CSC 252: Computer Organization Spring 2021: Lecture 4

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Department of Computer Science
University of Rochester

Announcement

- Programming Assignment 1 is out
  - Details: https://www.cs.rochester.edu/courses/252/spring2021/labs/assignment1.html
  - Due on Feb. 17, 11:59 PM
  - You have 3 slip days

7	8	9	10	11 **Today**	12	13
14	15	16	17 **Due**	18	19	20

Announcement

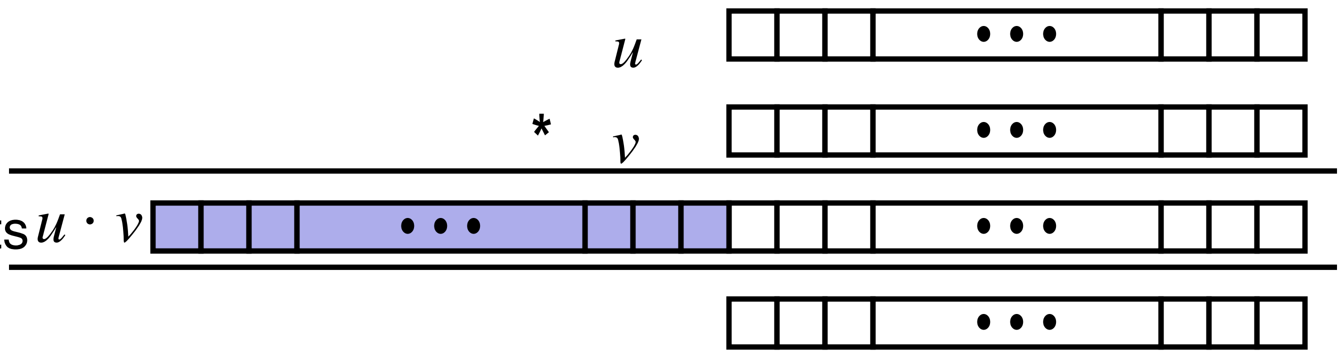
- Programming assignment 1 is in C language. Seek help from TAs.
- TAs are best positioned to answer your questions about programming assignments!!!
- Programming assignments do NOT repeat the lecture materials. They ask you to synthesize what you have learned from the lectures and work out something new.

Unsigned Multiplication in C

Operands: w bits

True Product: $2*w$ bits

Discard w bits: w bits



- Standard Multiplication Function
  - Ignores high order w bits
- Effectively Implements the following:

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

Multiplication

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- Goal: Computing Product of w-bit numbers x, y

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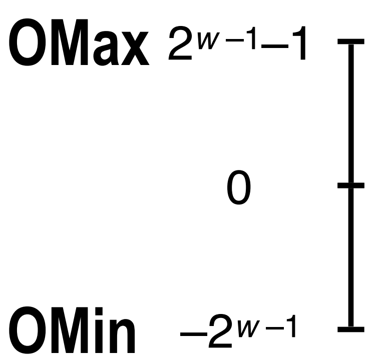
Original Number (w bits)



Multiplication

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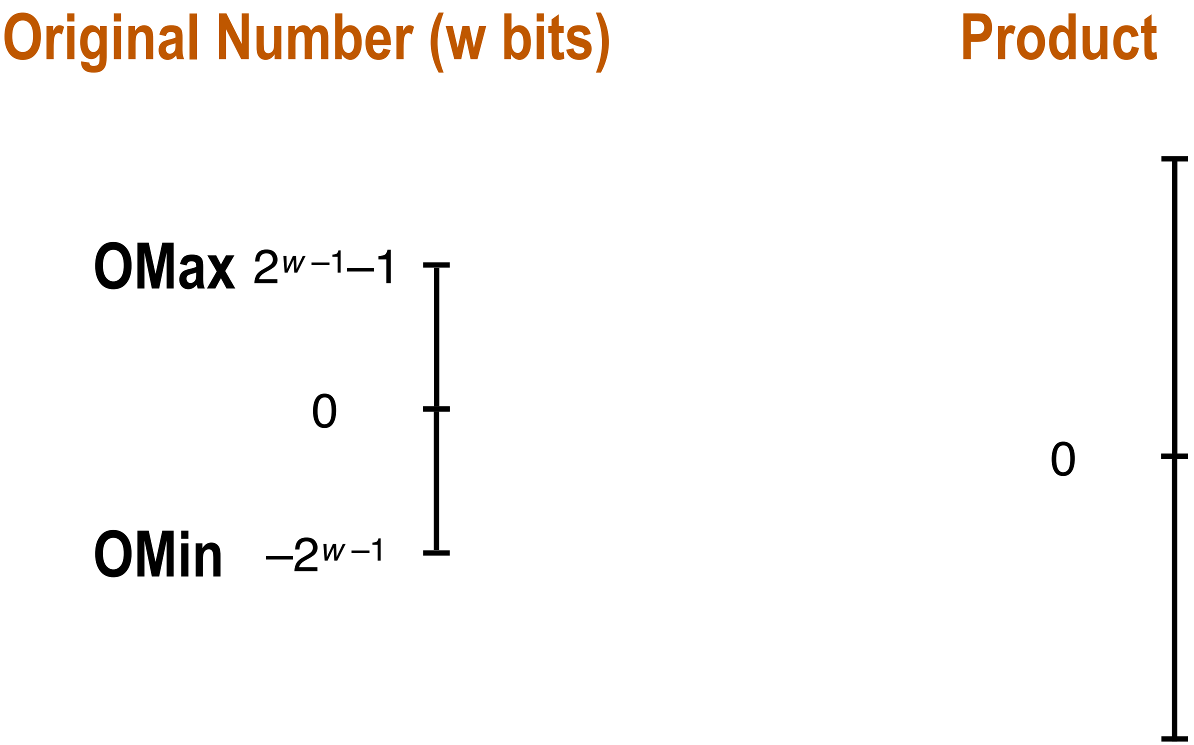

Multiplication

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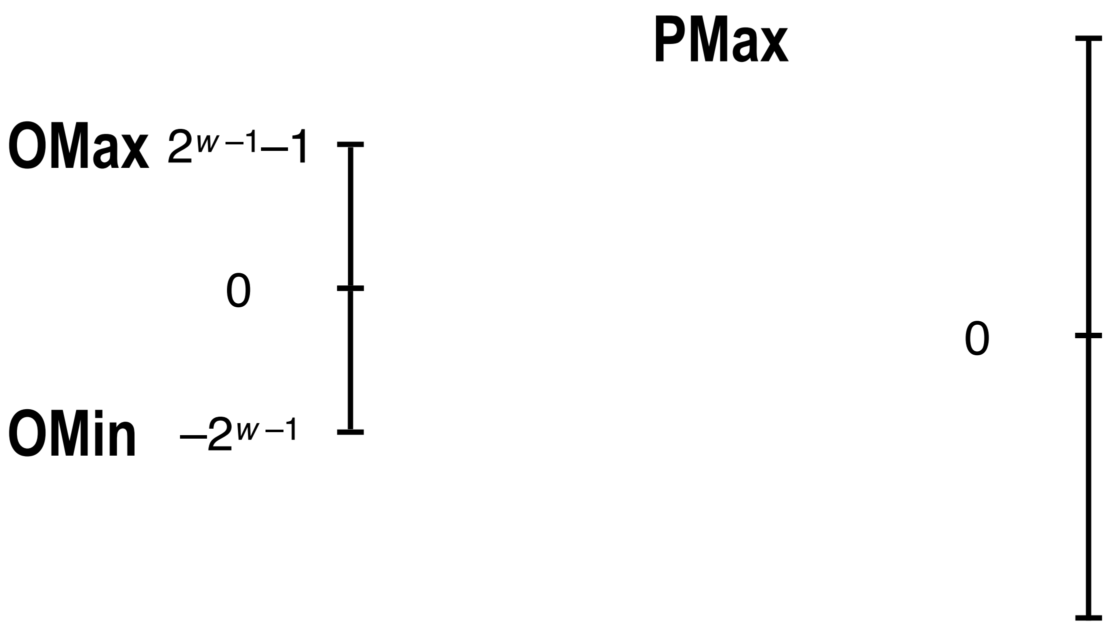
Original Number (w bits) **Product**



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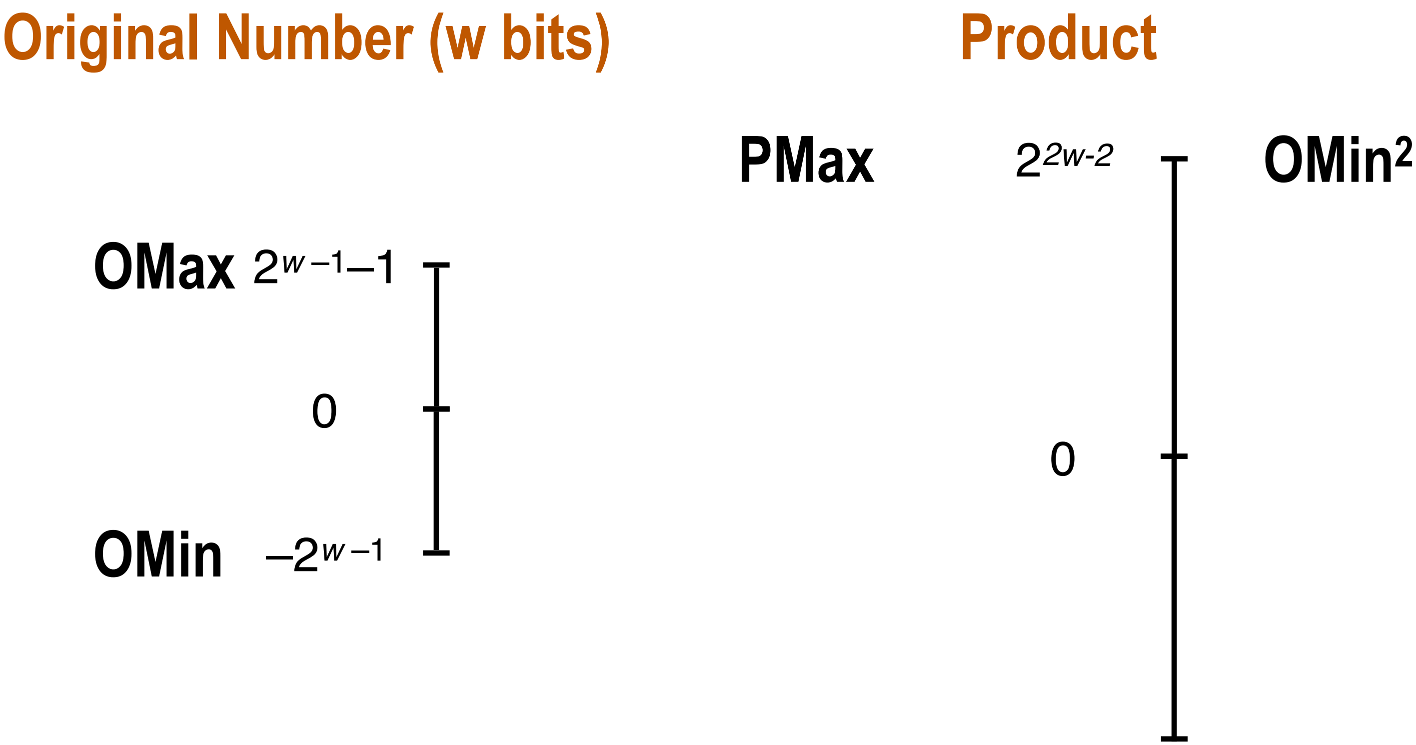

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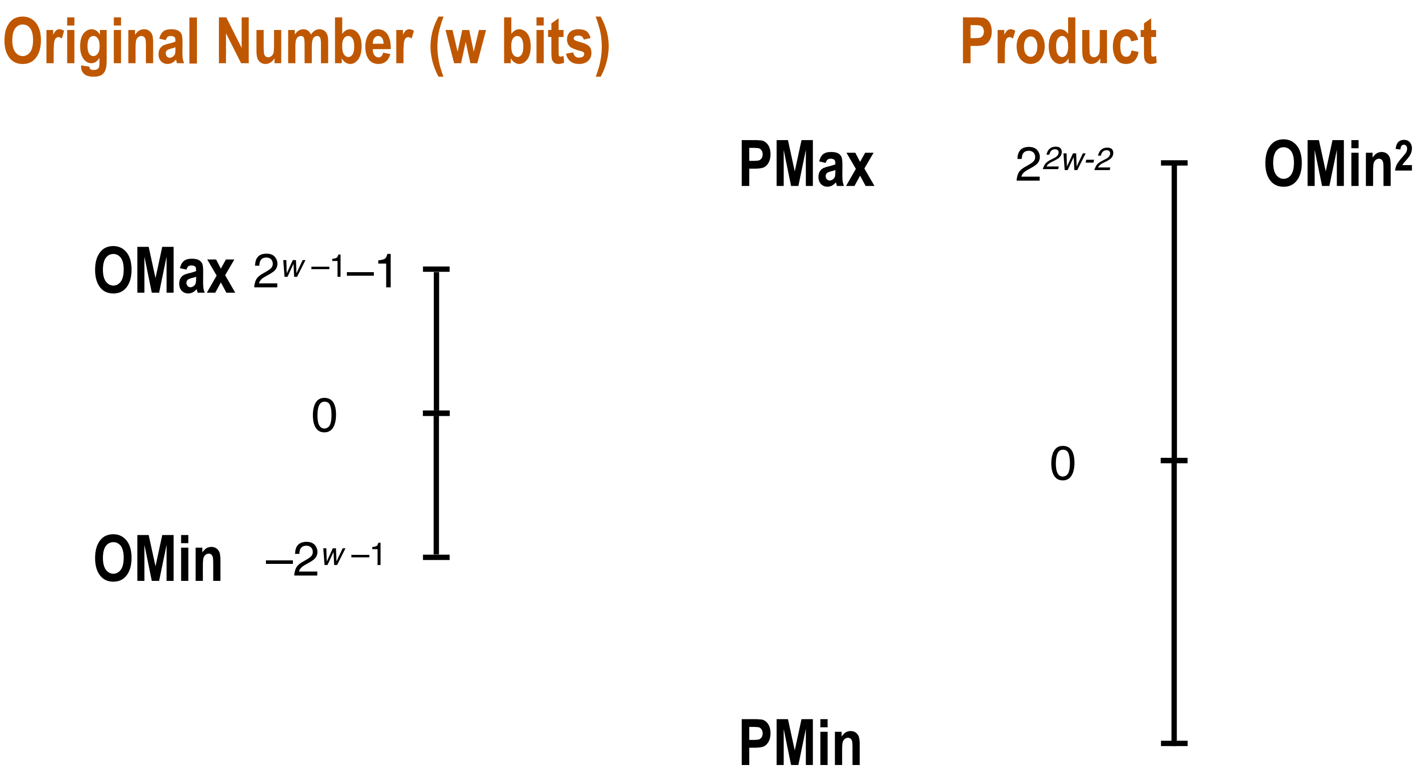

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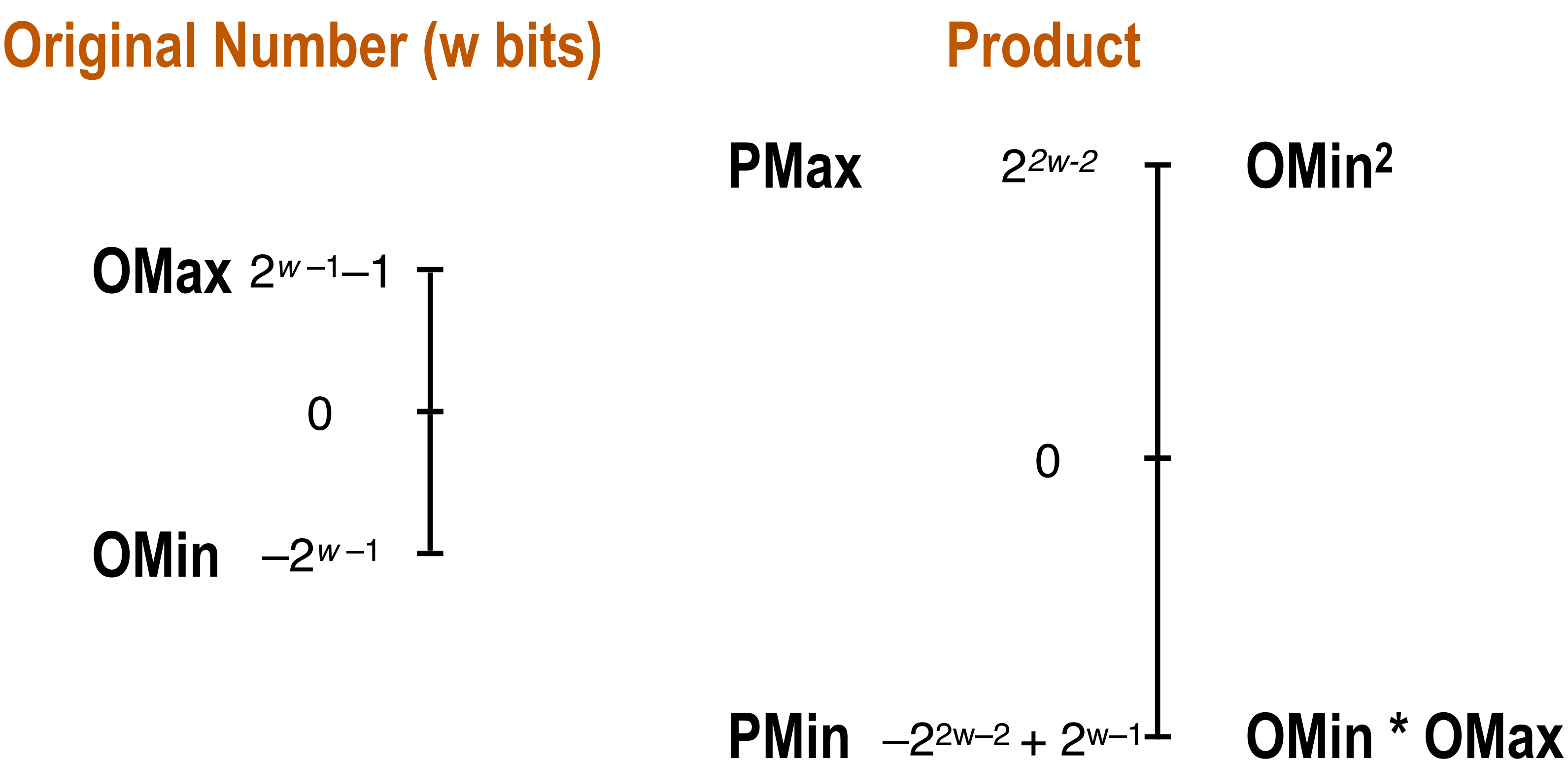

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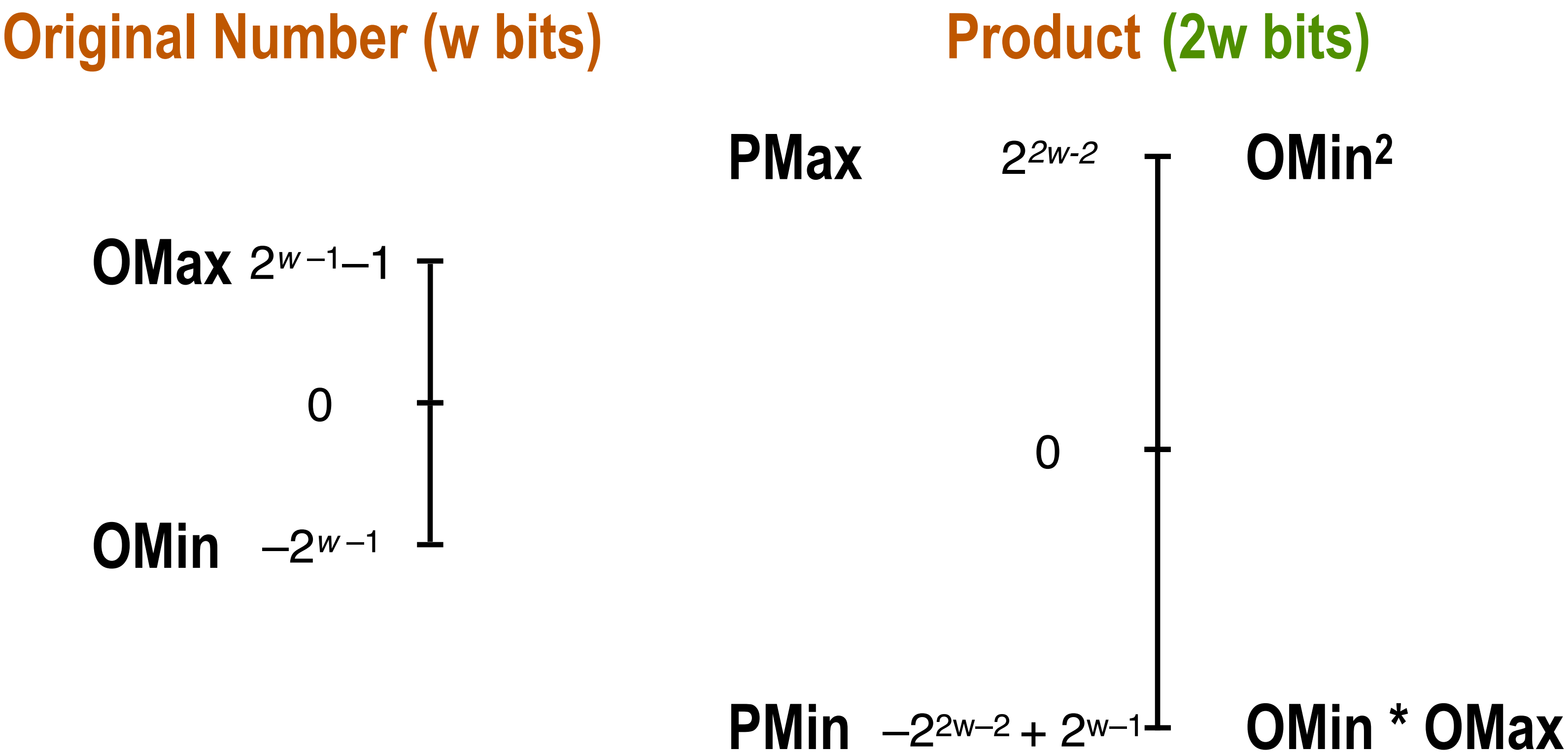
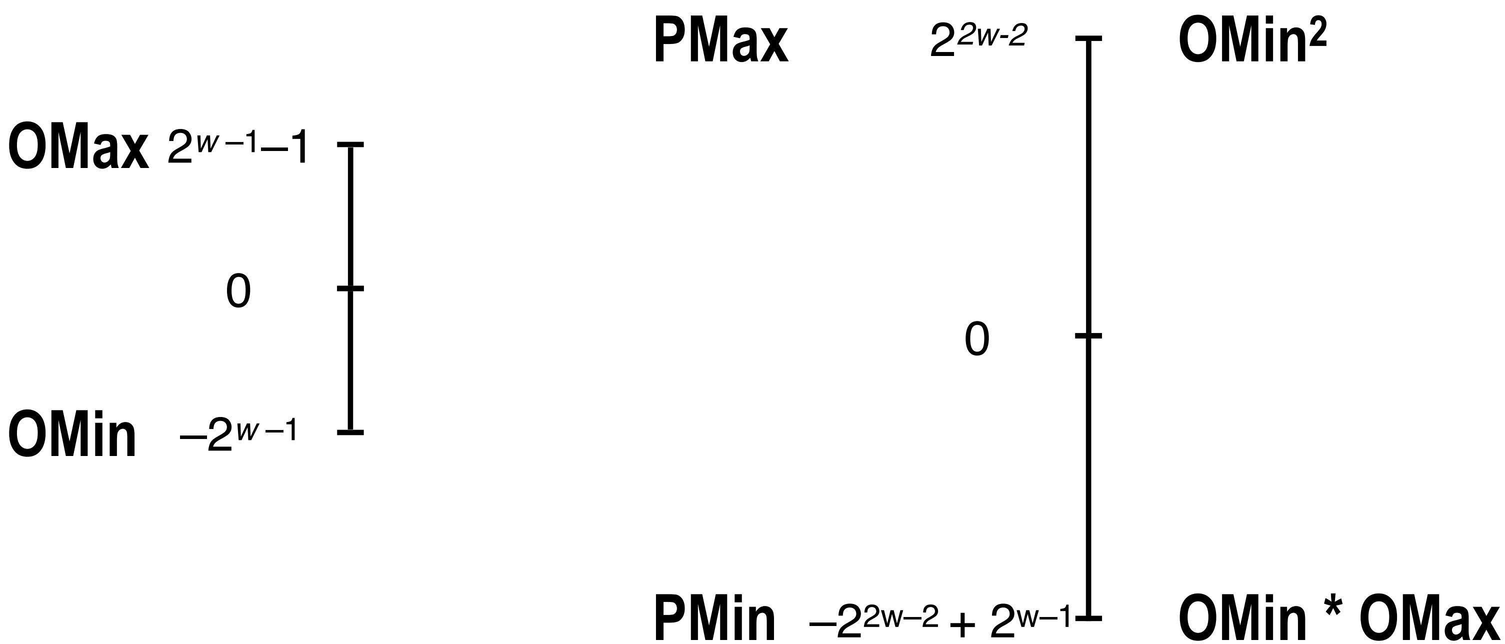


Multiplication

- Goal: Computing Product of *w*-bit numbers *x*, *y*
- Exact results can be bigger than *w* bits
  - Up to *2w* bits (both signed and unsigned)

Original Number (w bits) **Product (2w bits)**



Today: Floating Point

- Background: Fractional binary numbers and fixed-point
- Floating point representation
- IEEE 754 standard
- Rounding, addition, multiplication
- Floating point in C
- Summary

Can We Represent Fractions in Binary?

- What does 10.01_2 mean?
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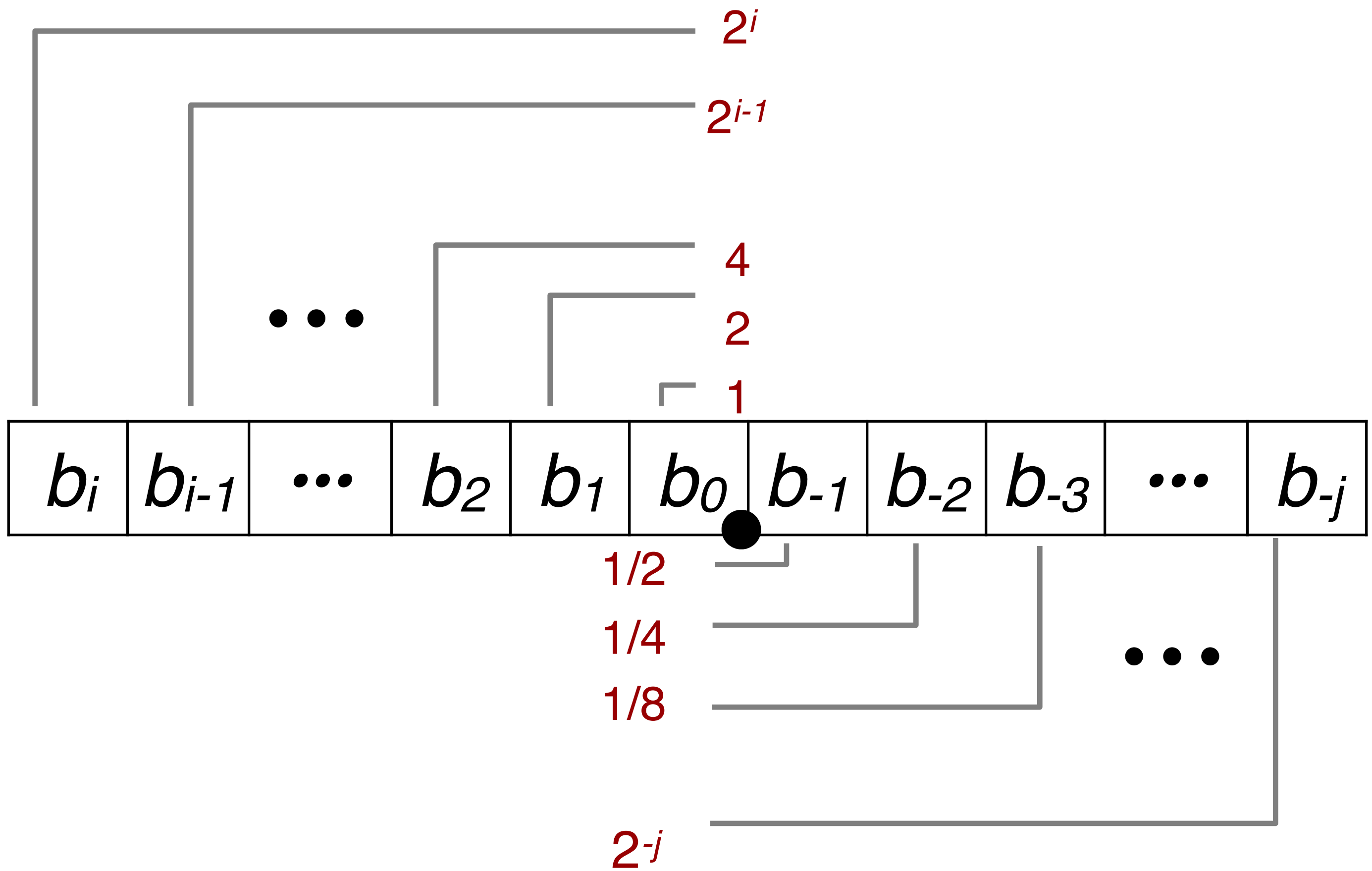
$$= 2.25_{10}$$

Fractional Binary Numbers



Fixed-Point Representation

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- Binary point stays fixed

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

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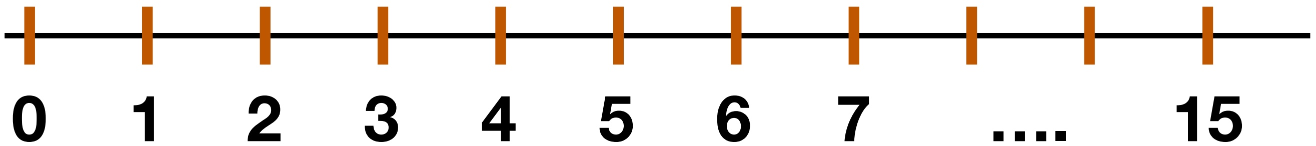

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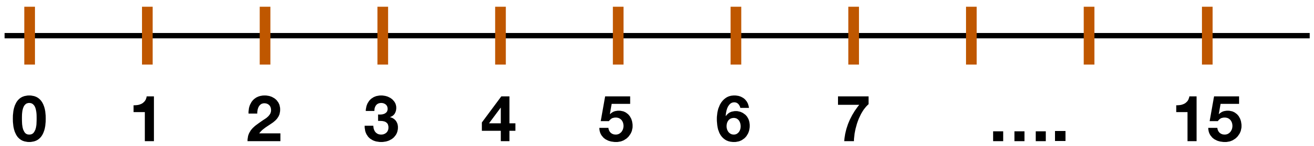

Decimal	Binary
0	00.00
0.25	00.01
0.5	00.10
0.75	00.11
1	01.00
1.25	01.01
1.5	01.10
1.75	01.11
2	10.00
2.25	10.01
2.5	10.10
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3	11.00
3.25	11.01
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Fixed-Point Representation

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- Fixed interval between representable numbers
  - The interval in this example is 0.25_{10}

- Still need to remember the binary point, but just once for all numbers, which is implicit given the data type
- Usual arithmetics still work
  - No need to align (already aligned)

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0.25	00.01
0.5	00.10
0.75	00.11
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1.25	01.01
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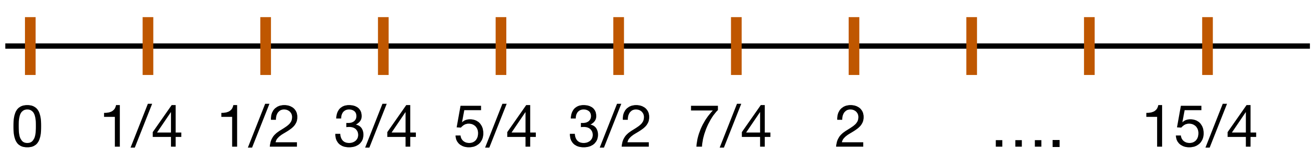

$b_3b_2.b_1b_0$

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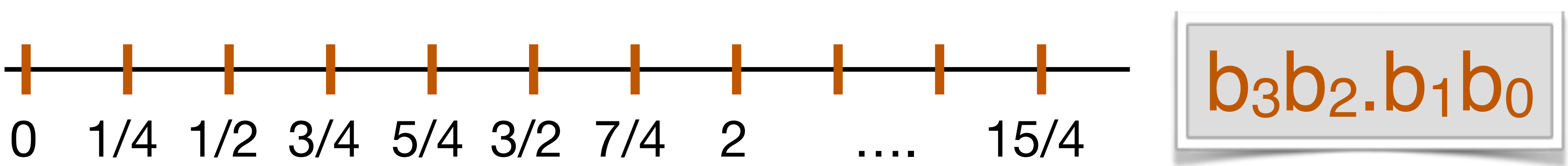

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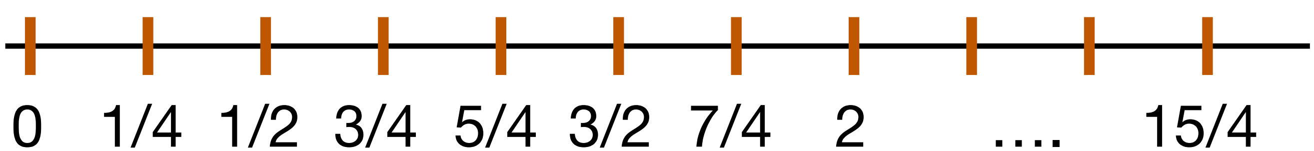
Decimal Value	**Binary Representation**
1/3	0.0101010101[01]…
1/5	0.001100110011[0011]…
1/10	0.0001100110011[0011]…



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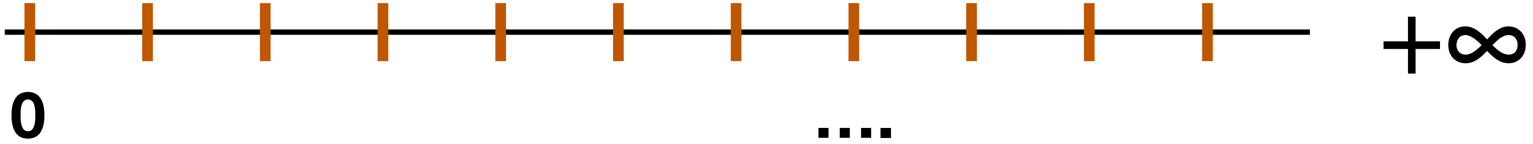

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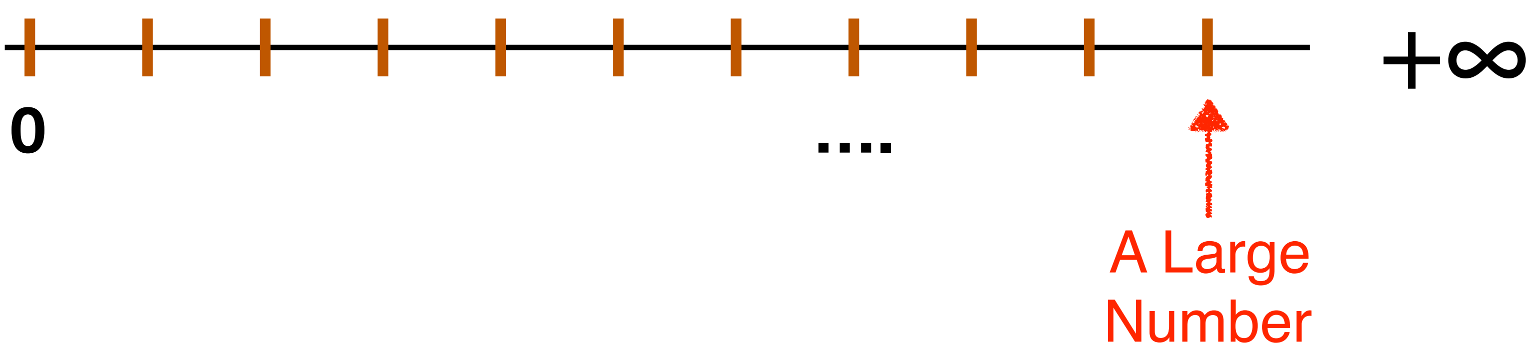

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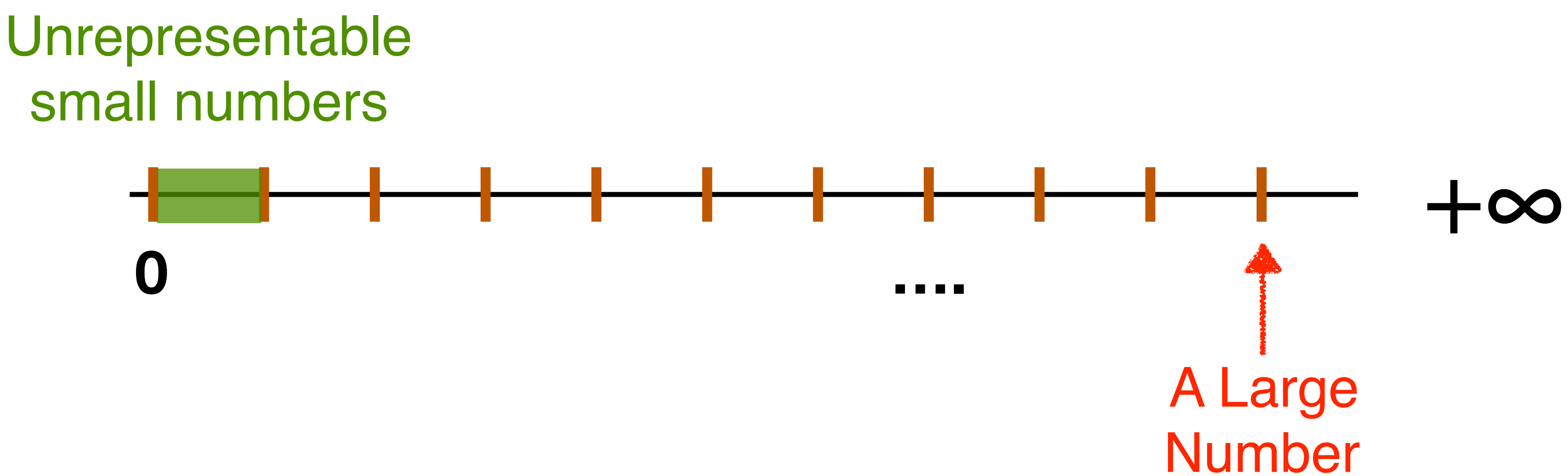

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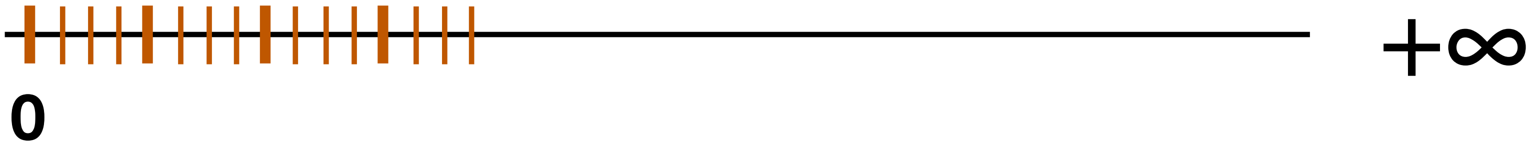

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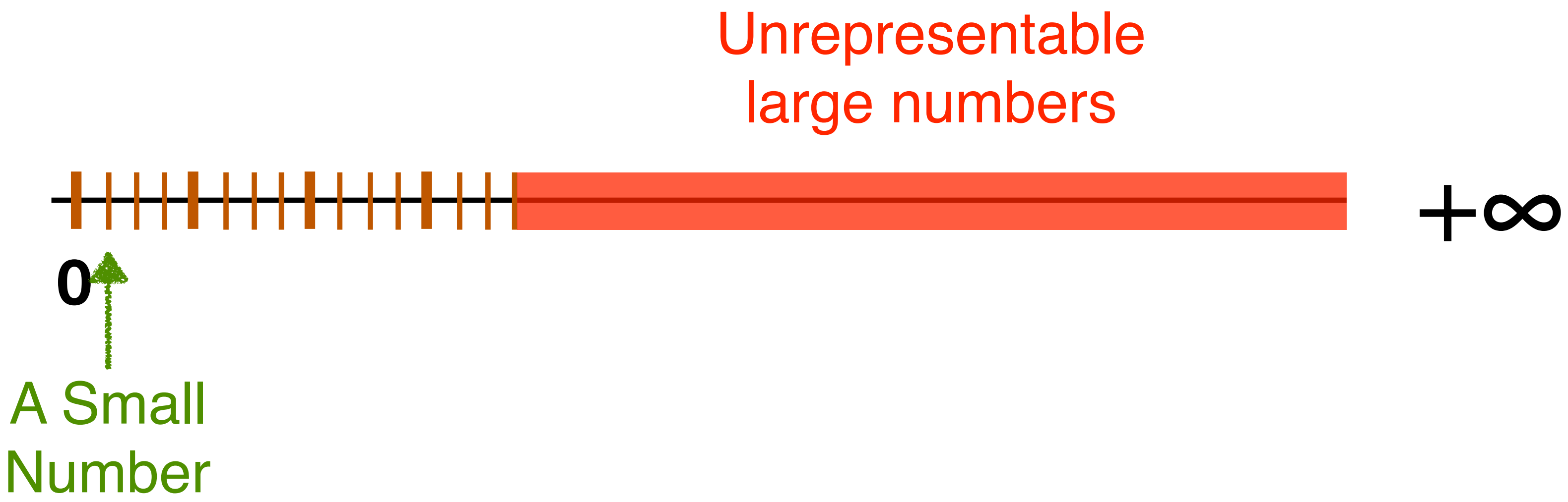

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Primer: (Normalized) Scientific Notation

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Decimal Value	Scientific Notation
2	2×10^{0}
-4,321.768	-4.321768×10^{3}
0.000 000 007 51	7.51×10^{-9}

Primer: (Normalized) Scientific Notation

- In decimal: $M \times 10^E$
  - E is an integer
  - Normalized form: $1 <= |M| < 10$

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Exponent

Significand Base

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$$(-1)^{s} M \times 2^{E}$$

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- Normalized form:
  - $1 <= M < 2$
  - $M = 1.b_0b_1b_2b_3\ldots$

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Fraction

Sign

Exponent

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    Fraction

Sign Exponent

$$(-1)^{s}\, M \times 2^{E}$$

Significand Base

- If I tell you that there is a number where:
  - Fraction = 0101
  - s = 1
  - E = 10
  - You could reconstruct the number as $(-1)^1 1.0101 \times 2^{10}$

Primer: Floating Point Representation

- In binary: $(-1)^s \, M \, 2^E$
- Normalized form:
  - $1 <= M < 2$
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  - MSB s is sign bit s

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  - MSB s is sign bit s
  - *exp* field encodes Exponent (but not exactly the same, more later)

Sign Exponent

$$(-1)^{s}\, M \times 2^{E}$$

Significand Base

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  - $1 <= M < 2$
  - $M = 1.\underbrace{b_0 b_1 b_2 b_3 \ldots}_{\text{Fraction}}$

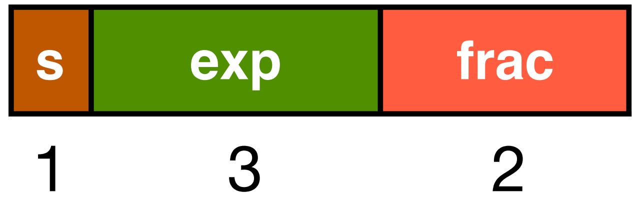
$$\overset{\text{Sign}}{(-1)^{s}}\ \underset{\text{Significand}}{M} \times \underset{\text{Base}}{2}^{\overset{\text{Exponent}}{E}}$$

- Encoding
  - MSB *s* is sign bit s
  - *exp* field encodes Exponent (but not exactly the same, more later)
  - *frac* field encodes Fraction (but not exactly the same, more later)

s	exp	frac

6-bit Floating Point Example

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



6-bit Floating Point Example

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

s	exp	frac
1	3	2

- *exp* has 3 bits, interpreted as an unsigned value

6-bit Floating Point Example

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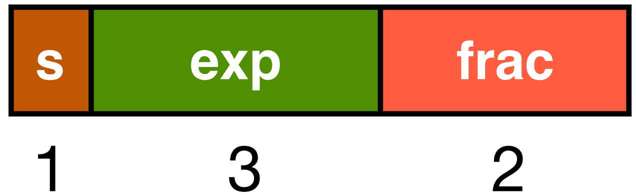

- *exp* has 3 bits, interpreted as an unsigned value
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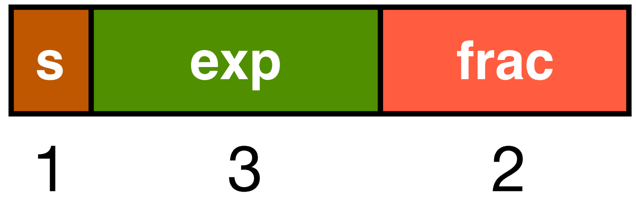

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  - If $E = -2$, *exp* is 1 (001_2)

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  - bias is always $2^{k-1} - 1$, where k is number of exponent bits
- Example when we use 3 bits for exp (i.e., $k = 3$):
  - bias = 3
  - If $E = -2$, *exp* is 1 (001_2)

E	exp
-3	000
-2	001
-1	010
0	011
1	100
2	101
3	110
4	111

6-bit Floating Point Example

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

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1	3	2

- *exp* has 3 bits, interpreted as an unsigned value
  - If *exp* were *E*, we could represent exponents from **0 to 7**
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  - bias is always $2^{k-1} - 1$, where k is number of exponent bits
- Example when we use 3 bits for exp (i.e., $k = 3$):
  - bias = 3
  - If $E = -2$, *exp* is 1 (001_2)
  - Reserve 000 and 111 for other purposes (more on this later)

E	exp
~~-3~~	~~000~~
-2	001
-1	010
0	011
1	100
2	101
3	110
~~4~~	~~111~~

6-bit Floating Point Example

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

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  - If *exp* were *E*, we could represent exponents from **0 to 7**
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  - Subtract a bias term: *E = exp - bias* (i.e., exp = E + bias)
  - bias is always $2^{k-1} - 1$, where k is number of exponent bits
- Example when we use 3 bits for exp (i.e., *k* = 3):
  - bias = 3
  - If *E* = -2, *exp* is 1 (001_2)
  - Reserve 000 and 111 for other purposes (more on this later)
  - We can now represent exponents from **-2 (exp 001) to 3 (exp 110)**

E	exp
~~-3~~	~~000~~
-2	001
-1	010
0	011
1	100
2	101
3	110
~~4~~	~~111~~

6-bit Floating Point Example

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

s	exp	frac
1	3	2

6-bit Floating Point Example

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

- *frac* has 2 bits, append them after “1.” to form M
  - *frac* = 10 implies M = 1.10

6-bit Floating Point Example

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

s	exp	frac
1	3	2

- *frac* has 2 bits, append them after “1.” to form M
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- Putting it Together: An Example:

$$-10.1_2 = (-1)^1 \; 1.01 \times 2^1$$

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6-bit Floating Point Example

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

1	exp	frac
1	3	2

- *frac* has 2 bits, append them after “1.” to form M
  - *frac* = 10 implies M = 1.10
- Putting it Together: An Example:

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E	exp
~~-3~~	~~000~~
-2	001
-1	010
0	011
1	100
2	101
3	110
~~4~~	~~111~~

6-bit Floating Point Example

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

1	100	frac
1	3	2

- *frac* has 2 bits, append them after "1." to form M
  - *frac* = 10 implies M = 1.10
- Putting it Together: An Example:

$$-10.1_2 = (-1)^1\ 1.01 \times 2^1$$

E	exp
~~-3~~	~~000~~
-2	001
-1	010
0	011
1	100
2	101
3	110
~~4~~	~~111~~

6-bit Floating Point Example

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

1	100	frac
1	3	2

- *frac* has 2 bits, append them after "1." to form M
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E	exp
~~-3~~	~~000~~
-2	001
-1	010
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1	100
2	101
3	110
~~4~~	~~111~~

6-bit Floating Point Example

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

1	100	01
1	3	2

- *frac* has 2 bits, append them after “1.” to form M
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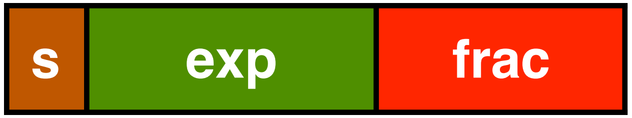
E	exp
~~-3~~	~~000~~
-2	001
-1	010
0	011
1	100
2	101
3	110
~~4~~	~~111~~

Representable Numbers (Positive Only)

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



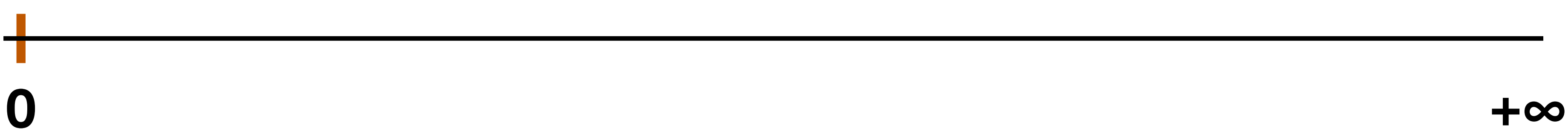
E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

Representable Numbers (Positive Only)

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

0	exp	frac

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

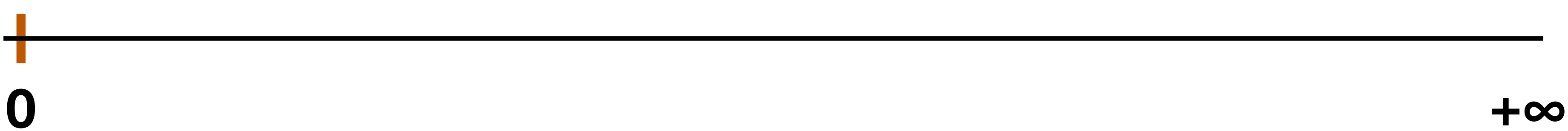


Representable Numbers (Positive Only)

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

0	exp	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

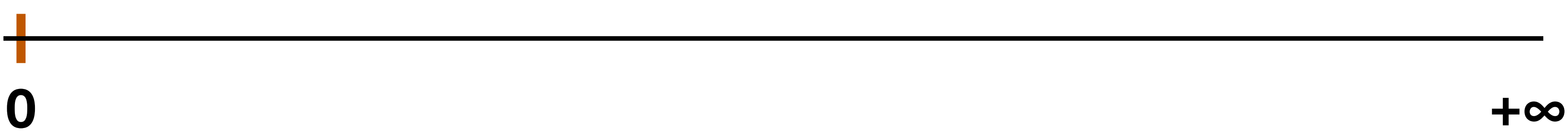


Representable Numbers (Positive Only)

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

0	001	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~



Representable Numbers (Positive Only)

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

0	001	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

Representable Numbers (Positive Only)

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

0	010	00

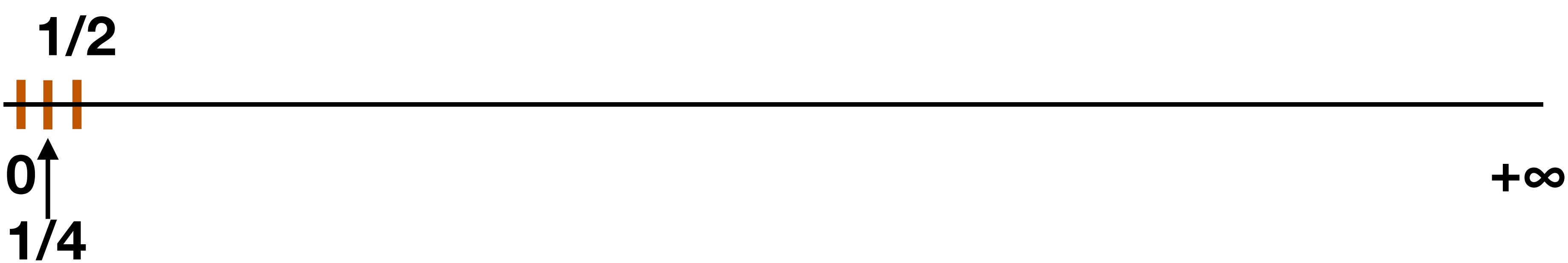
E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

Representable Numbers (Positive Only)

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

0	010	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

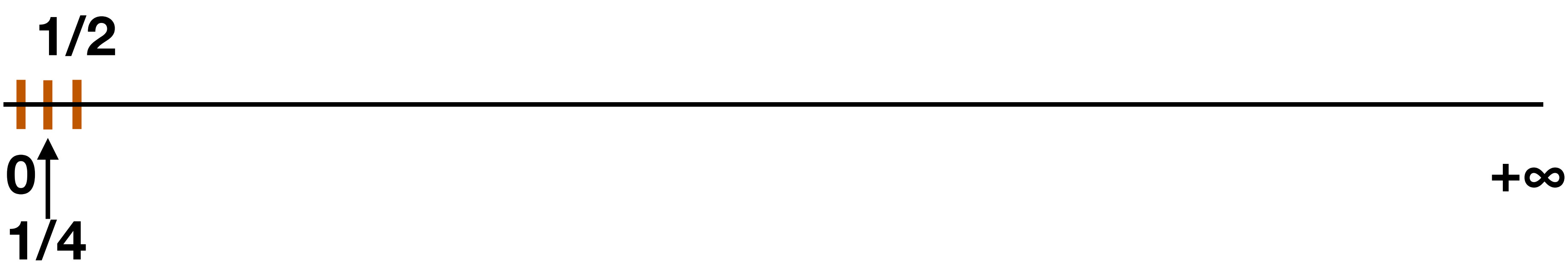


Representable Numbers (Positive Only)

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

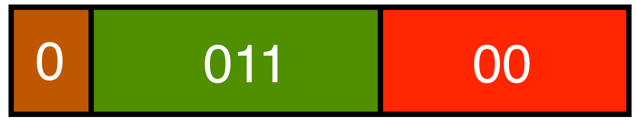
0	011	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

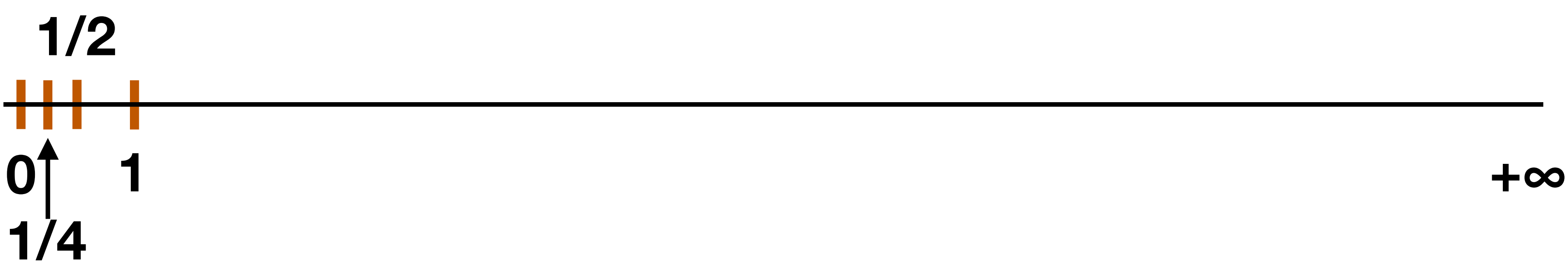


Representable Numbers (Positive Only)

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



E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

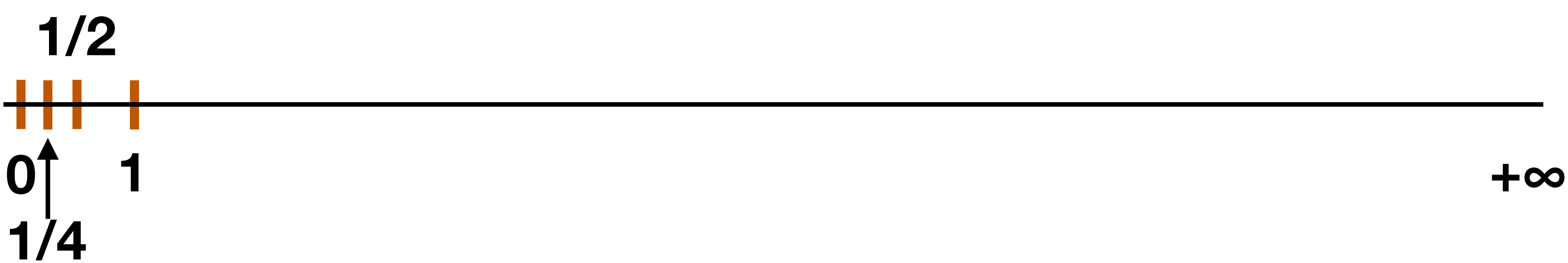


Representable Numbers (Positive Only)

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

0	100	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

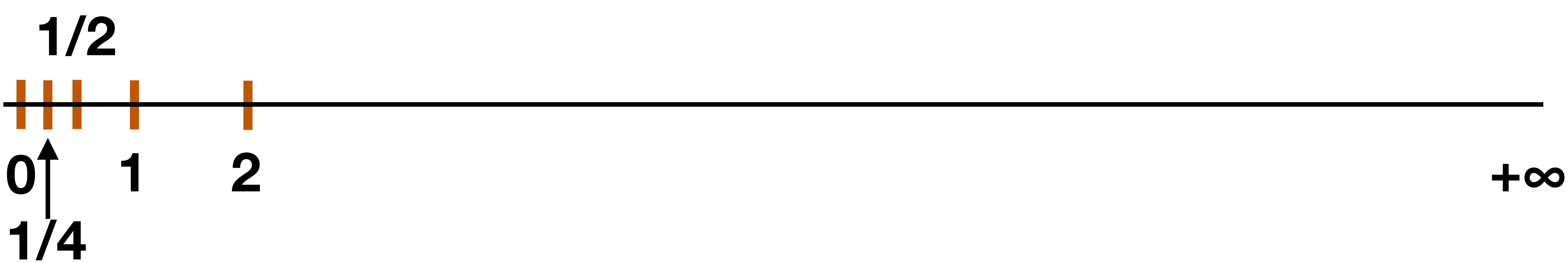


Representable Numbers (Positive Only)

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

0	100	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

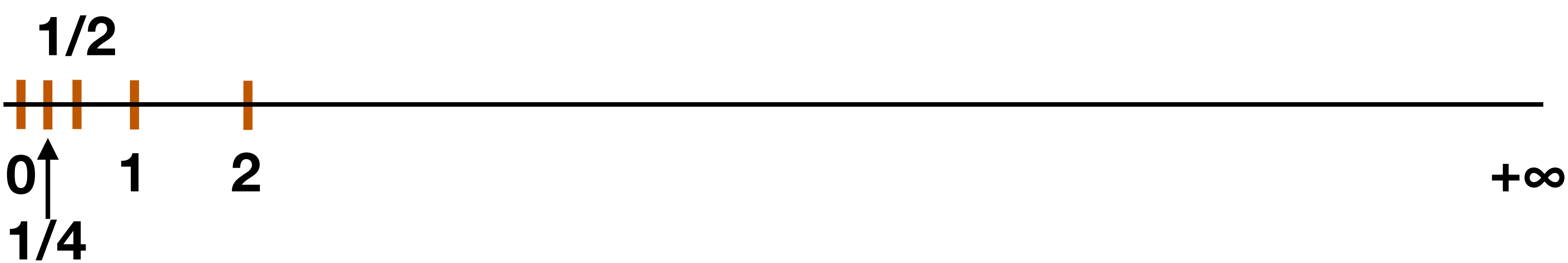


Representable Numbers (Positive Only)

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

0	101	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~



Representable Numbers (Positive Only)

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E	exp	E	exp
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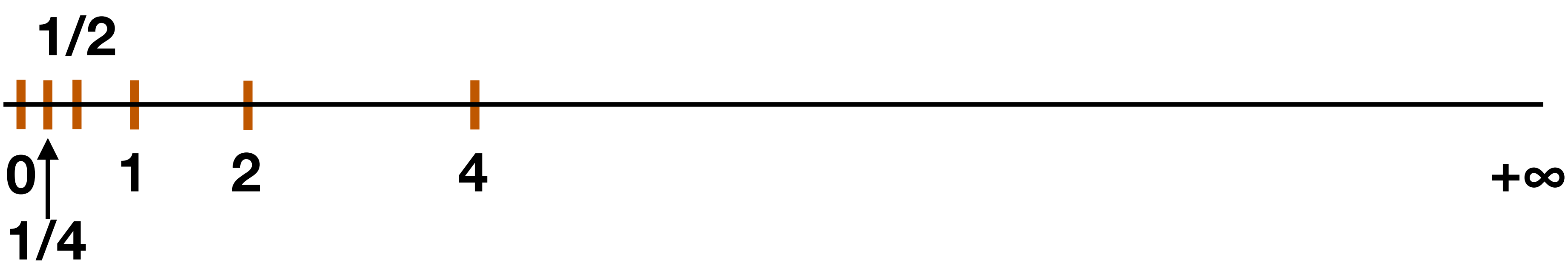
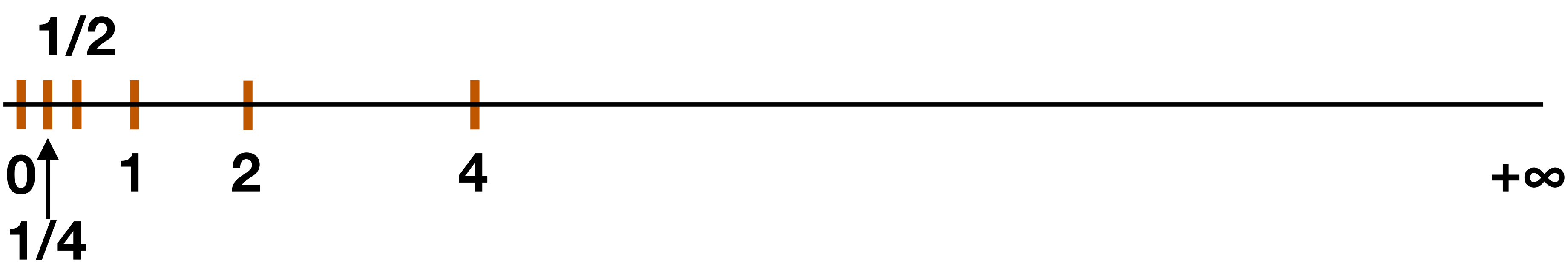


Representable Numbers (Positive Only)

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

0	110	00

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~



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0	110	00

E	exp	E	exp
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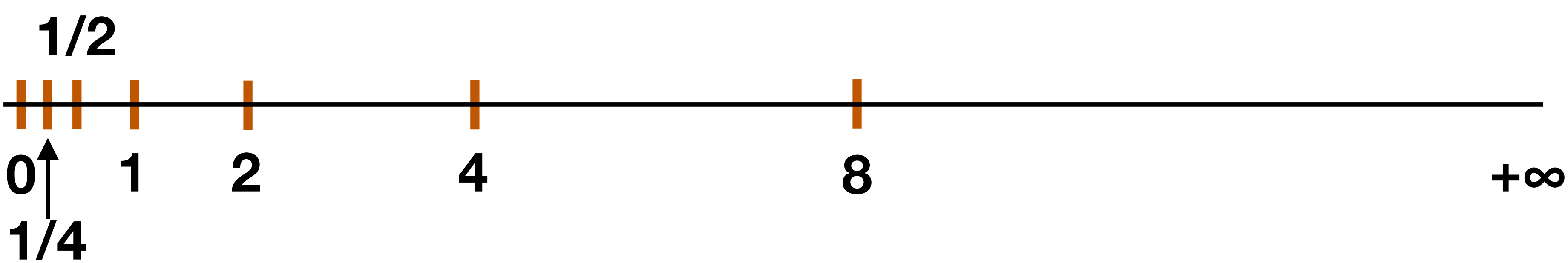
0	011	~~4~~	~~111~~



Representable Numbers (Positive Only)

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0	110	01

E	exp	E	exp
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-2	001	2	101
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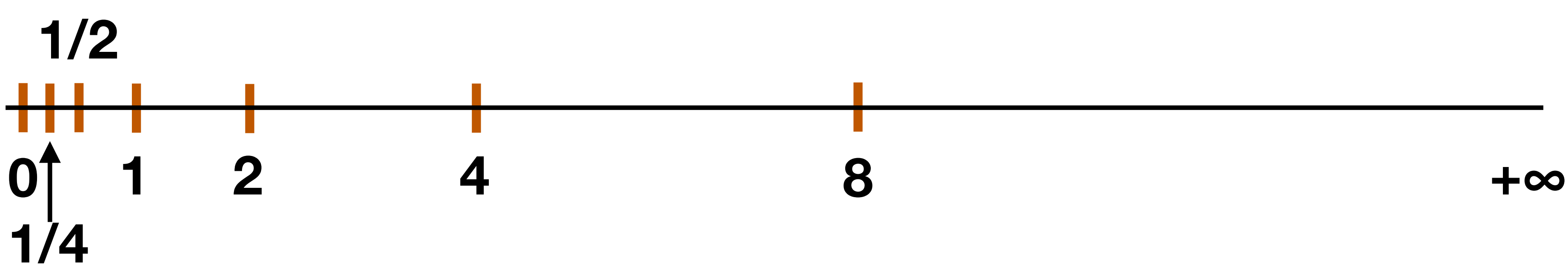

Representable Numbers (Positive Only)

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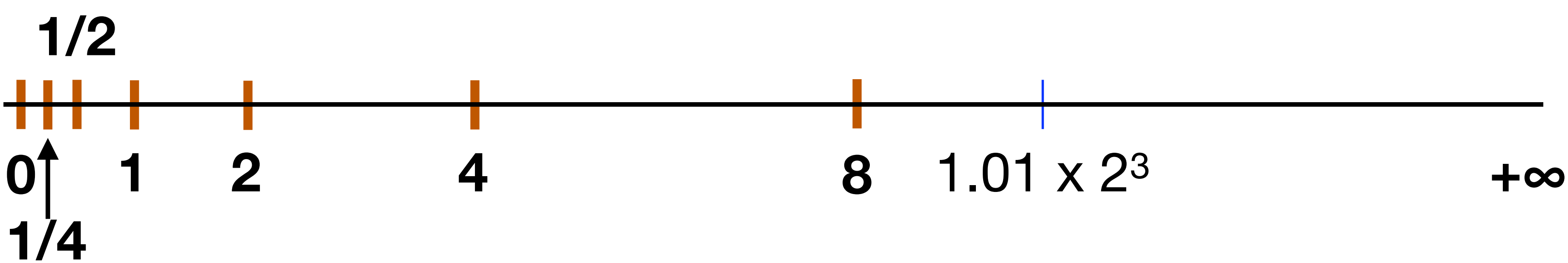
0	110	01

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

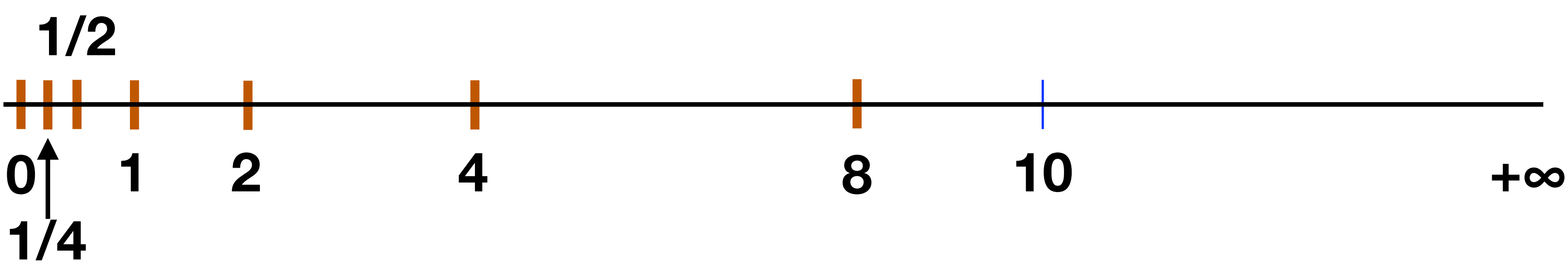


Representable Numbers (Positive Only)

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

0	110	01

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

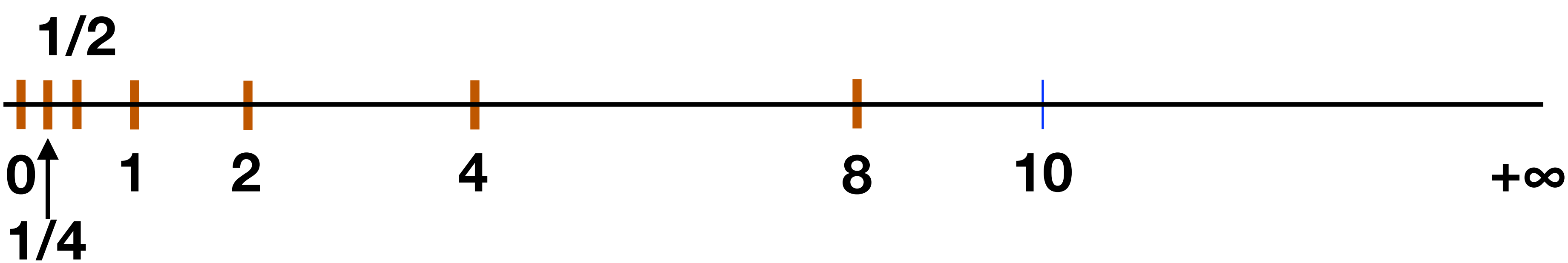


Representable Numbers (Positive Only)

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

0	110	10

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

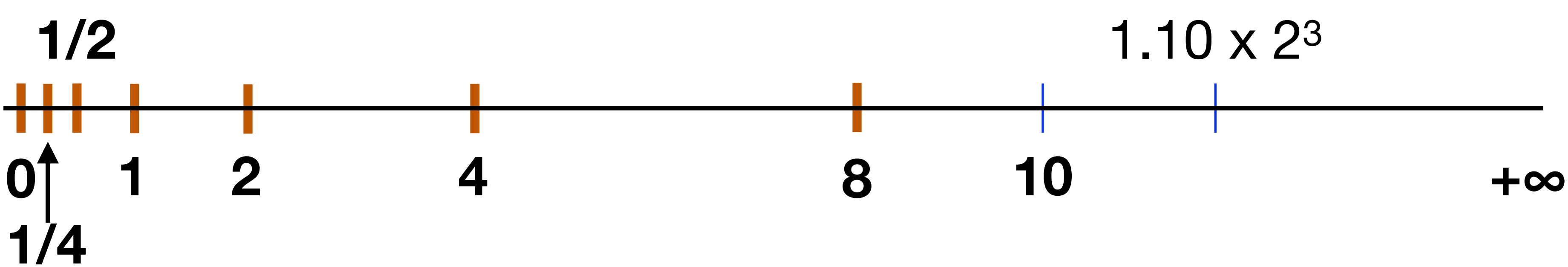


Representable Numbers (Positive Only)

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

0	110	10

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

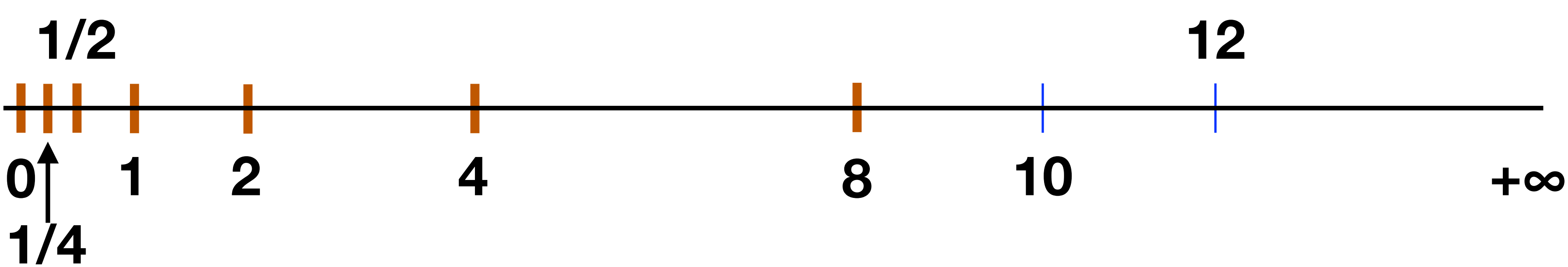


Representable Numbers (Positive Only)

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

0	110	10

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

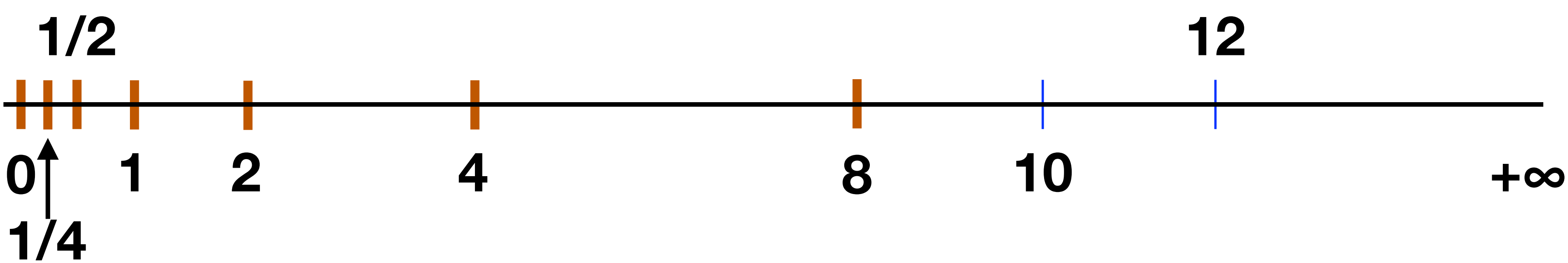


Representable Numbers (Positive Only)

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

0	110	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

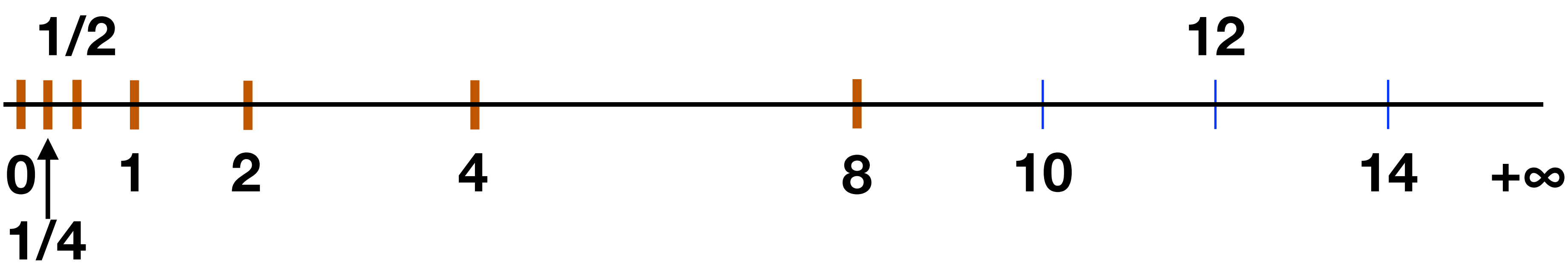


Representable Numbers (Positive Only)

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

0	110	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

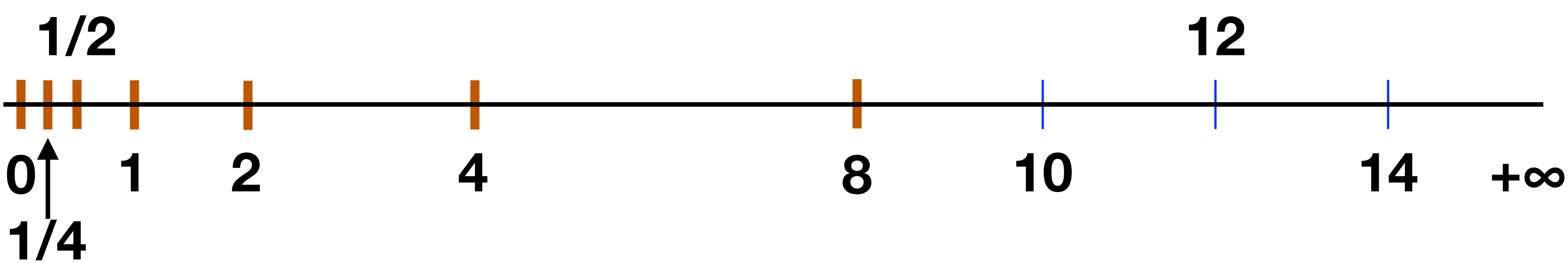


Representable Numbers (Positive Only)

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

0	101	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

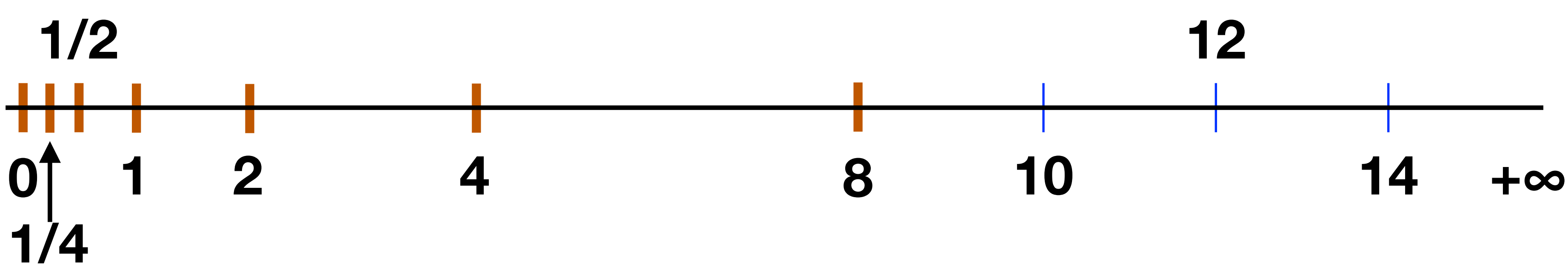


Representable Numbers (Positive Only)

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

0	101	01

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

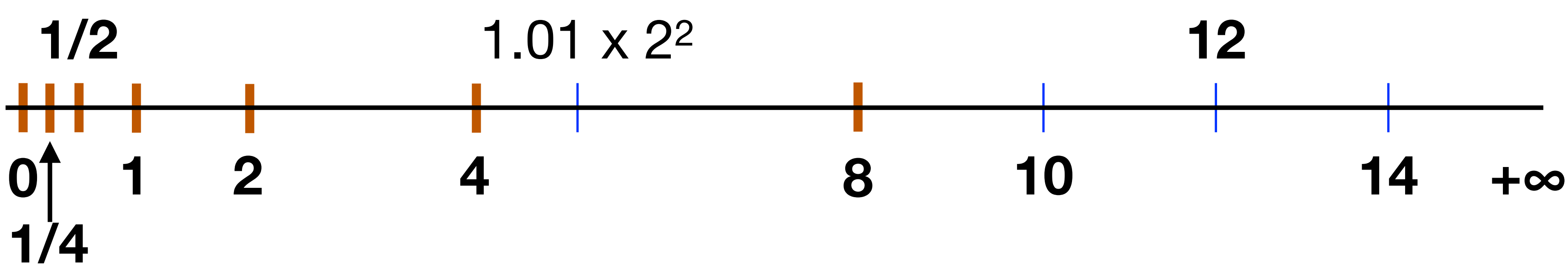


Representable Numbers (Positive Only)

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

0	101	01

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

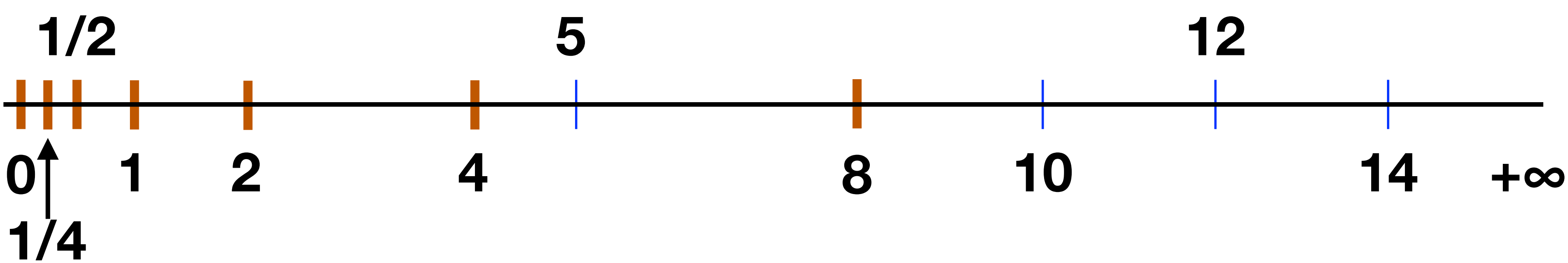


Representable Numbers (Positive Only)

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

0	101	01

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

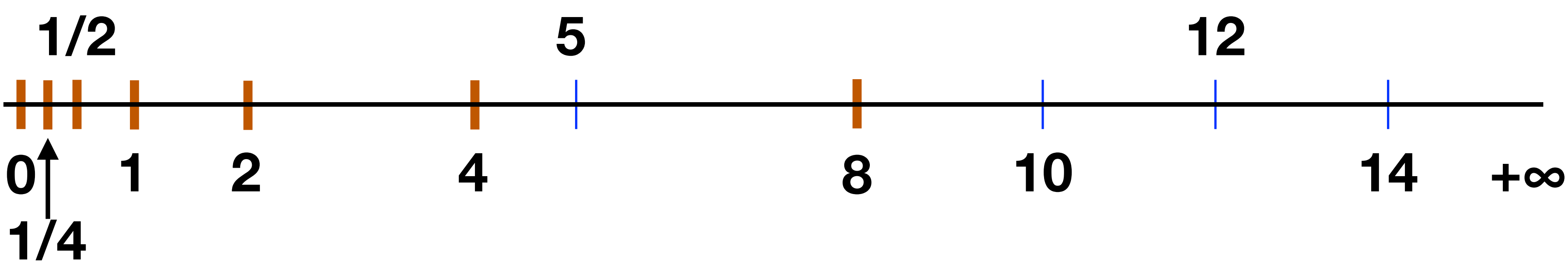


Representable Numbers (Positive Only)

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

0	101	10

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

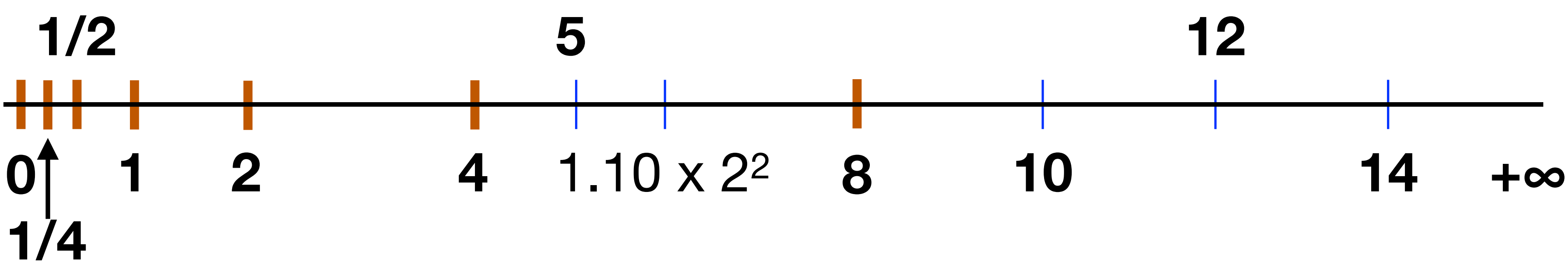


Representable Numbers (Positive Only)

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

0	101	10

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

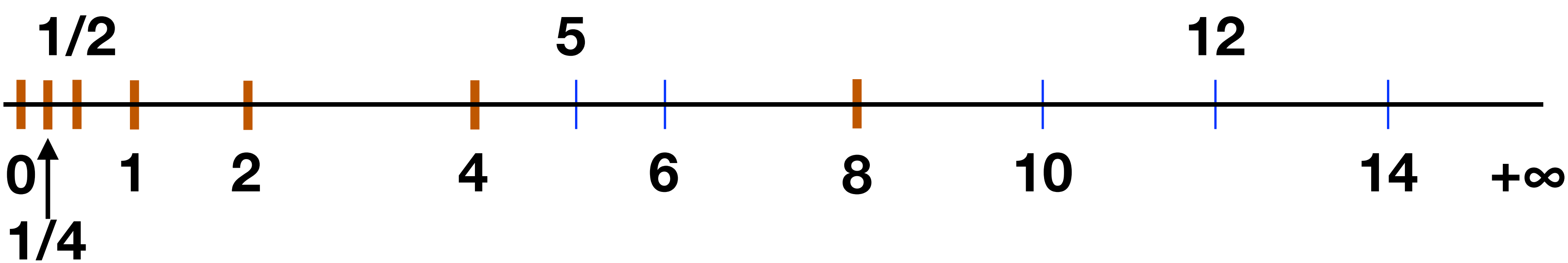


Representable Numbers (Positive Only)

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

0	101	10

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

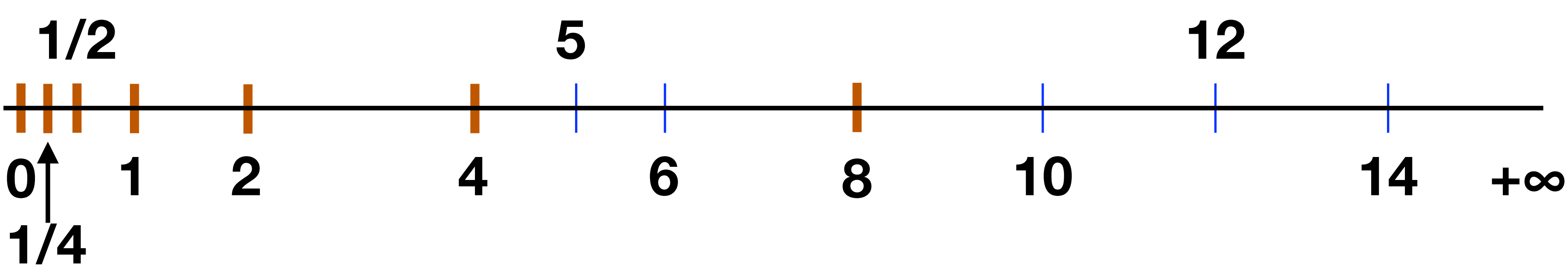


Representable Numbers (Positive Only)

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

0	101	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

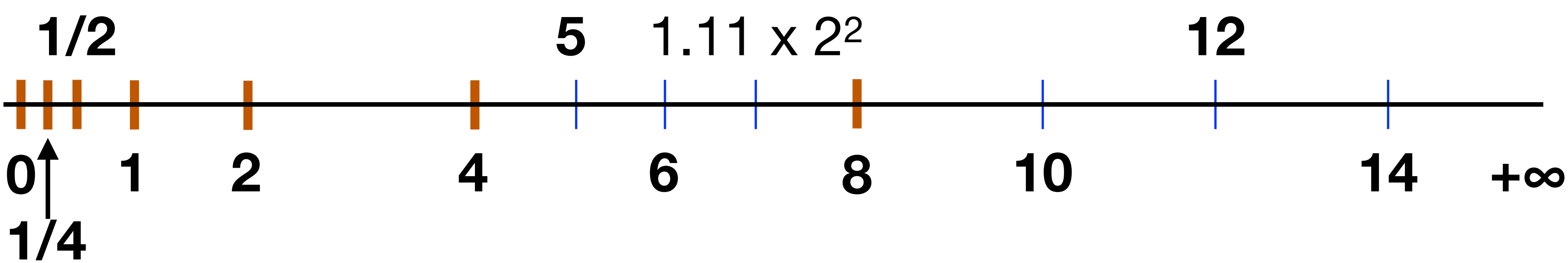


Representable Numbers (Positive Only)

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

0	101	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

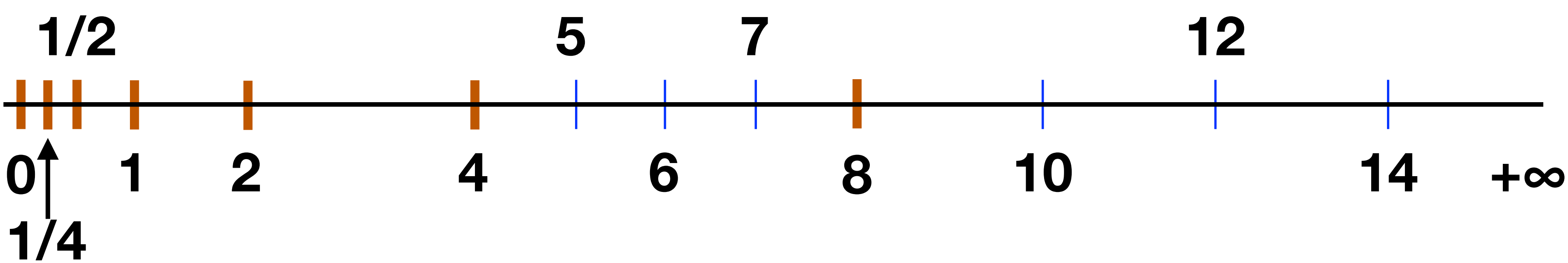


Representable Numbers (Positive Only)

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

0	101	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

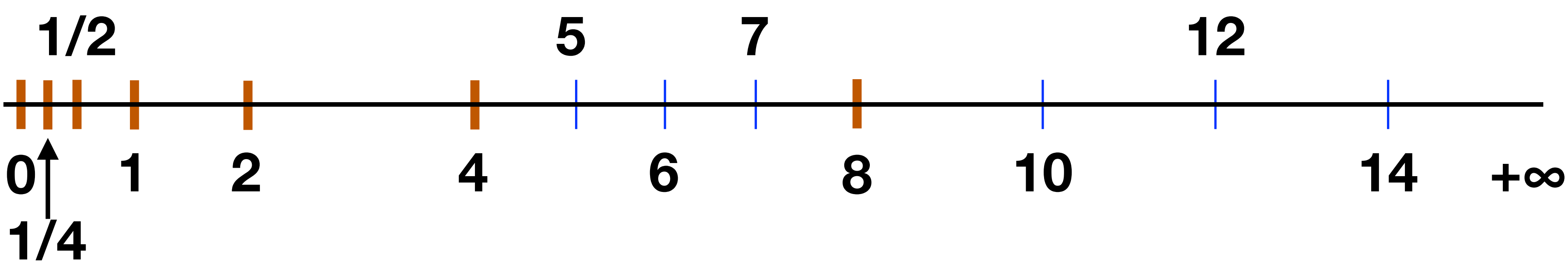


Representable Numbers (Positive Only)

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

0	100	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

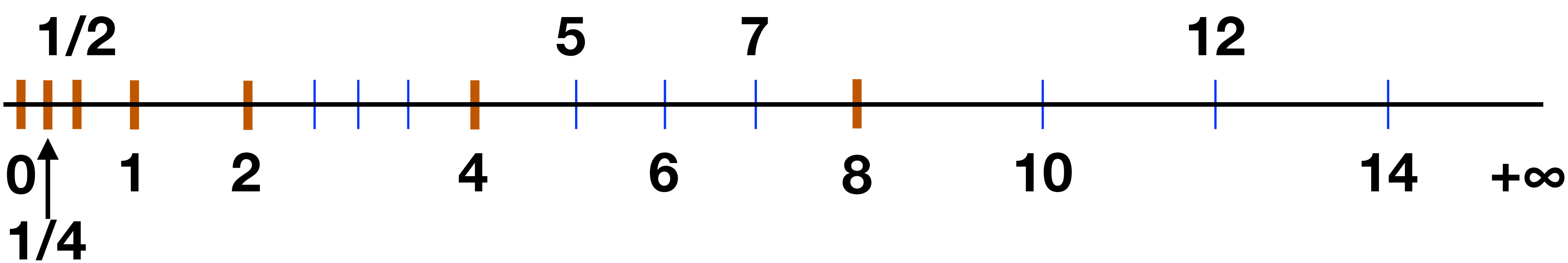


Representable Numbers (Positive Only)

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

0	100	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

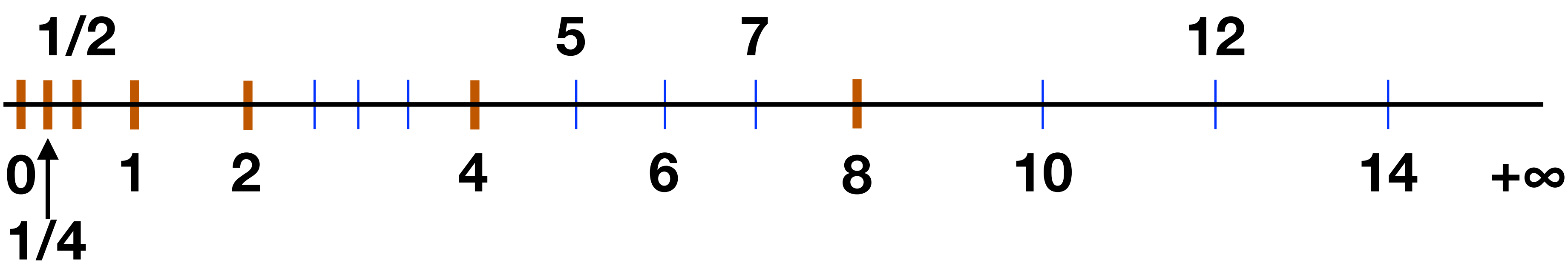


Representable Numbers (Positive Only)

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

0	011	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

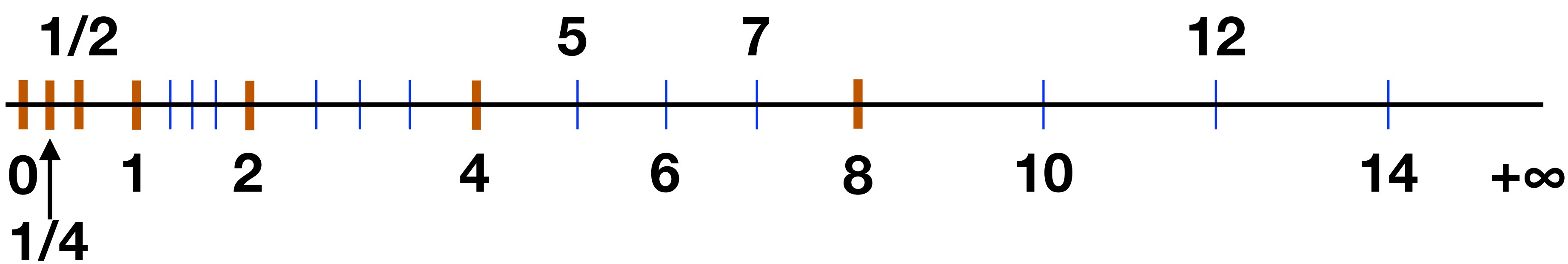


Representable Numbers (Positive Only)

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

0	011	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

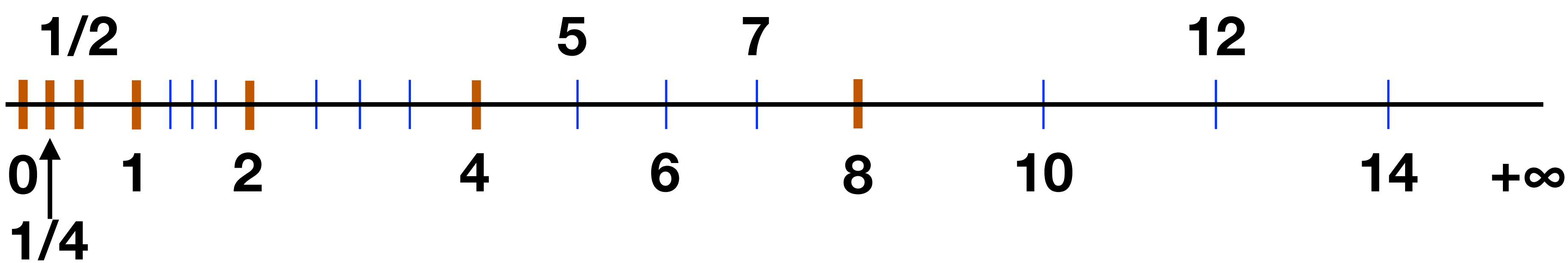


Representable Numbers (Positive Only)

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

0	010	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

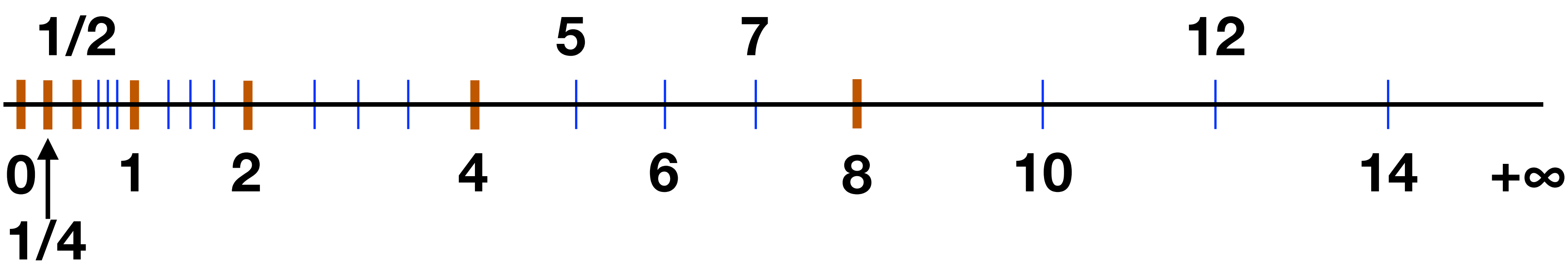


Representable Numbers (Positive Only)

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

0	010	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

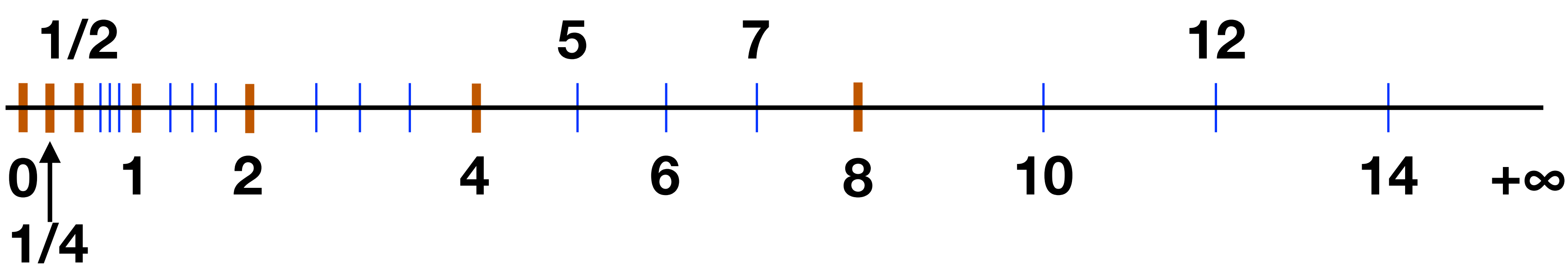


Representable Numbers (Positive Only)

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

0	001	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

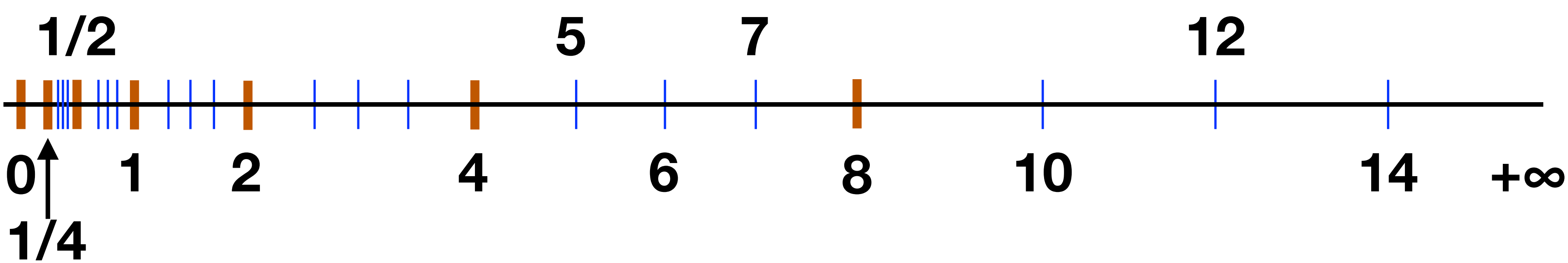


Representable Numbers (Positive Only)

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

0	001	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~



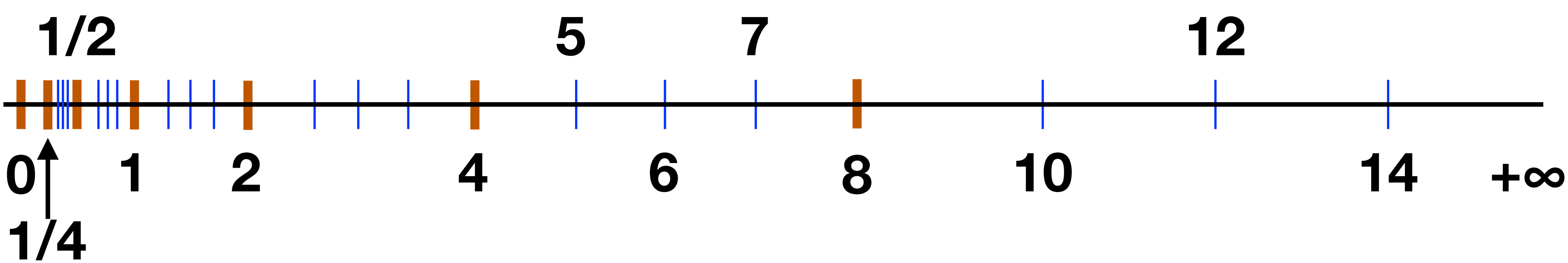
Representable Numbers (Positive Only)

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

0	001	11

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Uneven interval (c.f., fixed interval in fixed-point)
  - More dense toward 0, sparser toward infinite
  - Allow encoding small and large numbers at the same time



Representable Numbers (Positive Only)

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

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

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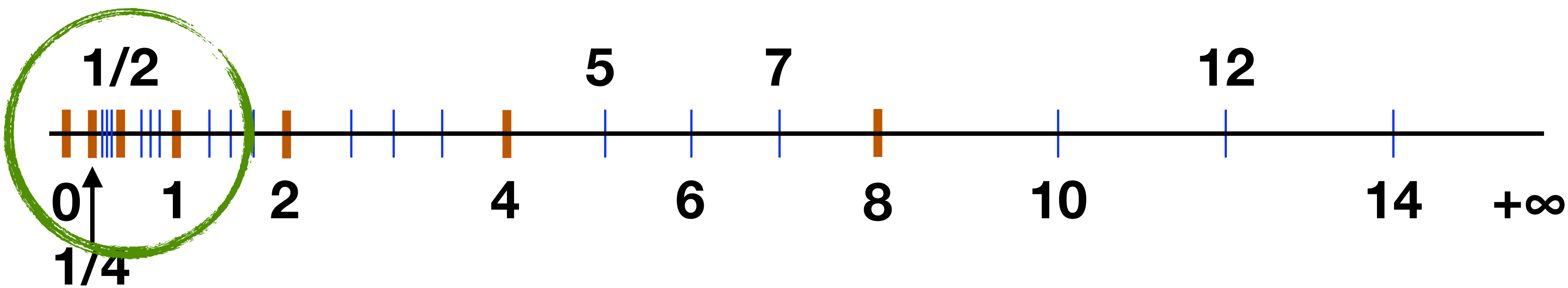
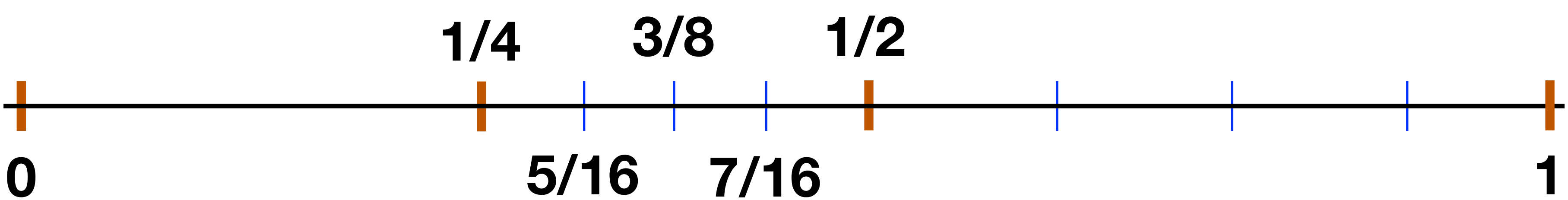


Representable Numbers (Positive Only)

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

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

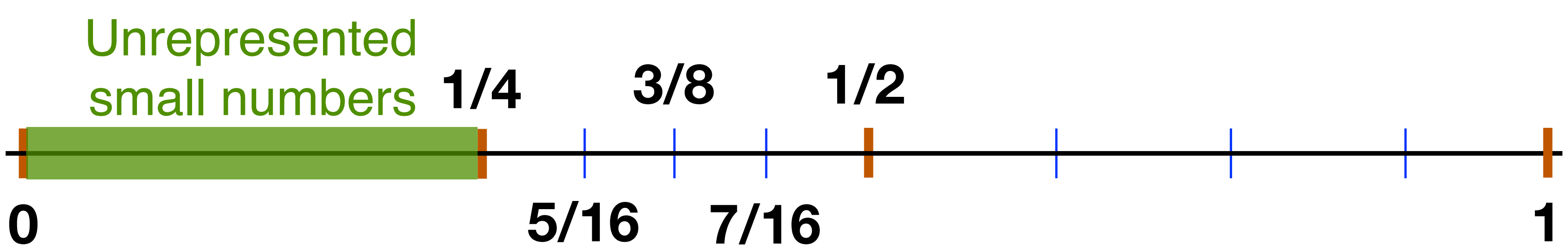


Representable Numbers (Positive Only)

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

s	exp	frac

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~



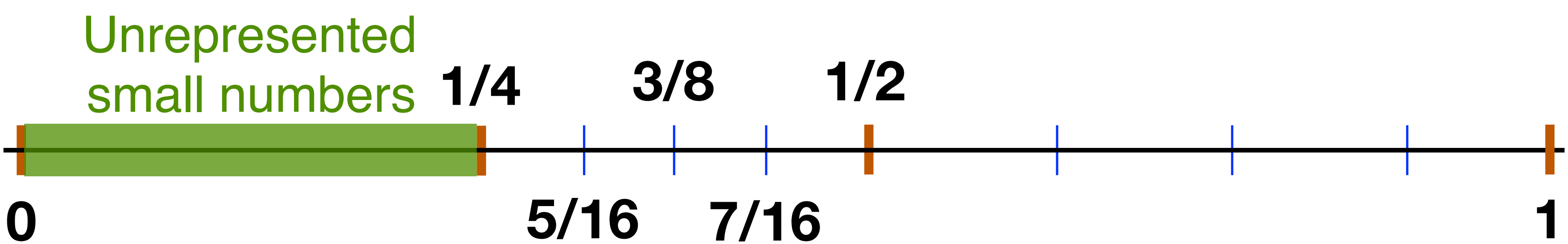
Representable Numbers (Positive Only)

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

s	exp	frac

E	exp	E	exp
~~-3~~	~~000~~	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Always round to 0 is inelegant



Representable Numbers (Positive Only)

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

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

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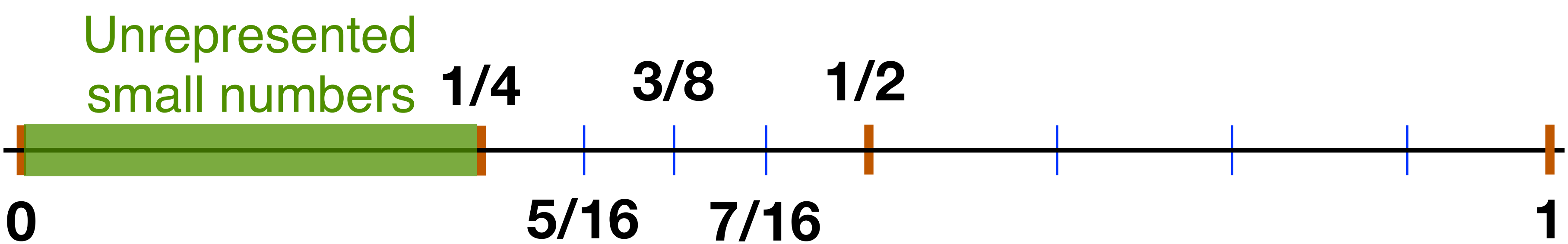

Representable Numbers (Positive Only)

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

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

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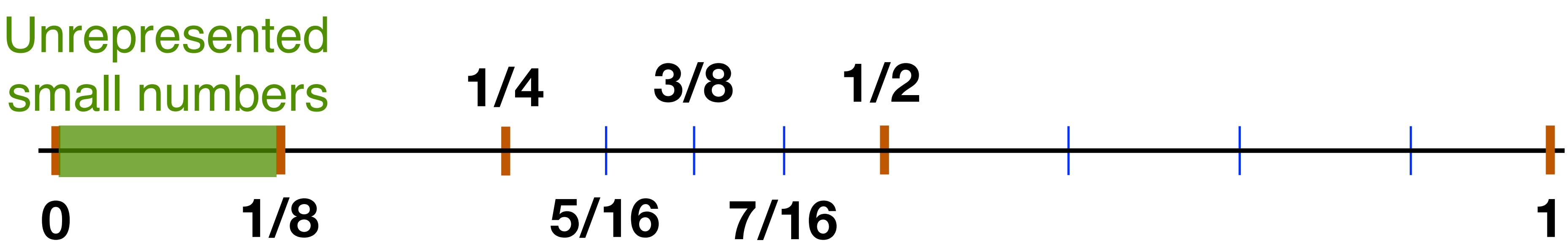


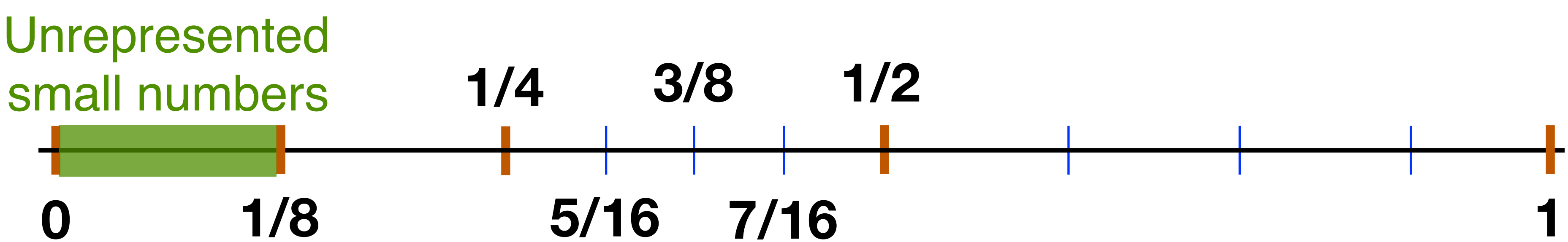
Representable Numbers (Positive Only)

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

s	exp	frac

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Always round to 0 is inelegant
- Using 000 for *exp* would only “delay” the problem rather than solving it



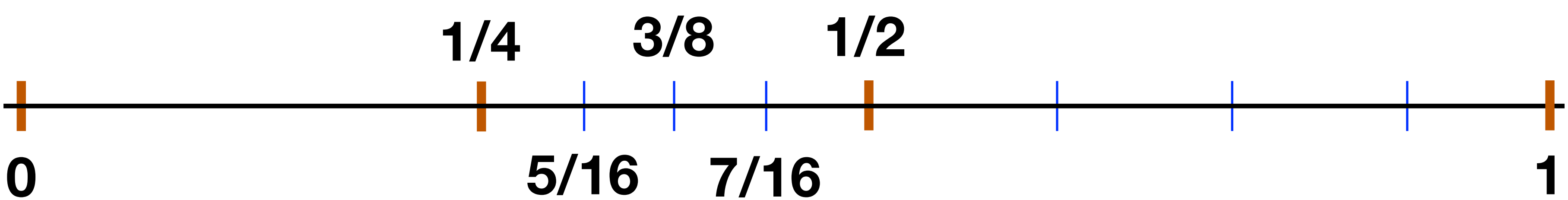
Subnormal (De-normalized) Numbers

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

s	exp	frac

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Idea: Evenly divide between 0 and 1/4 rather than exponentially decreasing **when *exp* = 0** (subnormal/denormalized numbers)



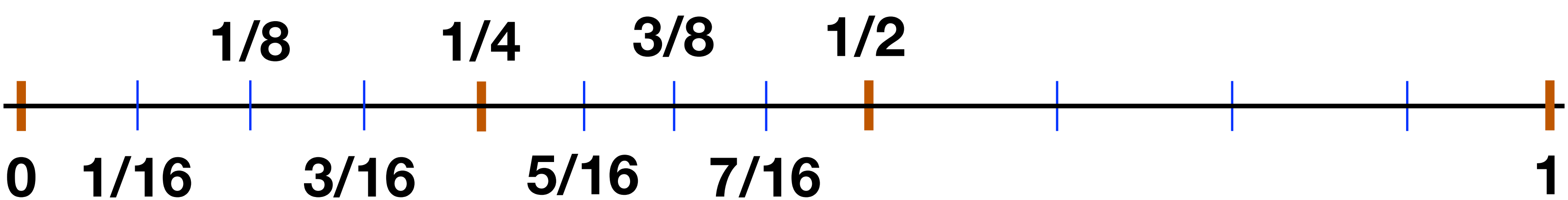
Subnormal (De-normalized) Numbers

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

s	exp	frac

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Idea: Evenly divide between 0 and 1/4 rather than exponentially decreasing **when *exp* = 0** (subnormal/denormalized numbers)



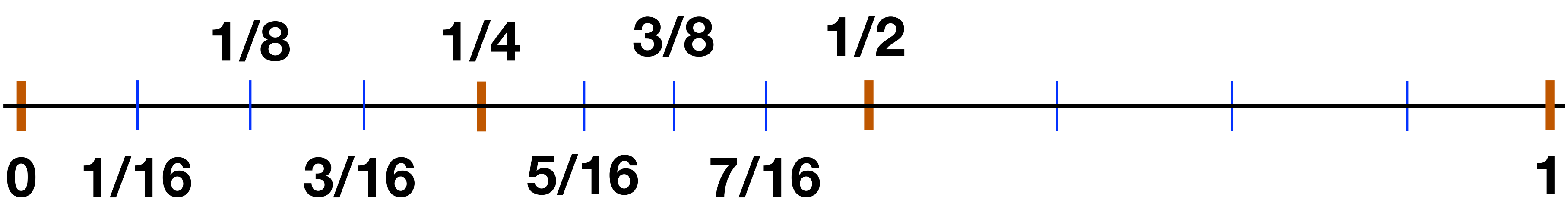
Subnormal (De-normalized) Numbers

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

s	exp	frac

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Idea: Evenly divide between 0 and 1/4 rather than exponentially decreasing **when *exp* = 0** (subnormal/denormalized numbers)
- $E = (exp + 1) - \text{bias}$ (instead of *exp* - *bias*)
- $M = 0.frac$ (instead of 1.frac)



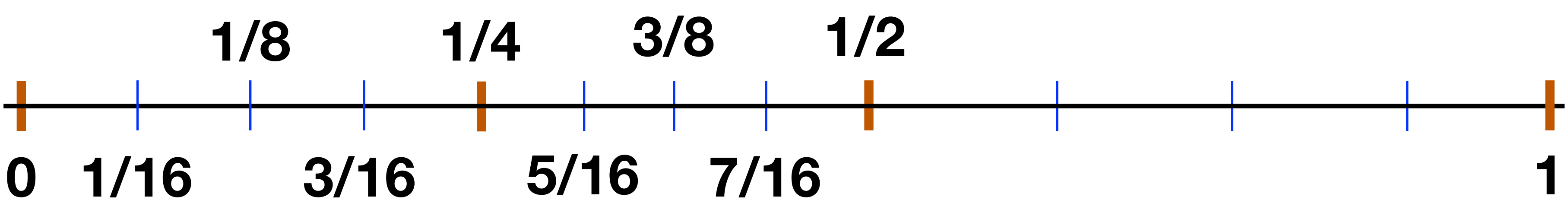
Subnormal (De-normalized) Numbers

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

s	exp	frac

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Idea: Evenly divide between 0 and 1/4 rather than exponentially decreasing **when *exp* = 0** (subnormal/denormalized numbers)
- $E = (exp + 1) - \text{bias}$ (instead of *exp* - *bias*)
- $M = 0.frac$ (instead of 1.frac)



0	000	01

$= (-1)^0 \, 0.01 \times 2^{(0+1-3)} = 1/16$

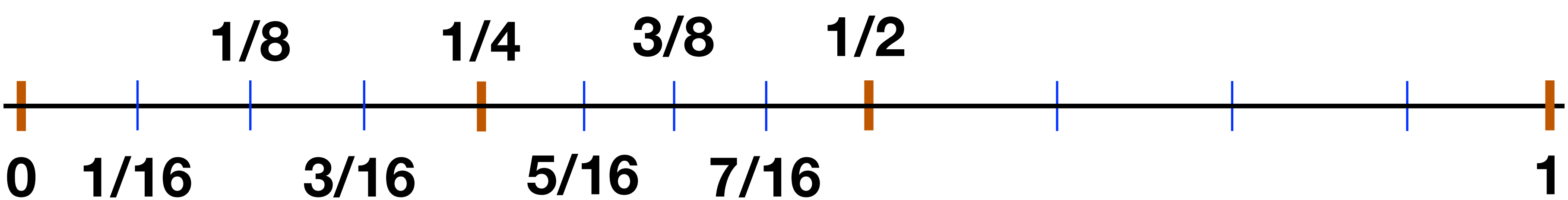
Subnormal (De-normalized) Numbers

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

s	exp	frac

E	exp	E	exp
-3	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- Idea: Evenly divide between 0 and 1/4 rather than exponentially decreasing **when *exp* = 0** (subnormal/denormalized numbers)
- $E = (exp + 1) - \text{bias}$ (instead of *exp* - *bias*)
- $M = 0.frac$ (instead of 1.frac)
- Subnormal numbers allow graceful underflow



0	000	01

$= (-1)^0 \, 0.01 \times 2^{(0+1-3)} = 1/16$

Special Values

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

s	exp	frac

E	exp	E	exp
-2	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

Special Values

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

s	exp	frac

E	exp	E	exp
-2	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- There are many special values in scientific computing
  - +/- ∞, Not-a-Numbers (NaNs) (e.g., 0 / 0, 0 / ∞, ∞ / ∞, sqrt(–1), ∞ - ∞, ∞ x 0, etc.)

Special Values

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

E	exp	E	exp
-2	000	1	100
-2	001	2	101
-1	010	3	110
0	011	~~4~~	~~111~~

- There are many special values in scientific computing
  - +/- ∞, Not-a-Numbers (NaNs) (e.g., 0 / 0, 0 / ∞, ∞ / ∞, sqrt(–1), ∞ - ∞, ∞ x 0, etc.)
- exp = 111 is reserved to represent these numbers

Special Values

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

s	exp	frac

E	exp	E	exp
-2	000	1	100
-2	001	2	101
-1	010	3	110
0	011		111

- There are many special values in scientific computing
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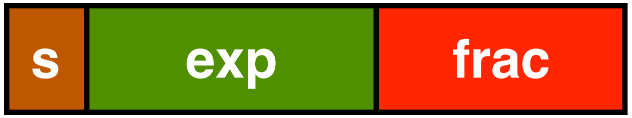
Special Values

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

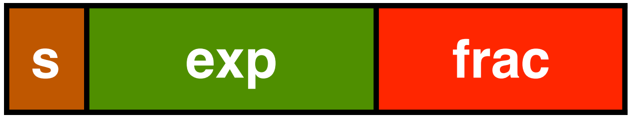


E	exp	E	exp
-2	000	1	100
-2	001	2	101
-1	010	3	110
0	011		111

- There are many special values in scientific computing
  - +/- ∞, Not-a-Numbers (NaNs) (e.g., 0 / 0, 0 / ∞, ∞ / ∞, sqrt(–1), ∞ - ∞, ∞ x 0, etc.)
- exp = 111 is reserved to represent these numbers
- exp = 111, frac = 00
  - +/- ∞ (depending on the *s* bit). Overflow results.
  - Arithmetic on ∞ is exact: 1.0/0.0 = –1.0/–0.0 = + ∞, 1.0/–0.0 = -∞

Special Values

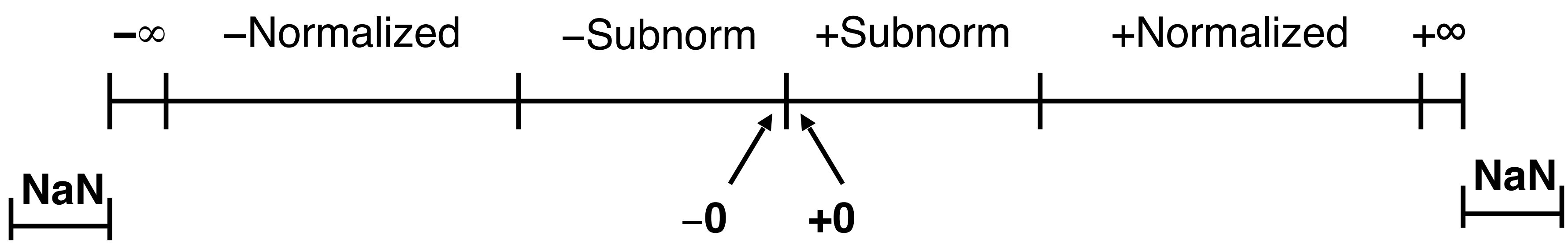
$$v = (-1)^s \, M \, 2^E$$



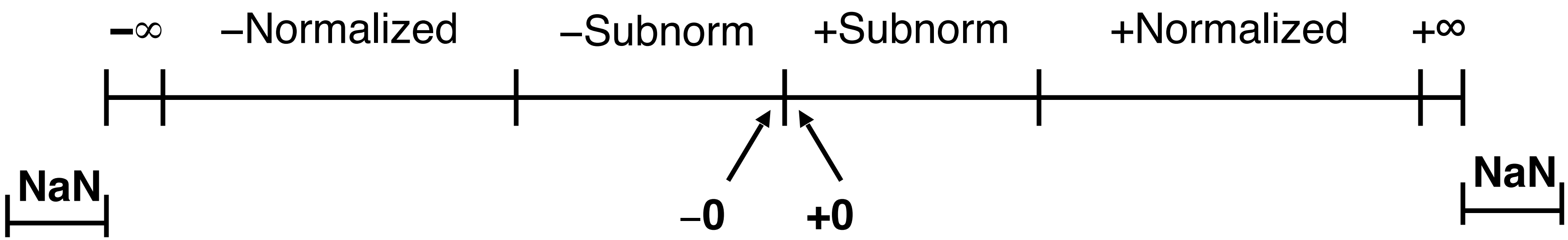
E	exp	E	exp
-2	000	1	100
-2	001	2	101
-1	010	3	110
0	011		111

- There are many special values in scientific computing
  - +/- ∞, Not-a-Numbers (NaNs) (e.g., 0 / 0, 0 / ∞, ∞ / ∞, sqrt(–1), ∞ - ∞, ∞ x 0, etc.)
- exp = 111 is reserved to represent these numbers
- exp = 111, frac = 00
  - +/- ∞ (depending on the *s* bit). Overflow results.
  - Arithmetic on ∞ is exact: 1.0/0.0 = –1.0/–0.0 = + ∞, 1.0/–0.0 = -∞
- exp = 111, frac != 00
  - Represent NaNs

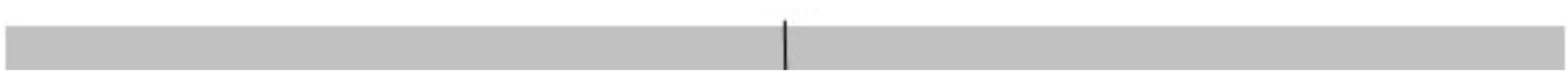
Visualization: Floating Point Encodings



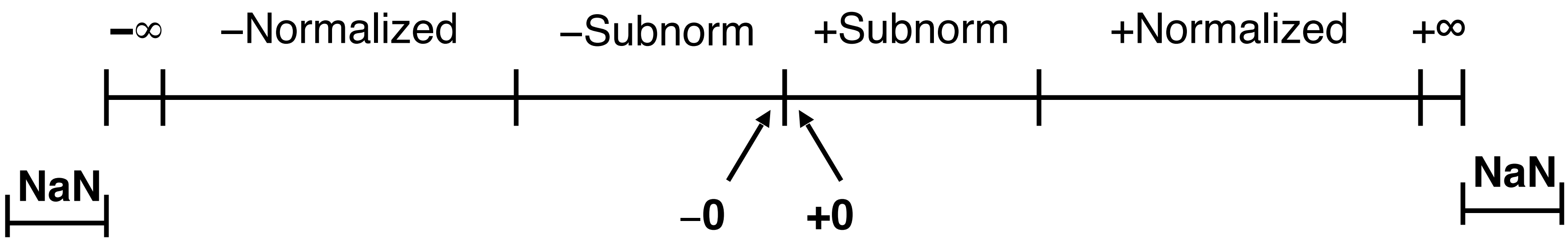
Visualization: Floating Point Encodings



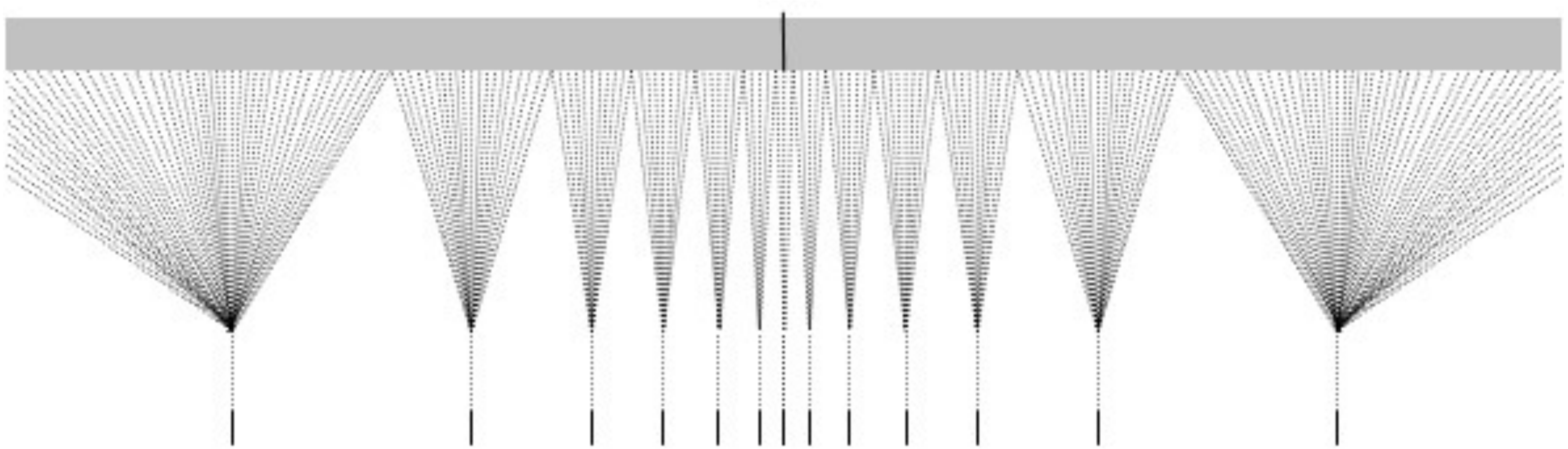
Infinite Amount of Real Numbers



Visualization: Floating Point Encodings

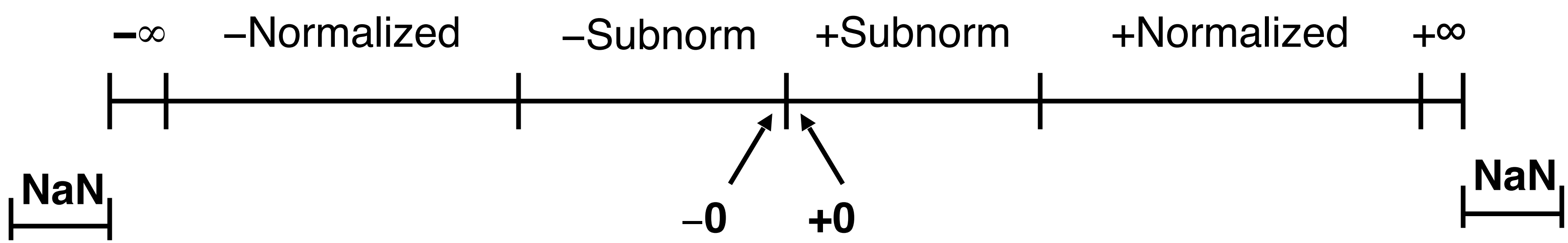


Infinite Amount of Real Numbers

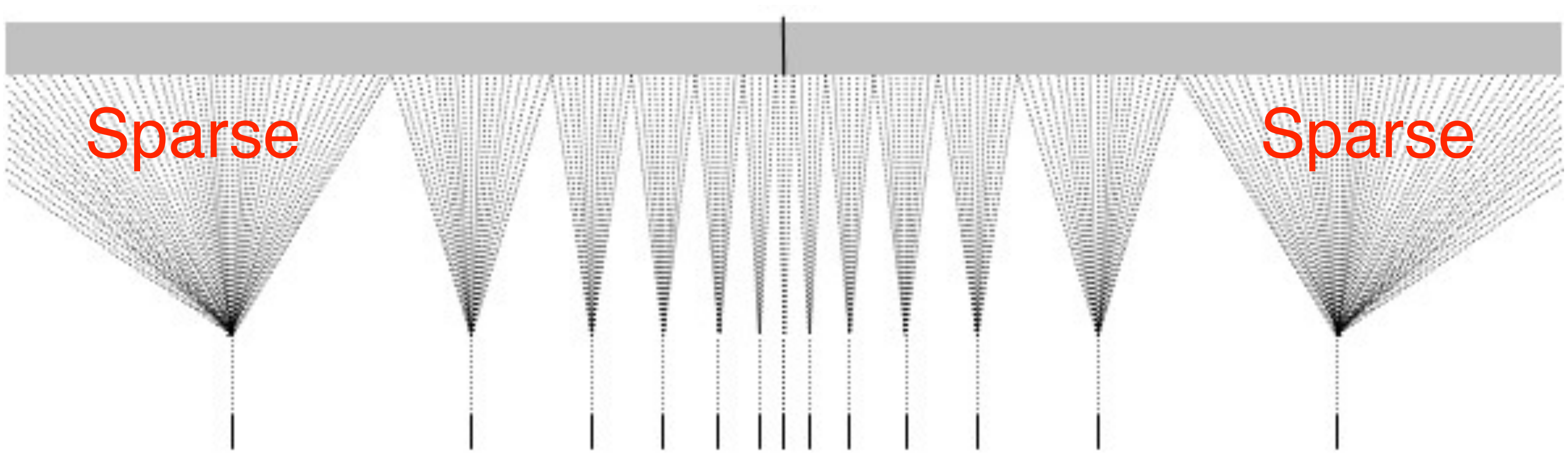


Finite Amount of Floating Point Numbers

Visualization: Floating Point Encodings

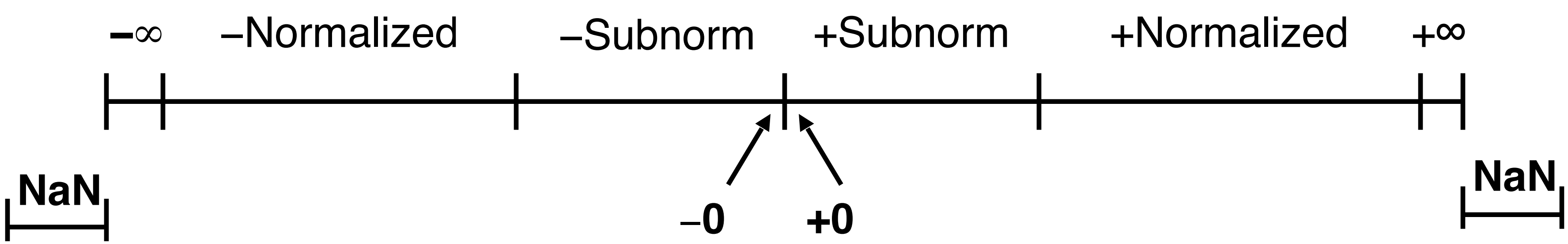


Infinite Amount of Real Numbers

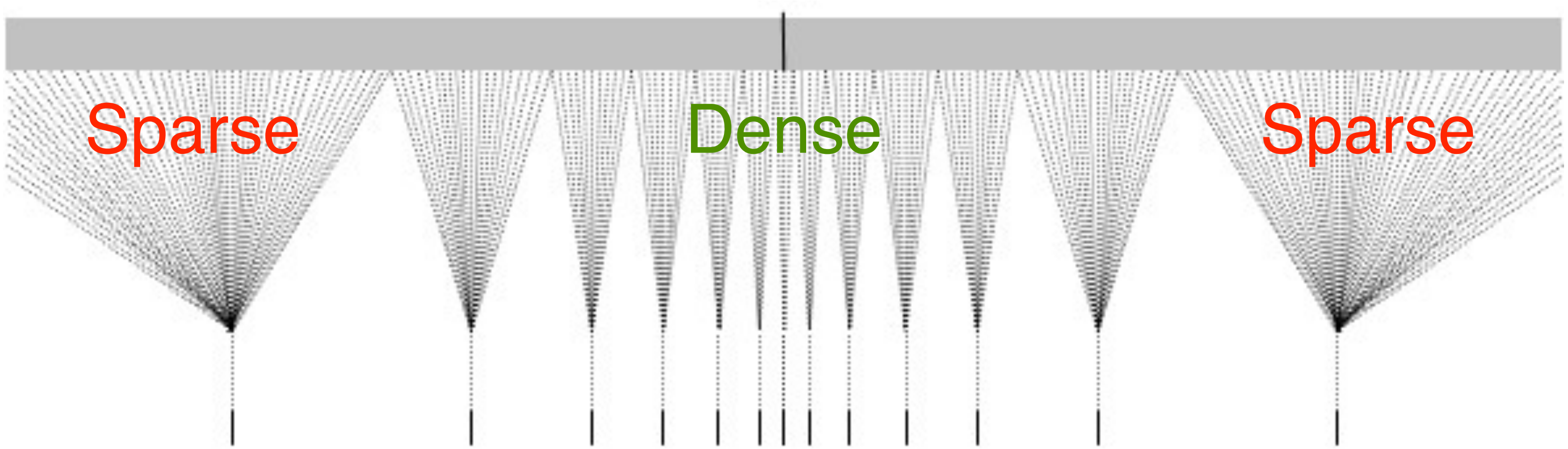


Finite Amount of Floating Point Numbers

Visualization: Floating Point Encodings



Infinite Amount of Real Numbers



Finite Amount of Floating Point Numbers

Today: Floating Point

- Background: Fractional binary numbers and fixed-point
- Floating point representation
- IEEE 754 standard
- Rounding, addition, multiplication
- Floating point in C
- Summary

IEEE 754 Floating Point Standard

- Single precision: 32 bits

s	exp	frac
1	8-bit	23-bit

- Double precision: 64 bits

s	exp	frac
1	11-bit	52-bit

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 (and even GPUs and other processors)

- 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

Single Precision (32-bit) Example

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

bias = $2^{(8-1)}-1 = 127$

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

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1	8-bit	23-bit

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Floating Point Computations

- The problem: Computing on floating point numbers might produce a result that can't be precisely represented
- Basic idea
  - We perform the operation & produce the infinitely precise result
  - Make it fit into desired precision
    - Possibly overflow if exponent too large
    - Possibly round to fit into frac

Rounding Modes (Decimal)

- Common ones:
  - Towards zero (chop)
  - Round down ($-\infty$)
  - Round up ($+\infty$)

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Rounding Mode	**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

Rounding Modes (Binary Example)

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- Assuming 3 bits for *frac*

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Precise Value	Rounded Value	Notes
1.000011	1.000	1.000 is the nearest (down)
1.000110	1.001	1.001 is the nearest (up)
1.000100	1.000	1.000 is the nearest even (down)
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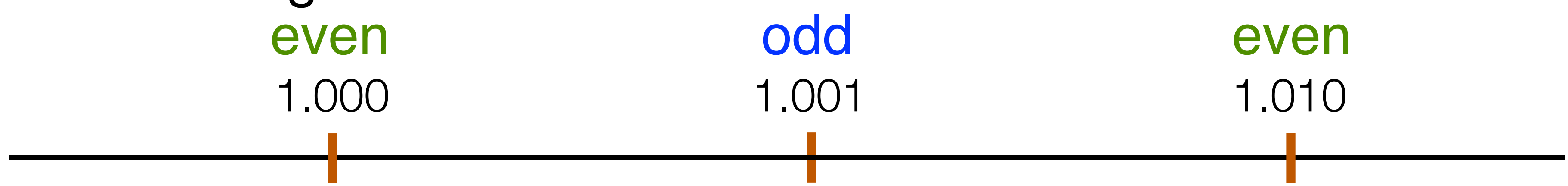

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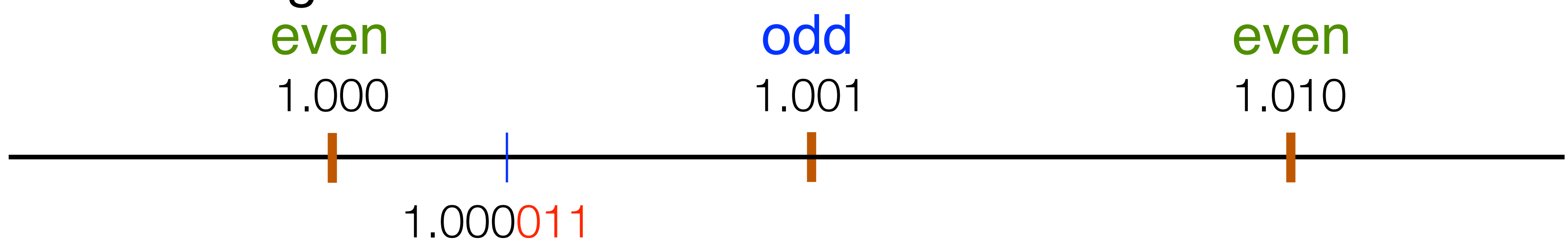

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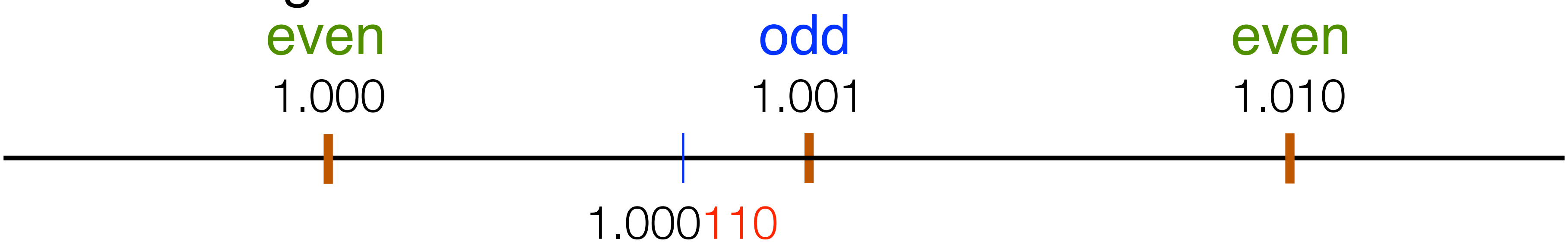

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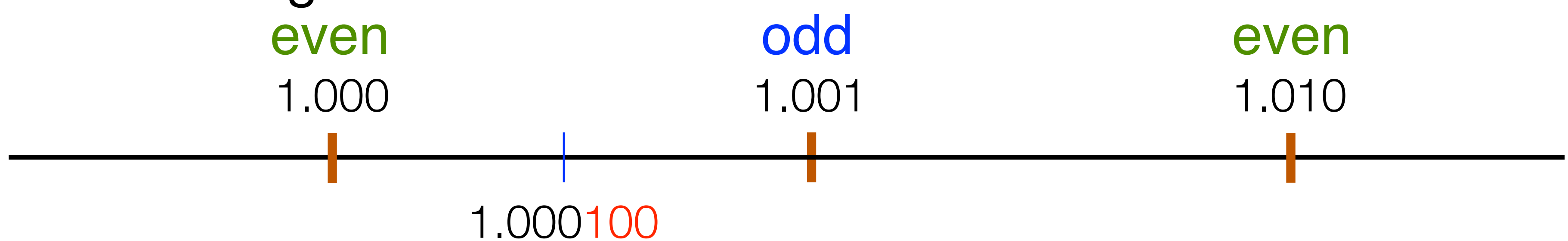

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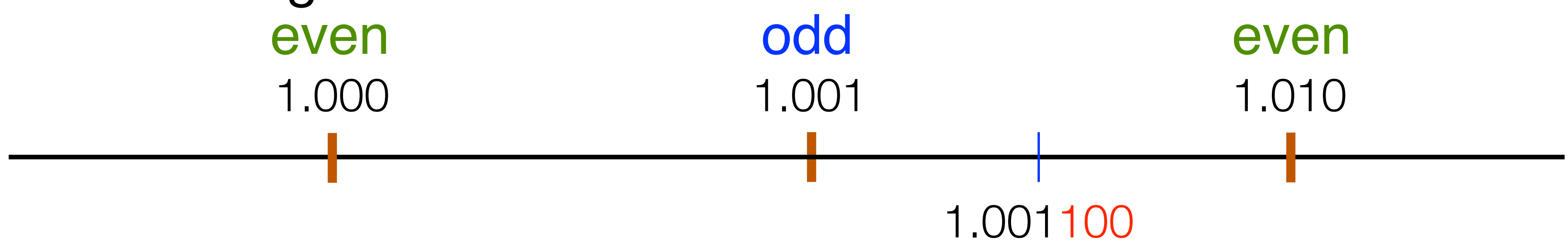

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Floating Point Addition

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

$1.000 \times 2^{-1} + 11.10 \times 2^{-3}$

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$\downarrow$

align $1.000 \times 2^{-1} + 0.111 \times 2^{-1}$

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add $\quad 1.111 \times 2^{-1}$

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- Exact Result: $(-1)^{s}\ M\ \ 2^{E}$
  - Sign *s*, significand *M*:
    - Result of signed align & add
  - Exponent E: E1
    - Assume E1 > E2

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$$1.111 \times 2^{-1}$$

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    - Assume E1 > E2
- 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

$1.000 \times 2^{-1} + 11.10 \times 2^{-3}$

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1.111×2^{-1}

Mathematical Properties of FP Add

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- Commutative?

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  - Overflow and inexactness of rounding
  - `(3.14+1e10)-1e10 = 0, 3.14+(1e10-1e10) = 3.14`

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

Floating Point Multiplication

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  - Significand M: $M1$ x $M2$
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  - If M ≥ 2, shift M right, increment E
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    - 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

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  - Ex: `(1e20*1e20)*1e-20= inf, 1e20*(1e20*1e-20)= 1e20`

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- Multiplication distributes over addition? ***No***
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  - `1e20*(1e20-1e20)= 0.0,  1e20*1e20 - 1e20*1e20 = NaN`

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

Floating Point Review

$$v = (-1)^{s} \times 1.\mathit{frac} \times 2^{E}$$

Floating Point Review

$v = (-1)^s \times 1.frac \times 2^E$

s	exp	frac

Denormalized

s	*exp*	*frac*	**Value**	**Value**
0	000	00	0.00×2^{-2}	0
0	000	11	0.11×2^{-2}	3/16

- Denormalized (exp == 000)
  - E = (exp + 1) – bias
  - M = 0.frac

Floating Point Review

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- Denormalized (exp == 000)
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- Normalized (exp != 000)
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  - M = 1.frac

Denormalized

Normalized

s	***exp***	***frac***	**Value**	**Value**
0	000	00	0.00×2^{-2}	0
0	000	11	0.11×2^{-2}	3/16
0	001	00	1.00×2^{-2}	1/4
0	001	11	1.11×2^{-2}	7/16
0	010	00	1.00×2^{-1}	1/2
0	010	11	1.11×2^{-1}	7/8
0	100	00	1.00×2^{0}	1
0	100	11	1.11×2^{0}	1 3/4
0	101	00	1.00×2^{1}	2
0	101	11	1.11×2^{1}	3 1/2
0	110	00	1.00×2^{2}	4
0	110	11	1.11×2^{2}	7

Floating Point Review

$$v = (-1)^s \times 1.\mathit{frac} \times 2^E$$

s	exp	frac

- Denormalized (exp == 000)
  - E = (exp + 1) – bias
  - M = 0.frac
- Normalized (exp != 000)
  - E = exp – bias
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Denormalized

Normalized

Special Value

s	*exp*	*frac*	Value	Value
0	000	00	0.00×2^{-2}	0
0	000	11	0.11×2^{-2}	3/16
0	001	00	1.00×2^{-2}	1/4
0	001	11	1.11×2^{-2}	7/16
0	010	00	1.00×2^{-1}	1/2
0	010	11	1.11×2^{-1}	7/8
0	100	00	1.00×2^{0}	1
0	100	11	1.11×2^{0}	1 3/4
0	101	00	1.00×2^{1}	2
0	101	11	1.11×2^{1}	3 1/2
0	110	00	1.00×2^{2}	4
0	110	11	1.11×2^{2}	7
0	111	00	infinite	infinite
0	111	11	NaN	NaN

Floating Point Review

	s	exp	frac	Value	Value
Denormalized	0	000	00	0.00×2^{-2}	0
	0	000	11	0.11×2^{-2}	3/16
Normalized	0	001	00	1.00×2^{-2}	1/4
	0	001	11	1.11×2^{-2}	7/16
	0	010	00	1.00×2^{-1}	1/2
	0	010	11	1.11×2^{-1}	7/8
	0	100	00	1.00×2^{0}	1
	0	100	11	1.11×2^{0}	1 3/4
	0	101	00	1.00×2^{1}	2
	0	101	11	1.11×2^{1}	3 1/2
	0	110	00	1.00×2^{2}	4
	0	110	11	1.11×2^{2}	7
Special Value	0	111	00	infinite	infinite
	0	111	11	NaN	NaN

Floating Point Review

- If you do an integer increment on a positive FP number, you get the next larger FP number.

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	0	000	11	0.11×2^{-2}	3/16
Normalized	0	001	00	1.00×2^{-2}	1/4
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	0	100	11	1.11×2^{0}	1 3/4
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	0	110	00	1.00×2^{2}	4
	0	110	11	1.11×2^{2}	7
Special Value	0	111	00	infinite	infinite
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Floating Point Review

- If you do an integer increment on a positive FP number, you get the next larger FP number.
- Bit patterns representing non-negative numbers are ordered the same way as integers, so could use regular integer comparison.

	s	exp	frac	Value	Value
Denormalized	0	000	00	0.00×2^{-2}	0
	0	000	11	0.11×2^{-2}	3/16
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	0	010	11	1.11×2^{-1}	7/8
	0	100	00	1.00×2^{0}	1
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	0	101	00	1.00×2^{1}	2
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Special Value	0	111	00	infinite	infinite
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Floating Point Review

- If you do an integer increment on a positive FP number, you get the next larger FP number.
- Bit patterns representing non-negative numbers are ordered the same way as integers, so could use regular integer comparison.
- You don't get this property if:
  - *exp* is interpreted as signed
  - *exp* and *frac* are swapped

	s	***exp***	***frac***	**Value**	**Value**
Denormalized	0	000	00	0.00×2^{-2}	0
	0	000	11	0.11×2^{-2}	3/16
Normalized	0	001	00	1.00×2^{-2}	1/4
	0	001	11	1.11×2^{-2}	7/16
	0	010	00	1.00×2^{-1}	1/2
	0	010	11	1.11×2^{-1}	7/8
	0	100	00	1.00×2^{0}	1
	0	100	11	1.11×2^{0}	1 3/4
	0	101	00	1.00×2^{1}	2
	0	101	11	1.11×2^{1}	3 1/2
	0	110	00	1.00×2^{2}	4
	0	110	11	1.11×2^{2}	7
Special Value	0	111	00	infinite	infinite
	0	111	11	NaN	NaN