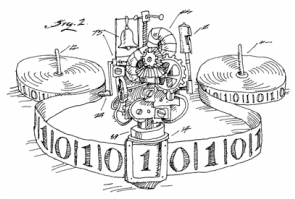
ENTERING THE QUANTUM REALM

Lecturer: Yuxiang Yang

PREVIOUSLY IN CCST 9077

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

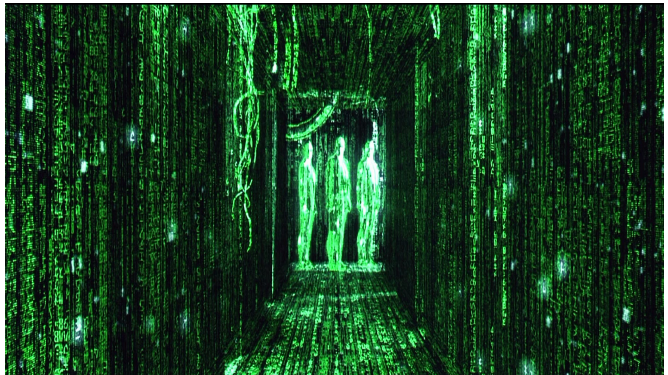
- **Information processing:** storage, transmission, computation



Information can be compressed, erased, or distorted.

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

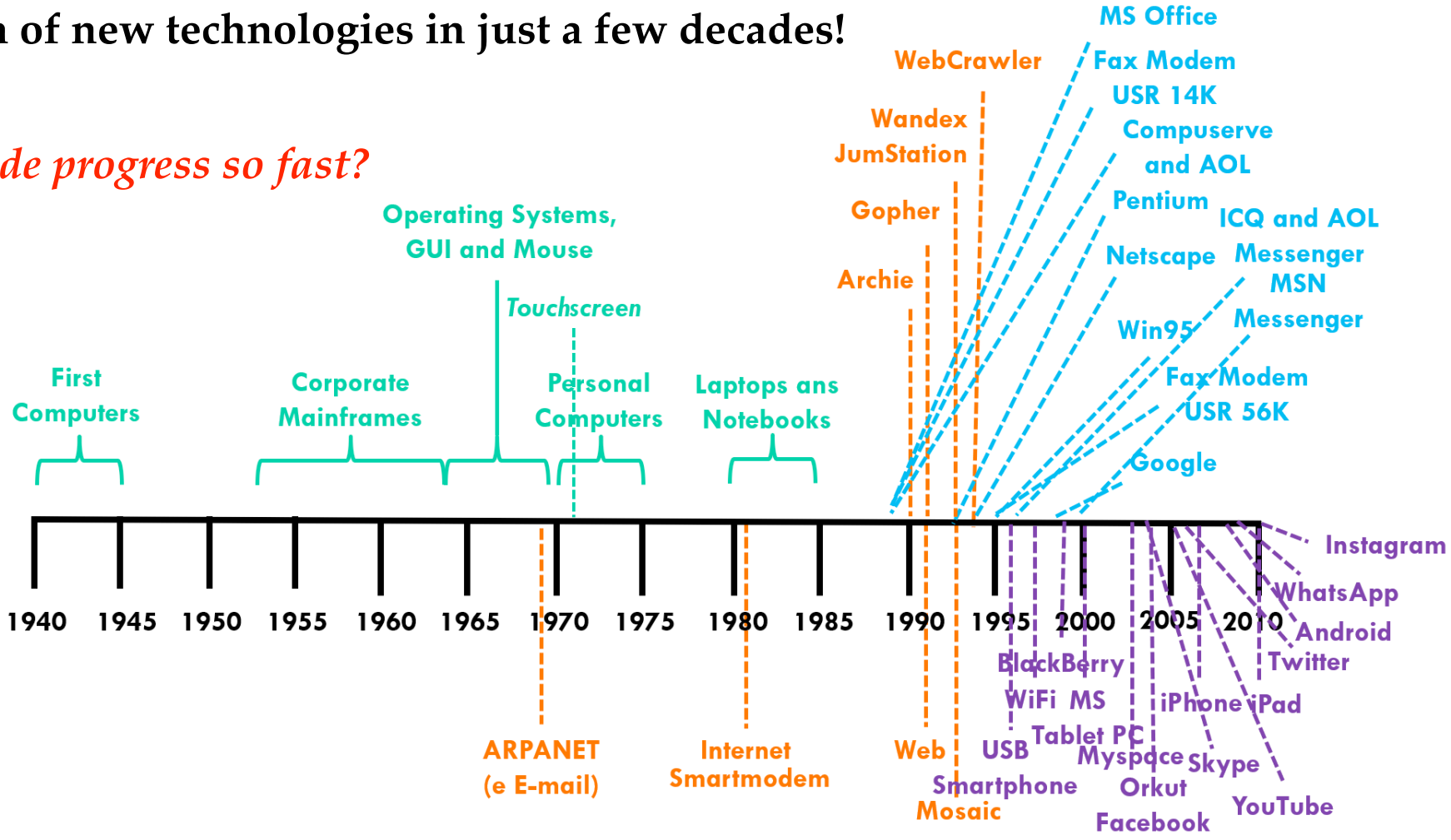
- **It from Bit:** the idea that everything in the universe is made of information.



In the past century, humankind has learnt how to harness the power of information.

The speed of the information revolution has been very fast:
explosion of new technologies in just a few decades!

What made progress so fast?

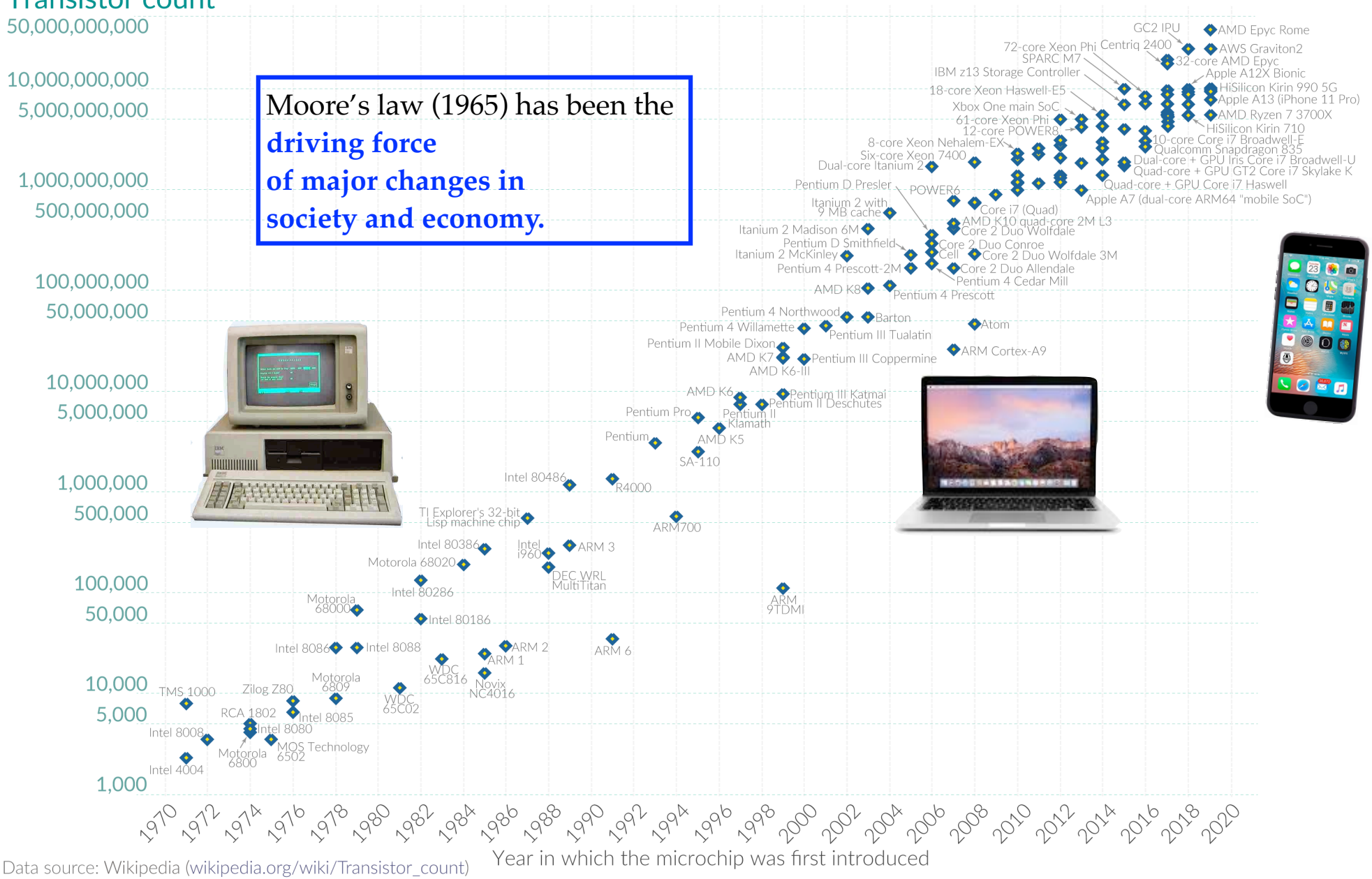


MOORE'S LAW

Moore's Law: The number of transistors on microchips doubles every two years

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years.
This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)

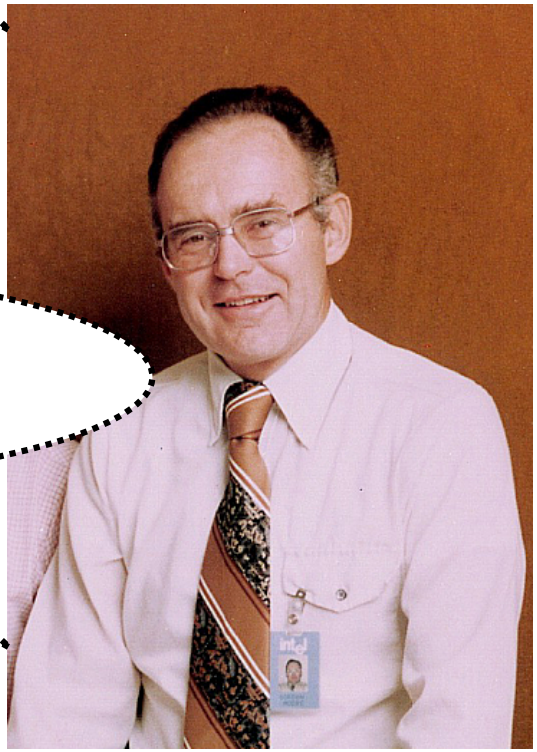
DO YOU KNOW …

Gordon Moore and his partner, Robert Noyce, co-founded a semiconductor company in 1968, and they had a problem finding a good name …

"Moore Noyce" doesn't sound nice for computers …

Let's try "Integrated Electronics" …

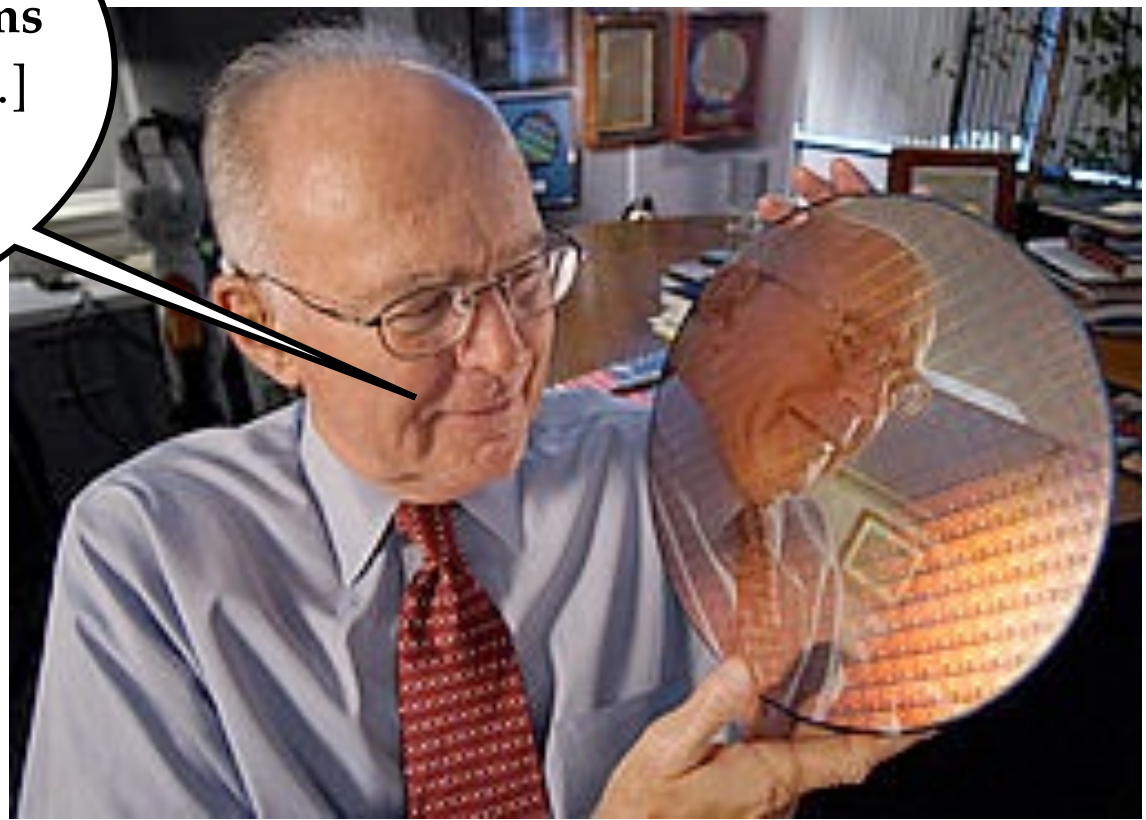
Or simply "Intel"!



THE END OF MOORE'S LAW

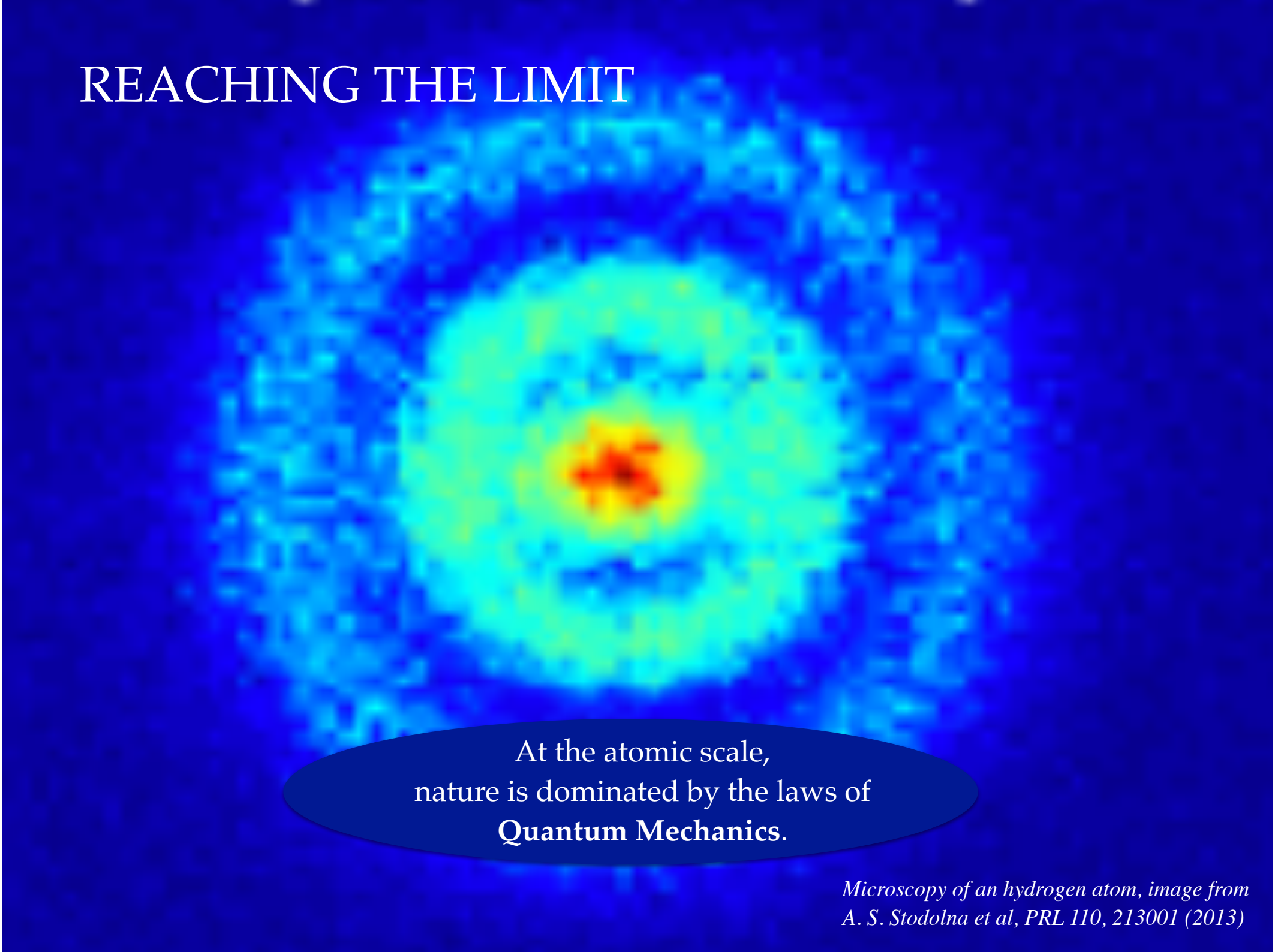
Moore's law is **not a law of nature,**
it is just a production target achieved by the electronics industry so far.

It can't continue forever. […]
In terms of size you can see that
we're approaching the size of atoms
which is a fundamental barrier. […]
We have another 10 to 20 years
before we reach
a fundamental limit.



Gordon Moore in 2005,
commenting on 40 years
of "Moore's law"

REACHING THE LIMIT



At the atomic scale,
nature is dominated by the laws of
Quantum Mechanics.

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

WHAT'S NEXT?

What will happen after the end of Moore's law?
Will computer technology stop improving?

Clearly, we will not be able to improve computers by making smaller transistors.
New ideas are needed!

A radically new approach:
take advantage of the laws of quantum mechanics to design a new type of computers.

In these computers, information is encoded in the states of atoms or other quantum systems.

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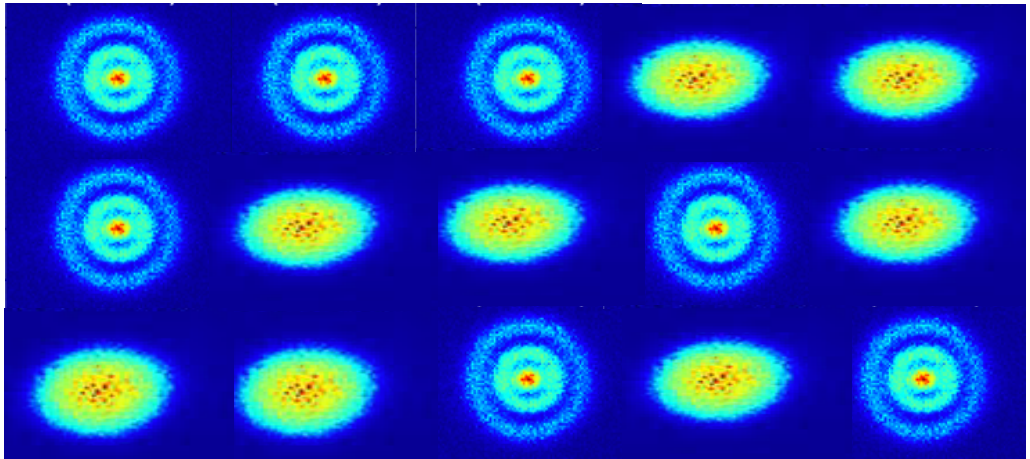


NOT ONLY COMPUTERS

This lecture:
Full-upgrade to Quantum!

Quantum mechanics revolutionizes the very notion of information:
the whole theory of information developed by Shannon needs to be revised!

- new units of information: ***qubits*** instead of bits
- new ways to transmit information: ***quantum communication***
- new way to process information: ***quantum information processing***

(classical) information theory

quantum information theory

INTRODUCTION TO QUANTUM INFORMATION

SCARY QUANTUM STUFF?

Popular presentations of quantum physics can be fascinating, but also quite frustrating.

Particles can be in two places at the same time

Sometime particles behave like waves…

…the cat can be alive and dead at the same time.

Reality is what you choose it to be

Spooky!

Weird!

Quantum measurements create many parallel universes

Nobody understands quantum mechanics

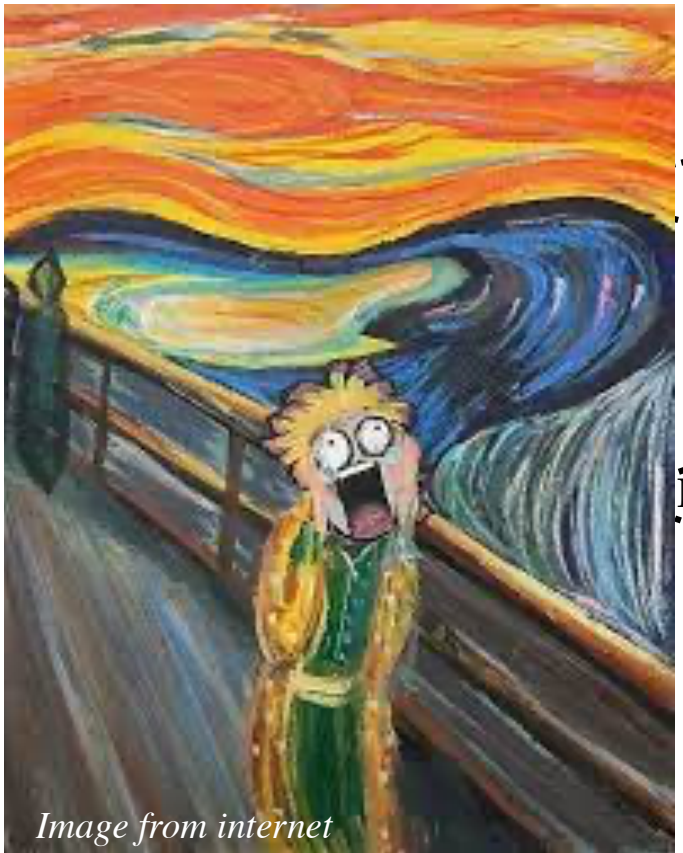
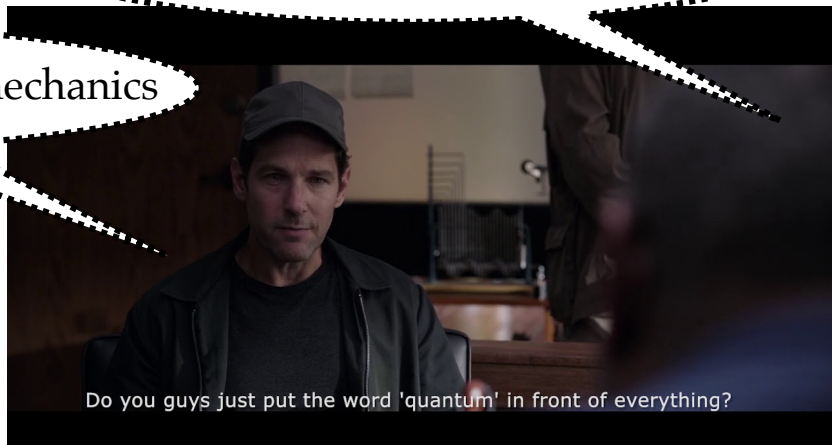


Image from internet



THE APPROACH OF THIS COURSE

Here we will introduce you to the main concepts
without using any prior knowledge in mathematics or physics.

At the same time, we will distinguish between

Good popularizations.
Make an effort
to find an accurate way
to describe the science.
Present inspiring/controversial
ideas without confusing them
with the established science.

Bad popularizations.
Distort the science,
jump to conclusions,
do not distinguish between
science and speculation.

FROM BITS TO QUBITS

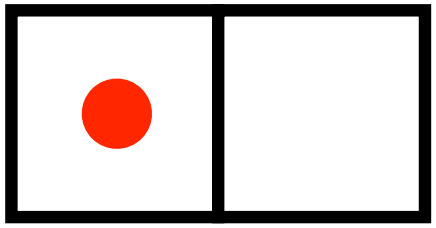
RECAP: BITS

The bit is the basic unit of (classical) information.
It has two possible *states (i.e., "status"),* usually called *0 and 1.*

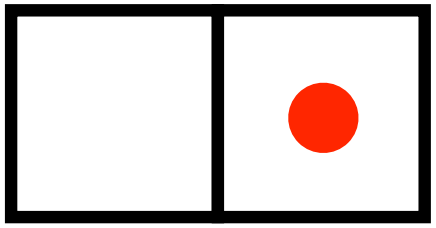
Every time we have two possible alternatives, we can associate them to a bit.

BALL IN A BOX

The main example of bit in today's lecture is
a box with two compartments, with a ball in one of them.



State 0:
ball on the left



State 1:
ball on the left

The box is **closed.**
If we want to know where the ball is, we have to open the box and look inside.

I will now give you an idea of what a **"quantum bit"** is.

To do this without math,
I will tell you a *tale.*

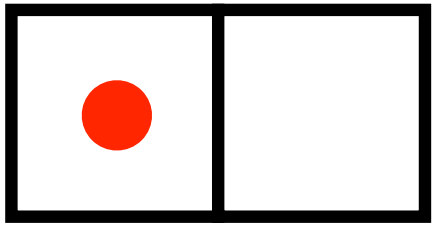
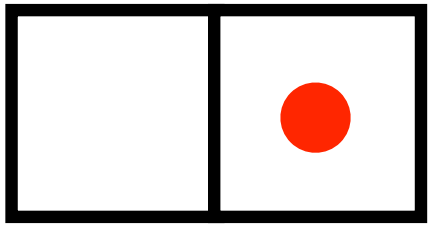
I will pretend that…

…and I will let you discover its key properties.


A
TALE
ABOUT
MAGIC BOXES

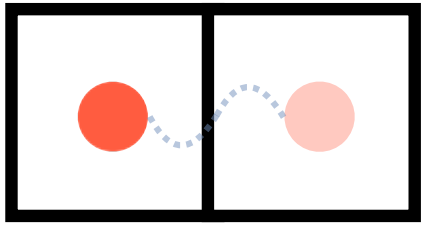
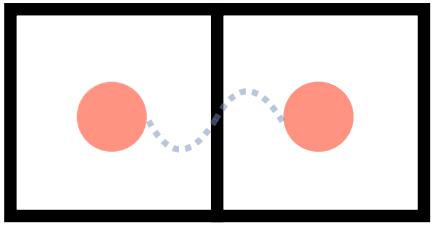
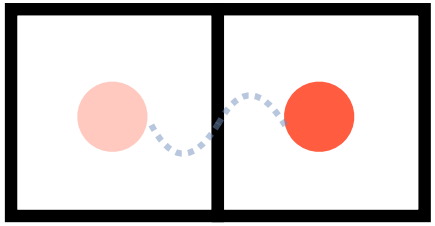
MAGIC BOXES

One day you find a **magic box**, which can be **not only in the (classical) states**

 and 

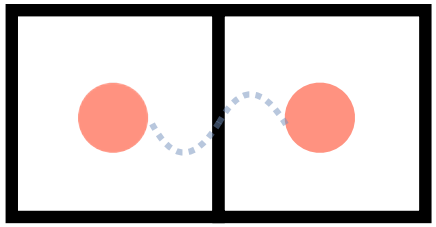
but also in some **new states.**

Here I will visualize these new states by adding color shades and a dotted line, such as

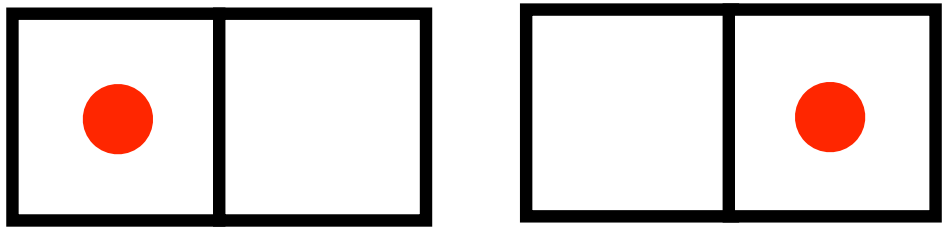
 ,  ,  , and so on

Let us call these new states **"superposition states."**

WHAT IS THE MEANING OF THE SUPERPOSITION STATES?

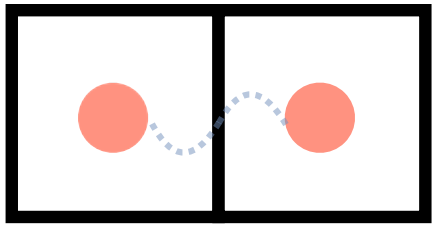
What does it mean for the box to be in the state  ?

Can it be described as sort of in-between classical states,



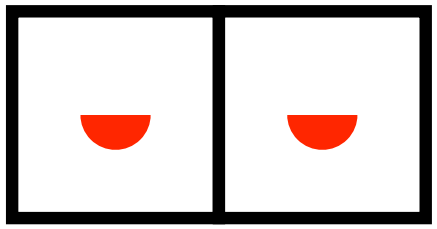
Or is it a genuinely new way of existence?

WHAT IS THE MEANING OF THE SUPERPOSITION STATES?

What does it mean for the box to be in the state  ?

Hypothesis 1: maybe the ball is like a fluid, which can be a bit on the left, and a bit on the right?

For example, half ball on the left, and half ball on the right



Scientific method:

- Propose several hypotheses that try to explain a phenomenon.
- to test an hypothesis, we have to make experiments.

Let's open the box and see what we find!

Imagine that we do the experiment.
This is how a few runs would look like:

Run 1:

The ball
is on the left!

Run 2:

The ball
is on the right!

Run 3:

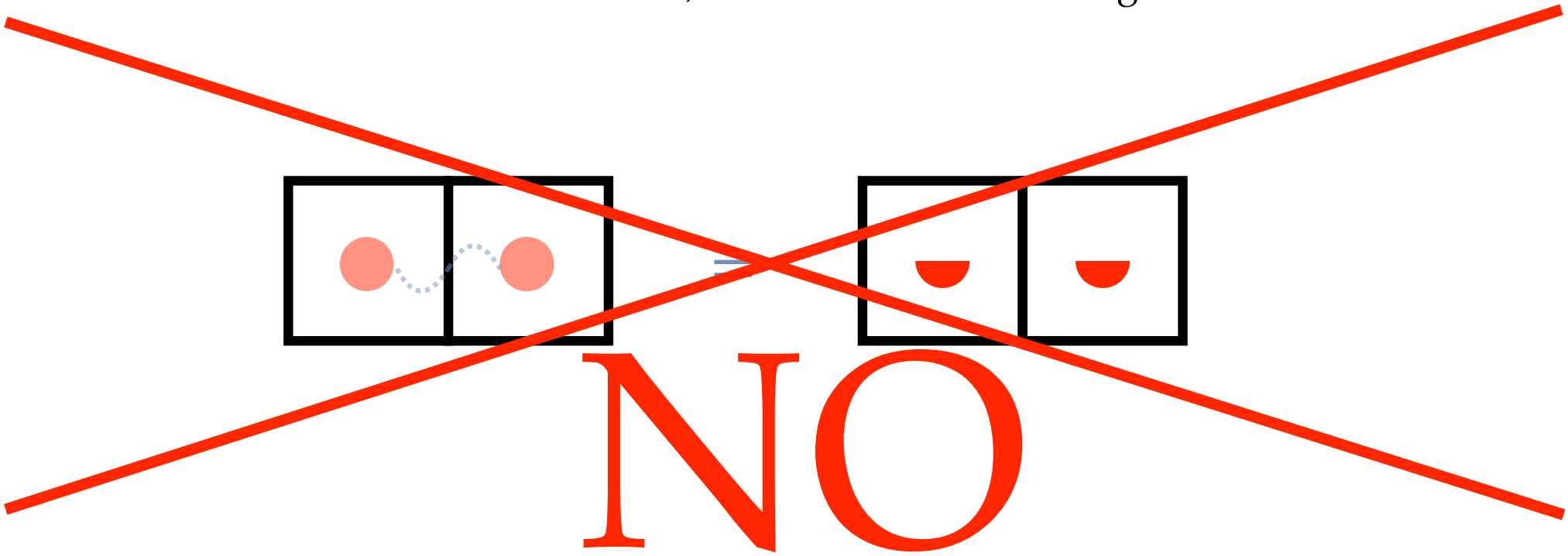
The ball
is on the right!

…and so on.

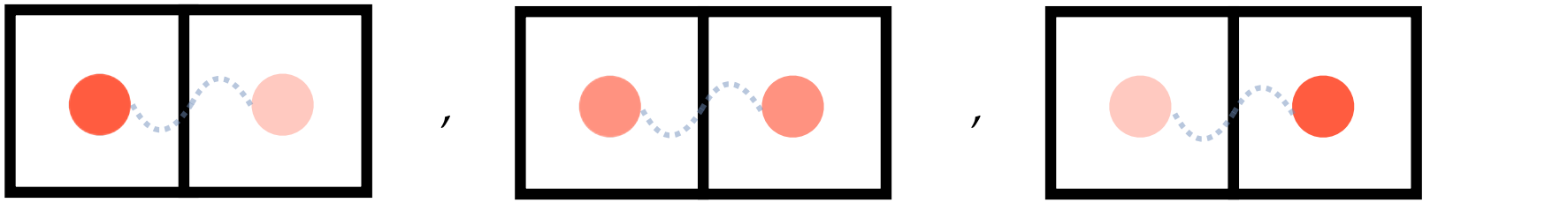
Hypothesis 1 “the ball is like a fluid” is false!

Every time we open the box, we only see the ball on the left or on the right.

We never see “half a ball on the left, and half a ball on the right”

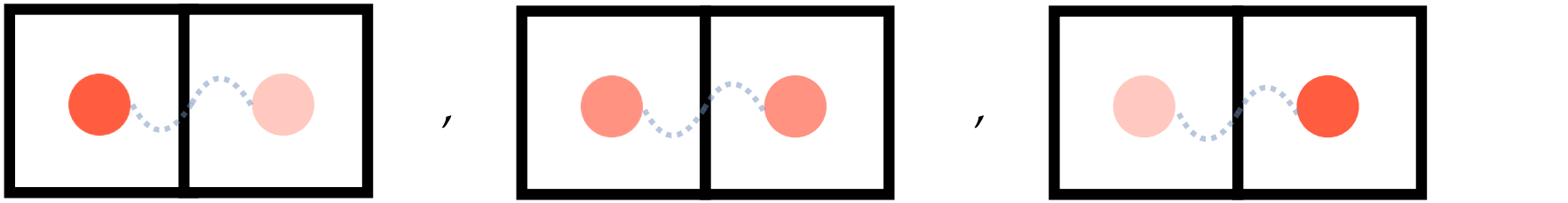


Our experiment shows that the superposition states



correspond to situations where the ball has some **probability** to be found on the left, and some probability to be found on the right.

For example:



75%	25%	50%	50%	25%	75%
left	right	left	right	left	right

Hypothesis 2:

the ball is either on the left or on the right,
but **we do not know where it is.**

This was Einstein's favorite interpretation.

At first sight, Hypothesis 2 looks OK,
as long as we do only one type of experiment:
opening the box and looking
on which side is the ball.

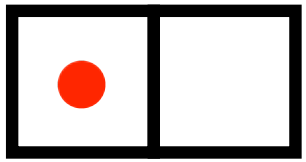
But, we find out that there are **other experiments** we can do.
For example, we can *"shake the box before opening it"*.

AN EXPERIMENT
THAT FALSIFIES HYPOTHESIS 2

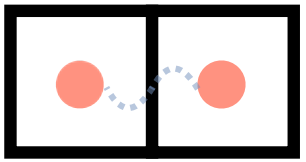
As it turns out, there is a **magic way of shaking the box.**

"Quantum dynamics" that evolves one state into another

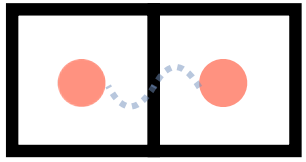
When we shake the box in this magic way, we turn



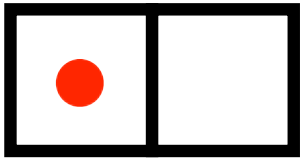
into



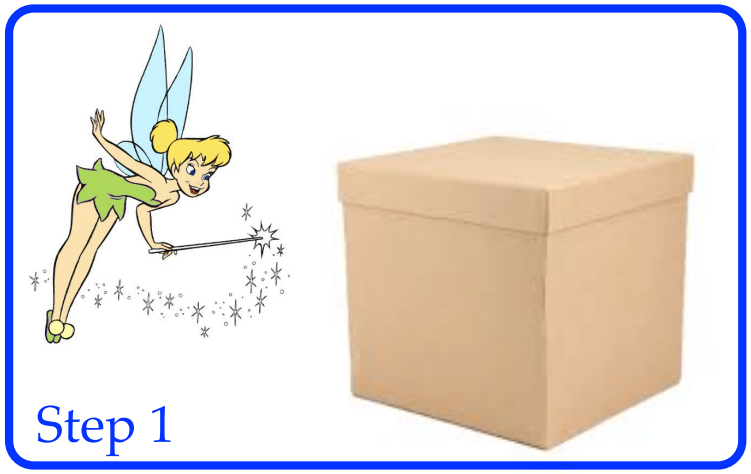
and

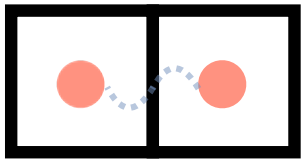


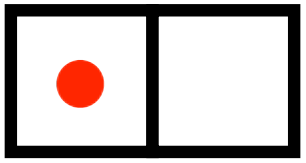
into



Let's perform an experiment: first shake the box, then open it.

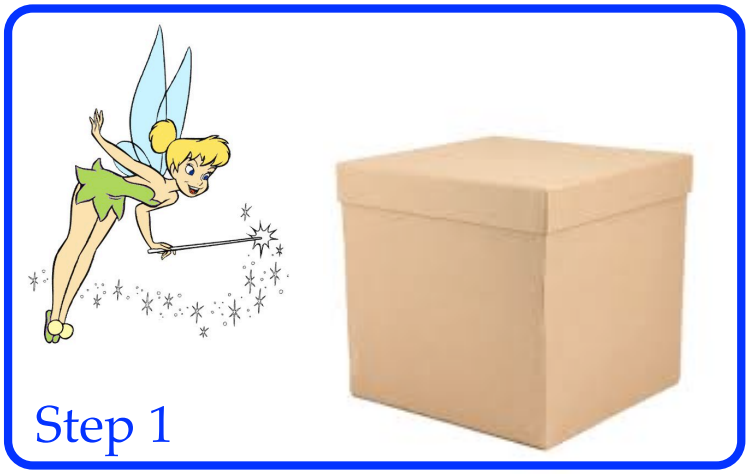


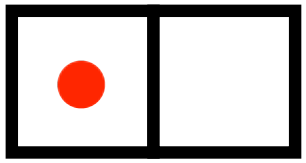
If initially the ball is in the state 

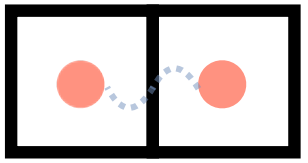
then the operation in Step 1 will change the ball's state into 

and in Step 2 we will **find the ball on the left side. Always!**

But what if the ball was initially on the left side?



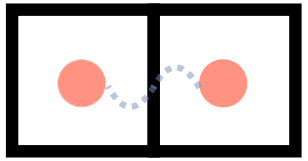
If the ball is in the state 

the operation in Step 1 will change the ball's state into 

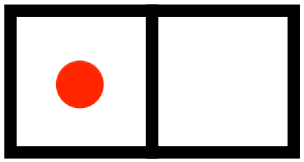
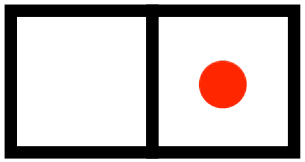
and in Step 2 we will have a **chance to find the ball on the right side.**

If at the start of the experiment the ball had a chance to be on the left side, then at the end we will have a chance to see it on the right side.

IN SHORT

Our experiment can distinguish whether (1) the ball was in the state 

or whether (2) the ball was

"in one of the two states  *and*  *with 50-50 probability."*

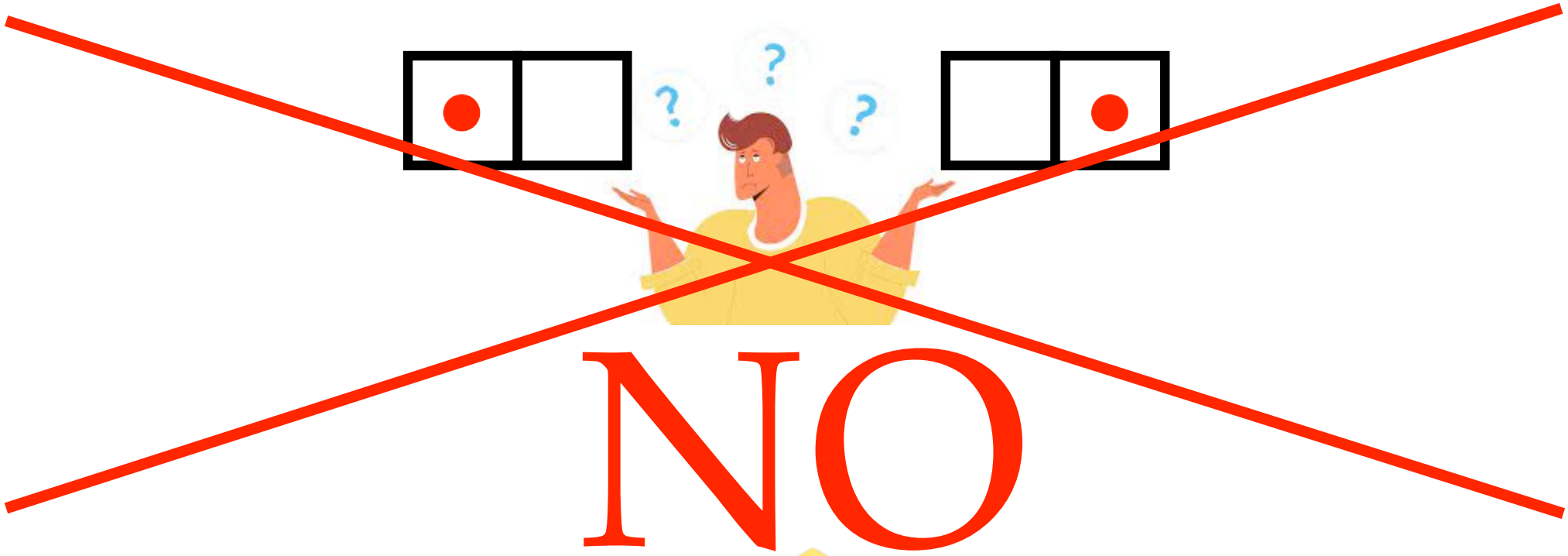
In Case (1), we always find the ball on the left.

In Case (2), we have a chance to find the ball on the right.

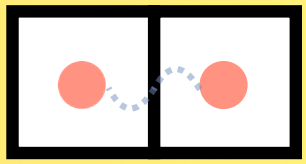
If we do the experiment many times
and always find the ball on the left,
then **we can confidently rule out Case (2).**

And this is indeed what we find in the experiments …
The ball is always found to be on the left.

Hypothesis 2 “we just don’t know where the ball is” is false!



NO

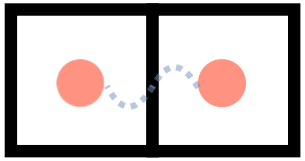
For a ball in the state 

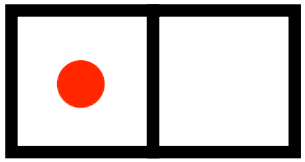
the position is **not defined** (at least, not in the conventional sense)

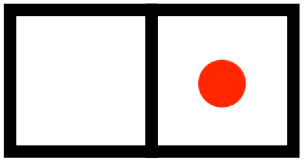
The “superposition states”
are genuinely a “new way to be.”

STATE COLLAPSE!

When we open the box,
we force the ball to be either on the left or on the right.

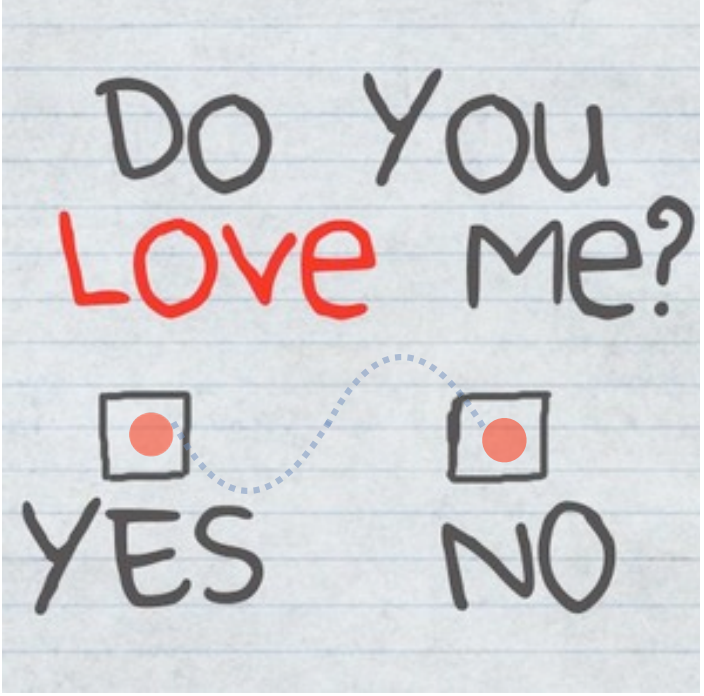
Our experiment transforms the superposition state 

into either the state 

or the state 

Experiments change the state of the system!
The mere act of observing a system
forces it state to jump (or "collapse")
to one of two possible alternative states.

A ROMANTIC ANALOGY

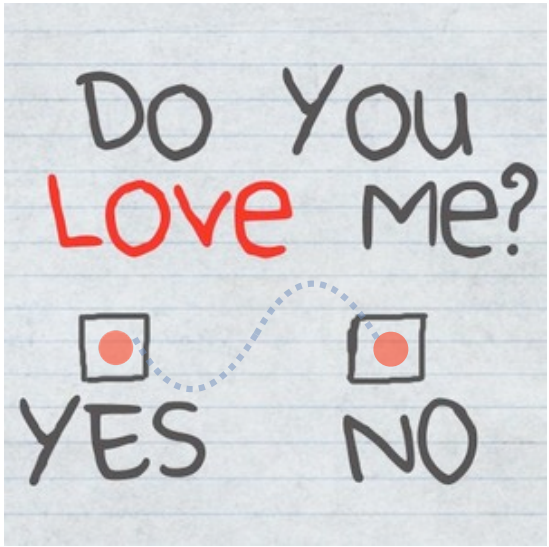


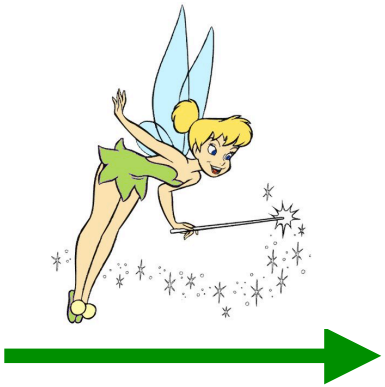
To give an intuition of what a "superposition state" is,
we can try to find some analogies.
For example, whether someone loves you or not.

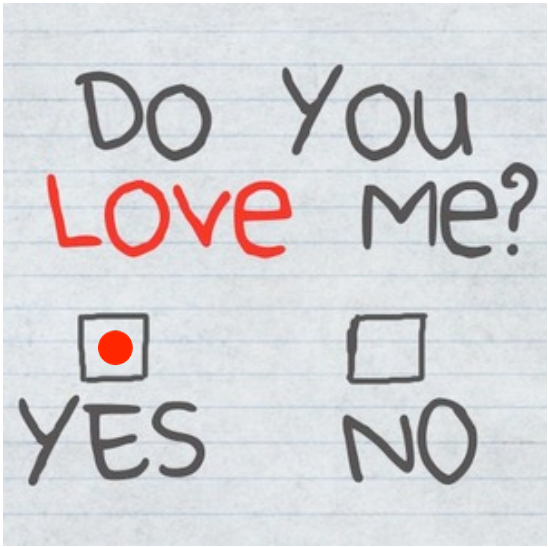
Maybe that person genuinely does not know yet.

When you ask for a decision ("open the box"),
you have some chance to get a "YES" and some chance to get a "NO."

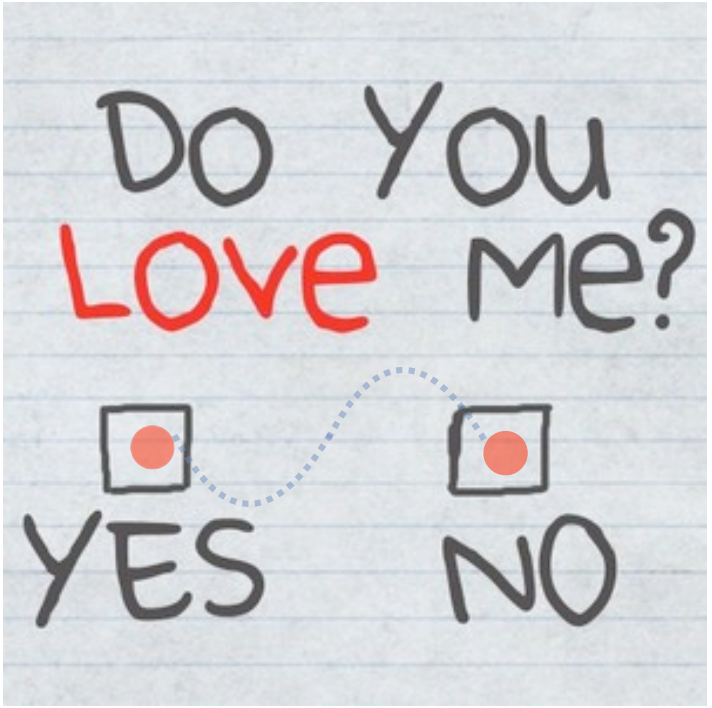
…but maybe there is some magic operation you can do before opening the box,
that turns the decision into a "YES" ;-)





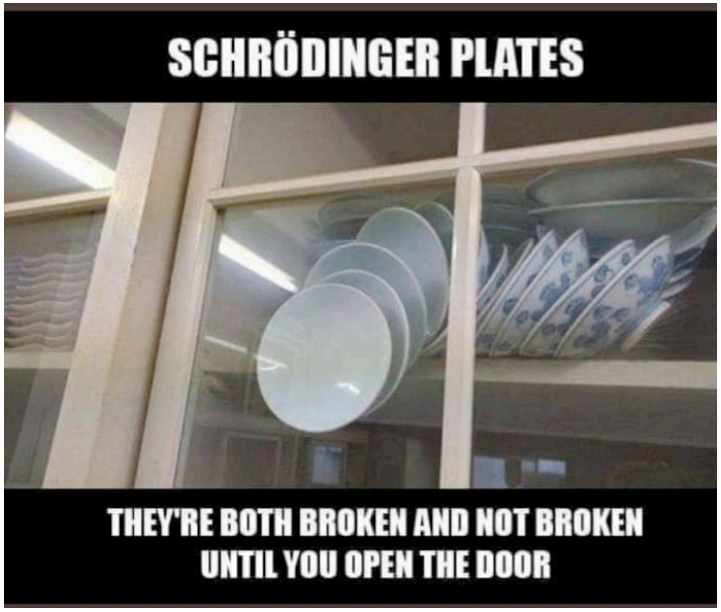


GOOD ANALOGY



GOOD ANALOGY?

The plates are in a classical state of “not broken” and will be transitioned to “broken” once you open the door.



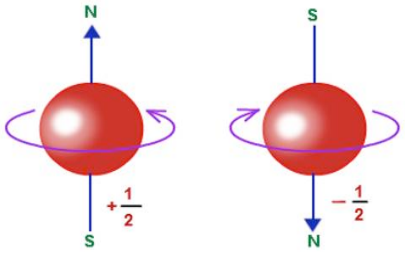
From Internet

QUBITS

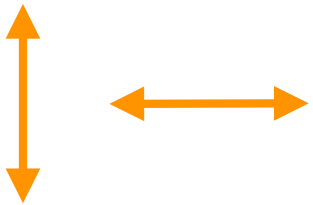
QUBITS

At the microscopic scale, physical systems behave like the magic balls of our tale.

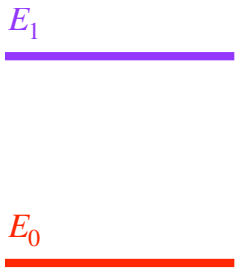
Every system that can be in two alternative states
can also be in infinitely many other states, called "quantum superpositions."



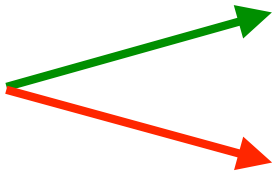
Spin of an electron



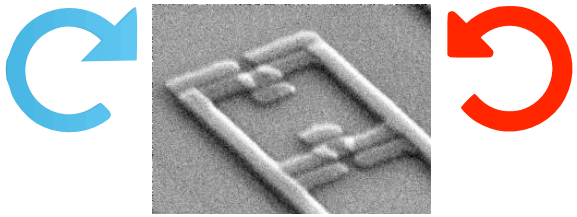
Polarization of a photon
(particle of light)



Two energy levels of an atom

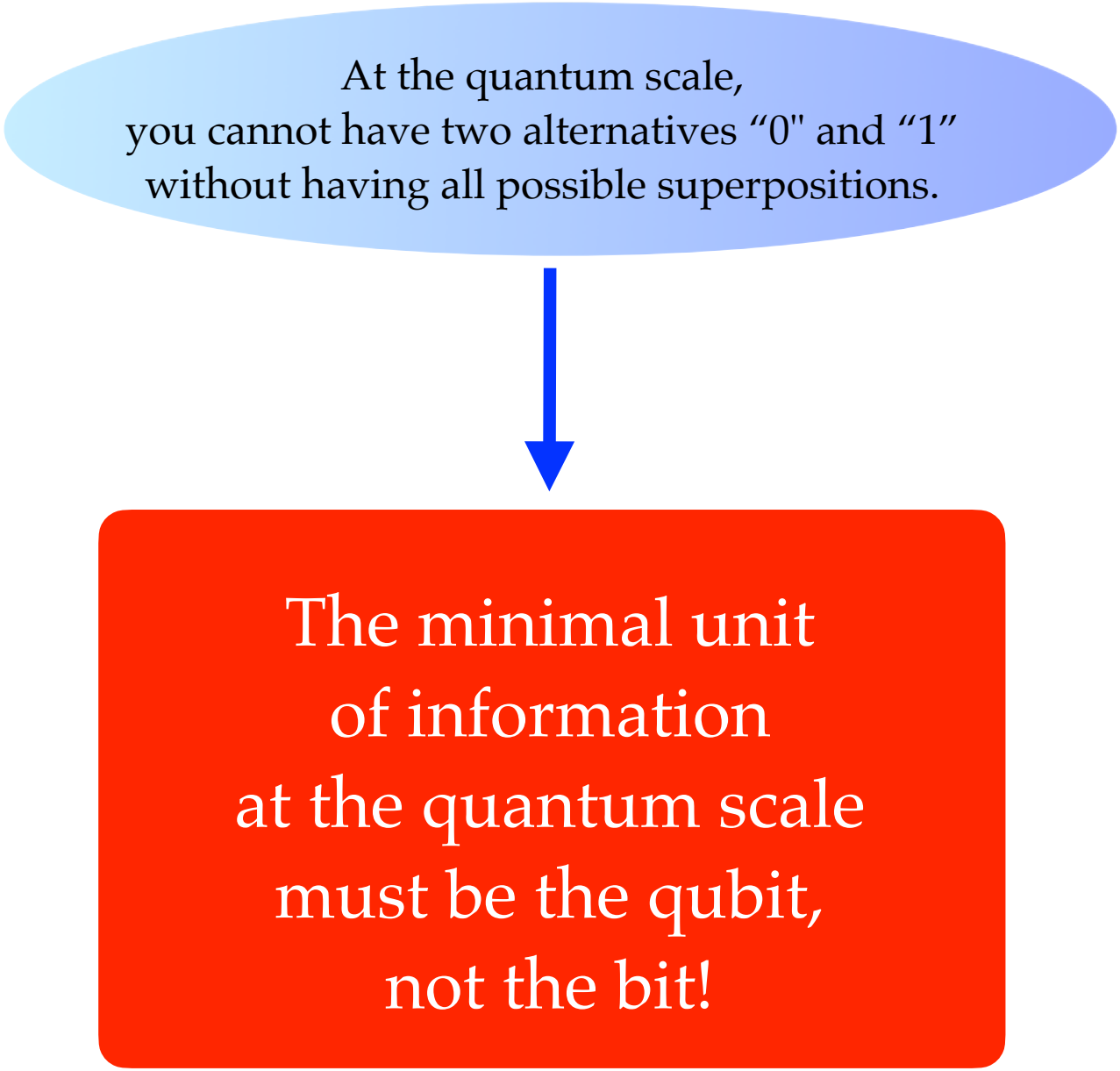


Two paths a particle can take



Clockwise and anti-clockwise currents
in a superconducting circuit.
Image from Wikipedia, Flux qubit.

Each of these systems can serve as as a **quantum bit (qubit).**


At the quantum scale,
you cannot have two alternatives “0" and “1”
without having all possible superpositions.
The minimal unit
of information
at the quantum scale
must be the qubit,
not the bit!

UNIQUENESS OF QUANTUM INFORMATION PROCESSING

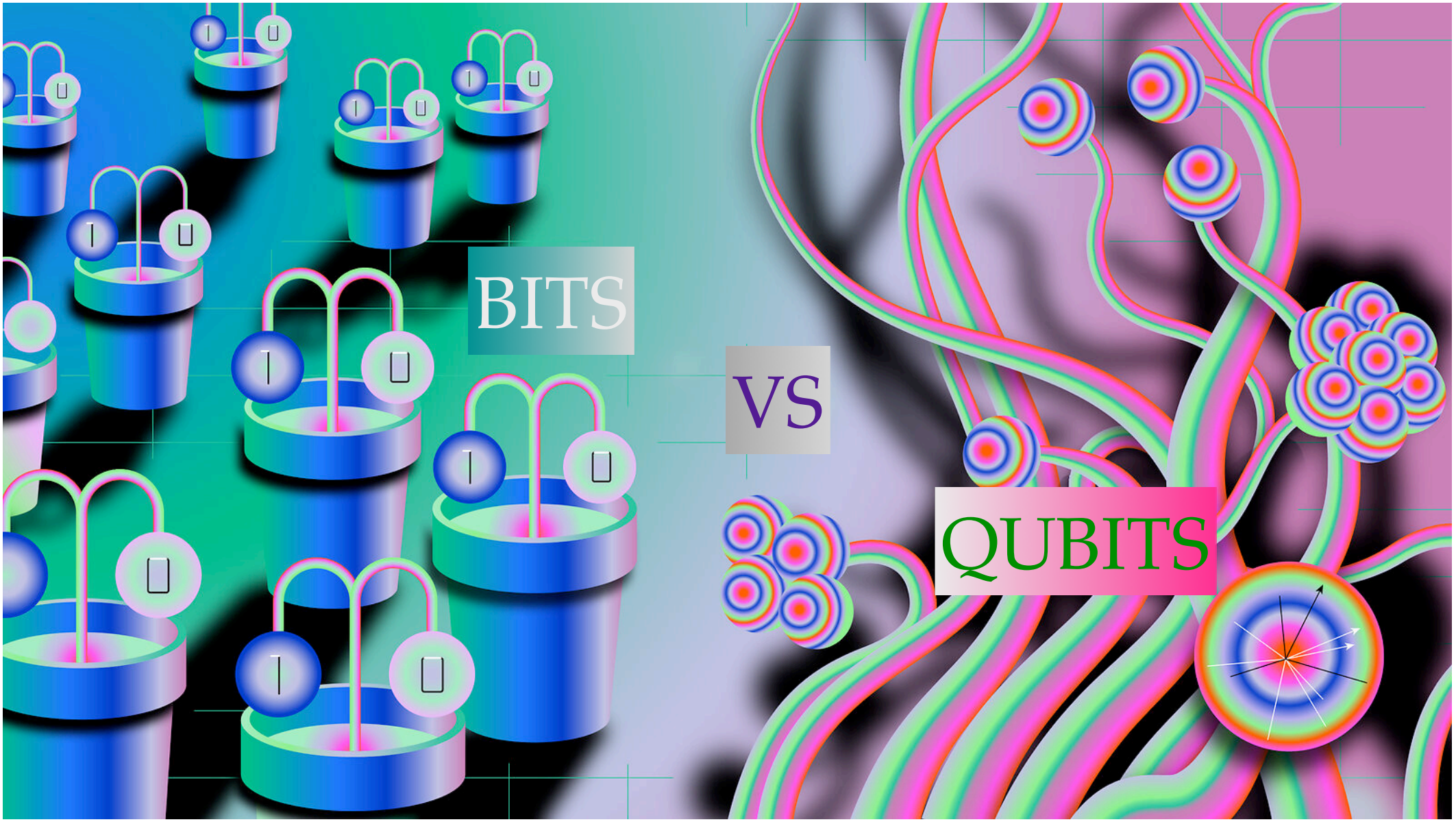


Illustration by Sandbox Studio, Chicago with Ana Kova

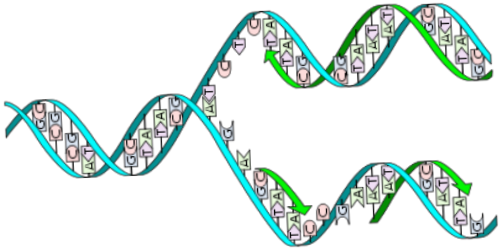
DIFFERENCE #1:

THE NO CLONING THEOREM

Clones of Dolly the sheep, photo from www.sciencenews.org

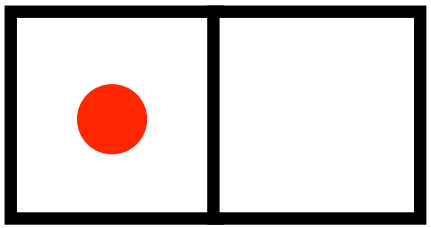
CAN WE COPY THE STATE OF A QUBIT?

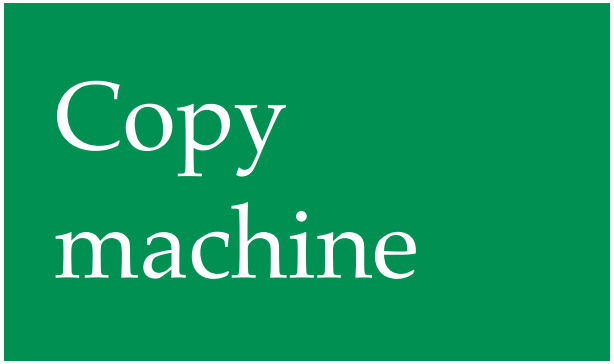
In the everyday classical world, information can always be copied.
No physical principle forbids copying.

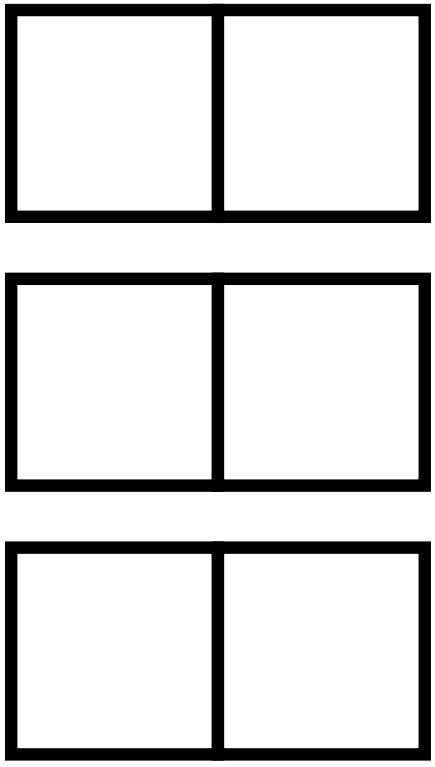


Can we also copy qubits?

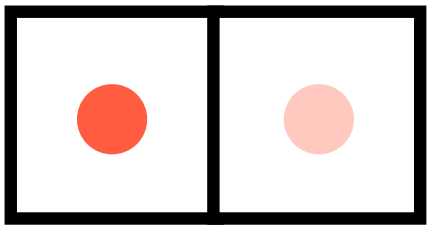
To approach this question, let us see how copying works in the classical world.





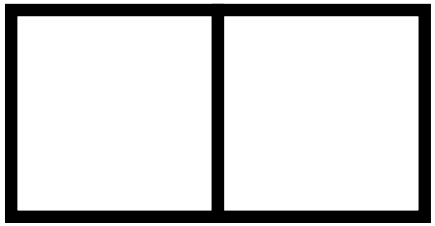


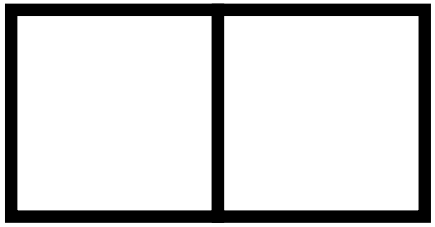
CAN WE BUILD A QUANTUM COPY MACHINE?

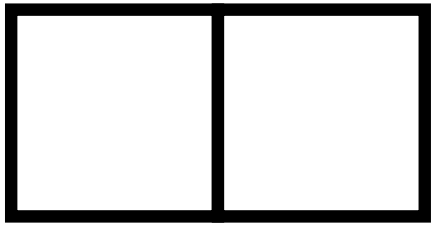


A quantum copy machine should be able to copy arbitrary superposition states.

Quantum copy machine







THE NO-CLONING THEOREM

letters to nature

Nature **299**, 802 - 803 (28 October 1982); doi:10.1038/299802a0

A single quantum cannot be cloned

W. K. WOOTTERS[*1] & W. H. ZUREK[2]

[1]Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712, USA
[2]Theoretical Astrophysics 130–33, California Institute of Technology, Pasadena, California 91125, USA
[*]Present address: Department of Physics and Astronomy, Williams College, Williamstown, Massachusetts 01267, USA.

W. K. Wootters W. H. Zurek

NO

Quantum copy machine

Quantum information
cannot
be copied!

DO YOU KNOW …

In 1982, Nick Herbert argued that one can communicate information faster than the speed of light, contradicting Einstein's theory of relativity.

Foundations of Physics, Vol. 12, No. 12, 1982

FLASH[1]—A Superluminal Communicator Based Upon a New Kind of Quantum Measurement

Nick Herbert[2]

Received January 15, 1982

Herbert's proposal violates the no-cloning theorem and cannot be realized.
But it facilitated the discovery of the no-cloning theorem later in the same year.

QUANTUM MONEY

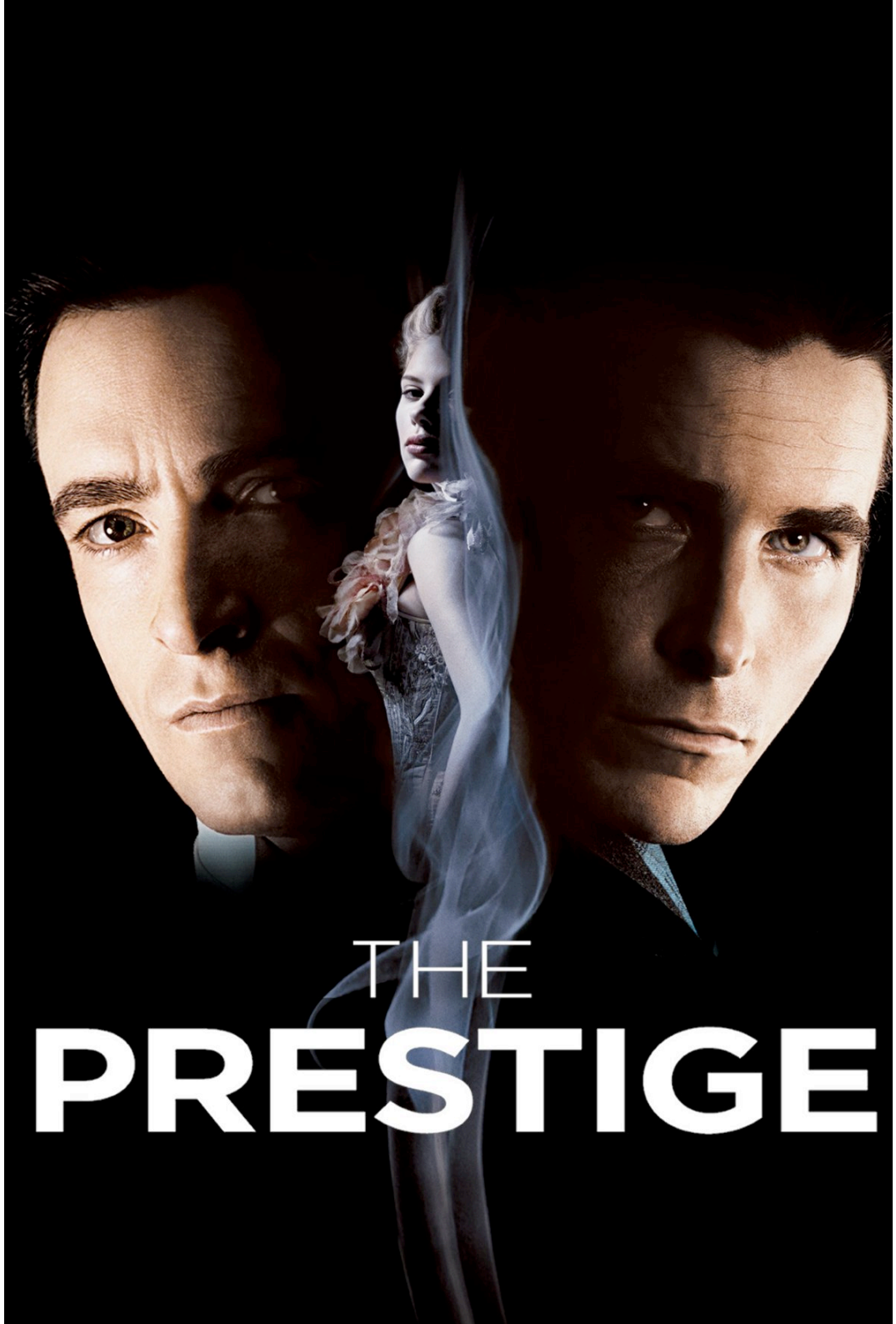
The idea (Stephen Wiesner ~1970; published 1983):
Since quantum states cannot be copied, we can make "unforgeable banknotes".

MOVIE ANALOGY (SPOILER ALERT)

In the 2006 movie "The Prestige"
by Christopher Nolan,
one of the characters has a machine
that can make copies of human beings.

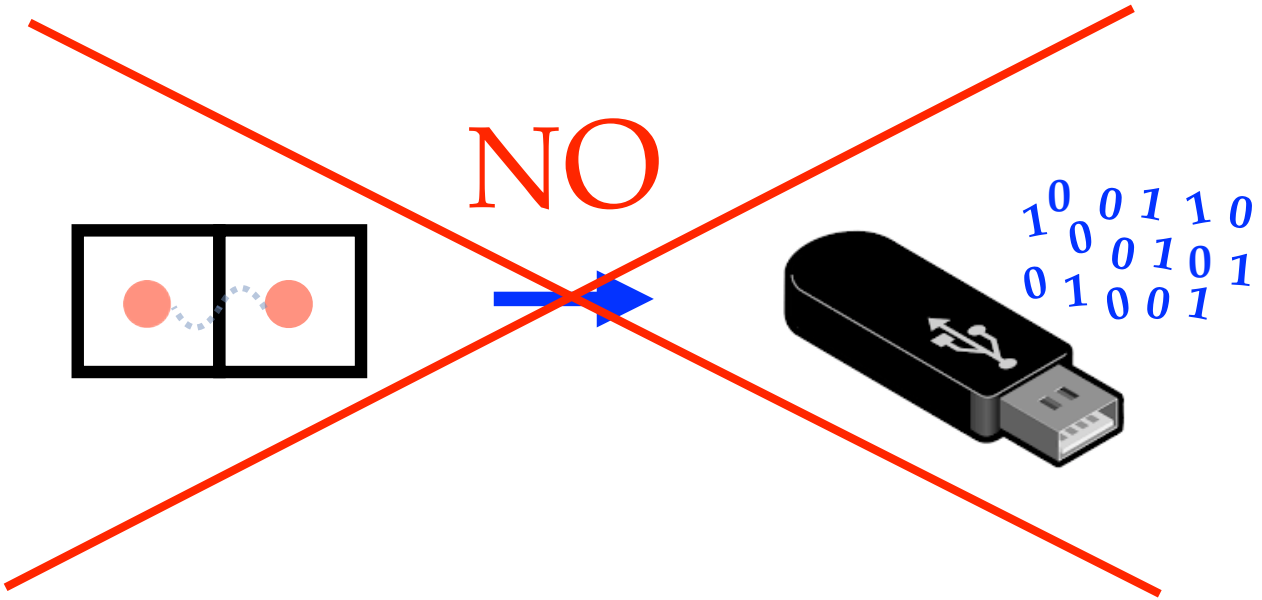
…but every time the machine is used,
a copy must be destroyed.

Idea: if you have seen the movie,
it may be fun to discuss the
similarities and differences between
the no-cloning theorem and the
situation in the movie.



DIFFERENCE #2:

QUBITS CANNOT BE STORED INTO BITS

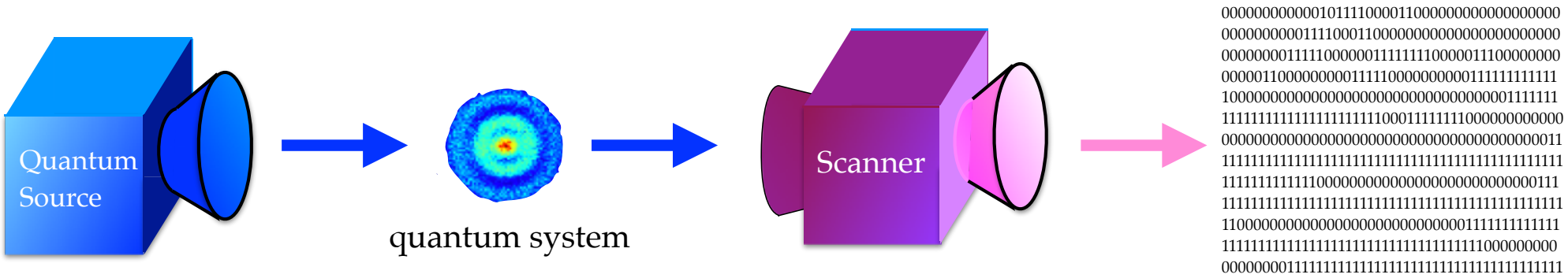


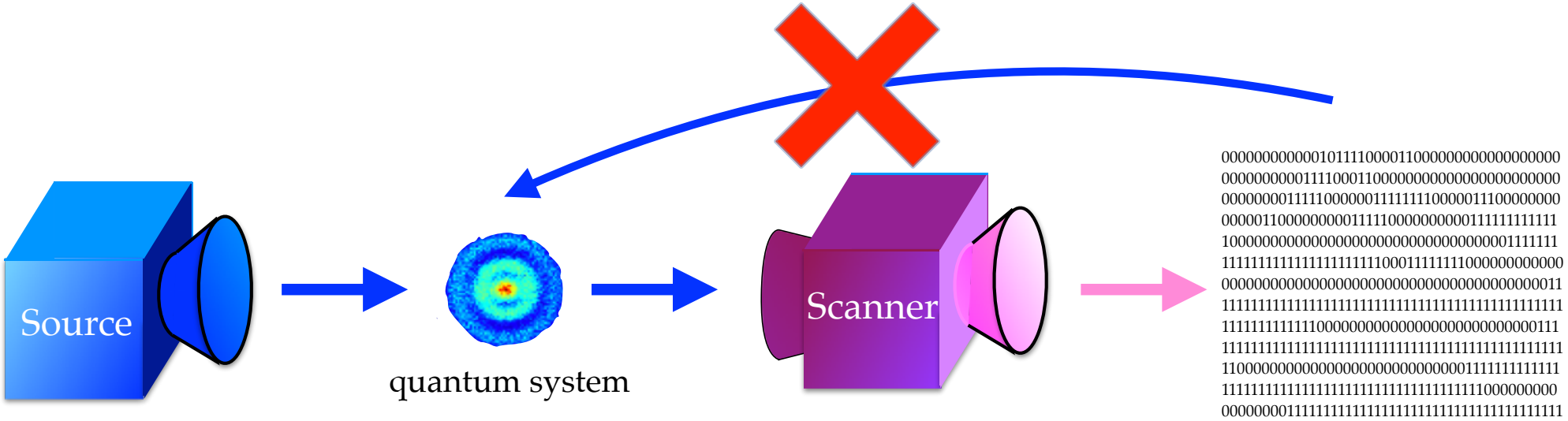
CAN WE CONVERT QUBITS INTO BITS?

Imagine that a source produces a quantum system, e.g. as an atom,

and that **we do not know a priori the state of the system.**

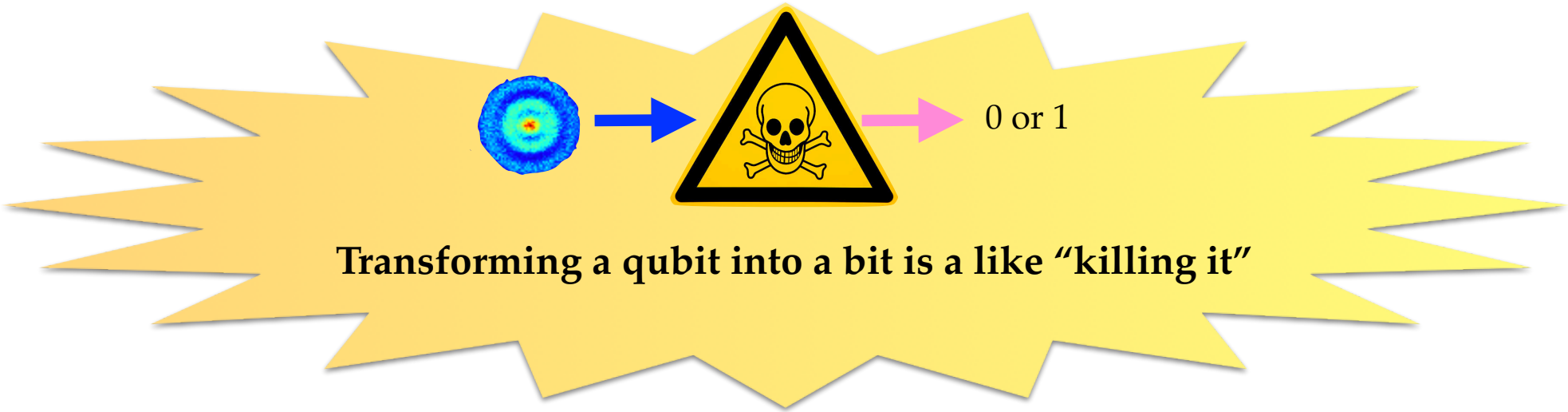
Can we scan the state of the system and store it into bits?





Answer. We *can* convert quantum information into bits,
but this conversion is **irreversible:**

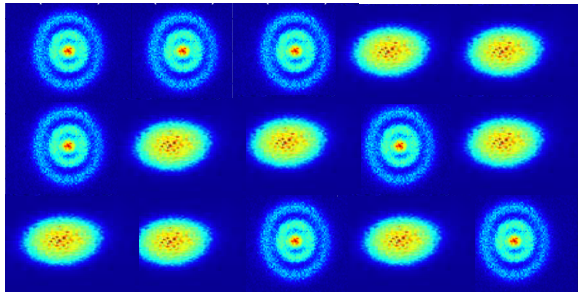
the bits obtained by scanning a quantum system are not enough to rebuild the original state of the system.



Qubits
cannot
be faithfully
stored
as bits.

QUANTUM INFORMATION!

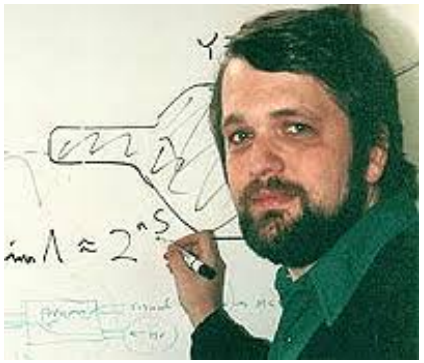
Quantum systems carry **a new type of information,** which cannot be faithfully converted into the "classical information" introduced by Shannon.



We call this new type of information **quantum information.**

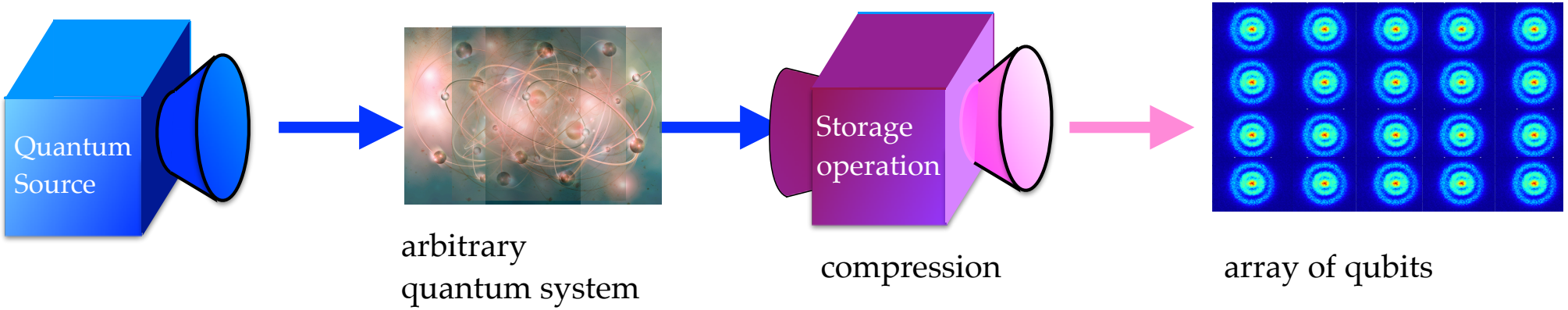
HOW
TO
MEASURE
QUANTUM INFORMATION

EVERY PHYSICAL SYSTEM CAN BE CONVERTED INTO QUBITS



Benjamin Schumacher

In 1995, Benjamin Schumacher showed that the **state of every quantum system can be faithfully stored into qubits.**



arbitrary quantum system

compression

array of qubits

For what we know, every physical system is made of quantum particles.
Hence, Schumacher tells us that, in principle, we can faithfully store every physical system into qubits!

Qubits
are the fundamental units of measurement
for quantum information.

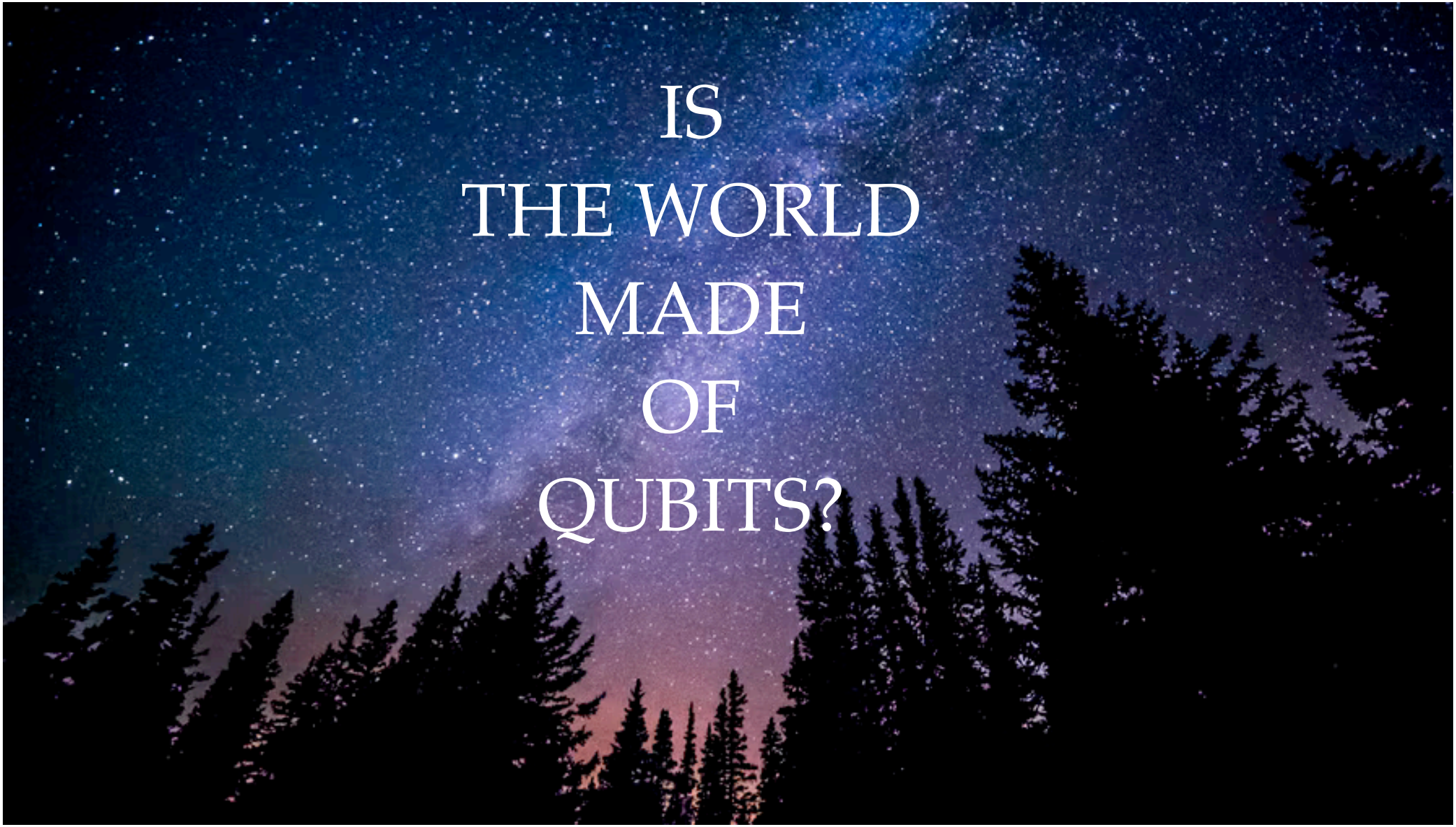


Photo of the Milky Way, by Ryan Hutton

IT FROM QUBIT

Maybe the whole **universe** is made of qubits?

Maybe the laws of physics are the basic rules for processing quantum information?

Image from HPC Wire

nature physics

COMMENTARY

Is information the key?

GILLES BRASSARD

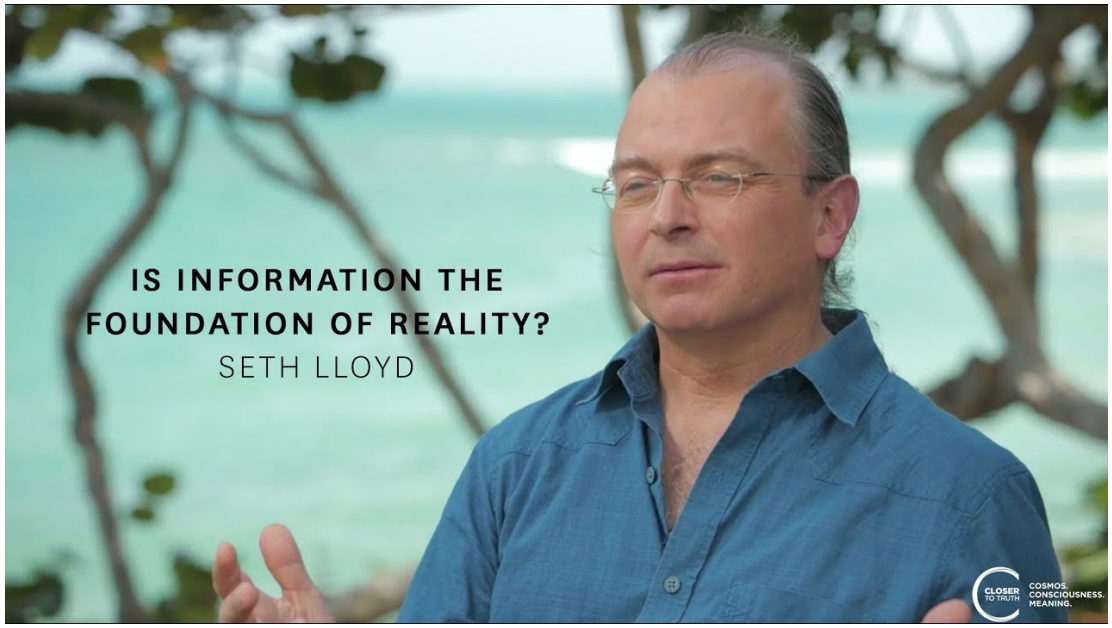
is in the Département d'informatique et de recherche opérationnelle, Université de Montréal, Québec H3C 3J7, Canada.

e-mail: brassard@iro.umontreal.ca

Quantum information science has brought us novel means of calculation and communication. But could its theorems hold the key to understanding the quantum world at its most profound level? Do the truly fundamental laws of nature concern — not waves and particles — but information?

Gilles Brassard,
Fellow of the Royal Society

For more discussion on this idea, see:
Seth Lloyd, *Is information the foundation of reality?*



Also available on the course Moodle page.

SUMMARY
OF
TODAY'S LECTURE

IN A NUTSHELL

- **End of Moore's law:** computer technology is reaching the atomic scale, dominated by quantum physics.

- **Qubits:** the fundamental unit of information at the quantum scale, not only 0 and 1, but also an infinite number of other states, called "superpositions"

- **Quantum information:** a new type of information that cannot be reduced to bits
  No-cloning theorem: quantum information cannot be copied.

- **Quantum information processing:**
  "Magic shaking the box" and
  "opening the box" (making measurements)

- **It from Qubit:** the idea that quantum information is at the foundation of nature.

NEXT TUTORIAL: LET'S TALK QUANTUM!

The next tutorial will help you **digest the new ideas in today's lecture.**

We will play a game: pick two alternatives situations, like "smiley face/sad face" and pretend that these two alternatives form a qubit.

We will look for good analogies in everyday life, art, and fiction.