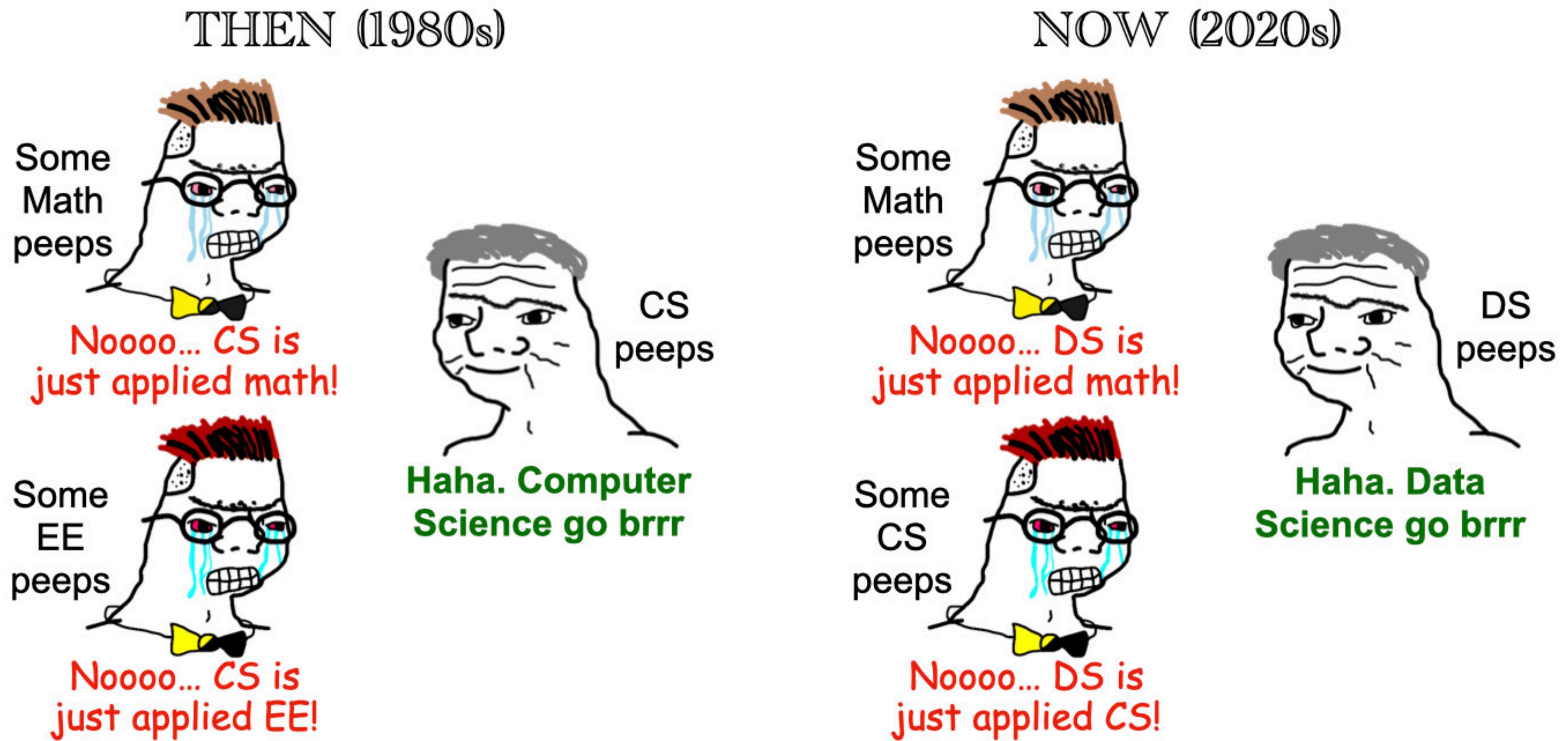


DSC 102

Systems for Scalable Analytics

- Haojian Jin



Meme idea credit: <https://datasystemsfun.tumblr.com/>

Where are we in the class?

Week	Topic	Systems Principles
1-2	Basics of Machine Resources: Computer Organization	
2-3	Basics of Machine Resources: Operating Systems	
4	Basics of Cloud Computing	
4-5	Parallel and Scalable Data Processing: Parallelism Basics	
6	Midterm Exam on TBD	
6-7	Parallel and Scalable Data Processing: Scalable Data Access	
7-8	Parallel and Scalable Data Processing: Data Parallelism	
9	Dataflow Systems	
10	ML Model Building Systems	
11	Final Exam on Dec 15	

Where are we in the class?

- ❖ Basics of Computer Organization
 - ❖ **Digital Representation of Data**
 - ❖ **Binary, integer, float, tradeoffs**
 - ❖ Processors and Memory Hierarchy
- ❖ Basics of Operating Systems
 - ❖ Process Management: Virtualization; Concurrency
 - ❖ Filesystem and Data Files
 - ❖ Main Memory Management
- ❖ Persistent Data Storage

What is data?

データとは、情報の集合です。情報は、物事の特徴や状況などを示す情報であり、データは、その情報を記述する文字や数字などの組合せです。

データには、以下のような種類があります。

- 構造化データ：データが明確なルールで組織されているもの。たとえば、CSVファイルやJSON形式のデータなど。
- 非構造化データ：データが明確なルールで組織されていないもの。たとえば、テキストファイルや画像、音楽などのデータなど。
- 時間系列データ：データが時間の流れとともに収集されたもの。たとえば、気温や降雨量などのデータなど。
- 地理空間データ：データが位置情報を含むもの。たとえば、地図やGPSデータなど。
- 音声データ：データが音波や音楽などの形で表現されるもの。たとえば、音楽や会話などのデータなど。
- 映像データ：データが映像や動画などの形で表現されるもの。たとえば、映画やテレビ番組などのデータなど。

データを用いて、AIや機械学習などの技術によって、さまざまな分析や予測が行われます。

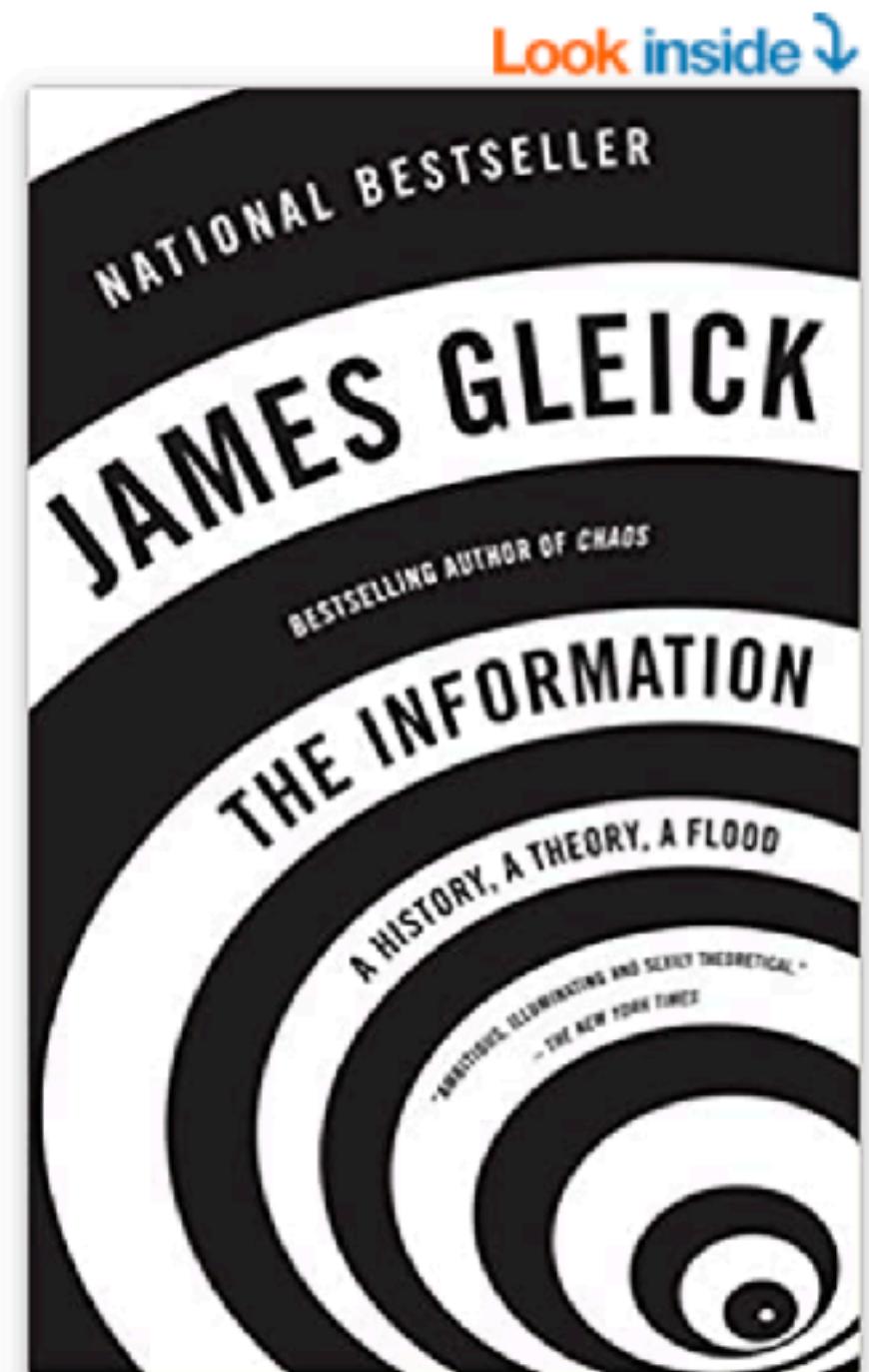
Digital Representation of Data

- **Bits:** 01010101
- **Data type:** Boolean, Byte, Integer, “floating point” number (Float), Character, and String
- **Data structure:** Array, Linked list, Tuple, Graph, etc.

Programmer

Machine?

Why bits?



Listen



[See this image](#)

The Information: A History, A Theory, A Flood Paperback – Illustrated, March 6, 2012

by [James Gleick](#) (Author)

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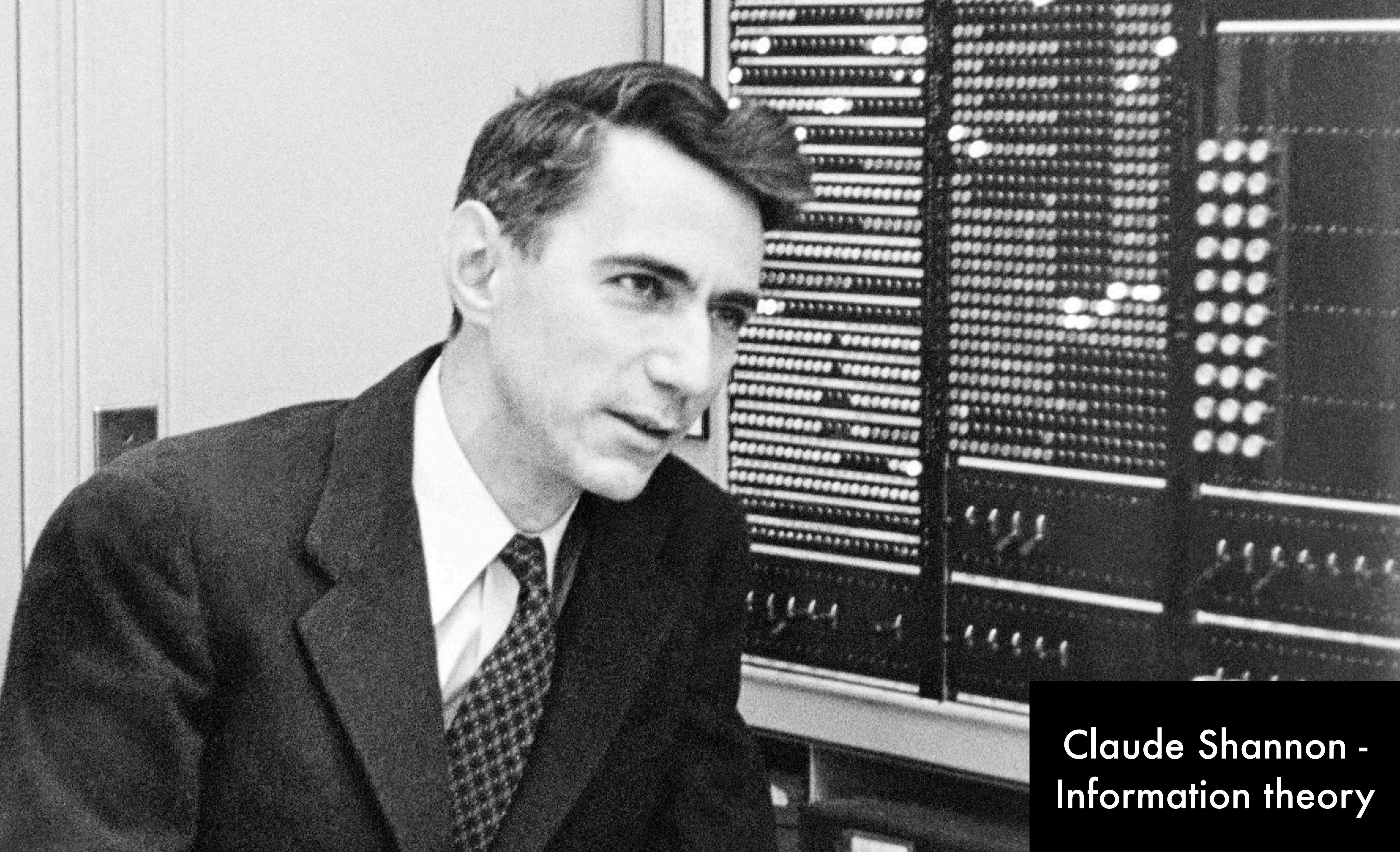
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[8 Used from \\$21.06](#)

From the bestselling author of the acclaimed *Chaos* and *Genius* comes a thoughtful and provocative exploration of the big ideas of the modern era: Information, communication, and information theory.

Acclaimed science writer James Gleick presents an eye-opening vision of how our relationship to information has transformed the very nature of human consciousness. A fascinating intellectual journey through the history of communication and information, from the language of Africa's talking drums to the invention of written alphabets; from the electronic transmission of code to the

[▼ Read more](#)



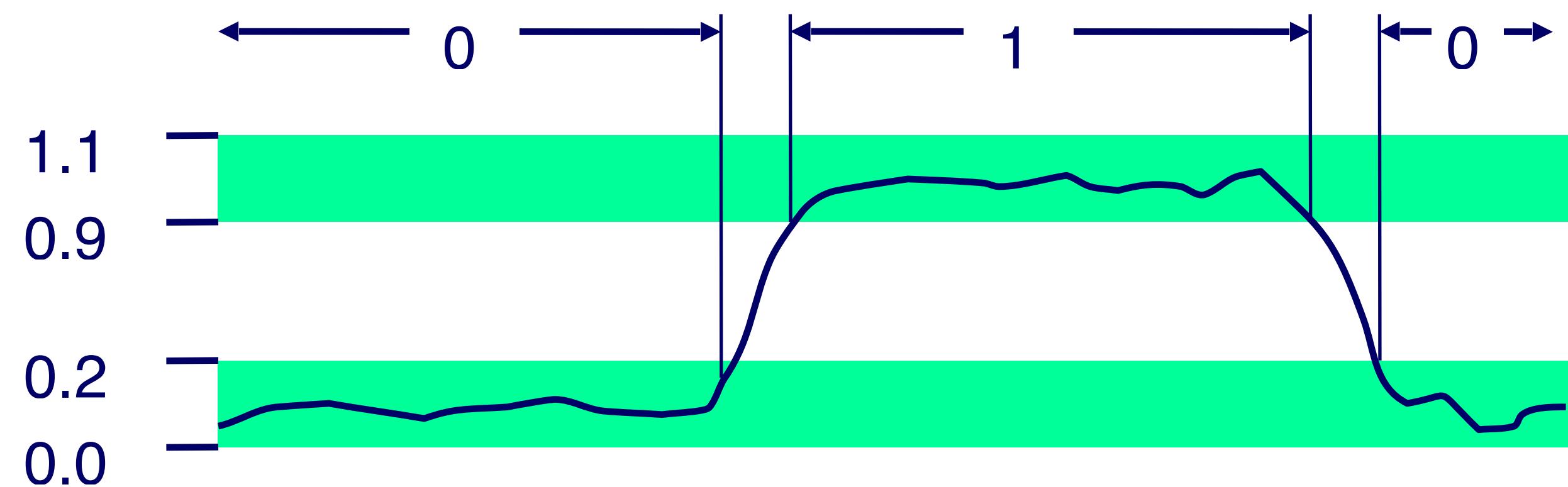
Claude Shannon -
Information theory

Before bits

- By 1948 more than 125 million conversations passed daily through the Bell System's 138 million miles of cable and 31 million telephone sets.
- Count words, characters, electricity consumption, minutes.

Why bits?

- Physics! Electronic Implementation
 - Easy to store with bistable elements.
 - e.g., high-low/off-on electromagnetism on disk.
 - Reliably transmitted on noisy and inaccurate wires
- Very expressive and efficient.
- Quantum computers?



Count everything in binary

- **Base 2 Number Representation**
 - 0, 1, 10, 11, 100, 101, ...
 - Represent 15213_{10} as 0011 1011 0110 1101₂
 - Represent 1.20_{10} as 1.0011 0011 0011 0011 [0011]...₂
 - Represent $(1.5213 \times 10^4)_{10}$ as $(1.1101\ 1011\ 0110\ 1 \times 2^{13})_2$
- **Represent negative numbers as ...?**
 - (we'll come back to this)

Encoding Byte Values

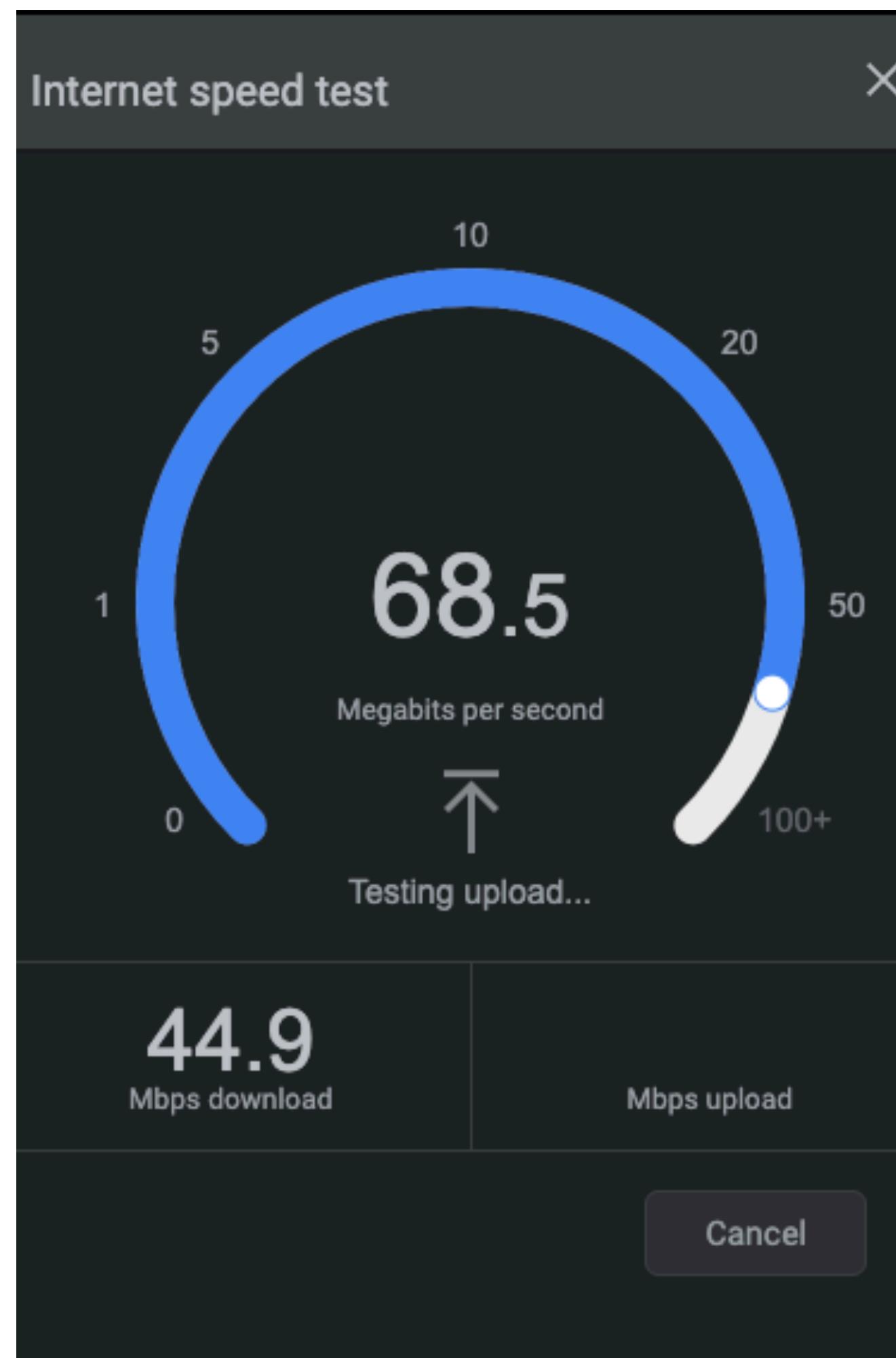
- **Byte = 8 bits. Why?**

- Decimal: 0_{10} to 255_{10}
 - $255 = 2^8 - 1$
- Binary: $0000\ 0000_2$ to $1111\ 1111_2$
- *Hexadecimal*: 00_{16} to FF_{16} .
 - Why? Example: #FF5733, RGB 255, 87, 51
 - Base 16 number representation
 - Use characters '0' to '9' and 'A' to 'F'
 - Write in C with leading '0x', either case

- $0101\ 1010_2 = 0x5a = 0x5A = 0X5a$

15213: 0011 1011 0110 1101
3 B 6 D

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



Name	Size	Kind
HB50 cupcakes.JPG	2 MB	JPEG image
Roller Skating.JPG	1.3 MB	JPEG image
50HBJukebox2.jpg	720 KB	JPEG image
Facebook.tiff	399 KB	TIFF image
7_days_to_enrol.png	173 KB	PNG image
JoggingShoes.jpg	71 KB	JPEG image

Digital Representation of Data

- The size and *interpretation* of a data type depends on PL
- A **Byte** (B; 8 bits) is typically the basic unit of data types
 - CPU can't address anything smaller than a byte.
- **Boolean:**
 - Examples in data sci.: Y/N or T/F responses
 - Just 1 bit needed but actual size is almost always 1B, i.e., 7 bits are wasted! (**Q:** Why?)
- **Integer:**
 - Examples in data science: #friends, age, #likes
 - Typically 4 bytes; many variants (short, unsigned, etc.)
 - Java *int* can represent -2^{31} to $(2^{31} - 1)$; C *unsigned int* can represent 0 to $(2^{32} - 1)$;
Python3 *int* is effectively unlimited length (PL magic!)

Digital Representation of Data

- **Bits:** All digital data are sequences of 0 & 1 (binary digits)
- **Data type:** First layer of abstraction to interpret a bit sequence with a human-understandable category of information; interpretation fixed by the PL
 - Example common datatypes: Boolean, Byte, Integer, “floating point” number (Float), Character, and String
- **Data structure:** A second layer of abstraction to organize multiple instances of same or varied data types as a more complex object with specified properties
 - Examples: Array, Linked list, Tuple, Graph, etc.

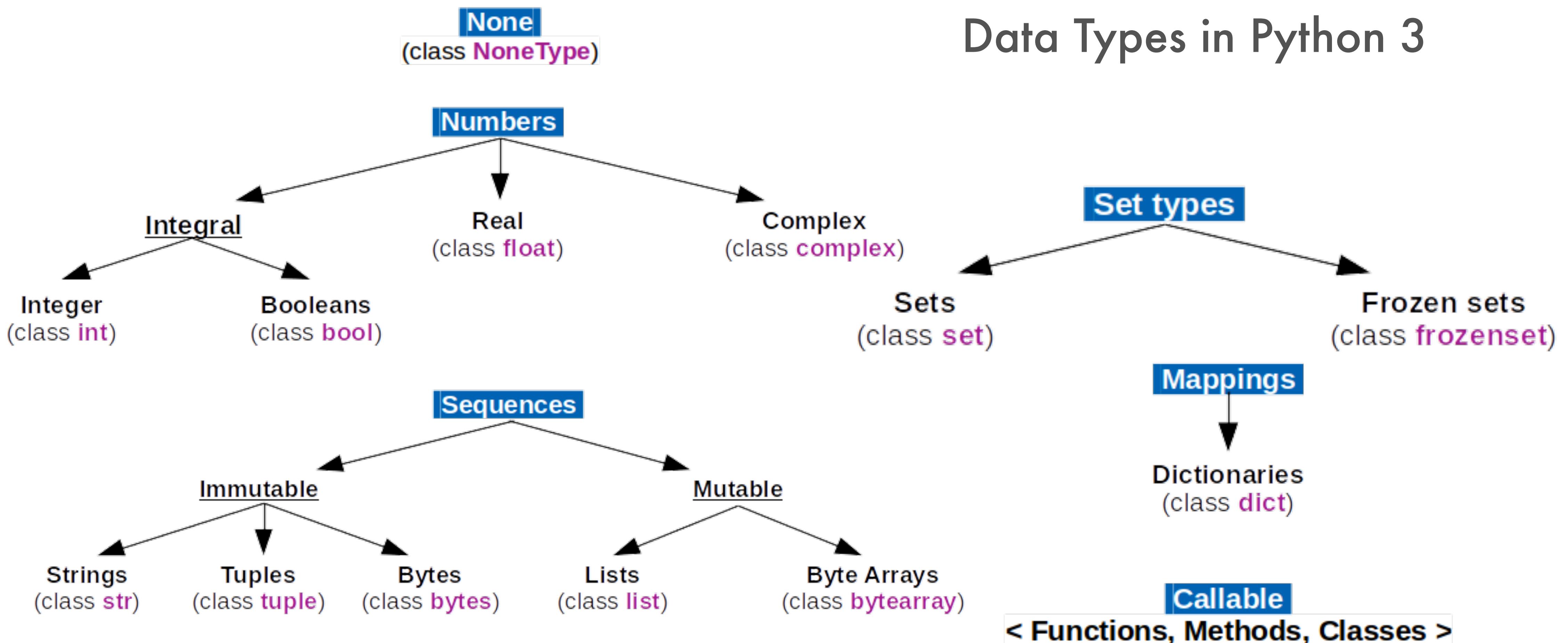
Combine bytes to make *scalar data types*

C Data Type	Size (# of bytes)	
	Typical 32-bit	Typical 64-bit
char	1	1
short	2	2
int	4	4
long	4	8
float	4	4
double	8	8
pointer	4	8

“ILP32” “LP64”

Estimate the object size in
your memory, network,
storage!

Digital Representation of Data



Why?

- Human
- Machine
 - Storage
 - Computation

Digital Representation of Data

Q: How many unique data items can be represented by 3 bytes?

- Given k bits, we can represent 2^k unique data items
- 3 bytes = 24 bits $\Rightarrow 2^{24}$ items, i.e., 16,777,216 items
- Common approximation: 2^{10} (i.e., 1024) $\sim 10^3$ (i.e., 1000); recall kibibyte (KiB) vs kilobyte (KB) and so on

Q: How many bits are needed to distinguish 97 data items?

- For k unique items, invert the exponent to get $\log_2(k)$
- But #bits is an integer! So, we only need $\lceil \log_2(k) \rceil$
- So, we only need the next higher power of 2
- $97 \rightarrow 128 = 2^7$; so, 7 bits

Digital Representation of Data

Q: How to convert from decimal to binary representation?

- Given decimal n, if power of 2 (say, 2^k), put 1 at bit position k; if $k=0$, stop; else pad with trailing 0s till position 0
- If n is not power of 2, identify the power of 2 just below n (say, 2^k); #bits is then k; put 1 at position k
- Reset n as $n - 2^k$; return to Steps 1-2
- Fill remaining positions in between with 0s

	7	6	5	4	3	2	1	0	Position/Exponent of 2
Decimal	128	64	32	16	8	4	2	1	Power of 2
5_{10}						1	0	1	
47_{10}				1	0	1	1	1	
163_{10}	1	0	1	0	0	0	1	1	
16_{10}				1	0	0	0	0	

Q: Binary to decimal?

Digital Representation of Data

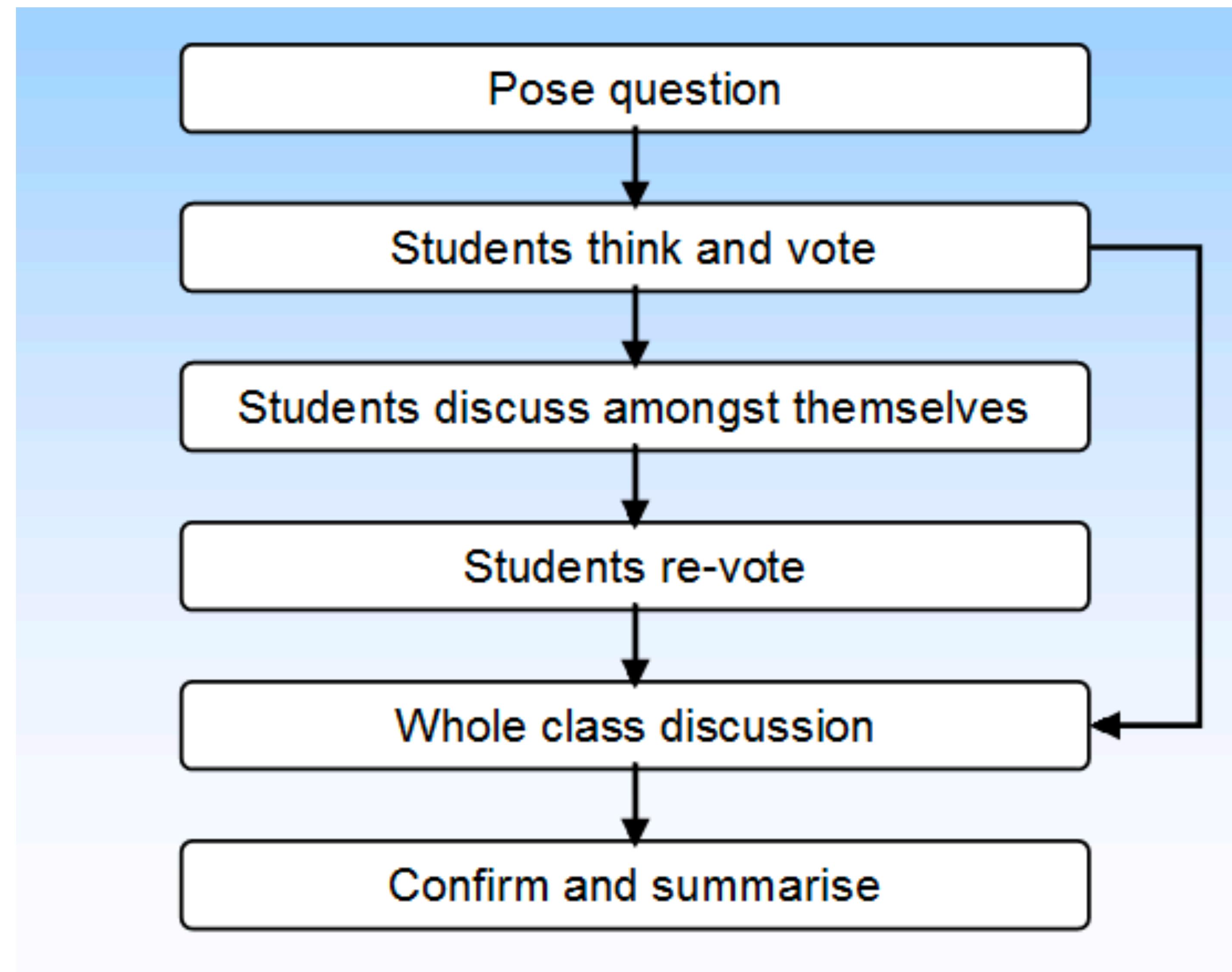
- *Hexadecimal* representation is a common stand-in for binary representation; more succinct and readable
 - Base 16 instead of base 2 cuts display length by $\sim 4x$
 - Digits are 0, 1, ... 9, A (10_{10}), B, ... F (15_{10})
 - From binary: combine 4 bits at a time from lowest

Decimal	Binary	Hexadecimal	
5_{10}	101_2	5_{16}	Alternative notations
47_{10}	$10\ 1111_2$	$2F_{16}$	
163_{10}	$1010\ 0011_2$	$A3_{16}$	$0xA3$ or $A3_H$
16_{10}	$1\ 0000_2$	10_{16}	

Oct 6. 2023

- PIA for basic data representations
- Revisit float representations
- Other data representations
- PIA for float representations (optional)

Peer instruction activity



Peer Instruction Activity

Rough time tip: About 1 min per 1 pt.

Use your UCSD email

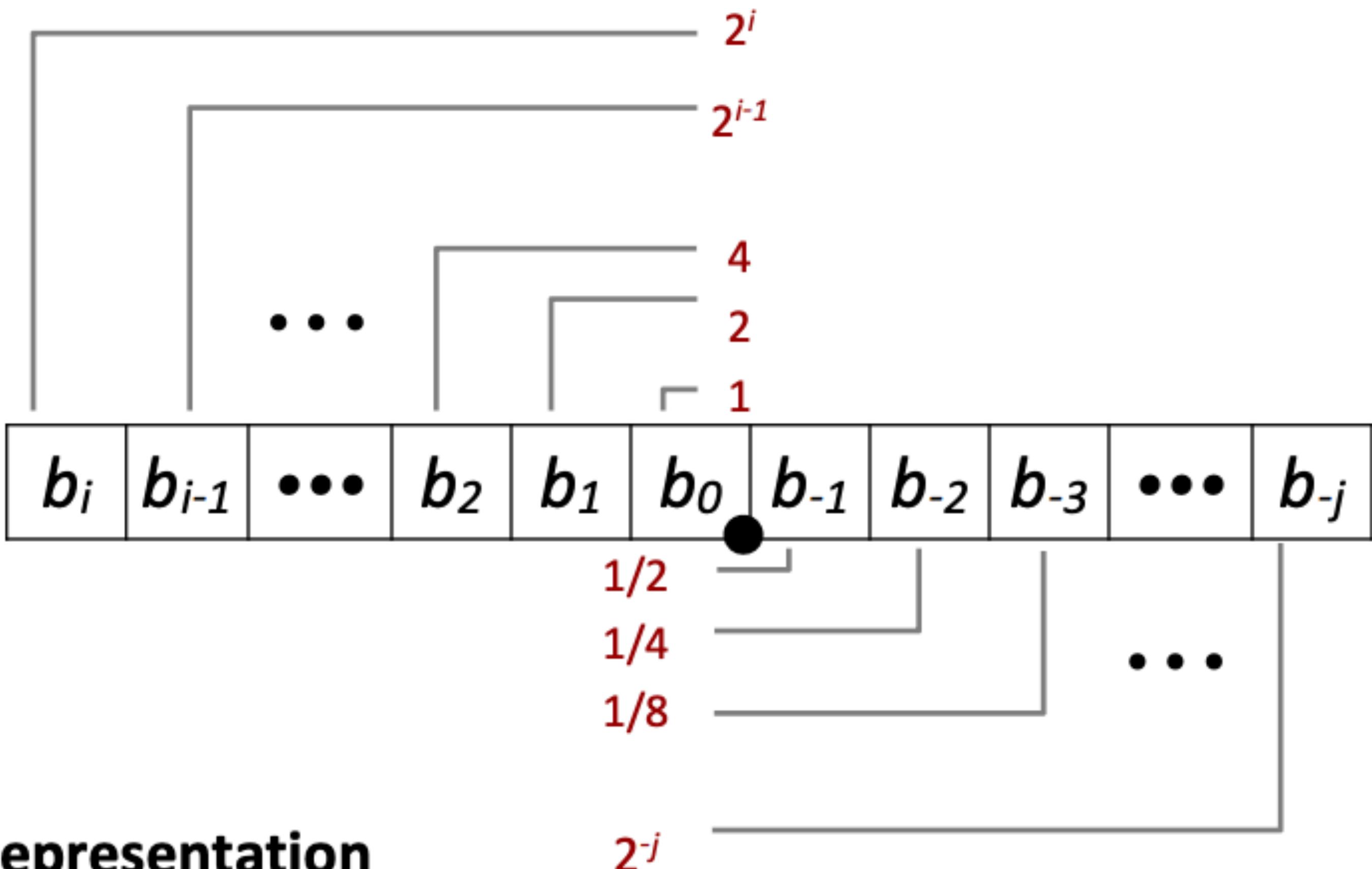
Q1) [3 x 3pts] What is the hexadecimal representation of these numbers in the given bases?

- A. 161 in base 10
- B. 32 in base 4
- C. 64 in base 8

Q2) [3 x 4pts] What is the result of these calculations in final decimal representation?

- A. $10_2 + 10_{10} + 10_{16}$
- B. $0xABC - 0xBC + 0xC$
- C. $101_3 * 0x10$

Fractional Binary Numbers



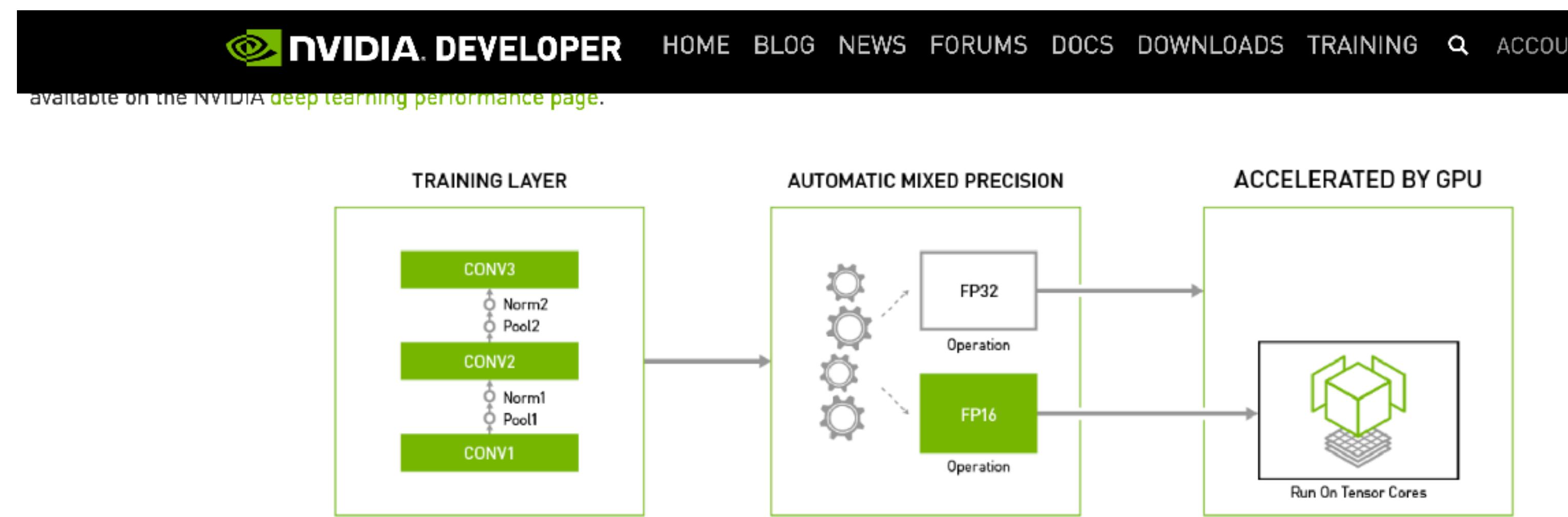
■ Representation

- Bits to right of “binary point” represent fractional powers of 2
- Represents rational number:

$$\sum_{k=-j}^i b_k \times 2^k$$

Digital Representation of Data

- **Float:**
 - Examples in data sci.: salary, scores, model weights
 - IEEE-754 single-precision format is 4B long; double-precision format is 8B long
 - Java and C *float* is single; Python *float* is double!

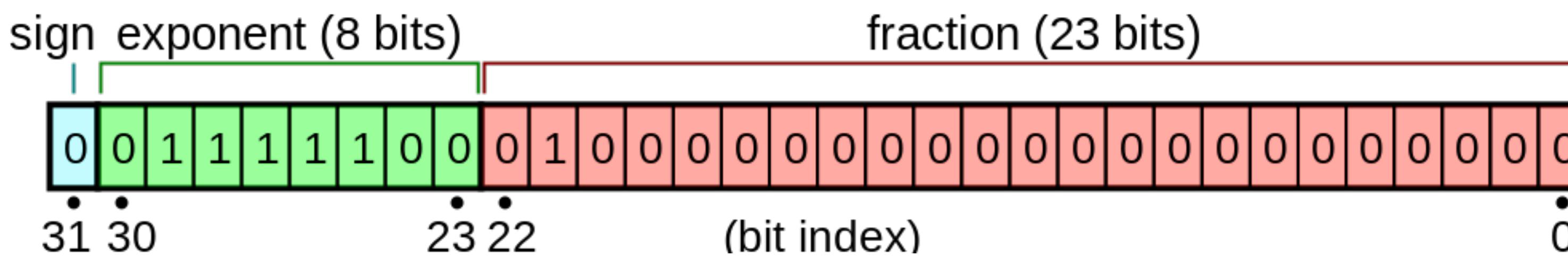


Using Automatic Mixed Precision for Major Deep Learning Frameworks

Digital Representation of Data

- **Float:**

- Standard IEEE format for single (aka binary32):

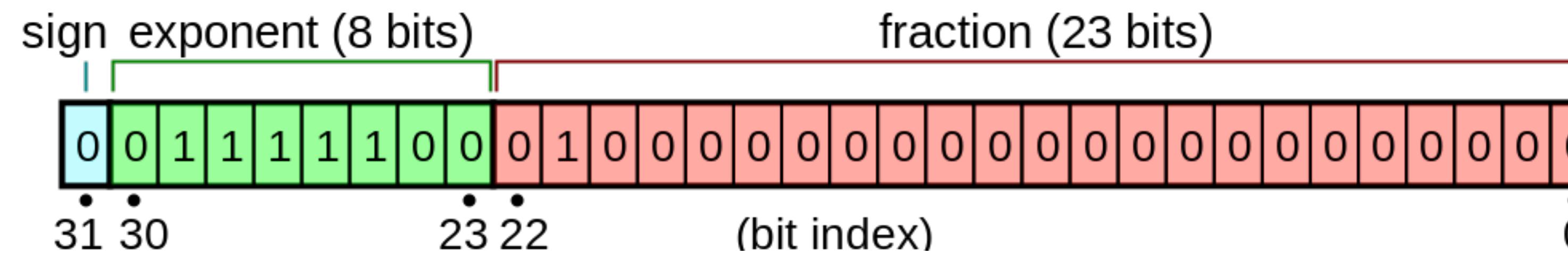


$$(-1)^{sign} \times 2^{exponent-127} \times \left(1 + \sum_{i=1}^{23} b_{23-i} 2^{-i}\right)$$

High-level intuition.

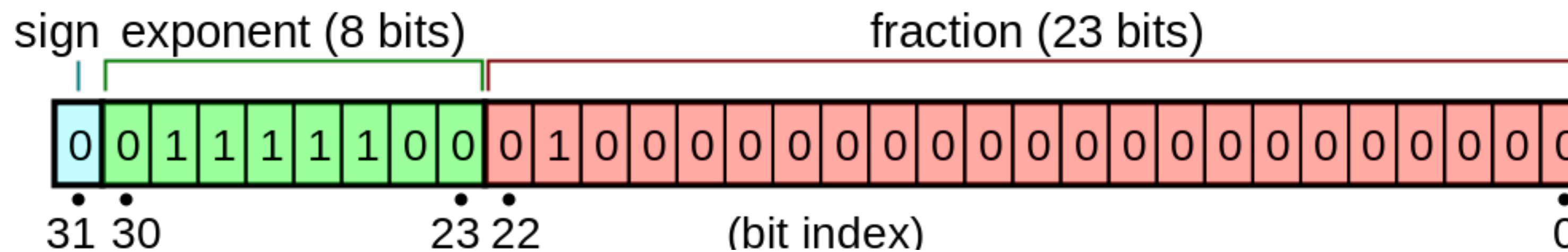
- Two extremes:
 - 0.000000000123455666
 - 99999999999999.0
- Key idea 1: turn them into scientific notion.
 - 1.23455666*10⁻¹⁰
 - 9.9999999999999*10¹³
- Key idea 2: Represent these two components (10^X) and ($Y.Z$) separately.

Many concepts in data science is an invention rather than a discovery.



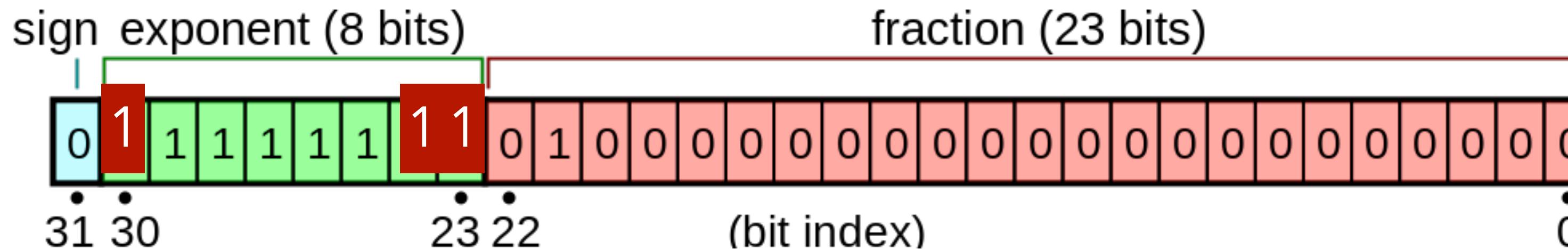
How can we represent a number in float?

- Key idea 1: turn them into scientific notion.
 - $1.23455666 \times 10^{-10}$
 - $9.99999999999999 \times 10^{13}$
- Key idea 2: Represent these two components (10^X) and ($Y.Z$) separately.



- Key idea 3: Everything is binary. $10^X \Rightarrow 2^W$

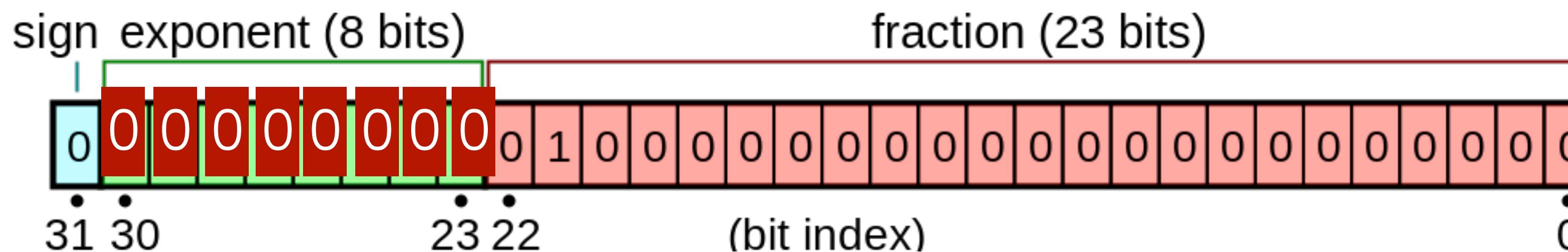
Examples



$$(-1)^{sign} \times 2^{exponent-127}$$

- Exponent = $(11111111)_2 = 255$
 - $2^{(255-127)} = 2^{128}$

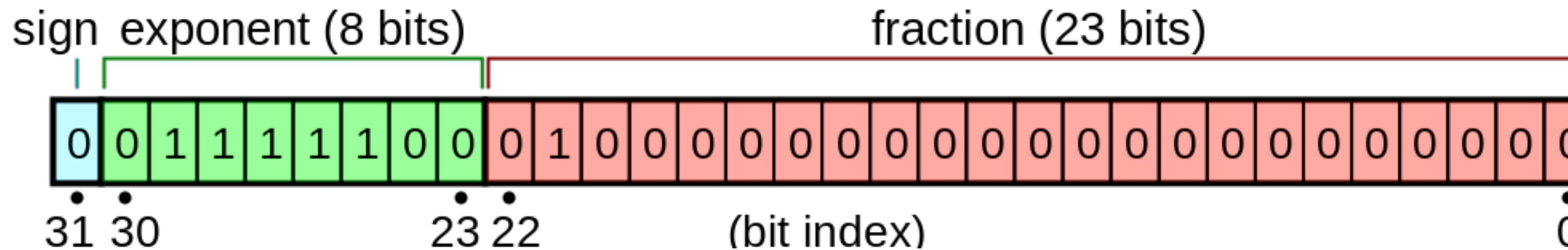
Examples



$$(-1)^{sign} \times 2^{exponent-127}$$

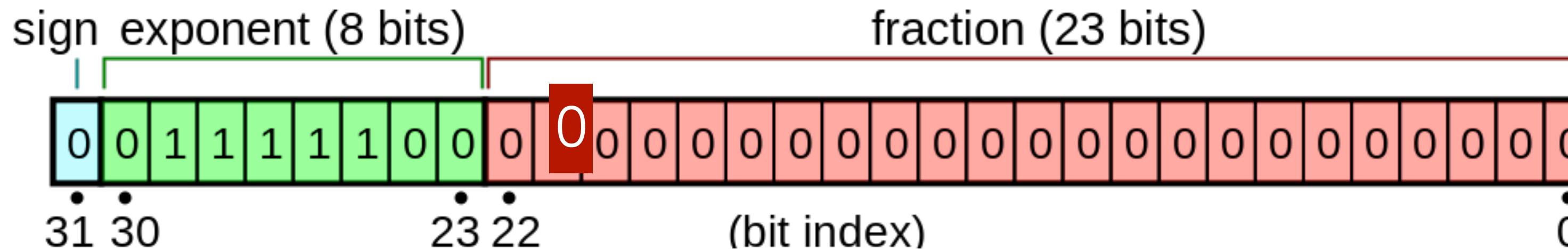
- **Exponent = (0000000)₂ = 0**
- $2^{(0-127)} = 2^{-127}$
- * This is a simplified version.

Examples



- $1 < \text{Mantissa} < 2$
 - Why 23? What is i?
 - $1 + 1/2 + 1/4$

Examples

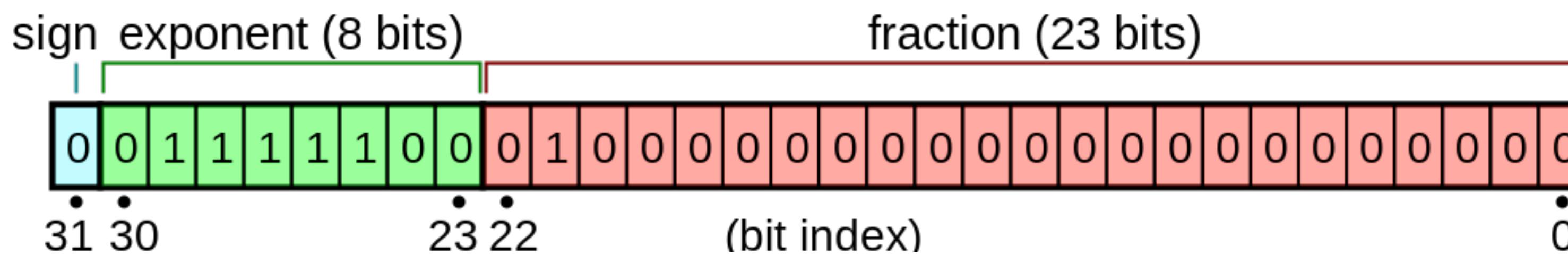


$$(-1)^{sign} \times 2^{exponent-127} \times (1 + \sum_{i=1}^{23} b_{23-i} 2^{-i})$$

- $1.0 \leq \text{Mantissa} < 2$
 - Why 23? What is i?
 - How about the biggest number?

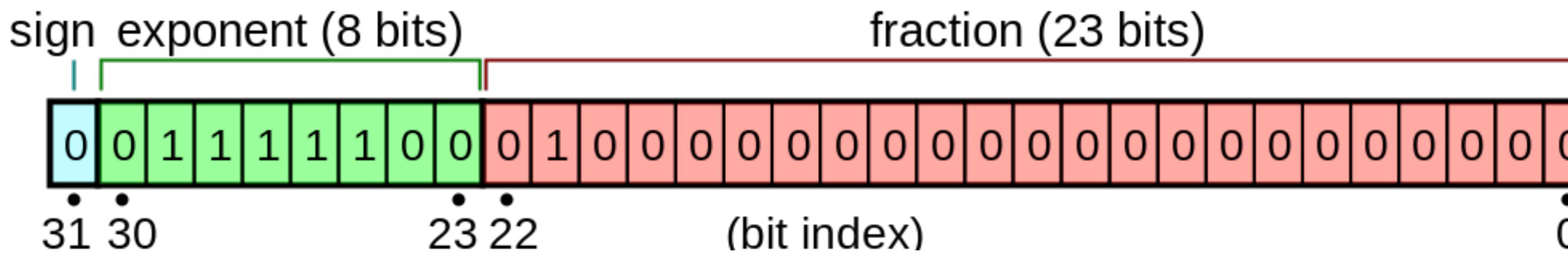
Digital Representation of Data

- **Float:**
 - Standard IEEE format for single (aka binary32):



$$(-1)^{sign} \times 2^{exponent-127} \times \left(1 + \sum_{i=1}^{23} b_{23-i} 2^{-i}\right)$$

Digital Representation of Data.



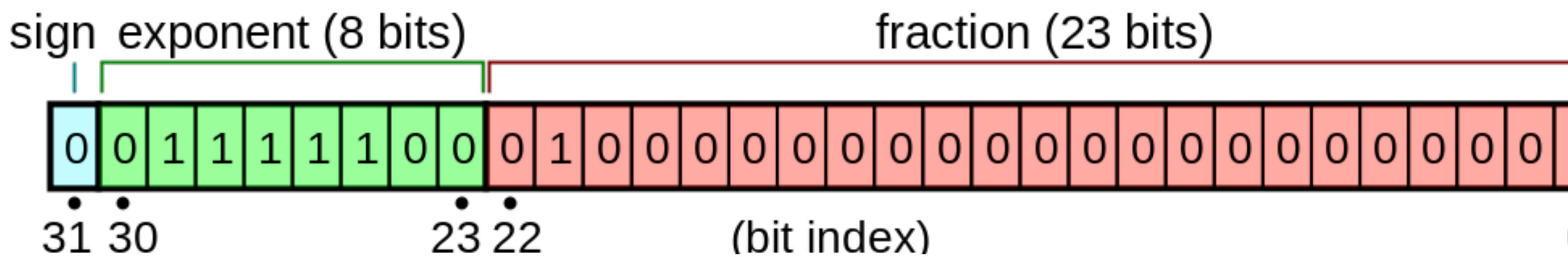
$$(-1)^{sign} \times 2^{exponent-127} \times (1 + \sum_{i=1}^{23} b_{23-i} 2^{-i})$$

- Special encodings recognized:
 - Exponent 0x00 and fraction 0 is “+/- 0”.
 - 0 00000000 00000000000000000000000 = +0
 - Exponent 0xFF and fraction 0 is +/- “Infinity”
 - 0 1111111 00000000000000000000000 = +INF
 - Not a number/Undefined (Dividing 0 by 0)
 - 0 1111111 10000000000000000000000 = NaN

Review

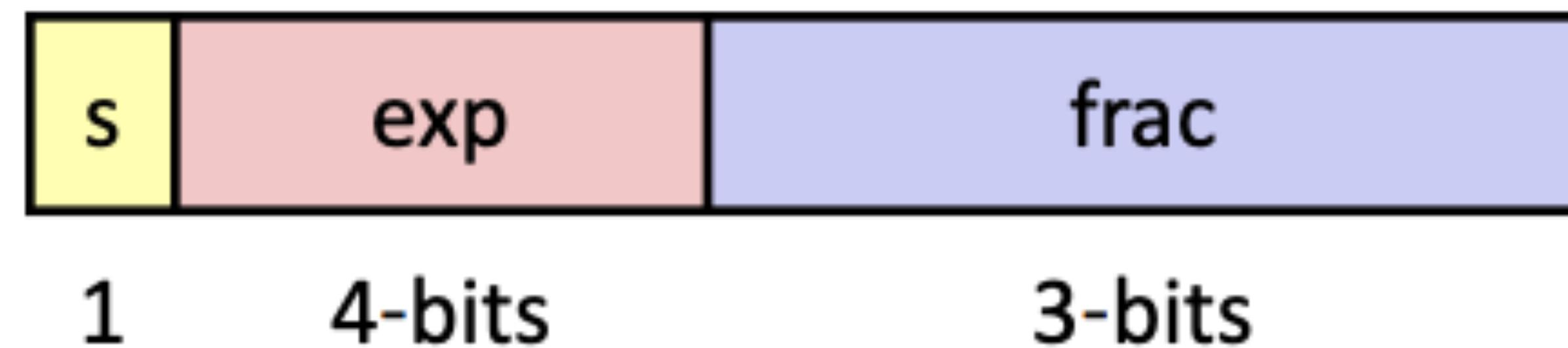
- Wide range of values
- Precision
- Compatibility
- Easy to use
- - Complexity
- - Rounding errors
- - Speed.
- - Limitate precisions

Digital Representation of Data. Why?



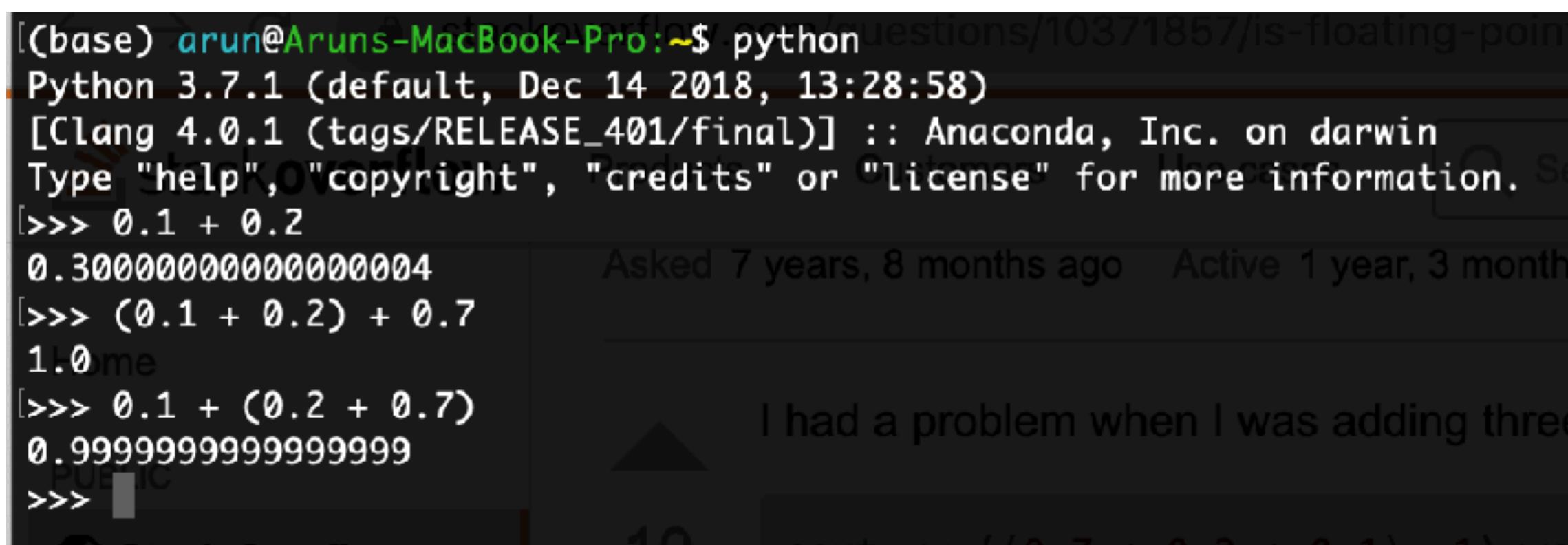
- Exponent for Range, Fraction (significant) for Accuracy
 - Max: 0 11111110 111111111111111111111111 =>
 - $2^{(254-127)} * (1.111111\dots)_2 = 2^{(254-127)} * \left(1 + \frac{1}{2} + \frac{1}{4} + \dots + \frac{1}{8388608}\right)$
 - Max = $2 * 2^{127} = 2^{128} = 3.4 \times 10^{38}$
 - Why not 0 1111111 111111111111111111111111?
 - Scientific notation.
 - Dynamic accuracy.

Examples in the final exam?



Digital Representation of Data

- Due to representation imprecision issues, floating point arithmetic (addition and multiplication) is not associative!



A screenshot of a Stack Overflow question titled "Is floating-point arithmetic associative?" The question was asked 7 years, 8 months ago and has been active for 1 year, 3 months. The user, "Arun", describes a problem with adding three floating-point numbers. The Python code in the question shows:

```
[base] arun@Aruns-MacBook-Pro:~$ python
Python 3.7.1 (default, Dec 14 2018, 13:28:58)
[Clang 4.0.1 (tags/RELEASE_401/final)] :: Anaconda, Inc. on darwin
Type "help", "copyright", "credits" or "license" for more information.
[>>> 0.1 + 0.2
0.3000000000000004
[>>> (0.1 + 0.2) + 0.7
1.0
[>>> 0.1 + (0.2 + 0.7)
0.9999999999999999
>>>
```

- In binary32, special encodings recognized:
 - Exponent 0xFF and fraction 0 is +/- “Infinity”
 - Exponent 0xFF and fraction <> 0 is “NaN”
 - Max is ~ 3.4×10^{38} ; min +ve is ~ 1.4×10^{-45}

Digital Representation of Data

- More float standards: double-precision (float64; 8B) and half-precision (float16; 2B); different #bits for exponent, fraction
- Float16 is now common for deep *learning* parameters:
 - Native support in PyTorch, TensorFlow, etc.; APIs also exist for weight quantization/rounding post training
 - NVIDIA Deep Learning SDK support mixed-precision training; 2-3x speedup with similar accuracy!
 - New processor hardware (FPGAs, ASICs, etc.) enable arbitrary precision, even 1-bit (!), but accuracy is lower

Digital Representation of Data

```
void show_squares()
{
    int x;
    for (x = 5; x <= 5000000; x*=10)
        printf("x = %d x^2 = %d\n", x, x*x);
}
```

x = 5 x² = 25

x = 50 x² = 2500

x = 500 x² = 250000

x = 5000 x² = 25000000

x = 50000 x² = -1794967296

x = 500000 x² = 891896832

x = 5000000 x² = -1004630016

In C, int uses a 32-bit

Digital Representation of Data

```
import sys

i = sys.maxsize
print(i)
# 9223372036854775807
print(i == i + 1)
# False
i += 1
print(i)
# 9223372036854775808

f = sys.float_info.max
print(f)
# 1.7976931348623157e+308
print(f == f + 1)
# True
f += 1
print(f)
# 1.7976931348623157e+308
```

```
import numpy as np

a = np.array([3095693933], dtype=int)
s = np.sum(a)
print(s)
# 3095693933
s * s
# -8863423146896543127
print(type(s))
# numpy.int64
py_s = int(s)
py_s * py_s
# 9583320926813008489
```

In Python, Integers are implemented as “long”.
In NumPy, Integers are implemented as np.int64.

Digital Representation of Data

```
# using array-scalar type
import numpy as np
dt = np.dtype(np.int32)
print dt
```

Sr.No.	Data Types & Description
1	bool_ Boolean (True or False) stored as a byte
2	int_ Default integer type (same as C long; normally either int64 or int32)
3	intc Identical to C int (normally int32 or int64)
4	intp Integer used for indexing (same as C ssize_t; normally either int32 or int64)
5	int8 Byte (-128 to 127)
6	int16 Integer (-32768 to 32767)

Encoding Integers

Unsigned

$$B2U(X) = \sum_{i=0}^{w-1} x_i \cdot 2^i$$

Two's Complement

$$B2T(X) = -x_{w-1} \cdot 2^{w-1} + \sum_{i=0}^{w-2} x_i \cdot 2^i$$

Sign Bit

```
short int x = 15213;  
short int y = -15213;
```

	Decimal	Hex	Binary
x	15213	3B 6D	00111011 01101101
y	-15213	C4 93	11000100 10010011

Two-complement: Simple Example

$$\begin{array}{rccccc} & -16 & 8 & 4 & 2 & 1 \\ 10 = & 0 & 1 & 0 & 1 & 0 \end{array} \quad 8+2 = 10$$

$$\begin{array}{rccccc} & -16 & 8 & 4 & 2 & 1 \\ -10 = & 1 & 0 & 1 & 1 & 0 \end{array} \quad -16+4+2 = -10$$

Two-complement Encoding Example (Cont.)

x =	15213:	00111011	01101101
y =	-15213:	11000100	10010011

Weight	15213	-15213	Sum	15213	-15213
1	1	1		1	1
2	0	0		1	2
4	1	4		0	0
8	1	8		0	0
16	0	0		1	16
32	1	32		0	0
64	1	64		0	0
128	0	0		1	128
256	1	256		0	0
512	1	512		0	0
1024	0	0		1	1024
2048	1	2048		0	0
4096	1	4096		0	0
8192	1	8192		0	0
16384	0	0		1	16384
-32768	0	0		1	-32768

Numeric Ranges

- Unsigned Values

- $UMin = 0$
• 000...0
- $UMax = 2^w - 1$
• 111...1

- Two's Complement Values

- $TMin = -2^{w-1}$
100...0
- $TMax = 2^{w-1} - 1$
011...1
- Minus 1
111...1

Values for $W = 16$

	Decimal	Hex	Binary
UMax	65535	FF FF	11111111 11111111
TMax	32767	7F FF	01111111 11111111
TMin	-32768	80 00	10000000 00000000
-1	-1	FF FF	11111111 11111111
0	0	00 00	00000000 00000000

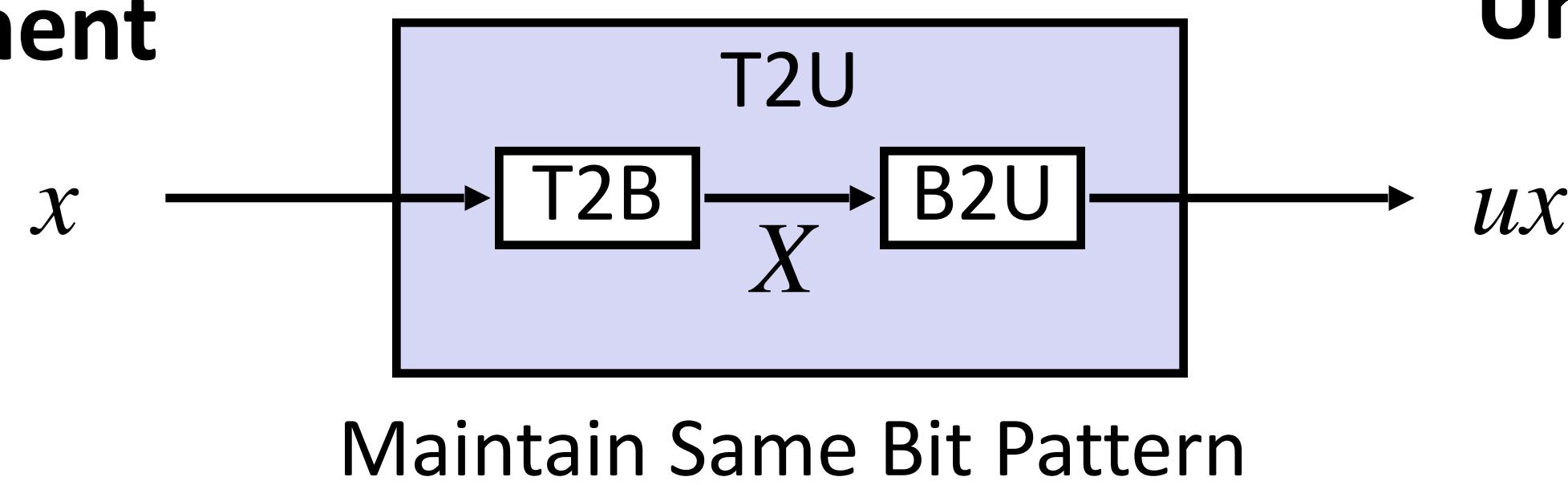
Unsigned & Signed Numeric Values

- **Equivalence**
 - Same encodings for nonnegative values
- **Uniqueness**
 - Every bit pattern represents unique integer value
 - Each representable integer has unique bit encoding
- \Rightarrow **Can Invert Mappings**
 - $U2B(x) = B2U^{-1}(x)$
 - Bit pattern for unsigned integer
 - $T2B(x) = B2T^{-1}(x)$
 - Bit pattern for two's comp integer

X	$B2U(X)$	$B2T(X)$
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	-8
1001	9	-7
1010	10	-6
1011	11	-5
1100	12	-4
1101	13	-3
1110	14	-2
1111	15	-1

Mapping Between Signed & Unsigned

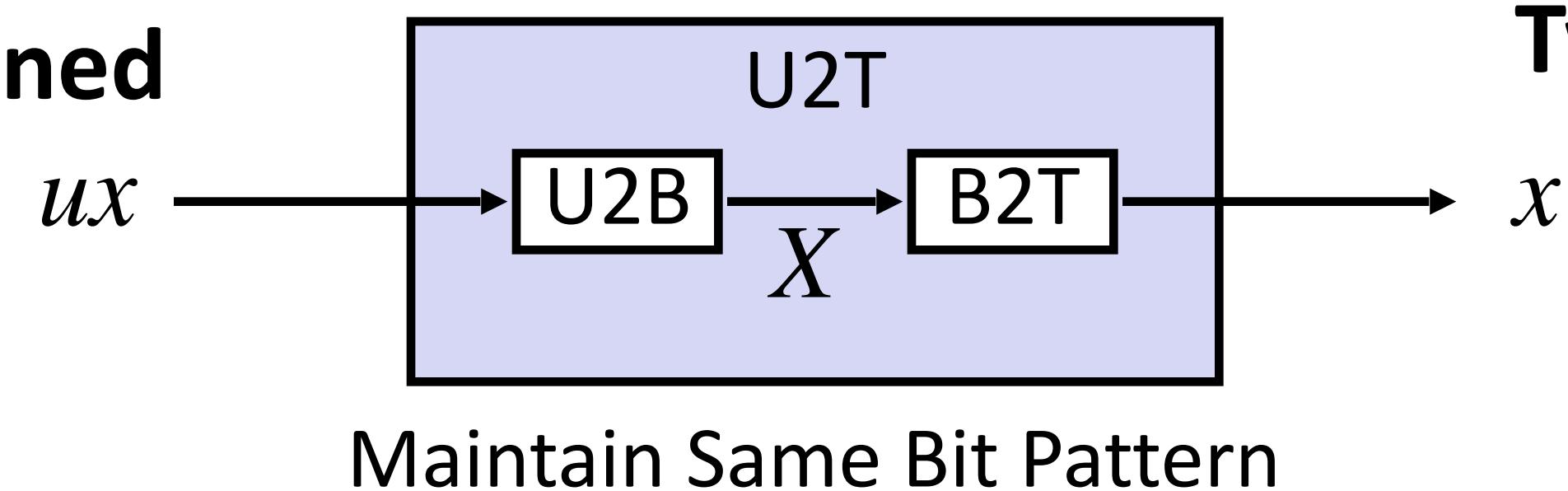
Two's Complement



Unsigned

Maintain Same Bit Pattern

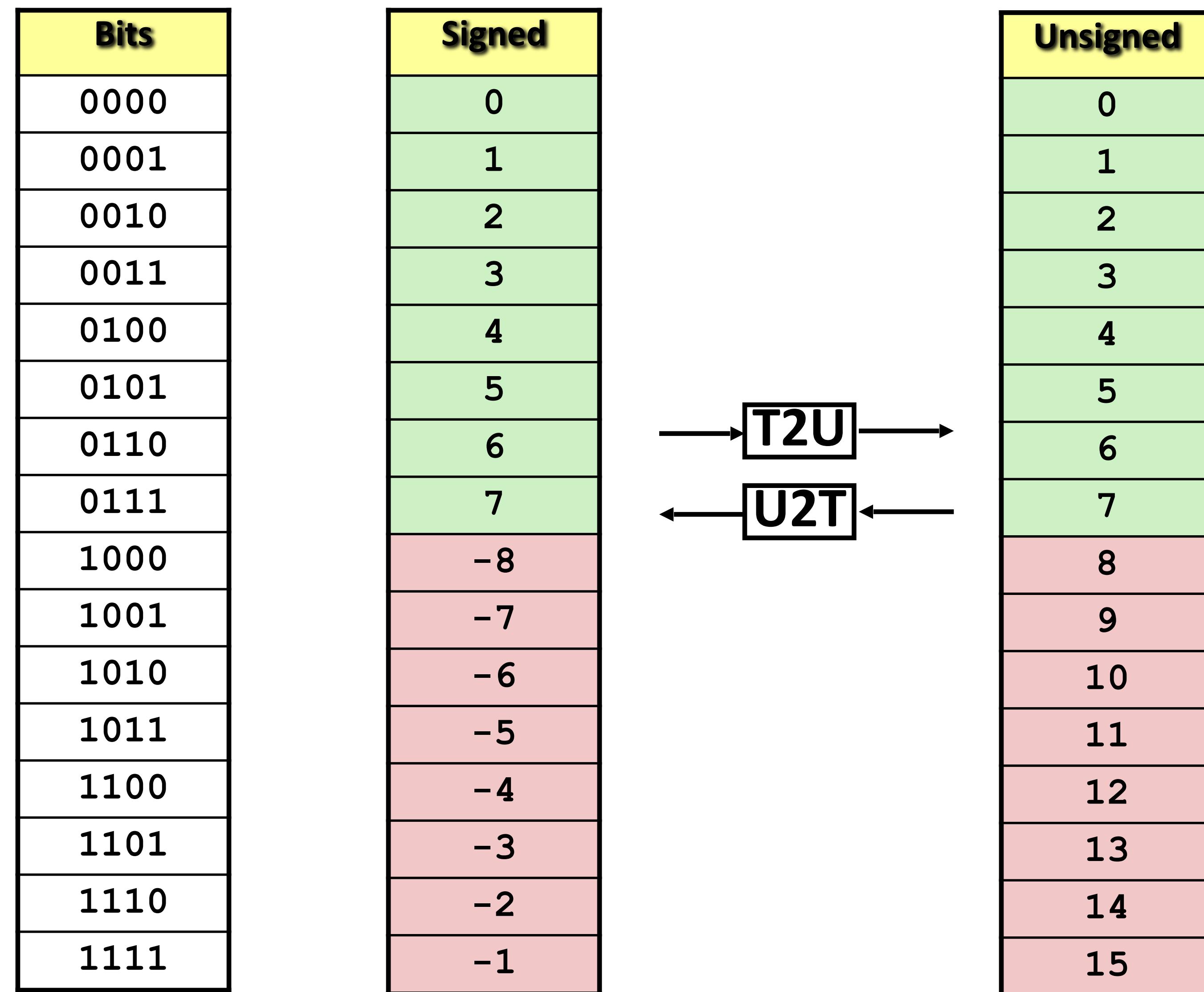
Unsigned



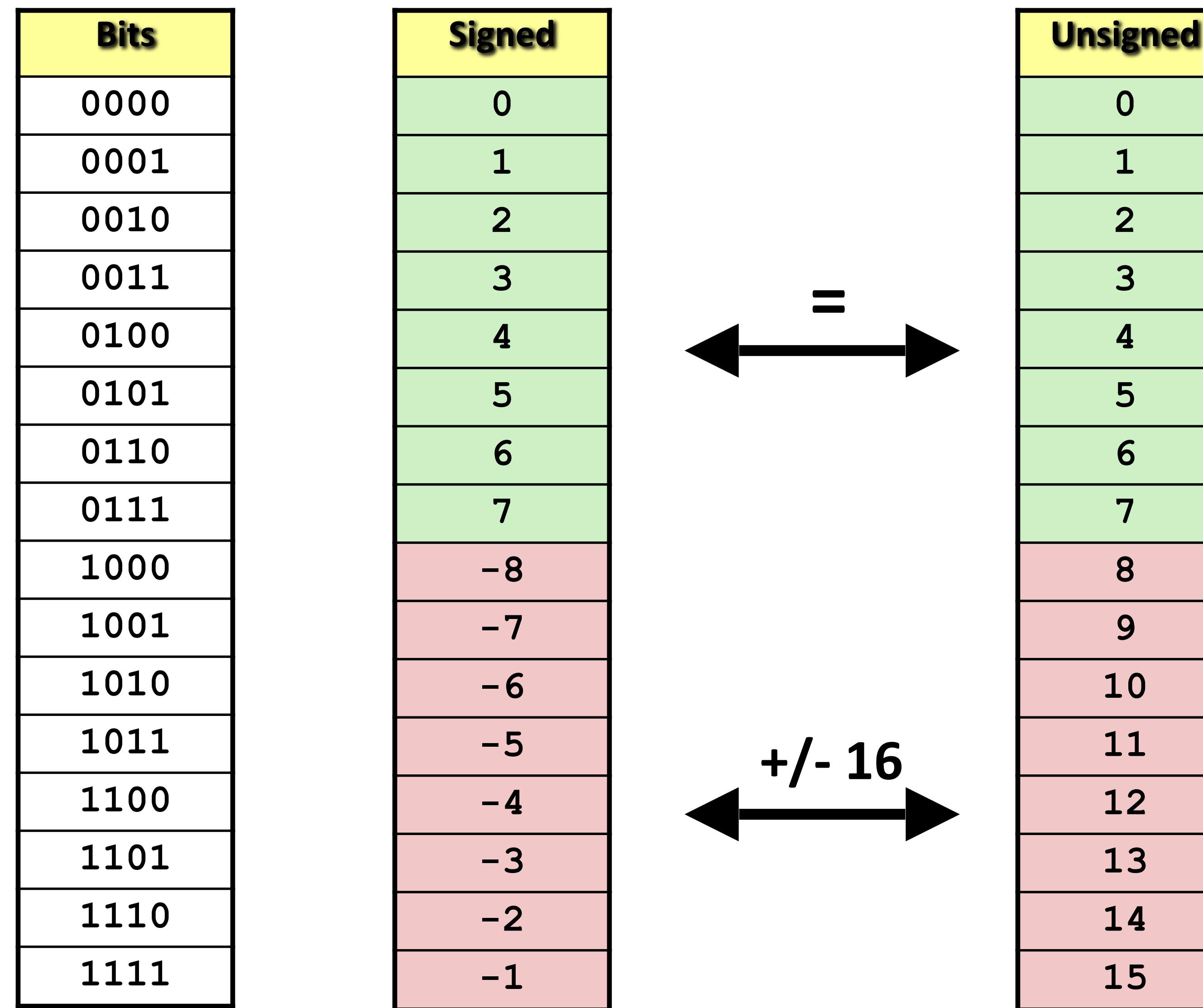
Two's Complement

Maintain Same Bit Pattern

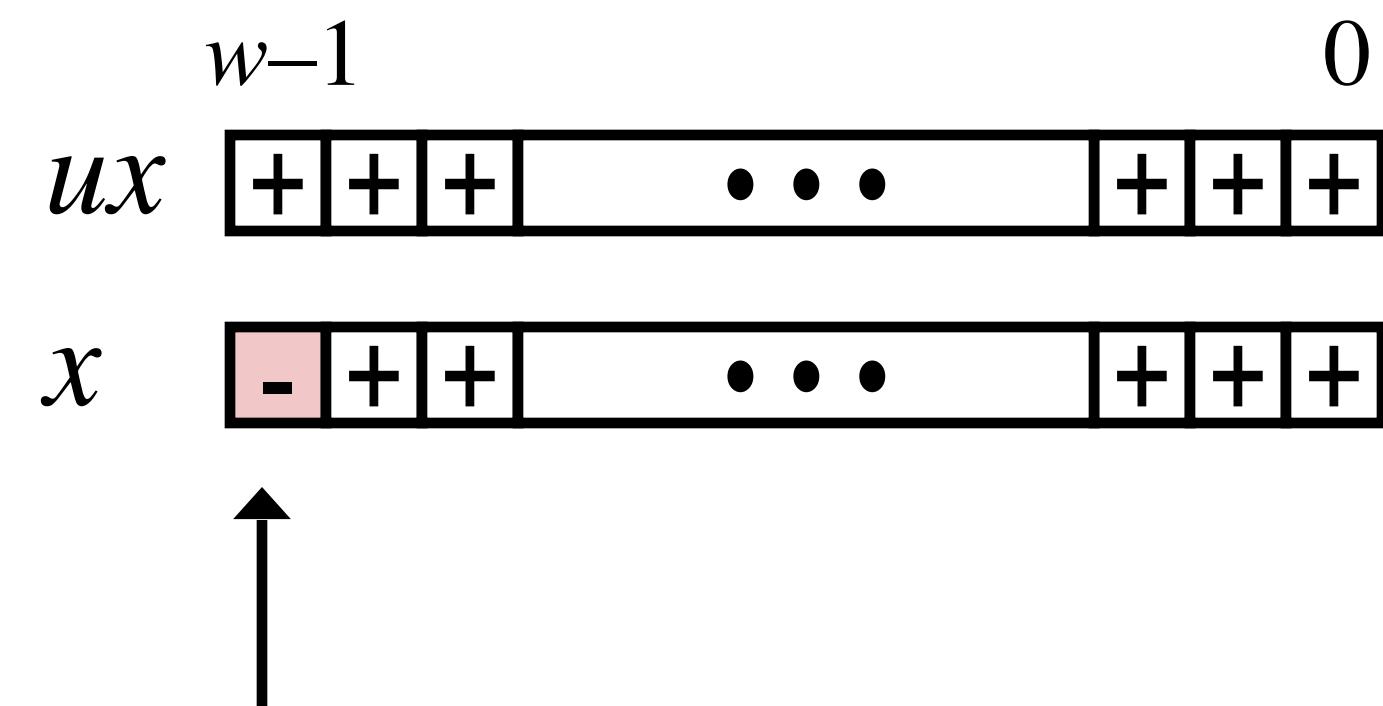
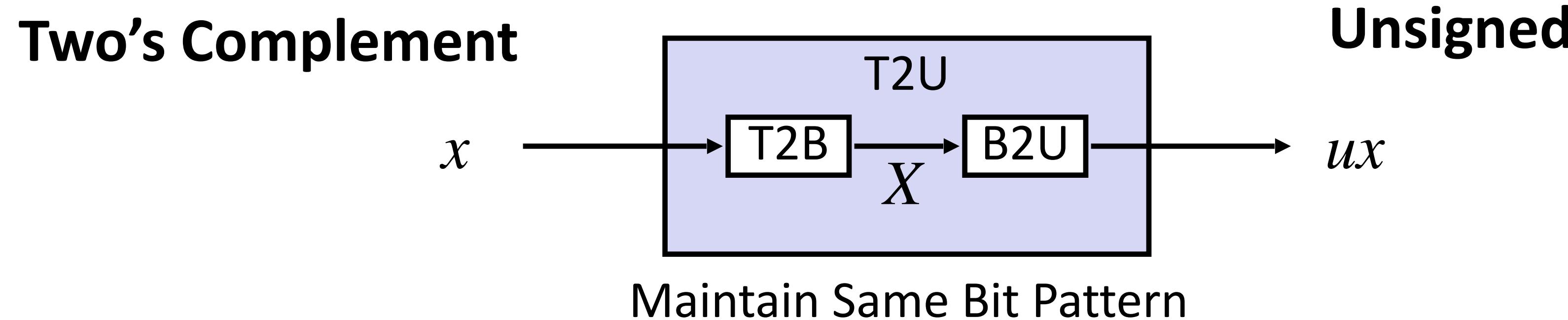
Mapping Signed ↔ Unsigned



Mapping Signed \leftrightarrow Unsigned



Relation between Signed & Unsigned



**Large negative weight
becomes
Large positive weight**

Digital Representation of Data

- Representing **Character (char)** and **String**:
 - Letters, numerals, punctuations, etc.
 - A string is typically just a variable-sized array of char
 - C *char* is 1B; Java *char* is 2B; Python does not have a char type (use *str* or *bytes*)
 - American Standard Code for Information Interchange (ASCII) for encoding characters; initially 7-bit; later extended to 8-bit
 - Examples: ‘A’ is 61, ‘a’ is 97, ‘@’ is 64, ‘!’ is 33, etc.
 - *Unicode UTF-8* is now common, subsumes ASCII; 4B for ~1.1 million “code points” incl. many other language scripts, math symbols, emojis, etc. ☺

Other type casting

```
string = "56"
number = 44

# Converting the string into an integer number.
string_number = int(string)

sum_of_numbers = number + string_number
print("The Sum of both the numbers is: ", sum_of_numbers)
```

```
The Sum of both the numbers is: 100
```

Other type casting

```
string = "01101"
floating_number = 45.20

# Converting the string as well as integer number into floating point number.
new_str = int(string)
new_number = int(floating_number)
print("String converted into integer: ", new_str)
print("The floating-point number converted into integer: ", new_number)
```

```
String converted into integer: 1101
The floating-point number converted into integer: 45
```

Data Type conversion examples

int(10)	=> 10	float(10)	=> 10.0
int(10.1)	=> 10	float(10.1)	=> 10.1
int('10')	=> 10	float('10')	=> 10.0
int('10.1')	=> Error	float('10.1')	=> 10.1
int('kitten')	=> Error	float('kitten')	=> Error

str(10)	=> '10'
str(10.1)	=> '10.1'
str('kitten')	=> 'kitten'

Digital Representation of Data

- All digital objects are *collections* of basic data types (bytes, integers, floats, and characters)
 - SQL dates/timestamp: string (w/ known format)
 - ML feature vector: *array* of floats (w/ known length)
 - Neural network weights: *set* of multi-dimensional *arrays* (matrices or tensors) of floats (w/ known dimensions)
 - Graph: an *abstract data type* (ADT) with *set* of vertices (say, integers) and *set* of edges (*pair* of integers)
 - Program in PL, SQL query: string (w/ grammar)
 - Other data structures or digital objects?

Review Questions

- Why do computers use binary digits?
- How many integers can you represent with 5 bits?
- How many bits do you need to represent 5 integers?
- What is the hexadecimal for 20_{10} ?
- Why do we need a float standard?
- Why should a data scientist know about float formats?
- What does “lower precision” mean for a float weight in DL?
- Why is serialization needed?



Peer Instruction Activity

Rough time tip: About 1 min per 1 pt.

Use your UCSD email

Here is a custom float6 representation and interpretation:

sign (1 bit)	exponent (2 bits)	fraction (3 bits)			
0	0	1	0	1	0
Bit index:	5	4	3	2	1

$$(-1)^{sign} \times 2^{exponent-2} \times \left(1 + \sum_{i=1}^3 b_{3-i} 2^{-i}\right)$$

Q3) [2 x 6pts] What is the decimal real number representation of these float6 bit sequences:

- A. 001010
- B. 111101