Is the Past Determined?

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References:

- Zwirn, H. *Les limites de la connaissance,* Odile Jacob (2000).
- Zwirn, H. *The Measurement Problem: Decoherence and Convivial Solipsism*. Found. Phys., Vol. 46, p.635 (2016).
- Zwirn, H. *Delayed choice, complementarity, entanglement and measurement*. Phys. Essays. 30, 3 (2017).
- Zwirn, H. *Non Locality versus modified realism*. Found. Phys., Vol. 50, pp. 1–26 (2020).
- Zwirn, H. "L’observateur, un défi pour la physique quantique**";** *Pour la Science* N°509, Mars 2020.
- Zwirn, H. *Is the Past Determined?* Found. Phys., Vol. 51, 57 (2021).

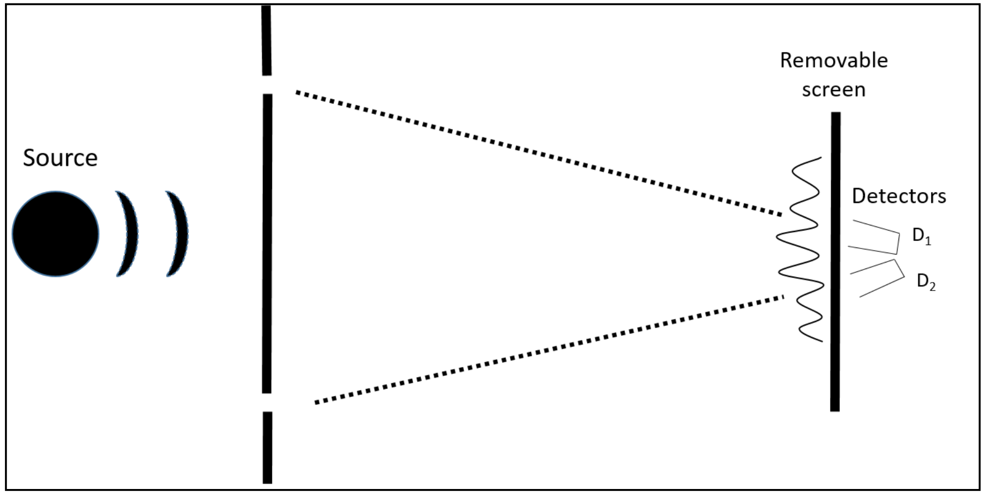
Outline

- Delayed choice experiments
- The measurement problem
- Overview of Convivial Solipsism
- Back to the delayed choice experiments
- Is the Past Determined?

Wheeler’s description

https://youtu.be/u54IPWqF6no

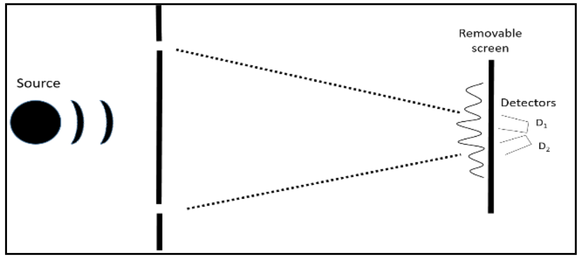
Delayed Choice Experiment



Our realization of Wheeler's delayed choice GedankenExperiment demonstrates beyond any doubt that the behavior of the photon in the interferometer depends on the choice of the observable which is measured, even when that choice is made at a position and at a time such that it is separated from the entrance of the photon in the interferometer by a space-like interval. […] We have a strange inversion of the normal order of the time.

(Jacques, V. ; Wu, E.; Grosshans, F.; Treussart, F. ; Grangier, P.; Aspect, A.; Roch, J.-F) (2007)

Delayed Choice Experiment



- *Spherical waves*

$$\psi(\vec{r}) = \frac{1}{|\vec{r}-\vec{r_1}|} e^{ik|\vec{r}-\vec{r_1}|} + \frac{1}{|\vec{r}-\vec{r_2}|} e^{ik|\vec{r}-\vec{r_2}|}$$

k is the wavenumber of the particle and r_1, r_2 are the locations of the two slits

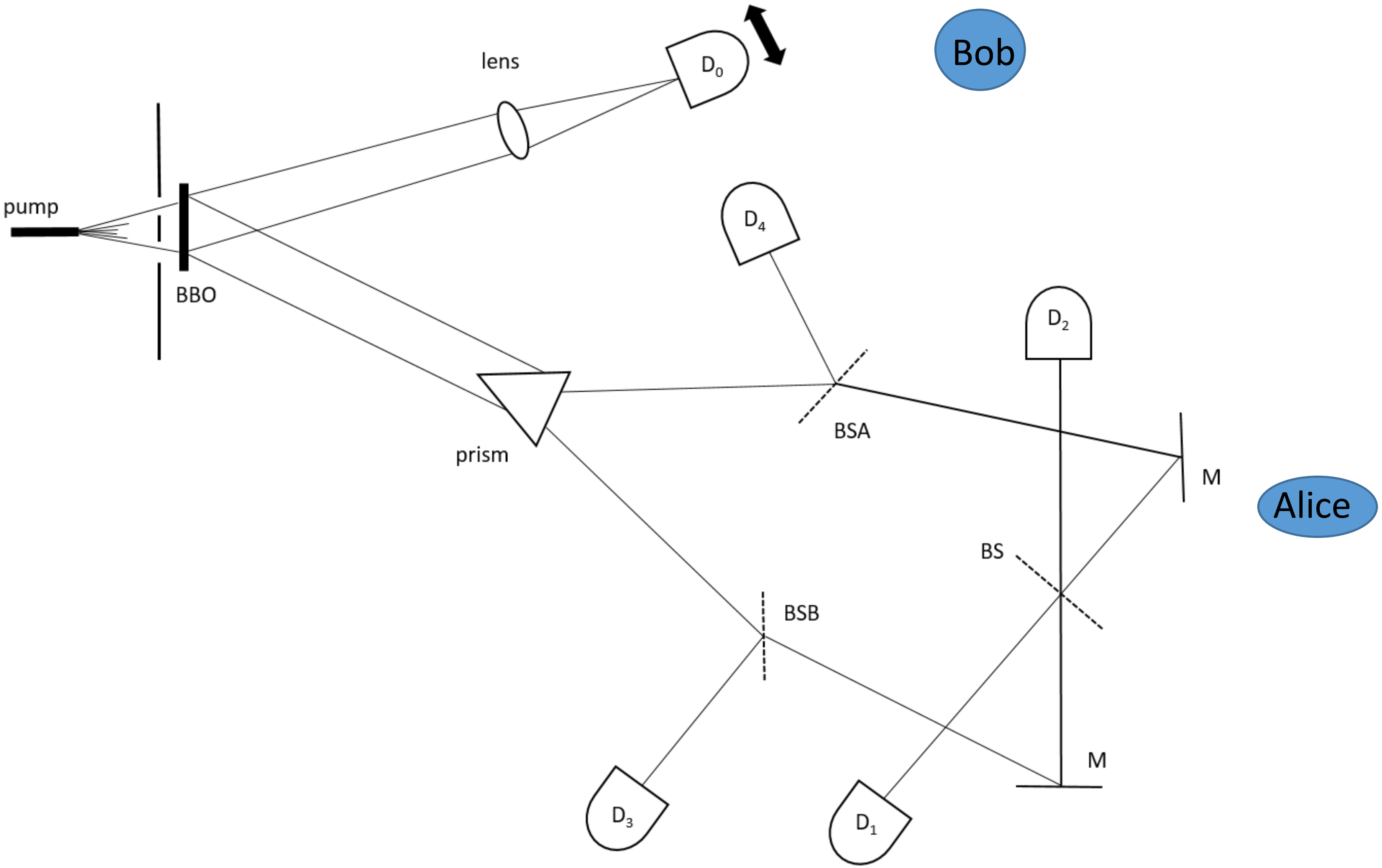
- *Planar waves*

$$\psi(\vec{r}) \frac{1}{|\vec{r}-\vec{r_1}|} e^{i\vec{k_1}(\vec{r}-\vec{r_1})} + \frac{1}{|\vec{r}-\vec{r_2}|} e^{i\vec{k_2}(\vec{r}-\vec{r_2})}$$

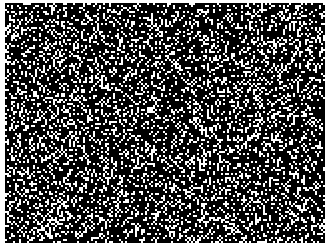
k_1 and k_2 are wavevectors of size k directed along $r_T - r_1$ and $r_T - r_2$ and r_T is the location of the detectors

Prob ½ for each detector to click BUT that does not mean that before the measurement the path was determined!

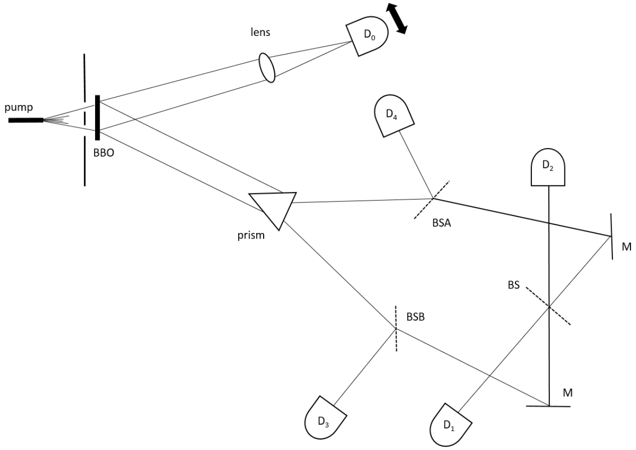
Delayed Choice Experiment

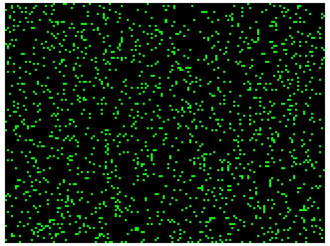


Detections D_0

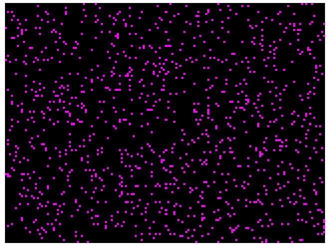


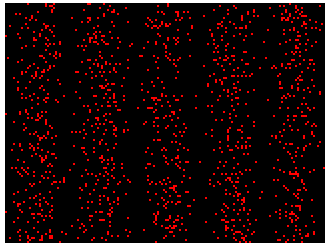
All impacts



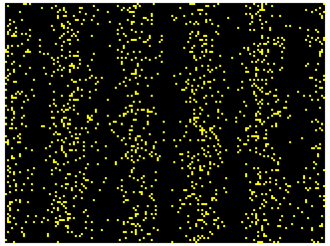


<- D3 impacts D4 ->





<- D1 impacts D2 ->



The measurement problem

2 postulates for the evolution of a system:

- The Schrödinger equation: $i\hbar\frac{d\Psi}{dt} = H\Psi$

- The reduction postulate: $\Psi = \sum c_i|\varphi_i\rangle \rightarrow \varphi_k$

The measurement problem

If you consider that:

- H1: The quantum state is the complete objective description of the real state of the system
- H2: A mesurement is nothing else than an interaction with a measurement apparatus
- H3: QM is a universal theory

Then you have a problem

The measurement problem

Before the interaction between S and A:

System S: $|\Psi_S\rangle = \sum c_i |\varphi_i\rangle$. Apparatus A: $|A_0\rangle$

Grand system state product: $\Psi_{SA} = |\Psi_S\rangle|A_0\rangle = \sum c_i \big|\varphi_i\rangle|A_0\rangle$

After the interaction between S and A, 2 possible points of view:

- Schrödinger equation: $\Psi_{SA} = \sum c_i \big|\varphi_i\rangle|A_0\rangle \rightarrow \sum c_i \big|\varphi_i\rangle|A_i\rangle$
- Reduction postulate: $|\Psi_S\rangle = \sum c_i |\varphi_i\rangle \rightarrow \varphi_k$ and $|A_0\rangle \rightarrow |A_k\rangle$

The measurement problem

2 points of view

- When should we use the Schrödinger equation and when the reduction principle?
- The reduction principle : during a measurement
- What is a measurement? (Cannot be a simple interaction with an apparatus)

The measurement problem

A logical inconsistency inside the quantum formalism if you accept H1,H2 and H3

- Either change the quantum formalism
- Or abandon H1 or H2 or H3 (or all)

The measurement problem

Change the quantum formalism

- Modifying the Schrödinger Equation (G.R.W. formalism)
- Adding hidden variables (De Broglie-Bohm theory)

Worthy to try to find an interpretation inside the standard quantum formalism

- The Copenhagen interpretation (Bohr, Heisenberg, …)
- Epistemic interpretations (QBism, Relational interpretation, …)
- Transactional interpretation (Cramer)
- Consistent histories (Griffiths)
- Pragmatism
- ………

- The role of consciousness (London & Bauer, Wigner, von Neumann)
- Many worlds (Everett)
- Decoherence

The Everett interpretation

Relative States / Many Worlds / Many Minds

No reduction (the global Universe remains in a superposed state) but the observer is divided and the world splits

$$\Psi_{SAEO} = \sum c_i \left|\varphi_i\right\rangle \left|A_0\right\rangle \left|E_0\right\rangle \left|O_0\right\rangle \rightarrow \sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|E_i\right\rangle \left|O_i\right\rangle$$

There are as many observers and as many worlds as there are possible branches

☹

- Continuous infinity! Not very economical
- Probabilities?

The Convivial Solipsism

- Initial remark from Bernard d'Espagnat in « Conceptual Foundations of Quantum Mechanics » (1971) and « Veiled Reality » (1994)

$$\Psi_{SAEO} = \sum c_i \left|\varphi_i\right\rangle \left|A_0\right\rangle \left|E_0\right\rangle \left|O_0\right\rangle \rightarrow \sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|E_i\right\rangle \left|O_i\right\rangle$$

As in the Everett interpretation there is no reduction (the physical universe remains in a superposed state) but contrarily to what happens in the Everett interpretation, there is no multiplication of worlds and observers. There is only one universe, one world and one observer.

The Convivial Solipsism

How is it then possible to get one unique result?

The idea is very simple

Our brain does not allow us to perceive directly superposed states. When we look at a superposed state we perceive only one component of the superposition.

"The reason we do not experience superpositions is not because they do not exist, but because we are not capable of experiencing several different states simultaneously"

Lev Vaidman "All is ψ" Journal of Physics: Conference Series 701 (2016)

There is no need to have many worlds and many observers.

The Convivial Solipsism

How is it then possible to get one unique result?

The idea is very simple

The universe and the observer remain physically in a superposed state but her / his awareness is hung-on to only one branch of the superposition which is chosen at random according to the Born rule. This solves the problem of probabilities that is pregnant in MWI.

So a measurement is nothing else than the fact that when we look at a superposed state our brain selects one component of the superposition (written in the prefered basis) and our awareness hangs-on to this component.

Nothing physical happens!

The Convivial Solipsism

Important points

- Everything in the physical world remains entangled. In particular this is true also of the other observers who are, for one given observer, exactly similar to any other physical system.

- So an observer has to be treated by another observer exactly as a potential measurement apparatus when he does an observation. If Alice makes a measurement this is not a measurement for Bob. It is, for Bob, just an interaction between Alice, an apparatus and the system.

- An observer has no direct access to another observer's perceptions. When Bob asks Alice which result she got, Bob makes a measurement on Alice who stays, for Bob, in an entangled state until she has been measured.

The Convivial Solipsism

Two principles:

- The hanging-on mechanism
- The relativity of states. There is no absolute state. States (and observables and hamiltonians, …) are relative to an observer (similarly to QBism and Relational interpretation).

The Convivial Solipsism

The hanging-on mechanism

$$\Psi_{SAEO} = \sum c_i \left|\varphi_i\right\rangle \left|A_0\right\rangle \left|E_0\right\rangle \left|O_0\right\rangle \rightarrow \sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|E_i\right\rangle \left|O_i\right\rangle$$

There is a distinction to make between the physical state of the brain and what the observer perceives. The brain (as any other physical system) remains in a superposed state. But, due to the limits of the perception, the observer can be aware of only one component of the superposition and this component is choosen at random according to the Born rule.

Let's denote by C_k the perception of the observer corresponding to a definite state $|O\rangle_k$

The Convivial Solipsism

The hanging-on mechanism

$$\Psi_{SAEO} = \sum c_i \left|\varphi_i\right\rangle \left|A_0\right\rangle \left|E_0\right\rangle \left|O_0\right\rangle \rightarrow \sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|E_i\right\rangle \left|O_i\right\rangle$$

$$\sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|E_i\right\rangle \left|O_i\right\rangle \xrightarrow{\text{is perceived as}} \left|\varphi_k\right\rangle \left|A_k\right\rangle \left|E_k\right\rangle \left|O_k\right\rangle$$

C_O -> C_k

which corresponds to the perception of the observer corresponding to a definite state $|O\rangle_k$

The probability that the branch k be chosen is given by the Born rule $p_k = |c_k|^2$

The Convivial Solipsism

The hanging-on mechanism

Once the awareness of an observer is hung-on to one branch, it can hang-on only to daughters of this branch for all the subsequent observations.

This garantees that:

- Repeating the same observation will give the same result

What happens if two observers Bob and Charles do the same measurement on a system?

Every communication between people is a measurement of one by the other.

$\Rightarrow$ No conflict is possible

The Convivial Solipsism

What happens if two observers Alice et Bob do the same measurement on a system?

For Bob :

$\Psi_{SAB} = \sum c_i|\varphi_i\rangle|A_0\rangle\,|B_0\rangle \rightarrow \sum c_i\big|\varphi_i\rangle|A_i\rangle\,|B_i\rangle$

Bob's awareness hangs-on to one branch: C^B_0 → C^B_k

For Charles:

$\Psi_{SAC} = \sum c_i|\varphi_i\rangle|A_0\rangle\,|C_0\rangle \rightarrow \sum c_i\big|\varphi_i\rangle|A_i\rangle\,|C_i\rangle$

Charles's awareness hangs-on to one branch: C^C_0 → $C^C_{k'}$

There is no reason for k = k'

Is there a conflict?

The Convivial Solipsism

Assume Bob makes a measurement first. After that Bob has done his measurement, Charles knows that Bob's state is entangled with the state of the system. For Charles, the system and Bob are in the state:

$\Psi_{SAB} = \sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|B_i\right\rangle$

Bob's awareness is hung-on to the branch k, but Charles has no access to Bob's awareness

When Charles does his own measurement of the system, he becomes entangled and the global state becomes $\Psi_{SABC} = \sum c_i \left|\varphi_i\right\rangle \left|A_i\right\rangle \left|B_i\right\rangle \left|C_i\right\rangle$

Then Charles's awareness hangs-on to the branch k': $c_{k'} \left|\varphi_{k'}\right\rangle \left|A_{k'}\right\rangle \left|B_{k'}\right\rangle \left|C_{k'}\right\rangle$

Then Charles asks Bob what he saw. This is similar to make a measurement of Bob by Charles

The Convivial Solipsism

What is the meaning of $|B_i\rangle$ in $\Psi_{SABC} = \sum c_i \big|\varphi_i\rangle|A_i\rangle\,|B_i\rangle\,|C_i\rangle$?

Remind that for an observer another observer is similar to a measurement apparatus. Asking to somebody which result he got and hearing a definite resut is similar to having a look at the needle of an apparatus and reading a definite position. For Charles, $|B_i\rangle$ is analogous to $|A_i\rangle$ which is the state of the apparatus which indicates the result *i*. So $|B_i\rangle$ must be considered as a state such as if Bob is asked what he saw, he will replies « I saw *i* »

The Convivial Solipsism

According to the hanging-on mechanism, during a second measurement, the observer's awareness can only hang-on to branches that are daughters of the branch to which it is already hung-on. The physical global state remains:

$\Psi_{SABC} = \sum c_i |\varphi_i\rangle |A_i\rangle\, |B_i\rangle\, |C_i\rangle$

But for this measurement of Bob, Charles's awareness can only hang-on to a daughter to the branch k' (here the only possibility is the branch k' itself)

So Charles who is hung-on to the branch $c_{k'} |\varphi_{k'}\rangle |A_{k'}\rangle |B_{k'}\rangle\, |C_{k'}\rangle$ will hear Bob saying that he also got the result k'

No conflict BUT that must not be interpreted as the fact that Bob perceived the result k'

How is that possible?

The Convivial Solipsism

- The seeming paradox comes from a question that can be asked only from a meta observer point of view able to witness both Bob and Charles's awareness. For the need of the presention, the description we gave was from such a point of view but this meta observer (God point of view) does not exist (cf Everett).

- There is no absolute reality that is the same for all the observers. Talking simultaneously of Bob's and Charles's perceptions is not allowed. Any sentence mixing the perceptions of two observers is forbidden.

- States vectors and branches are relative to each observer. So are the results.

- Solipsism : Each observer perceives only his own branch independently of what the others perceive. A sentence has a meaning only if it is expressed from one observer's point of view.

- Convivial : No conflict.

The Convivial Solipsism

A modified reality : for each observer there are two levels of reality (relative to the observer)

- **The empirical reality**

All the potentialities that the observer could actualize. It is described by the global entangled wave function (which is often called the universal wave function in the Everett's interpretation) and evolves only through the Schrödinger equation. It remains entangled and no reduction happens.

- **The phenomenal reality**

Each observer creates his own phenomenal reality. All the results that the observer got through the measurements he did on his empirical reality. It is described by a tree of sub branches of the global entangled wave function.

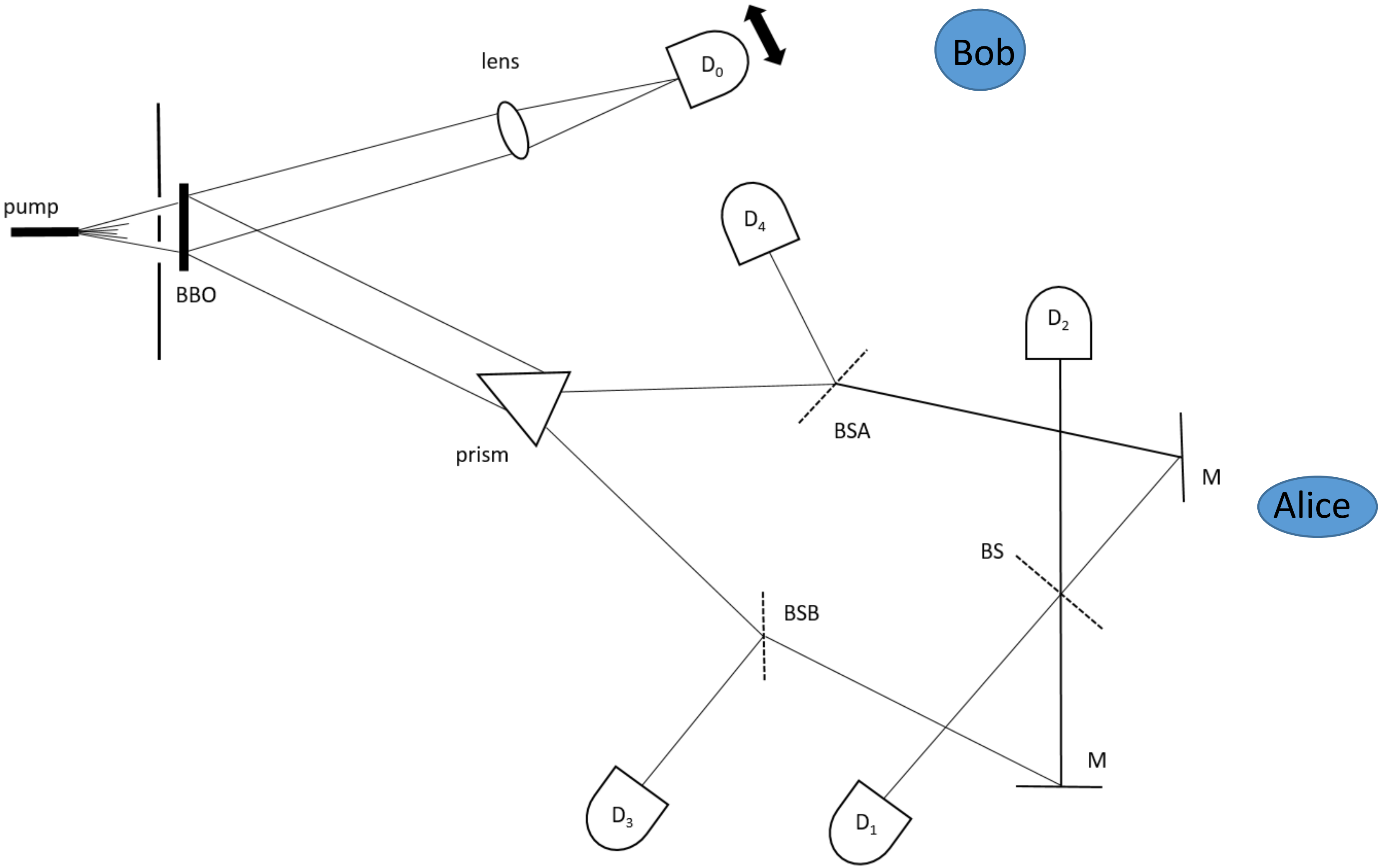
The phenomenal reality is what we usually call the Reality
but
It is relative to each observer. There is no common and shared reality

The Convivial Solipsism

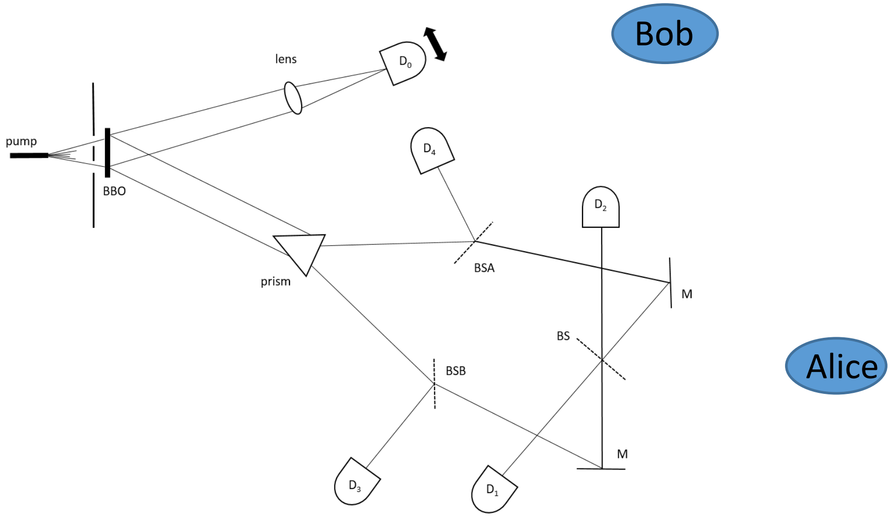
EPR PARADOX AND NON-LOCALITY

- Allows to understand the EPR experiment and to avoid non-locality
- EPR correlations are not a real physical effect with an instantaneous action at a distance but are noticed by a first observer only when he meets the second observer or when he sees the results of the measurement of the second particle and this can happen only in a time-like interval
- No spooky action at a distance / No non-locality

Delayed Choice Experiment



Delayed Choice Experiment



With BS

$$|\psi\rangle = \frac{1}{2\sqrt{2}}\,|1\rangle^{\searrow}[\,|U\rangle + \,|L\rangle]^{\nearrow} + \frac{1}{2\sqrt{2}}\,|2\rangle^{\searrow}[\,|U\rangle + \,|L\rangle]^{\nearrow} + \frac{1}{2}\,|3\rangle^{\searrow}\,|L\rangle^{\nearrow} + \frac{1}{2}\,|4\rangle^{\searrow}\,|U\rangle^{\nearrow}$$

Without BS

$$|\psi\rangle = \frac{1}{2}\,|1\rangle^{\searrow}\,|U\rangle^{\nearrow} + \frac{1}{2}\,|2\rangle^{\searrow}\,|L\rangle^{\nearrow} + \frac{1}{2}\,|3\rangle^{\searrow}\,|L\rangle^{\nearrow} + \frac{1}{2}\,|4\rangle^{\searrow}\,|U\rangle^{\nearrow}$$

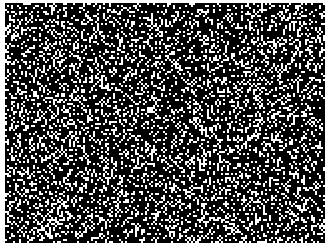
Alice’s point of view

- Alice uses the detectors $D_{i(1,\ldots 4)}$ and asks Bob which results he got from the signal photons at D_0
- She can get results coming only from the branch she is hung-on to. For all the signal photons j corresponding to idler photons for which she got the result 1, she is hung-on to $\left\{\frac{1}{\sqrt{2}}\;|1\rangle_j^A[\;|U\rangle +\;|L\rangle]_j^B\right\}$.
- That means that before she asks Bob, the position of the signal photons at D_0 are not defined even though the measurement by Bob through D_0 is supposed to have been made well before.
- For Alice, Bob is entangled with the signal photons. It is only when Alice asks Bob about the results he got on the photons for which she saw a D_1 click that she makes a measurement on these photons through the measurement she does on Bob.
- This is an example of past events supposed to have happened at T_{-1} (for Bob) that are not defined at a time $T_0>T_{-1}$ (for Alice) and that become defined at T_0 (for Alice) and from then, can be assumed to have been true at T_{-1}.

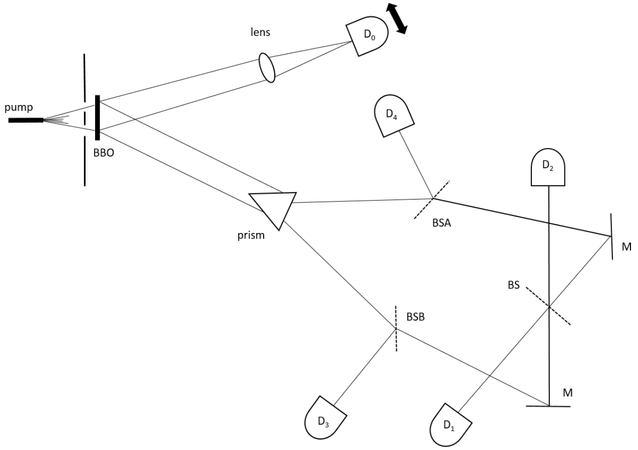
Bob’s point of view

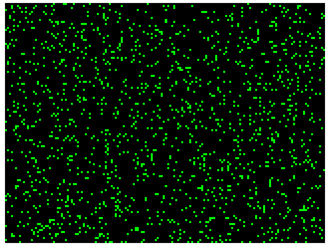
- Assume Bob does his measurements during a certain period and that, due to the design of the experimental device, the idler photons arrive in the area of the detectors D_1 to D_4 only a long time after the measurement of the last signal photon by Bob.
- Assume as well that the decision to put or to remove the beam splitter is made at random just a minute before the first idler photon enters the area of detection. Let’s remember that if the beam splitter is present then signal photons associated with idler photons detected by D_1 and D_2 will show an interference pattern while if there is no beam splitter, there will be no interference.
- So, how can a signal photon detected by D_0 at T_0 and associated with an idler photon detected by D_1 at $T_1 >> T_0$ know if it must interfere or not at T_0 since it is detected well before the decision to put the beam splitter is made (a very short time before T_1)?
- It seems that it is possible to send a message from the future to the past just by deciding in the future to put or to remove the beam splitter and the result would be that the corresponding signal photon would interfere or not, letting the observer in the past know what the decision in the future will be.

Detections D_0

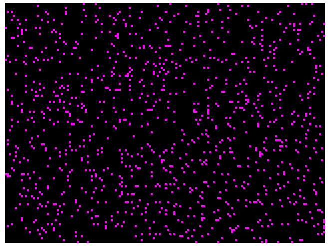


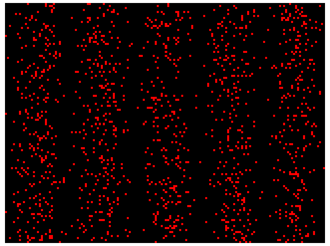
All impacts



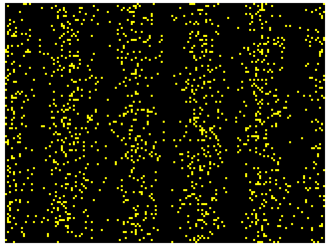


<- D3 impacts D4 ->





<- D1 impacts D2 ->



Bob's point of view

- The interference patterns are created by the post selection process of the second measurements and are in no way present before! It is just that using the distribution function which links a signal photon to a detector D_i can be done in two different ways through two different wave functions which give for the first one a pattern of interference for the photons filtered by D_1 (resp. D_2) and no pattern for the second one, from exactly the same initial list of signal photons gotten from D_0. The interference pattern is created during the last measurements which link signal photons to detectors through the wave function

With BS

$$|\psi\rangle = \frac{1}{2\sqrt{2}}\,|1\rangle^{\searrow}[\,|U\rangle + \,|L\rangle]^{\nearrow} + \frac{1}{2\sqrt{2}}\,|2\rangle^{\searrow}[\,|U\rangle + \,|L\rangle]^{\nearrow} + \frac{1}{2}\,|3\rangle^{\searrow}\,|L\rangle^{\nearrow} + \frac{1}{2}\,|4\rangle^{\searrow}\,|U\rangle^{\nearrow}$$

- Not before!

Without BS: $|\psi\rangle = \frac{1}{2}\,|1\rangle^{\searrow}\,|U\rangle^{\nearrow} + \frac{1}{2}\,|2\rangle^{\searrow}\,|L\rangle^{\nearrow} + \frac{1}{2}\,|3\rangle^{\searrow}\,|L\rangle^{\nearrow} + \frac{1}{2}\,|4\rangle^{\searrow}\,|U\rangle^{\nearrow}$

The Convivial Solipsism

IS THE PAST DETERMINED?

It can happen that a past property A of a system S_1 at T_{-1} is not yet determined at a posterior time $T_0 > T_{-1}$, but becomes determined when the observer makes at $T_1 > T_0 > T_{-1}$ a measurement of another property B (possibly on another system S_2) whose result is linked to the value that A should have had at T_{-1} to be coherent with the result obtained on B at T_1.

The Convivial Solipsism

IS THE PAST DETERMINED?

A and B two entangled particles:

$$|\psi\rangle = \frac{1}{\sqrt{3}}[\,|a\rangle + \,|b\rangle]^B[\,|X\rangle]^A + \frac{1}{\sqrt{3}}\,|a\rangle^B\,|Y\rangle^A$$

- If Alice measures A first she has a probability 2/3 to find X and a probability 1/3 to find Y.
- If she finds Y, she will be hung-on to the branch $|a\rangle^B\,|Y\rangle^A$ and when she will measure B she will necessarily find a. This is what happens in the EPR experiment. Finding a result for one particle fixes the result for the other.
- If she finds X, she will be hung-on to the branch $\frac{1}{\sqrt{2}}[\,|a\rangle + \,|b\rangle]^B[\,|X\rangle]^A$ and when she will measure B, she will have an equal probability ½ to find a or b. Knowing the result of the measurement on A does not determine the result of the measurement on B which remains undefined until a true measurement is made.

The Convivial Solipsism

IS THE PAST DETERMINED?

When the tree of branches constituting the phenomenal reality of the observer contains a superposition of values for A, A is not determined. Now A can refer to an event that is supposed to have happened in the past, for example A can be the value gotten by another observer during a measurement in the past. According to what has been said, the value remains undetermined until the observer from which the point of view is adopted makes a measurement of something that is compatible with only one value for A: For exemple asking the other observer what he saw or reading a result recorded with a date.

The Convivial Solipsism

IS THE PAST DETERMINED?

Example: On Monday at noon, the value of the spin along Oz of this particle that has been measured yesterday by Bob is undetermined for Alice who knows that the masurement has been done but has not communicated with Bob nor seen any report of the result, nor made any measurement correlated to this result. Alice's phenomenal reality is made of branches that contain a superposition of results for this measurement. At 1pm, Alice asks Bob about his result. That means that she makes a measurement on Bob who is (for her) entangled with the system. Through the hanging-on mechanism she hangs-on to one of the two component of the superposition and becomes aware of a defined value, let's say +. Then at 1pm it becomes true for Alice that the spin along Oz of the particle has been + since yesterday, while at noon it was still undefined.

The Convivial Solipsism

IS THE PAST DETERMINED?

The past of each observer contains many properties that are undetermined until the observer makes a measurement that is compatible with only one value of them. It is at the time of this measurement that the value of the past property becomes determined.

The Convivial Solipsism

Thanks

QUESTIONS