MAKING THINGS UNDERSTANDABLE

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## 1. Abstract

The impact of science on society does not concern only technology. It is also relevant with regard to the prevailing "mode of thought". It shapes how we see and interact with the world.

In that respect, the message physicists convey to society is that it is not humanly possible to understand physics at microscopic level. Some also claim that since predictions are Ok, why bother? Somehow, we know how to handle instruments and can predict the outcome of experiments, but we don't understand why it works as it does: we know but we don't understand. In other fields of knowledge, having an accurate understanding of things is essential for progress. In physics, do we have to content ourselves with mastering the technology without understanding how the reality is?

I review some of the quantum experiments, raising a number of questions and seeking new ideas to explain phenomena in a simplified way. I argue that it is possible to conceive new realist models worth exploring.

Simple is frequently understood as macroscopically explainable. As classical physics, based on macroscopic assumptions, was unable to explain subatomic phenomena, simplicity was dropped in favour of other complex theories. It could be that the physical laws at microscopic level are understandable through a different type of simplicity from the macroscopic one, so that we can say: we don't know but we understand.

## 2. Introduction

I was going to entitle this paper "The quest for intelligibility" but I doubt that it is a good example of facilitating understanding.

The subject of the essay contest is how humanity should steer the future in light of the radically different modes of thought and new technologies that are becoming relevant and “what is your plan for getting us there”. I will not discuss about technology but about modes of thought and more specifically about making things, and in particular theoretical physics, understandable.

Trying to have an accurate understanding of things is indeed essential for progress. To face a problem, we need first to understand the situation, to interpret it correctly. Otherwise, the issue cannot be duly addressed.

The impact of science on society is very large. The most obvious influence concerns the development of new technologies. For example, research on semi-conductors allowed the development of transistors, which are the key components of computer chips.

That said, the impact of science is also relevant as regard the prevailing "mode of thought". How to cope with problems or to address challenges, for instance, is directly influenced by science. Physics, in particular, plays a significant role, as an essential part of the educational system. It promotes adopting a rational approach, being rigorous, re-examining critically untested assumptions and basing judgments on facts. Moreover, some of the main physical principles are integrated in the common social beliefs, although in a somewhat filtered form: "everything is relative" (Einstein) or "everything is uncertain" (Heisenberg).

What about understanding? At present, physics is a complex subject, not only because much of the concepts used are remote from ordinary experience or because it relies on an abstract mathematical formulation but also because the foundational principles are intrinsically difficult to understand: entanglement & locality, problem of measurement, quantum & general relativity, etc. The message transmitted to society is that microscopic physical reality transcends human understanding. For instance, Richard Feynman pointed out the following: "I think I can safely say that nobody understands quantum mechanics". Somehow, we can accurately predict the outcome of experiments, but we don't understand how it works as it does: we know but we don't understand. Do we have to give up seeking for understandable solutions? Mastering something without understanding how it works is specific to physics?

Intelligibility and simplicity are closely related. For instance, the movement of planets in the Solar System could be described assuming that the Earth is stationary at the centre, through complex equations only accessible to experts in the field. However, assuming that the Sun is at the centre simplifies equations and facilitates understanding.

A usual way for making things simpler is drawing or making them visual (try, for instance, to explain how to tie a tie in words). Is it not possible to visualize the most basic components of the nature or to describe them in a comprehensible way? Let's review some of the key quantum experiments.

## 3. EPR paradox and entanglement

Einstein, Rosen and Podolski proposed a thought experiment, called EPR paradox, to show that quantum mechanics was inconsistent with other known laws of physics. The paradox can be summarized as follows: let us consider a system that emits in a single event two entangled particles in opposite directions. Conservation laws ensure that if the entangled property of one particle is measured, the same property of the other particle will be instantaneously known.

According to the classical physics, the property was already defined at source and the measurement only reveals something that was already present in both particles. Quantum physics, instead, considers that the state of both particles is probabilistic until one of the two particles is measured. The measurement will determine not only the state of that particle but also, at the same time, the state of the other particle, even if they are extremely far. Hence, one of the following three statements must be wrong:

- Quantum mechanics is a complete theory (completeness);
- No signal or entity can travel faster than the speed of light (relativity);
- There cannot be any interaction between events that are too far in space and too close in time (locality).

Einstein, Rosen and Podolsky thought that the first statement is the wrong one. In 1964, J. Bell formulated a theorem that showed that local realism yields predictions that disagree with those of quantum mechanical theory. Thus, it became possible to verify experimentally which of the two theories was wrong. Numerous experiments performed since the 70s have demonstrated that the predictions of quantum mechanics are correct in this regard. Therefore, one of the previous three statements must be discarded. As the relativity and the completeness of quantum mechanics are considered proved, the experimental results on Bell's theorem have been taken as refuting the concept of locality.

Let us briefly describe the experiment carried out by A. Aspect in 1982 to test Bell's theorem: a source of photons sends pairs of photons with the same polarization in opposite directions. Each photon encounters a two-channel polariser whose orientation ($\alpha$ or $\beta$) can be set by the experimenter. Emerging signals from each channel (either *+1* or *-1*, depending on the polarization of the photon and the orientation of the polarizer) are detected and ordered by two detectors *A* and *B* and then the coincidences are counted.

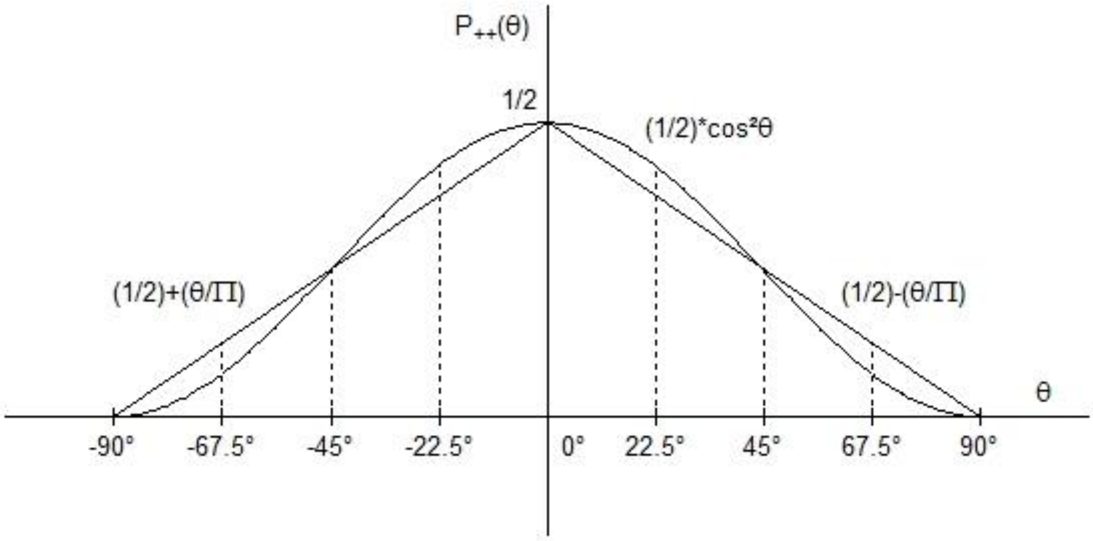
A will perceive a set of signals. For instance, + + - + - - - + + - + ...
B will perceive another set of signals. For instance, + - - + + - - + + + - ...

If $\alpha$ and $\beta$ are the same angle, all signals are equal in pairs (which seems logic as the polarization of each couple of photons is the same and the orientation of the polarizers is also the same). Similarly, if $\alpha$ and $\beta$ are perpendicular, all signals will be opposite in pairs. Now, if the difference between $\alpha$ and $\beta$ is greater than $0^\circ$ and smaller than $90^\circ$, what will be the probability that a pair of photons produce the same signal?

According to quantum mechanics, the probability is the following:

$$P_{++}(\alpha,\beta) = P_{--}(\alpha,\beta) = \frac{1}{2}\cos^2(\alpha-\beta)$$

Bell's theorem claims that any local "classical" theory cannot predict those results but only linear probabilities. Let us draw the two probabilities ($\theta = \alpha - \beta$).




The greatest disparity between the two probabilities is reached when $|\theta| = |\alpha - \beta| = 22,5^\circ$ or $67,5^\circ$.

All the experiments performed so far have confirmed the prediction of quantum mechanics. However, quantum mechanics does not provide a clear explanation for how it happens. How does the measurement of one photon determine instantaneously the state of the other photon if they are separated by an arbitrarily large distance? Quantum physics assumes that the two photons are entangled and that their state must be described in a global way because each photon has no local independent existence. But, through what mechanism the entanglement happens in a way that is compatible with relativity?

Let us analyse the two graphs above. The graph of classical mechanics is a straight line from $-90^\circ$ to $0^\circ$ and from $0^\circ$ to $90^\circ$ and it has a peak in $0^\circ$. The graph of quantum mechanics is flatter at the peak. This difference between the two graphs may be expressed in another way: whereas in classical mechanics probability is continuous but its change is not, in quantum mechanics, not only the probability and its change are continuous, but also all the other derivatives. Can we generalize this principle of continuity?

Let us consider velocity, for instance. Velocity cannot change from $v_0$ to $v_1$ without taking all intermediate values. In the same way, if velocity is continuous but it is not differentiable, then acceleration will not be continuous. However, acceleration cannot jump either from one value $a_0$ to another $a_1$ without taking all values between. Hence, acceleration needs to be continuous, and not only continuous but also differentiable; and we can repeat the same idea successively. Therefore, velocity must be described by a smooth function (infinitely differentiable).

The disparity between classical and quantum predictions on the probability of the polarization reminds the discrepancy on potential barriers. While in classical mechanics a particle cannot go through a potential barrier, in quantum mechanics there is a not null probability that the particle penetrates the barrier.

A large number of observed phenomena, correctly predicted by quantum mechanics, cannot be explained in classical mechanics because the changes measured, either of real properties or of probabilities, occur continuously in time. Classical mechanics can describe the motion of macroscopic objects considering that changes occur instantaneously (like for instance the acceleration, from *0* to $a_0$ or the potential energy, from *0* to $V_0$) but at microscopic level, it becomes necessary to take into consideration that changes happen continuously in time.

How can this reflexion be linked with Bell's theorem? The latter yields a result which doesn't fit the experimental outcome. Hence, at least one of its assumptions must be wrong. The theorem deduces that the probability of any local theory must be linear, just applying the laws of probability to the assumption that events are local (independent) and that it works for perfect correlation (which is experimentally observed). There is no other option than to abandon locality? Can we question instead, the laws of probability, which are linear? Or the logic behind?

Why the binary logic (true-false) we use macroscopically is the most appropriate one to understand subatomic phenomena? Logic is a reasoning tool that allows us to deduce from experiments which physical theories are compatible with the outcomes of those experiments. Among all different types of logic we can invent, there must be one which fits to physics, which is to be used to understand physical reality. Is it the binary logic? Or could it be another logic for which the macroscopic binary logic is an approximation? For instance, a logic where the trueness of a proposition can take any continuous value between 0 and 1 (a type of fuzzy logic)?

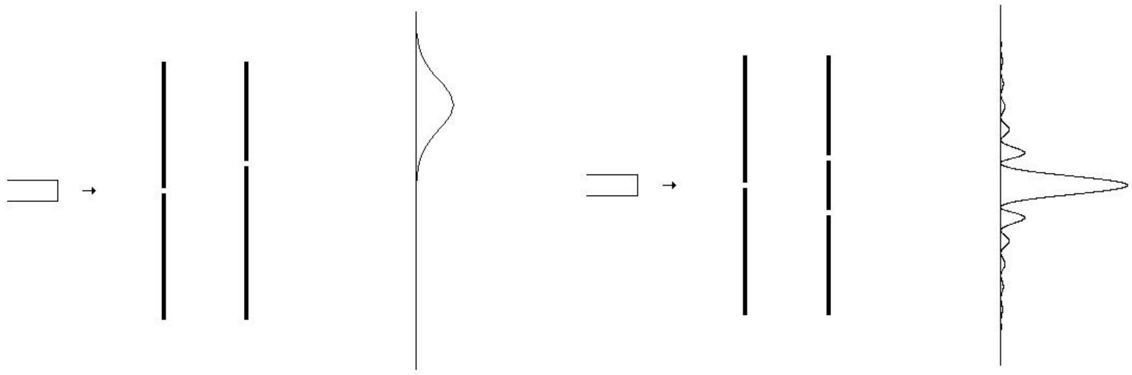
This may be considered complex. However, it is a different type of complexity from the one of quantum world. How a measurement carried out in a place can instantaneously attribute a value to a property in another distant place in a way which is compatible with relativity? Why the act of measurement of a system (which is a combination of changes in that system) causes the set of probabilities describing its state to immediately assume one of the possible values while other changes in the system don't? How to imagine a quantum system without observers? These questions are inherently difficult to understand.

Questioning probability or logic laws, we would admit that our propositions are not absolutely true or absolutely false, that the trueness is approximate, but we could maybe keep determinism and locality and be in a position to say: we don't know but we understand.

## 4. Double slit experiment

Thomas Young showed that if a white light source illuminates a thin plate pierced by two slits, the light passing through the slits is diffracted and displays interference patterns in a screen behind the plate. This phenomenon can be repeated with single photons, electrons or even atoms, getting similar results.  It is used to describe the wave-particle duality of the nature.  Richard Feynman considered that this single experiment "has in it the heart of quantum mechanics".

Let us consider an electron gun which shots single electrons (one at a time) to a plate with a single slit.  The electrons that pass through that slit will strike a second plate with two slits.  Some of the electrons will pass through this second plate, either through the first slit or through the second one (in principle) and then will strike the screen, making a discrete mark, as expected.  When the experiment is repeated with many electrons, an interference pattern emerges.  The electron gun can shot the electrons with such a slow rate that they don't interact with other electrons.  However, after some time, the interference pattern builds up.  How is it possible?



The experiment proves that electrons are diffracted (don't move in a straight line but are spread out) and interfere.  If one of the slits is closed the electrons that pass through the other slit are diffracted but don't interfere.  Similarly, if we add detectors to identify which slit each particle passes through, the interference pattern is destroyed.  Nowadays, it is possible to make "weak" measurements in order to gain some information without appreciably disturbing the interference but the information obtained from any individual measurement is limited.

Initially, the emergence of an interference pattern when electrons were sent one at a time suggested that each electron interfered with itself and therefore, that the electron went through both slits.  The various interpretations of quantum physics explain differently this experiment. The Copenhagen interpretation, which is the most widely accepted interpretation of quantum mechanics, considers that the probability of observing a particular outcome when an experiment is performed is given by the wave function (Schrodinger equation).  The interference pattern in the double slit experiment is explained assuming that the probability wave function associated to each particle passes through both slits and that the result that emerges from each slit interferes with the result from the other slit.

The De Broglie-Bohm interpretation of quantum mechanics assumes that every particle is accompanied by a wave (the pilot wave, described by the usual wave function) which guides the motion of the particle.  The theory is deterministic and assumes that all particles occupy precisely defined regions of space at all times. With regard to the double slit experiment, the De Broglie–Bohm theory assumes that the pilot wave travels through both slits but the electron passes only through one. The wave function interferes with itself and guides the electron in such a way that many electrons create an interference pattern on the screen.

All these theories explain the experimental results at the expense of intelligibility. The De Broglie–Bohm theory is simpler than the Copenhagen interpretation because it re-establishes the determinism and the electron has a single trajectory but it remains a non-local theory and the nature and the origin of the surrounding pilot wave are unclear.

Theories suggesting that electrons pass through both slits mix-up what electrons do with what electrons are. Since a single electron leaves a discrete mark, we can assume that the electron is a discrete item (otherwise its mark would be continuous). On the other hand, its trajectory is such that the discrete marks of a high number of electrons produce an interference pattern. This suggests that the medium, i.e. the space (or the space-time, but not the electron itself) is interfered.

We can suppose that the motion of the electron is diffracted (curved) because the space is curved and interfered because the space is interfered. This leads us to think that space (or space-time) has a wave nature. Maybe the wave nature of the space-time is not perceived at macroscopic level but must be considered at microscopic scale. This can explain why different objects, like electrons, photons or atoms, behave in the same way: because the medium is the same. They are bound to move following the shape of the space-time.

If we take that space-time has a wave nature, what is its origin? How is it created? We could assume that space-time is created by particles. For instance, to be simple, we can visualize particles as spherical tiny items emitting a wave field (the space-time) at the speed of light in the three dimensional directions. Space-time would be, according to this, the superposition of the fields of all particles.

The superposition yields interference only when waves are in phase, which happens when the two slits of the second plate are open and the fields of particles pass through both slits and meet again. When only one slit is open, space is superposed but does not interfere. Similarly, putting detectors breaks the symmetry and prevents space from interfering.

I am not saying that this is the real model, that particles are spheres that emit a wave space-time field. My point is that it is possible to conceive new “classical" models (classical meaning realistic, not macroscopic) to try to explain subatomic results in an understandable way. Let us review the quantization of atomic energy levels.

## 5. Quantized energy levels

Classical physics, by means of gravitational and electromagnetic interactions, has not been able to explain why the energy of a system or particle confined spatially can only take certain discrete values. Indeed, classical objects can have any energy. Moreover, since orbiting objects are accelerating, they should be losing energy and fall towards the nucleus.

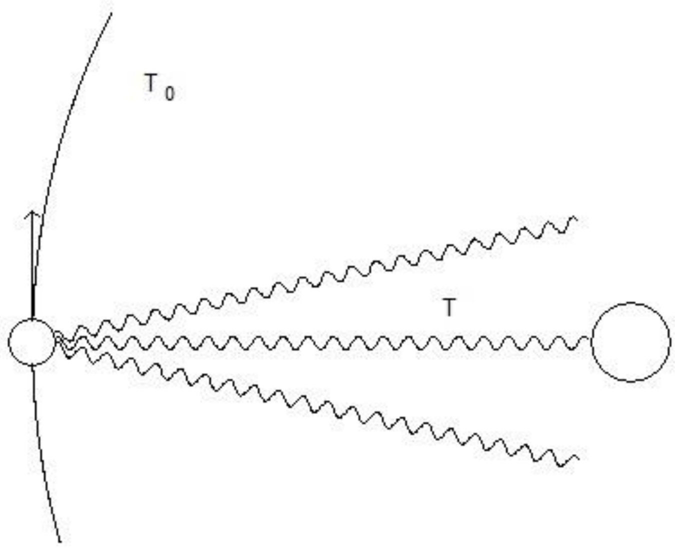
This is not, however, the observed fact: electrons orbit around the nucleus and only in defined orbitals at some discrete distances.

Let us consider the simplest possible atom: hydrogen, which consists of only one proton and one electron. The electron rotates periodically around the proton at a given distance and with a certain energy level. What is it that keeps the electron within that discrete distance from the proton?

Quantum mechanics doesn't visualize the electron as a tiny corpuscular material object but as a sort of standing wave (given by the Schrödinger equation) whose wavelength fits the circumference a whole-number of times. The states or positions of the electron correspond to the observed energy levels. Predictions of quantum mechanics have been thoroughly tested and always found accurate. However, the problem of understanding how it works remains. Is it not possible to find a "classical" mechanism through which electrons are forced to rotate at a given distance from the proton?

Let us take the idea suggested in the previous section: particles as spherical bodies emitting space-time through a wave field. Can we visualize a mechanism that keeps the electron rotating around the proton at a given distance in a stable way?

We can try, for example, to link the period of the rotation of the electron around the nucleus with the period of the field emitted by the electron. For instance, we can assume that stability is only reached if the period of the rotation of the electron is a multiple of the period of the field it emits. Geometrically, it may make sense to link both periods. We can assume that if the rotation period is not a multiple of the field's period, then the electron needs to adjust its motion until it reaches a radius in which the stability condition is respected. To explain why the electron doesn't fall towards the nucleus, we can assume, for instance, that the energy emitted by the electron (through the field) and the energy it receives from the nucleus are the same at any instant.



Moreover, the field's period is a time-lapse. Time is included in the equation of a wave field by introducing a “t” parameter, whose graphical effect is the rotation of the wave around its axis. Then, we can consider that time is created by the rotation of the waves around their axis (otherwise we would not need the “t” parameter). Space may be created by the three dimensional field and time by the rotation of the field. In other words, according to this model, time would exist because particles' fields rotate around their axis. If fields didn't rotate, space would exist but time would not.

Furthermore, we could try to define other properties of the particle, like mass and charge, through its field. Ideally, space and time would be the only components of all physical entities.

Following this line, we could visualize photons as tiny pieces of the space-time wave field, emitted by particles when they need to adapt to a new requirement on energy and momentum leaving the field unchanged. This might help explain photons' wave-particle dual behaviour.

Moreover, assuming that particles emit the space-time field at the speed of light in the three-dimensional directions may also explain why particles cannot move faster than the speed of light: if particles did so, they would not be able to emit space-time in the direction of motion.

Again, I am not saying that this is the actual model but that it is possible to conceive other geometric and "realistic" ways to try to explain microscopic phenomena.

## 6. Final note

Einstein tried to unify gravity and electromagnetism through a field theory. He admitted the difficulty of describing the outcomes of subatomic physics in that way but considered that it was the only way to remain compatible with the general relativity.

Maybe, rather than to deduce differential equations from basic general principles, it is more convenient to start by drawing a particle and the space-time field around and then, relate the fundamental interactions to the geometrical shape of the field, using its curvature for instance, like in general relativity. Then, microscopic phenomena involving the continuous space-time field could be analysed by using a continuous fuzzy logic, like mentioned in section 3.

This path or other similar ones are not easy to follow but it may be worth exploring. The alternative is to consider that certain aspects of the physical reality transcend human understanding. Simple explanations are more difficult to find than complex ones, because the latter may be adapted whatever is necessary to get the desired result, but at the expense of intelligibility. The solution is maybe simple; what is complex is to find it.