On testing the simulation hypothesis

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Abstract

Can the hypothesis that reality is a simulation be tested? We investigate this question based on the assumption that if the system performing the simulation is finite (i.e. has limited resources), then to achieve low computational complexity, such a system would, as in a video game, render content (reality) only at the moment that information becomes available for observation by a player and not at the moment of detection by a machine (that would be part of the simulation and whose *detection* would also be part of the internal computation performed by the Virtual Reality server before rendering content to the player). Guided by this principle we describe conceptual wave/particle duality experiments aimed at testing the simulation hypothesis.

1 Introduction

Wheeler advocated [42] that "Quantum Physics requires a new view of reality" integrating physics with digital (quanta) information. Two such views emerge from the presupposition that reality could be computed. The first one, which includes Digital Physics [46] and the cellular automaton interpretation of Quantum Mechanics [35], proposes that the universe *is* the computer. The second one, which includes the simulation hypothesis [7, 9, 43], suggests that the observable reality is entirely virtual and the system performing the simulation (the computer) is distinct from its simulation (the universe). In this paper we investigate the possibility of experimentally testing the second view and base our analysis on the assumption that the system performing the simulation has limited computational resources. Such a system would therefore use computational complexity as a minimization/selection principle for algorithm design.

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On the emergence of probabilistic computation. It is well understood in Information Based Complexity (IBC) [37, 44, 30, 24, 45] that low complexity computation requires computation with partial/incomplete information. As suggested in [30] and shown in [27] the identification of near optimal complexity algorithms requires playing repeated adversarial (minimax) games against the missing information. As in Game [38, 39] and Decision Theory [40], optimal strategies for such games are randomized strategies [27]. Therefore Bayesian computation emerges naturally [29, 10] in the presence of incomplete information (we refer to [31, 34, 22, 11, 33, 25, 26, 16, 28, 27, 10, 29] for a history of the correspondence between Bayesian/statistical inference, numerical analysis and algorithm design). Given these observations the fact that quantum mechanics can naturally be interpreted as Bayesian analysis with complex numbers [8, 6] suggests its natural interpretation as an optimal form of computation in presence of incomplete information (it is interesting to note that in [6] the Bayesian formulation of Quantum Mechanics is also logically derived in a game theoretic setting). Summarizing these observations, in the simulation hypothesis, to achieve near optimal computational complexity by computing with partial information and limited resources, the system performing the simulation would have to *play dice*.

On the compatibility of the simulation hypothesis with Bell's *no go theorem*. Bell's *no-go theorem* shows that the predictions of quantum mechanics cannot be recovered/interpreted, in terms of classical probability through the introduction of *local* random variables. Here, the "*vital assumption*" [5, p. 2] made by Bell is the absence of action at distance (i.e. as emphasized in [5, eq. 1], the independence of the outcome of an experiment performed on one particle, from the setting of the experiment performed on another particle). Therefore Bell's no-go theorem does not prevent a (classical) probabilistic interpretation of quantum mechanics using a "spooky action at distance" [12]. Here, the simulation hypothesis offers a very simple explanation for the violation of the principle of locality implied by Bell's *no-go theorem* [5], the EPR paradox [12], Bell's inequalities violation experiments [1, 3] and quantum entanglement [18]: notions of locality and distance defined within the simulation do not constrain the action space of the system performing the simulation (i.e. from the perspective of the system performing the simulation, changing the values of variables of spins/particles separated by 1 meter or 1 light year has the same complexity).

On rendering reality It is now well understood in the emerging science of Uncertainty Quantification [15] that low complexity computation must be performed with hierarchies of multi-fidelity models [13]. It is also now well understood, in the domain of game development, that low computational complexity requires rendering/displaying content only when observed by a player. Recent games, such as *No-Man's Sky* and *Boundless*, have shown that vast open universes (potentially including "over 18 quintillion planets with their own sets of flora and fauna" [17]) by creating content, only at the moment the corresponding information becomes available for observation by a player, through randomized generation techniques (such as procedural generation). Therefore, to minimize computational complexity in the simulation hypothesis, the system performing the simulation would render reality only at the moment the corresponding information becomes available for observation by a conscious observer (a player), and the resolution/granularity of the rendering would be adjusted to the level of perception of the observer. More precisely, using such techniques, the complexity of simulation would not be constrained by the apparent size of the universe or an underlying pre-determined mesh/grid size [4] but by the number of players and the resolution of the information made available for observation.

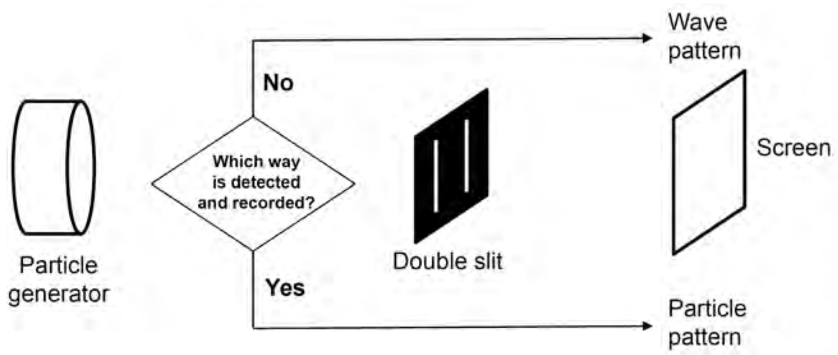

Figure 1: The classical double slit experiment [14, 2] with *which way* detected before or at the slits. We write “wave pattern” for interference patten, and “particle pattern” for non-interference pattern.

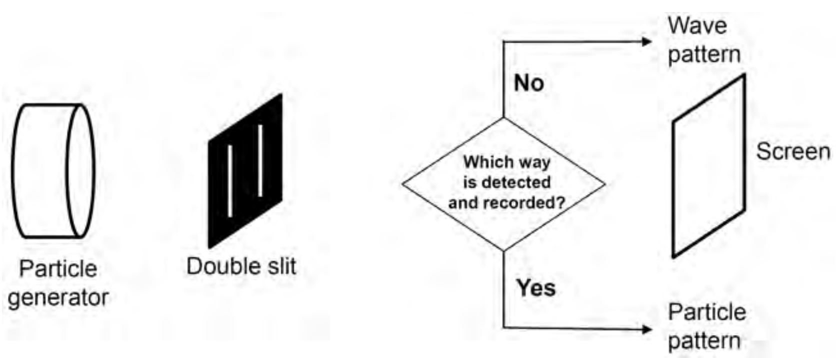

Figure 2: The delayed choice experiment [41, 19]. The choice of whether or not to detect and record *which way* data is delayed until after each particle has passed through a slit but before it reaches the screen.

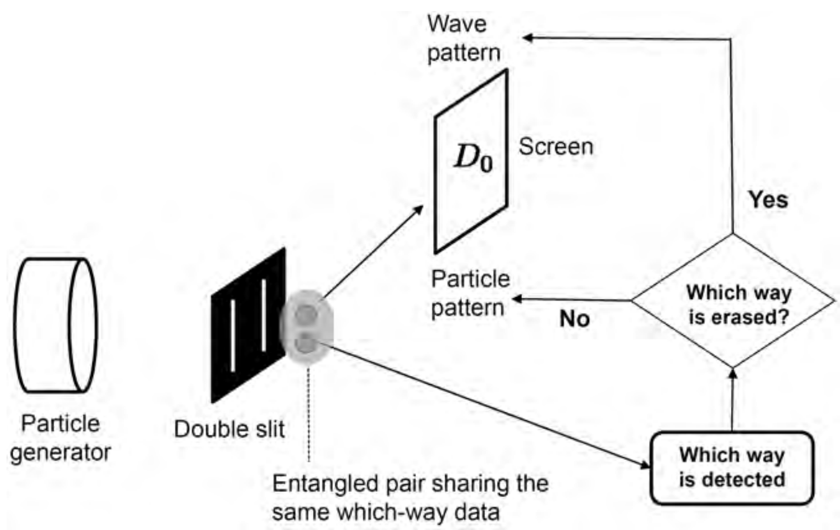

Figure 3: The delayed choice quantum eraser experiment [32, 21]. *Which way* data is collected before, at, or after each particle has passed through a slit, however, this *which way* data may be erased before the particle hits the screen. This experiment is sometimes called a delayed erasure experiment since the decision to erase is made after the particle has passed through a slit (chosen one path or the other).

2 Wave-particle duality experiments

Although the double slit experiment has been known as a classic thought experiment [14] since the beginning of quantum mechanics, and although this experiment was performed with "feeble light" [36] in 1909 and electron beams [20] in 1961, the first experiment with single photons was not conducted prior to 1985 (we refer to [2], which also describes how the interpretation of "feeble light" experiments in terms of quantum mechanics is ambiguous due to the nature of the Poisson distribution associated with "feeble light"). The double slit experiment, illustrated in its simplified and conceptual form in Figure 1, is known as the classical demonstration of the concept of wave/particle duality of quantum mechanics. In this classical form, if *which way* (i.e. which slit does each particle pass through) is "detected and recorded" (at the slits), then particles (e.g. photons or electrons) behave like particles and a non-diffraction pattern is observed on the screen. However, if *which way* is not "detected and recorded," then particles behave like waves and an interference pattern is observed on the screen. Since in the classical set up, the *which way* detection is done at the slits, one may wonder whether the detection apparatus itself, could have induced the particle behavior, through a perturbation caused by its interaction with the photon/electron going through those slits. Motivated by this question, Wheeler [41] argued, using a thought experiment (illustrated in its simplified and conceptual form in Figure 2), that the choice to perform the *which way* detection could be delayed and done after the double-slits. We refer to [19] for the experimental realization of Wheeler's delayed-choice gedanken experiment. Comparing Figure 2 with Figure 1, it appears that whether the *which way* data is detected and recorded before, at, or after the slits makes no difference at the result screen. In other words, the result at the screen appears to not be determined by when or how that *which way* data is detected but by having the recorded *which way* data before a particle impacts that screen.

Following Wheeler, Scully and Drühl [32] proposed and analyzed an experiment (see Figure 3), realized in [21], where the *which way* detection is always performed "after the beam has been split by appropriate optics" but before it is possibly erased (with probability 1/2 using a beam-splitter). We also refer to [23] for a set-up with significant separation in space between the different elements of the experiment. Comparing Figure 3 with Figure 2, it appears that whether the *which way* data is or is not erased determines the screen result. Again, the result at the screen seems to be determined, not by the detection process itself but by the availability of the *which way* data. Erasing the *which way* data appears to be equivalent to having never detected it.

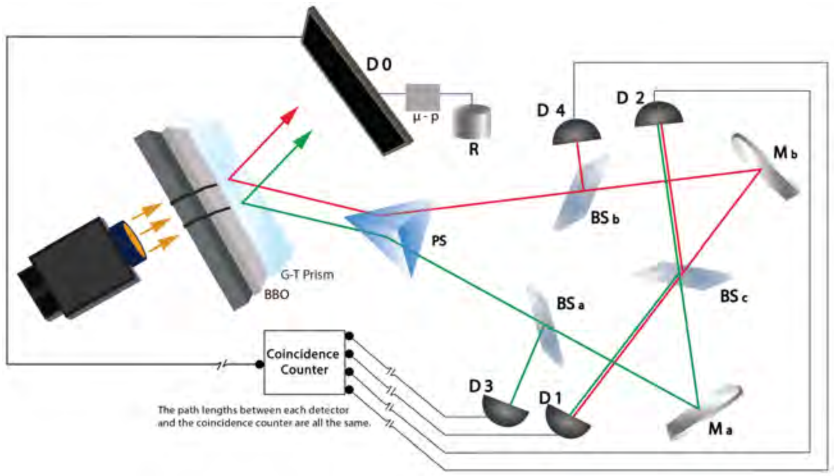

Figure 4: The delayed choice quantum eraser experiment set up as described in [21]. The microprocessor (μ-p) represents an addition to the original experiment and will be discussed in Section 3 and in the Appendix.

Remark 1. A remarkable feature of the delayed choice quantum eraser experiment [21] (see figures 3 and 4) is the creation of an entangled photon pair (using a type-II phase matching nonlinear optical crystal BBO: $\beta - BaB_2O_4$) sharing the same *which way* data and the same creation time. One photon is used to trigger the coincidence counter (its impact location screen D_0 is also recorded) and the second one is used to detect the *which way* data and possibly erase it (by recording its impact on detectors D_1, D_2, D_3 and D_4). The coincidence counter is used to identify each pair of entangled photon by tagging each impact on the result screen D_0 and each event on the detectors D_1, D_2, D_3 and D_4 with a time label. Using the coincidence counter to sort/subset the impact locations (data) collected on the result screen D_0, by the name (D_1, D_2, D_3 or D_4) of the detector activated by the entangled photon, one obtains the following patterns:

D1: Interference pattern (*which way* is erased).

D2: Interference pattern (*which way* is erased).

D3: Particle pattern (*which way* is known, these photons are generated at Slit 1).

D4: Particle pattern (*which way* is known, these photons generated at Slit 2).

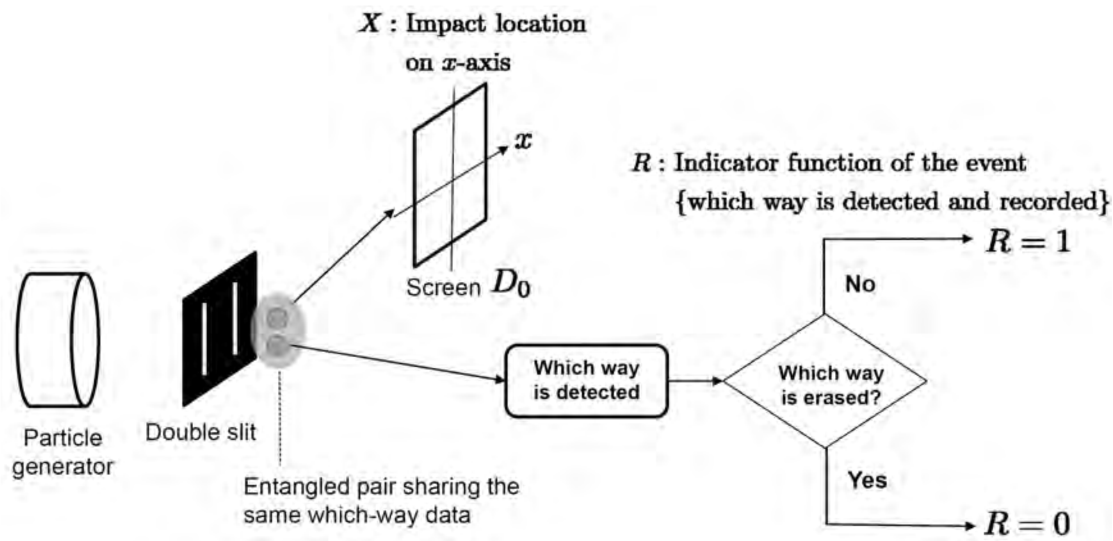

Figure 5: Delayed Erasure Experiment. *Which way* data is randomly recorded with probability 1/2.

3 Predicting erasure in the delayed choice quantum eraser experiment

We will now describe wave-particle duality experiments aimed at testing the simulation hypothesis by testing the hypothesis that reality is not rendered (or the wave function is not collapsed) at the moment of detection by an apparatus that would be part of the simulation, but rather at the moment when the corresponding information becomes available for observation by an experimenter. More precisely our hypothesis is that wave or particle duality patterns are not determined at the moment of detection but by the existence and availability of the *which way* data when the pattern is observed. The first test is based on a modification of the delayed choice quantum eraser experiment [21]. In this modification, we use the facts that (1) the entangled pair of photons discussed in Remark 1 share the same *which way* data (2) the experiment can be arranged so that the first photon hits the screen (sending a pulse toward the coincidence counter) before the second one reaches the beam-splitter causing the erasure or recording of the *which way* data with probability 1/2 (but the time interval between these two events must be significantly smaller than the time interval between creation of photon pairs to preserve the information provided by the coincidence counter). The location X of the impact (on the x-axis) of the first photon on the screen (see Figure 5) is then recorded and used to predict whether the *which way* information will be erased ($R=0$) or kept/recorded ($R=1$). More precisely by applying Bayes' rule we obtain that $\mathbb{P}[R=1|x \leq X \leq x+\delta x] = \frac{\mathbb{P}[R=1]}{\mathbb{P}[x\leq X\leq x+\delta x]}\mathbb{P}[x \leq X \leq x+\delta x|R=1]$. Using $\mathbb{P}[x \leq X \leq x+\delta x] = \mathbb{P}[x \leq X \leq x+\delta x|R=0]\mathbb{P}[R=0] + \mathbb{P}[x \leq X \leq x+\delta x|R=1]\mathbb{P}[R=1]$ and $\mathbb{P}[R=0] = \frac{1}{2}$ we deduce that

$$\mathbb{P}[R=1|x \leq X \leq x+\delta x] = \frac{1}{1+f(x)} \text{ with } f(x) = \frac{\mathbb{P}[x \leq X \leq x+\delta x|R=0]}{\mathbb{P}[x \leq X \leq x+\delta x|R=1]}. \quad (1)$$

Let d be the distance between the two slits and L the distance between the slits and the screen (where X is recorded). Write λ the wavelength of the photons and $a := \frac{\lambda L}{d}$. Using the standard approximations $\mathbb{P}[x \leq X \leq x+\delta x|R=1] \approx 2I_0\,\delta x$ and $\mathbb{P}[x \leq X \leq x+\delta x|R=0] \approx 4I_0 \cos^2(\pi\frac{x}{a})\,\delta x$ (valid for $x \ll L$) we obtain that

$$\mathbb{P}[R=1|x \leq X \leq x+\delta x] \approx \frac{1}{1+2\cos^2(\pi\frac{x}{a})}\,. \quad (2)$$

Therefore if the proposed experiment is successful, then the distribution of the random variable R would be biased by that of X and this bias could be used by a microprocessor whose output would predict the value of the random variable R (prior to its realization) upon observation of the value of X. This bias is such that, if the value of X corresponds to a dark fringe of the interference pattern and a high intensity part of the particle pattern, i.e. if $\cos(\pi\frac{x}{a}) \approx 0$ and $x/a \approx 0$, then the photon must be reflected at BS_a and BS_b (i.e. $R=1$) with a probability close to one. Observe that the value of R is determined by whether the photon is reflected rather than transmitted the beam splitters BS_a and BS_b (which are large masses of materials that could be at large distance from the screen D_0). Therefore, if the proposed experiment is successful, then for values of X corresponding to a dark fringe of the interference pattern, it would appear as if the measuring, recording, and observing of impact location X determines whether the *which way* data will or will not be erased. Such a result would solve the causal flow of time issue in delayed erasure experiments: detection at D_0 would now determine (or introduce a bias in) the choice, i.e. reflection or transmission, at BS_a and BS_b. However, a new issue would be created: The detection at D_0 deterministically selecting (or, for a general value of X, strongly biasing the probability of) the choice at BS_a and BS_b (reflection or transmission) when that choice is supposed to be random (or, for a general value of X, independent from X). Although this could be seen as a paradox such a result would have a very simple explanation in a "simulated universe": the values of X and R are realized at the moment the recorded data becomes available to the observer (experimenter).

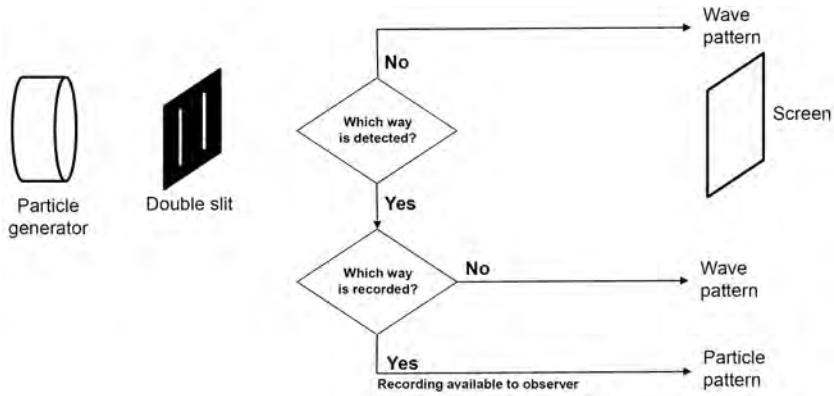

Figure 6: Detecting but not recording "which way"

4 Detecting but not making the data available to an observer

We will now describe experiments, which if proven successful, would provide even stronger evidence in favor of the simulation hypothesis. The following experiments are designed based on the hypothesis that the availability of *which way* data to an observer is the key element that determines the pattern found on the result screen: the simulated content (the virtual reality) is computed and available to be rendered to an *experimenter* only at the moment that information becomes available for observation by an *experimenter* and not at the moment of detection by an apparatus.

In the second experiment, illustrated in a simplified and conceptual form in Figure 6, the *which way* data is detected but not recorded (which translates into the non availability of the *which way* data to the experimenter/observer). There are many possible set ups for this experiment. A simple instantiation would be to place (turned on) detectors at the slits and turn off any device recording the information sent from these detectors (or this could be simply done by unplugging cables transmitting impulses from the detectors to the recording device, the main idea for this experiment is to test the impact of "detecting but not making the data available to an observer").

This test could also be implemented with entangled pairs using the delayed choice quantum eraser experiment (see Figure 4) by:

- Simply removing the coincidence counter from the experimental setup and recording (only) the output of D_0 (result screen). D_0 should display the wave pattern if the experiment is successful.

- Or by turning off the coincidence counter channels D_3 and D_4 (and/or the detectors). If the experiment is successful, then D_0 should (without the available information for sorting/subsetting between D_3 and D_4) display an interference pattern (and sorting the impacts at D_0 by D_1 or D_2 should also show interference patterns).

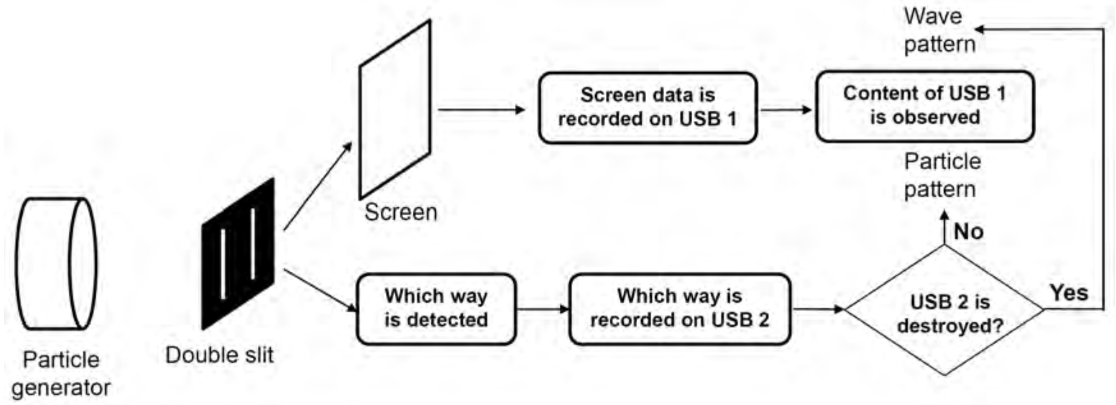

Figure 7: Erasing the *which way* data on a macroscopic scale

5 Erasing the *which way* data on a macroscopic scale

In the third experiment, illustrated in a simplified and conceptual form in Figure 7, the decision to erase the *which way* data is delayed to a macroscopic time-scale. This can be implemented by using the classical double slit experiment shown in Figure 1 where the recordings of the *which way* data and the screen data (impact pattern) are collected on two separate USB flash drives. By repeating this process n times one obtains n pairs of USB flash drives (n is an arbitrary non-zero integer). For each pair, the *which way* USB flash drive is destroyed with probability $p_d = 1/2$. Destruction must be such that the data is not recoverable and no trace of the data is left on the computer that held and transferred the data. For n even, one can replace the coin flipping randomization by that of randomly selecting a subset composed of half of the pairs of USB flash drives containing *which way* data for destruction (with uniform probability over such subsets). The test is successful if the USB flash drives storing impact patterns show an interference pattern only when the corresponding *which way* data USB flash drive has been destroyed. This test can also be performed by using the delayed choice quantum eraser experiment or its modified version illustrated in Figure 5. For this implementation, one USB flash drive is used to record the data generated by the photons for which X is measured (output of D_0) and other USB flash drives to record the data generated by D_1, D_2, D_3 and D_4 along with the associated output of the coincidence counter.

6 Discontinuities in rendering reality

What determines the result at the screen D_0 (the value of X)? What causes and determines the collapse of the wave function? Or in Virtual Reality (VR) terminology, what causes the virtual reality engine to compute and make information defining the VR available to an experimenter within the VR?

Is it

(I) entirely determined by the experimental/detection set-up?

(II) or does the observer play a critical role in the outcome?

Under the simulation hypothesis, these questions can be analyzed based on the idea that a good/effective VR would operate based on two, possibly conflicting, requirements: (1) preserving the consistency of the VR (2) avoiding detection (from the players that they are in a VR). However, the resolution of such a conflict would be limited by computational resources, bounds on computational complexity, the granularity of the VR being rendered and logical constraints on how inconsistencies can be resolved. Occasionally, conflicts that were unresolvable would lead to VR indicators and discontinuities (such as the wave/particle duality).

Although the experiments of Figures 5, 6 and 7 have been aimed at testing the simulation hypothesis by testing the moment of rendering, it also possible to design thought experiments where the conflicting requirement of logical consistency preservation and detection avoidance would lead to strong discontinuities.

We refer the reader to the appendix for one such experiment (a hypothetical thought experiment) where the VRs rendering engine would be forced to create discontinuities in its rendering or be constrained to produce a clear and measurable signature event within our reality that would be an unambiguous indicator that our reality must be simulated.

As a secondary purpose, the thought experiment discussed in the appendix will also be used clarify the notion of availability of *which way* data in a VR.

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Appendix

The purpose of the thought experiment (illustrated in a simplified and conceptual form in Figure 8) described here is not only to test the role of the observer in the outcome of a variant of the delayed choice quantum eraser experiment, but also to show that if the conscious observer/experimenter plays no role in the outcome then the rendering of reality would have significant discontinuities. More precisely, we will use the logical flow of this thought experiment to prove, per absurdum, that at least one of the following outcomes must hold true.

(I) Steps (1) or (2) in Figure 8 do not hold true (which would be a discontinuity in the rendering reality).

(II) Reality is rendered at the moment the corresponding information becomes available for observation by an experimenter (which would be an indication that the simulation (VR) hypothesis is true).

(III) *Which way* data can be recorded with a wave pattern (which would be a paradox).

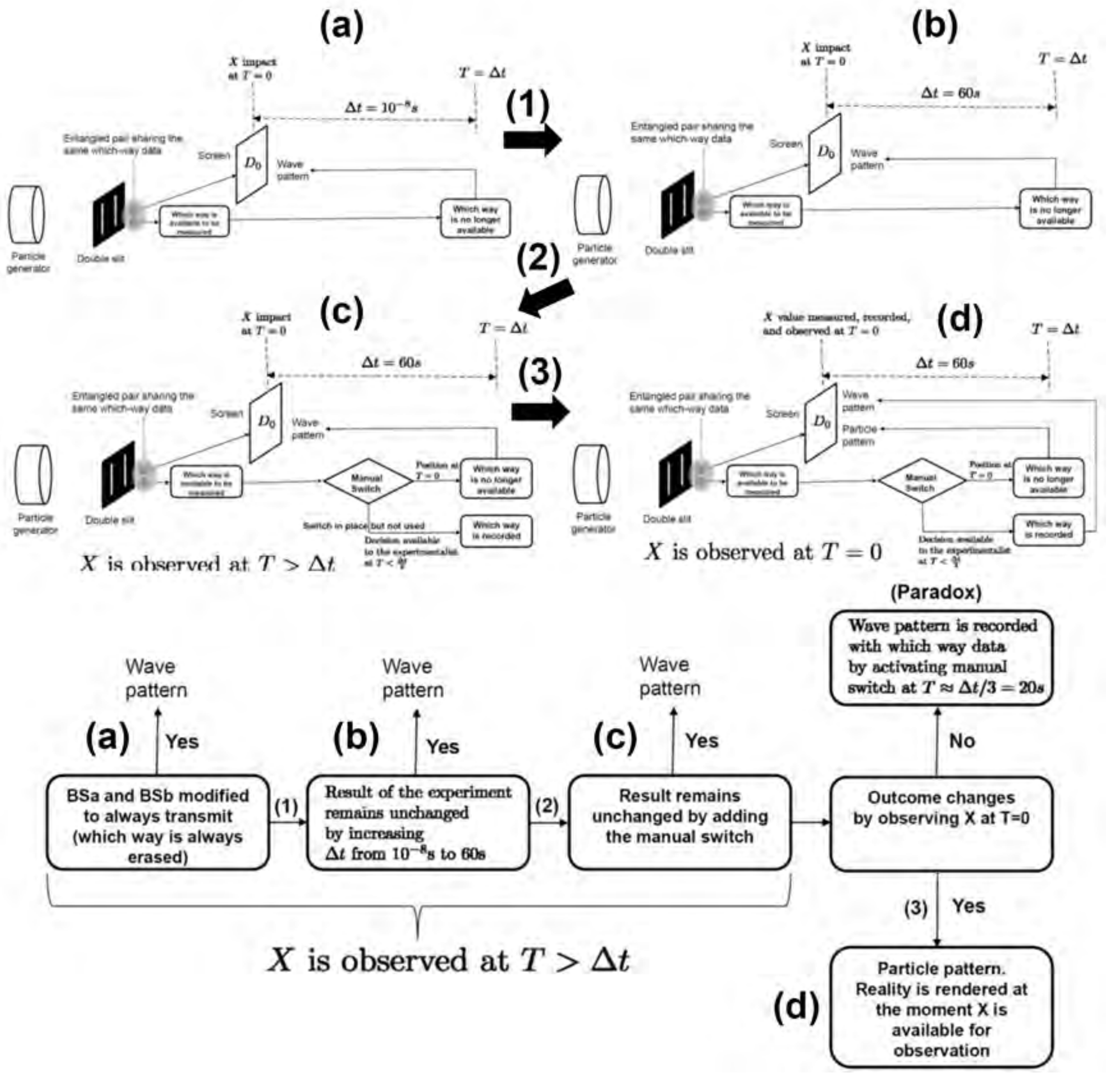

Figure 8: Testing the role of the observer

Consider the delayed choice quantum eraser experiment [32, 21] illustrated in Figure 3. Let Δt be the interval of time (in the reference of lab where the experiment is performed) separating the impact of the first (signal) photon on the screen D_0 from the moment the second (idler) photon reaches the beam splitter BS_c causing the *which way* data to be either available (recorded) or not available (erased). The experiments of X. Ma, J. Kofler, A. Qarry et al. [23] suggest that the set-up could be such that Δt could be arbitrarily large without changing the outcome of the delayed erasure (we will make that assumption). We will also assume that the time interval between the production of entangled pairs of photons can be controlled so that during each time interval Δt, only one pair of photons runs through the experiment.

Write $\mathbb{P}_{\text{wave}}$ the probability distribution on X associated with a wave pattern. Write $\mathbb{P}_{\text{particle}}$ the probability distribution on X associated with a particle pattern. For I a subset of the possible values of X, write

$$\delta(I) := \mathbb{P}_{\text{particle}}[X \in I] + \mathbb{P}_{\text{wave}}[X \notin I] \tag{3}$$

Assume that the distance separating the two slits and the distance separating the screen D_0 from the two slits are such that I can be chosen so that $\delta(I) < 0.9$. Observe that $\delta(I) = 1+\mathbb{P}_{\text{particle}}[X \in I]-\mathbb{P}_{\text{wave}}[X \in I]$, therefore $\min_I \delta(I) = \text{TV}(\mathbb{P}_{\text{particle}}, \mathbb{P}_{\text{wave}})$ where $\text{TV}(\mathbb{P}_{\text{particle}}, \mathbb{P}_{\text{wave}})$ is the total variation distance between $\mathbb{P}_{\text{particle}}$, and $\mathbb{P}_{\text{wave}}$. Therefore the possibility of choosing I so that $\delta(I) < 0.9$ is equivalent to $\text{TV}(\mathbb{P}_{\text{particle}}, \mathbb{P}_{\text{wave}}) > 0.1$

(a) Remove the beam splitters BS_a and BS_b (or modify them to be totally transparent) so that *which way* data is not available. The experimentalist observes the outcome of the experiment after X has been realized and the possibility of which-way data has been eliminated. One should get an interference pattern at D_0, as illustrated in Figure 8-(a).

(b) Increase Δt from $\Delta t \approx 10^{-8}$s to $\Delta t \approx 60$s. The totally transparent beam splitters BS_a and BS_b occur on the timeline at $\Delta t/2$. The experimentalist observes the outcome of the experiment after X has been realized and the possibility of *which-way* has been eliminated. If the outcome of the experiment does not depend on Δt then one should get an interference pattern at D_0, precisely as it did in 8-(a) and as illustrated in Figure 8-(b).

(c) Introduce, as illustrated in Figure 8-(c), a manual switch that, when activated, causes beam splitters BS_a and BS_b to totally reflect (become mirrors) so that *which way* data will always be collected and remain available. This manual switch gives the experimentalist the option to produce and record (or not) *which way* data by activating the switch (or not) at $T < \Delta t/2$). Assume the switch can be quickly activated or not at the (arbitrary) decision of the experimentalist. If the position of the switch at $T = 0$ leads to erasure of the *which-way* data, and if the experimentalist observes the outcome of the experiment at $T > \Delta t$ (after X has been realized and *which-way* has been erased), then an interference pattern should be observed as illustrated in Figure 8-(c).

(d) If the experimentalist observes the value of X at $T = 0$ instead of at $T > \Delta t$. Then the following outcomes are possible

   i X is sampled from $\mathbb{P}_{\text{wave}}$ (an interference pattern) when the switch is inactive and from $\mathbb{P}_{\text{particle}}$ (a particle pattern) when the switch is active.

   ii X is always sampled from $\mathbb{P}_{\text{particle}}$ (a particle pattern).

   iii X is always sampled from $\mathbb{P}_{\text{wave}}$ (an interference pattern).

   iv Not (i), (ii) or (iii).

Assume that alternative (i) holds. Let the experimentalist implement the following switch activation strategy with I chosen so that $\delta(I) < 0.9$.

Strategy 1. Use the following algorithm

- If $X \notin I$ then do not activate the switch (let *which way* be erased).
- If $X \in I$ then activate the switch (record *which way*).

Let $\mathbb{P}$ be the probability distribution of X in outcome (i). Observe that

$$1 = \mathbb{P}[X \in I] + \mathbb{P}[X \notin I] = \mathbb{P}_{\text{particle}}[X \in I] + \mathbb{P}_{\text{wave}}[X \notin I] = \delta(I), \tag{4}$$

which is a contradiction with $\delta(I) < 0.9$, and therefore outcome (i) cannot hold. Outcome (iv) would be a discontinuity. Outcome (iii) would allow the experimentalist to always activate the switch and record *which way* with an interference pattern as illustrated in Figure 8-(d). Outcome (ii) would would be a strong indicator that this reality is simulated. Indeed if one gets a particle pattern at D_0 independent of the position of the switch, then the observation at $T = 0$ would have been the cause since this would be the only difference between (c) and (d) if the switch is not activated.

If the outcome of the experiment of Figure 8-(c) is a wave pattern and that of Figure 8-(d) is a particle pattern then the test is successful: the outcome is not entirely determined by the experimental/detection set-up and X (reality/content) must be realized/rendered at the moment when *which way* becomes available to an experimenter/observer. This experiment is likely to be successful in the sense that the only possible outcomes are: the exposure of discontinuities in the rendering of reality, or paradoxes.

Clarification of the notion of pattern in Figure 8. Since in the experiments illustrated in Figure 8, samples/realizations X_i of X are observed one (X_i/photon) at a time (at $T = 0$ or for $T > \Delta t$), we define "pattern" as the pattern formed by a large number n of samples/realizations $X_1, \ldots, X_n$ of X. In Figures 8-(a), 8-(b) and 8-(c) these samples are observed after the erasure of the *which way* data and the resulting aggregated pattern (formed by $X_1, \ldots, X_n$ for large n) must be that of an interference pattern. In the experiment illustrated in Figure 8-(d) samples/realizations of X are observed one at a time, and the experimenter can decide after observing each X_i to record (by turning the switch on) the corresponding *which way* data or let that information be erased (by leaving the switch in its initial off state). Since the experimenter can base his decision to activate the switch at any step i on the values of $X_1, \ldots, X_i$, the experimenter can implement an activation strategy such that the pattern formed by the subset of elements of $\{X_1, \ldots, X_n\}$ with switch *on* is, to some degree, arbitrary (e.g. create a 3 slit pattern by activating the switch only when the value of X is in 3 predetermined narrow intervals). Similarly the experimenter can implement an activation strategy such that the pattern formed by the subset of elements of $\{X_1, \ldots, X_n\}$ with switch *off* is, to some degree, arbitrary. However he has no control over the pattern formed by all the elements $\{X_1, \ldots, X_n\}$ (with switch positions *on* or *off*). Either

1. The pattern formed by aggregates of the values of $X_1, \ldots, X_n$ is independent of the positions of the switch (at all steps $1, \ldots, n$), if each X_i is observed at $T = 0$, and is that of a particle pattern (due to the availability of the which way information to the experimenter at T=0). In particular, in the experiment of Figure 8-(d), the experimenter may always keep the switch *off* so that none of the samples has a paired/recorded *which way* data and he would still obtain a particle pattern. This is not a paradox since the rendering is triggered through the availability of *which way* at $T = 0$. There is also no contraction with the suggested outcome of the experiment of Figure 6 since in that experiment the recording of the *which way* data is determined prior to the realization of X.

2. Or the pattern formed by aggregates of the values of $X_1, \ldots, X_n$ depends on the positions of the switch (at all steps $1, \ldots, n$) that are, at each step i, determined by the experimentalist $20s$ after the observation of X_i (i.e. not produce an X_i in a dark fringe of the diffraction pattern if the experimentalist decides $20s$ later to not activate the switch, which would be the paradoxes discussed around Strategy 1 since the activation strategy is arbitrary).

Difference between the experiment of Figure 5 and that of Figure 8-(d). Observe that in the experiment illustrated in Figure 5, the value of X is used at $T = 0$ (by a microprocessor, μ-p) to predict the later value of R (i.e., the erasure or recording of *which way*). In Figure 8-(d), the value of X is observed by an experimenter before deciding whether *which way* should be erased or recorded. Although in both experiments the value of X seems to be *operated on* at $T = 0$ two different outcomes should be expected if the simulation hypothesis is true based on the analysis of how a VR engine would operate. In Figure 5 the pattern at D_0 formed by the subset of elements of $\{X_1, \ldots, X_n\}$ for which $R = 0$ is that of an interference pattern; and the pattern at D_0 formed by the subset of elements of $\{X_1, \ldots, X_n\}$ for which $R = 1$ is that of a particle pattern. In Figure 8-(d) the pattern at D_0 is always that of a particle pattern (independently from the decision of the experimenter to activate the switch and record the data). This difference is based on the understanding that, if the decisions of the experimenters are external to the simulation, then, while in the experiment of Figure 5 the VR engine would be able to render the values of X and R at the same moment to the experimenter (since the microprocessor using the value of X would be part of the simulation), the VR engine would not necessarily be able to predict the (arbitrary) decision (that may or may not depend on the value of X) of the experimenter (to activate the switch) in the experiment proposed in Figure 8-(d) (*which way* is available for observation by the experimenter at $T = 0$). This difference could also be understood as a clarification of the notion of availability of *which way* data in a VR.

Control of the switch by a microprocessor. The switch of Figure 8-(d) could in principle be activated by microprocessor. In that setup the time interval Δt could be significant reduced from the value proposed in Figure 8-(d). Since Strategy 1 would still be available for implementation (as an algorithm), Alternative (i) discussed in the outcome of Figure 8-(d) would still lead to a contradiction. Alternative (iii) would allow us to record *which way* with an interference pattern. Alternative (iv) would be a discontinuity. Alternatives (ii) or (iii) would an indicator of an intelligent VR engine reacting to the intention of the experimentalist. Alternative (i) leads to a logical paradox for $\delta(I) < 0.9$.

Note that Eqn. (4) would still be a contradiction if $\delta(I) < 1$ (and the existence of such an I is ensured by $\mathrm{TV}(\mathbb{P}_{\text{particle}}, \mathbb{P}_{\text{wave}}) > 0$). We use $\delta(I) < 0.9$ to account for experimental noise. Although we cannot predict the outcome of the proposed experiment, we can prove based on Eqn. (4) that the pattern produced at the screen D_0 cannot be the result of sampling X from a particle distribution when the switch is active and a wave distribution when the switch is inactive. Therefore, although the experiment has not been performed yet we can already predict that its outcome will be new. One possible outcome is that the X will be sampled from a particle distribution independently of the position of the switch which would also be an indicator of a VR engine reacting to the intent of the experiment.