THE QUANTUM REVOLUTION

From secret codes to black holes

Course Introduction

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We live in the age of information.

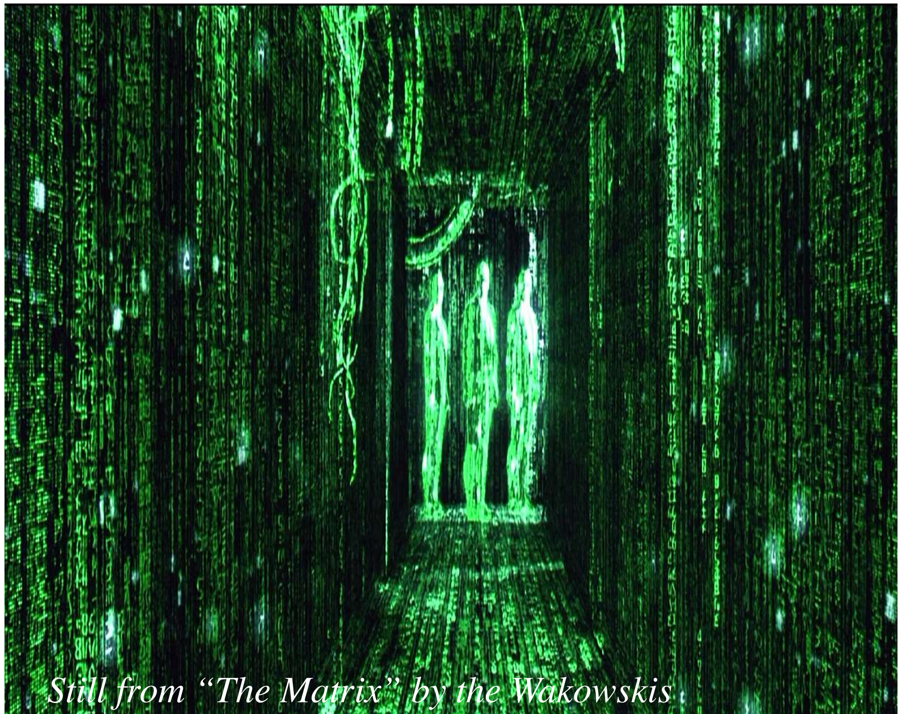
Image from time.graphics

Image from medium.com

But did you know the fundamental roles that information plays in nature?

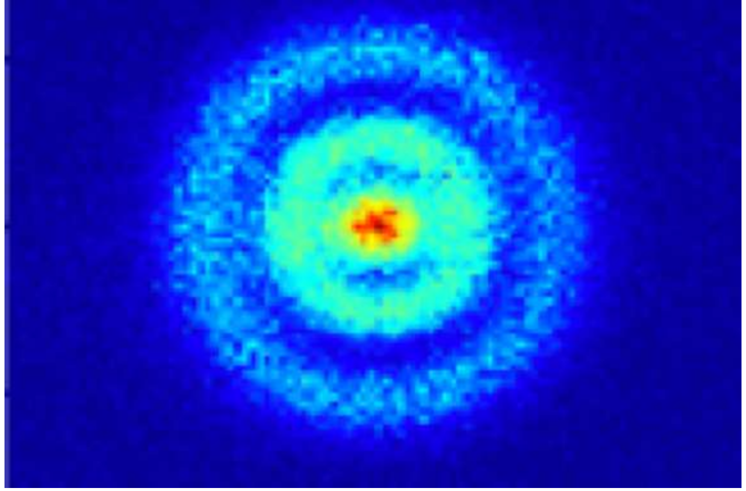
*Have you ever thought that the **world** around us could be **made of information**?*

*That the whole **universe** could be a **gigantic computer**?*



Still from "The Matrix" by the Wakowskis

*This course explores the links between **information** and the **laws of nature.***



Microscopy of an hydrogen atom, image from A. S. Stodolna et al, PRL 110, 213001 (2013)

You will discover a **new type of information** that pops up in the world of elementary particles.

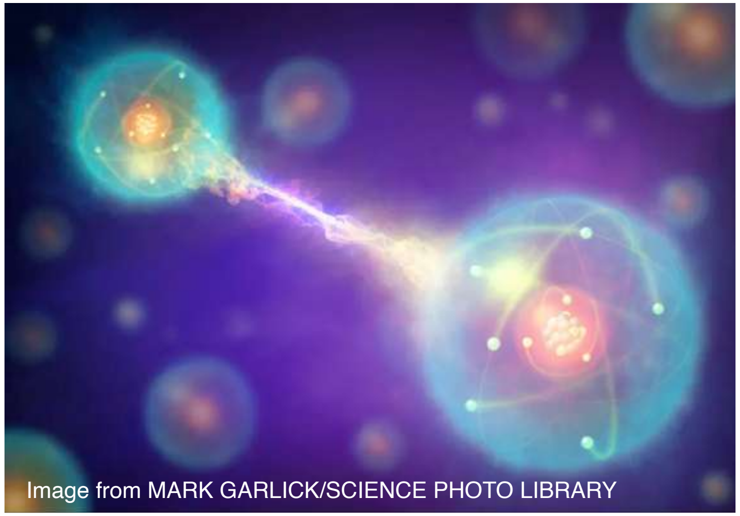


Image from MARK GARLICK/SCIENCE PHOTO LIBRARY

This new type of information is called **quantum information**, and has many strange and fascinating properties.

It **revolutionizes our technologies**, and **the way we look at the world.**

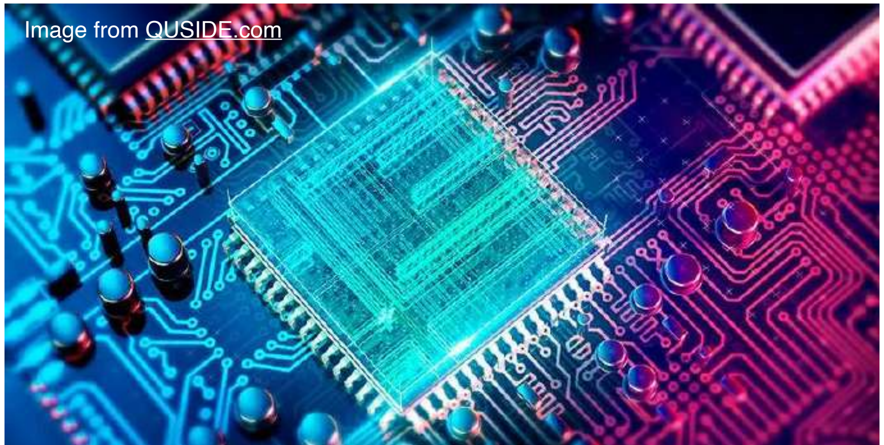
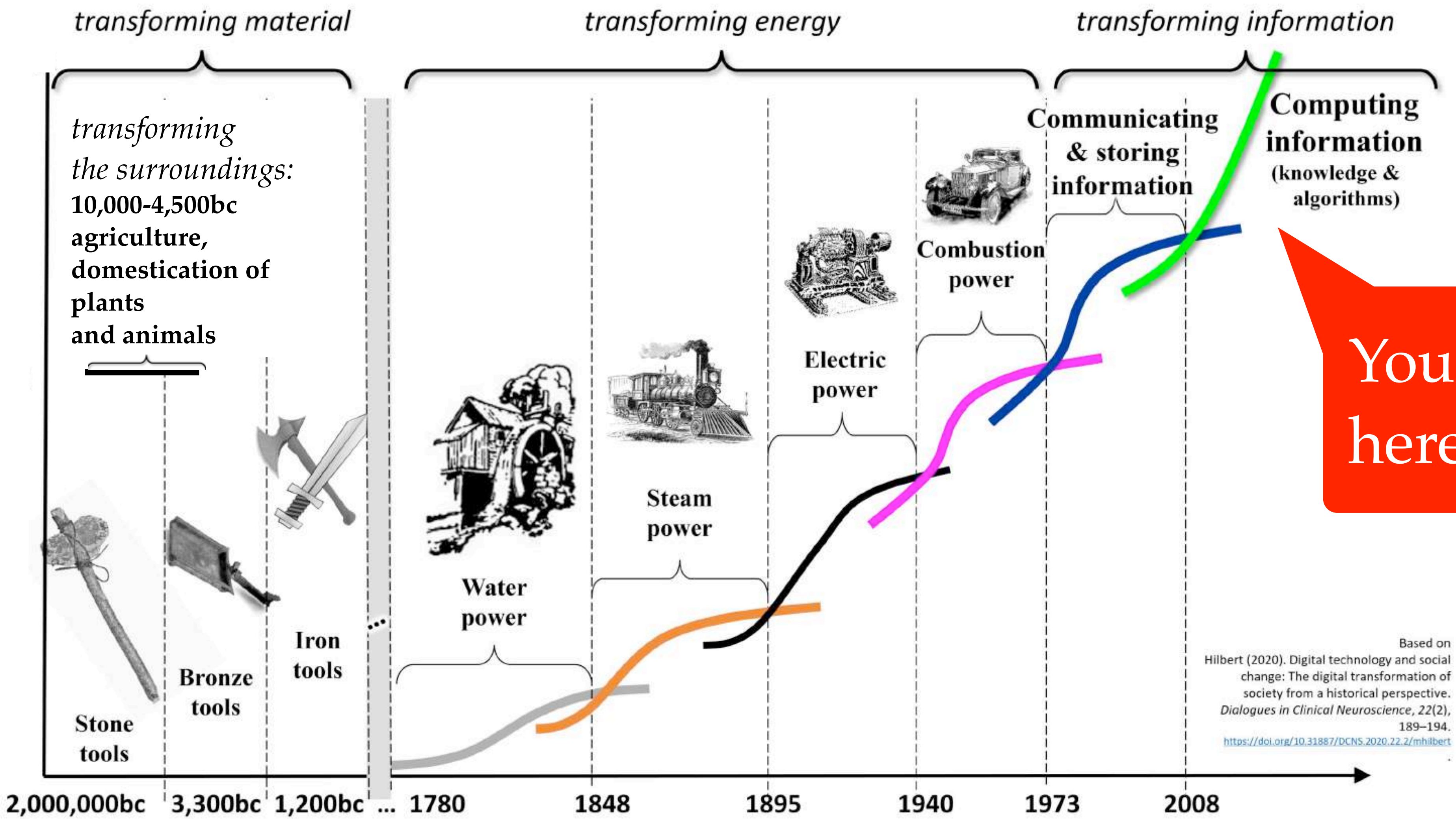


Image from QUSIDE.com

MAIN TECHNOLOGICAL REVOLUTIONS



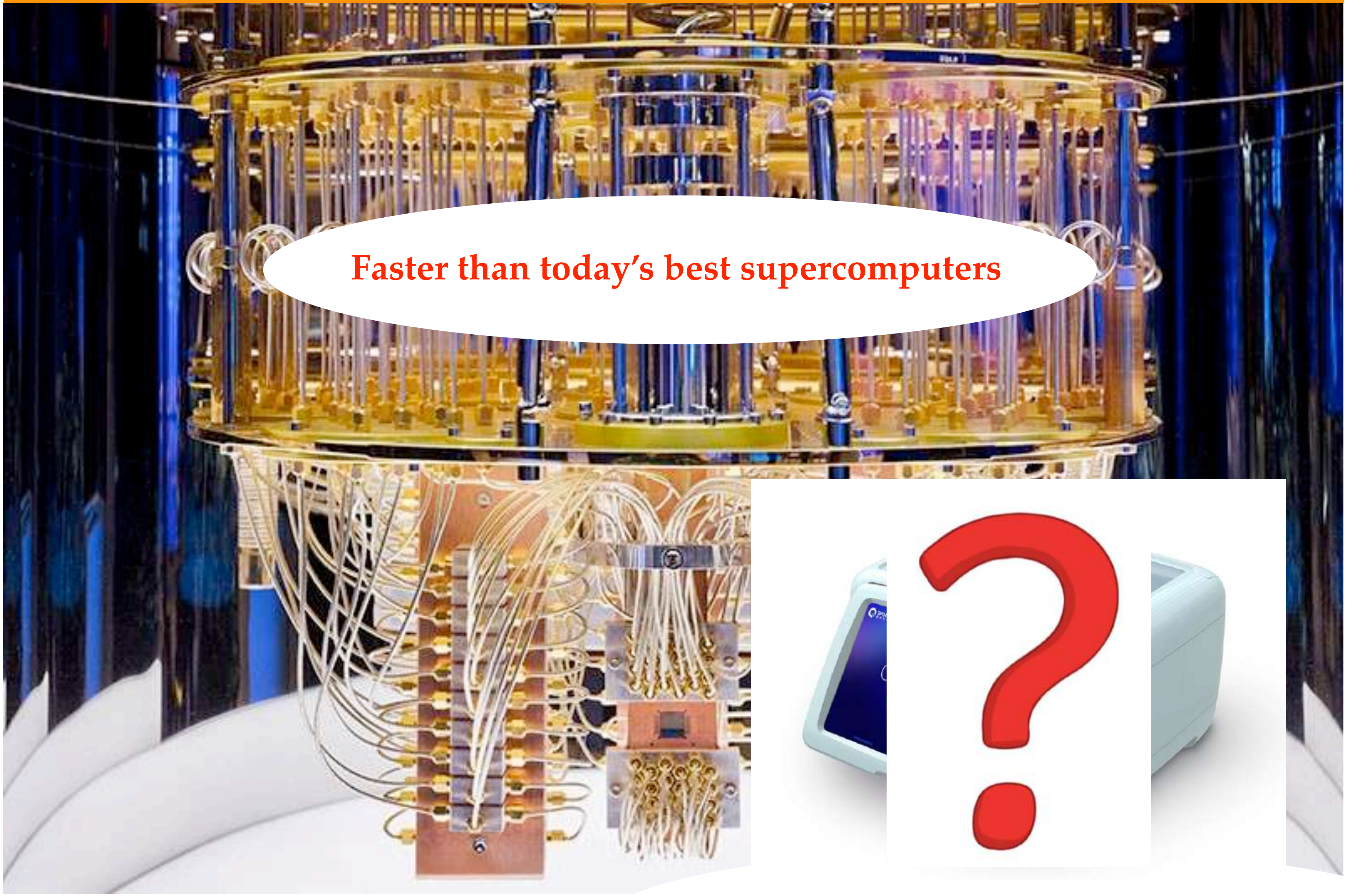
You are here…

. . .and this course is about the next stage!

New types of communication

Time-lapse photo of Xinglong Observatory communicating with Micius quantum satellite. Courtesy of Ying-Wei Chen

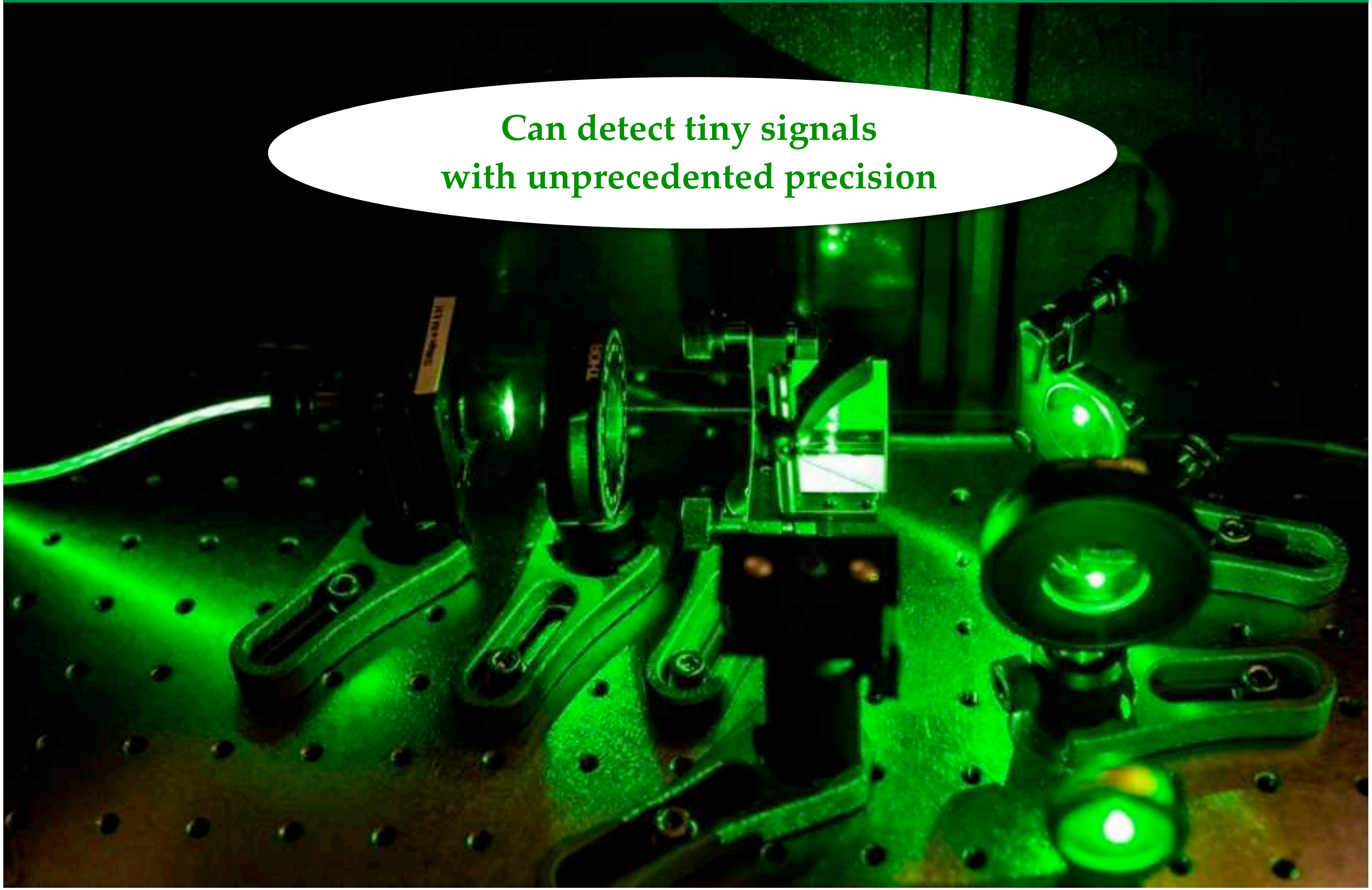
New computers



IBM Quantum computer. Credit IBM

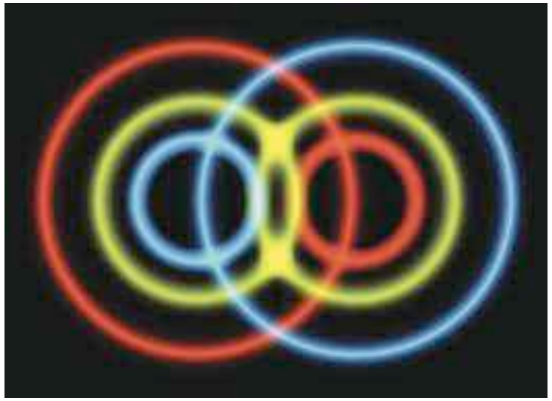
You will see one later in this course!

New sensors



Quantum sensor. Credit RLE, MIT

QUANTUM INFORMATION TECHNOLOGIES



Summary: The next stage of the information revolution is the development of information technologies that exploit **the power of quantum physics.**

Aaargh!
Did you say *"Quantum Physics"*???
That sounds *sooo* difficult!

Don't worry!
You don't need
to know/learn quantum physics
for this course!

This course is about **appreciating** the **impact** of quantum physics **on our society,**
and **the way we see the world.**
No formulas, no technical stuff.
Only plain English and visuals.

Anyone
can take this course!

NOT ONLY TECHNOLOGY

The quantum revolution brings a
new view of physics,
with **the notion of information at its core.**

Image from HPC Wire

Maybe the **universe** is
a **giant quantum computer**?

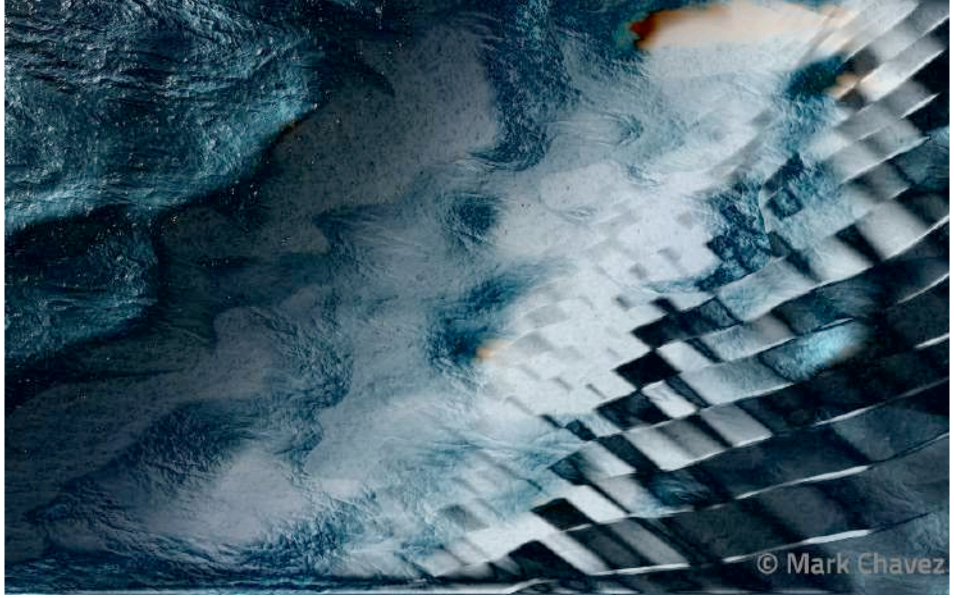
Image from owlcation

Maybe **space and time**
just **emerge from information**?

NOT ONLY SCIENCE

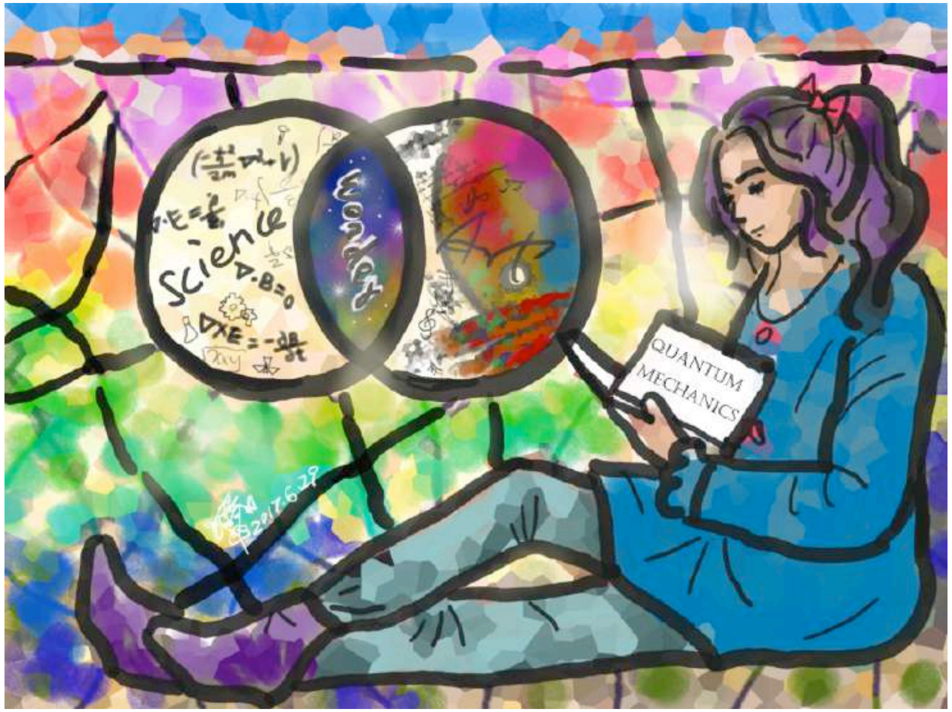
Quantum physics **changes some of our most fundamental notions:** objective reality, space, time, cause-and-effect.

It has **impact on society, economy, philosophy, literature, visual arts, and even music!**



Still from Quantum Logos, by Mark Chavez

Quantum Entanglement, Jesse Melanson



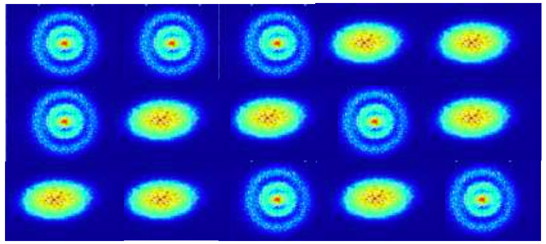
A renaissance woman in the 21st century, Kitty Yeung

The disintegration of the persistence of memory, by Salvator Dalí

Still from "Antman and the wasp" by Peyton Reed

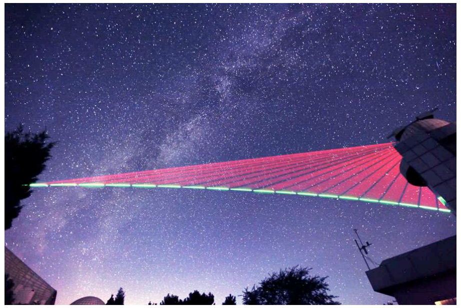
THIS COURSE

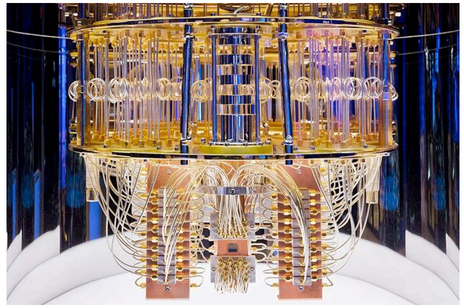
PLAN OF THE COURSE



(1) Basics

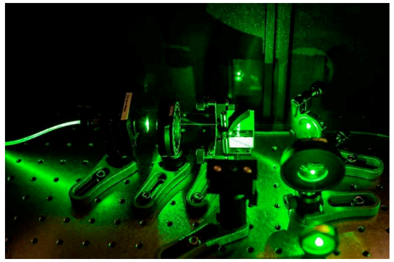
- what is information?
- what is *quantum* information?

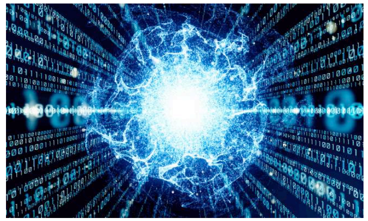




(2) The quantum revolution

- hack-proof communication
- ultrafast computers
- ultraprecise sensors
- quantum in popular culture





(3) The universe as a quantum computer

- space, time, and information
- how quantum information will change our notions of space and time?
- how it will change the way we see the universe?

See Moodle for detailed, week-by-week schedule.

GOALS

(1) To make you aware of quantum information technologies

→ know what can they do for you!

(2) To make you aware of the impact of quantum information on society

→ be prepared for new opportunities!
new businesses, new ideas

(3) To train your critical skills

→ be able to distinguish between science and hype!

(4) To make you able to engage in science popularization

→ be able to bring exciting new ideas to everyday people
using your favorite way of expression (talking, writing, art…)

BENEFITS

For students from Business & Economics

- learn main directions in the market of quantum technologies
- learn to distinguish true market potential from hype

For students from Social Sciences, Law, Art, and Education

- get a sense of the social impact of quantum technologies
- learn to distinguish good from bad science popularization
- get inspiration for new art projects

For students from Science and Engineering

- hear about the latest frontiers of science/technology
- learn to explain the impact of science/technology to the general public.

METHODS

(1) Lectures: get the basics in class

- lecturer introduces key ideas and examples of science popularization
- you are encouraged to ask questions/express your thoughts
  - slides uploaded on Moodle
  - Face-to-face only.

(2) Tutorials: group discussion in class

- share your ideas
- TAs will serve as facilitators

Pick your slot on Moodle after today's lecture

(3) Assignments: individual & group work off class

- do your own exploration
- collaborate with your classmates

Workload

- this course is designed to be light-weight
- you can choose your workload depending on your interest in the course: if you are more interested, you can explore more. If not, you can do less.

ASSESSMENT

Class participation: 10%

- actively participate to tutorials and lectures
- TAs will record your attendance

Two quizzes: 30%

- short (20 minutes), taken during tutorials

Midterm write-up: 20%

- 1-2 pages
- **no group project**

Final project: 40%

- **realize a creative work**
- can be a video, a science fiction story, a popular article, a poem, a song, a graphic novel…
- **multi-media format is encouraged (see Moodle for good examples)**
- **group projects are encouraged**

FEEDBACK

Quizzes:

- answers discussed in class right after the quiz
- grades announced in 1 week through Moodle

Midterm write-up:

- graded within 2 weeks of submission
- grades and feedback provided through Moodle

Final project

- graded within 2 weeks of submission
- grades and feedback provided through Moodle

INSPIRATION VS PLAGIARISM

You are encouraged to search for online resources,
critically examine them,
take inspiration from them,
and even to insert part of them in your work
(for example, as we do in the lecture slides)

You are also encouraged to discuss with classmates,
or even with people outside this course.

But your work should be clearly identifiable as your own.
Plagiarism is strictly forbidden.

- **do not use materials by others without giving credit**

- **no cheap cut-and-paste of online materials.**
  When you use someone else's material,
  you should weave it into your own work
  (for example, as we do in our lectures slides)

POLICY ON CHAT GPT & AI TOOLS

You may use them to improve your writing or suggest materials.

But AI tools should be assistants to you when learning.
They are NOT to replace you in learning.

Do NOT ask AI tools to generate your homework.

In case you used any AI tool to assist you (e.g., for translating materials),
You should be responsible for its output.
Check and revise.

GRADE POINTS

Standard	Grade	Grade Point
Excellent	A+	4.3
	A	4.0
	A-	3.7
Good	B+	3.3
	B	3.0
	B-	2.7
Satisfactory	C+	2.3
	C	2.0
	C-	1.7
Sufficient	D+	1.3
	D	1.0
Fail	F	0

We expect 95% of the class to be here

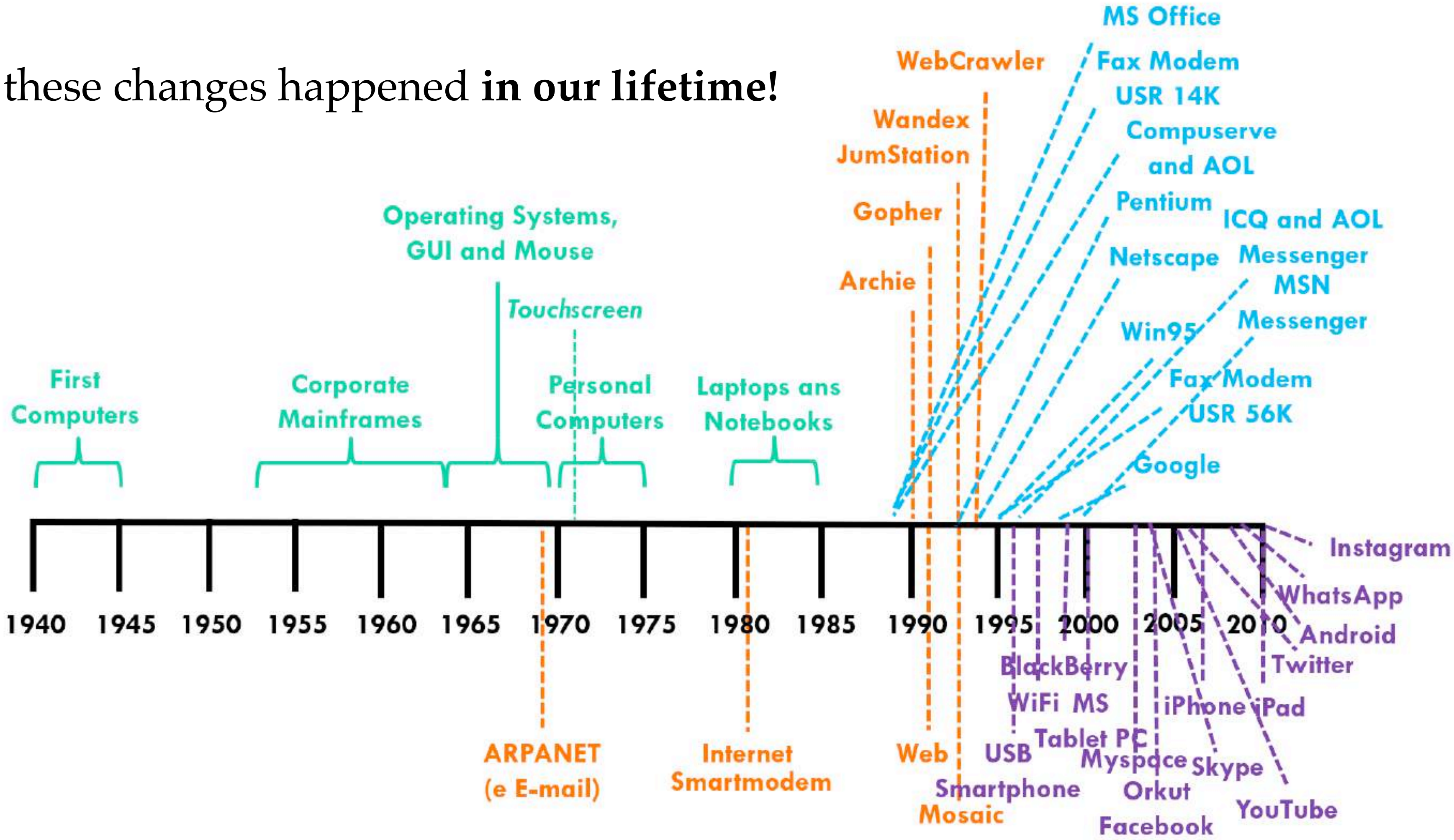
Getty image

LECTURE 1: THE INFORMATION AGE

A VERY FAST REVOLUTION

In less than 100 years, information technologies have transformed our world.
radio, TV, telephone, copy machines, fax, computers, the internet, wireless networks, GPS, medical imaging, smartphones, Google, Youtube, Facebook, Wechat, ChatGPT, AI….

Many of these changes happened **in our lifetime!**



WHO WOULD HAVE THOUGHT SO?

Monday, February 12, 1996 THE DENVER POST 7

Granddaddy of computers turning 50

COMPUTERS from Page 1A

"Without it, we wouldn't have the space program, we wouldn't have modern airplanes," said Michael Williams, editor in chief of the Annals of the History of Computing. "Pilots would still be trying to fly by looking outside the window occasionally."

ENIAC long ago outgrew its usefulness as a number cruncher — a $40 calculator has more computing power.

But it has not lost its relevance.

The university planned an entire year of events to honor ENIAC's birthday, including turning on part of the original machine. Vice President Al Gore will throw a switch Wednesday, the day of the anniversary, and ENIAC will count from 46 to 96.

The Postal Service will unveil a stamp commemorating "The Birth of Computing." And Garry Kasparov, the World Chess Federation champion, this week is playing against IBM's "Deep Blue" computer.

The original assemblage of wires, vacuum tubes, resistors and switches was constructed in about a year and a half at the university's Moore School of Electrical Engineering.

When fully operational, ENIAC filled up a 30-by-50-foot room. Every second it was on, it used enough electricity — 174 kilowatts — to power a typical Philadelphia home for 1½ weeks.

Costing more than $486,000, ENIAC might never been attempted were it not for World War II.

"A lot of people said we were dreaming," said Herman Goldstine, who served as liaison between the Army and ENIAC team.

"The electronics people said there were too many vacuum tubes and it would never run. The mathematics people said there were no problems complex enough that computers were needed."

The Army provided both the complex problems and the money.

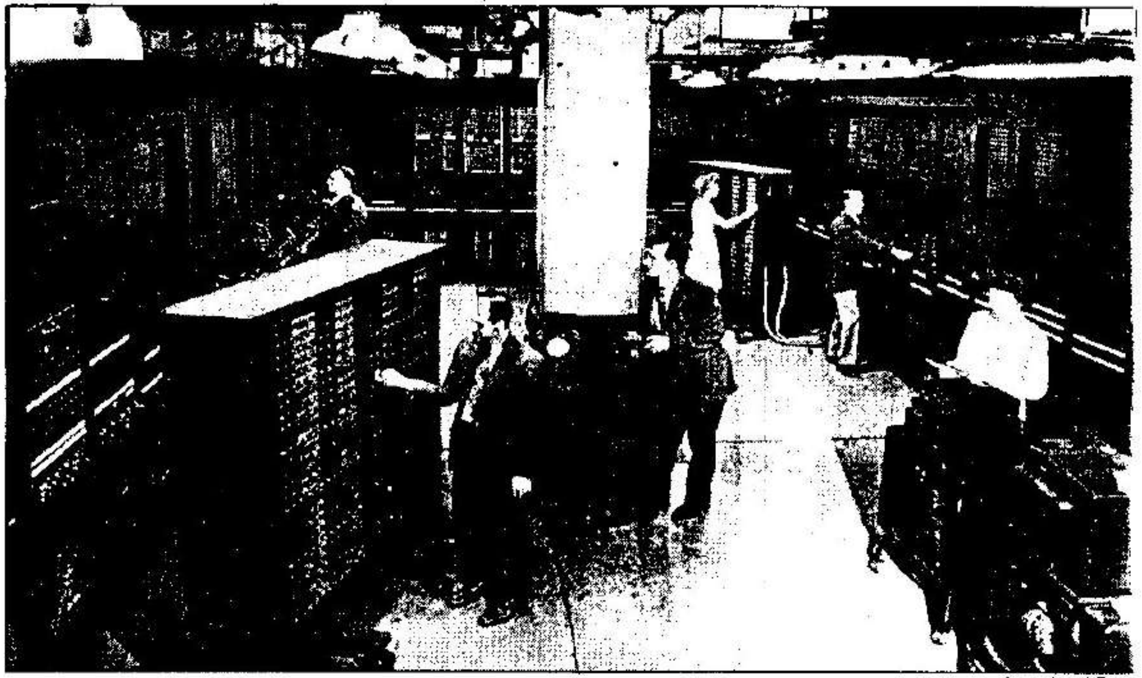
John Mauchly, one of two masterminds behind ENIAC, knew the Army was having a terrible time working out the complicated firing tables to help gun crews aim new artillery being used against German forces.

Each firing table had to list numbers for hundreds of potential trajectories. Calculating a single trajectory could take 40 hours using a mechanical desktop calculator, and 30 minutes using a sophisticated machine called a differential analyzer.

Mauchly, then 32, bravely told Army officials his machine could do the job in a matter of minutes.

ENIAC was completed just as the war was ending, too late for those artillery tables.

However, it fulfilled another military purpose. During test runs in 194[illegible] it did millions of calculations on ther[illegible] monuclear chain reactions, predicting the destruction that could b[illegible] caused by the hydrogen bomb.



Associated Press

CALCULATING MINDS: J. Presper Eckert, left foreground, and John Mauchly, near pole, masterminded ENIAC, pictured in undated photo from the University of Pennsylvania Archives.

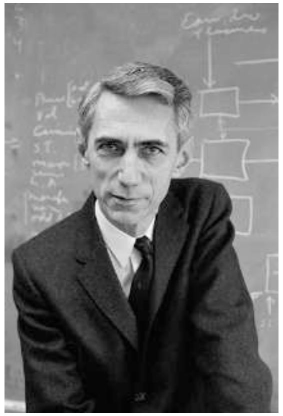
Prior to WWII: "… there were too many vacuum tubes and it would never run … there were no problems complex enough that computers were needed."

Credit to Chris Monroe

WHAT MADE IT POSSIBLE?

Ideas

Theory of communication (1948)



Claude Shannon

Theory of computation (1936)

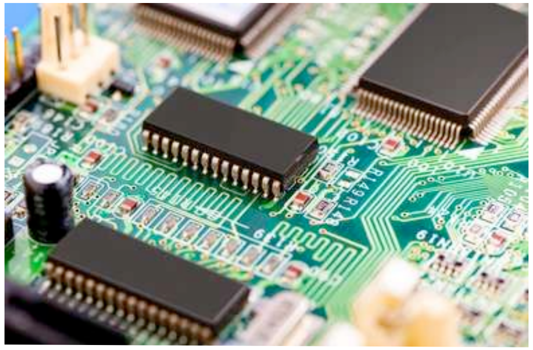
Alan Turing

Works like a switch

Technologies

The transistor, 1947

Integrated circuits ~1960s



THE NOTION OF INFORMATION

WHAT IS INFORMATION?

In everyday life: **information = a relevant fact about something**

Examples:

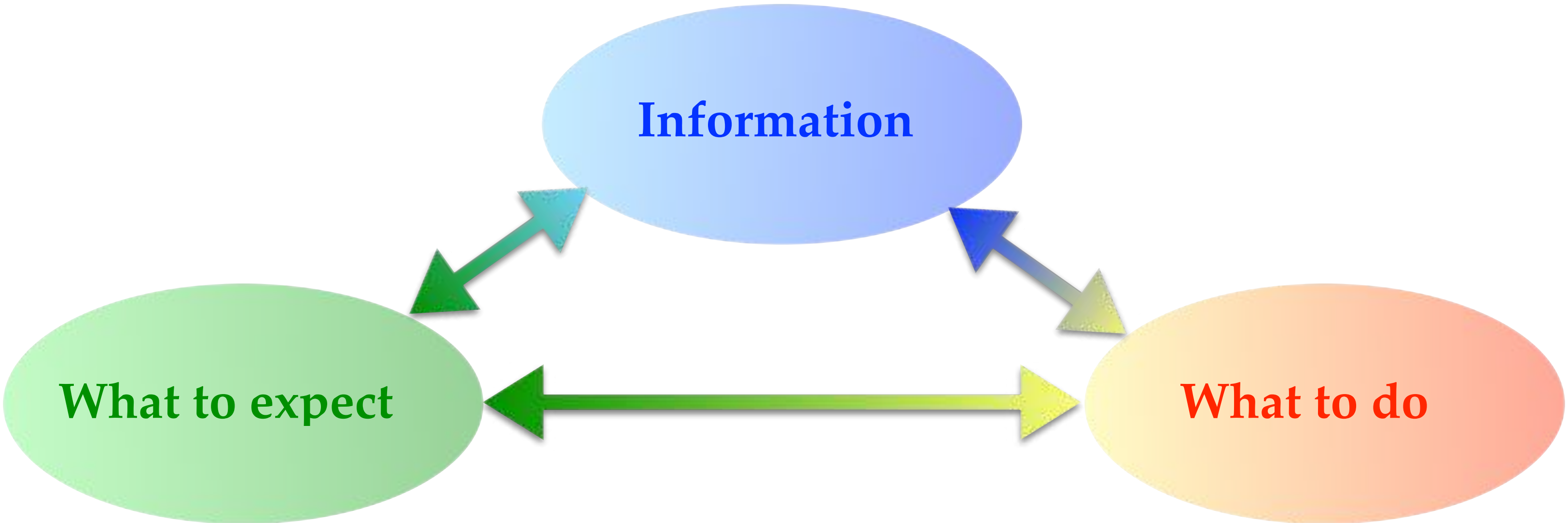
- the “Course Information” on the Moodle page of this course
- weather information
- financial information
- personal information
- secret information

More generally: **an arrangement of symbols or things**

Examples:

- a sequence of 0s and 1s
- the notes on a music score
- a novel
- a computer program
- genetic information in the DNA

WHY IS INFORMATION IMPORTANT?



- course information
- weather forecast
- financial information

…

- music score
- directions on a map
- computer program

…

INFORMATION SCIENCE

In 1948, Claude E. Shannon developed a **mathematical theory of information.**

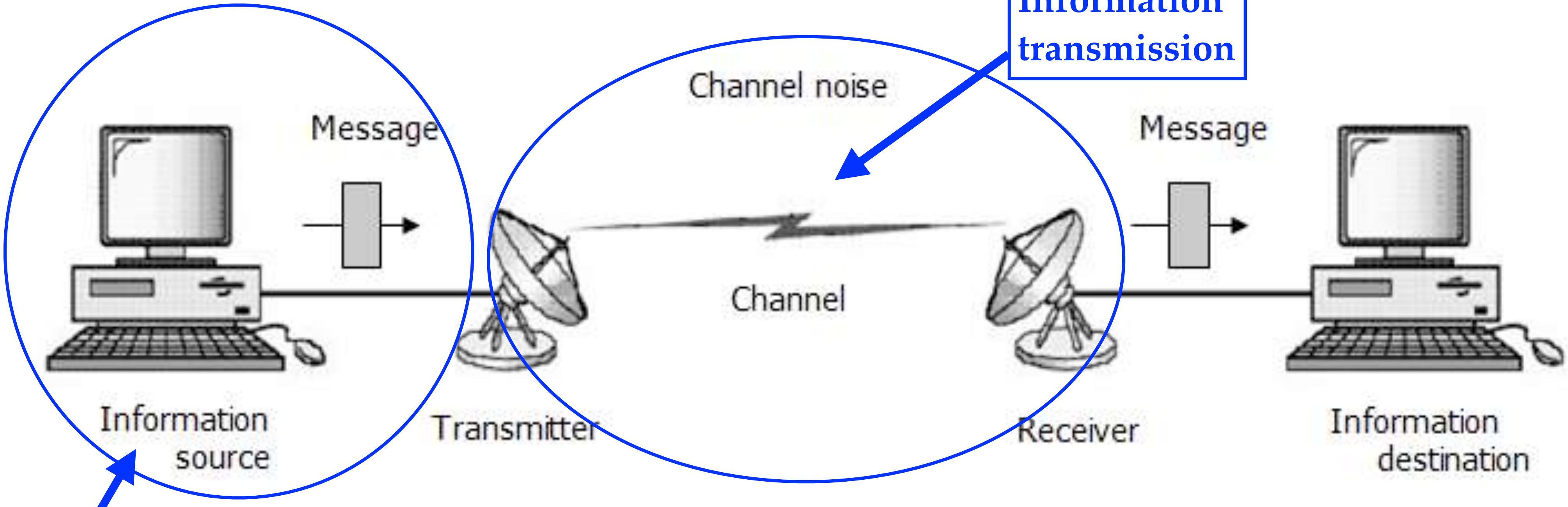
Shannon was a very interesting person. Loved games, toys, and tricks…
https://spectrum.ieee.org/claude-shannon-tinkerer-prankster-and-father-of-information-theory

My first thinking
was how you best improve
information transmission
over a noisy channel.
This was ***a specific problem****,*
where you're thinking about
a telegraph system
or a telephone system.
But
when you get to thinking about that,
you begin to generalize
in your head
about all these broader
applications.

Photo: © Stanley Rowin

SHANNON'S PROBLEM

Information transmission

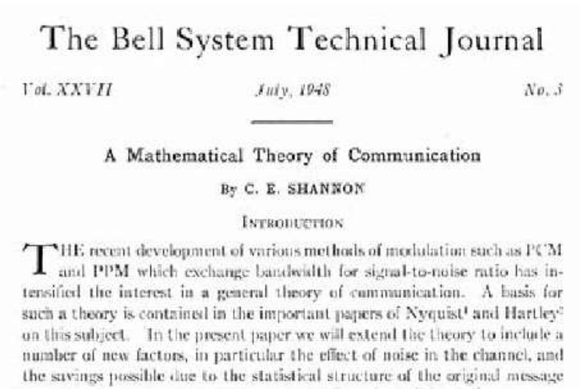


Information source produces a message
(a sequence of symbols).

Main questions:

(1) how much information is in the message?

(2) how much information can I send through the communication channel?



The Bell System Technical Journal

Vol. XXVII July, 1948 No. 3

A Mathematical Theory of Communication

By C. E. SHANNON

INTRODUCTION

THE recent development of various methods of modulation such as PCM and PPM which exchange bandwidth for signal-to-noise ratio has intensified the interest in a general theory of communication. A basis for such a theory is contained in the important papers of Nyquist[1] and Hartley[2] on this subject. In the present paper we will extend the theory to include a number of new factors, in particular the effect of noise in the channel, and the savings possible due to the statistical structure of the original message

All in Shannon's 1948 paper (we will not study it)

ANALOGY:
TRAFFIC BETWEEN HK ISLAND AND KOWLOON

Mhm…
we can measure the traffic
by the number of vehicles.
But how do we measure
the amount of
information?

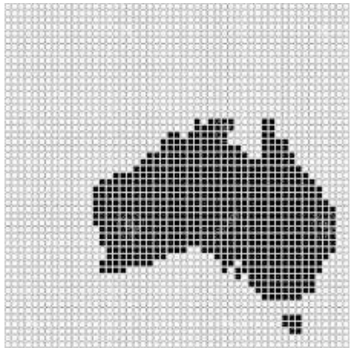
Hong Kong Island
→ information source

Tunnels
→ communication channel(s)

QUANTIFYING INFORMATION

Information source

produces a sequence of symbols



Suppose you **don't know** what the sequence is.
To find it out, you need to **get information**, for example by **asking some questions.**

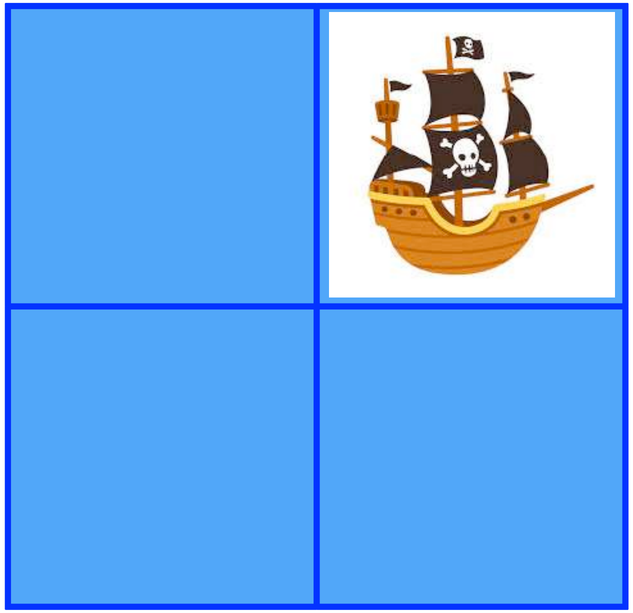
How many yes/no questions do you have to ask to find out what the sequence is?

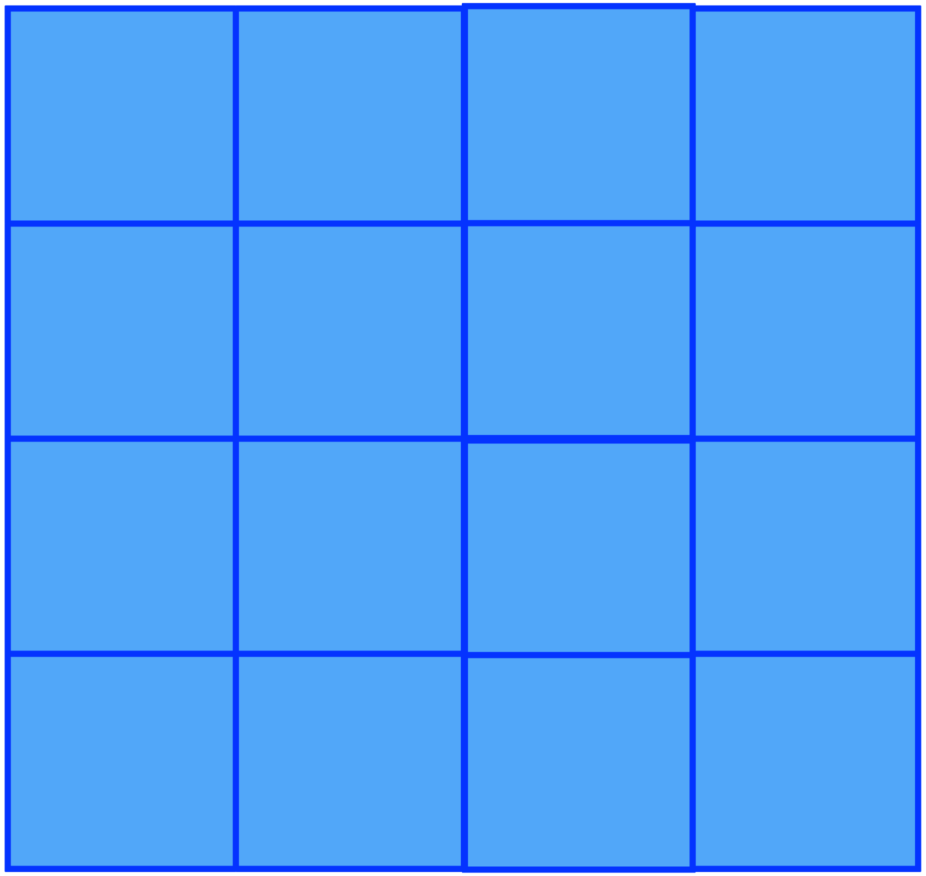
Example of the computer image. You can ask: "Is the first square black?"
"Is the second square black?"
and so on.

the minimum number of yes/no questions you need to ask is a measure of the amount of information.

A CONTEST FOR YOU

A battleship game: how many yes/no questions to find a  ?





Answer: 2 questions
- is it on the left?
- is it on the top?

Position of ship = (no, yes)

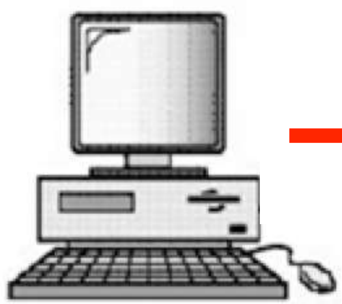
BITS

For each yes/no question, you can write down a 0 if the answer is "no"
or a 1 if the answer is "yes"

In this way, **you can transform every piece of information into a sequence of 0s and 1s,** like 0010001111111110000000000.

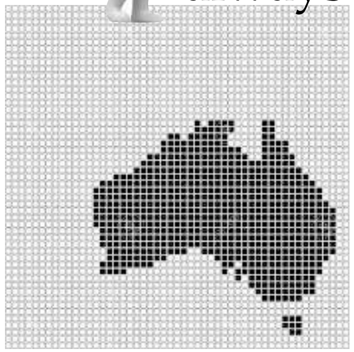
The binary digits in the sequence are called **bits**.

What if I know the first 3 rows of any image to transmit are always blank?



Information source

produces a sequence of symbols



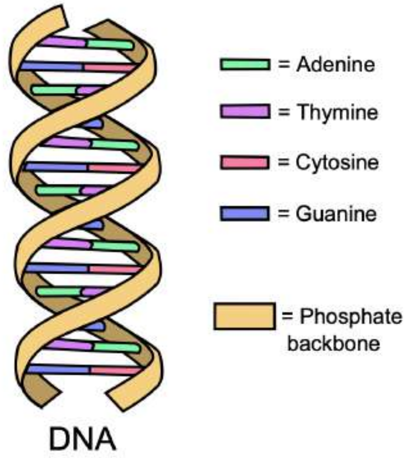
transform into bits

Amount of information
=
minimum number of bits

00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000010111100001100000
00000000000000000000000111100011000000000000000000000000000000000000000000011111000000111111110000011100000000000000011000000000
11111000000000011111111111100000000000000000000000000000000000000000000000011111111111111111111111111000111111110000000000000000
00000000000000000000000000000000000011111111111111111111111111111111111111111111111111111111111111111111111000000000000000000000
00000011111111111111111111111111111111111111111111111111111111111111000000000000000000000000000011111111111111111111111111111111
11111111111100000000000000000111111111111111111111111111111111111111111111111111111111111111111111111111…

ALL MEASURES TO BITS

Other measures of information?
How are they related to bits?



Example: DNA data storage (ACTGACT…). Four symbols A, C, T, G

A= 00, C = 01,
T = 10, G = 11

Shorter sequences

ACTGACT ⇄ 00011011000110

Simpler alphabet

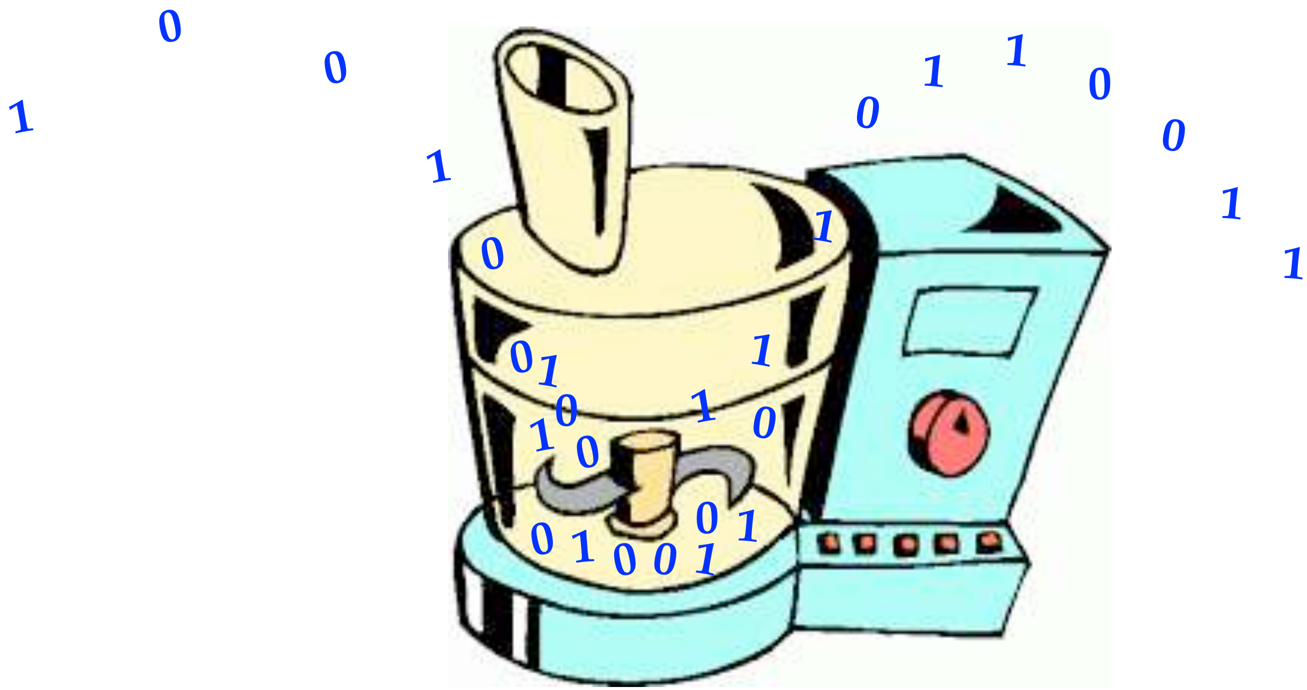
Analogy:
In most nations things are weighted in "kilograms",
whereas in UK people use "pounds" (= 0.4535…kg)

Units are interconvertible;
Bits are the simplest and mostly used.

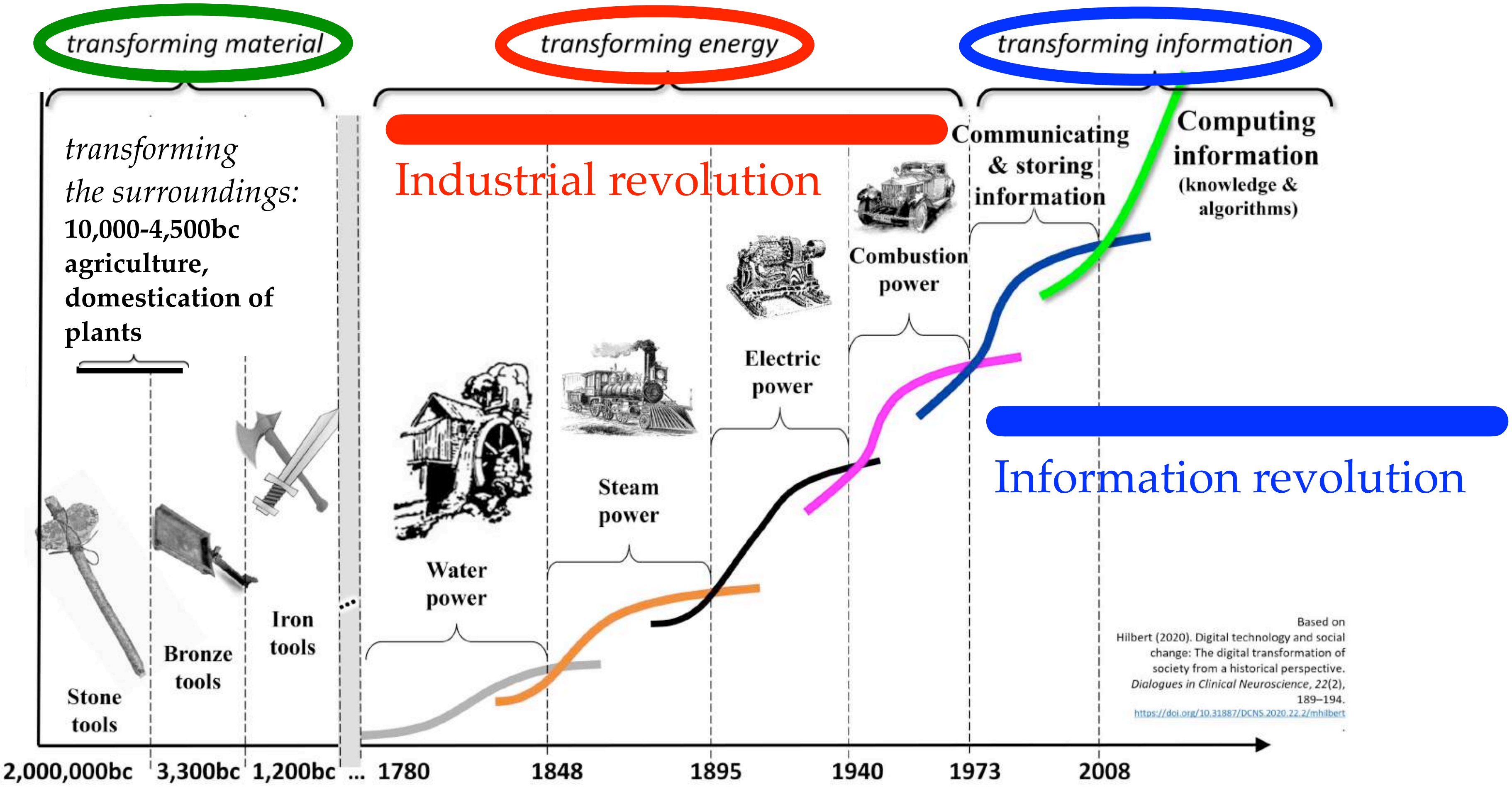
Bits
are the fundamental units of measurement
for information.

Like "grams" for measuring mass,
"calories" for measuring energy

INFORMATION PROCESSING



The hallmark of the Information Age is
the development of technologies for transforming (a.k.a processing) information.



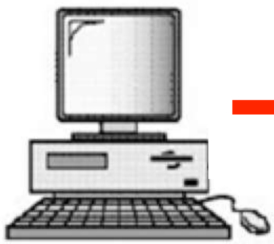
STORAGE

The basic form of information processing is **storage**: **storing the information into some physical object.**

Examples:

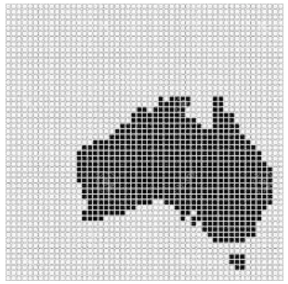
- SIM card of your phone
- hard disk of your laptop
- USB stick

…



Information source

produces a sequence of symbols

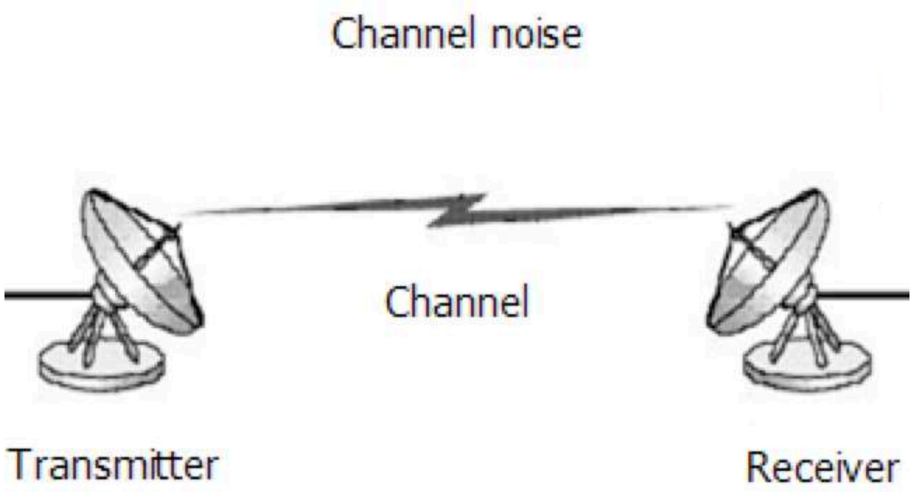


store bits into a physical object

Physical realization:
encode bits into some property of the object.
For example, 0 and 1 could correspond to 2 possible states of a transistor.
With many transistors, we can encode many bits.

Compression: less bits if there is some prior knowledge (e.g., first 3 rows are blank)

TRANSMISSION



Move information from one place to another.

Examples:

- send a text message or an email
- make a video call
- talk

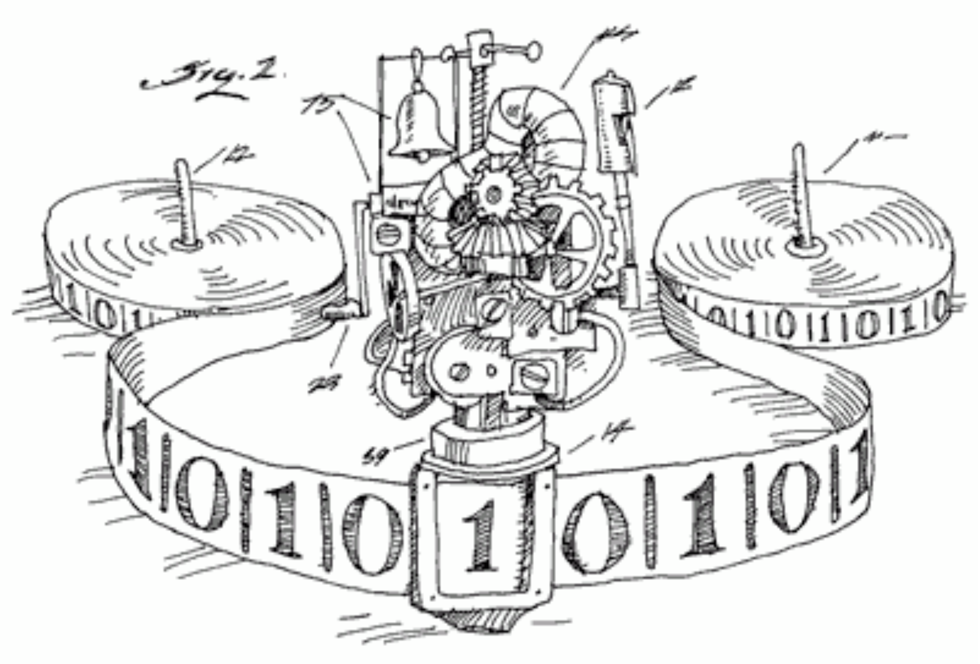
...

Physical realization: encode information into some traveling object,
and then decode once the object arrives at destination.
for example, encode bits into an electromagnetic wave,
or in a sound wave.

***Storage is a special form of transmission**
... over time, instead of space!

COMPUTATION

Transform input information
into some output information,
by performing a set of basic operations.



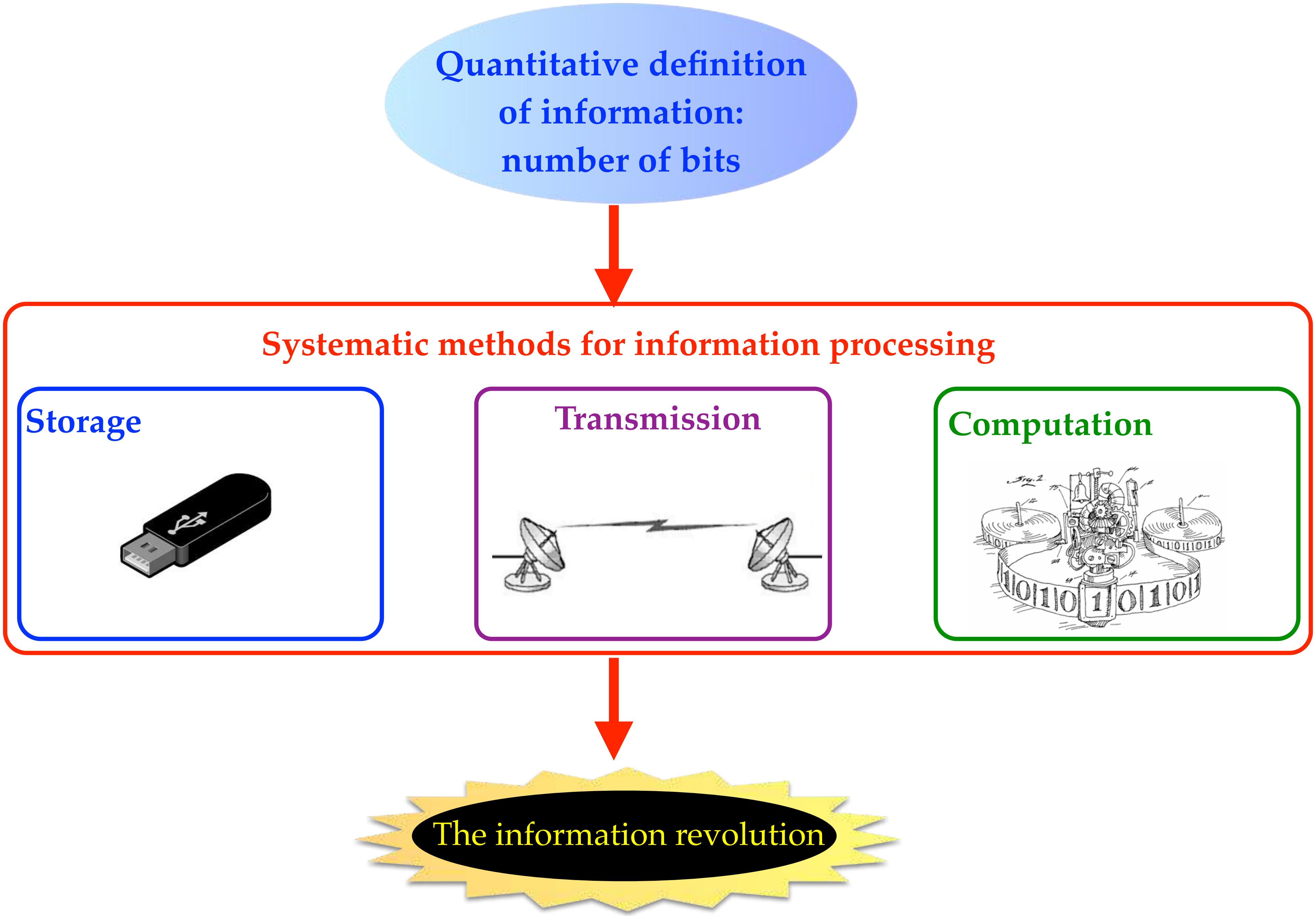
Example. Turing Machine:
transforms bits written on a tape,
moving back and forth along the tape

Examples:

- compute the sum of two numbers
- find the shortest route on Google Maps
- choose the next move in a game of chess
- crack a secret code

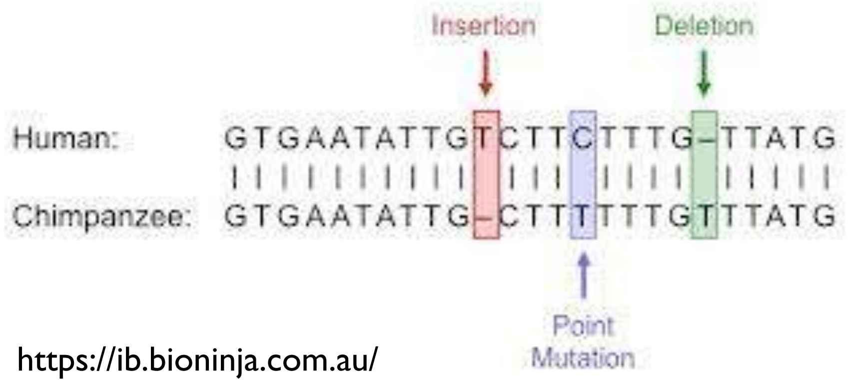
…

Physical realization:
encode bits into physical objects
and let the objects interact together.
for example, use transistors
and connect them together in an electrical circuit.


Quantitative definition
of information:
number of bits
Systematic methods for information processing
Storage
Transmission
Computation
The information revolution

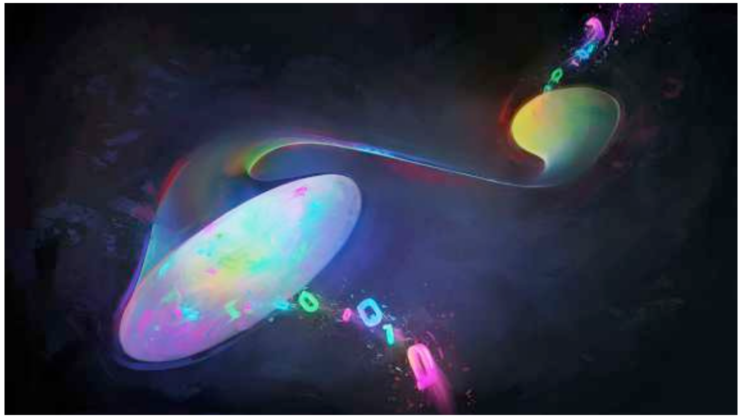
IMPACT BEYOND TECHNOLOGY

A KEY TO UNDERSTAND NATURE



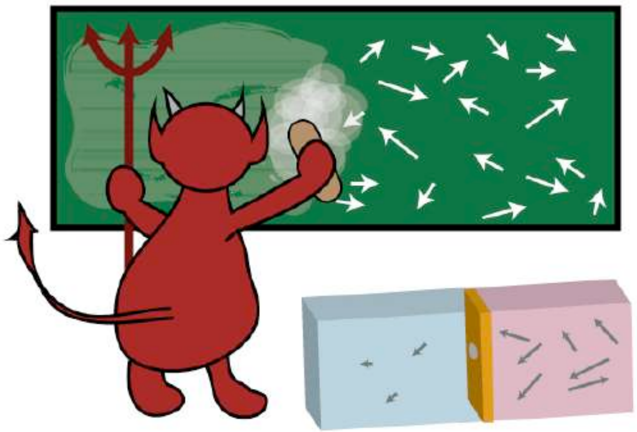
https://ib.bioninja.com.au/

Genetic mutations can be viewed as **transmission of information through a noisy channel.**



Olena Shmahalo/Quanta Magazine

Black holes can be viewed as information processing machines that **take information and scramble it.**



drawing and copyright by Lidia del Rio

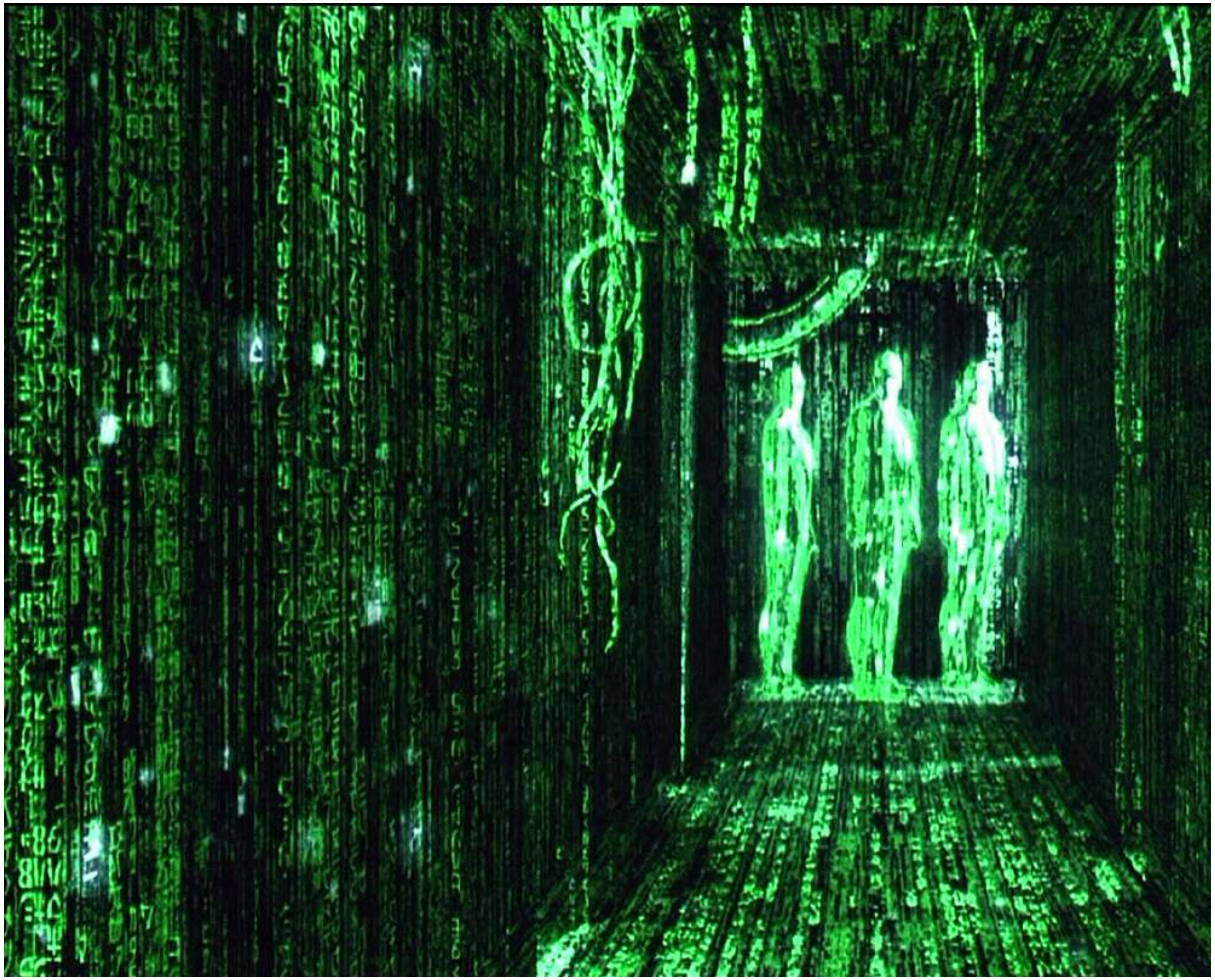
Every process that erases information requires work and causes heat (Landauer's principle)

IT FROM BIT

Physicist John A. Wheeler **suggested** that
everything in the universe
is made of information.

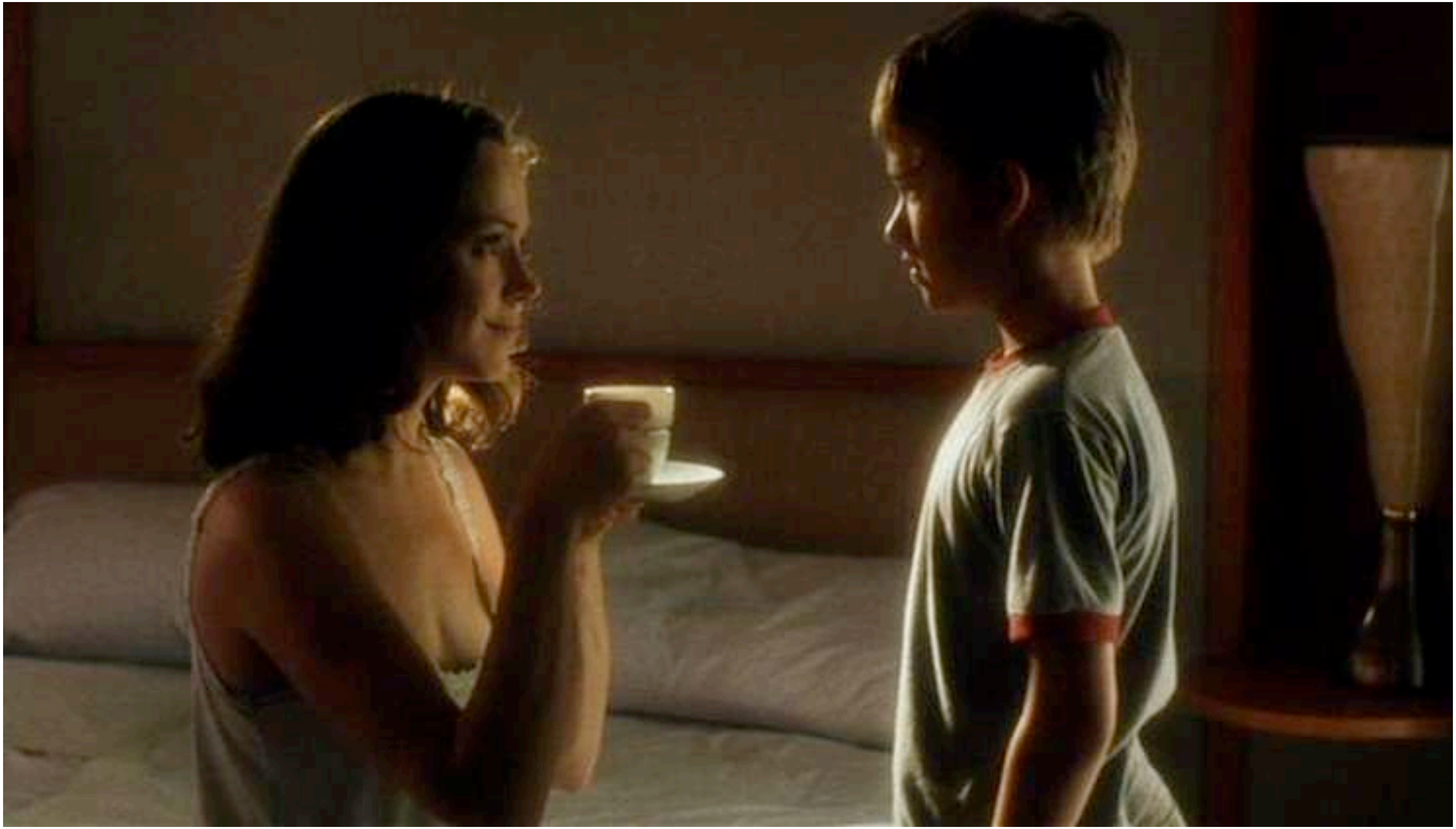
It from Bit.
Every it — every particle,
every field of force,
even the space-time continuum itself —
derives its function, its meaning,
its very existence entirely […]
from […] answers to yes-or-no questions,
binary choices, bits.
All things physical
are information-theoretic
in origin.

IMPACT ON MOVIES



"The Matrix" (1999)

"Ready Player One" (2018)



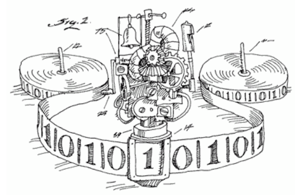
Still from "A.I." by Steven Spielberg

SUMMARY
OF
TODAY'S LECTURE

IN A NUTSHELL

- **Basic unit of information:** the bit

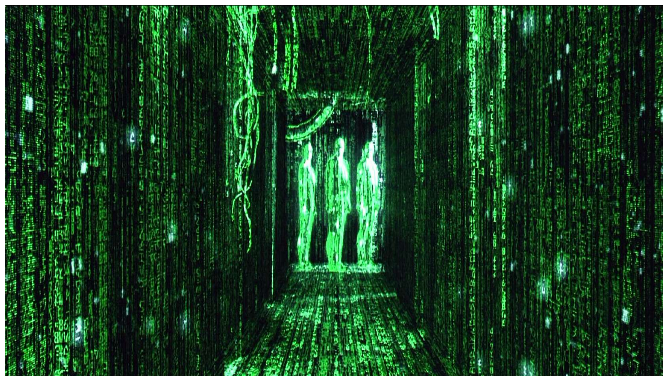
- **Information processing:** storage, transmission, computation



Information can be compressed, erased, or distorted.

- **The information revolution:** information processing technologies revolutionized our world.

- **It from Bit:** the idea that everything in the universe is made of information.



TUTORIALS NEXT WEEK

We will split into smaller groups and discuss the question:

Can everything be reduced to "information"?

In preparation, please watch

V. Vedral, *Everything is information*
https://www.youtube.com/watch?v=QfQ2r0zvyoA

Also available on the course Moodle page.