

- 0. MOTIVATION
- 1. PROBLEM SOLVING
- 2. INFORMATION
- 3. COUNTING
- 4. BITS
- 5. CODES
- 6. ALGORITHMS
- 7. COMPUTERS
- 8. ARITHMETIC
- 9. MEMORY
- 10. ANALOG VS. DIGITAL

The slides are meant as visual support for the lecture.
They are neither a documentation nor a script.

Please do not print the slides.

Comments and feedback at n.meseth@hs-osnabrueck.de

MOTIVATION

a few
experts

digitally uneducated
society



digitally illiterate society with a few experts

collective understanding

you?



society with a distributed and high degree of digital education

representation

representation

processing

representation

processing

programming

representation

processing

programming

digital fundamentals

data analysis

representation

processing

programming

digital fundamentals

data analysis

artificial
intelligence

representation

processing

programming

digital fundamentals

digital applications

data analysis

artificial
intelligence

representation

processing

programming

digital fundamentals

digital applications

data analysis

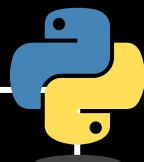
artificial
intelligence

representation

processing

programming

digital fundamentals



digital applications

data analysis

artificial
intelligence



representation

processing

programming



digital fundamentals



PROBLEM SOLVING

a model for solving problems



a model for solving problems





a model for solving problems







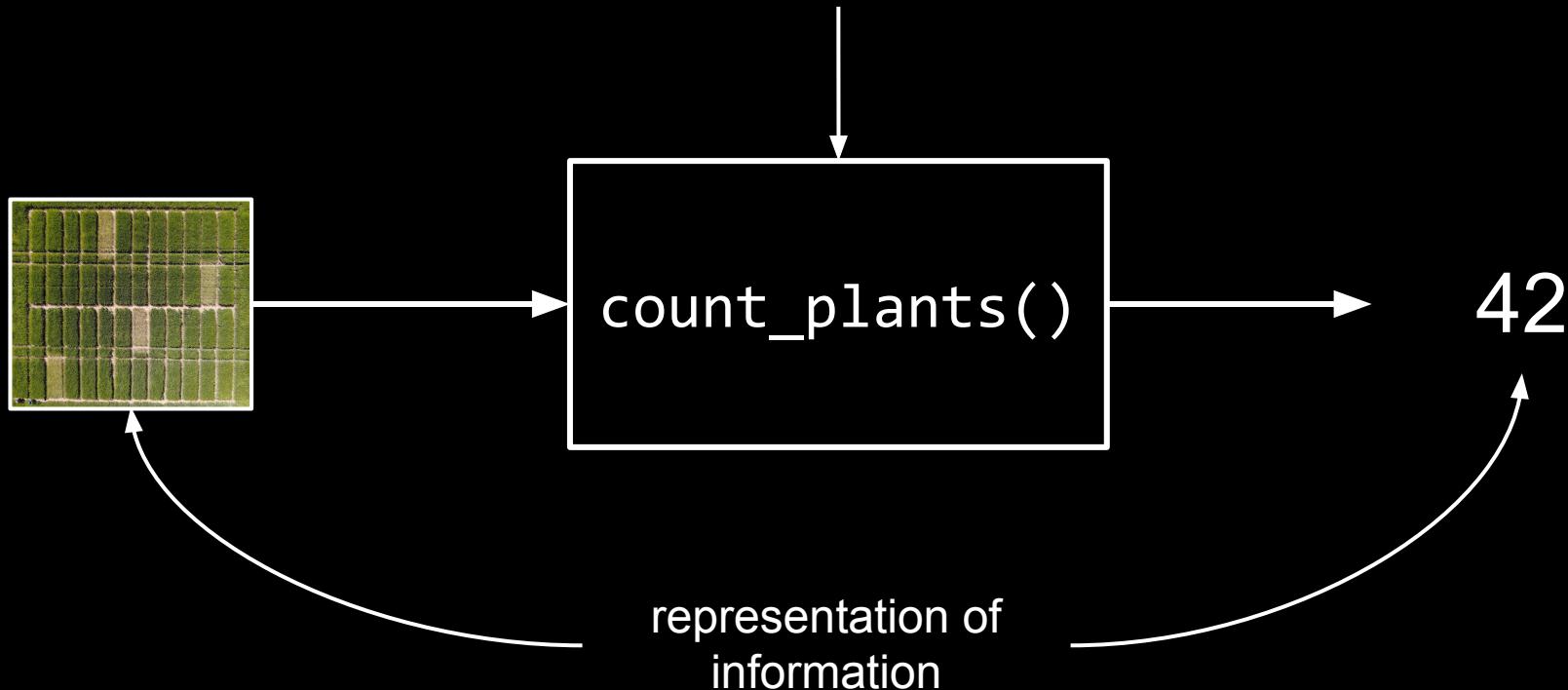
output



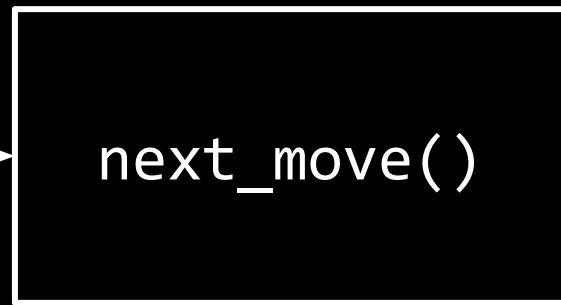
count_plants()

42

processing of
information







E2 → E4

problem solving strategies

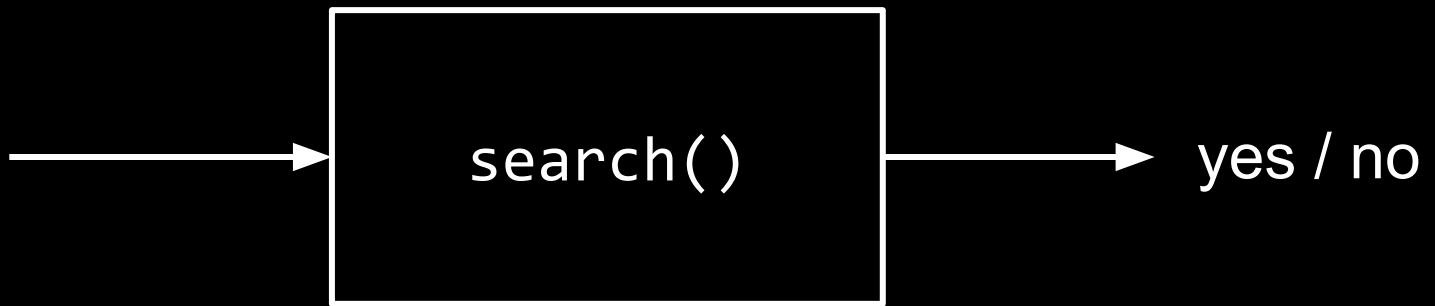
divide and conquer

large and complex problem





sorted list +
element



is 67 a prime number?

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

linear search



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

linear search



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

linear search



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

linear search



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

linear search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



19 steps... can't we do better?

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



large and complex
problem

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

large and complex problem

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

smaller problem

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41

smaller problem

43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

binary search

67 != 41



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

binary search

$67 > 41$



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, **41**,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

binary search

$67 > 41$



2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 \neq 71$$

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 \neq 71$$

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 < 71$$

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 \neq 59$$

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 > 59$$

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 = 67$$

binary search

2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 = 67$$

3 splits → much better

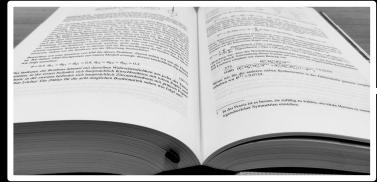
2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41,
43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97



$$67 = 67$$



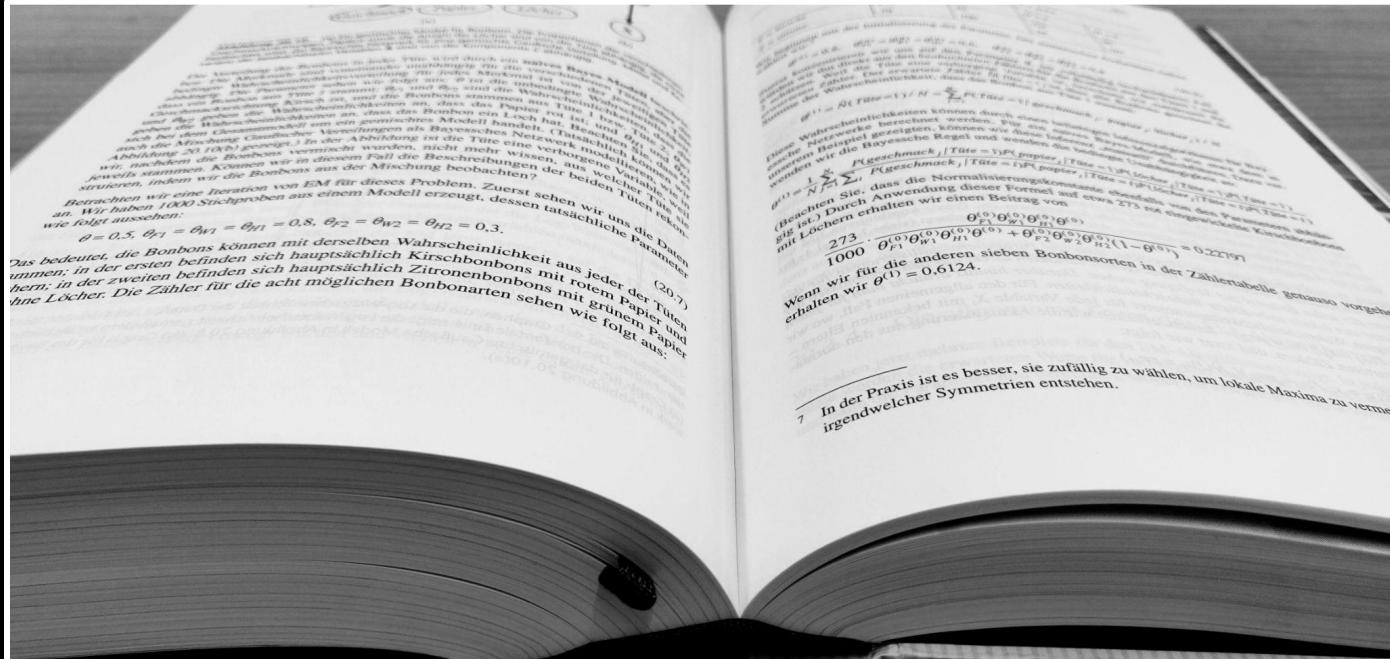
how efficient are linear and
binary search in general?



count_words()

word count

how many words are in the book?



strategies, anyone?



7 In der Praxis ist es besser, sie zufällig zu wählen, um lokale Maxima zu vermeiden.



page 1







187

212



page 1



page 2



187

212

55



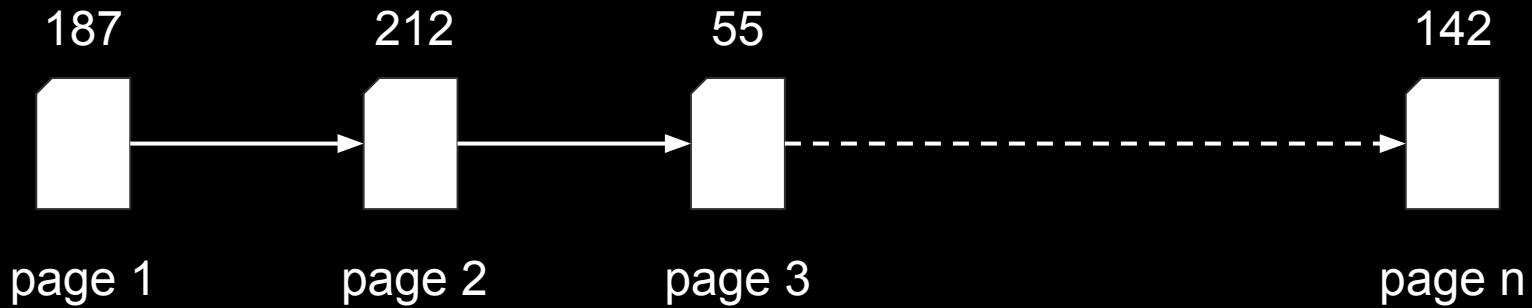
page 1



page 2



page 3





7. In der Praxis ist es besser, sie zufällig zu wählen, um lokale Maxima zu vermeiden.



$n = 1327$ pages

$\varnothing 2:23$ minutes per page

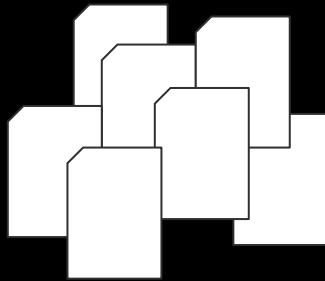
~ 52.34 hours

divide and conquer

+

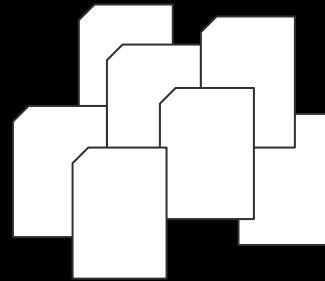
?

pages 1 - 700



student 1

pages 701 - 1327



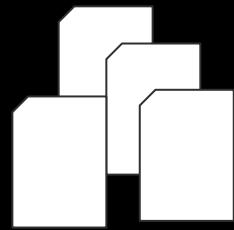
student 2

pages 1 - 350

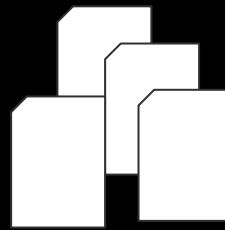
pages 351 - 700

pages 701 - 1050

pages 1051- 1327



student 1



student 2



student 3



student 4

divide and conquer

+

distribution and parallelization



INFORMATION

“Information is that which allows you to make a correct prediction with accuracy better than chance.”

Adami, Christoph. “What Is Information?” Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 374, no. 2063, Mar. 2016, p. 20150230, <https://doi.org/10.1098/rsta.2015.0230>.

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defining and measuring information

guess the number am I thinking of!

what is the most efficient approach?



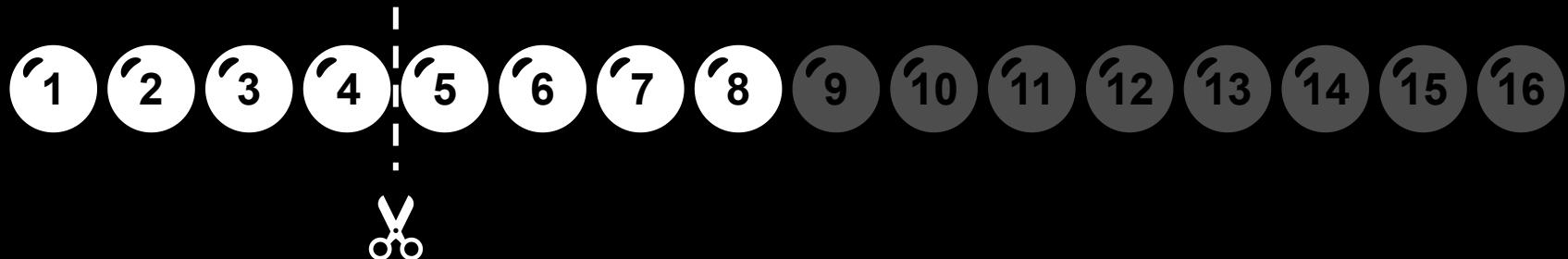
is it > 8 ?



is it $> 8?$ 



is it $> 8?$ X
is it $> 4?$



is it > 8 ? X

is it > 4 ? ✓



is it > 8? ✗

is it > 4? ✓

is it > 6?



is it > 8? ✗

is it > 4? ✓

is it > 6? ✓

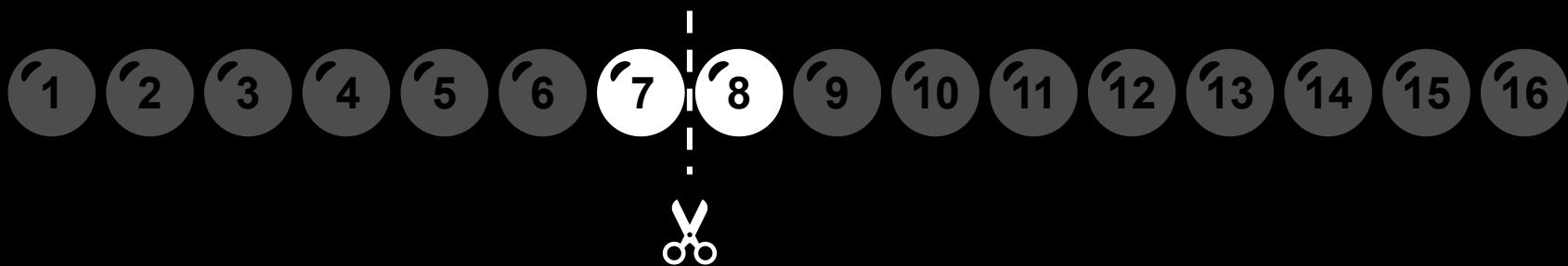


is it > 8? X

is it > 4? ✓

is it > 6? ✓

is it > 7?



is it > 8? ✗

is it > 4? ✓

is it > 6? ✓

is it > 7? ✗



is it > 8? ✗

is it > 4? ✓

is it > 6? ✓

is it > 7? ✗



with 4 questions from 16 to 1

is it > 8?	✗	0
is it > 4?	✓	1
is it > 6?	✓	1
is it > 7?	✗	0



with 4 questions from 16 to 1

where is the information?

where is the information?



where is the information?

$N = 16$



where is the information?

$$\begin{aligned} N &= 16 \\ N &= 8 \end{aligned}$$



where is the information?

$\overline{N} = 16$

$\overline{N} = 8$

$N = 4$



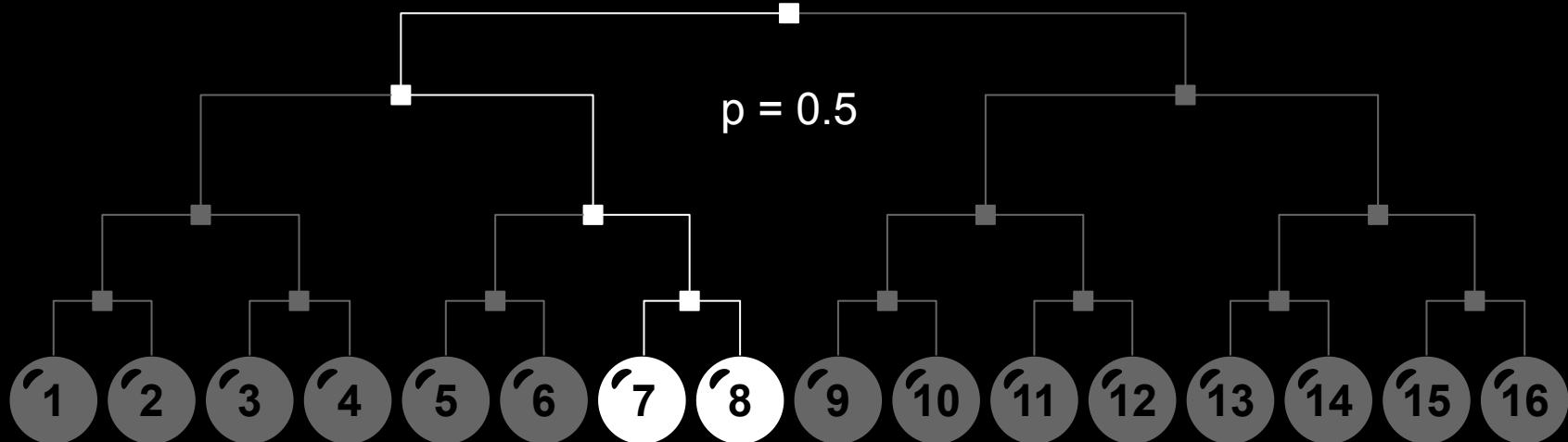
where is the information?

$N = 16$

$N = 8$

$N = 4$

$N = 2$



where is the information?

$N = 16$

$N = 8$

$N = 4$

$N = 2$

$N = 1$



information = reduced uncertainty
uncertainty is measured with the logarithm of N

$$H = \log_2(N)$$



or: how often can we cut the remaining possibilities in half?

$$H = \log_2(N)$$



$$H_0 = \log_2(16) = 4$$



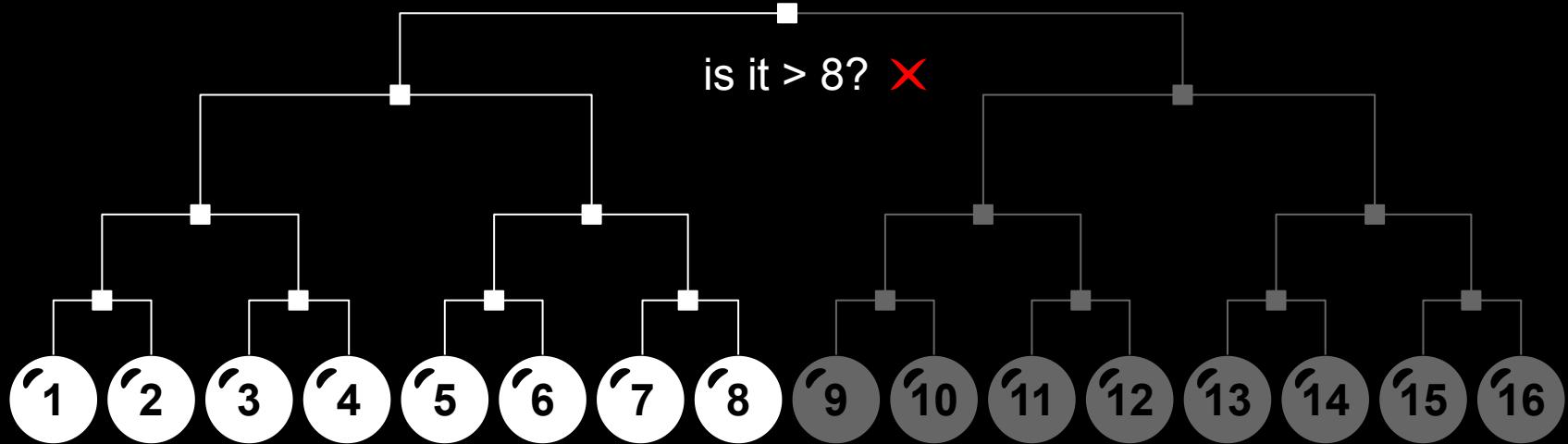
$$H_1 = \log_2(8) = 3$$



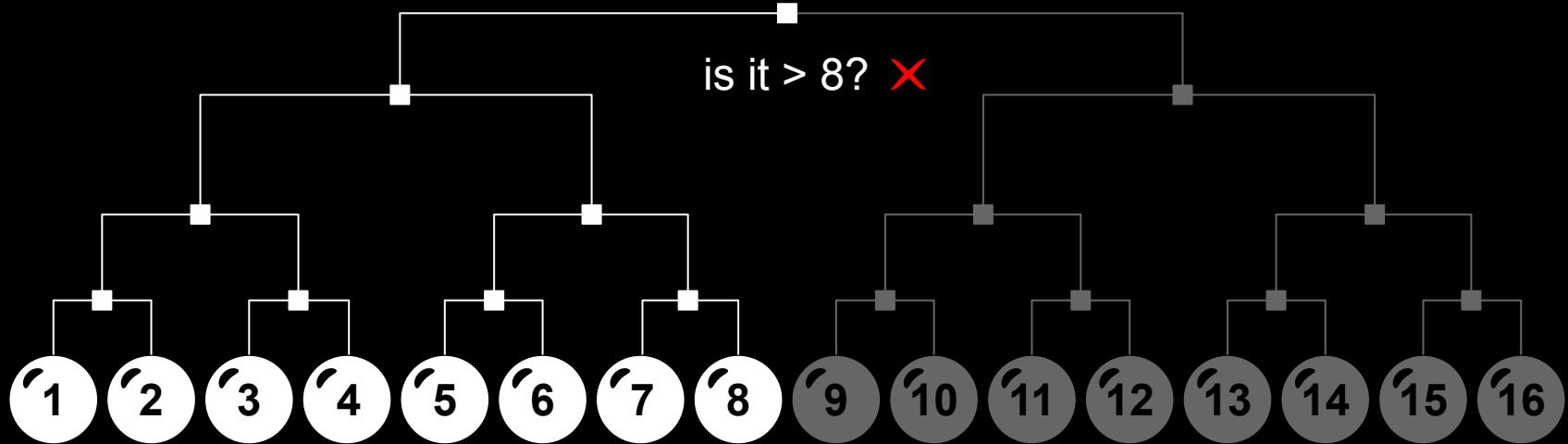
$$I = H_0 - H_1$$



$$I = \log_2(16) - \log_2(8)$$



$$I = 4 - 3 = 1$$



uncertainty and information are
measured in **bits**

how many yes/no questions to reduce uncertainty to zero?

$$H = 0 = \log_2(1)$$

how many yes/no questions to reduce uncertainty to zero?

$$H = 0 = \log_2(1)$$

$$H = \log_2(N)$$

poker

which card am I holding?



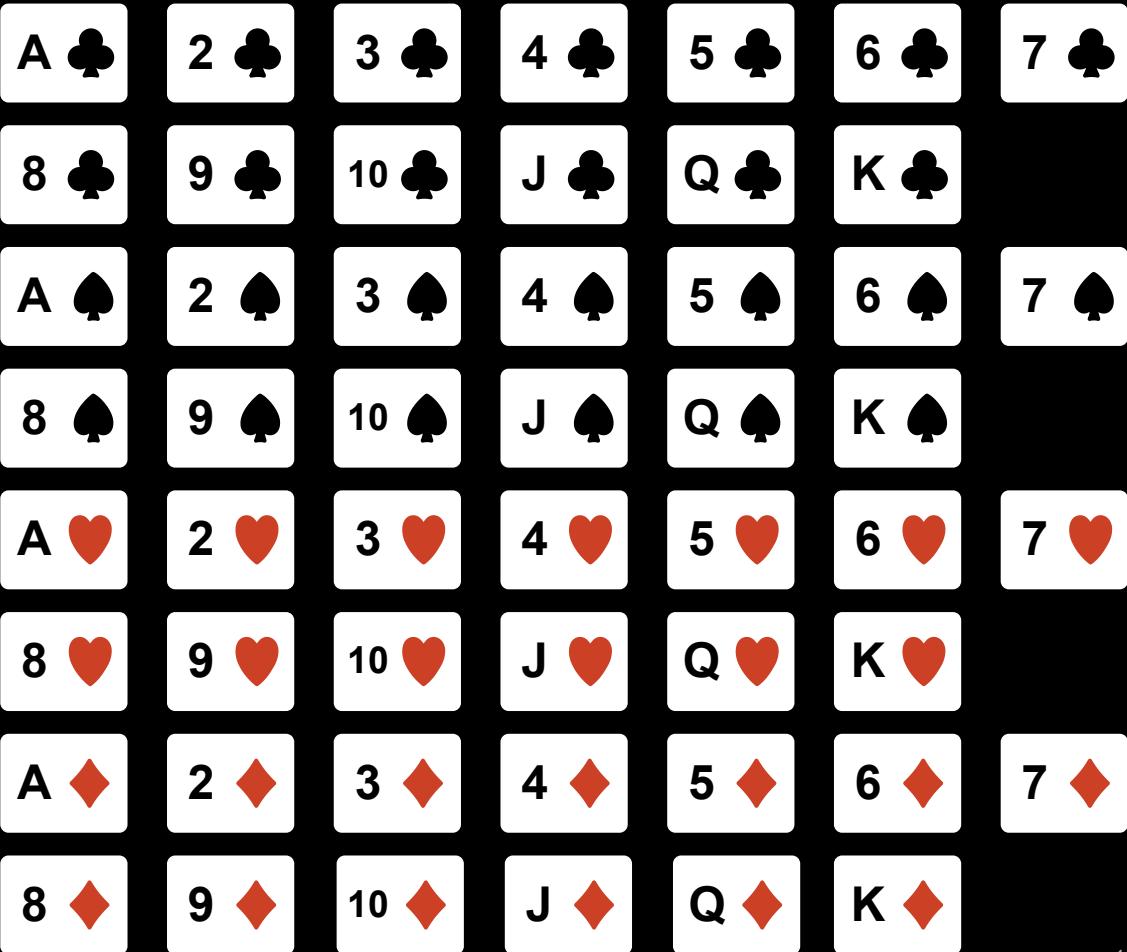
52 card poker deck



52 possible cards



is the card black?



is the card black?

no



is the card black?

no

is it hearts?

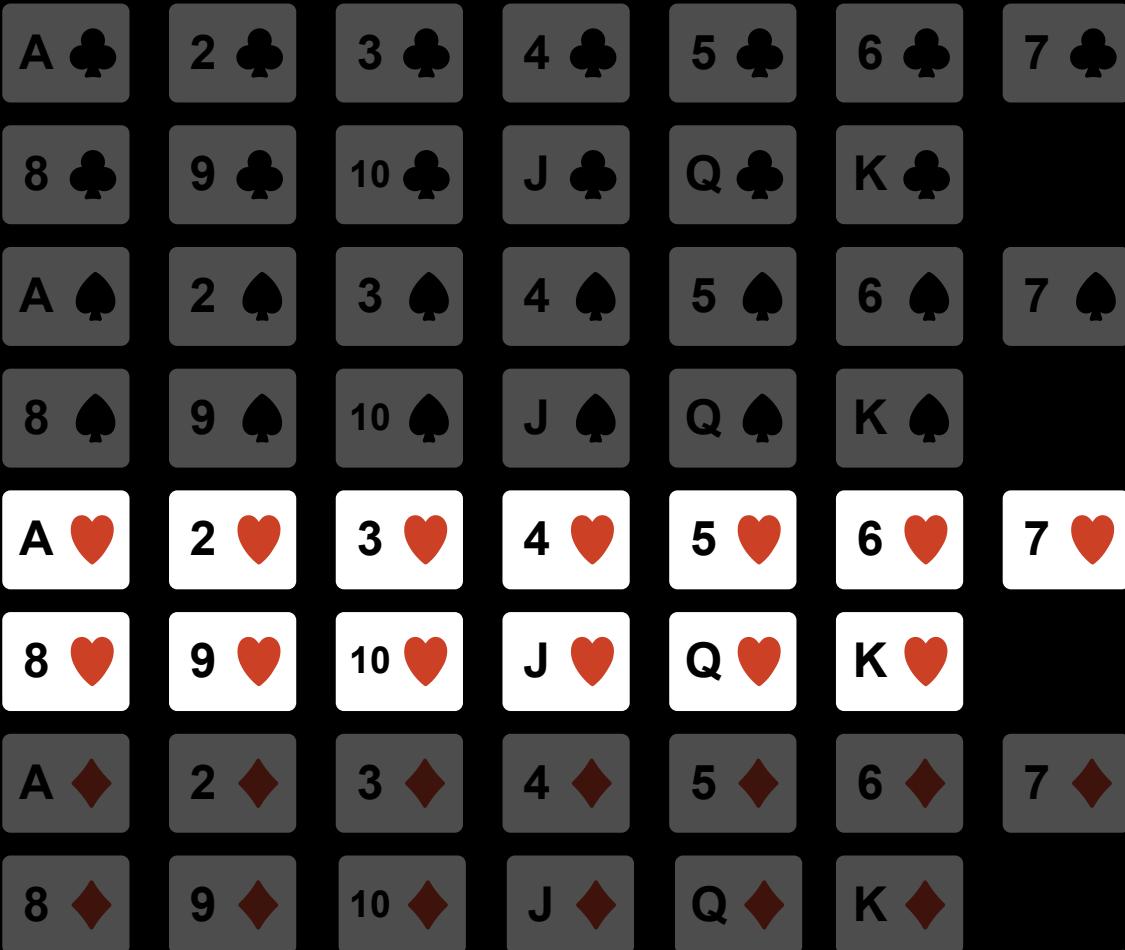


is the card black?

no

is it hearts?

yes



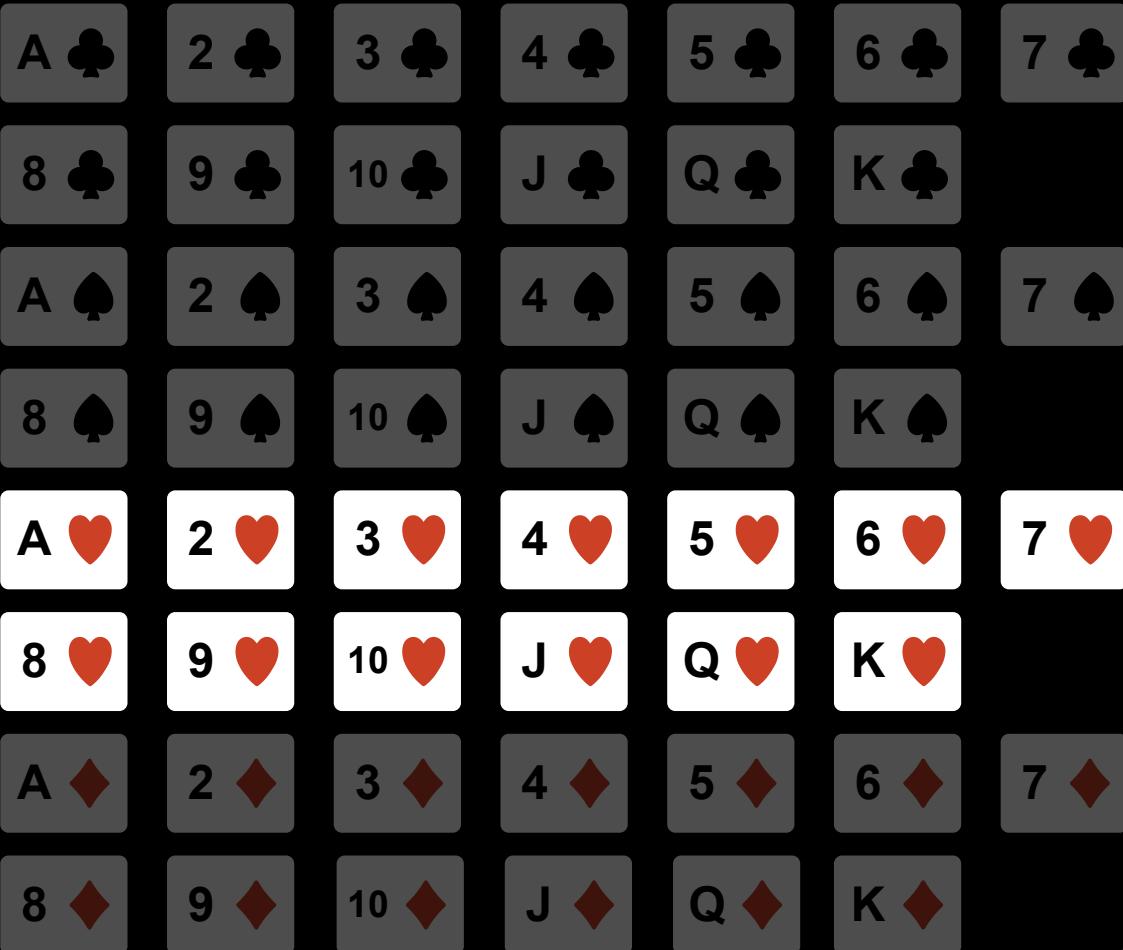
is the card black?

no

is it hearts?

yes

is it 8 or above?



is the card black?

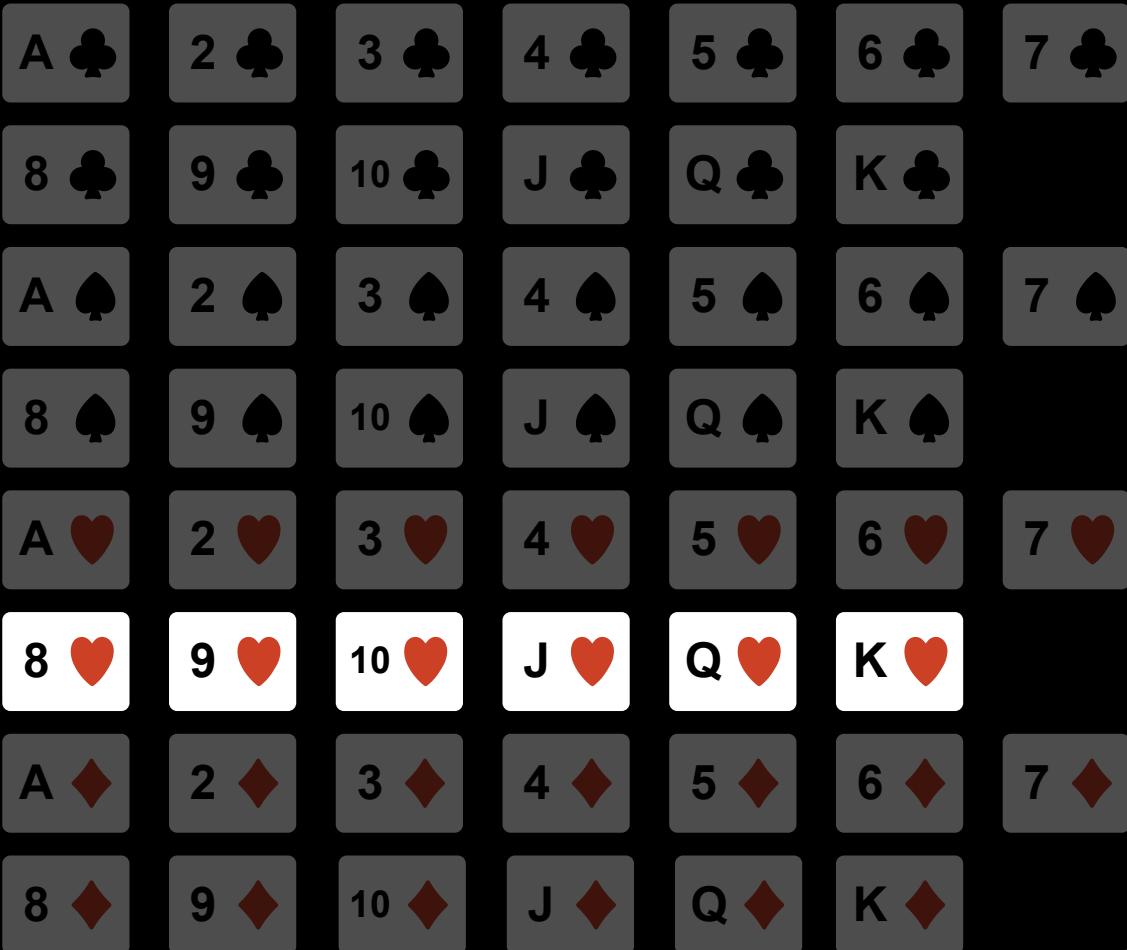
no

is it hearts?

yes

is it 8 or above?

yes



is the card black?

no

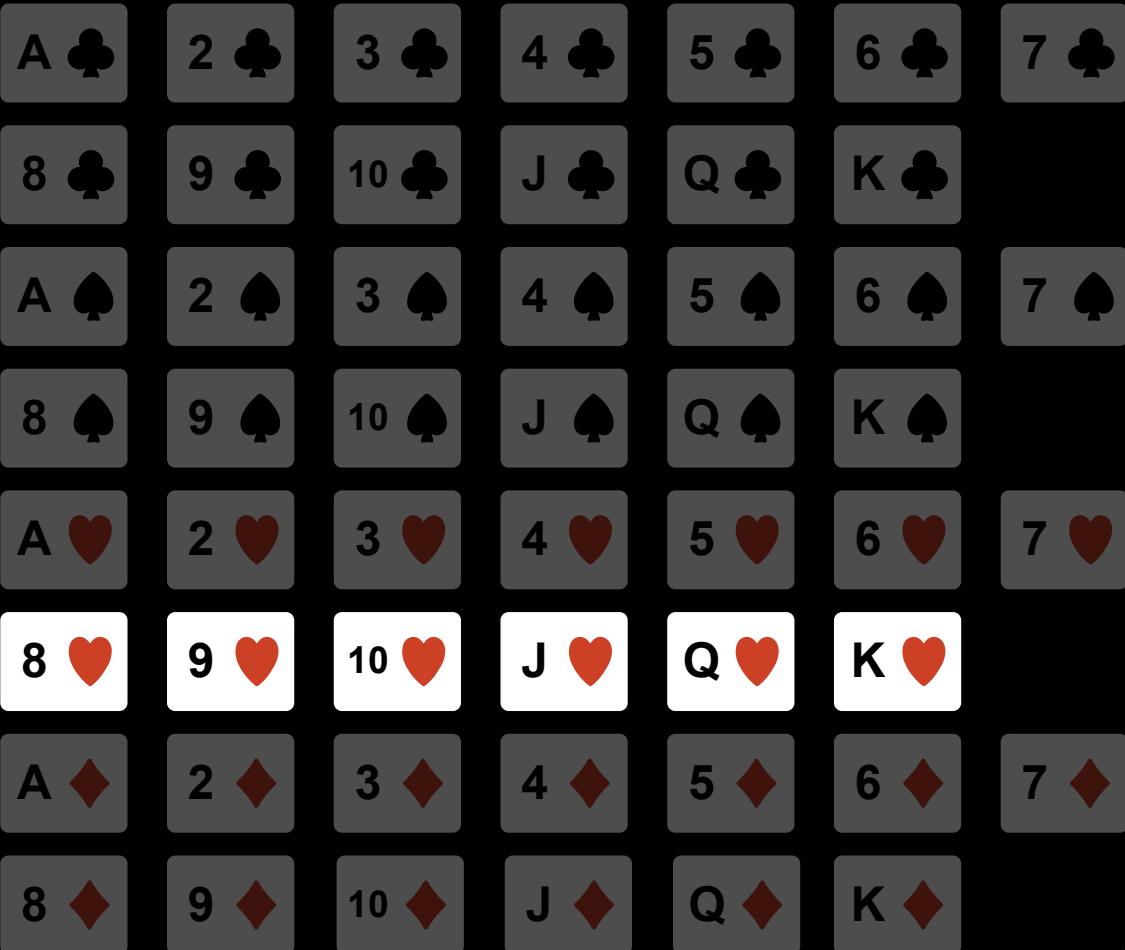
is it hearts?

yes

is it 8 or above?

yes

is it jack or above?



is the card black?

no

is it hearts?

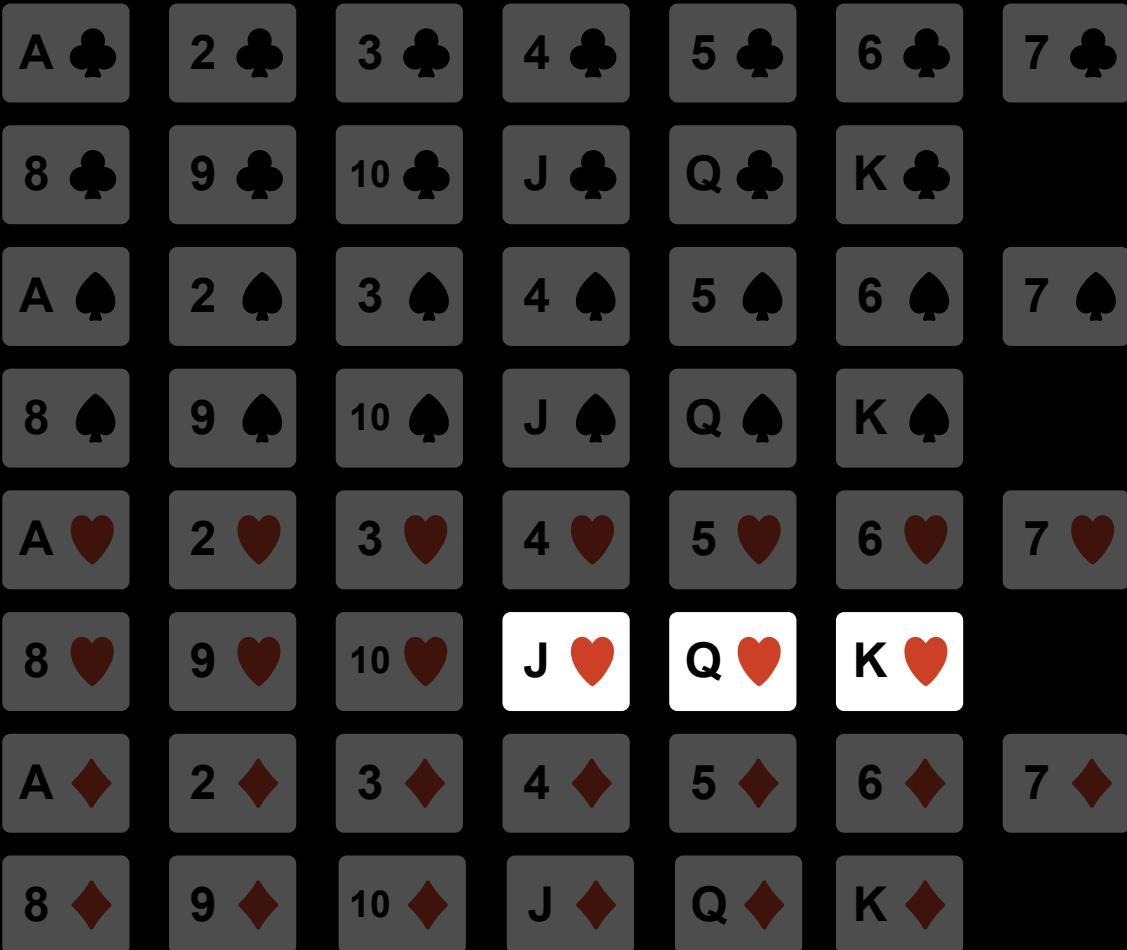
yes

is it 8 or above?

yes

is it jack or above?

yes



is the card black?

no

is it hearts?

yes

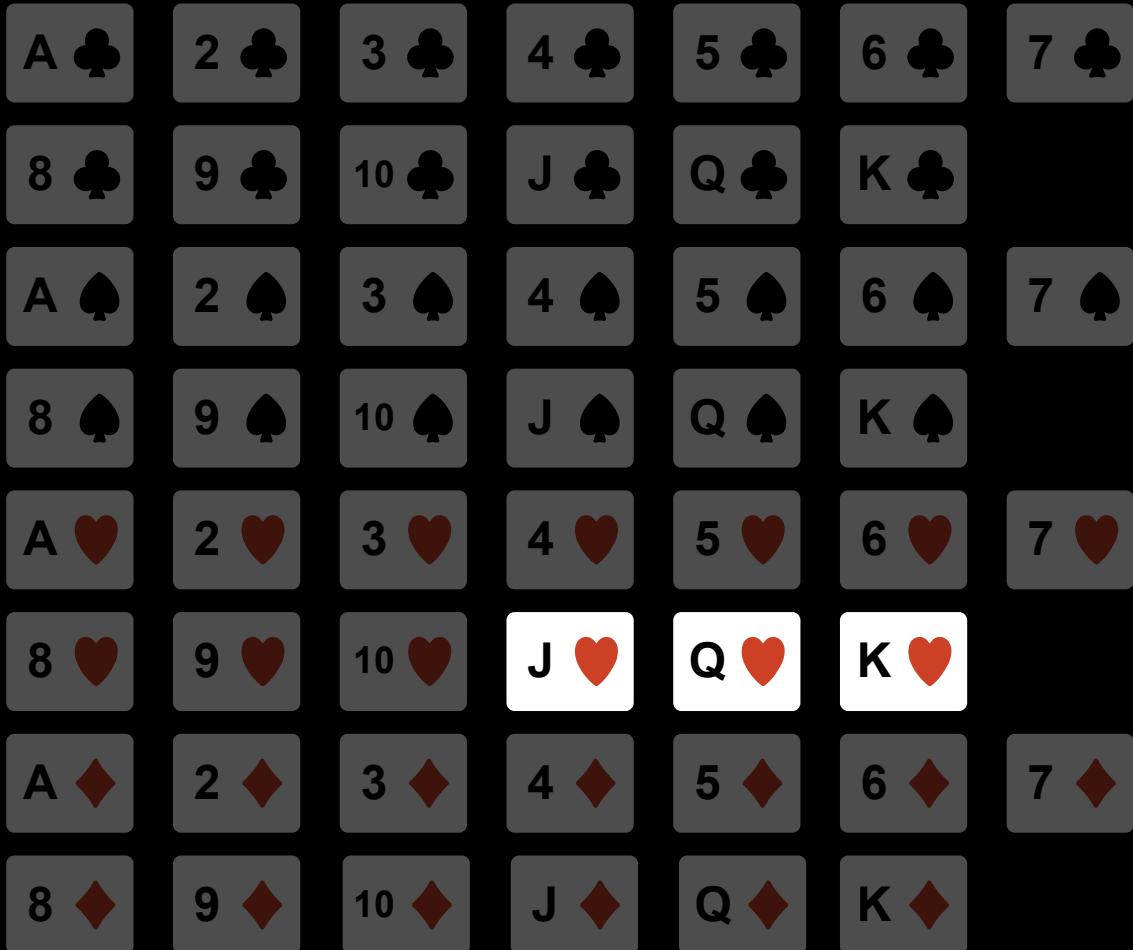
is it 8 or above?

yes

is it jack or above?

yes

is it queen or above?



is the card black?

no

is it hearts?

yes

is it 8 or above?

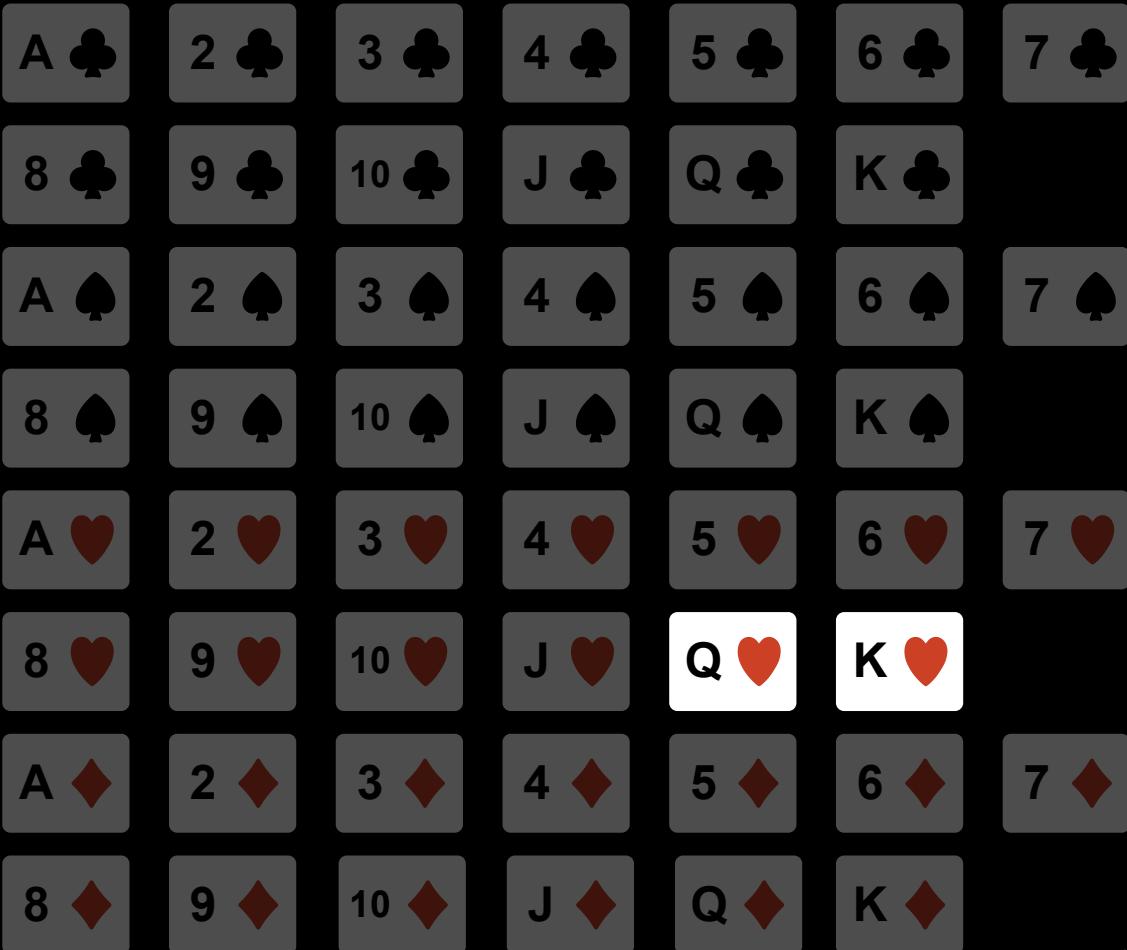
yes

is it jack or above?

yes

is it queen or above?

yes



is the card black?

no

is it hearts?

yes

is it 8 or above?

yes

is it jack or above?

yes

is it queen or above?

yes

is it king?



is the card black?

no

is it hearts?

yes

is it 8 or above?

yes

is it jack or above?

yes

is it queen or above?

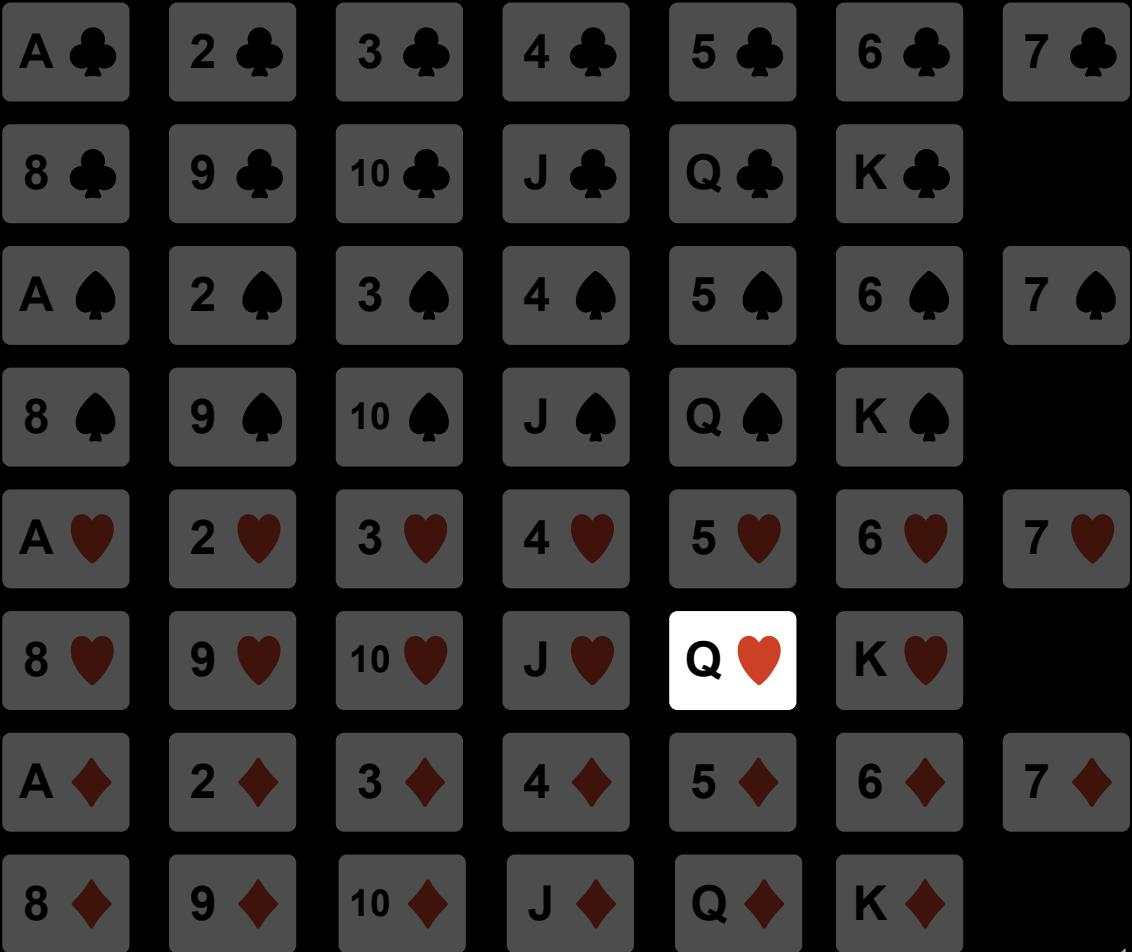
yes

is it king?

no



with 6 questions
from 52 to 1

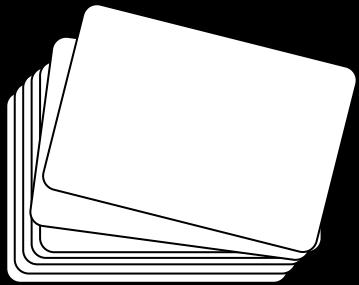


uncertainty with $N = 52$ possibilities?



$$H = \log_2(52) \approx 5.7$$

uncertainty with $N = 52$ possibilities?



average # of yes/no
questions



$$H = \log_2(52) \approx 5.7$$

one bit of information with each answer...

$$\log_2(52) - \log_2(26) = 1$$

one bit of information with each answer...

$$\log_2(52) - \log_2(26) = 1$$

...that cuts the remaining options in half

is it a spades card?



is it a spades card?

no



is it a spades card?

no

how much information?



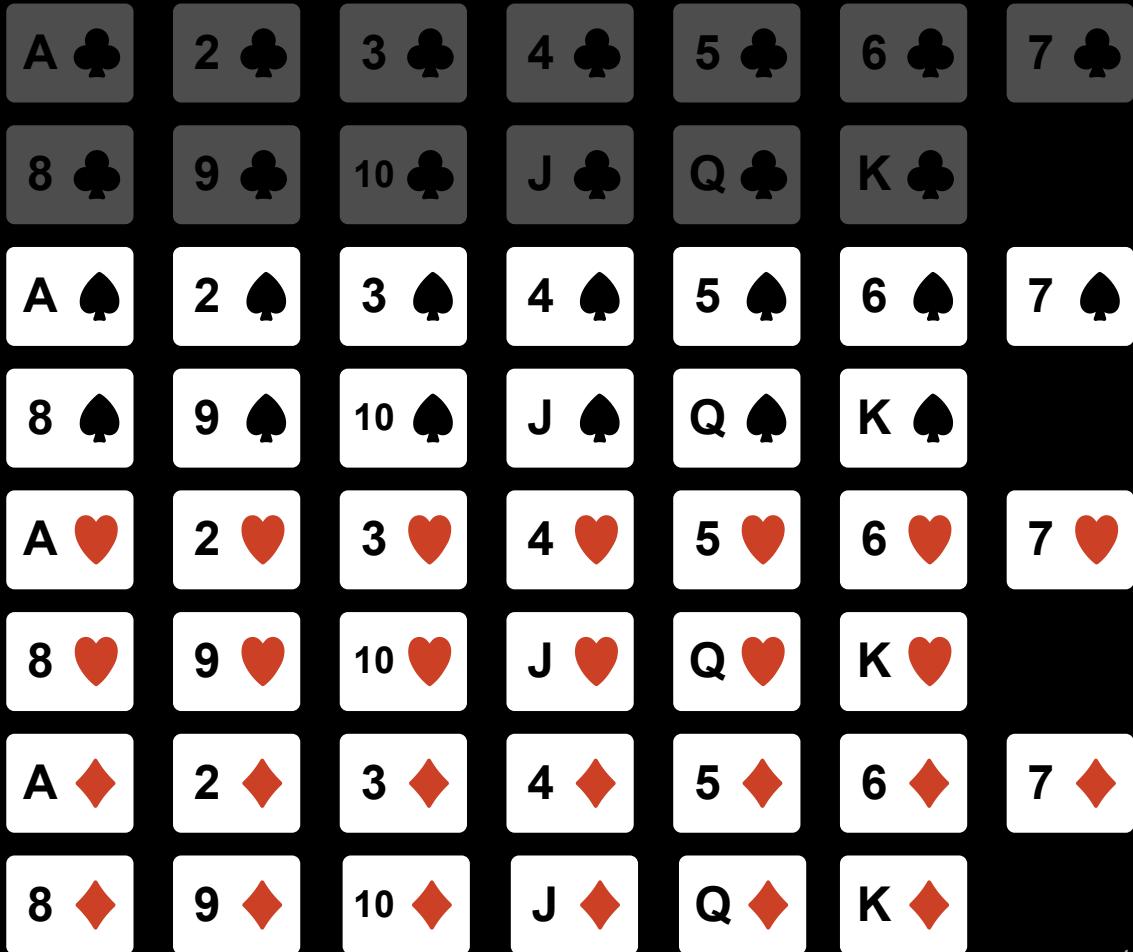
is it a spades card?

no

how much information?

$$H_0 = \log_2(52) \approx 5.7$$

$$H_1 = \log_2(39) \approx 5.29$$



is it a spades card?

no

how much information?

$$H_0 = \log_2(52) \approx 5.7$$

$$H_1 = \log_2(39) \approx 5.29$$

$$H_0 - H_1 \approx 0.41$$



is it a spades card?

no

how much information?

$$H_0 = \log_2(52) \approx 5.7$$

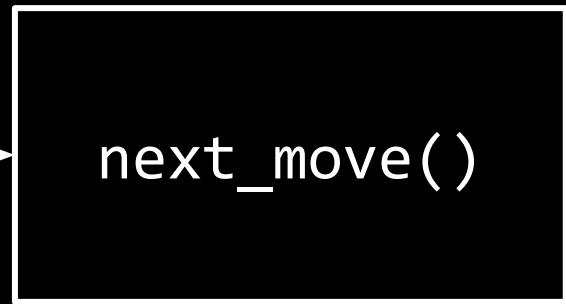
$$H_1 = \log_2(39) \approx 5.29$$

$$H_0 - H_1 \approx 0.41$$

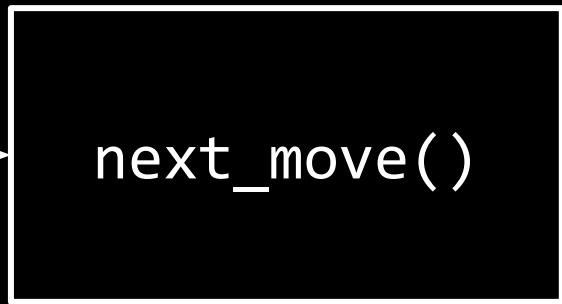
that's less than 1 bit



chess



how much information is
one move?









c2 → c4



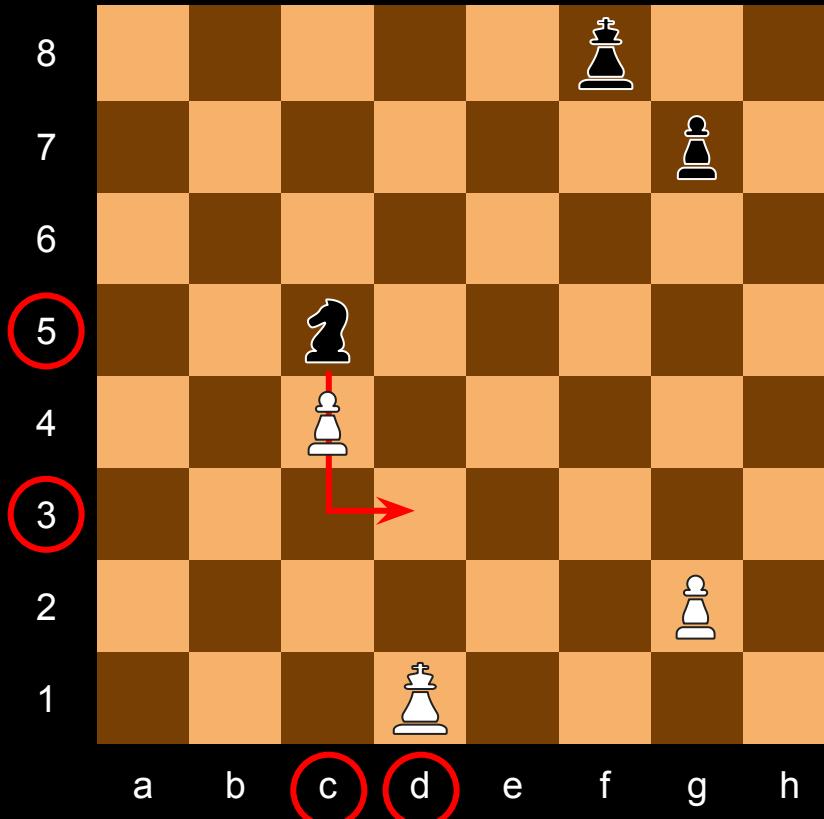
c2 → c4



c2 → c4



$c2 \rightarrow c4$
 $c5 \rightarrow d3$



$c2 \rightarrow c4$
 $c5 \rightarrow d3$
...



c2 → c4

how many possibilities?

64 fields x 64 fields

how many possibilities?

$$64 \times 64 = 4096$$

possible moves*

*disregarding impossible moves

$$64 \times 64 = 4096$$

$$H = \log_2(4096) = 12$$

$$64 \times 64 = 4096$$

$$H = \log_2(4096) = 12$$

one chess move is 12 bits of information

an alternative way to calculate # bits

c 2 c 4

4 digits

c 2 c 4

4 digits

8 possible symbols per digit

c 2 c 4

4 digits

8 possible symbols per digit
how many bits per digit?

c 2 c 4

4 digits

8 possible symbols per digit
how many bits per digit?

$$H_{digit} = \log_2(8) = 3$$

c 2 c 4

4 digits

8 possible symbols per digit
how many bits per digit?

$$H_{digit} = \log_2(8) = 3$$

$$H_{move} = \log_2(8) \times 4 = 12$$

$$H_{avg} = \log_2(S) \times n$$

S: number of possible symbols

n: number of digits in our message

$$H_{max} = \lceil \log_2(S) \rceil \times n$$

when calculating bits for storage, we must
always consider the worst case

digits and # symbols

{A}

— —

{A}

A A

{A, B}

— —

{A, B}

AA, AB, BA, BB

{A, B, C}

— —

{A, B, C}

AA, AB, BA, BB,
AC, BC, CA, CB, CC

{A, B, C, D}

— —

{A, B, C, D}

AA, AB, BA, BB, AC, BC, CA, CB,
CC, AD, DA, BD, DB, CD, DC, DD

{A, B, C, D, E}

— —

{A, B, C, D, E}

AA, AB, BA, BB, AC, BC, CA, CB, CC,
AD, DA, BD, DB, CD, DC, DD, AE, EA,
BE, EB, CE, EC, DE, ED, EE

with # digits n = 2

# symbols	# messages
1	1
2	4
3	9
4	16
5	25

with length $n = 2$

# symbols	$f(x)$	# messages
1		1
2	$f(x)$	4
3	→	9
4		16
5		25

and more digits?

{A, B}

— — —

{A, B}

AAA, AAB, ABA, ABB,
BBB, BBA, BAA, BAB

{A, B}



{A, B}

AAAA, AAAB, AABA, AABB,
ABAA, ABAB, ABBA, ABBB,
BAAA, BAAB, BABA, BABB,
BBAA, BBAB, BBBA, BBBB

with # symbols $S = 2$

# digits	# messages
1	2
2	4
3	8
4	16
5	32

with # symbols $S = 2$

# digits	$f(x)$	# messages
1		2
2	$f(x)$	4
3	→	8
4		16
5		32

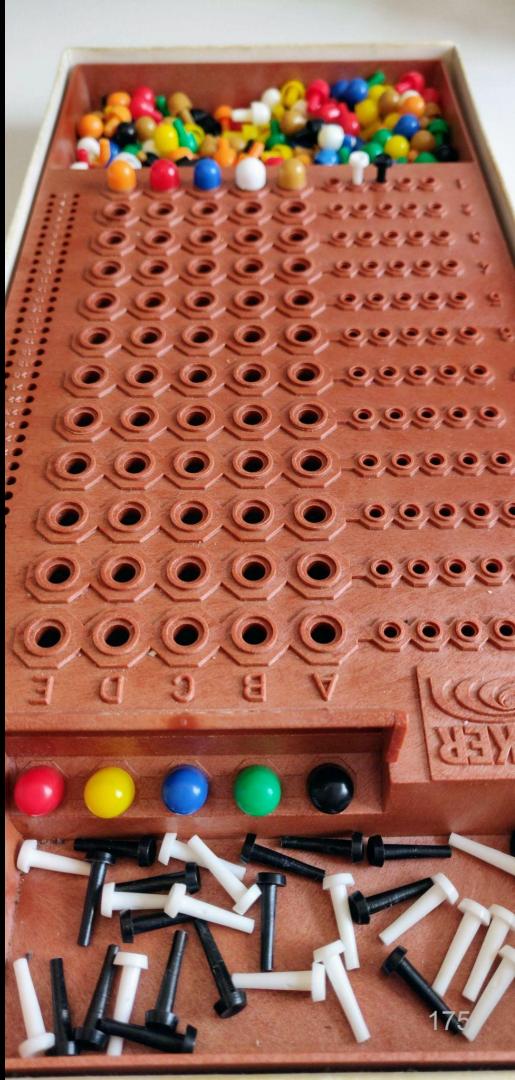
with # symbols $S = 2$

# digits	$f(x)$	# messages
1		2
2	$f(x)$	4
3	→	8
4		16
5		32

possible messages with n digits and S symbols

$$N = S^n$$

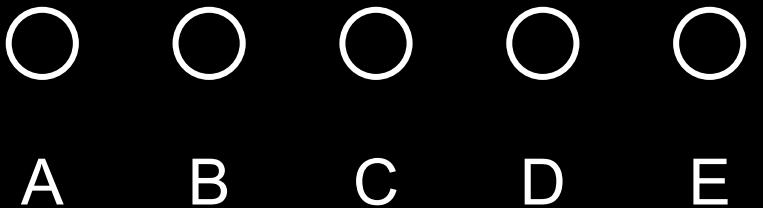
mastermind



eight colors



five slots



possible permutations

$$N = 5^8 = 390625$$

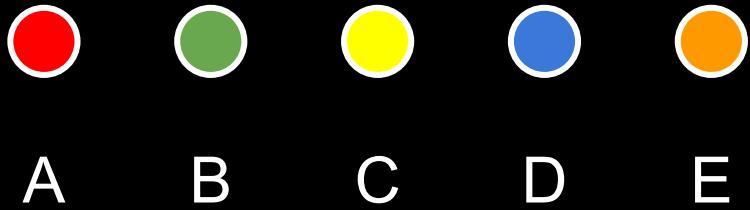
maximum entropy in bits

$$H_{max} = \log_2 5^8 = 18.575$$

hints reduce uncertainty (entropy)



first guess



opponent's hints



first guess

opponent's hints

correct



A

B

C

D

E

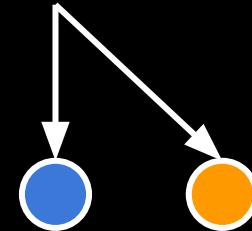
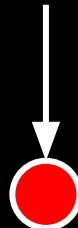


first guess

opponent's hints

correct

wrong position



A

B

C

D

E



how much information did we get?



A



B



C



D



E



colors left



slots left



A

B

C

D

E

new possible permutations?

$$N = 4^8 = 65536$$

reduced entropy in bits?

$$H = \log_2 4^8 = 16$$

COUNTING

1

2

3

1

2

3

10^2

10^1

10^0

1

2

3

10^2

10^1

10^0

$$= 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0$$

$$= 1 \times 100 + 2 \times 10 + 3 \times 1$$

$$= 123$$

4

1

2

3

?

10^2

10^1

10^0

$$\begin{array}{r} 4 \\ 1 \\ 2 \\ 3 \\ \hline ? & 10^2 & 10^1 & 10^0 \end{array}$$

$$= 4 \times 10^3 + 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0$$



$$= 4 \times 10^3 + 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0$$

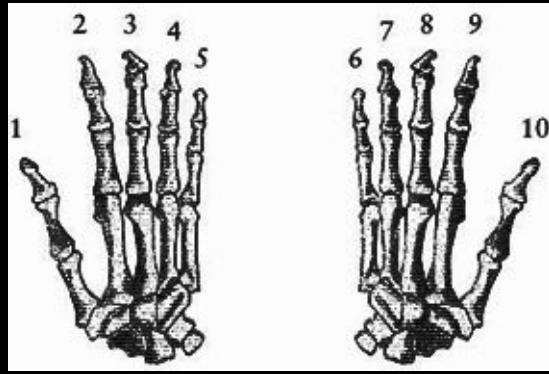
$$= 4 \times 1000 + 1 \times 100 + 2 \times 10 + 3 \times 1$$



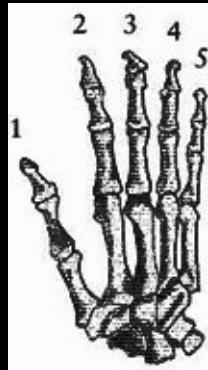
$$= 4 \times 10^3 + 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0$$

$$= 4 \times 1000 + 1 \times 100 + 2 \times 10 + 3 \times 1$$

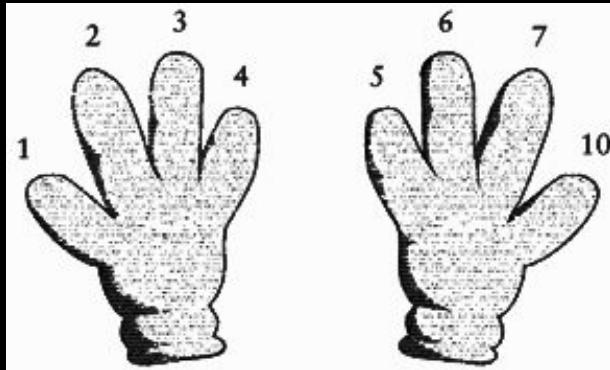
$$= 4123$$



human hand



human hand



cartoon character's hand

1

2

3

(octal)

1

2

3

(octal)

8²

8¹

8⁰

1

2

3

(octal)

8^2

8^1

8^0

$$= 1 \times 8^2 + 2 \times 8^1 + 3 \times 8^0$$

1

2

3

(octal)

8^2

8^1

8^0

$$= 1 \times 8^2 + 2 \times 8^1 + 3 \times 8^0$$

$$= 1 \times 64 + 2 \times 8 + 3 \times 1$$

1

2

3

(octal)

8²

8¹

8⁰

$$= 1 \times 8^2 + 2 \times 8^1 + 3 \times 8^0$$

$$= 1 \times 64 + 2 \times 8 + 3 \times 1$$

$$= \mathbf{83} \text{ (decimal)}$$

decimal

8

octal

?

decimal

octal

?



7

decimal

16

octal

?

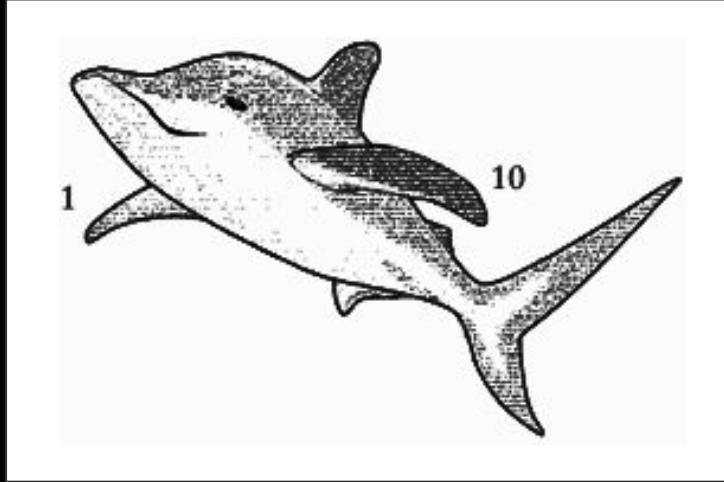
decimal

octal

?



100



what now?

0, 1, ...

0, 1, 10, ...

0, 1, 10, 11, ...

0, 1, 10, 11, 100, ...

0, 1, 10, 11, 100, 101, ...

0, 1, 10, 11, 100, 101, 110

1 1 0 (binary)

1

1

0

(binary)

2^2

2^1

2^0

$$\begin{array}{r} 1 & 1 & 0 \\ \hline 2^2 & 2^1 & 2^0 \end{array}$$

$$= 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0$$

$$\begin{array}{r} 1 & 1 & 0 \\ \hline 2^2 & 2^1 & 2^0 \end{array}$$

$$= 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0$$

$$= 1 \times 4 + 1 \times 2 + 0 \times 1$$

$$\begin{array}{r} 1 & 1 & 0 \\ \hline 2^2 & 2^1 & 2^0 \end{array}$$

$$= 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0$$

$$= 1 \times 4 + 1 \times 2 + 0 \times 1$$

$$= 6 \text{ (decimal)}$$

2 3 4 5 6

0, 1, 10, 11, 100, 101, 110

place value systems

$$N = d_n * R^{n-1} + \dots + d_2 * R^1 + d_1 * R^0$$

$$d \in \{ 0, 1, \dots R-1 \}$$

n = number of digits

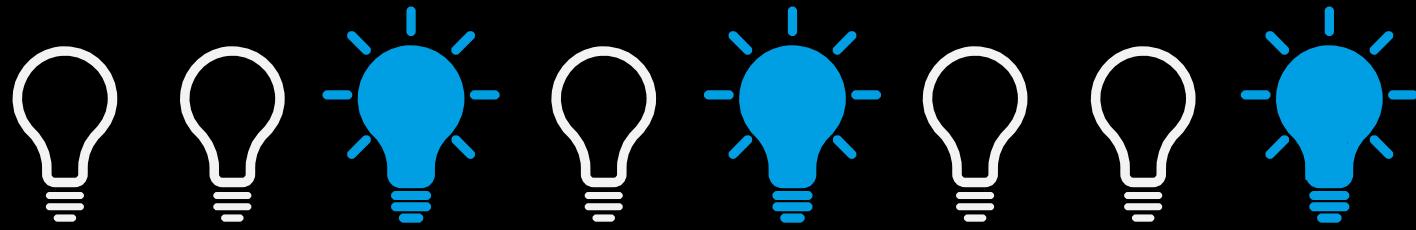
R = base

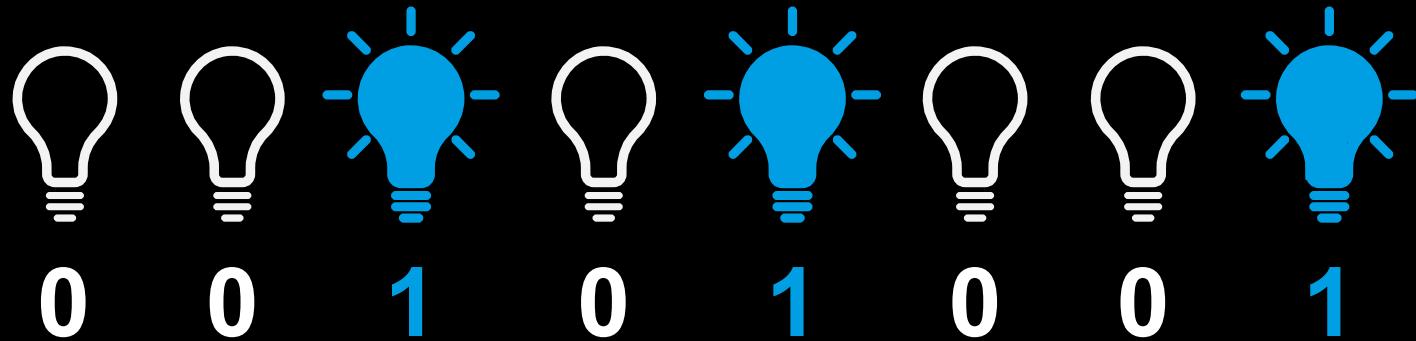
$R \geq 2$

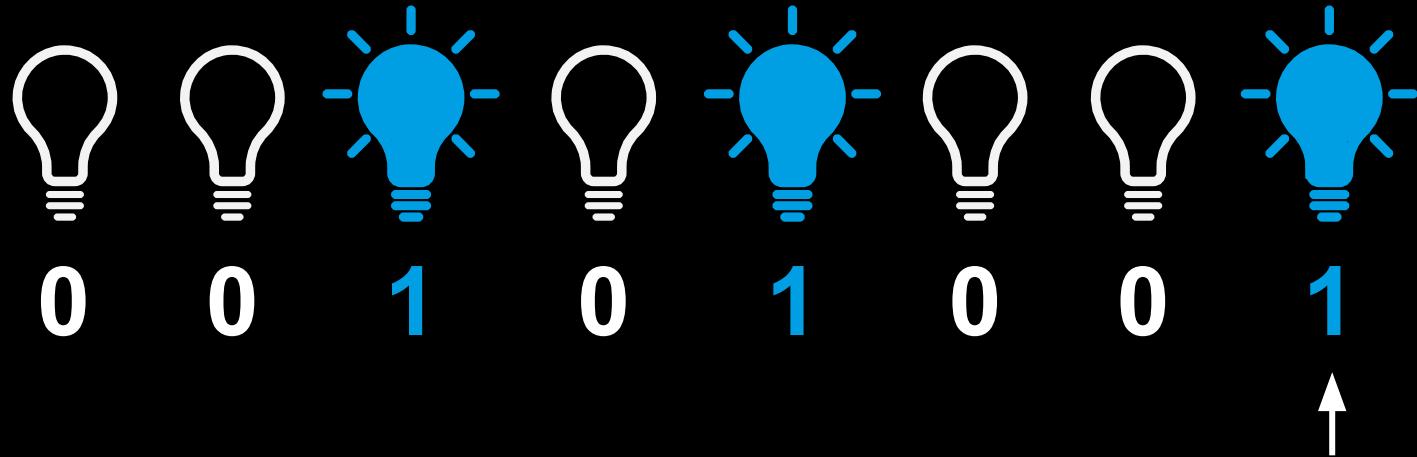
BITS

why do computers think binary?

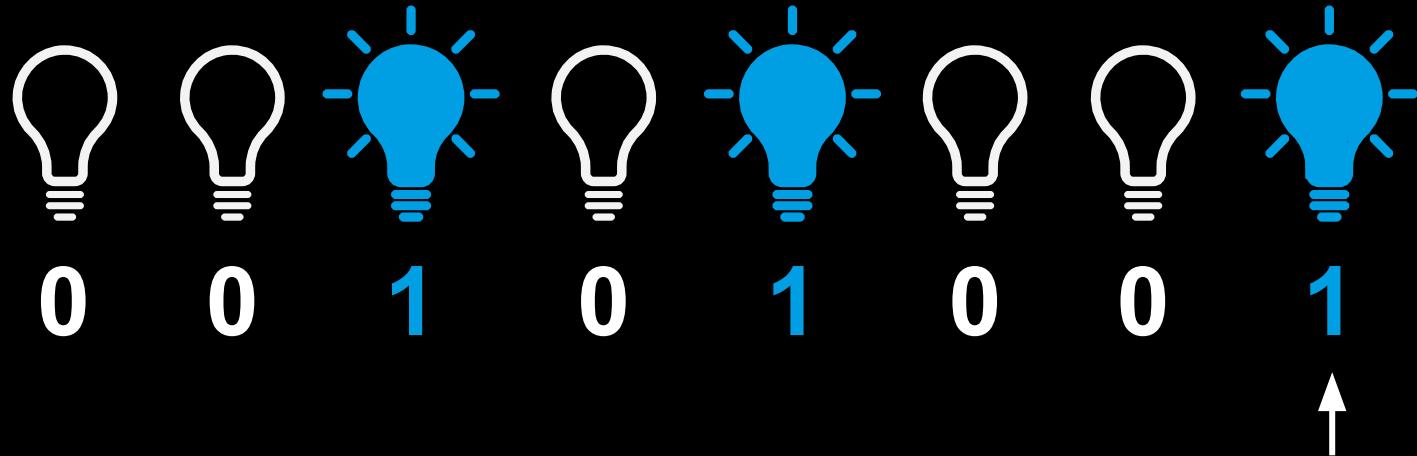








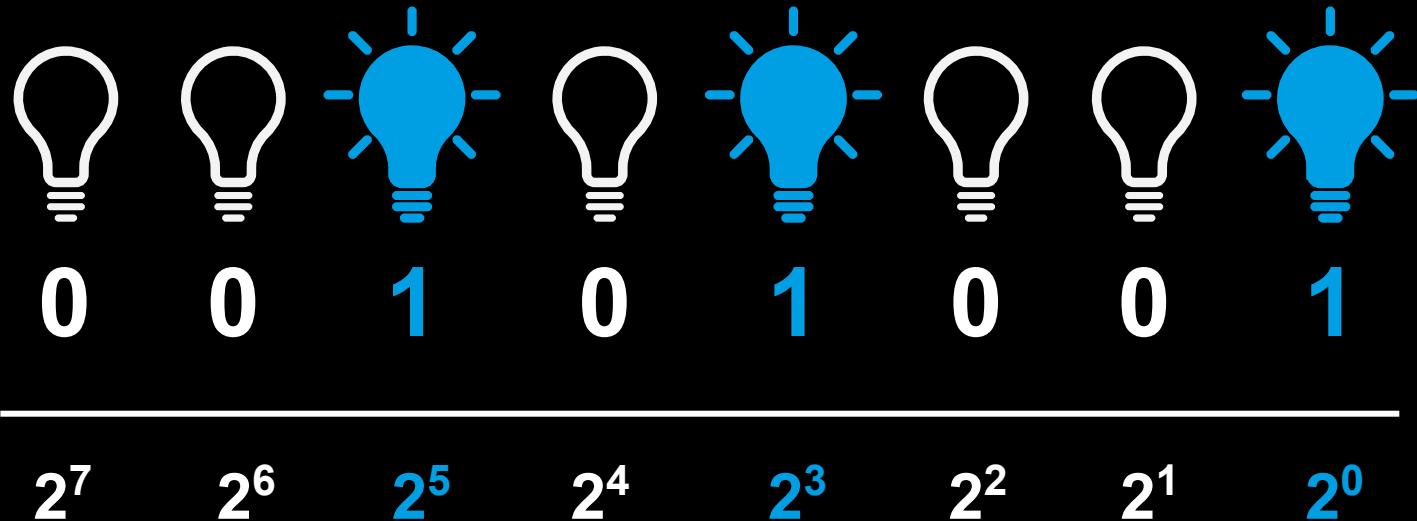
a **bit** (binary digit)

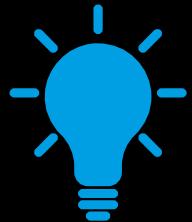
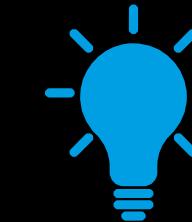
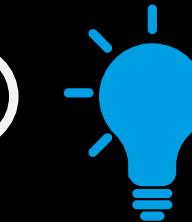


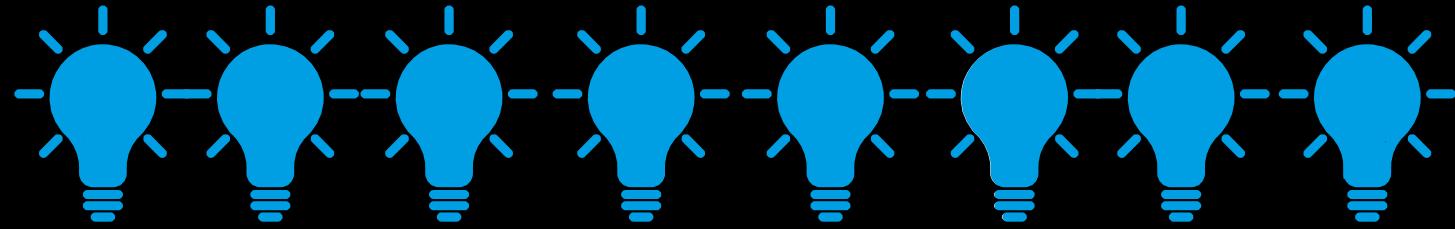
a **bit** (binary digit)

{

a **byte** (8 bits)



							
0	0	1	0	1	0	0	1
<hr/>							
2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
128	64	32	16	8	4	2	1



what can we store in one byte?

what comes after the byte?

2^{10} bytes = 1.024 bytes = 1 Kibibyte (KiB)

2^{20} bytes = 1.048.576 bytes = 1 Mebibyte (MiB)

2^{30} bytes = 1.073.741.824 bytes = 1 Gibibyte (GiB)

10^3 bytes = 1.000 bytes = 1 Kilobyte (KB)

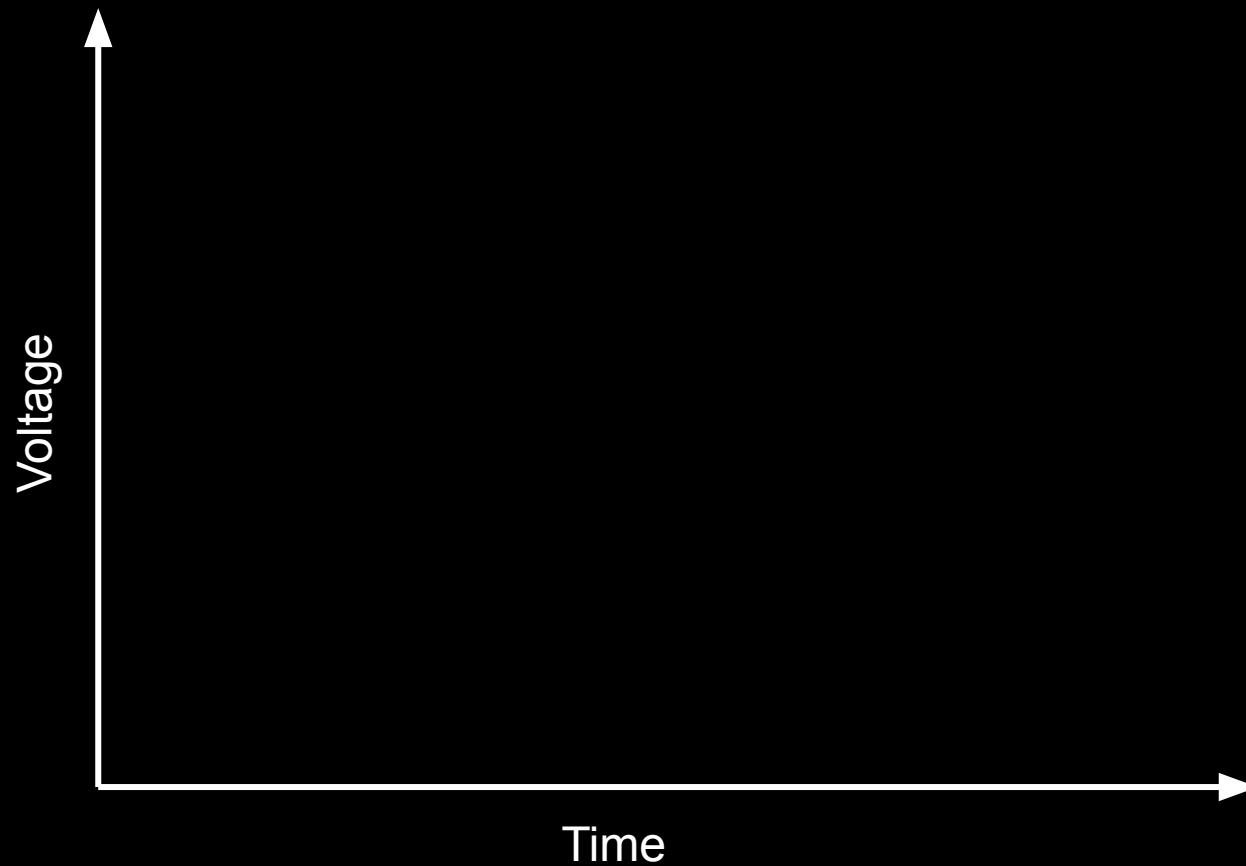
10^6 bytes = 1.000.000 bytes = 1 Megabyte (MB)

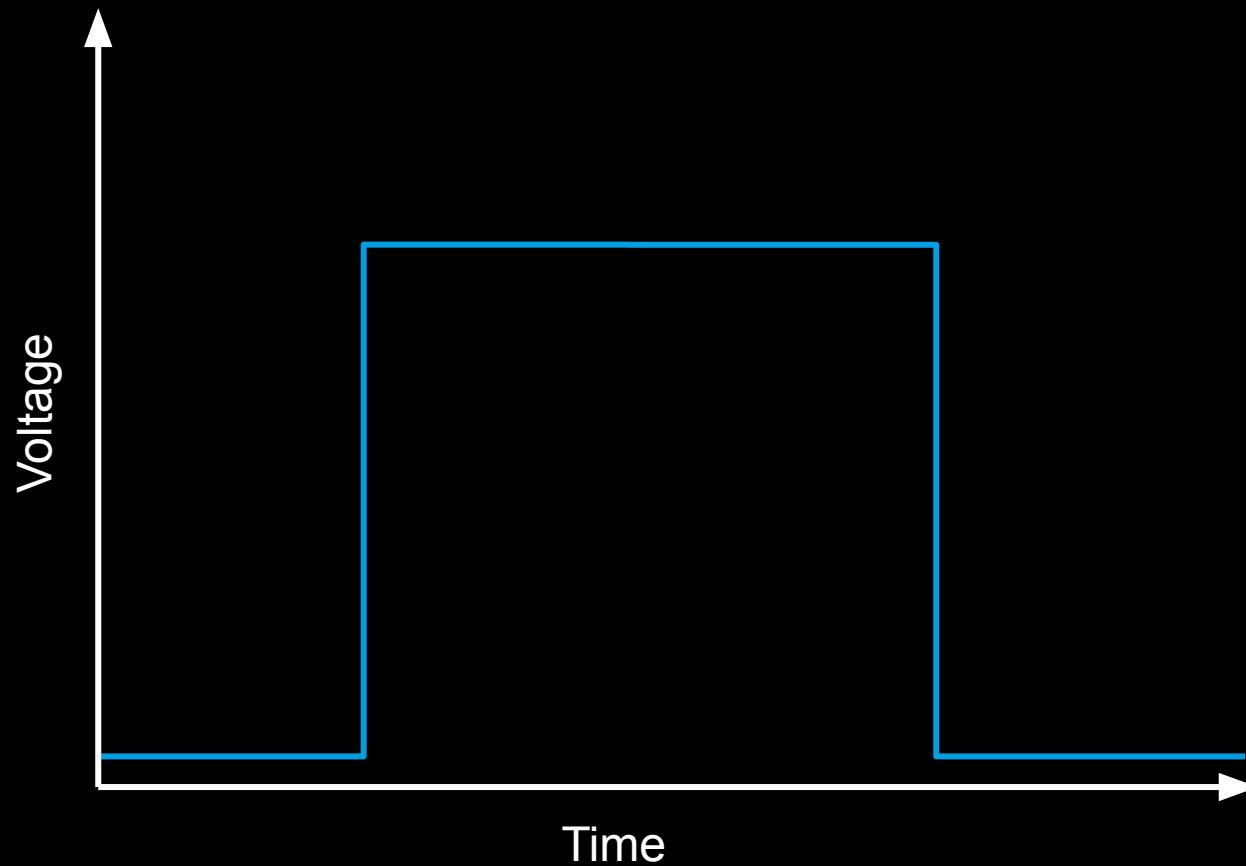
10^9 bytes = 1.000.000.000 bytes = 1 Gigabyte (GB)

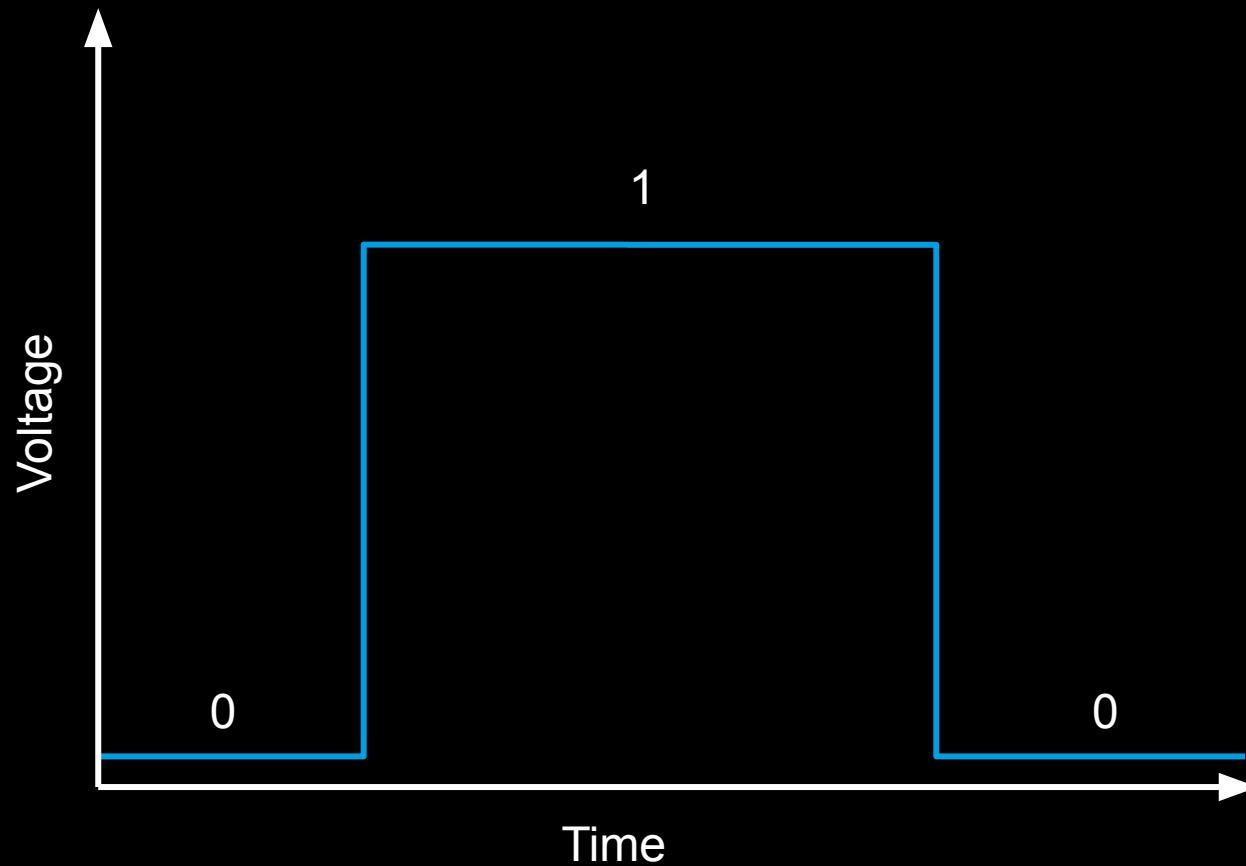
10^{12} bytes = ?

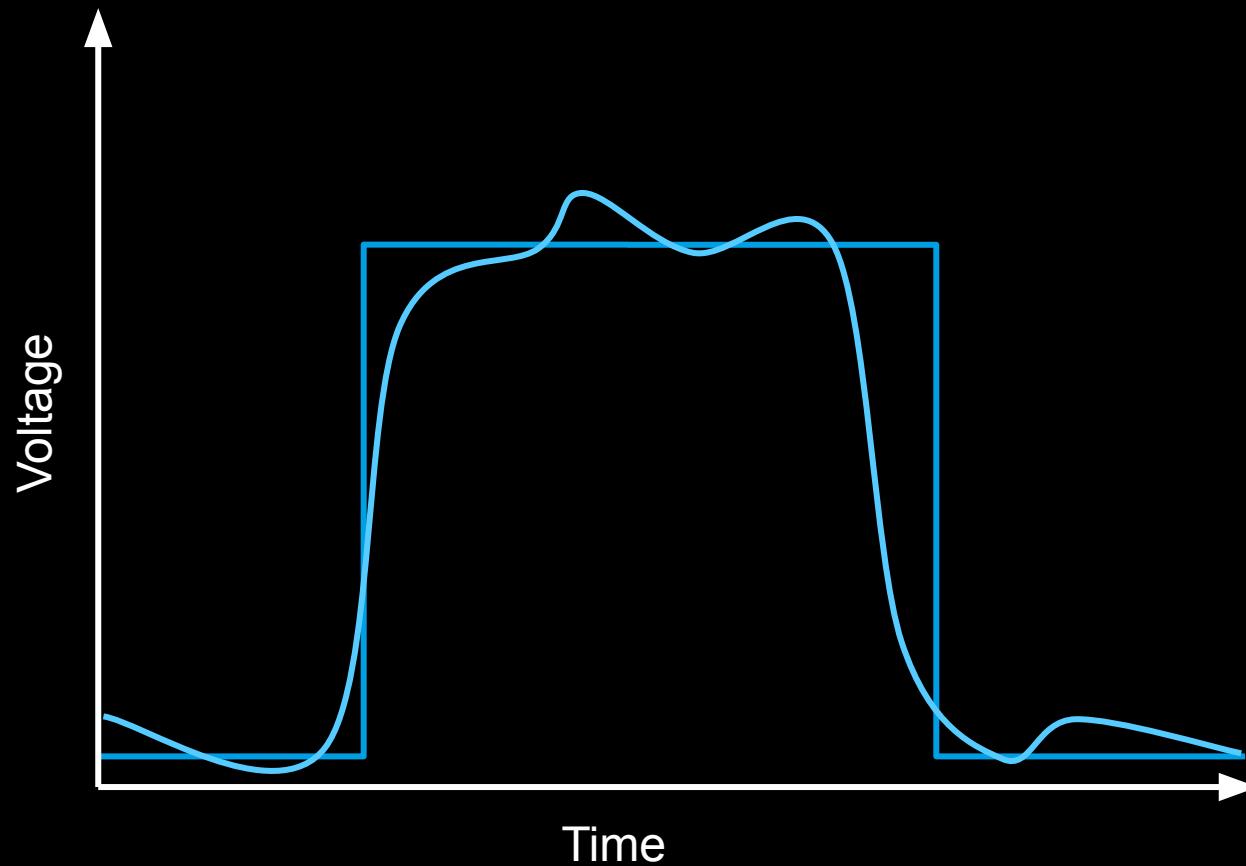
how many bits are on a DVD with
4.7 GB capacity?

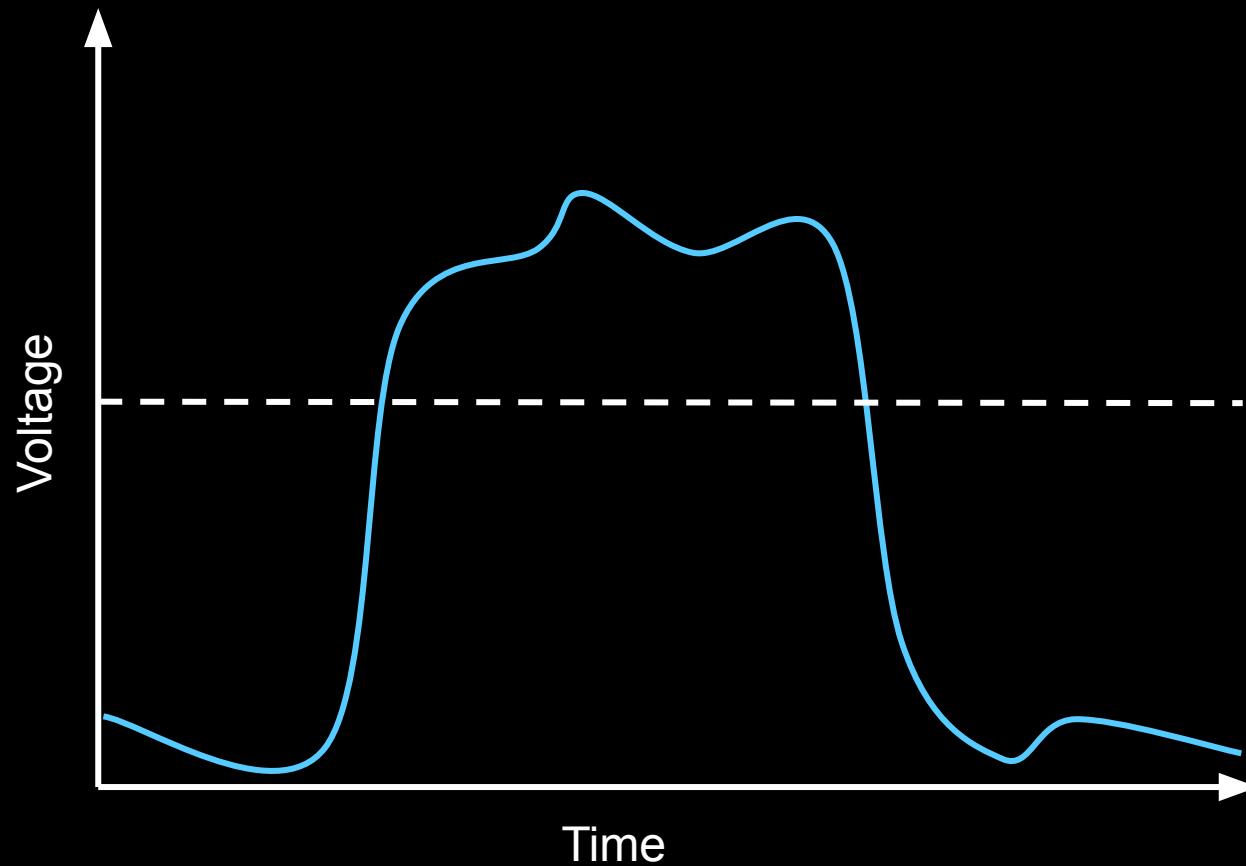
are we stuck with binary?

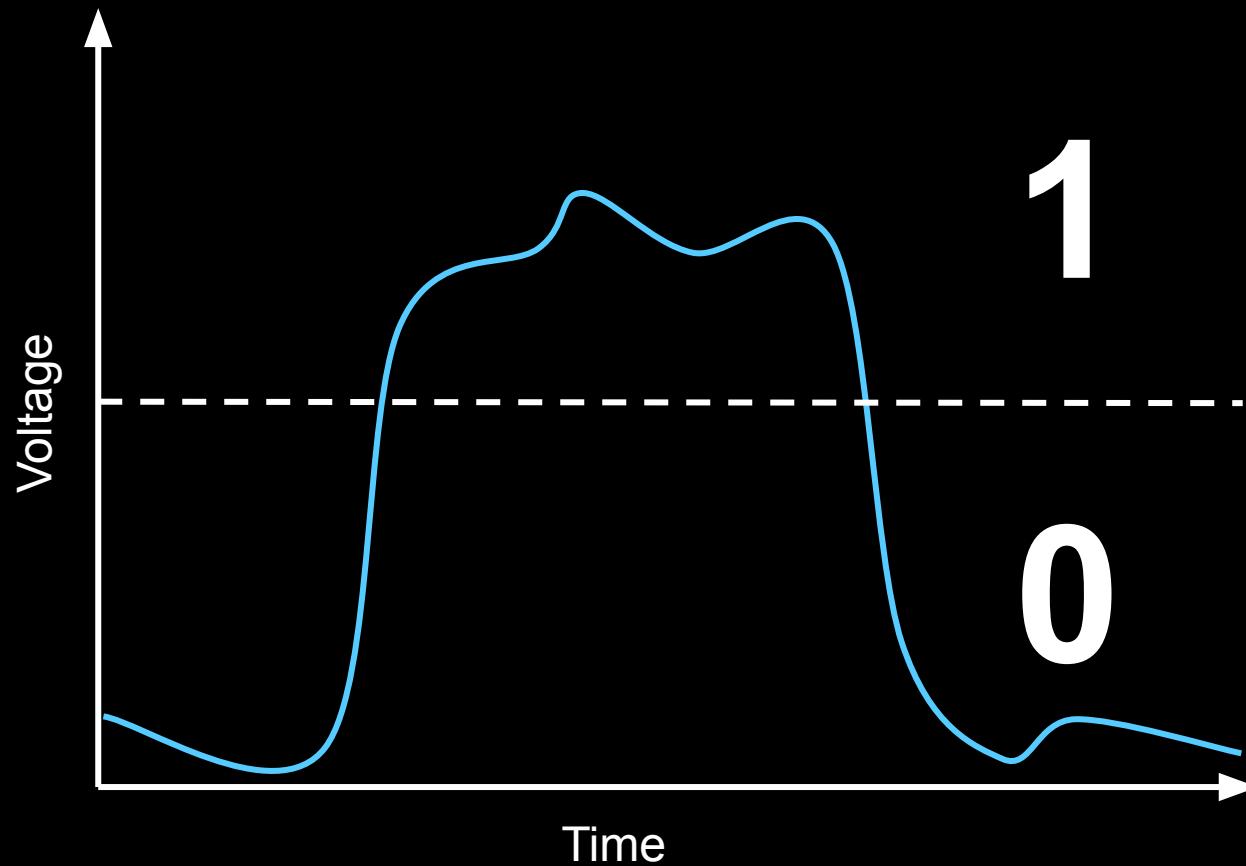


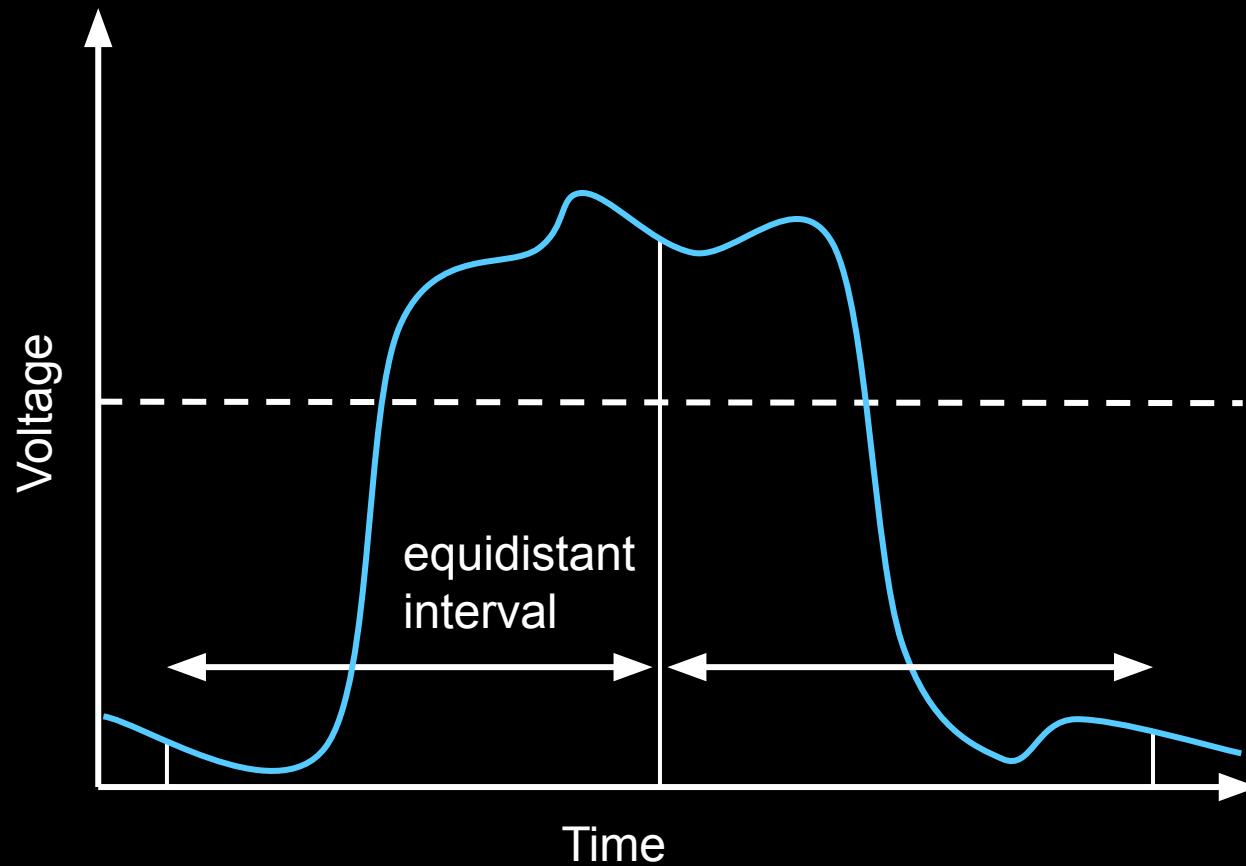


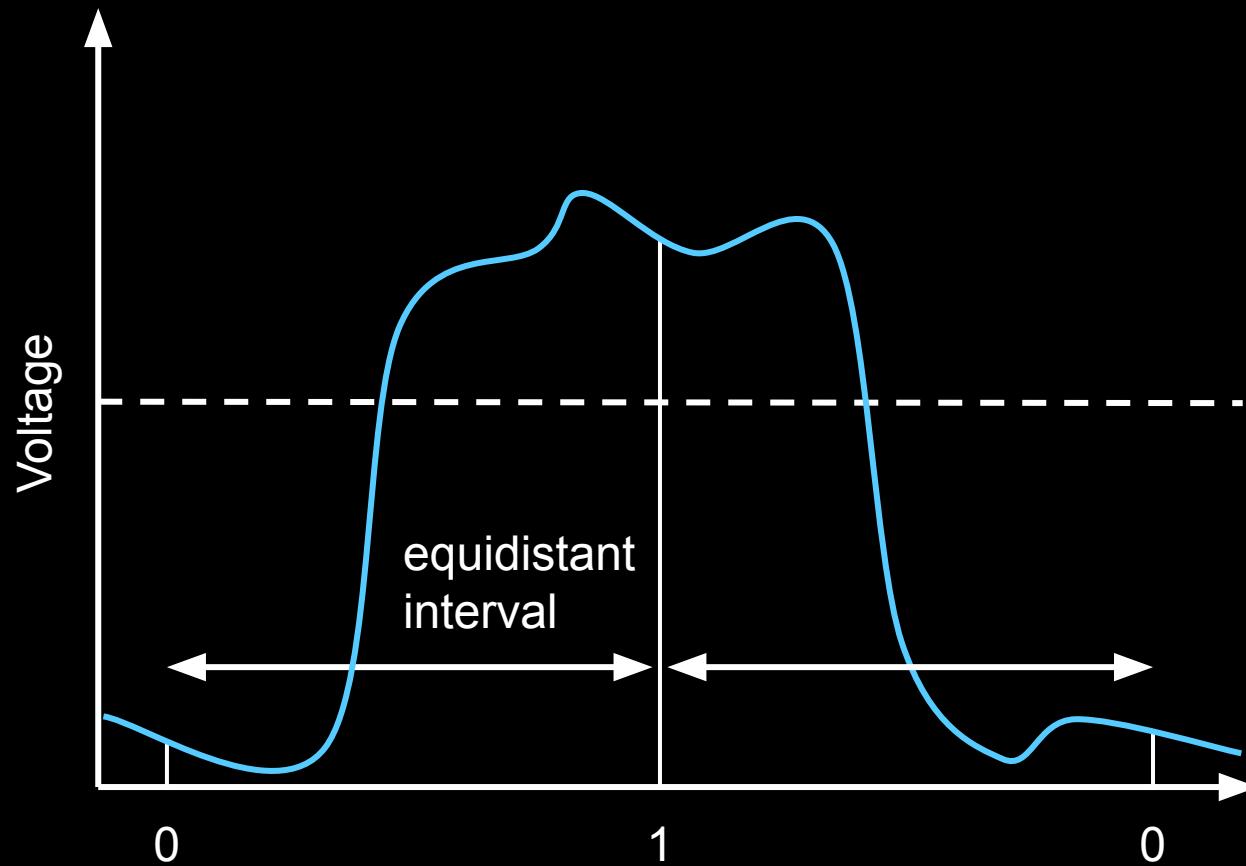


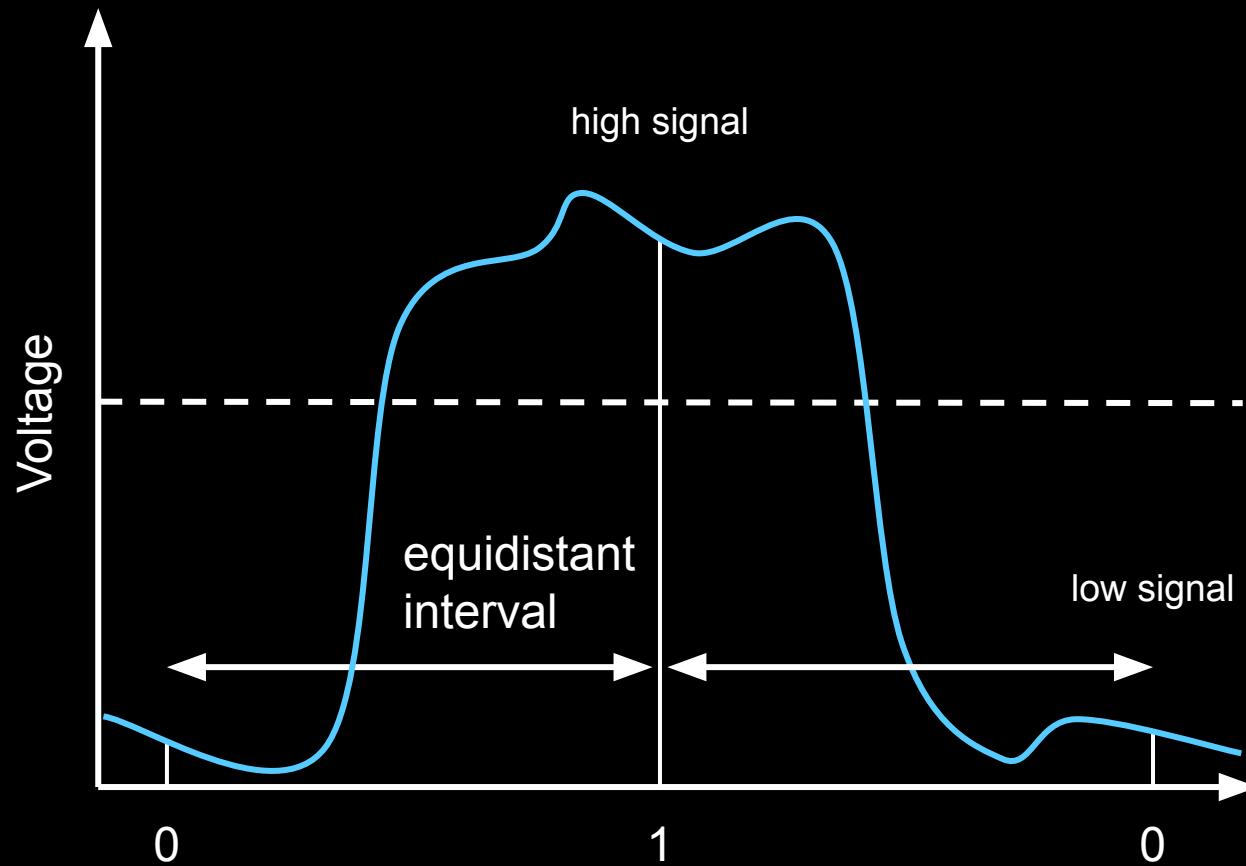




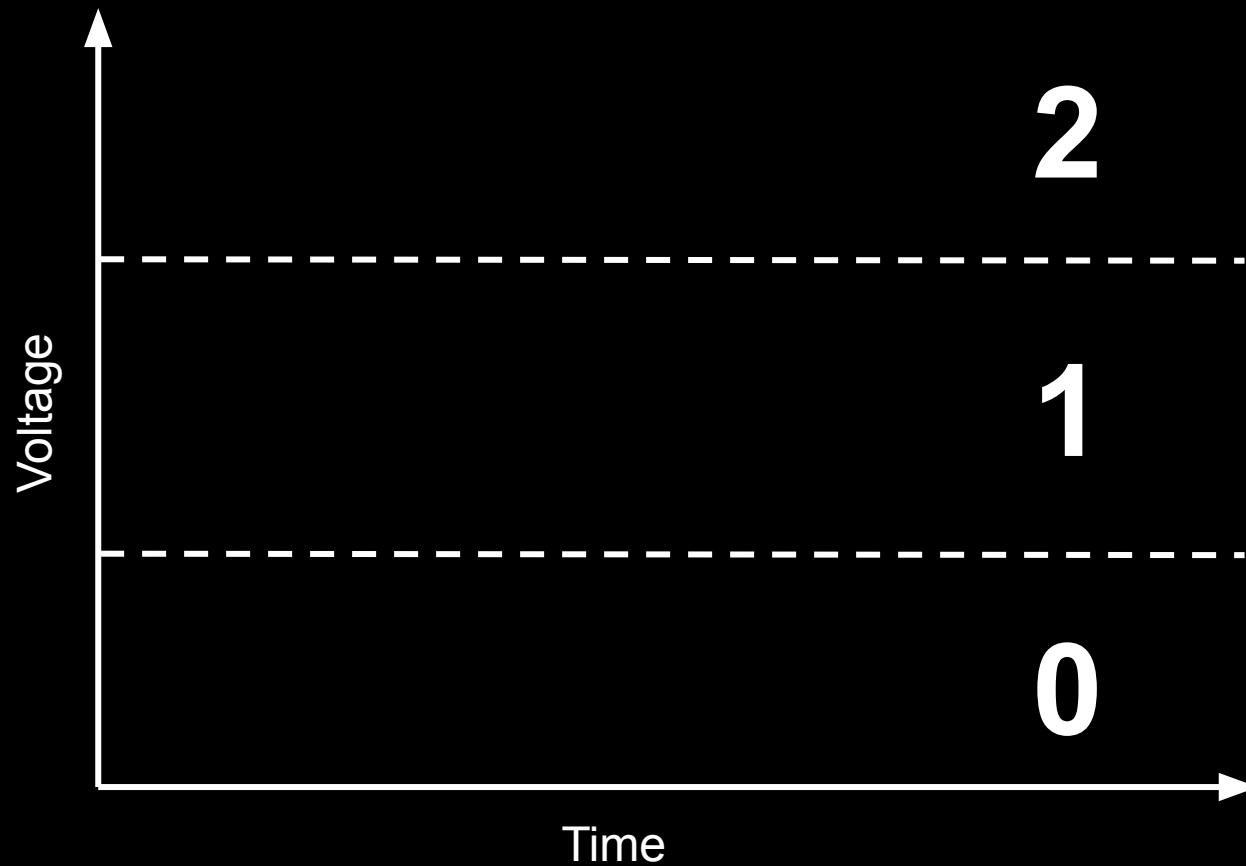


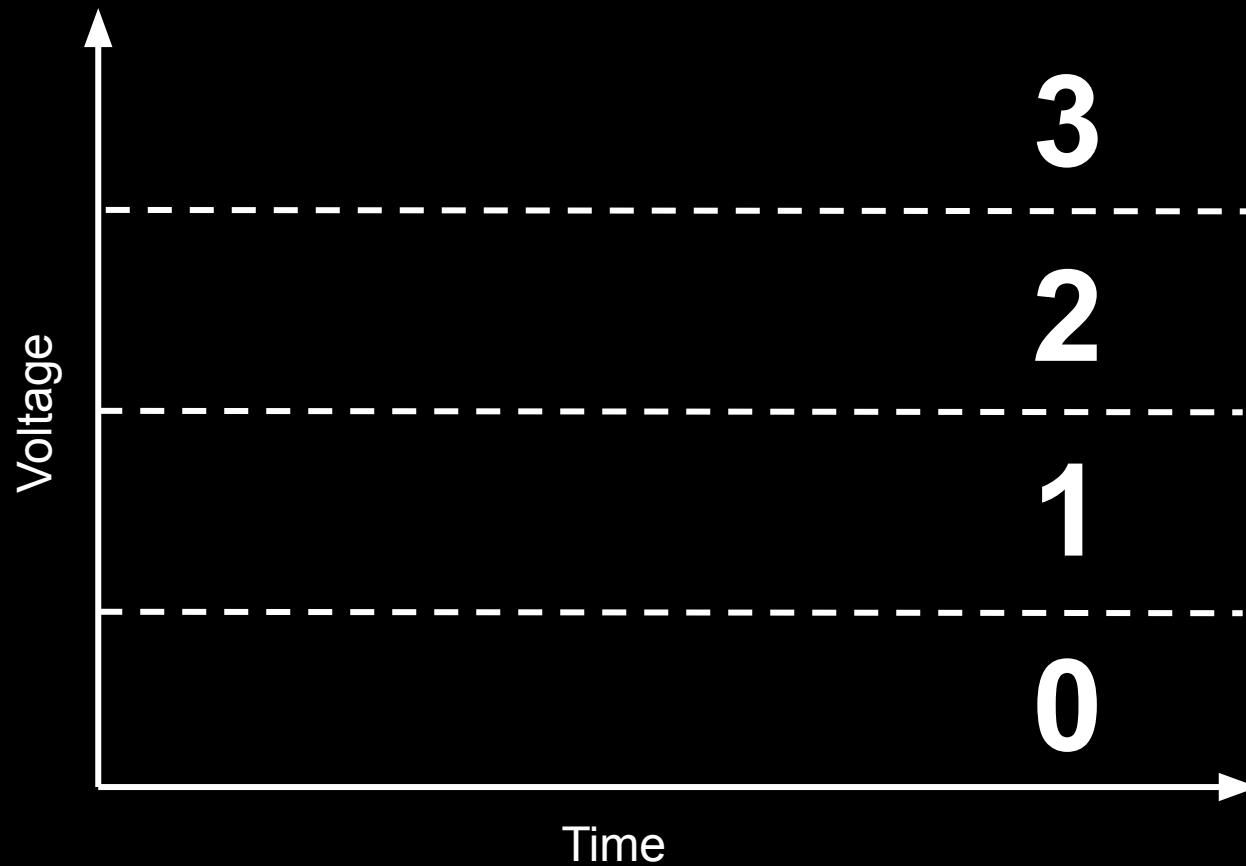


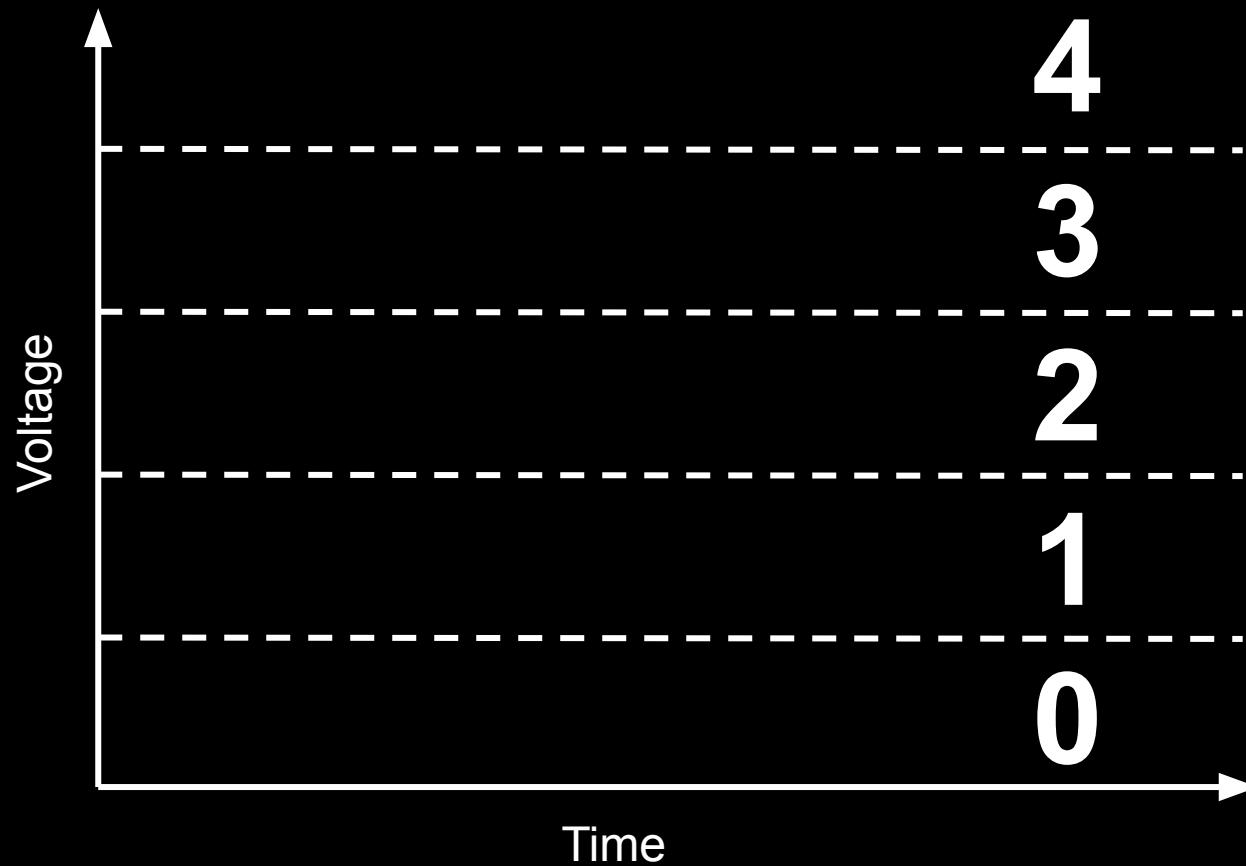


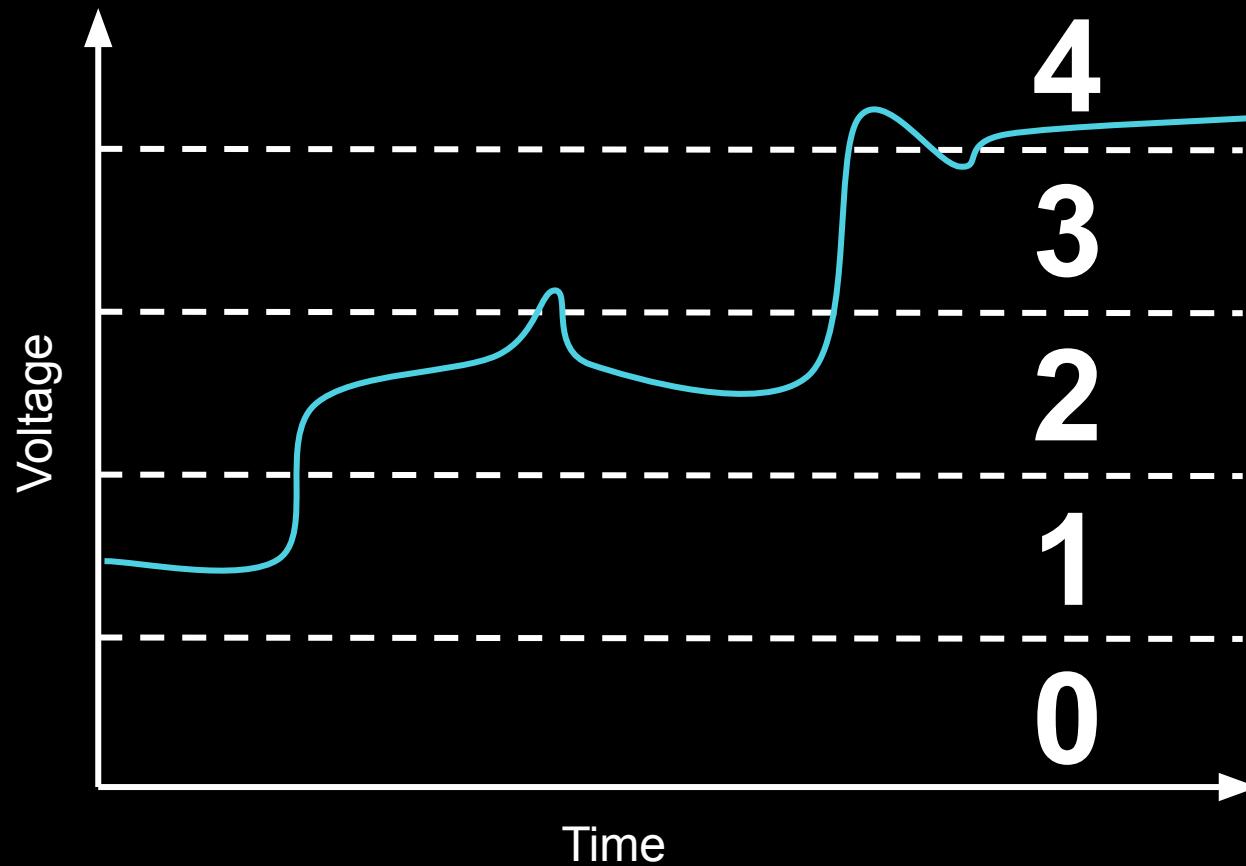


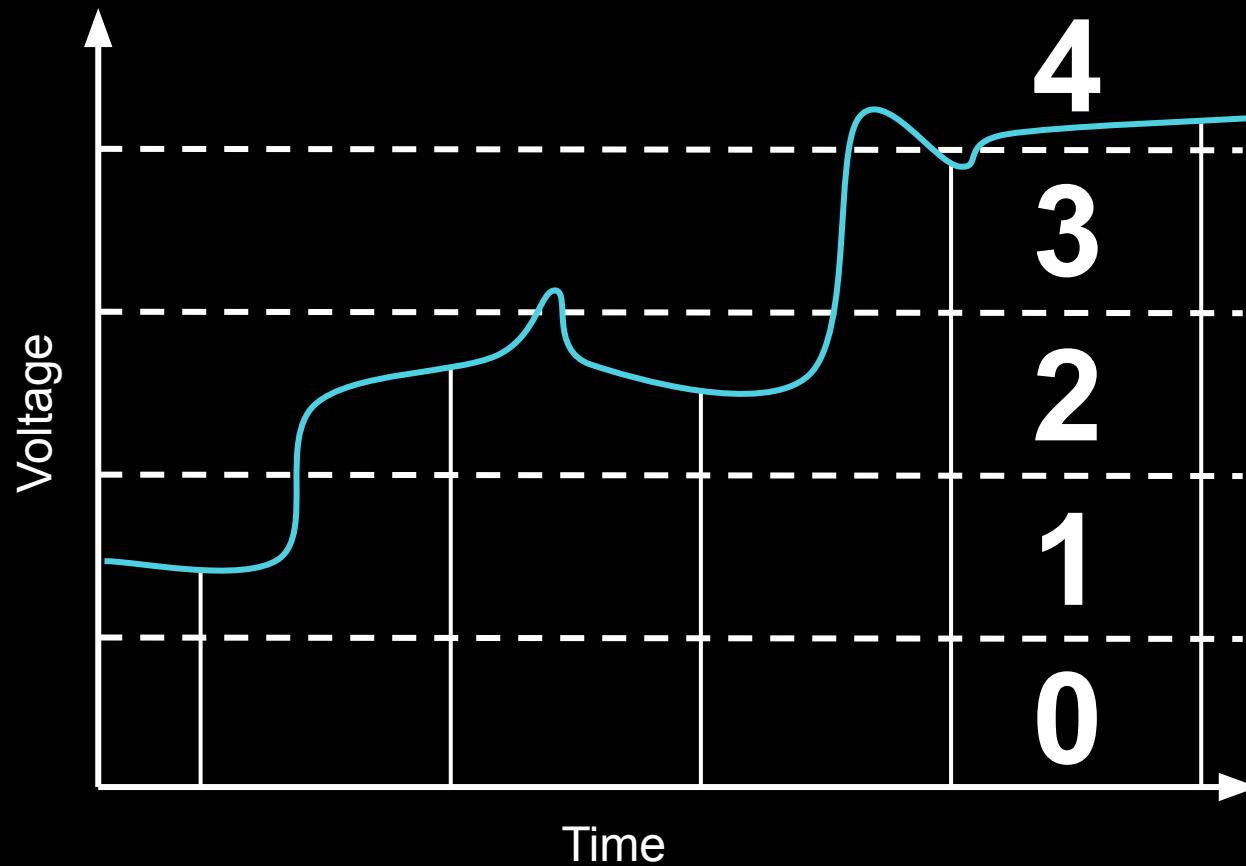
what about $R > 2$?

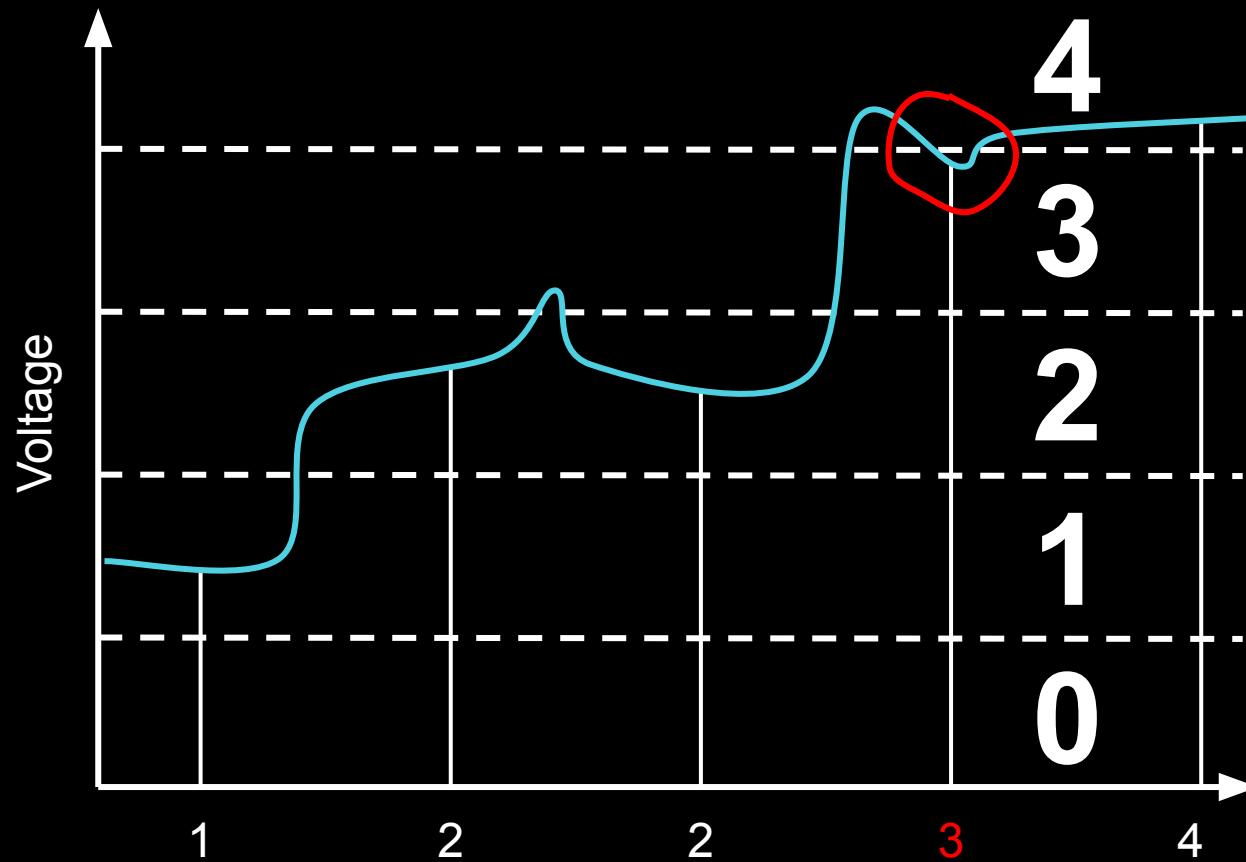












a higher base means less hardware

a higher base means less hardware
but more complex devices

a higher base means less hardware
but more complex devices
and more errors

CODES



representing text

A	B	C	D	...	a	b	c	d
65	66	67	68		97	98	99	100

ASCII Code

A	B	C	D	...	a	b	c	d
65	66	67	68		97	98	99	100



1F600



1F601



1F602



1F603

...



1F648



1F649



1F64A



1F64B

Unicode



1F600



1F601



1F602



1F603

...



1F648



1F649



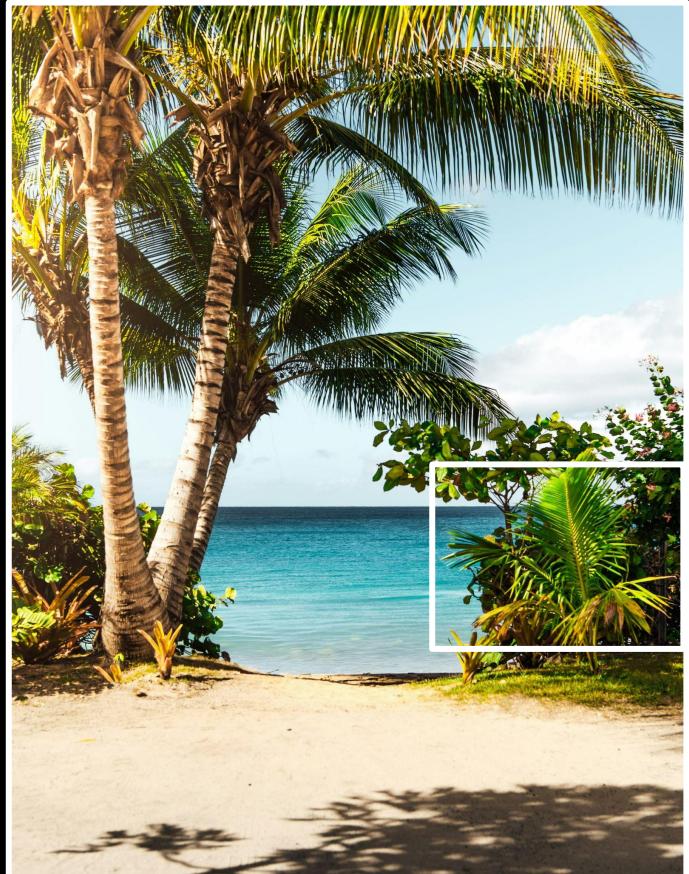
1F64A

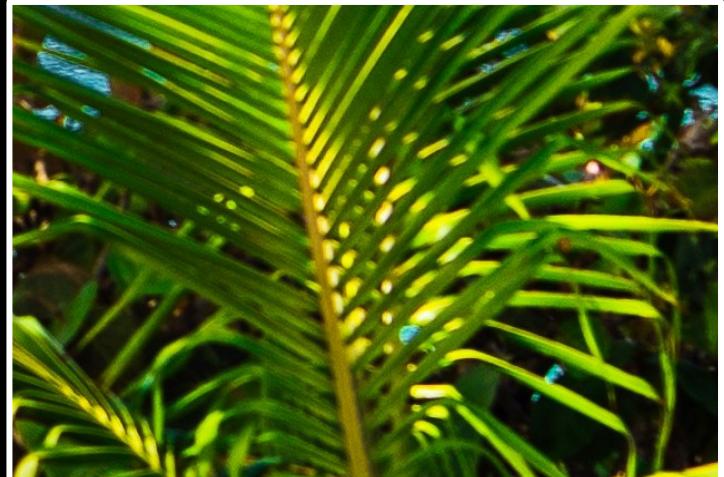
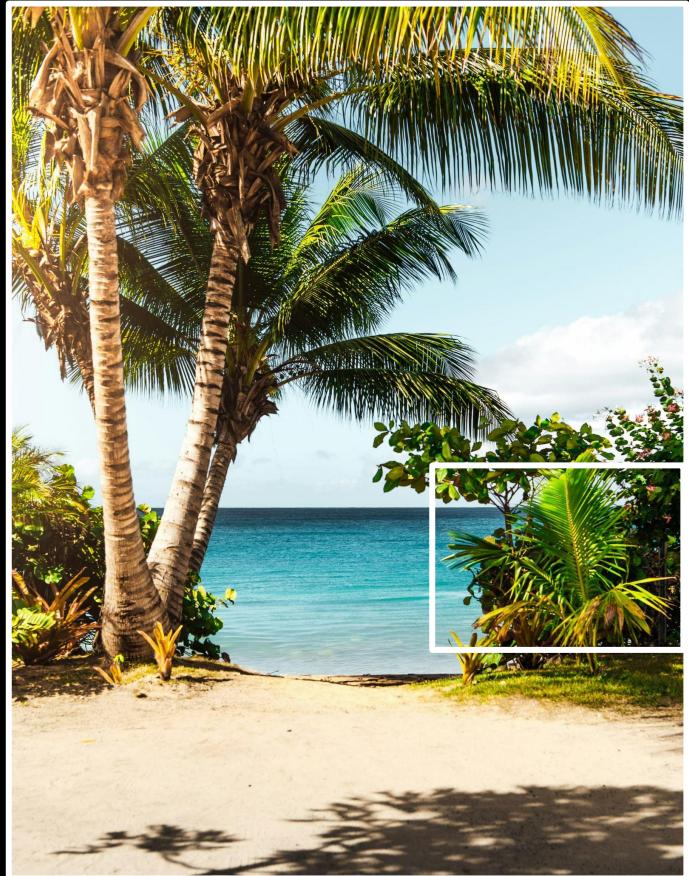


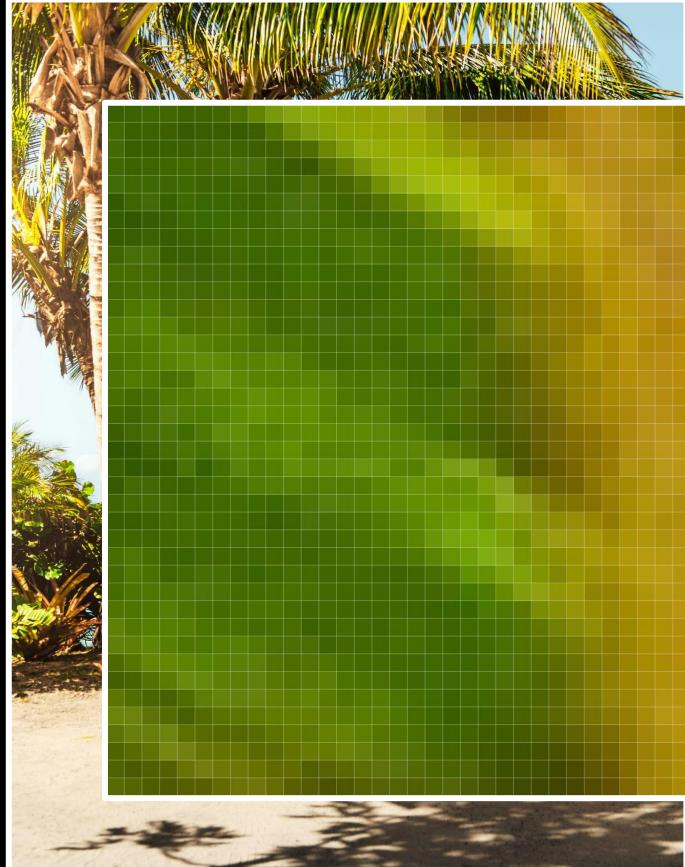
1F64B

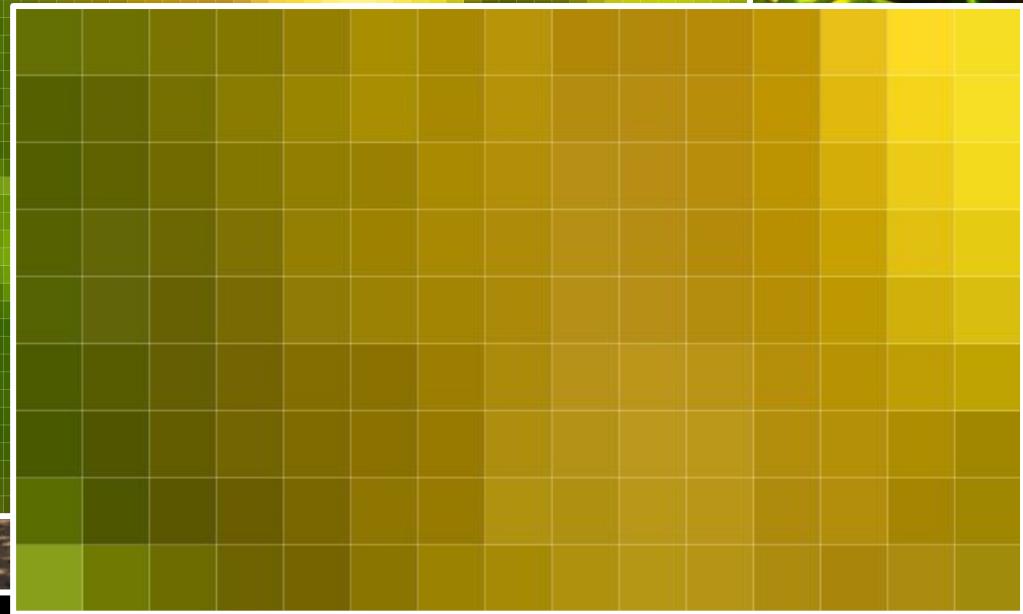
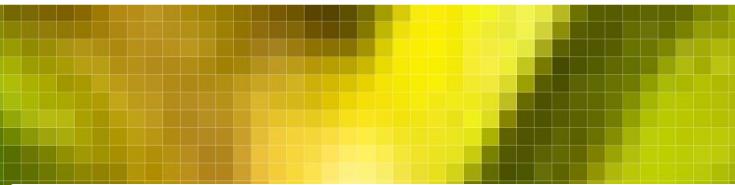
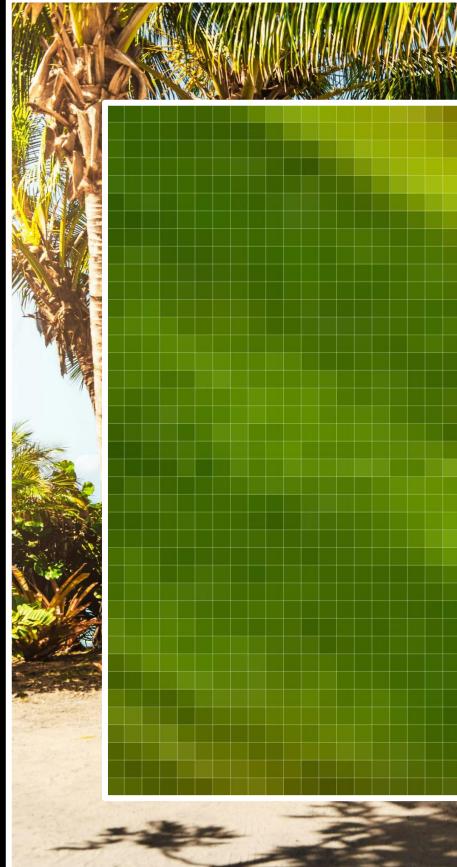
representing images

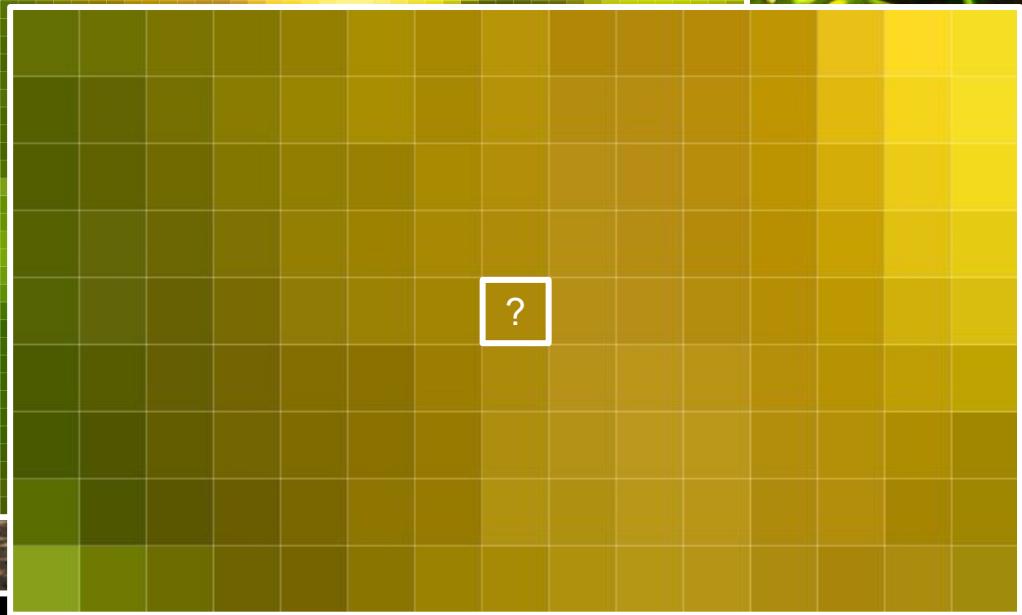
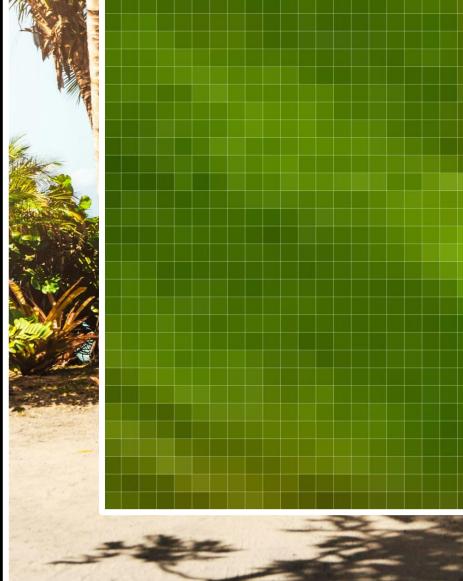




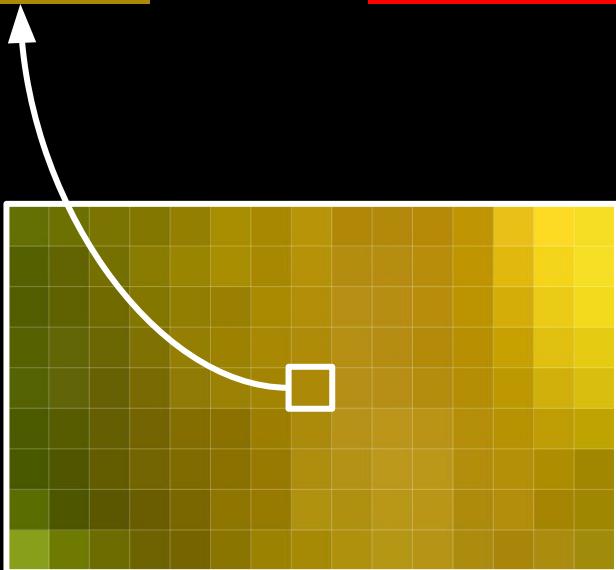




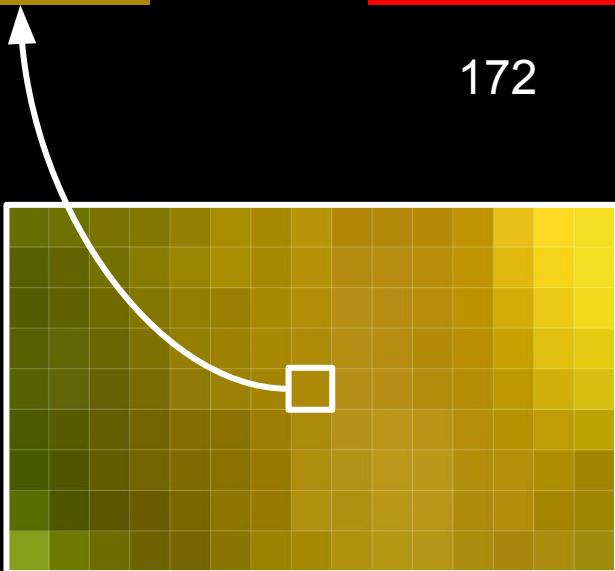




$$\text{Yellow} = \text{R} + \text{G} + \text{B}$$



$$\text{Yellow} = \text{R} + \text{G} + \text{B}$$



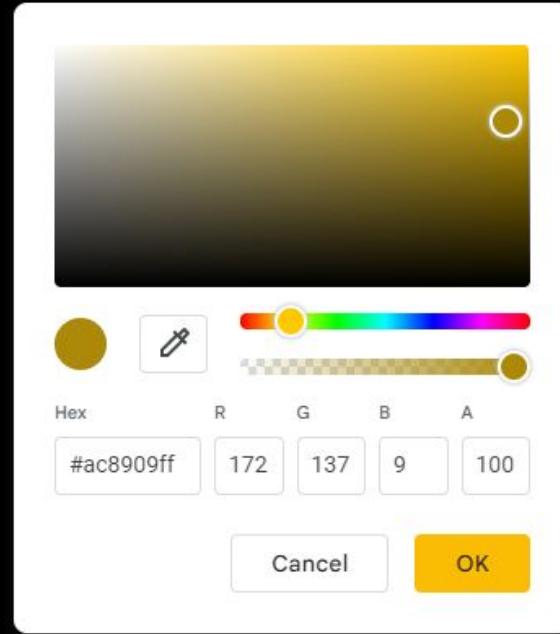
172

137

9

$$\begin{matrix} \text{Yellow} \\ = \end{matrix} \begin{matrix} \text{R} \\ 172 \end{matrix} + \begin{matrix} \text{G} \\ 137 \end{matrix} + \begin{matrix} \text{B} \\ 9 \end{matrix}$$

#AC8909



$$\text{Color} = \text{R} + \text{G} + \text{B}$$

172

137

9

#AC8909

AC

89

09

$$\begin{array}{c} \text{Yellow} \\ = \end{array} \begin{array}{c} \text{R} \\ 172 \\ \text{AC} \\ 10101100 \end{array} + \begin{array}{c} \text{G} \\ 137 \\ 89 \\ 01011001 \end{array} + \begin{array}{c} \text{B} \\ 9 \\ 09 \\ 00001001 \end{array}$$

possible colors?

R

$2^7 \quad 2^6 \quad 2^5 \quad 2^4 \quad 2^3 \quad 2^2 \quad 2^1 \quad 2^0$

R

G

B

$2^{23} 2^{22} 2^{21} 2^{20} 2^{19} 2^{18} 2^{17} 2^{16}$

$2^{15} 2^{14} 2^{13} 2^{12} 2^{11} 2^{10} 2^9 2^8$

$2^7 2^6 2^5 2^4 2^3 2^2 2^1 2^0$

R

G

B

$2^{23} 2^{22} 2^{21} 2^{20} 2^{19} 2^{18} 2^{17} 2^{16}$ $2^{15} 2^{14} 2^{13} 2^{12} 2^{11} 2^{10} 2^9 2^8$ $2^7 2^6 2^5 2^4 2^3 2^2 2^1 2^0$

$$8.388.608 + 8.388.607 = 16.777.215$$

R

G

B

$2^{23} 2^{22} 2^{21} 2^{20} 2^{19} 2^{18} 2^{17} 2^{16}$

$2^{15} 2^{14} 2^{13} 2^{12} 2^{11} 2^{10} 2^9 2^8$

$2^7 2^6 2^5 2^4 2^3 2^2 2^1 2^0$

{

{

{

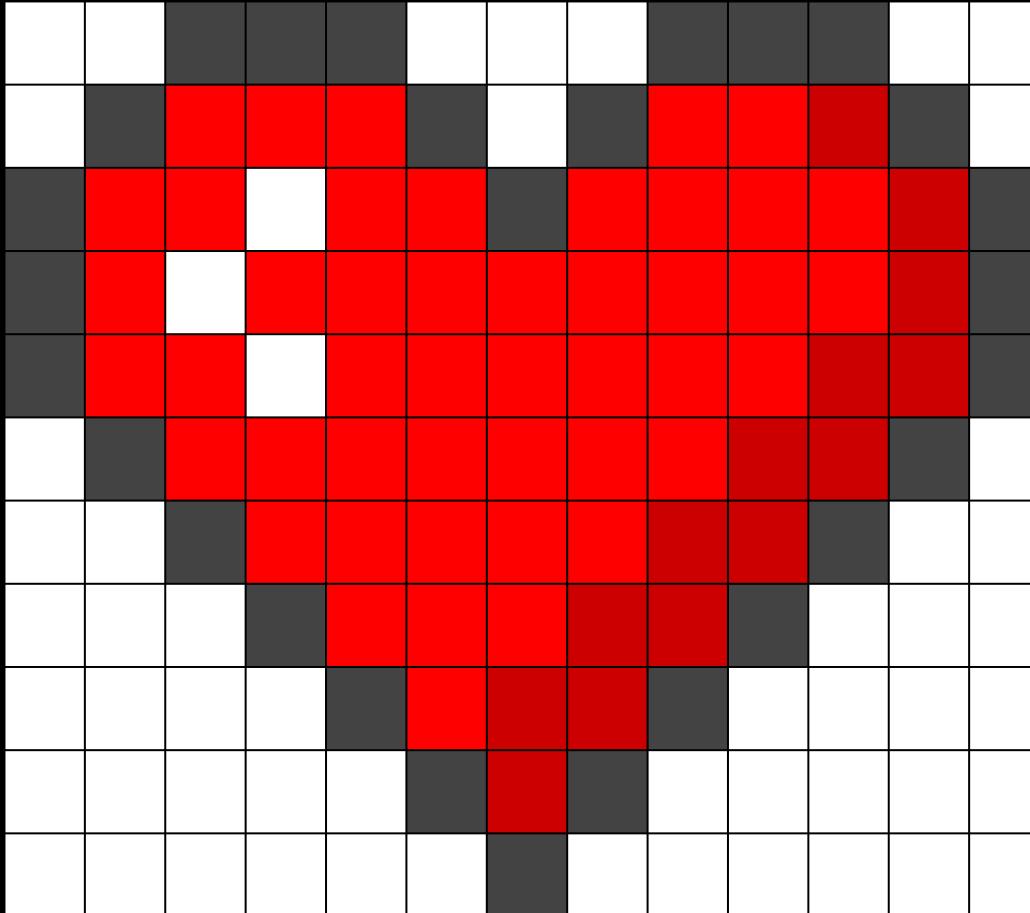
256

X

256

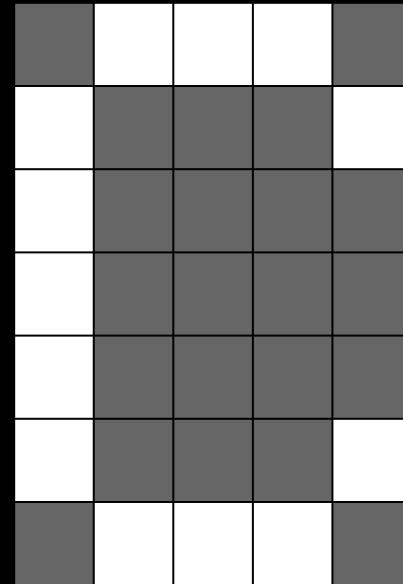
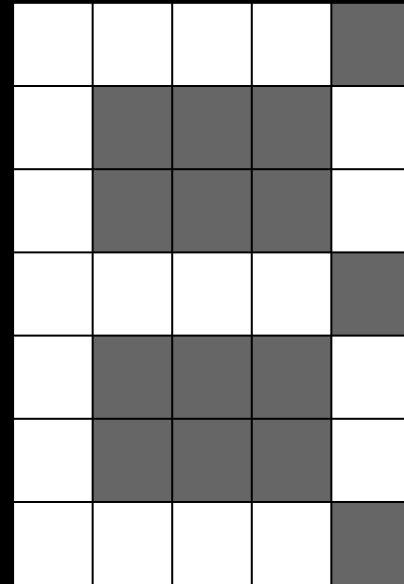
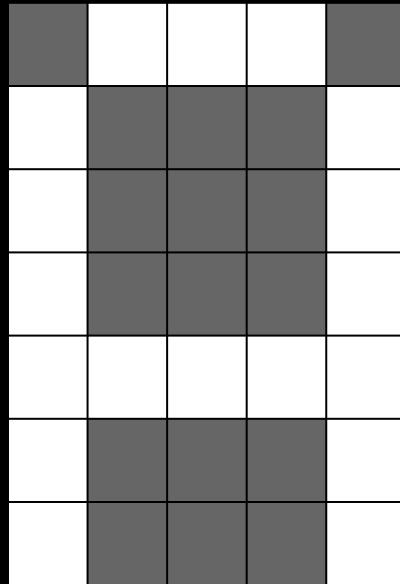
X

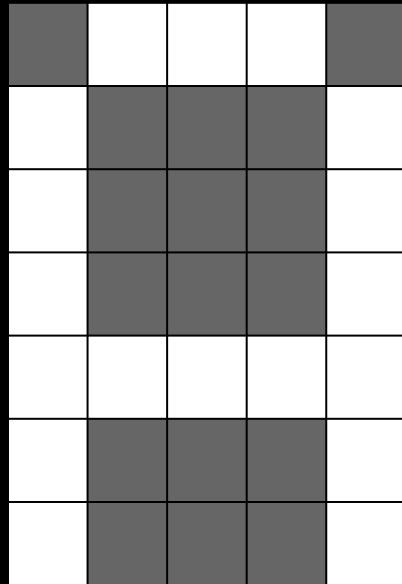
256





compression?





0	1	1	1	0
1	0	0	0	1
1	0	0	0	1
1	0	0	0	1
1	1	1	1	1
1	0	0	0	1
1	0	0	0	1

0	1	1	1	0
1	0	0	0	1
1	0	0	0	1
1	0	0	0	1
1	1	1	1	1
1	0	0	0	1
1	0	0	0	1



0 1 1 1 0 1 0 0 0 1 1 0 0 0 1 1 0 0
0 1 1 1 1 1 1 0 0 0 1 1 0 0 0 1

5

0	1	1	1	0
1	0	0	0	1
1	0	0	0	1
1	0	0	0	1
1	1	1	1	1
1	0	0	0	1
1	0	0	0	1

7



0 1 1 1 0 1 0 0 0 1 1 0 0 0 1 1 0 0
0 1 1 1 1 1 1 0 0 0 1 1 0 0 0 1

bitmap

vector graphics

grayscale

representing sound

telephone

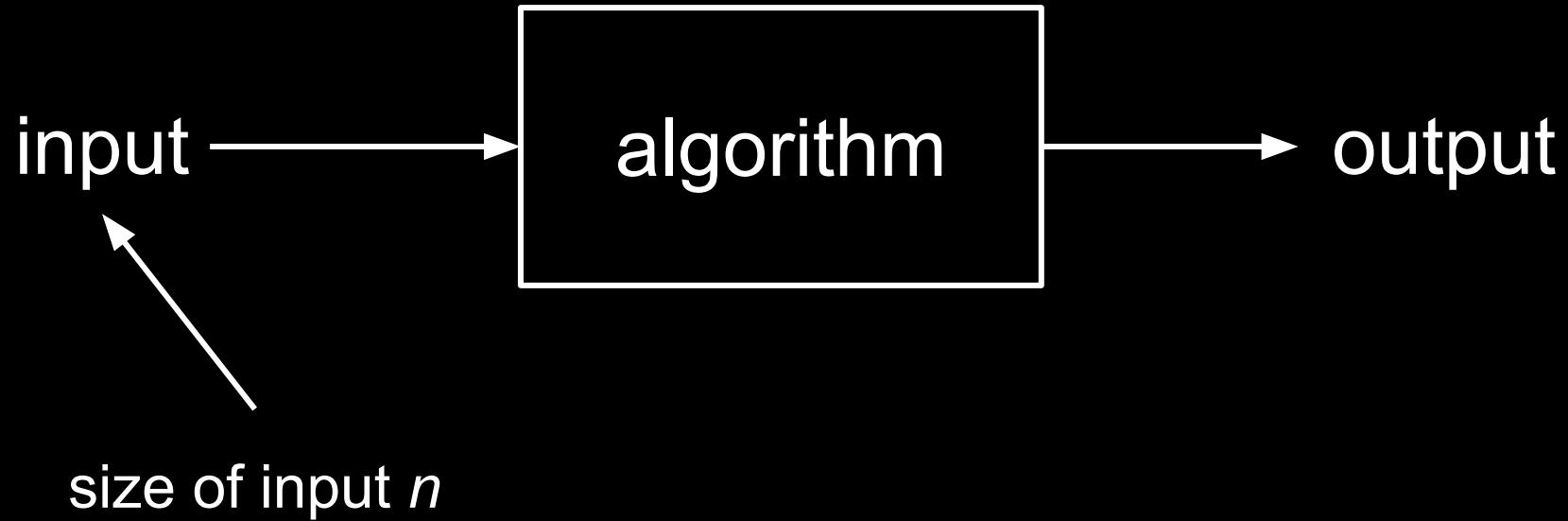
music

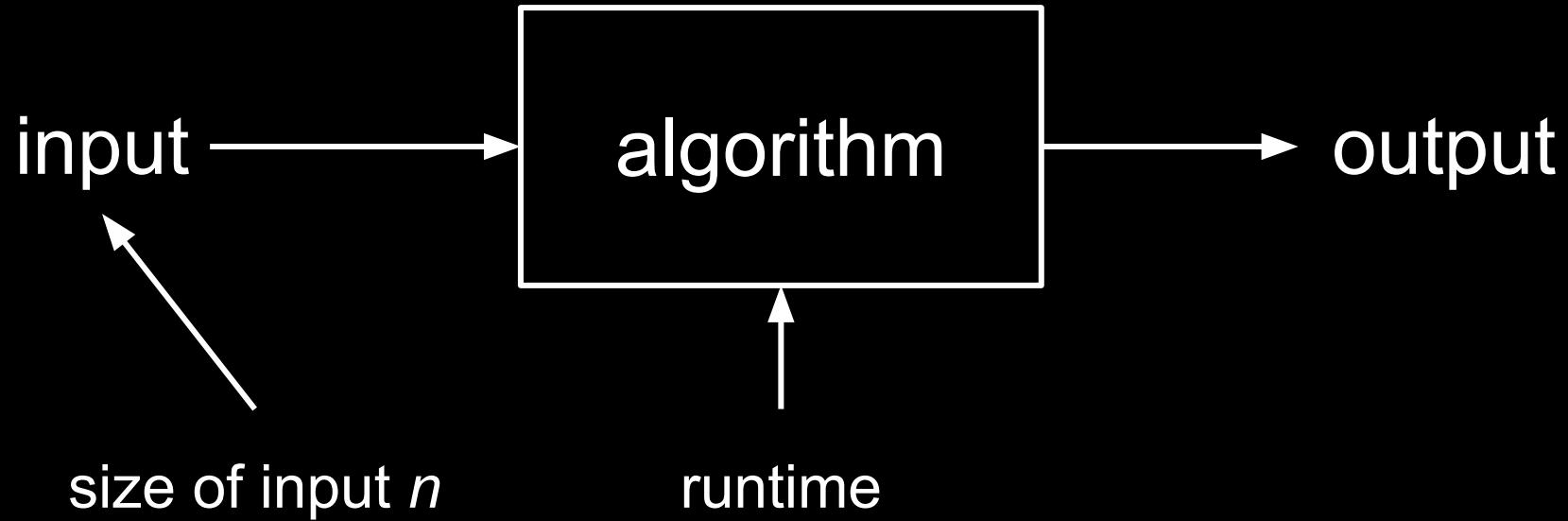
musical instrument digital interface (MIDI)

ALGORITHMS

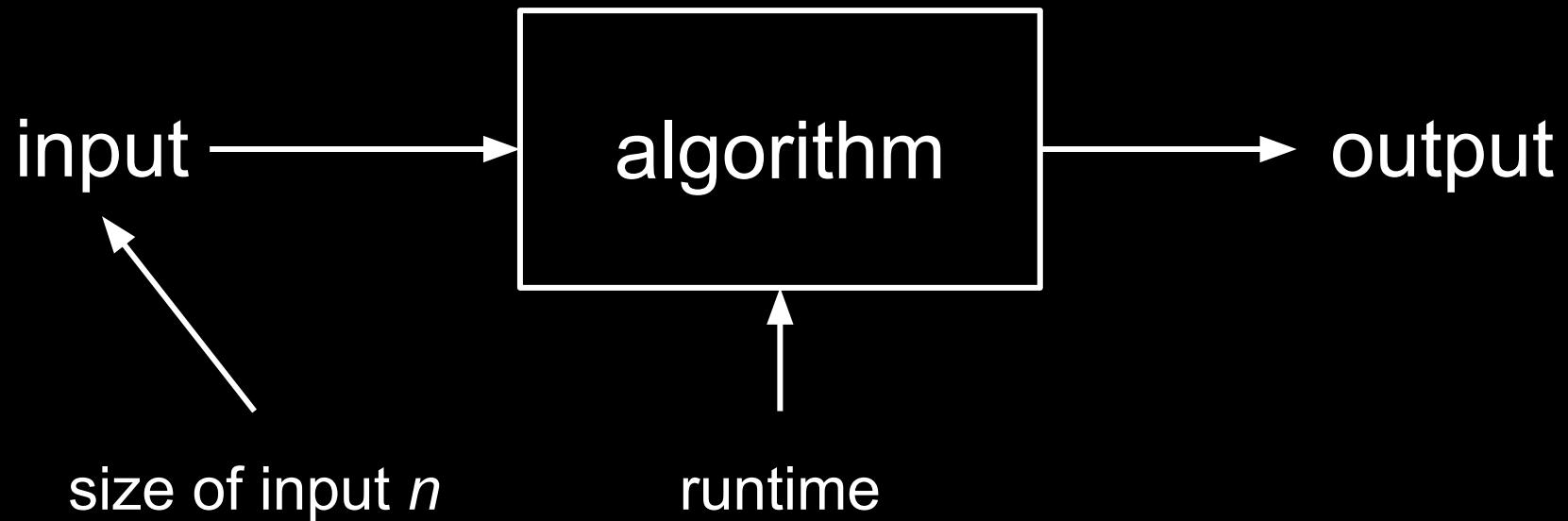
complexity







$O(n)$



COMPUTERS

ARITHMETIC

MEMORY

ANALOG VS. DIGITAL

which is better?

