Sundays in a Quantum Engineer’s Life

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I. I AM A QUANTUM ENGINEER, BUT ON SUNDAYS I HAVE PRINCIPLES

I am a Quantum Engineer, but on Sundays I have principles. John Bell opened his ”underground colloquium” in March 1983, words which I will never forget! What! John Bell, the great John Bell, presented himself as an engineer?! one of those people who make things work without even understanding how they function?!? whereas I thought of John Bell as one of the greatest theoreticians. In March 1983 the Association Vaudoise des Chercheurs en Physique organized their annual one-week course in Montana, an excellent combination of ski and physics, on the foundations of quantum mechanics [1]. For one of these reasons peculiar to the community of people interested solely in these foundations, John Bell was invited, but without any time slot for a presentation. With some friends we, i.e. the PhD students, managed to convince him to give us an evening lecture, after dinner, while the professors enjoyed the local wine. At first John declined, arguing that he had not his transparencies, but when we learned that his wife Mary was to join him during the week, we had the perfect counter-argument: Mary would bring the transparencies and we would organize a room and an overhead projector. The talk took place in the basement, the ceiling was too low and the students sat on the ground: a perfect underground atmosphere. When John Bell started you could ”hear the silence”: I am a Quantum Engineer, but on Sundays I have principles.

The next few pages are not supposed to be self-contained, for the physics the reader is directed to existing literature. These pages simply contain an illustration of my understanding of John’s words [2].

II. QUANTUM CRYPTOGRAPHY ON SUNDAYS

Today, quantum engineers have many good professional opportunities and even more should be expected in the near future. Nowadays, for example, they work on quantum cryptography [3,4]. For this purpose they develop techniques to send ”single photon pulses” through telecom optical fibers from a sender, conventionally called Alice, to a receiver called Bob. A convenient solution, according to the engineer, consists in mimicking the single photons by very weak laser pulses, so that the probability that a pulse contains more than a photon is negligible. But on a sunny Sunday the physicist says [5]: ”weak pulses are not good, because they may contain two photons”. So the engineer works out a better single-photon source, based on a photon pair source, using one photon as a trigger for the single photon pulse, see Fig. 1. The physicist, impressed by the engineer’s ability, likes the idea so much that a special issue of the journal of Pretty Rational Letters is edited [6–8]. However, on the following Sunday, he realizes that there is no need, in principle, to set the source on Alice’s side: the source could as well be at the center! This is much more elegant, because of higher symmetry.

But then, in this symmetric configuration, there is no longer any physical object transmitted from Alice to Bob: where does the correlation then come from? and, what then guaranties the confidentiality? The engineer doesn’t care (it is not even clear whether he understands the problem). Actually, it is also unclear to the physicist whether there is a problem or not. Until he discovers the inequality [9]. This inequality [10] doesn’t explain the correlation observed by the engineer, nor does it say anything about their fragility, hence about the security of quantum cryptography. The inequality, or more precisely, its violation, says that the correlation will never be explained by any theory based only on local variables (local beables in John’s word [12]), i.e. that any description of the ”world out there” must incorporate some nonlocal influences.

The quantum engineer enjoys his work. He develops better single photon sources (i.e. sources coming closer to the ideal case), he works on better detectors, higher bit rates, implements efficient error correction and privacy amplification algorithms, etc. During that time, the physicist writes things like $U_1 \otimes U_2 \Phi(+) = \mathbb{1} \otimes U_2 U_1 \Phi(+) \otimes \Phi(+) = \mathbb{1}$ and concludes that the 1-photon and the 2-photon schemes are logically equivalent [13]. He analyses the optimal eavesdropping attack, assuming Eve (the eavesdropper) is limited only by the laws of quantum physics. Thus, he finds that Alice and Bob are guaranteed to share a higher mutual (Shannon) information than Eve (with either Alice or Bob) if and only if the

\footnote{today I would add: one of those people who are unable to make anything work, but think they know why it doesn’t function!}

\footnote{How did John Bell mention his inequality? Very simple, he would just say the inequality!}
error rate between Alice and Bob (something the engineer calls QBER: Quantum Bit Error Rate) is smaller than $\frac{1}{2}(1 - 1/\sqrt{2}) \approx 15\%$. This result makes the engineer happy, his experimental results are well below this 15% threshold: he is on the safe side. The physicist, however, has mixed feelings: how can it be that this limit, obtained when comparing Shannon informations with their logarithms, defines precisely the noise limit above which the inequality can no longer be violated?! Is it a coincidence? or is it deep? (This is still an open question!)

III. LET’S ASSUME THAT THE COLLAPSE IS REAL

Several Sundays pass. The physicist is fascinated by the connection between the bound derived from the metaphysical assumption of local hidden variables and the security of his engineer friend’s quantum crypto device. Since a few weeks he got interested in the infamous wave packet collapse, as a possible interpretation the non local correlation. Suddenly he thinks: “What if the collapse is real? Could it be that the collapse triggered by Alice’s measurement really prepares the state of the photon flying to Bob?” The physicist knows, of course, that the collapse and the related measurement problem are notoriously bad questions, since their prediction are indistinguishable from those of quantum mechanics without any collapse. But, the metaphysical assumption of local hidden variables led to interesting physics (and interesting engineering), although the main result is that they do not exist. May be it is worth trying some metaphysical assumptions about the collapse and see what kind of experiments should be done to test the assumptions!

This was really a nice Sunday, and the physicist thought about testing the speed of what Einstein called the spooky action at a distance! If it is really Alice’s measurement that prepares Bob’s photon at a distance, says the physicist to the engineer, let’s carry out Bob’s measurement at precisely the same time as Alice’s, so that the nonlocal preparation has no time to operate. According to this assumption, the nonlocal correlation should disappear when proper timing is used. If the correlation remains, then either there is no collapse, or the speed of the spooky action is faster than the bound set by the timing accuracy.

The engineer likes the challenge of aligning his system such that both measurements take place “really at the same time”. This is far from obvious, knowing that Alice and Bob are connected by almost 20 km of optical fibers over a straight line distance of more than 10 km! But, the engineer has heard of relativity and asks: “In which reference frame should I align the experiment?”.

Well, hum, I do not really know!, admits the physicists, let’s try the most obvious choices: the reference frame in which the Swiss Alps are at rest! And also the reference frame of the cosmic background radiation (center of mass of the Universe)!

The engineer smiles, but since it is fun work he is willing to try the experiment (it gives him a break from the task of improving these photon counters that are so noisy that one needs to cool them, but if they are too cold then the dead time has to be increased because the after pulses take more time to resorb). Okay, says the engineer, but “What exactly should be aligned? The beam splitters? The detectors? The computers? The observers?”.

The physicist is amazed. Now that he dared to consider the assumption that the collapse is real, so many questions arise! and each hypothetical answer can, in principle, be tested! How to continue? The following Sunday, our physicist goes for a walk, with his friend David Bohm. They spoke about the engineer’s question: what should be aligned? Clearly, it should be the device that triggers the collapse. But what could one reasonably assume as the trigger? After a few minutes of silence, the physicist states: “it must be the detector! That’s where the irreversible event happens!”. Possibly, replies Bohm, but I bet it is the beam splitters! Because it is there that the particle makes its choice.

On Monday, the engineer starts aligning the detectors. Indeed, for him aligning the beam splitters sounds even stranger than aligning the detectors.

This experiment has really been performed in 1999 in Geneva. The referee reports are interesting, ranging from fascination to desperation. No doubt that the experiment was a performance (a better than 5 ps alignment over almost 20 km of fibers: $\approx 10^{-7}$ precision). No doubt that for many physicists the collapse is taboo (but

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3The error rate relates to the 2-photon interference visibility V as follows: QBER=$\frac{1}{2}(1-V)/2$ (recall that “outside the visibility” Bob still has one chance out of two to find the correct result). Hence the mentioned QBER threshold corresponds to a visibility of $1/\sqrt{2}$, wellknown as the threshold for the Bell-CHSH inequality [1].

4i.e. the reference frame in which all the massive parts of the experiment are at rest (the lab frame, if you prefer).

5John Bell always insisted that Bohm’s pilot wave model being experimentally undistinguishable from standard quantum mechanics should be taught to students at the same level [5], but ... who follows this advice?

6Indeed, in Bohm’s pilot wave model, the irreversible choice is made at the beam splitters, in this model the detectors merely reveal this choice. This influenced Antoine Suarez and Valerio Scarani when they developed their proposal [19].

7Notice that John Bell never published his papers on the foundation of quantum mechanics in regular physics journals! The reason being that he wanted to avoid these too often sterile discussions with more or less anonymous referees.
certainly not for John Bell\(^8\)). No doubt also that much remains to be done, both on the theory side and experimentally (an experiment with moving beam splitters is under progress in Geneva).

The experimental result established impressive lower bounds on the speed of the spooky action: \(2 \times 10^7\) and \(\frac{3}{2} \times 10^4\) times the speed of light in the "Swiss Alps" and the Cosmic Background Radiation frames, respectively. These numbers are very large, about similar to the ratio between the speed of sound in air and that of light (for a long time the speed of sound was the fastest measurable speed, while light was assumed to be instantaneously everywhere).

IV. ... AND RELATIVITY?

Yet comes another sunny Sunday. The physicist rests in his armchair and thinks: "All this is quite exciting! But what if we let relativity enter the game even deeper? What if the detectors are in relative motion such that each detector in its own reference frame analyses its photon before the other? It would seem then that each photon-detector pair must make their choice before the other???!\(^9\)"

"This renews the tension between quantum physics and relativity", says the physicist to himself. Indeed the tension is not new. Abner Shimony, a good friend of John Bell, termed this tension as "peaceful coexistence", because the tension does not lead to any testable conflict\(^21\). "However, continues loudly the physicist although he is alone, once one assumes that the collapse is a real phenomena, and once one considers specific models, then the conflict is real and is testable\(^10\). His idea is that the reference frame in which the collapse propagates is not the Swiss Alps frame, nor the cosmic background radiation frame, nor any environmental or universal frame. The intuition is that the frame is determined by the "trigger device", i.e. by the inertial reference frame of the massive device which triggers the collapse. If all trigger devices are at rest in some frame, then it is this frame which is the relevant one\(^4\). This new assumption opens

[usual text continues]
can keep one's fascination for the basic questions without losing ground in endless metaphysical discussions: there is nothing wrong with metaphysical assumptions, but the good ones are those that can be tested. For example, wouldn't it be nicer to dispute the collapse of the wave packet as a physical phenomenon by designing and performing experiments, rather than arguing that the collapse is a metaphysical assumption?

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FIGURE CAPTIONS

1. Schematics of the relation between the setups using faint laser pulses (top) and those used to test the inequality (bottom). In the upper scheme, each pulse has a mean photon number $\mu \approx 0.1$. In the second scheme, the source is replaced by a 2-photon ($2 \hbar \nu$) source, one is used as a trigger, the other is prepared according to the setting $\alpha$ and sent to Bob. In the third scheme, Alice’s photon is used to prepare (at a distance) Bob’s photon. Finally, the last scheme is completely symmetric between Alice and Bob.

2. Schematic of the Geneva long-distance quantum correlation experiments. When the 4 APDs (photon counters) are connected, this establishes a quantum channel for key distribution (i.e. quantum cryptography). The same setup allows to test - and violate - the Bell inequality [24]. When APD 1 and 2 are set precisely at the same optical distance from the source, bounds on the speed of the spooky action (nowadays called quantum information!) can be set, as discussed in section 3. When the APD 2 is replaced by the absorber on the fast rotating wheel, 2-photon interferences can be observed between APD 3 and 4. This realises the before-before experiment presented in section 1.

3. Quantum nonlocality is central to today’s physics! Logically it follows directly from the superposition
principle. This principle leads also to the measurement problem, a dead end since not testable (at least in the foreseeable future). Besides Quantum Nonlocality are Relativity and Information Theory, the two other main scientific achievements of the first half of the 20th century. Relativity is characterized by determinism, information theory by classical probabilities. From quantum nonlocality and the relativistic no-signaling condition one can derive the linearity of quantum dynamics, hence the Schrödinger equation [23]. From quantum nonlocality and information theory one derives quantum cryptography, whose security is intimately connected to Bell’s inequality (section 1). Finally, the optimal quantum cloning machine can be defined as the eavesdropping strategy on a quantum cryptographic channel providing Eve with optimal Shannon information and can be derived from the no-signaling condition and the existence of distant entangled states [26].
Superposition Principle
linearity of the kinematics

Tensor Product

Measurement Problem

RELATIVITY
No signaling
Determinism

QUANTUM NONLOCALITY
entanglement of distant systems
Quantum probabilities

Linearity of the Dynamics
Schrödinger eq.

Violation of Bell Inequality
(experiments, loopholes)

Optimal Quantum Cloning Machine

INFORMATION THEORY
Classical probabilities

Quantum Information Processing

Quantum cryptography

Many Universes view:
in theory everything is entangled, but in practice decoherence makes it impossible to reveal this entanglement

Collapse view:
things are entangled, but the theory can be challenged over a wide range of parameters (mass, distance, speed, etc)

Practical view:
entanglement is the resource for Quantum Information Processing (i.e. the art of turning a Quantum conundrum into a potential application)