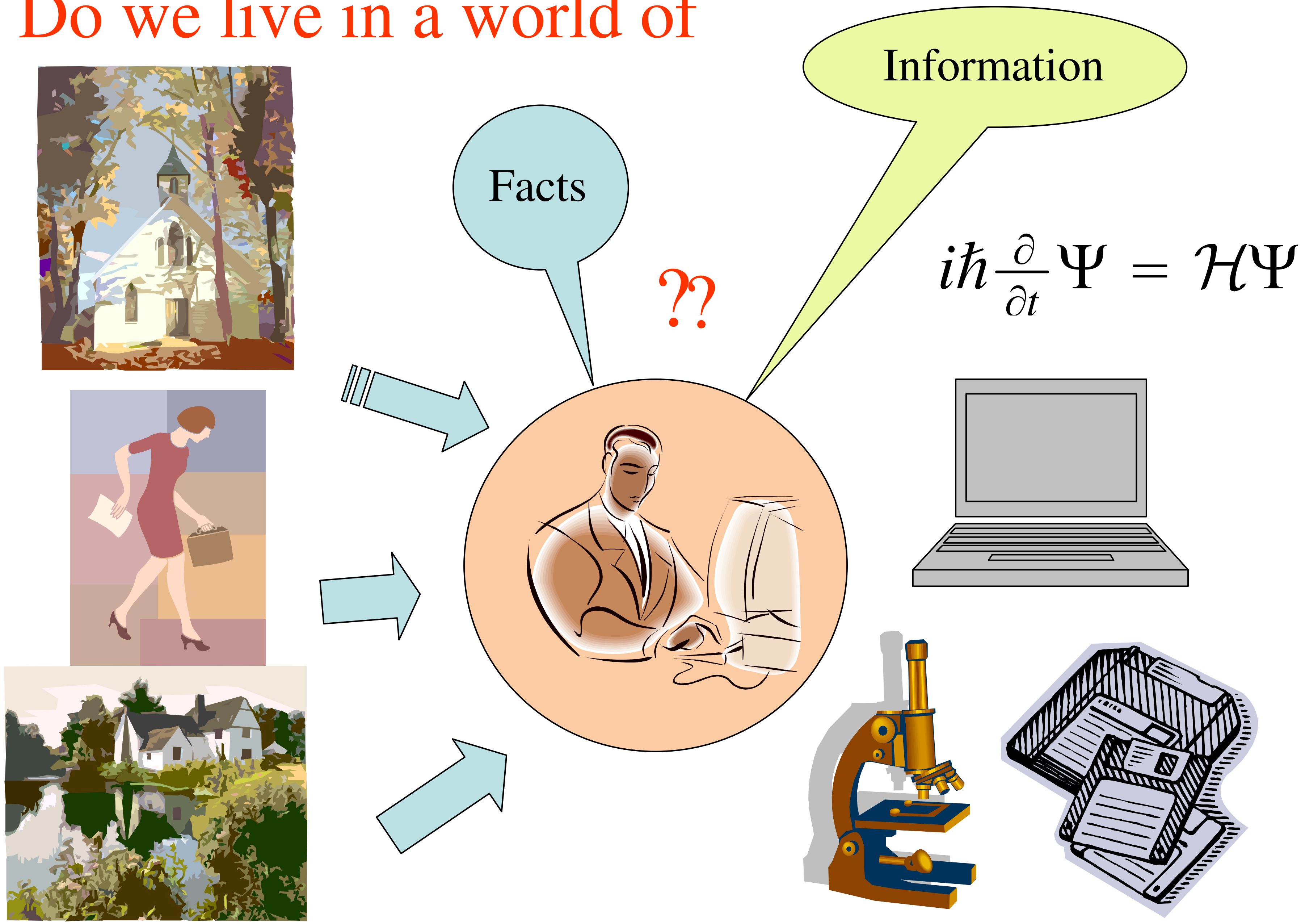
Do we live in a world of facts or information?

What information anyway?

Do we live in a world of



Knowledge and information

- The classical *World* consists of *objects* and their *observable properties.*
- We describe the World in terms of concepts created by humans.
- We communicate our knowledge by using arbitrary symbols we have agreed on.
- Such communication is part of our every-day life.
- Technology is based on efficient communication.

Salvador Dali

Beach and boat

Reclining philosopher

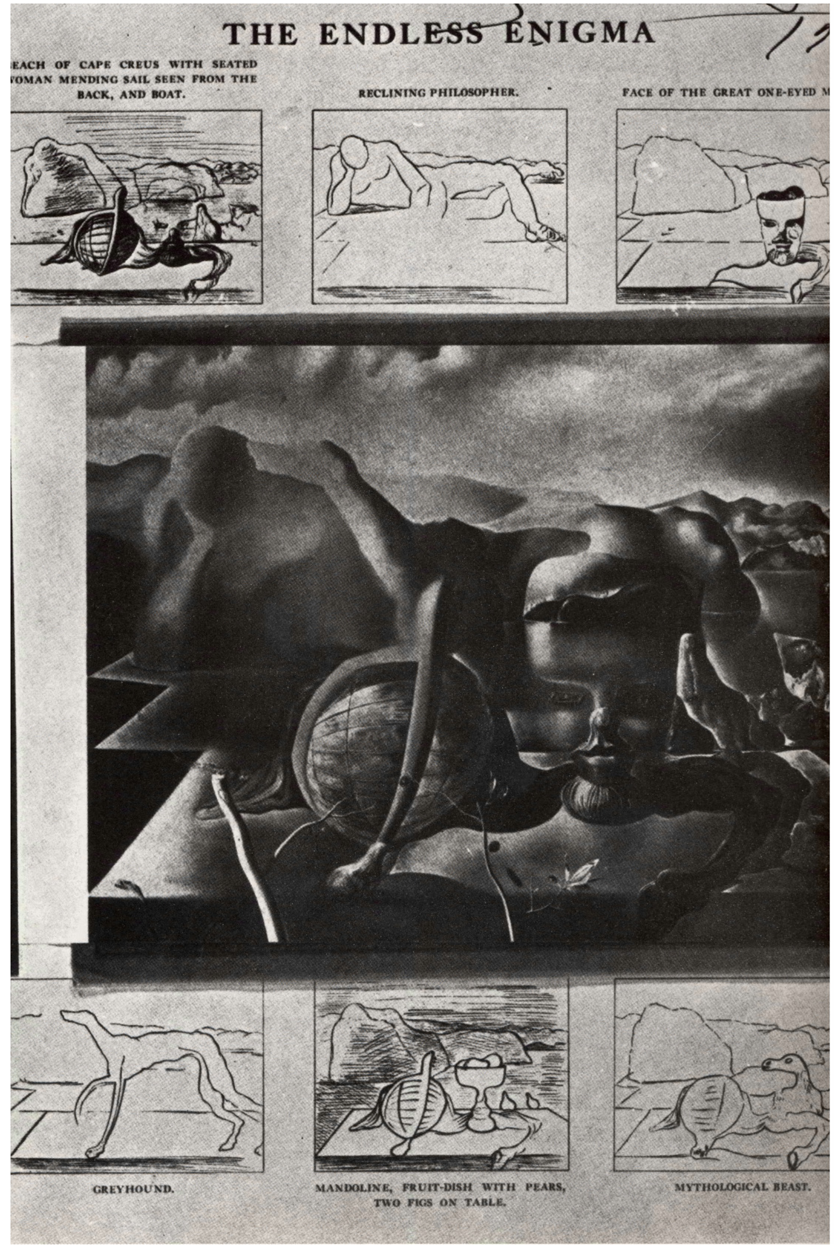
Big one-eyed Moron

Concepts structure the world.

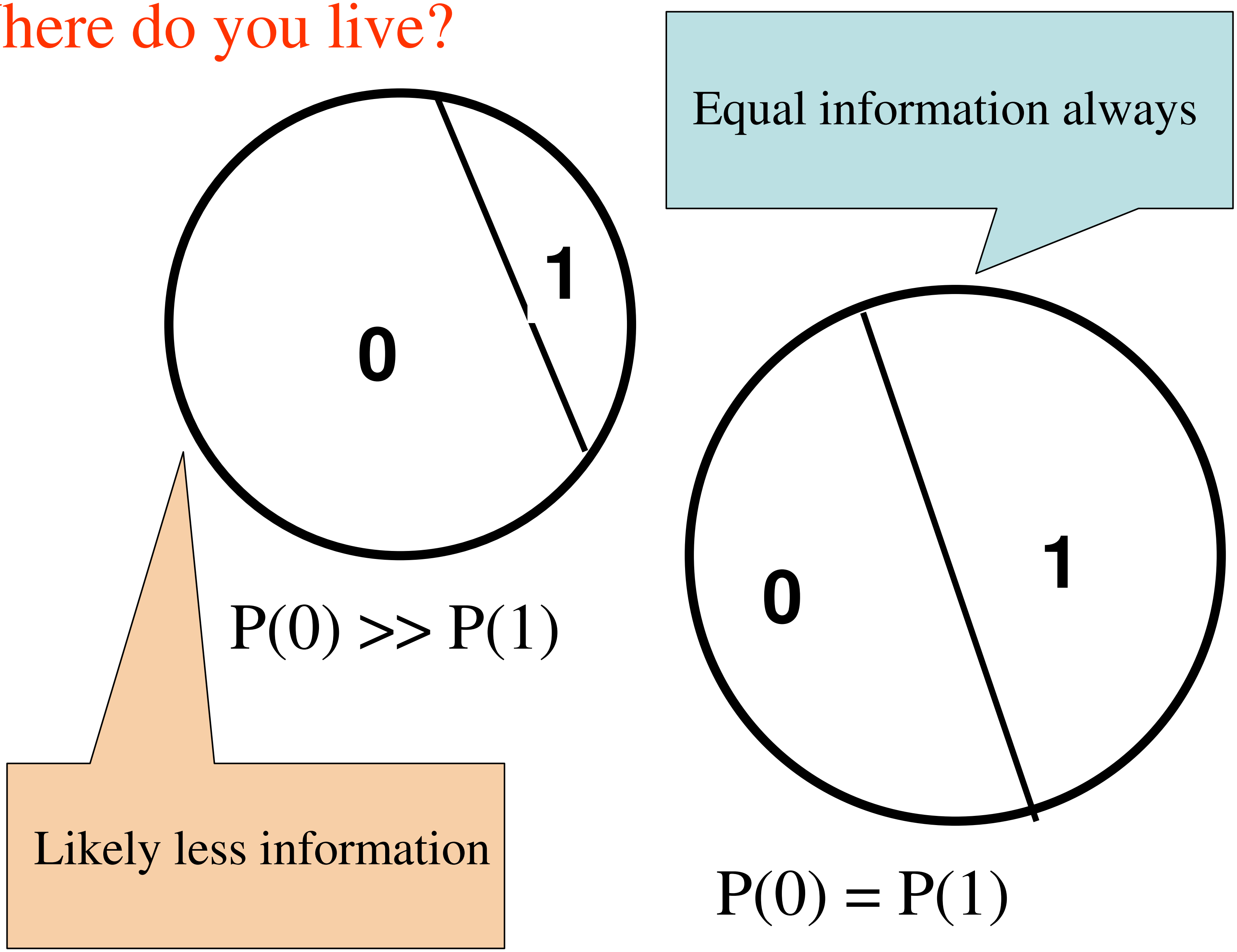
Gray-hound

Mandolin and fruits

Mythic Beast



Where do you live?



Theory of *Information*

- Theory developed by
  Claude Shannon, (1916 - 2001)

- Shannon, C. E. and Weaver, W.
  Mathematical Theory of Communication. (1963).

- Very formal but highly useful.

- Relation to thermophysics through *entropy*.

Measure of classical information

The events #1 and #2 occur with probabilities

$$\frac{1}{p} \text{ and} \frac{1}{q}.$$

The probability that events #1 and #2 occur is $p \times q$, what is the combined information?

$$\log\left(\frac{1}{pq}\right) = \log\left(\frac{1}{p}\right) + \log\left(\frac{1}{q}\right)$$

$$\text{Information} = -\ log(\text{probability})$$

Communication is based on an alphabet:

$\{00.01, 10, 11\} \equiv \{0, 1, 2, 3\}$

A text consists of the following distribution:

$$\begin{array}{lll} 00 & 50\ \% & 0 \\ 01 & 34\ \% & 10 \\ 10 & 8\ \% & 110 \\ 11 & 8\ \% & 111 \end{array} \quad \Rightarrow$$

Average word length

$0.5 \times 1 + 0.34 \times 2 + 0.08 \times 3 + 0.08 \times 3 = 1.66 < 2$

Compression of messages.

Shannon derived the maximum for this.

Heroes of Quantum Mechanics

Louis de Broglie
1924

P.A.M. Dirac

1926

Erwin Schrödinger
1926

Werner Heisenberg
1925

Quantum Facts

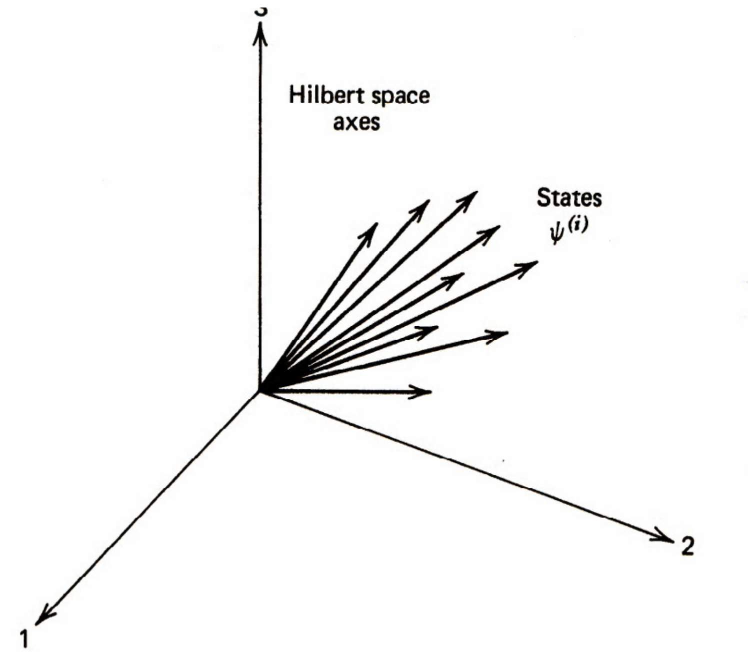
In Quantum Theory the state of a system is represented by a **vector**:

$\vec{\Psi} = \vec{\mathbf{a}}_1 + \vec{\mathbf{a}}_2 + \ldots$

If $\vec{\mathbf{a}}_1$ can happen then also $\vec{\mathbf{a}}_2$ can happen.

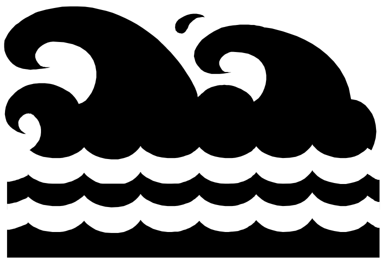
Classically these are exclusive.

Example: A system can be both a wave and a particle



Particle

Wave



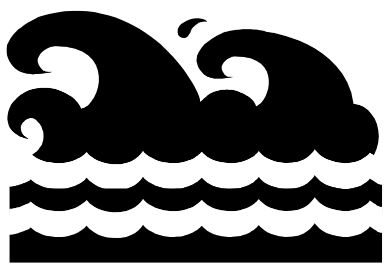
Physical Object

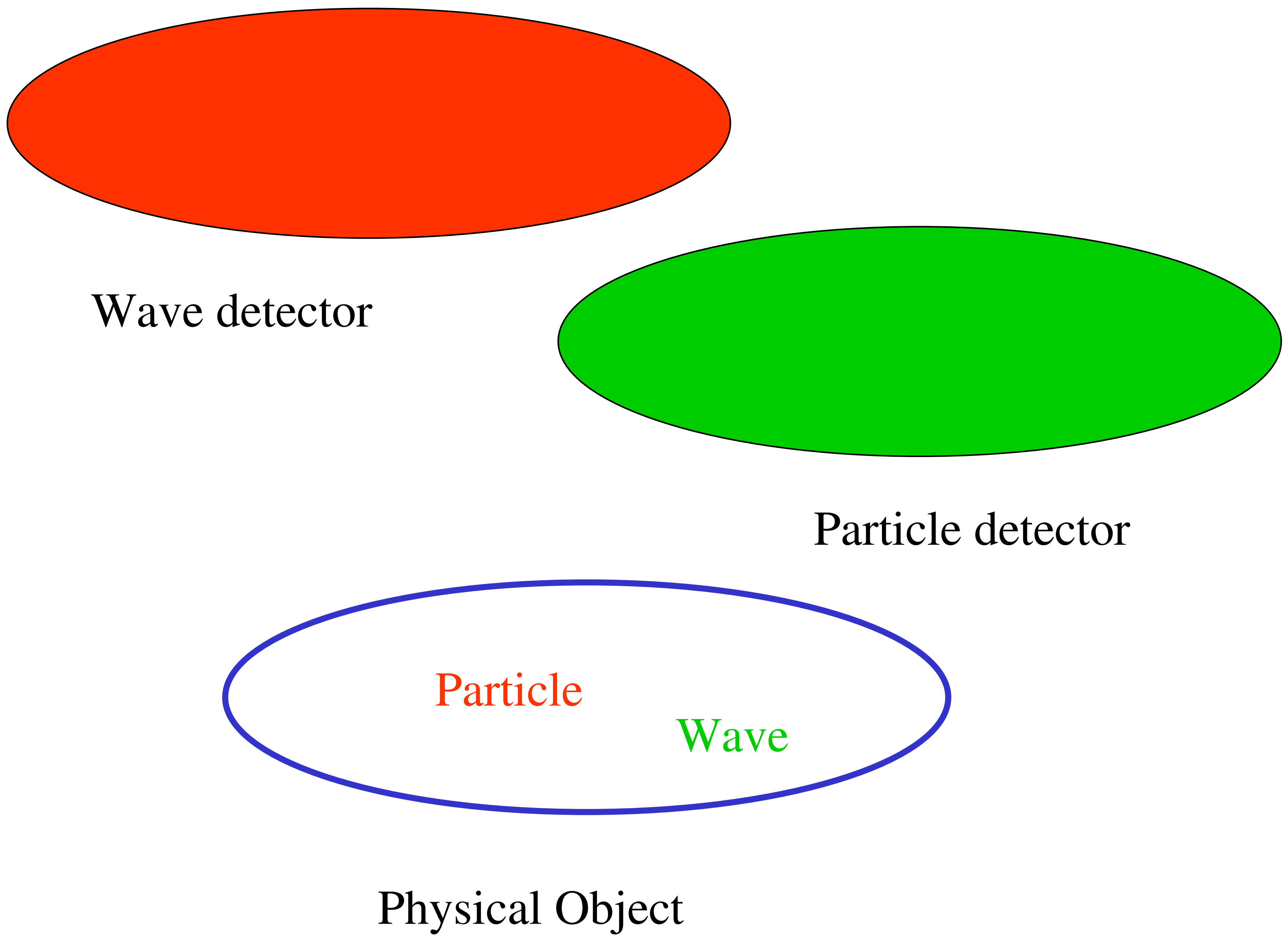
Cannot be observed

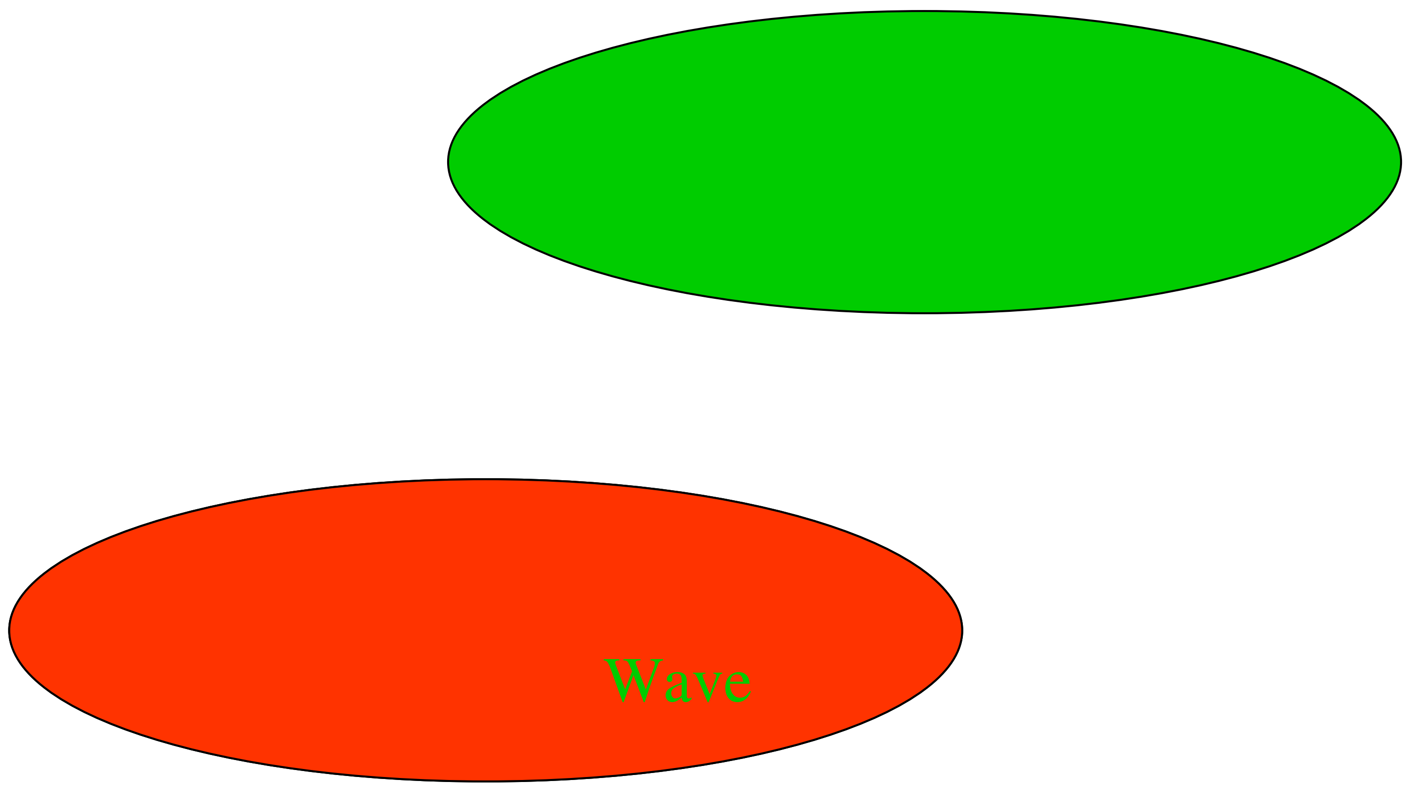
Particle

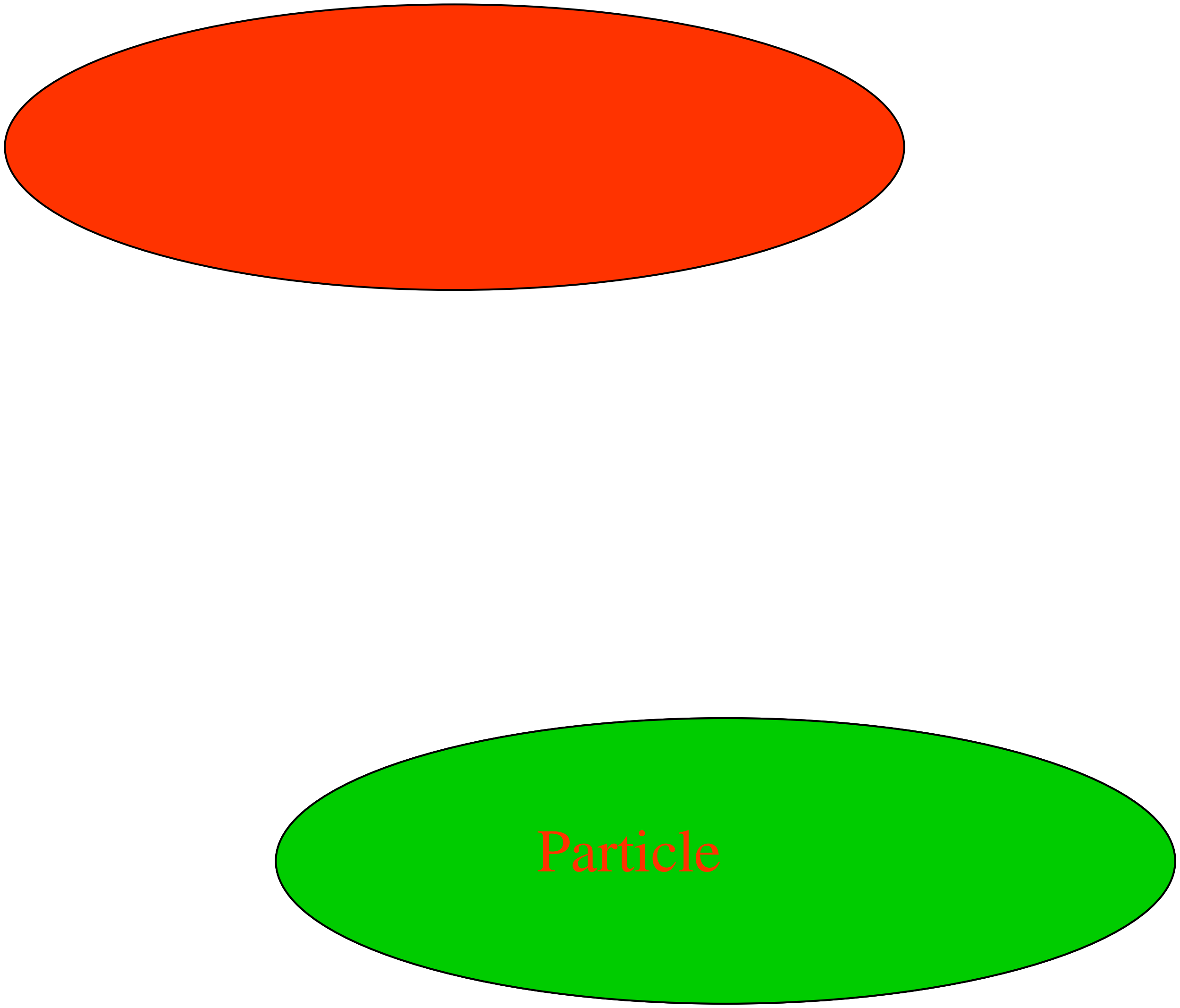
Wave

Physical Object




Wave detector
Particle detector
Particle
Wave
Physical Object


Wave

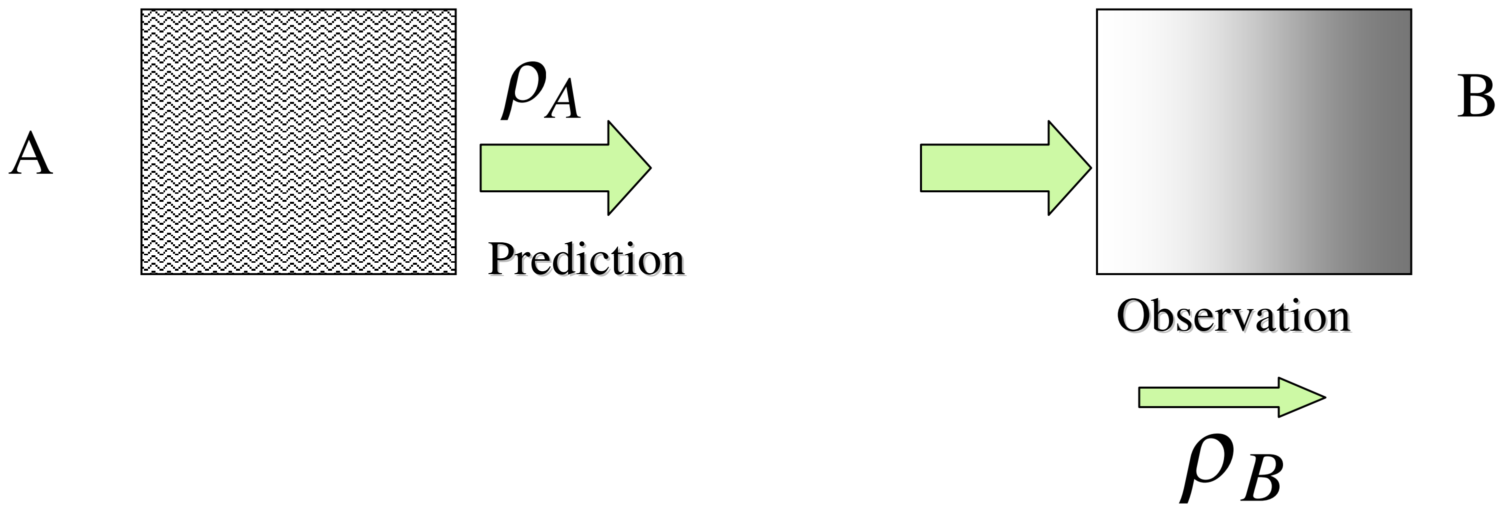

Particle

Whose Quantum Information?

★

If we have different information, whose state is ***real*** ?

- A prepares an ensemble of systems in a known state.
- B performs measurements on a finite sample, and assigns a different density matrix.



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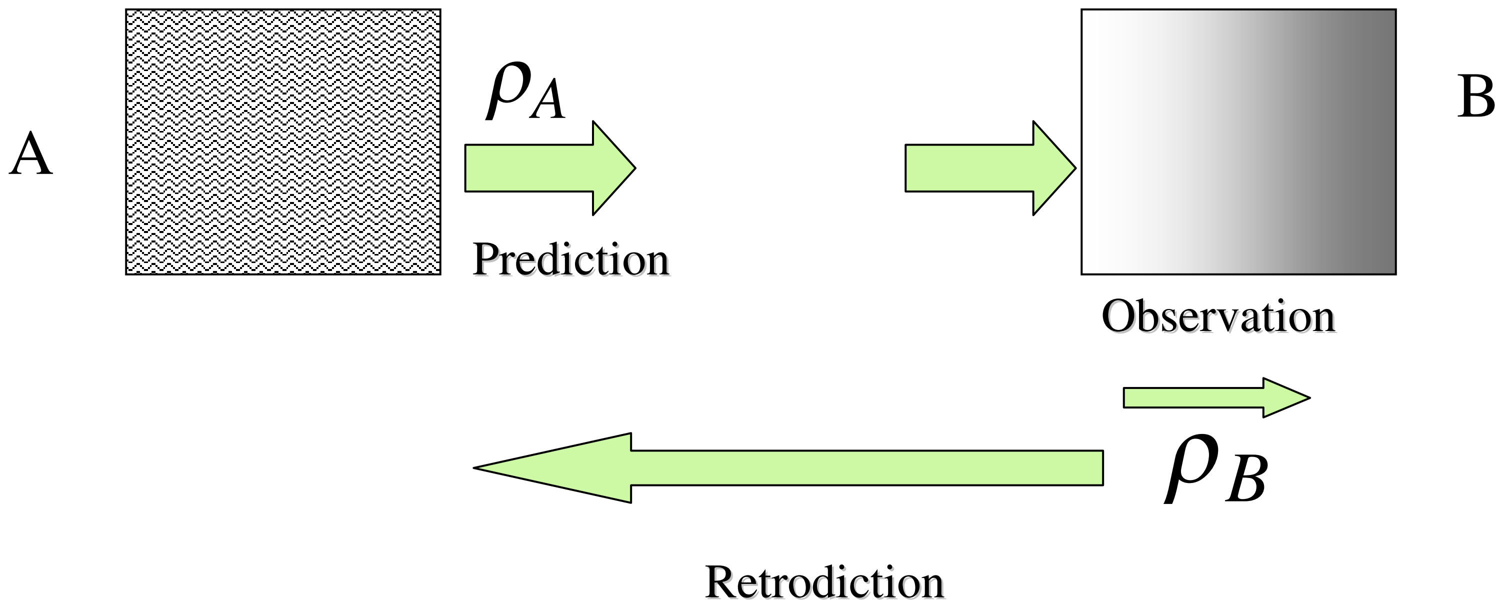

Which density matrix is ***an element of reality*** ?

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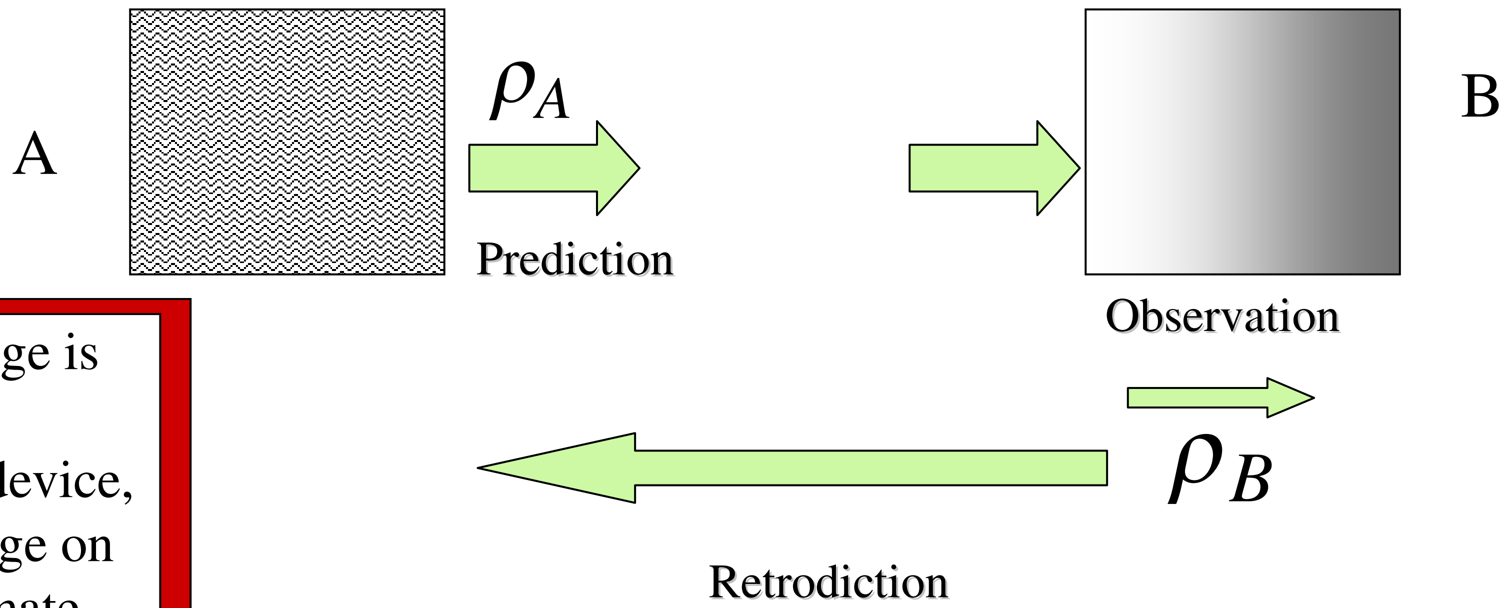
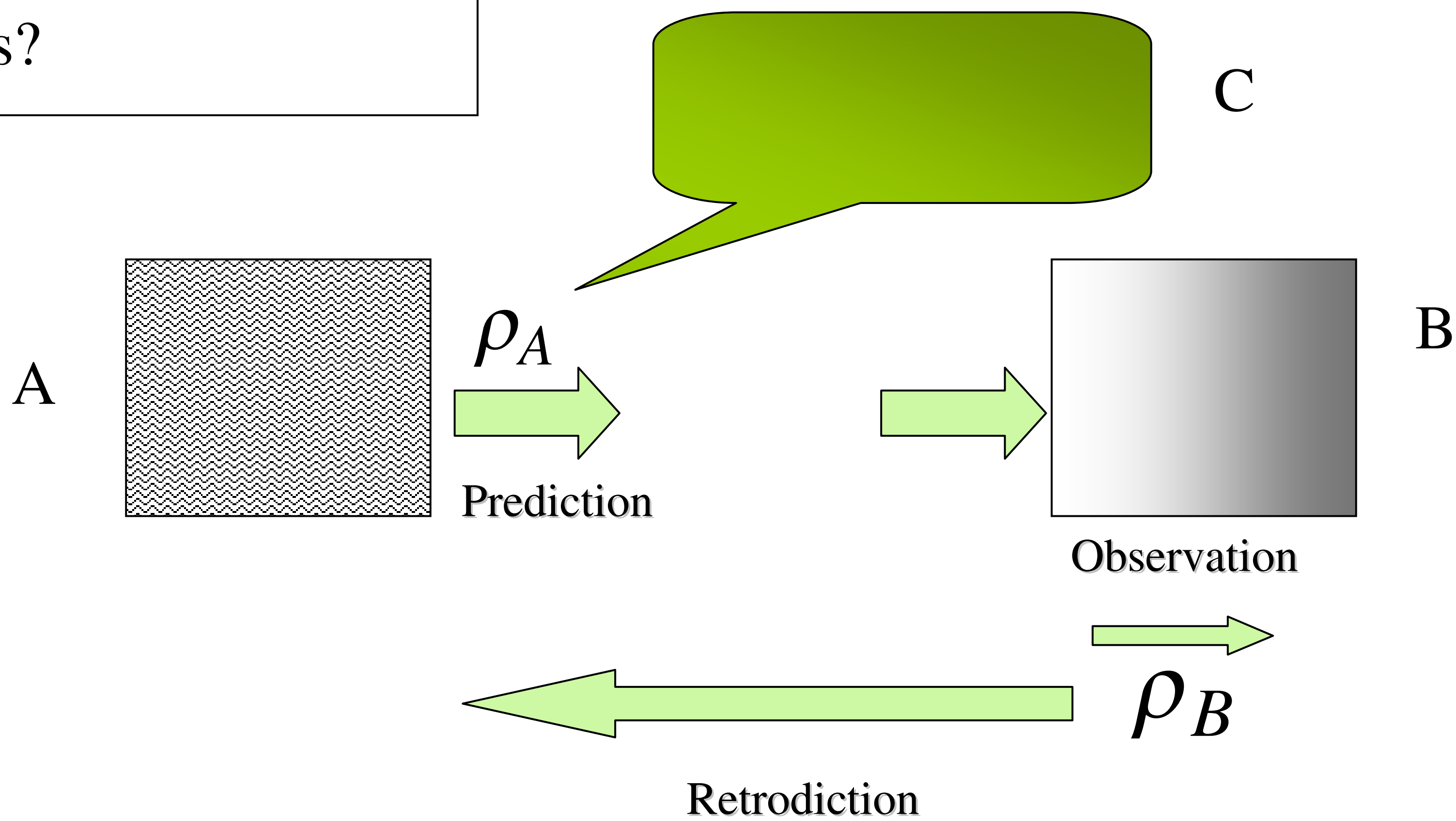


A's knowledge is based on the preparation device, B's knowledge on the best estimate (=communication?)

Along comes an independent observer C.

Whose density matrix will condition his results?



Information in Quantum States

- All experimental outcomes have to be predicted from the state vector of the system:
- A quantum system can be doing simultaneously all the things a classical system can do as alternatives.
- However, there are strict limitations on which observations we can make on a quantum system.
- Thus quantum systems can do *more* and *less* than a classical one.

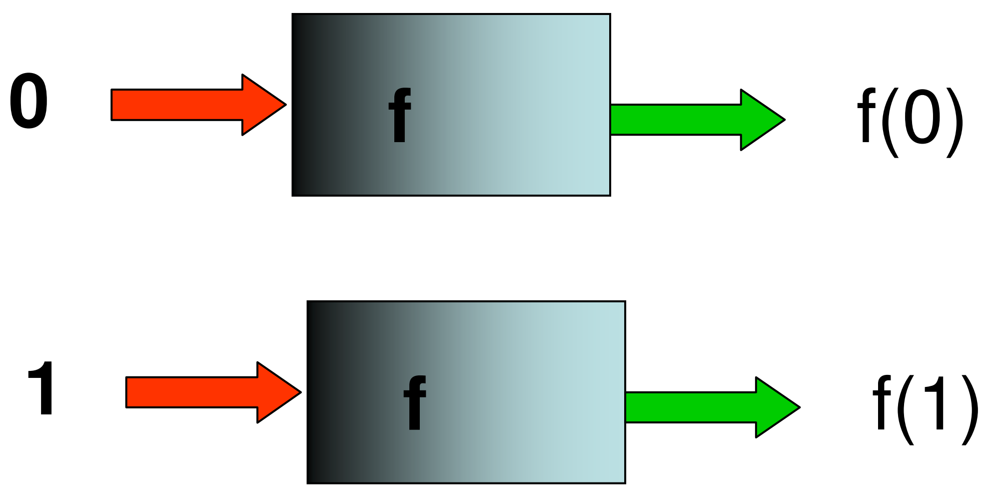
Quantum computing

What and why?

Calculation of simple function

$$f:\ \{0,1\} \to \{f(0), f(1)\}$$

To determine this function we need two operations.



Quantum Mecanically:

We prepare the system in a state:

$$\vec{\Psi} = \vec{\mathbf{a}}_0 + \vec{\mathbf{a}}_1$$

giving in one operation

$$f(0)\ \vec{\mathbf{a}}_0 + f(1)\ \vec{\mathbf{a}}_1$$

$$\mathbf{f}\left(\vec{\Psi}\right) \Rightarrow f(0)\ \vec{\mathbf{a}}_0 + f(1)\ \vec{\mathbf{a}}_1$$

both results are obtained.

Classical versus quantum computing

- Classical

$$\mathbf{f}:\{1,2,3,\ldots N\}\rightarrow$$

$$\{f(1),f(2),f(3),\ldots f(N)\}$$

This gives all the answers, but we have to carry out the operation N separate times.

- Quantum

$$\mathbf{f}:\vec{\Psi}=\vec{\mathbf{e}}_1+\vec{\mathbf{e}}_2+\ldots\vec{\mathbf{e}}_N$$

$$=f(1)\vec{\mathbf{e}}_1+f(2)\vec{\mathbf{e}}_2+\ldots f(N)\vec{\mathbf{e}}_N$$

The quantum computer gives all the answers in one operation, but the ”reading” has to involve all coefficients together.

Potential applications of quantum information:

- Quantum communication is secure.
  - If one observer measures a state, this is not available for anybody else.
  - Evesdroppers can be detected
- Quantum coding can be compact and efficient.
  - Large amounts of data can be stored and sorted.
  - Random search can be efficiently carried out.
- Quantum computing is highly parallel.
  - Computationally complex tasks can be speeded up.
  - Factoring huge numbers can be done efficiently..
  - Secret information exchange endangered.

Quantum theory; present and future

- What do we know?
- What do we want to do?

Quantum concepts and reality

- The *individual quantum system carries information* about its state function.
- It is conditioned on the amount of classical information available.
- When we learn more, we have to re-adjust our predictions at once.
- The ”knowledge” is an *objective feature*.
- Knowledge constitutes a feature of reality.
- The *universal web of knowledge* is part of Reality.

For the present we have to accept that quantum mechanics describes our interactions with elements of Reality.

Our experiments are performed in order to gather information about such reality.

The reality must somehow exist; it has to contain both state vectors and the totality of available information.

This assigns reality to a universal nexus of (classical) *information accessible to anybody*.

Is this the modern concept of the world as a web of phenomena and information only?

A heavy burden for the theory!

The stationary states possess as much or as little 'reality' as the elementary particles themselves. Thus both the quantum objects and their property to be in states are part of the same "reality"

Niels Bohr

What in the world is Quantum Mechanics talking about?

John Bell