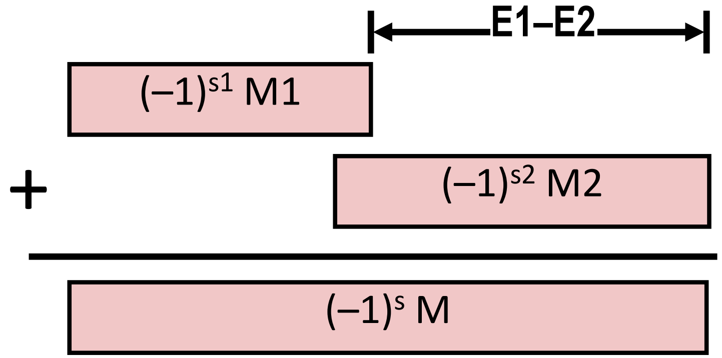
- $(-1)^{s1}$ M1 2^{E1} x $(-1)^{s2}$ M2 2^{E2}
- Exact Result: $(-1)^{s}$ M 2^{E}
  - Sign s: s1 ^ s2
  - Significand M: M1 x M2
  - Exponent E: E1 + E2
- Fixing
  - If M ≥ 2, shift M right, increment E
  - If E out of range, overflow
  - Round M to fit **`frac`** precision
- Implementation
  - Biggest chore is multiplying significands

4 bit significand: $1.010*2^2$ x $1.110*2^3 = 10.0011*2^5$
$= 1.00011*2^6 = 1.001*2^6$

Floating Point Addition

- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ +\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
  - Assume E1 > E2
- Exact Result: $(-1)^{s}\ M\ \ 2^{E}$
  - Sign s, significand M:
    - Result of signed align & add
  - Exponent E: E1
- Fixing
  - If M ≥ 2, shift M right, increment E
  - if M < 1, shift M left k positions, decrement E by k
  - Overflow if E out of range
  - Round M to fit `frac` precision

Get binary points lined up



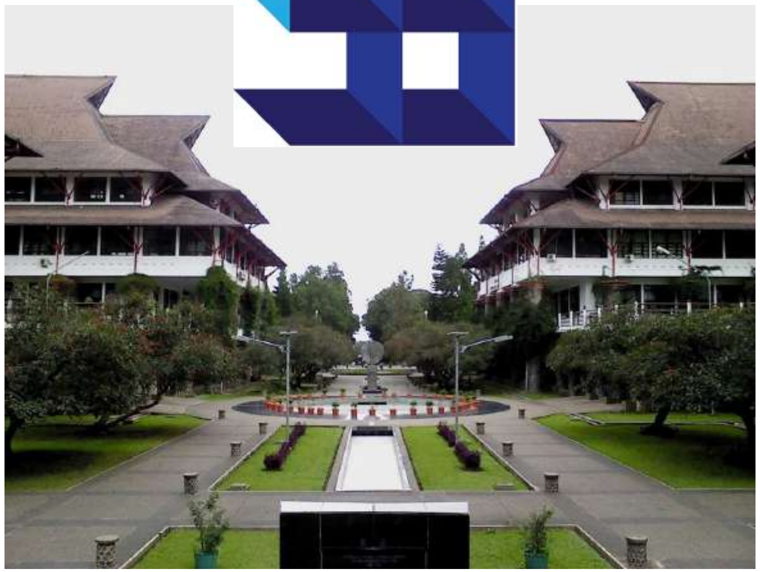
$$1.010*2^{2} + 1.110*2^{3} = (0.1010 + 1.1100)*2^{3}$$
$$= 10.0110 * 2^{3} = 1.00110 * 2^{4} = 1.010 * 2^{4}$$

Mathematical Properties of FP Add

- Compare to those of Abelian Group — Yes
  - Closed under addition?
    - But may generate infinity or NaN
  - Commutative? — Yes
  - Associative? — No
    - Overflow and inexactness of rounding
    - `(3.14+1e10)-1e10 = 0, 3.14+(1e10-1e10) = 3.14`
  - 0 is additive identity? — Yes
  - Every element has additive inverse? — Almost
    - Yes, except for infinities & NaNs
- Monotonicity
  - $a \geq b \Rightarrow a+c \geq b+c$? — Almost
    - Except for infinities & NaNs

Mathematical Properties of FP Mult

- Compare to Commutative Ring
  - Closed under multiplication? Yes
    - But may generate infinity or NaN
  - Multiplication Commutative? Yes
  - Multiplication is Associative? No
    - Possibility of overflow, inexactness of rounding
    - Ex: `(1e20*1e20)*1e-20= inf, 1e20*(1e20*1e-20)= 1e20`
  - 1 is multiplicative identity? Yes
  - Multiplication distributes over addition? No
    - Possibility of overflow, inexactness of rounding
    - `1e20*(1e20-1e20)= 0.0, 1e20*1e20 – 1e20*1e20 = NaN`
- Monotonicity
  - $a \geq b$ & $c \geq 0 \Rightarrow a * c \geq b * c$? Almost
    - Except for infinities & NaNs



STEI - Institut Teknologi Bandung

Modul 4. Floating Point

4.5. Floating Point in C

EL3011 Arsitektur Sistem Komputer

Floating Point in C

- C Guarantees Two Levels
  - **`float`** single precision
  - **`double`** double precision
- Conversions/Casting
  - Casting between **`int`**, **`float`**, and **`double`** changes bit representation
  - **`double`/`float`** → **`int`**
    - Truncates fractional part
    - Like rounding toward zero
    - Not defined when out of range or NaN: Generally sets to TMin
  - **`int`** → **`double`**
    - Exact conversion, as long as **`int`** has ≤ 53 bit word size
  - **`int`** → **`float`**
    - Will round according to rounding mode

Summary

- IEEE Floating Point has clear mathematical properties
- Represents numbers of form M x 2^E
- One can reason about operations independent of implementation
  - As if computed with perfect precision and then rounded
- Not the same as real arithmetic
  - Violates associativity/distributivity
  - Makes life difficult for compilers & serious numerical applications programmers