

Floating Point

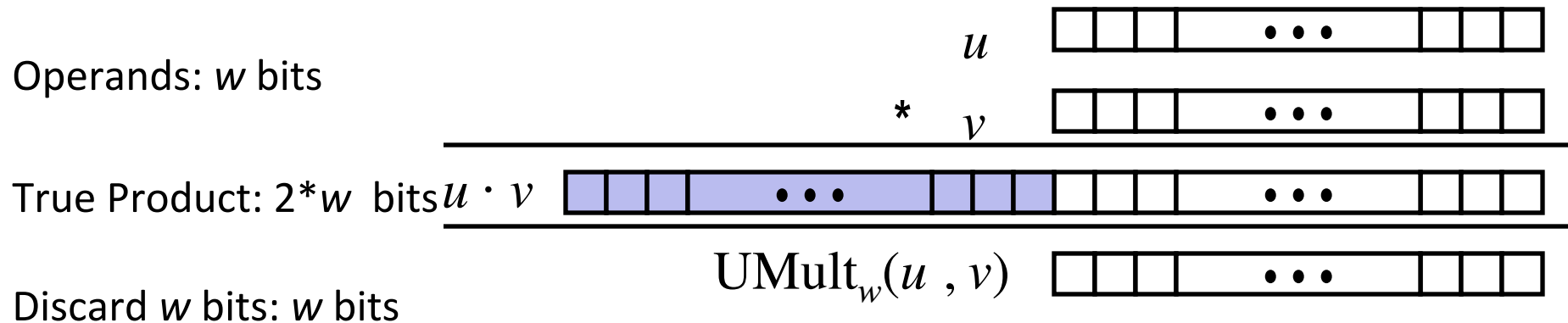
15-213: Introduction to Computer Systems
4th Lecture, Sept. 8, 2016

Today's Instructor:

Randy Bryant

Correction from last time

Unsigned Multiplication in C



■ Standard Multiplication Function

- Ignores high order w bits

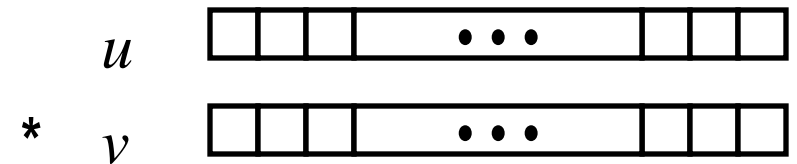
■ Implements Modular Arithmetic

$$\text{UMult}_w(u, v) = u \cdot v \bmod 2^w$$

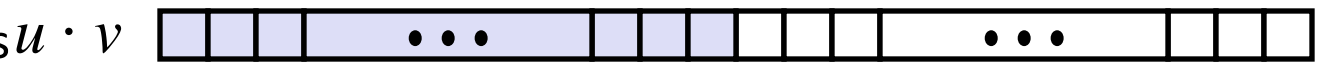
	1110 1001	E9	223
*	1101 0101	* D5	* 213
	1100 0001 1101 1101	C1DD	47499
	1101 1101	DD	221

Signed Multiplication in C

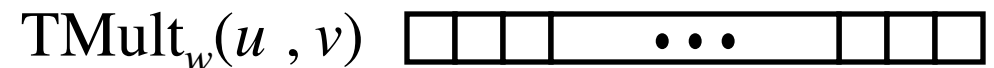
Operands: w bits



True Product: $2 \cdot w$ bits



Discard w bits: w bits



■ Standard Multiplication Function

- Ignores high order w bits
- *Some of which are different for signed vs. unsigned multiplication*
- Lower bits are the same

1111 1111 1110 1001	E9	-23
* 1111 1111 1101 0101	* D5	* -43
0000 0011 1101 1101	03DD	989
1101 1101	DD	-35

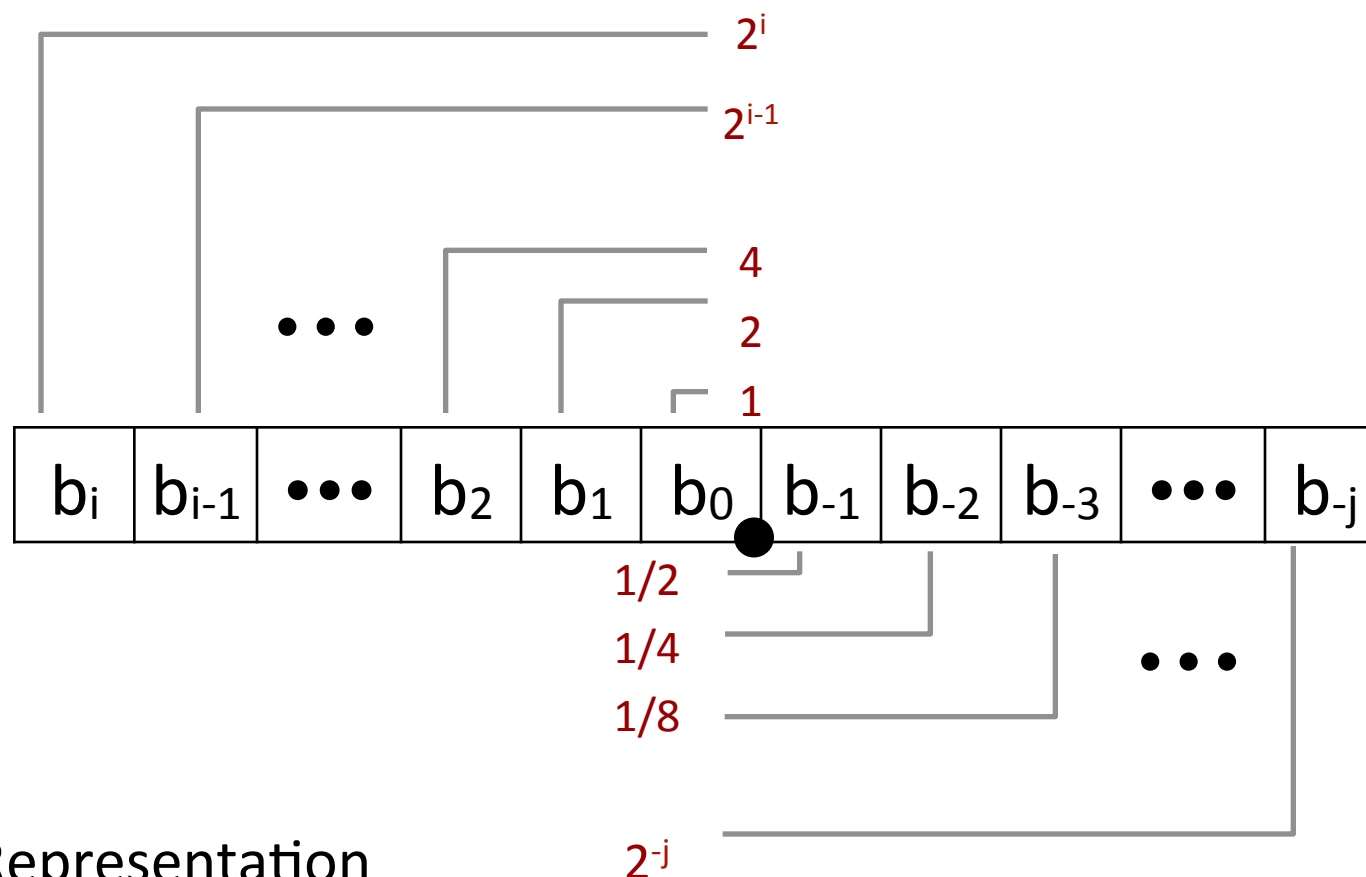
Today: Floating Point

- 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	
$5 \frac{3}{4} = \frac{23}{4}$	101.11_2	$= 4 + 1 + \frac{1}{2} + \frac{1}{4}$
$2 \frac{7}{8} = \frac{23}{8}$	10.111_2	$= 2 + \frac{1}{2} + \frac{1}{4} + \frac{1}{8}$
$1 \frac{7}{16} = \frac{23}{16}$	1.0111_2	$= 1 + \frac{1}{4} + \frac{1}{8} + \frac{1}{16}$

Observations

- Divide by 2 by shifting right (unsigned)
- Multiply by 2 by shifting left
- Numbers of form $0.111111\dots_2$ are just below 1.0
 - $\frac{1}{2} + \frac{1}{4} + \frac{1}{8} + \dots + \frac{1}{2^i} + \dots \rightarrow 1.0$
 - Use notation $1.0 - \epsilon$

Representable Numbers

■ Limitation #1

- Can only exactly represent numbers of the form $x/2^k$
 - Other rational numbers have repeating bit representations

Value	Representation
■ $1/3$	$0.0101010101 [01] \dots_2$
■ $1/5$	$0.001100110011 [0011] \dots_2$
■ $1/10$	$0.0001100110011 [0011] \dots_2$

■ 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
- Some CPUs don't implement IEEE 754 in full
e.g., early GPUs

■ 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

Example:

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

■ 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, $10^{\pm 38}$



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



- Other formats: half precision, quad precision

“Normalized” Values

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

- When: $\text{exp} \neq 000\dots 0$ and $\text{exp} \neq 111\dots 1$
- 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: $M = 1.\text{xxx}\dots\text{x}_2$
 - xxx...x: bits of frac field
 - Minimum when frac=000...0 ($M = 1.0$)
 - Maximum when frac=111...1 ($M = 2.0 - \epsilon$)
 - 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

$$M = 1.\underline{1101101101101}_2$$

$$\text{frac} = \underline{1101101101101}0000000000_2$$

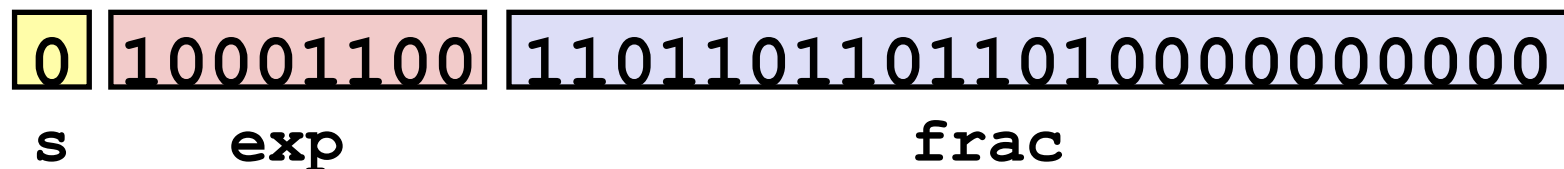
■ Exponent

$$E = 13$$

$$\text{Bias} = 127$$

$$\text{Exp} = 140 = 10001100_2$$

■ Result:



Denormalized Values

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

- Condition: $\text{exp} = 000\dots 0$
- Exponent value: $E = 1 - \text{Bias}$ (instead of $0 - \text{Bias}$)
- Significand coded with implied leading 0: $M = 0.\text{xxx}\dots\text{x}_2$
 - $\text{xxx}\dots\text{x}$: bits of frac
- Cases
 - $\text{exp} = 000\dots 0, \text{frac} = 000\dots 0$
 - Represents zero value
 - Note distinct values: $+0$ and -0 (why?)
 - $\text{exp} = 000\dots 0, \text{frac} \neq 000\dots 0$
 - Numbers closest to 0.0
 - Equispaced

Special Values

- Condition: $\text{exp} = 111\dots 1$
- Case: $\text{exp} = 111\dots 1, \text{frac} = 000\dots 0$
 - 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: $\text{exp} = 111\dots 1, \text{frac} \neq 000\dots 0$
 - Not-a-Number (NaN)
 - Represents case when no numeric value can be determined
 - E.g., $\text{sqrt}(-1)$, $\infty - \infty$, $\infty \times 0$

C float Decoding Example

float: 0xC0A00000

binary: _____



E = -> Exp = (decimal)

S =

M =

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

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

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

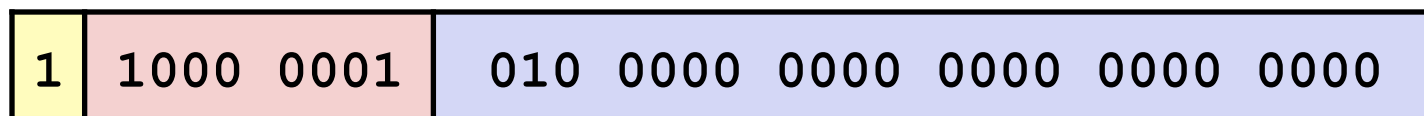
$$\text{Bias} = 2^{k-1} - 1 = 127$$

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

float: 0xC0A00000

binary: 1100 0000 1010 0000 0000 0000 0000 0000



1 8-bits

23-bits

$E =$ $\rightarrow \text{Exp} =$ (decimal)

$S =$

$M = 1.$

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

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

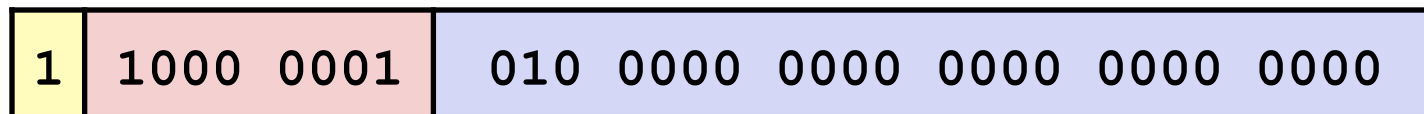
$$E = \text{Exp} - \text{Bias}$$

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

float: 0xC0A00000

binary: 1100 0000 1010 0000 0000 0000 0000 0000



1 8-bits

23-bits

$E = 129 \rightarrow \text{Exp} = 129 - 127 = 2$ (decimal)

$S = 1 \rightarrow$ negative number

$M = 1.010 \ 0000 \ 0000 \ 0000 \ 0000 \ 0000$
 $= 1 + 1/4 = 1.25$

$v = (-1)^S M 2^E = (-1)^1 * 1.25 * 2^2 = -5$

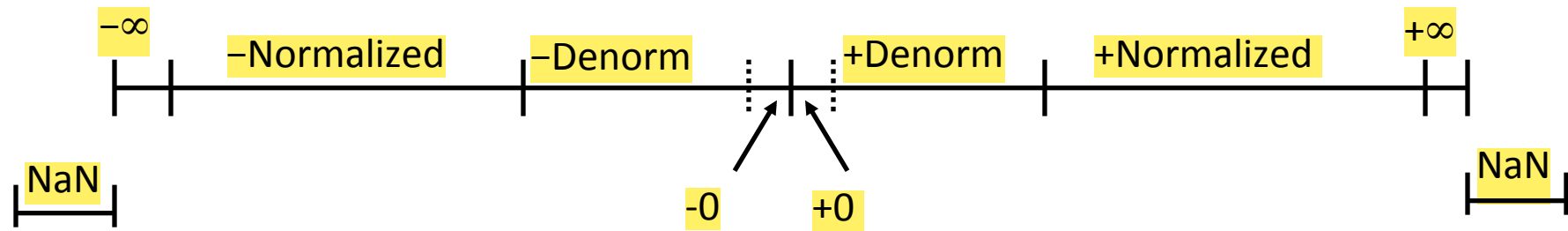
$$v = (-1)^S M 2^E$$

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

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

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

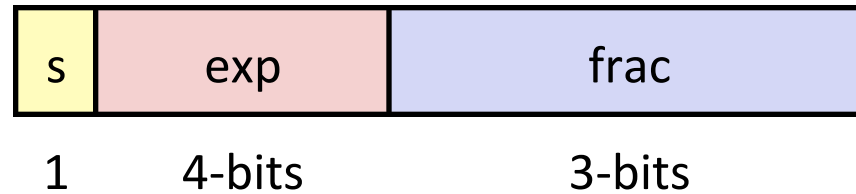
Visualization: Floating Point Encodings



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Tiny Floating Point Example



- 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)

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

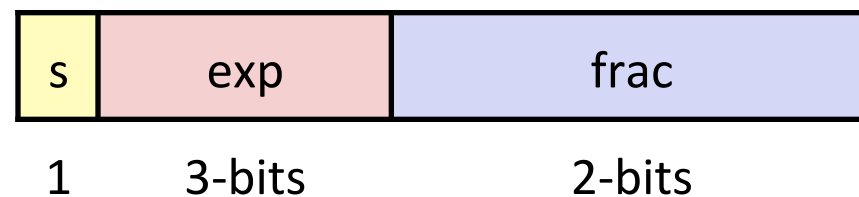
n: $E = \text{Exp} - \text{Bias}$
d: $E = 1 - \text{Bias}$

	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	

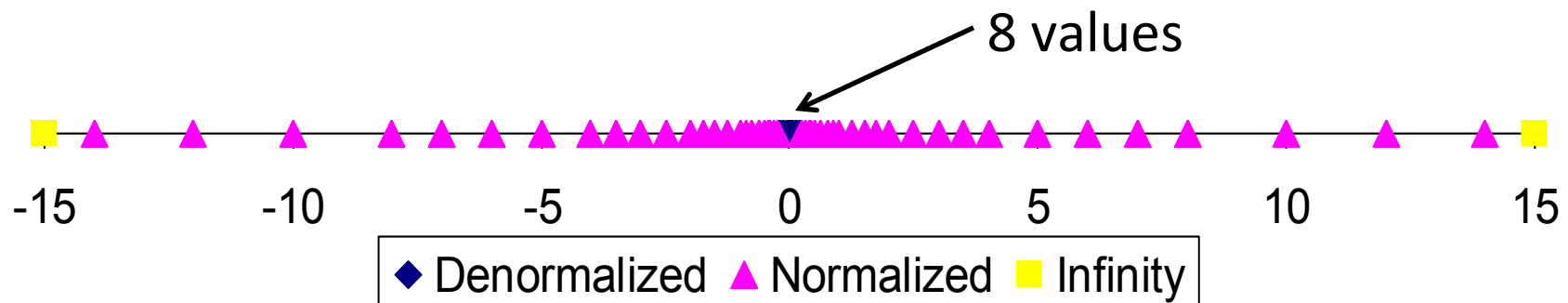
Distribution of Values

■ 6-bit IEEE-like format

- $e = 3$ exponent bits
- $f = 2$ fraction bits
- Bias is $2^{3-1}-1 = 3$



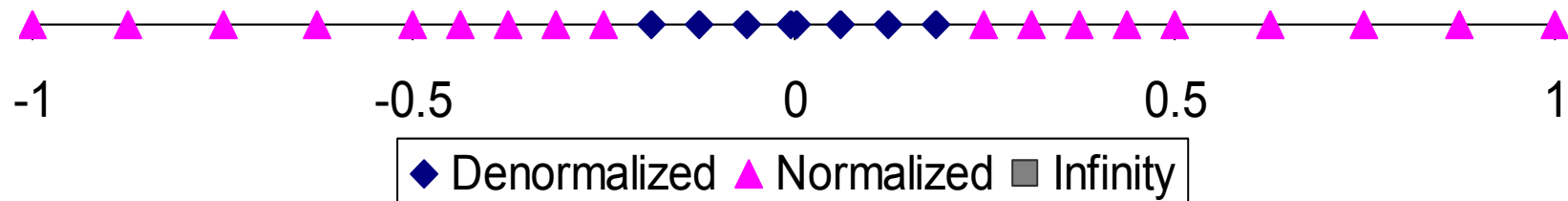
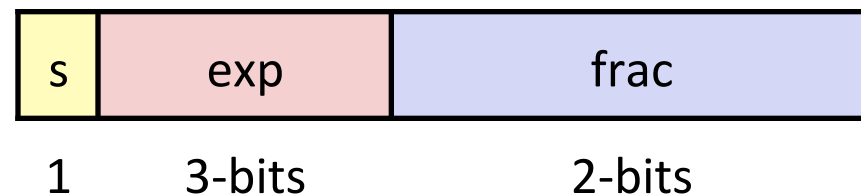
■ Notice how the distribution gets denser toward zero.



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

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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`

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 ↓

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 = $100..._2$

■ Examples

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

Value	Binary	Rounded	Action	Rounded Value
$2 \frac{3}{32}$	$10.00\textcolor{red}{011}_2$	10.00_2	($<1/2$ —down)	2
$2 \frac{3}{16}$	$10.00\textcolor{red}{110}_2$	10.01_2	($>1/2$ —up)	$2 \frac{1}{4}$
$2 \frac{7}{8}$	$10.11\textcolor{red}{100}_2$	11.00_2	($1/2$ —up)	3
$2 \frac{5}{8}$	$10.10\textcolor{red}{100}_2$	10.10_2	($1/2$ —down)	$2 \frac{1}{2}$

FP Multiplication

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

$$\begin{aligned}
 \text{4 bit mantissa: } 1.010 \times 2^2 &\times 1.110 \times 2^3 = 1\textcolor{red}{0}.0011 \times 2^5 \\
 &= 1.000\textcolor{red}{11} \times 2^6 = 1.00\textcolor{red}{1} \times 2^6
 \end{aligned}$$

Floating Point Addition

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

- Assume $E1 > E2$

■ Exact Result: $(-1)^s M 2^E$

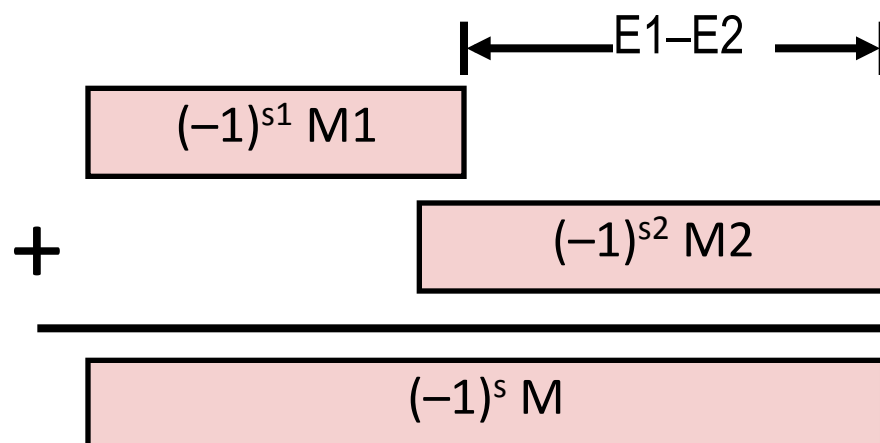
- Sign s , significand M :
 - Result of signed align & add

- Exponent E : $E1$

■ Fixing

- If $M \geq 2$, 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

- 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: $(1e20 * 1e20) * 1e-20 = \text{inf}$, $1e20 * (1e20 * 1e-20) = 1e20$
- 1 is multiplicative identity? Yes
- Multiplication distributes over addition? No
 - Possibility of overflow, inexactness of rounding
 - $1e20 * (1e20 - 1e20) = 0.0$, $1e20 * 1e20 - 1e20 * 1e20 = \text{NaN}$

■ Monotonicity

- $a \geq b \ \& \ c \geq 0 \Rightarrow a * c \geq b * c$ Almost
 - Except for infinities & NaNs

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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











Floating Point Puzzles

■ For each of the following C expressions, either:

- Argue that it is true for all argument values
- Explain why not true

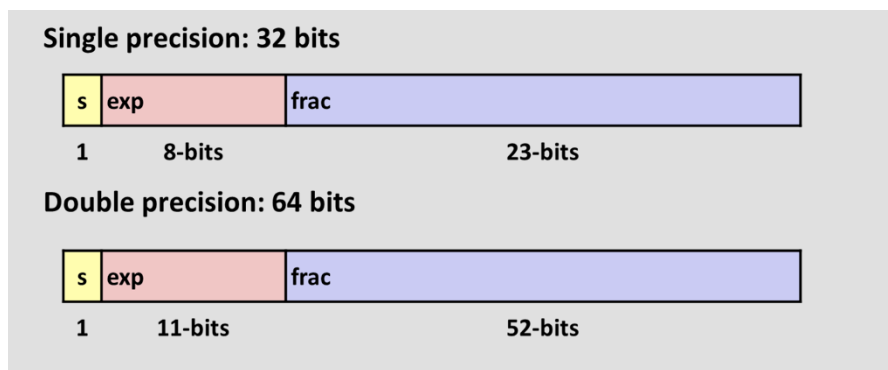
```
int x = ...;
float f = ...;
double d = ...;
```

Assume neither
d nor f is NaN

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

Summary

- IEEE Floating Point has clear mathematical properties
- Represents numbers of form $M \times 2^E$
- 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

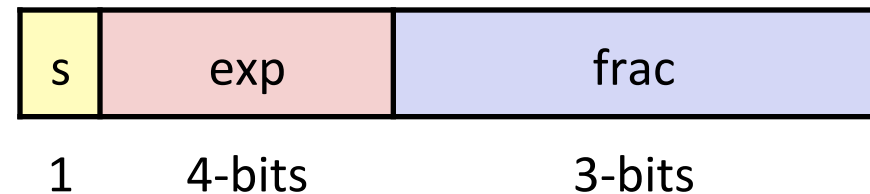


HOW ROUNDING WORKS

Creating Floating Point Number

■ Steps

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



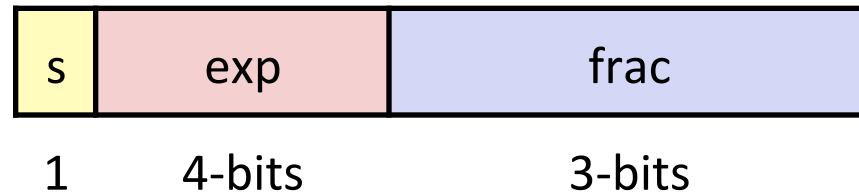
■ Case Study

- 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



■ 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 . BBG **R** XXX

Guard bit: LSB of result

Round bit: 1st bit removed

Sticky bit: OR of remaining bits

■ Round up conditions

- Round = 1, Sticky = 1 \rightarrow > 0.5
- Guard = 1, Round = 1, Sticky = 0 \rightarrow Round to even

Value	Fraction	GRS	Incr?	Rounded
128	1.000 0 000	0 00	N	1.000
15	1.101 0 000	1 00	N	1.101
17	1.000 1 000	0 10	N	1.000
19	1.001 1 000	1 10	Y	1.010
138	1.000 1 010	0 11	Y	1.001
63	1.111 1 100	1 11	Y	10.000

Postnormalize

■ Issue

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

Value	Rounded	Exp	Adjusted	Numeric 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

Additional Slides

Interesting Numbers

{single, double}

<i>Description</i>	<i>exp</i>	<i>frac</i>	<i>Numeric Value</i>
■ Zero	00...00	00...00	0.0
■ Smallest Pos. Denorm.	00...00	00...01	$2^{-\{23,52\}} \times 2^{-\{126,1022\}}$
■ Single $\approx 1.4 \times 10^{-45}$			
■ Double $\approx 4.9 \times 10^{-324}$			
■ Largest Denormalized	00...00	11...11	$(1.0 - \epsilon) \times 2^{-\{126,1022\}}$
■ Single $\approx 1.18 \times 10^{-38}$			
■ Double $\approx 2.2 \times 10^{-308}$			
■ 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	$(2.0 - \epsilon) \times 2^{\{127,1023\}}$
■ Single $\approx 3.4 \times 10^{38}$			
■ Double $\approx 1.8 \times 10^{308}$			