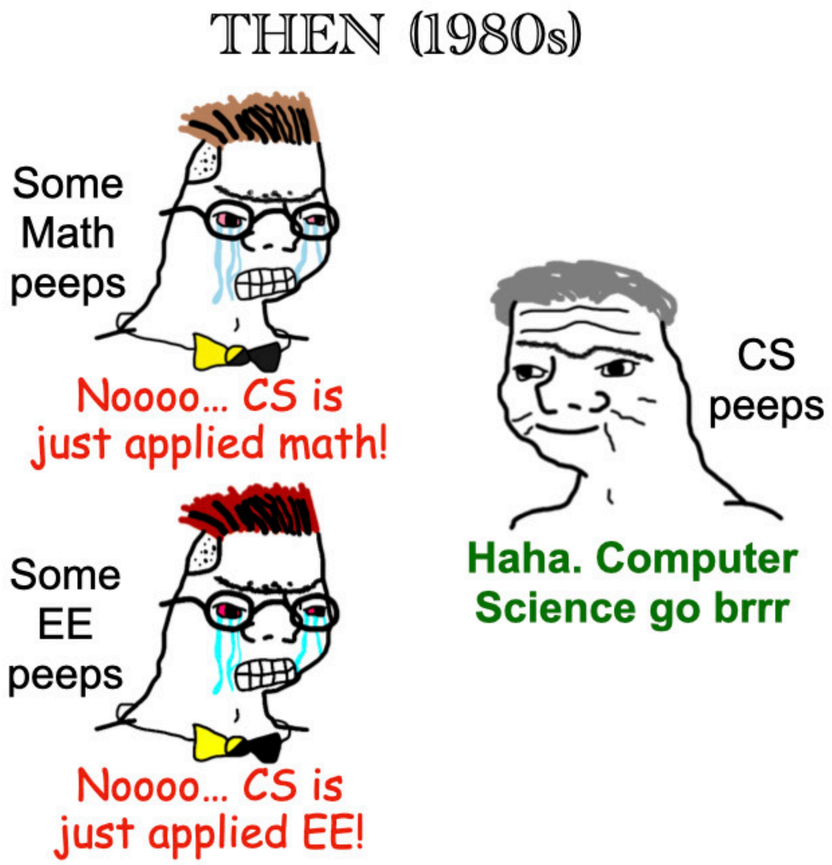
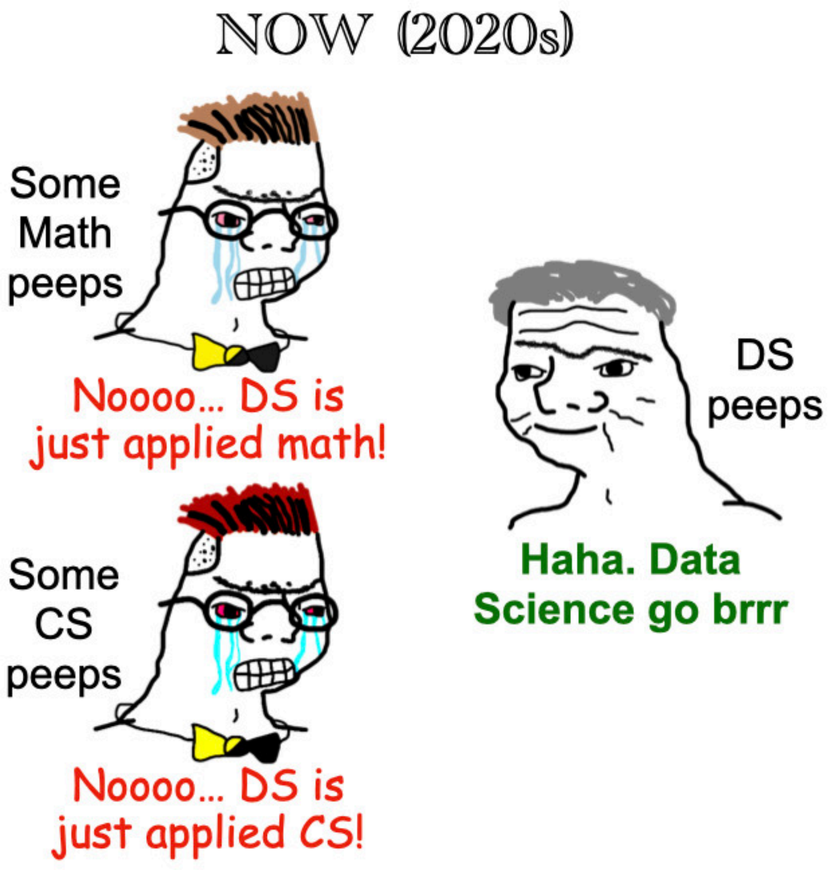




DSC 102

Systems for Scalable Analytics

- Haojian Jin

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

Where are we in the class?

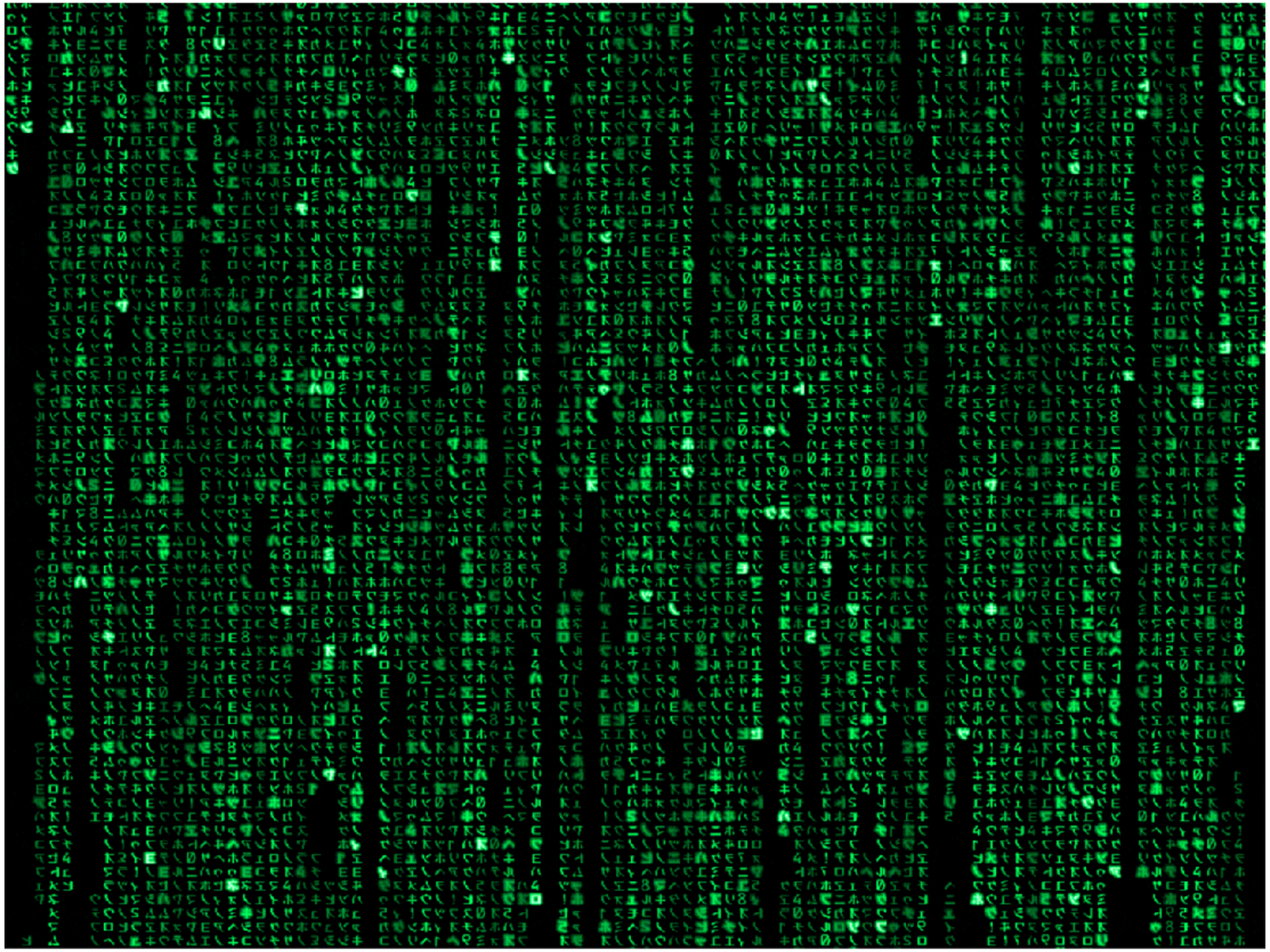
Week	Topic
1-2	Basics of Machine Resources: Computer Organization
2-3	Basics of Machine Resources: Operating Systems
4	Basics of Cloud Computing
4-5	Parallel and Scalable Data Processing: Parallelism Basics
6	Midterm Exam on TBD
6-7	Parallel and Scalable Data Processing: Scalable Data Access
7-8	Parallel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

Systems Principles

Where are we in the class?

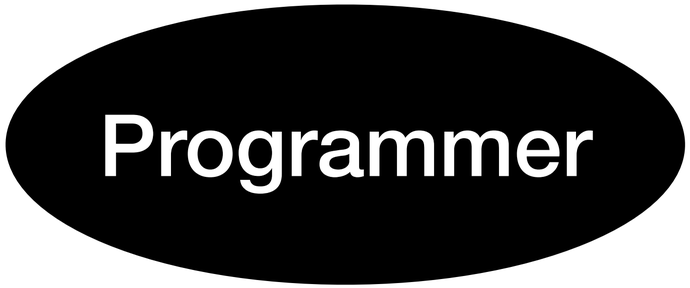
- Basics of Computer Organization
  - **Digital Representation of Data**
    - **Binary, integer, float, tradeoffs**
  - Processors and Memory Hierarchy
- Basics of Operating Systems
  - Process Management: Virtualization; Concurrency
  - Filesystem and Data Files
  - Main Memory Management
- Persistent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

What is data?

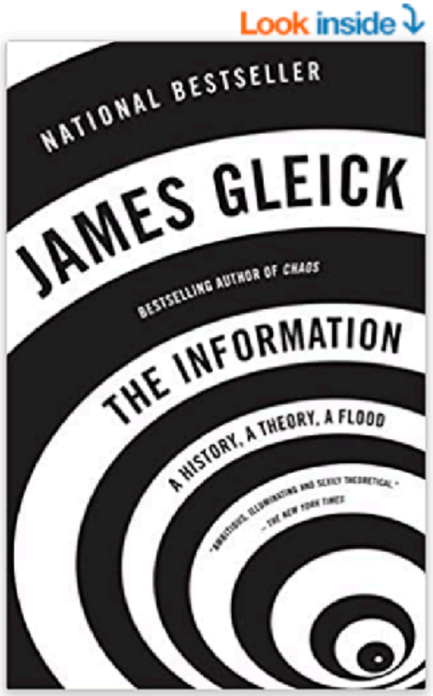


Digital Representation of Data

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



Why bits?



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

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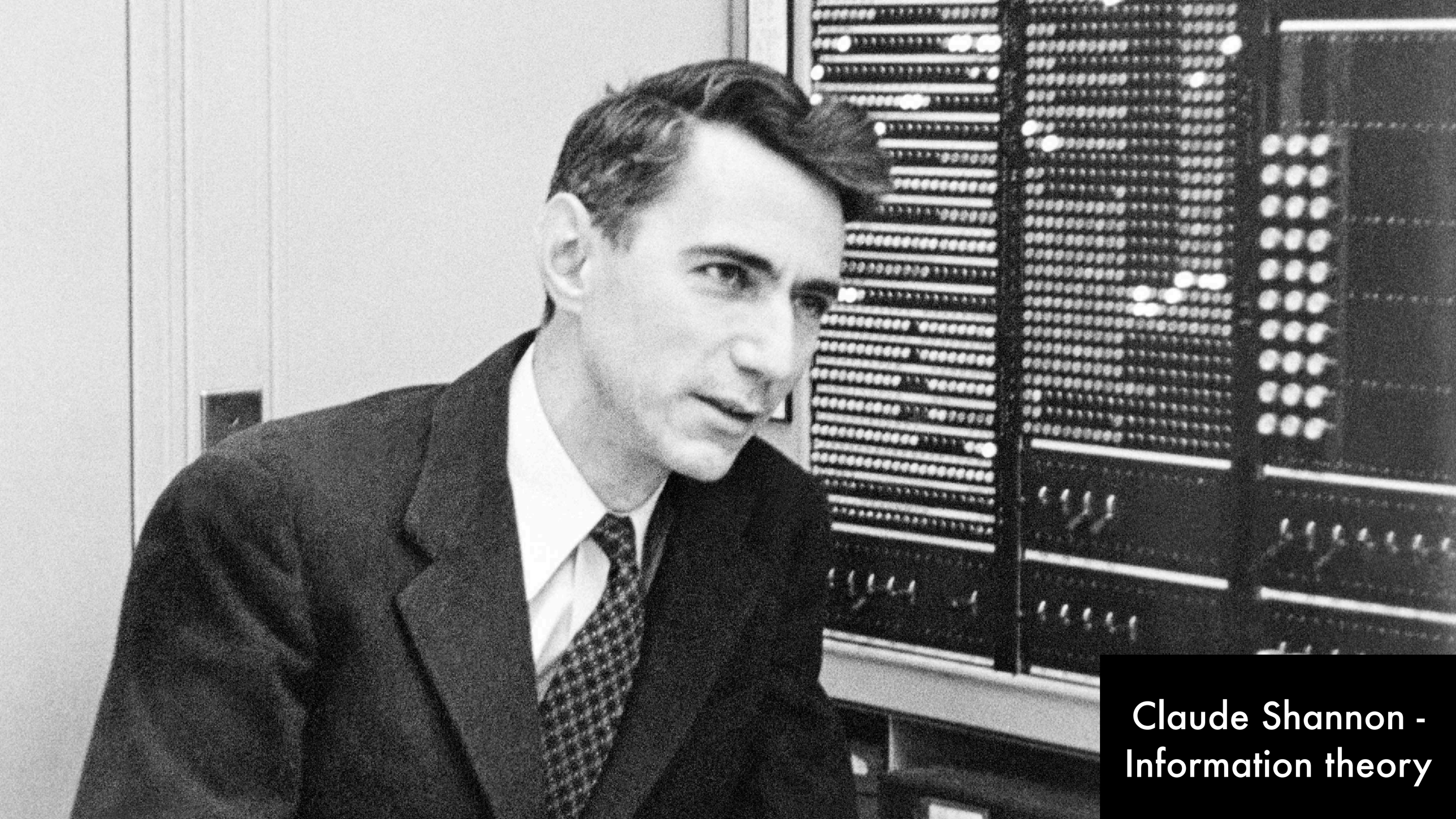
From the bestselling author of the acclaimed *Chaos* and *Genius* comes a thoughtful and provocative exploration of the big ideas of the modern era: Information, communication, and information theory.

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



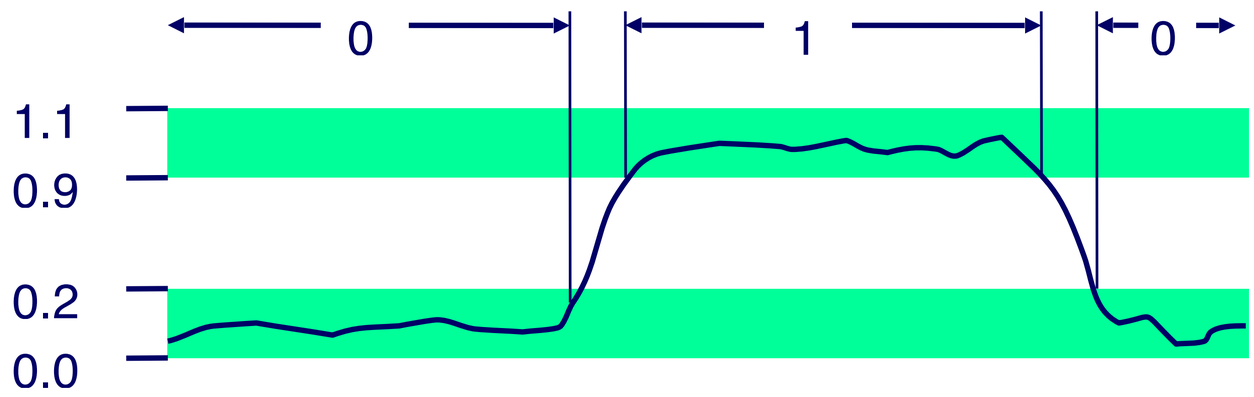
Claude Shannon -
Information theory

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

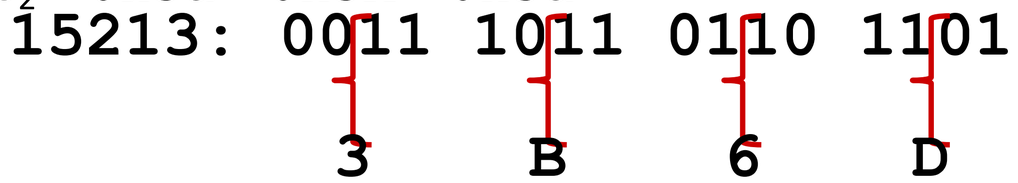
- **Base 2 Number Representation**
  - 0, 1, 10, 11, 100, 101, …
  - Represent 15213_{10} as $0011\ 1011\ 0110\ 1101_2$
  - Represent 1.20_{10} as $1.0011\ 0011\ 0011\ 0011\ [0011]\ldots_2$
  - Represent $\left(1.5213 \times 10^4\right)_{10}$ as $\left(1.1101\ 1011\ 0110\ 1 \times 2^{13}\right)_2$

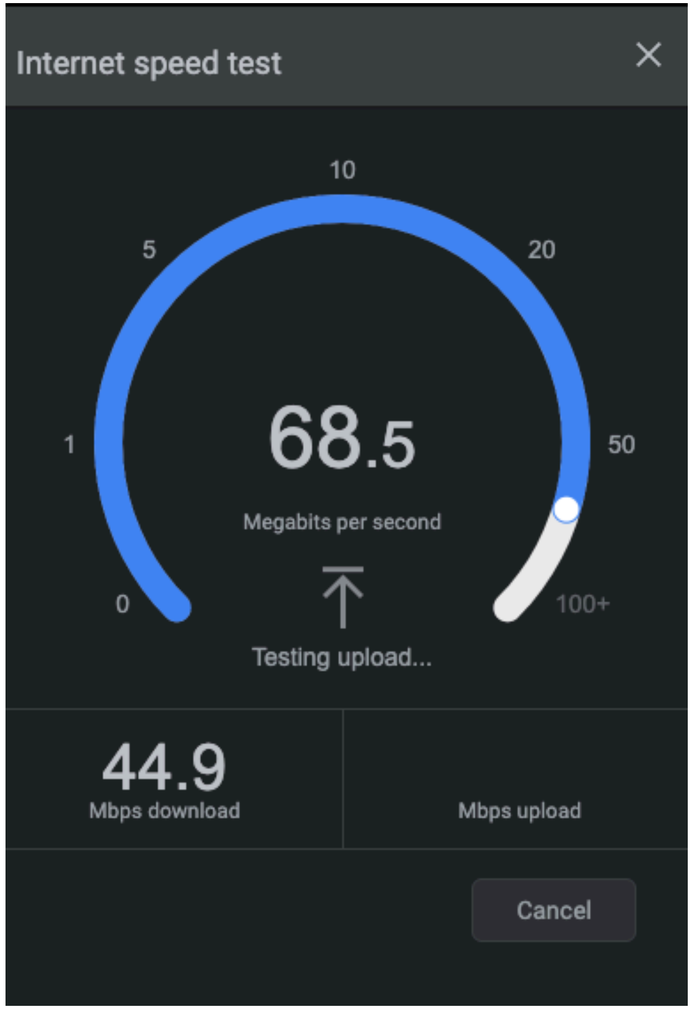
- **Represent negative numbers as …?**
  - (we'll come back to this)

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`

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

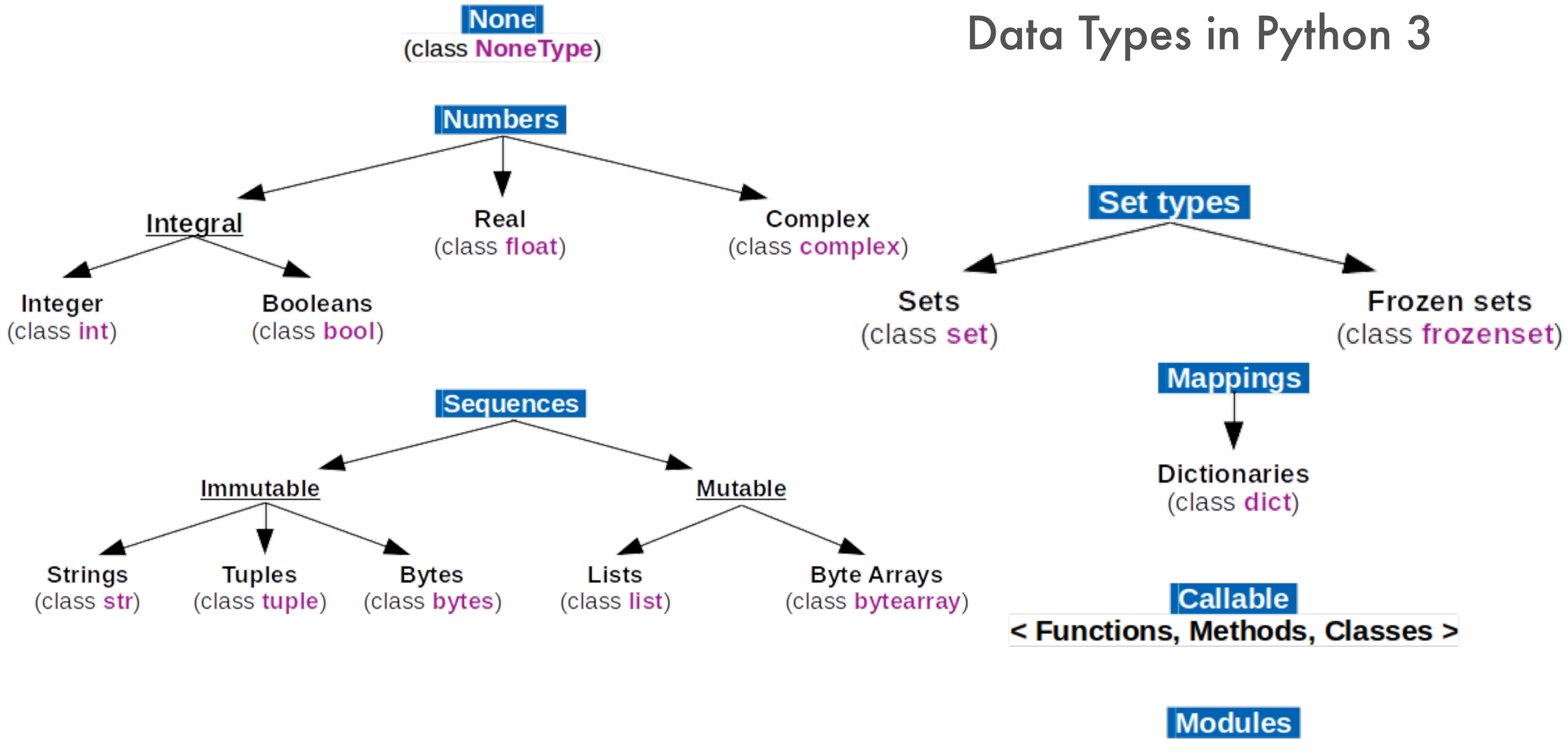
- **Bits:** All digital data are sequences of 0 & 1 (binary digits)
- **Data type:** First layer of abstraction to interpret a bit sequence with a human-understandable category of information; interpretation fixed by the PL
  - Example common datatypes: Boolean, Byte, Integer, "floating point" number (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*

	Size (# of bytes)	
C Data Type	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 => 2^{24} items, i.e., 16,777,216 items
- Common approximation: 2^{10} (i.e., 1024) ~ 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 ->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	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

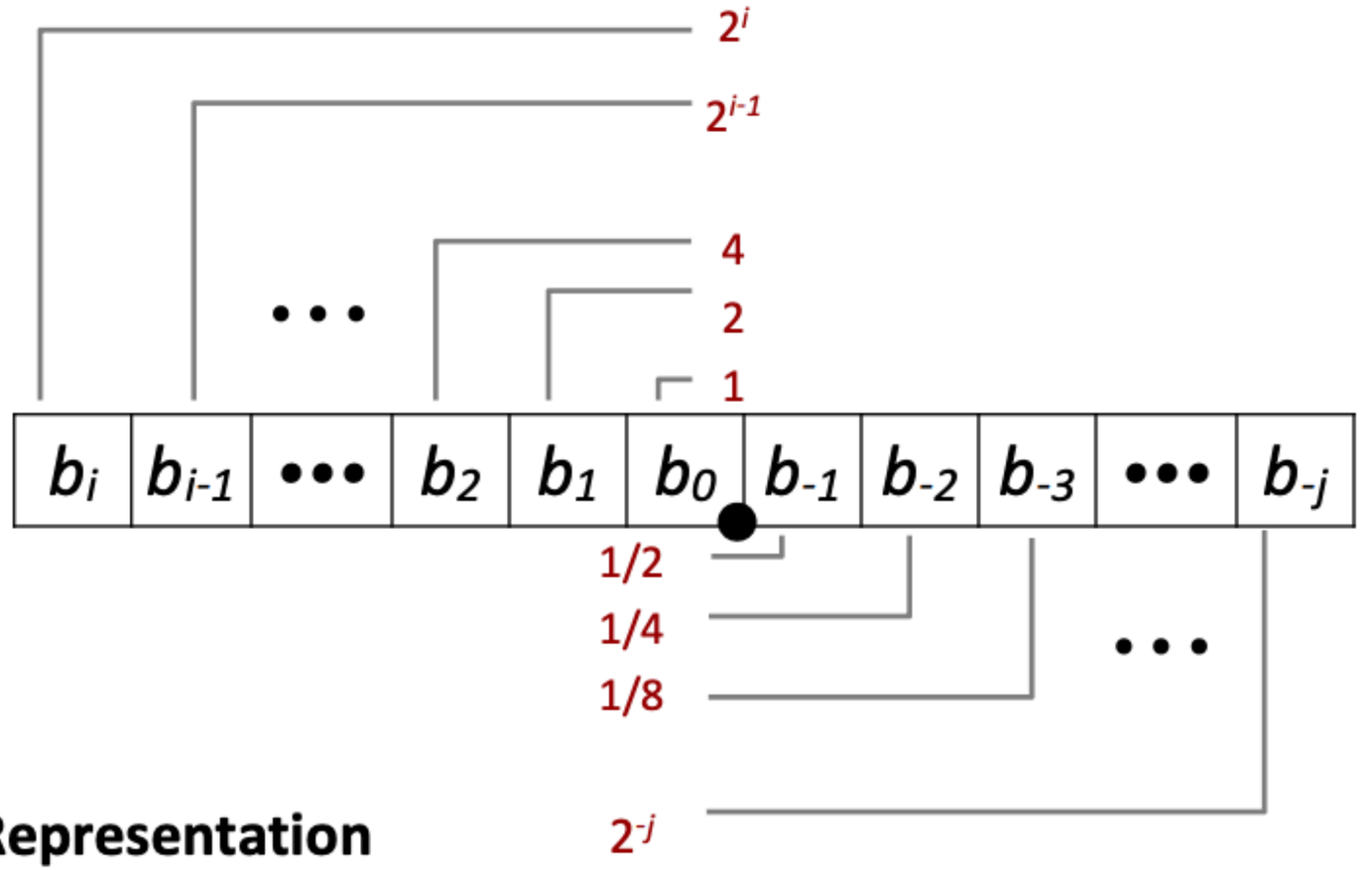
- *Hexadecimal* representation is a common stand-in for binary representation; more succinct and readable
  - Base 16 instead of base 2 cuts display length by ~4x
  - Digits are 0, 1, … 9, A (10_{10}), B, … F (15_{10})
  - From binary: combine 4 bits at a time from lowest

Decimal	Binary	Hexadecimal
5_{10}	101_2	5_{16}
47_{10}	$10\ 1111_2$	$2F_{16}$
163_{10}	$1010\ 0011_2$	$A3_{16}$
16_{10}	$1\ 0000_2$	10_{16}

Alternative notations

0xA3 or $A3_H$

Fractional Binary Numbers



- **Representation**
  - Bits to right of "binary point" represent fractional powers of 2
  - Represents rational number:

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

A straw man solution

	Sign	Integer		Fraction		
	0	0	1	0	1	0
Bit index:	5	4	3	2	1	0
	-4	2	1	1/2	1/4	1/8

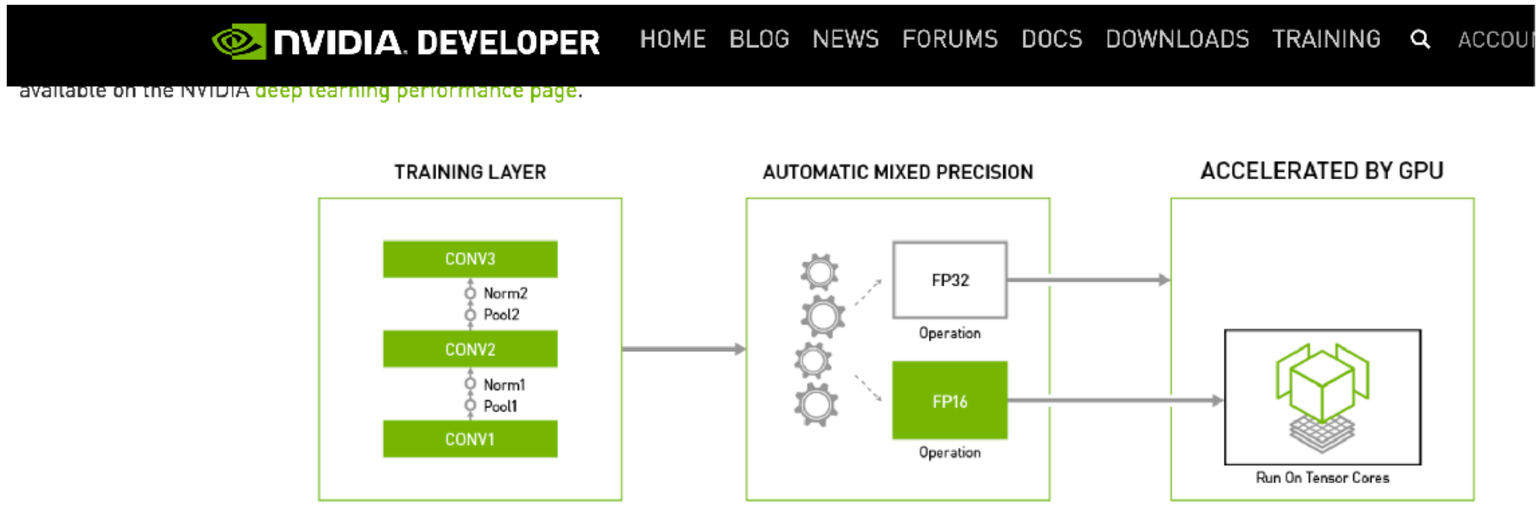
~~1+1/4= 1.25~~

A. 5/8, i.e., 0.625

Can only represent numbers from -4 (100000) to 3.875 (011111).

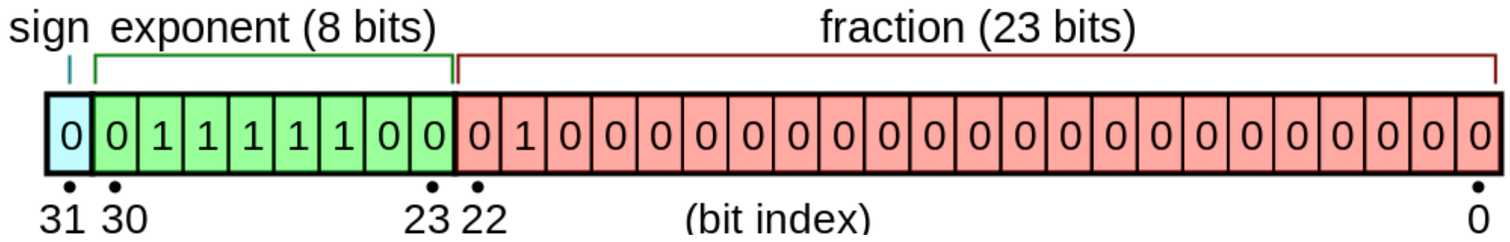
Digital Representation of Data

- **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!



Digital Representation of Data

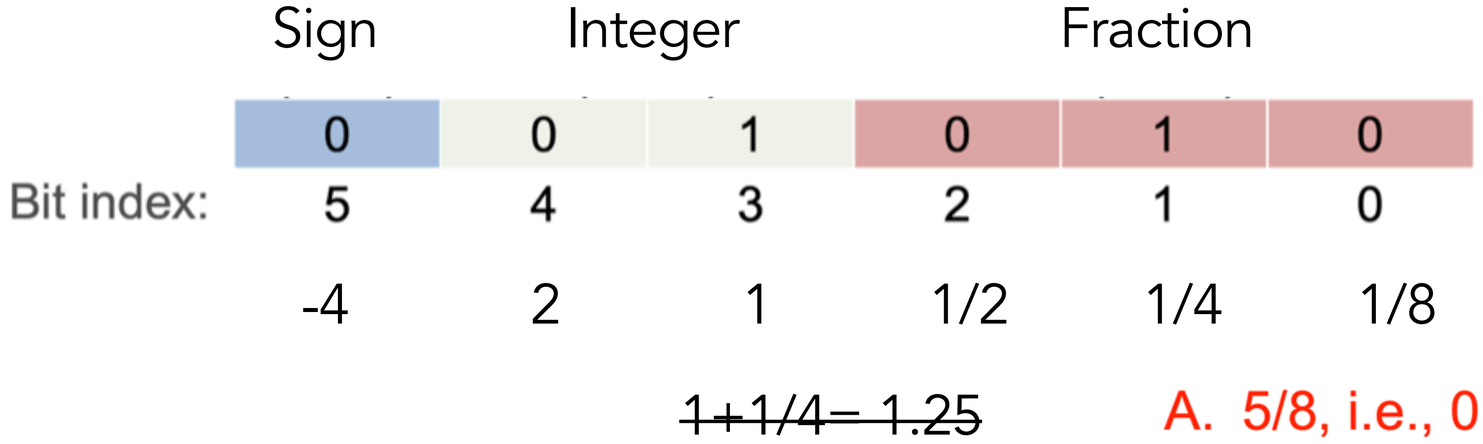
- **Float**:
  - Standard IEEE format for single (aka binary32):



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

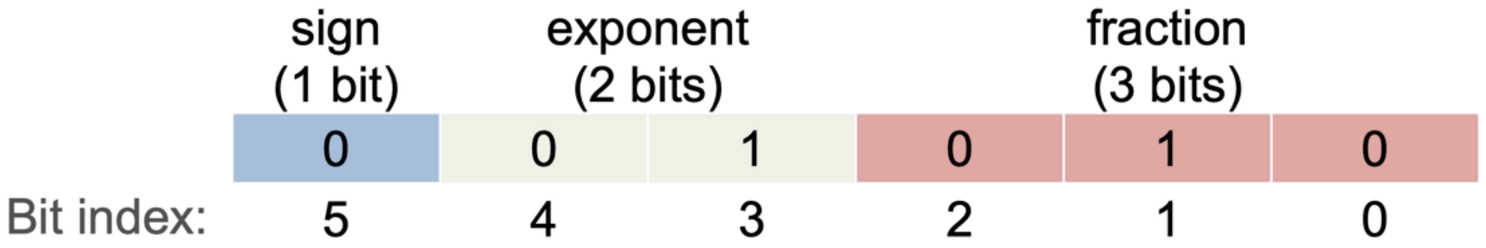
$$(-1)^0 \times 2^{124-127} \times (1 + 1 \cdot 2^{-2}) = (1/8) \times (1 + (1/4)) = 0.15625$$

An alternative representation?



Can only represent numbers from -4 (100000) to 3.875 (011111).

Revisit the representation (scientific notation)



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

$$(-1)^0 \cdot 2^{(1-2)} \cdot \left(1 + 0 \cdot \frac{1}{2} + 1 \cdot \frac{1}{4} + 0 \cdot \frac{1}{8}\right)$$

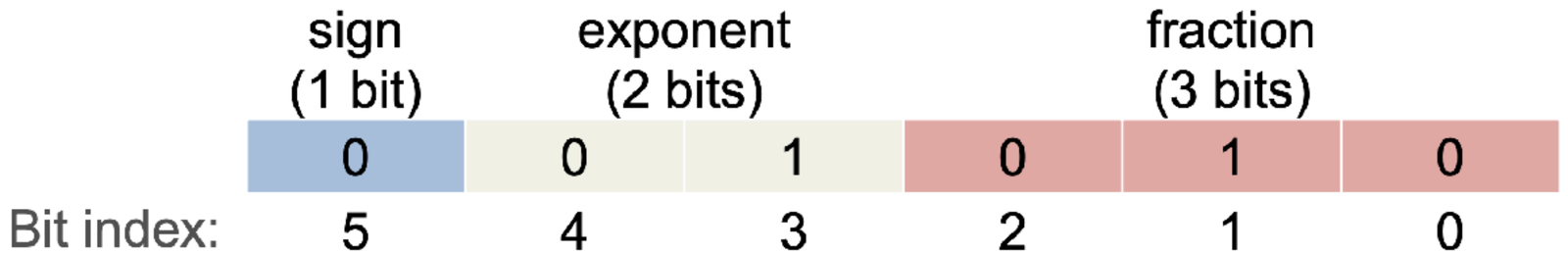
A. 5/8, i.e., 0.625

Reverse the representation (scientific notation)

$$0.625_{10} =$$

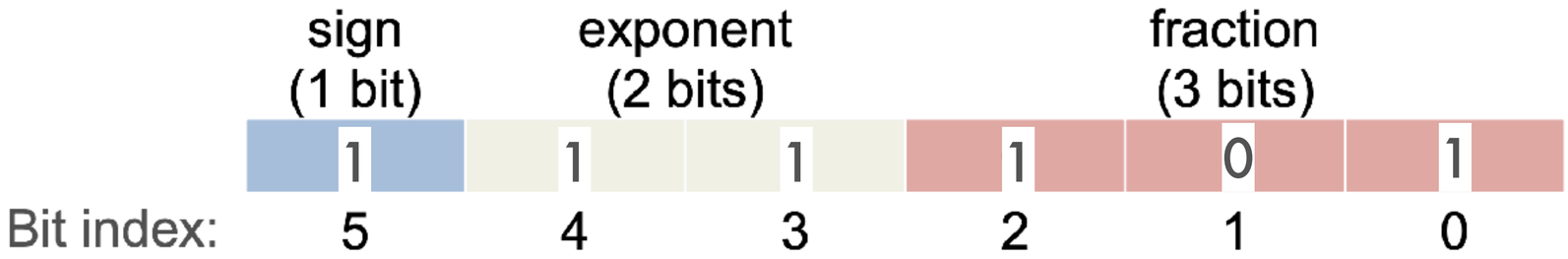
$$0.625_{10} = 0.101_2$$

$$0.625_{10} = 0.101_2 = 1.01 \cdot 2^{-1}$$



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

Another representation (scientific notation)



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

111101 => -3.25

$$(-1)^{1} \cdot 2^{3-2} \cdot \left(1 + \frac{1}{2} + \frac{1}{8}\right)$$

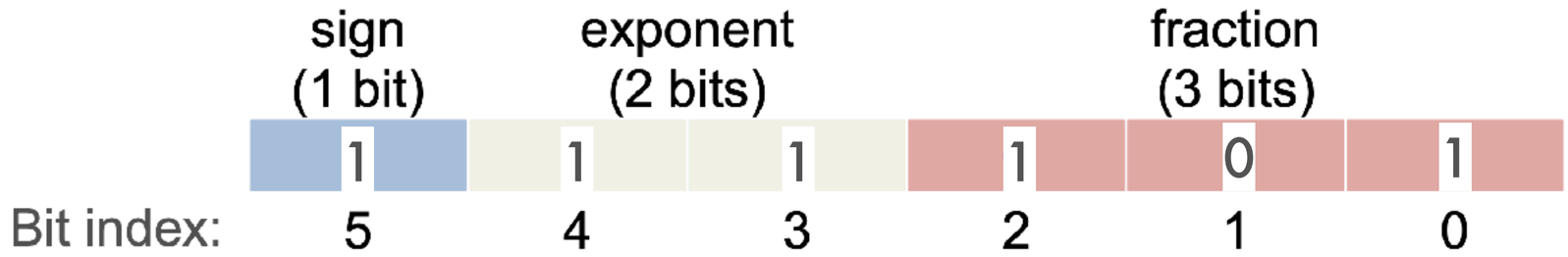
Reverse the representation (scientific notation)

$$3.25_{10} = 11.01_2$$

8	4	2	1	1/2	1/4	1/8
0	0	1	1	0	1	0

$$3.25_{10} = 11.01_2 = 1.101 \cdot 2^1$$

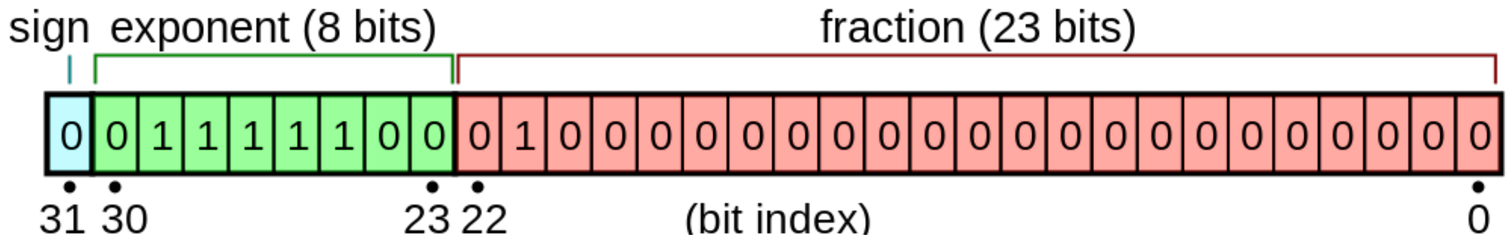
$$-3.25_{10} =$$



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

Digital Representation of Data

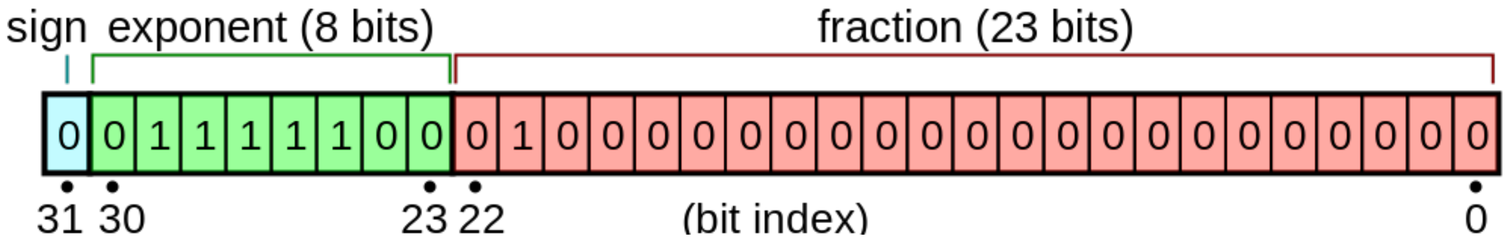
- **Float**:
  - Standard IEEE format for single (aka binary32):



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

$$(-1)^0 \times 2^{124-127} \times (1 + 1 \cdot 2^{-2}) = (1/8) \times (1 + (1/4)) = 0.15625$$

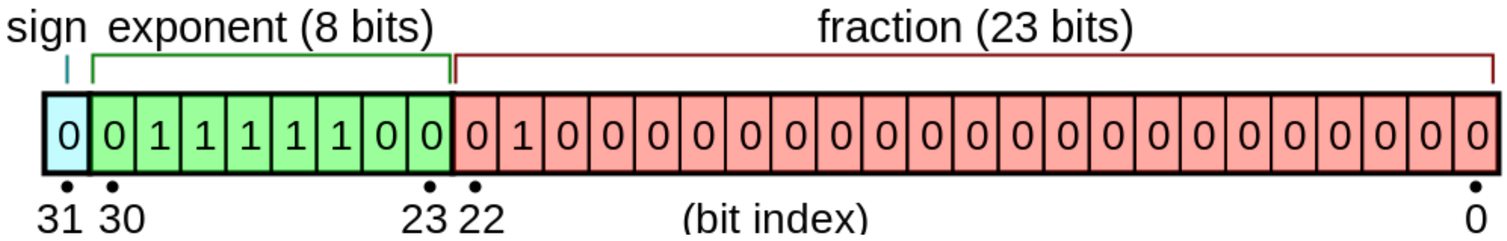
Digital Representation of Data.



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

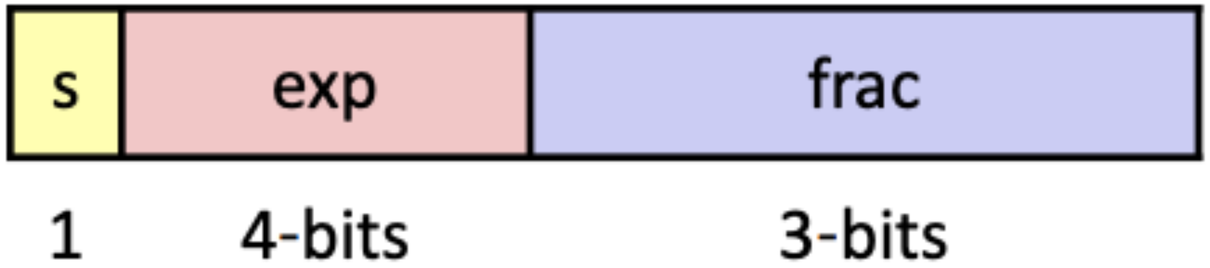
- Special encodings recognized:
  - Exponent 0x00 and fraction 0 is “+/- 0”.
    - 0 00000000 00000000000000000000000 = +0
  - Exponent 0xFF and fraction 0 is +/- “Infinity”
    - 0 11111111 00000000000000000000000 = +INF
  - Not a number/Undefined (Dividing 0 by 0)
    - 0 11111111 10000000000000000000000 = NaN

Digital Representation of Data. Why?



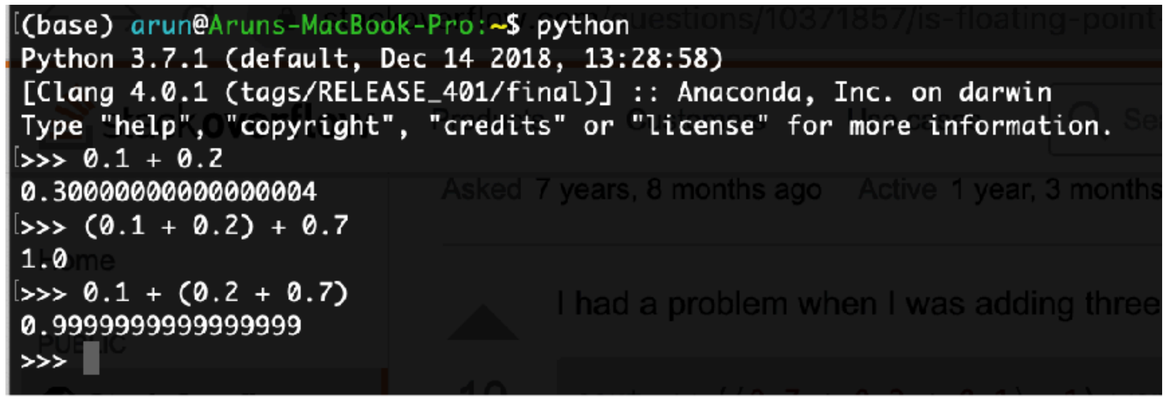
- Exponent for Range, Fraction (significant) for Accuracy.
  - Max: 0 11111110 11111111111111111111111 =>
  - $2^{(254-127)} * (1.111111\ldots)_2 = 2^{(254-127)} * \left(1 + \frac{1}{2} + \frac{1}{4} + \ldots + \frac{1}{8388608}\right)$
  - Max = 2*2^127 = 2^128 = 3.4 x 10^{38}
  - Why not 0 11111111 11111111111111111111111?
- 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!



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

https://docs.nvidia.com/deeplearning/sdk/mixed-precision-training/index.html

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 x^2 = 25
x = 50 x^2 = 2500
x = 500 x^2 = 250000
x = 5000 x^2 = 25000000
x = 50000 x^2 = -1794967296
x = 500000 x^2 = 891896832
x = 5000000 x^2 = -1004630016
```

In C, int uses a 32-bit

http://csapp.cs.cmu.edu/3e/perspective.html

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.

https://stackoverflow.com/questions/52151647/integer-overflow-in-python3

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)

https://www.tutorialspoint.com/numpy/numpy_data_types.htm

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

```
          -16   8   4   2   1
10 =        0   1   0   1   0      8+2 = 10
```

```
          -16   8   4   2   1
-10 =       1   0   1   1   0      -16+4+2 = -10
```

Two-complement Encoding Example (Cont.)

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

Weight	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
Sum		**15213**		**-15213**

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

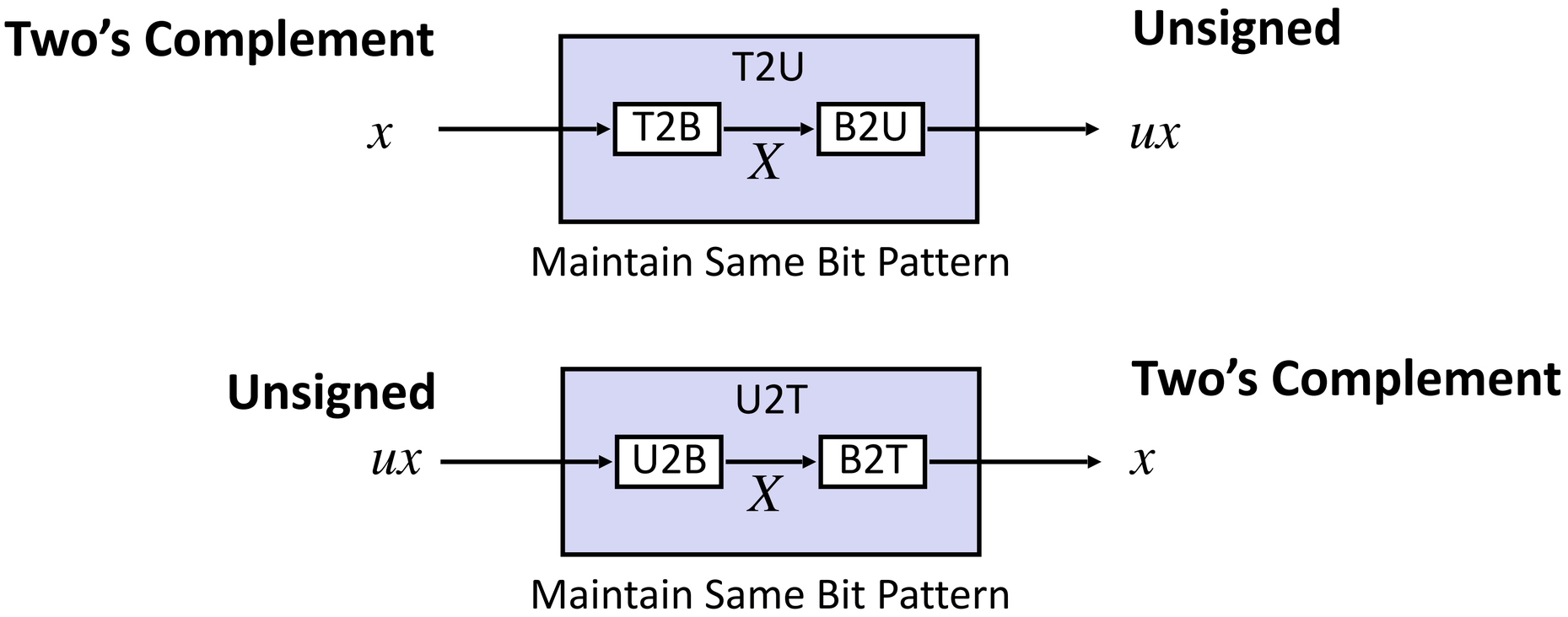
	Decimal	Hex	Binary
UMax	65535	FF FF	11111111 11111111
TMax	32767	7F FF	01111111 11111111
TMin	-32768	80 00	10000000 00000000
-1	-1	FF FF	11111111 11111111
0	0	00 00	00000000 00000000

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
- ⇒ 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



Mapping Signed ↔ Unsigned

Bits	Signed	Unsigned
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	-7	9
1010	-6	10
1011	-5	11
1100	-4	12
1101	-3	13
1110	-2	14
1111	-1	15

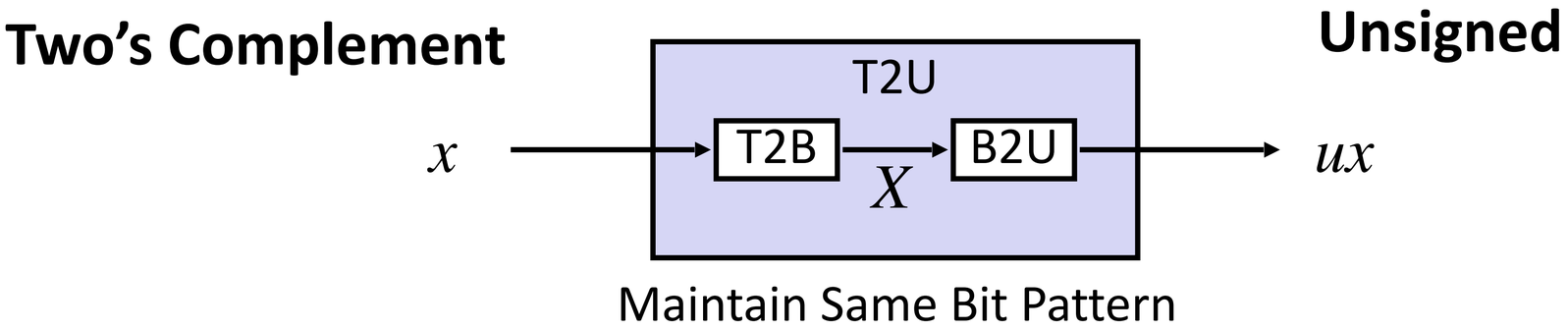
T2U

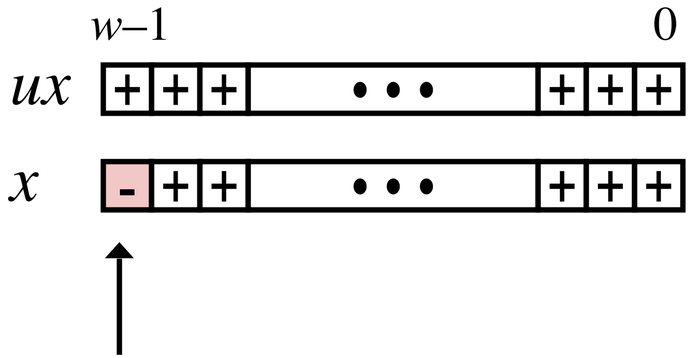
U2T

Mapping Signed ↔ Unsigned

Bits	Signed		Unsigned
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	-7		9
1010	-6		10
1011	-5	+/- 16	11
1100	-4	⟷	12
1101	-3		13
1110	-2		14
1111	-1		15

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

float(10)        => 10.0
float(10.1)      => 10.1
float('10')      => 10.0
float('10.1')    => 10.1
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?


9:41
Bariloche
30°
Snow
H:36° L:22°
Windy conditions from 3PM–5PM, with heavy snow expected at 6PM.
Now 10AM 11AM 12PM 1PM
30° 30° 31° 32° 33°
10-DAY FORECAST
Today 22° 36°
Tue 21° 34°
Wed 29° 38°
Thu 24° 40°
9:41
London
58°
Partly Cloudy
H:72° L:49°
Cloudy conditions from 1AM–7AM, with sunny conditions expected at 8AM.
Now 10PM 11PM 12AM 1AM
58° 56° 54° 51° 50°
10-DAY FORECAST
Today 49° 72°
Tue 63° 77°
Wed 51° 70°
Thu 48° 69°
10:41
Paris
47°
Heavy Rain
H:62° L:41°
Rainy conditions tonight, continuing through the morning.
Now 11PM 12AM 1AM 2AM
47° 45° 44° 43° 41°
10-DAY FORECAST
Today 41° 62°
Tue 38° 56°
Wed 41° 54°
Thu 42° 57°