Floating Point

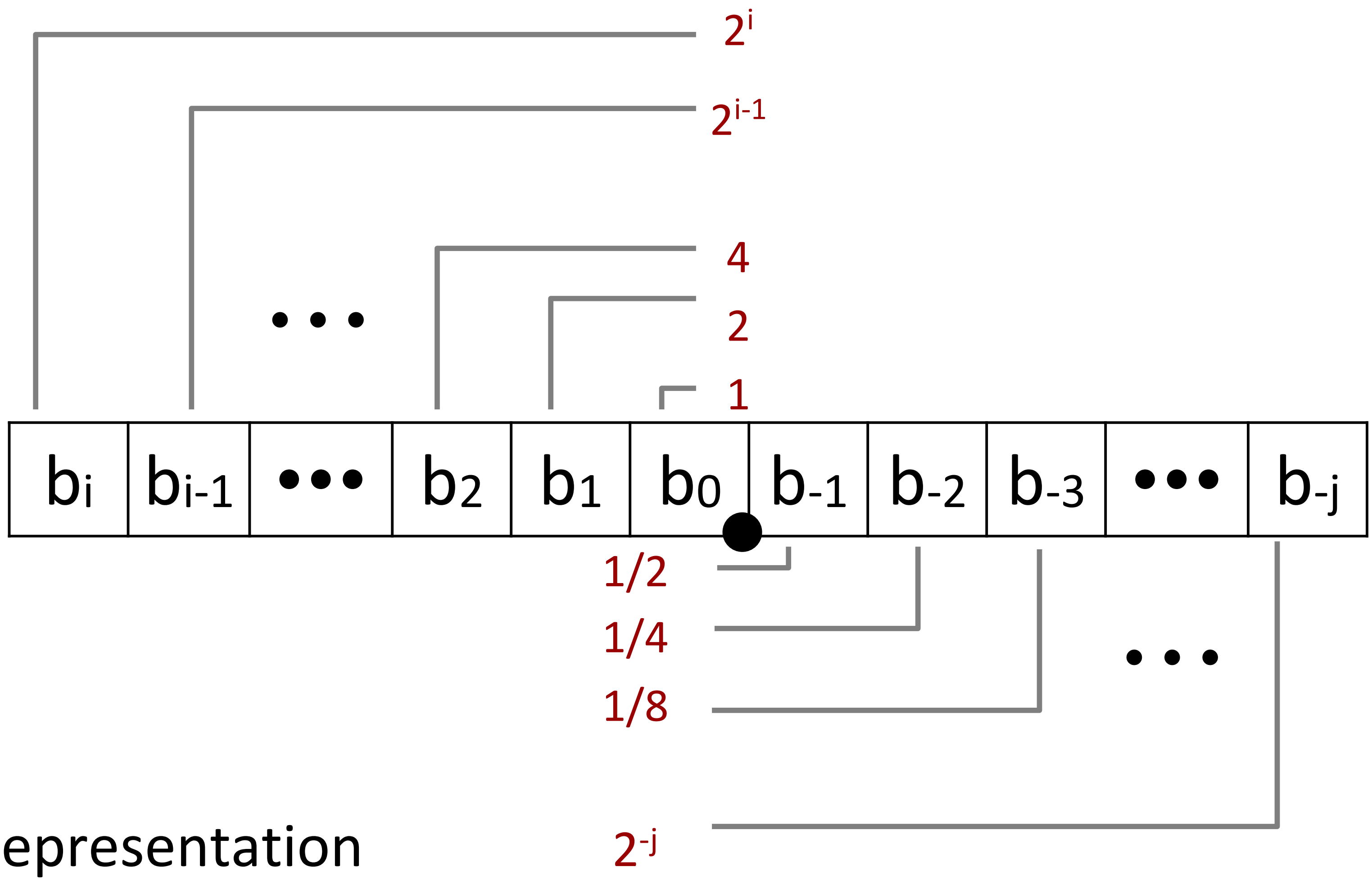
Today: Floating Point

- Background: Fractional binary numbers
- IEEE floating point standard: Definition
- Example and properties
- Rounding, addition, multiplication
- Floating point in C
- Summary

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	`101.11`$_2$
2 7/8	`10.111`$_2$
1 7/16	`1.0111`$_2$

- 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?)

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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

- 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

Floating Point Representation

- 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

s	exp	frac
1	8-bits	23-bits

- Double precision: 64 bits

s	exp	frac
1	11-bits	52-bits

- Extended precision: 80 bits (Intel only)

s	exp	frac
1	15-bits	63 or 64-bits

"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
- Significand coded with implied leading 1: M = $1.xxx…x_2$
  - xxx…x: bits of frac field

"Normalized" Values

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

- When: exp ≠ 000…0 and exp ≠ 111…1
- Exponent coded as a biased value: $E = \text{Exp} - \text{Bias}$
  - 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

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

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

- **Significand**

  M = `1.`$\underline{\texttt{1101101101101}}_2$
  `frac=` $\underline{\texttt{1101101101101}}\texttt{0000000000}_2$

- **Exponent**

  E = 13
  $Bias$ = 127
  Exp = 140 = $\texttt{10001100}_2$

- **Result:**

s	exp	frac
0	10001100	11011011011010000000000

Denormalized Values

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

- Condition: exp = 000…0

- Exponent value: E = 1 – Bias (instead of E = 0 – Bias)
- Significand coded with implied leading 0: $M = 0.xxx\ldots x_2$
  - `xxx…x`: bits of `frac`

Denormalized Values

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

- Condition: exp = 000…0

- Exponent value: E = 1 – Bias (instead of E = 0 – Bias)
- 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

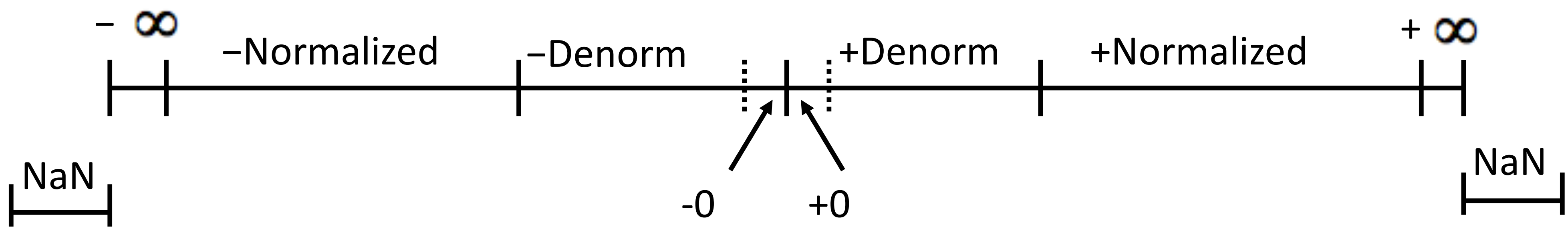
Special Values

- 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), $\infty - \infty$, $\infty \times 0$

Visualization: Floating Point Encodings



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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 exponent, 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

Dynamic Range (Positive Only)

$$v = (-1)^s\ M\ 2^E$$
n: $E = Exp - Bias$
d: $E = 1 - Bias$

	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	
	…					
	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	
	…					
	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	

Dynamic Range (Positive Only)

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

n: $E = \text{Exp} - \text{Bias}$

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Normalized numbers	0	0001	000	-6	8/8*1/64 = 8/512	**smallest norm**
	0	0001	001	-6	9/8*1/64 = 9/512	
	…					
	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**
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Dynamic Range (Positive Only)

$v = (-1)^s M 2^E$
n: E = Exp – Bias
d: E = 1 – Bias

	s exp frac	E	Value	
				closest to zero
Denormalized numbers				
	0 0000 110	-6	6/8*1/64 = 6/512	
	0 0000 111	-6	7/8*1/64 = 7/512	largest denorm
	0 0001 000	-6	8/8*1/64 = 8/512	smallest norm
	0 0001 001	-6	9/8*1/64 = 9/512	
	…			
	0 0110 110	-1	14/8*1/2 = 14/16	
	0 0110 111	-1	15/8*1/2 = 15/16	closest to 1 below
Normalized numbers	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	

Dynamic Range (Positive Only)

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

n: $E = \text{Exp} - \text{Bias}$

d: $E = 1 - \text{Bias}$

	s exp frac	E	Value	
				largest denorm
	0 0001 000	-6	8/8*1/64 = 8/512	smallest norm
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	…			
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Normalized numbers	0 0111 000	0	8/8*1 = 1	
	0 0111 001	0	9/8*1 = 9/8	closest to 1 above
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	…			
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	0 1111 000	n/a	inf	

Dynamic Range (Positive Only)

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

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Dynamic Range (Positive Only)

$v = (-1)^s M 2^E$
n: E = Exp – Bias
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	s	exp	frac	E	Value	
Denormalized numbers	0	0000	000	-6	0	
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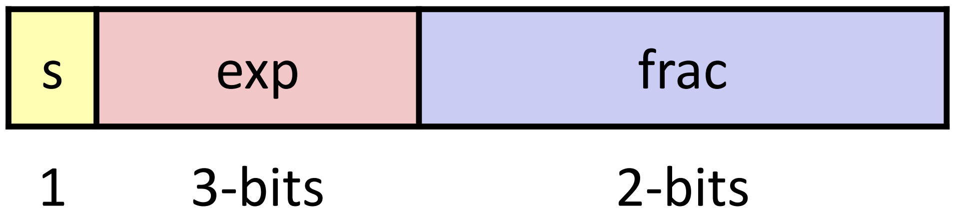
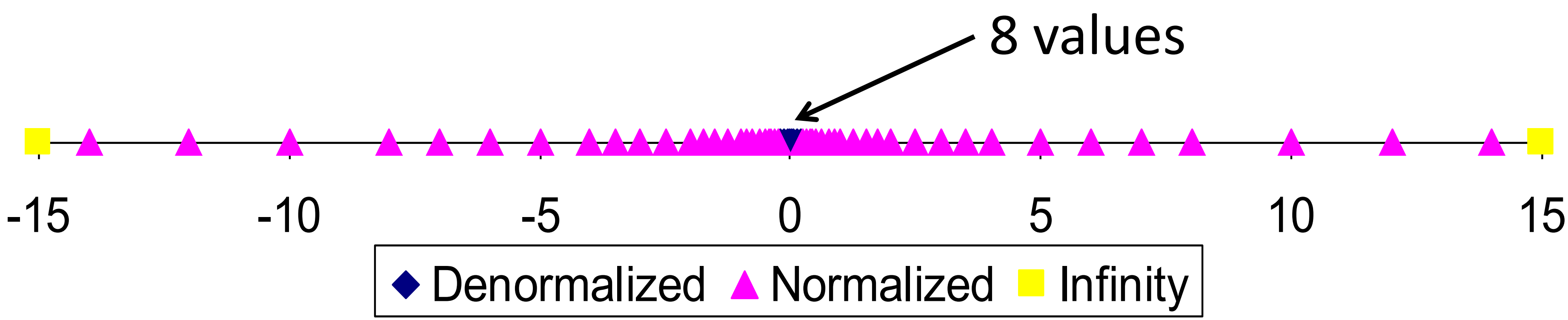
	…					
	0	1110	110	7	14/8*128 = 224	
	0	1110	111	7	15/8*128 = 240	largest norm
	0	1111	000	n/a	inf	

Distribution of Values

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

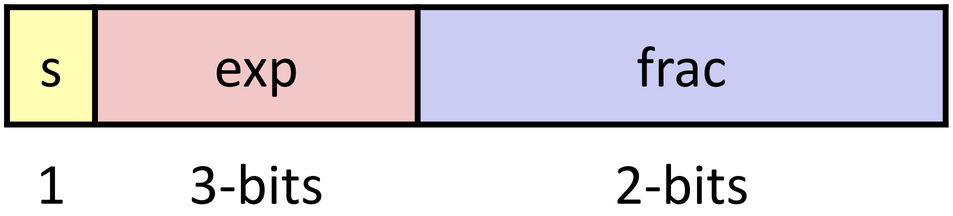


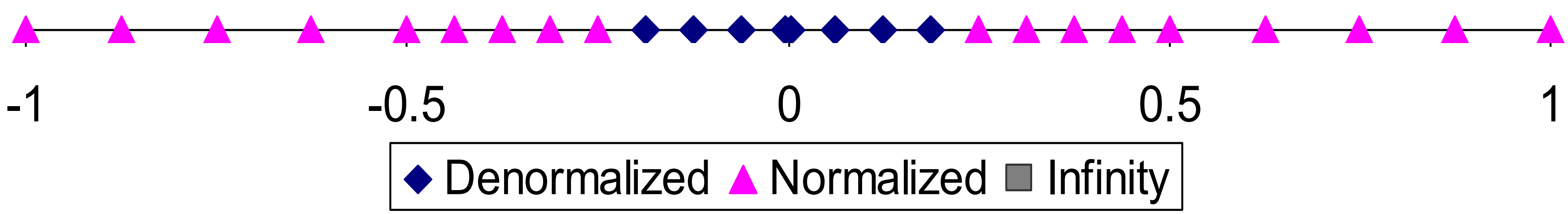
- Notice how the distribution gets denser toward zero.



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?
  - Otherwise OK
    - Denorm vs. normalized
    - Normalized vs. infinity

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Floating Point Operations: Basic Idea

- $x +_f y = \text{Round}(x + y)$

- $x \times_f y = \text{Round}(x \times y)$

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

FP Multiplication

- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ \times\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
- Exact Result: $(-1)^{s}\ M\ \ 2^{E}$
  - Sign s: s1 ^ s2
  - Significand M: M1 x M2
  - Exponent E: E1 + E2

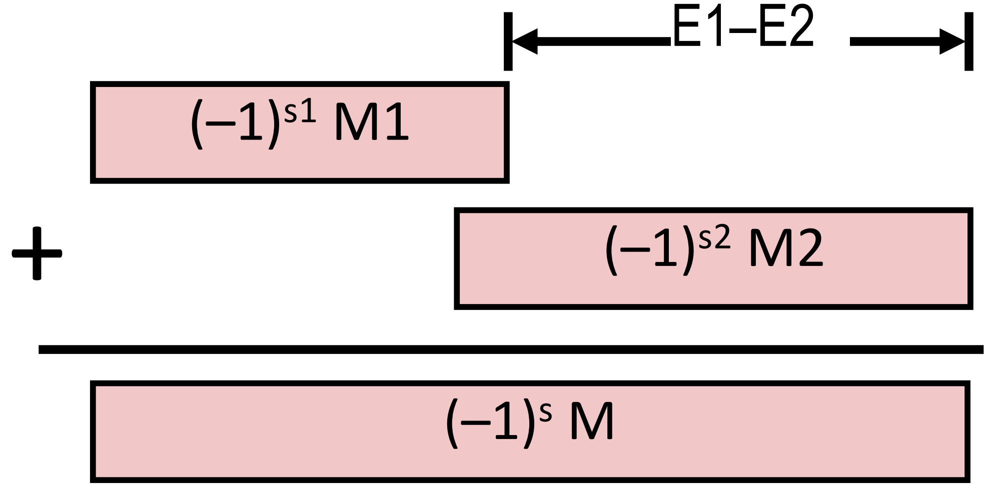
- Fixing
  - If M ≥ 2, shift M right, increment E
  - If E out of range, overflow
  - Round M to fit `frac` precision

- Implementation
  - Biggest chore is multiplying significands

Floating Point Addition

- $(-1)^{s1}\ M1\ \ 2^{E1}\ \ +\ \ (-1)^{s2}\ M2\ \ 2^{E2}$
  - Assume E1 > E2

Get binary points lined up



- 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

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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

Interesting Numbers

`{single,double}`

Description	*exp*	*frac*	*Numeric Value*
■ Zero	00…00	00…00	0.0
■ Smallest Pos. Denorm.	00…00	00…01	$2^{-\{23,52\}} \times 2^{-\{126,1022\}}$
▪ Single ≈ 1.4×10^{-45}			
▪ Double ≈ 4.9×10^{-324}			
■ Largest Denormalized	00…00	11…11	$(1.0 - \varepsilon) \times 2^{-\{126,1022\}}$
▪ Single ≈ 1.18×10^{-38}			
▪ Double ≈ 2.2×10^{-308}			
■ Smallest Pos. Normalized	00…01	00…00	$1.0 \times 2^{-\{126,1022\}}$
▪ Just larger than largest denormalized			
■ One	01…11	00…00	1.0
■ Largest Normalized	11…10	11…11	$(2.0 - \varepsilon) \times 2^{\{127,1023\}}$
▪ Single ≈ 3.4×10^{38}			
▪ Double ≈ 1.8×10^{308}			

Mathematical Properties of FP Add

- Compare to those of Abelian Group
  - Closed under addition? Yes
    - 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

Ariane 5

- Exploded 37 seconds after liftoff
- Cargo worth $500 million

- Why
  - Computed horizontal velocity as floating point number
  - Converted to 16-bit integer
  - Worked OK for Ariane 4
  - Overflowed for Ariane 5
    - Used same software

Floating Point Puzzles

- For each of the following C expressions, either:
  - Argue that it is true for all argument values
  - Explain why not true

```
int x = …;
float f = …;
double d = …;
```

Assume neither `d` nor `f` is NaN

- F `x == (int)(float) x`
- T `x == (int)(double) x`
- T `f == (float)(double) f`
- F `d == (double)(float) d`
- T `f == -(-f);`
- F `2/3 == 2/3.0`
- `d < 0.0  ⇒  ((d*2) < 0.0)`
- `d > f  ⇒  -f > -d`
- `d * d >= 0.0`
- `(d+f)-d == f`

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

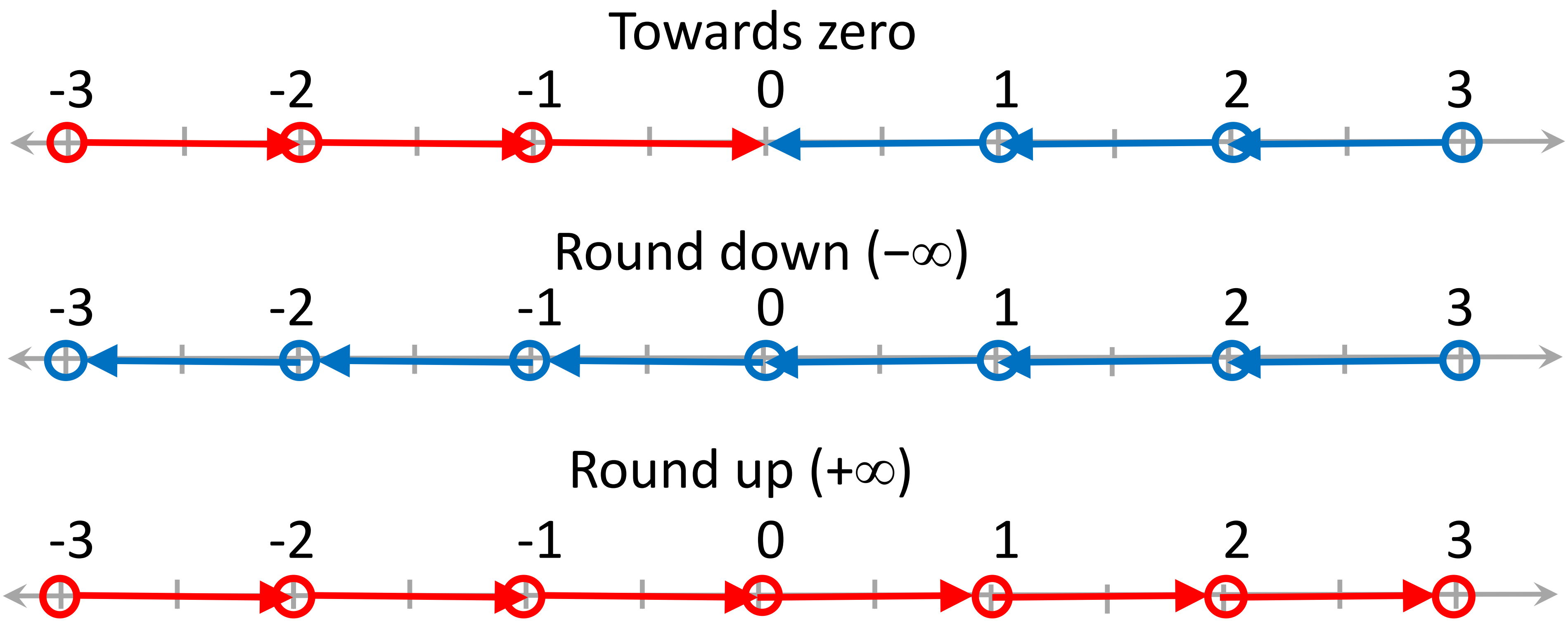
Additional Slides

Rounding

- Rounding Modes (illustrate with $ rounding)

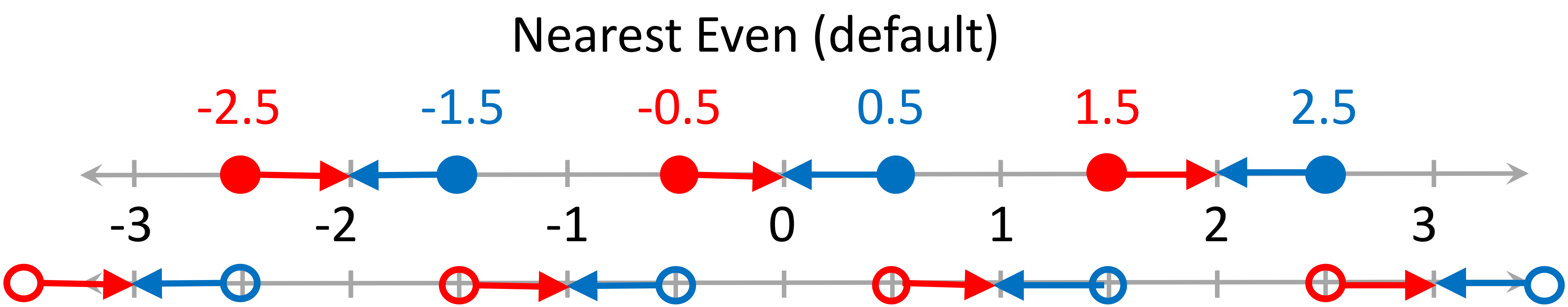
	$1.40	$1.60	$1.50	$2.50	–$1.50
Towards zero	$1	$1	$1	$2	–$1
Round down ($-\infty$)	$1	$1	$1	$2	–$2
Round up ($+\infty$)	$2	$2	$2	$3	–$1
Nearest Even (default)	$1	$2	$2	$2	–$2

Rounding



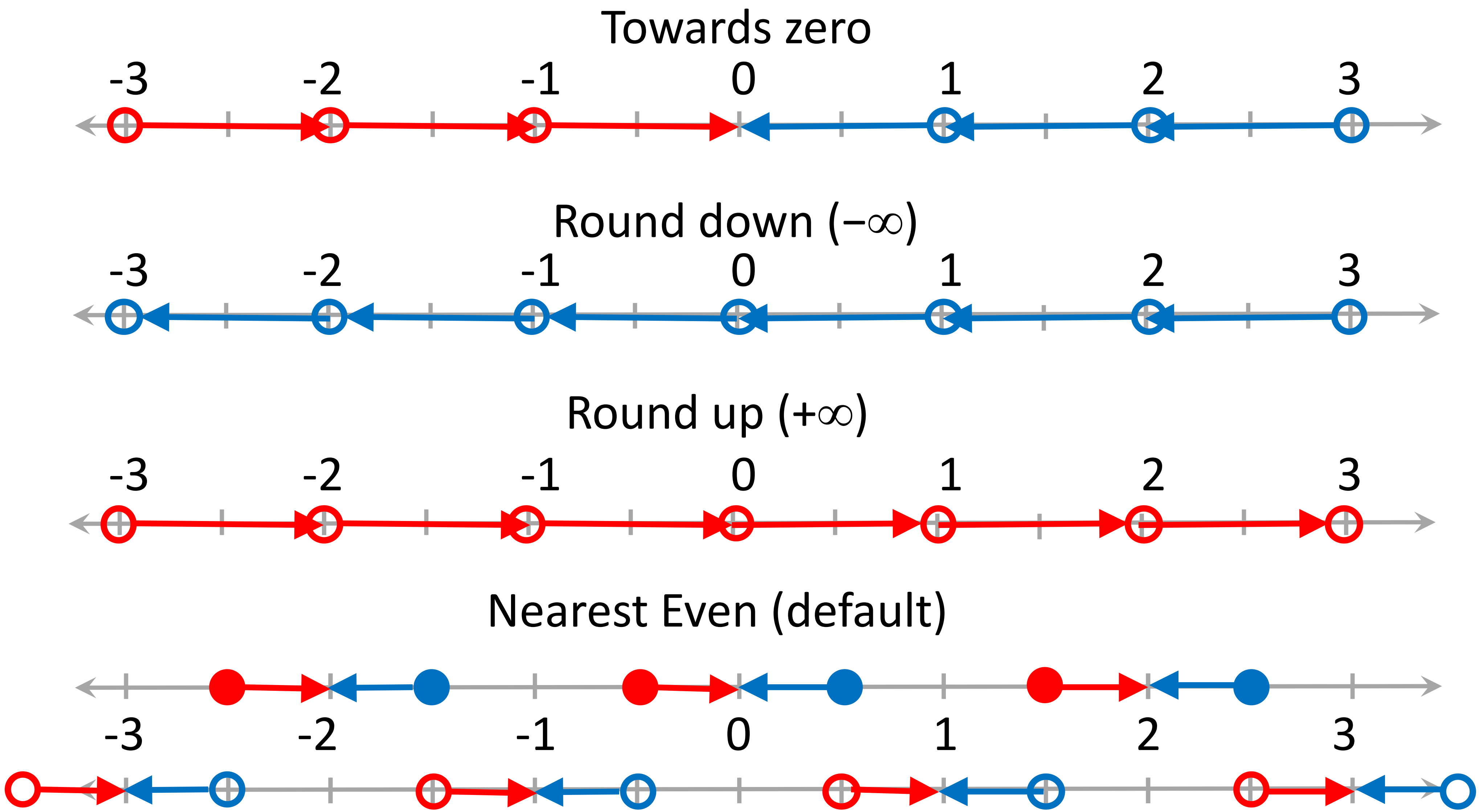
Rounding changes the statistical properties (such as mean and variance) of the numbers.

Rounding: Nearest Even



- Each value is rounded to the closest number
- midway values are rounded to the closest EVEN number
- does not change the statistical properties (such as mean and variance) of the numbers,
- Default rounding mode

Rounding (4 modes together)



Closer Look at Round-To-Even

- Default Rounding Mode
  - Hard to get any other kind without dropping into assembly
  - 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`…$_2$
- Examples
  - Round to nearest 1/4 (2 bits right of binary point)

Value	Binary	Rounded	Action	Rounded Value
2 3/32	10.00011_2 3/8	10.00_2	(<1/2—down)	2
2 3/16	10.00110_2 6/8	10.01_2	(>1/2—up)	2 1/4
2 7/8	10.11100_2 4/8	11.00_2	(1/2—up)	3
2 5/8	10.10100_2 4/8	10.10_2	(1/2—down)	2 1/2

Creating Floating Point Number

s	exp	frac
1	4-bits	3-bits

- Steps
  - Normalize to have leading 1
  - Round to fit within fraction
  - Postnormalize to deal with effects of rounding

- Case Study
  - Convert 8-bit unsigned numbers to tiny floating point format

Example Numbers

```
128      10000000
 15      00001101
 33      00010001
 35      00010011
138      10001010
 63      00111111
```

Normalize

s	exp	frac
1	4-bits	3-bits

- Requirement
  - Set binary point so that numbers of form 1.xxxxx
  - Adjust all to have leading one
    - Decrement exponent as shift left

Value	Binary	Fraction	Exponent
128	10000000	1.0000000	7
15	00001101	1.1010000	3
17	00010001	1.0001000	4
19	00010011	1.0011000	4
138	10001010	1.0001010	7
63	00111111	1.1111100	5

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

Value	Fraction	GRS	Incr?	Rounded
128	1.0000000	000	N	1.000
15	1.1010000	100	N	1.101
17	1.0001000	010	N	1.000
19	1.0011000	110	Y	1.010
138	1.0001010	011	Y	1.001
63	1.1111100	111	Y	10.000

Postnormalize

- Issue
  - Rounding may have caused overflow
  - Handle by shifting right once & incrementing exponent

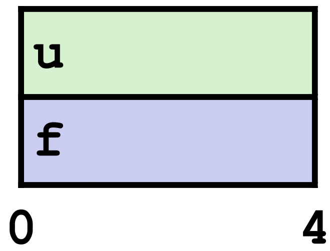
Value	Rounded	Exp	Adjusted	Result
128	1.000	7		128
15	1.101	3		15
17	1.000	4		16
19	1.010	4		20
138	1.001	7		134
63	10.000	5	1.000/6	64

Rounding in C

- http://www.gnu.org/s/libc/manual/html_node/Rounding-Functions.html
  - double rint (*double x*), float rintf (*float x*), long double rintl (*long double x*)
    These functions round *x* to an integer value according to the current rounding mode. See Floating Point Parameters, for information about the various rounding modes. The default rounding mode is to round to the nearest integer; some machines support other modes, but round-to-nearest is always used unless you explicitly select another.
  - If *x* was not initially an integer, these functions raise the inexact exception.
- http://www.gnu.org/s/libc/manual/html_node/Floating-Point-Parameters.html#Floating-Point-Parameters
  - FLT_ROUNDS characterizes the rounding mode for floating point addition. Standard rounding modes:
    - -1: The mode is indeterminable.
    - 0: Rounding is towards zero.
    - 1: Rounding is to the nearest number.
    - 2: Rounding is towards positive infinity.
    - 3:Rounding is towards negative infinity.

Using Union to Access Bit Patterns

```
typedef union {
  float f;
  unsigned u;
} bit_float_t;
```




```
float bit2float(unsigned u)
{
  bit_float_t arg;
  arg.u = u;
  return arg.f;
}
```

Same as `(float) u` ?

```
unsigned float2bit(float f)
{
  bit_float_t arg;
  arg.f = f;
  return arg.u;
}
```

Same as `(unsigned) f` ?

Using f instead of i?

```
float f=0;
for (f=0;f<10000000000.0;f+=1)
      printf(“%f\n”);
```

- What would happen?

- What would happen if we had a “short float” representation?

s	exp	frac
1	7-bits	8-bits

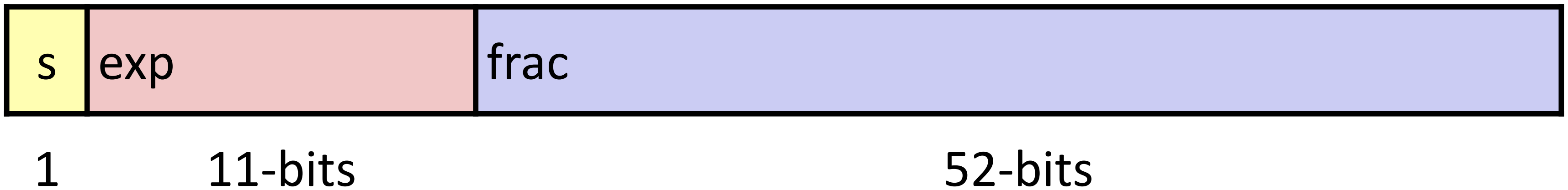
Quiz 1

- **Write a C expression that will yield a word consisting of the least significant byte of x and the remaining bytes of y. For instance, for operands x = 0x89ABCDEF and y = 0x76543210, the Result = 0x765432EF. Your code should work for all word sizes (short/int/long). Write the C expression that would be inserted into the blank shown below:**
- `Result = (x&0xFF)|(y&~0xFF);`
- `Answers such as`

(x & 0xFF) + y &

Quiz 2

- e= 11 bits => Bias=2^(e-1)-1 = 2^10-1= 1023



- Smallest Positive Nonzero number as double
  - 0 00000000000 0000000000000000000000000000000000000000000000000001
  - Value = (-1)^0 * 2^(-52) *2^(1-1023) = 2^(-1074)
- Largest positive Non-infinity number as double
  - e= 11 bits => Bias=2^(e-1)-1 = 2^10-1= 1023
  - 0 11111111110 1111111111111111111111111111111111111111111111111111
  - Value = (-1)^0 * 2^(-52) *2^(1-1023) = 2^(-1074)

- e= 8 bits => Bias=2^(e-1)-1 = 2^7-1= 127

s	exp	frac
1	8-bits	23-bits

2^{10}

- Float representation of 1024.75 in Hex
- Binary representation
  - 1024.75 = 10000000000.11
  - = 1.000000000011 * 2^10
  - M=1.000000000011
    - frac = 00000000001100000000000
  - E=10
    - exp= Bias + E = 137 = 10001001
- 0 10001001 00000000001100000000000
- 0100 0100 1000 0000 0001 1000 0000 0000
- 0x44801800

10000000000.11

$1.0000000000\,11 * 2^{10}$