CLASSICAL APPLES AND QUANTUM POTATOES

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My subject indeed is about coherence, in our thinking, that is, and imaging processes, namely, mental ones.

What are these "things" we are theorizing upon and experimenting with : photons (visible, X-rays, etc.), neutrons, electrons, phonons, etc. ? They show a strange behaviour ; at least, "they are all crazy in the same way" (1). It has become customary to describe these "things" (let us adopt for the moment this non-committing terminology) in terms of waves and particles, since these were familiar ideas at the beginning of the quantum era.

Stripped down to its essentials, the particle concept is that of a localized and discrete object (where ? how many ? are meaningful questions), while the wave concept is that of an extended and continuous object (a "field") ; both the extension in space-time and the continuous nature accounts for the occurence of new patterns in a region of space-time where two previously separated waves recombine (superpose, if the theory is linear), patterns which we describe as interference or diffraction effects.

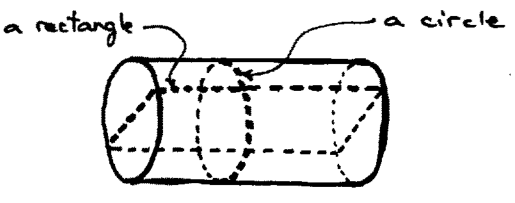
Now, the "things" of the quantum level can be counted, that is, they have a discrete nature, as they transport quanta of energy and momentum, and they are extended as well, since they give rise to diffraction phenomena. It may well be understood why they were first described in terms of particles and waves, since these were the familiar, classical, ideas. Depending on the prominent features of the specific situation, a particle-like or wave-like picture suggested itself. Of course, there was a serious logical difficulty in using two contradictory ideas for describing the same "thing". It was the role of the so-called "complementarity" principle to give a sort of philosophical insurance against the risks of conceptual conflicts.

It must be realized to-day that this view of the quantum world, adapted as it was to its first explorations, is totally outdated. In the past fifty years, we have accumulated sufficient familiarity, theoretical as well as experimental, with the quantum world to no longer look at it through classical glasses(2). Indeed, the very development of quantum physics has shown that our "things" are not waves or particles, not even waves and particles ; in fact, they are neither waves, nor particles. As such, they deserve a new name, "quantons", for instance(3). Of course, the question is not one of pure terminology, and we may well use old words - waves or particles - provided we know and let know that they have a new meaning, in order to prevent dangerous confusions. Similar situations prevail in daily life : if, on a French menu, you read "bifteck, pommes frites", it means "beefsteak, French fries" and the "pommes" are not "apples" : an old world, "pommes (de terre)", was used in the 17^{th} century for a new thing, "potatoes". However, and this shows the possibility of misunderstanding, on the same menu, "boudin aux pommes" means "black pudding with mashed apples" and the word here keeps its old meaning ; the dish is a very different one !

Various examples of such confusions in quantum theory could be given. Let me mention one : the Landé pseudo-paradox. Landé, as several physicists of his generation, never fully accepted quantum mechanics, and tried to explain it away in terms of an underlying classical theory. Landé stressed what he thought was a serious inconsistency at the very basis of quantum theory, namely, the De Broglie relationship $p = h/\lambda$ between the momentum of a quanton (as "particle") and its wavelength (as "wave"). Indeed, he argued(4), this relationship is incompatible with our views on space-time and the equivalence of inertial frames. In Galilean relativity theory, the momentum of course depends on the frame, while the wavelength is an invariant ; De Broglie's relationship thus cannot be true in all equivalent frames, and must be dismissed as a foundation of quantum mechanics (Landé then showed by an elaborate scheme while, nevertheless, it seemed to work). The amusing point about this argument is that it has nowadays become rather difficult to grasp for quantum experimentalists. Indeed, neutron physicists, especially, know quite well that λ <u>is</u> related to p by $\lambda = h/p$ and <u>does</u> change from one inertial frame to the other. This effect has been experimentally checked and is even put to use in neutron technology(5). How then can Landé state that λ is an invariant ? This is precisely the crux of the matter ! In classical wave theory, λ indeed is an invariant : the crest-to-crest distance of sea waves is the same to an aircraft pilot and to a lighthouse keeper. However, a quantum wave-function is essentially different from a classical wave and its wave-length indeed changes, according to quantum theory, so that it matches perfectly the momentum in De Broglie's relationship[6]. In other words, Landé failed to recognize the specific nature of quantum theory and the change in meaning it brings about for "wave functions", "wave-lengths", etc. He mistook "pommes (de terre)" for "pommes (de l'air)", and ordered apples with his steak ; no wonder he did not like it. The irony is that to-day we have become so familiar with quantum waves, as shown by the neutron physicists reaction, that we might forgot about classical waves ; it would be a pity, though, not to appreciate the subtleties of "boudin aux pommes".

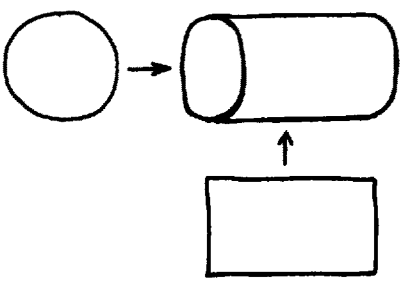
In this one example, the quantum features of the wavelength are readily understood. But there are many instances, in recent times, of situations where naive interpretations, by not recognizing the abuses of language implied by the "wave" or "particle" terminologies within quantum physics, either led to lengthy arguments about the observability of a predicted physical phenomenon, or to disagreements concerning its explanation once observed, or still to the overlooking of potentially useful effects. As examples, let me give for the first case, the recent controversy about the Aharonov-Bohm effect which is now claimed to be nonexistent[7] ! The Hanbury Brown and Twiss experiment and intensity interferometry in general, offer an illustration of the second case, with the dispute over its quantal or otherwise nature. Finally, the elegant "spin-echo" technique in neutron spectroscopy invented by F. Mesei a few years ago[8], clearly shows the power of a full quantum-mechanical picture beyond simple-minded images.

It still remains to understand the rather large domain of applicability of classical "wave" or "particle" ideas. Let me propose here an elementary metaphor. Consider a cylinder. It presents both circular and rectangular features :



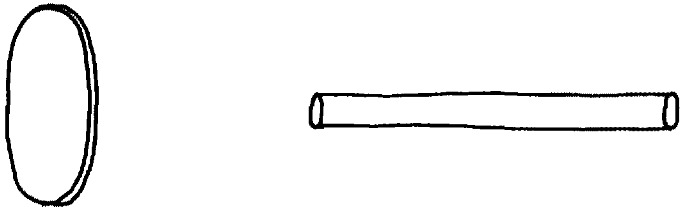
However, it _is_ not a circle or a rectangle, and the ideas of "complementarity" or "duality" of circle and rectangle would be of little use in understanding and describing it. The situation is the same for quantons with respect to waves and particles. A general quantum situation cannot be analyzed in purely classical wave or particle terms, exactly as a cylinder in general transcends the circle or rectangle descriptions. It is true, yet, that very good approximate descriptions of a cylinder can be given with circle or rectangle pictures, exactly as wave or particle pictures may be used for quantons. The conditions for the validity of such approximations nevertheless deserve some attention. One should distinguish, it seems to me, two very different cases where such classical descriptions may be valid, namely 1) a specific description of a general object, 2) a general description of a specific object.

Consider case 1). Using our metaphor, take a general cylinder. Now it is true that there are two specific points of view under which the cylinder is seen either as a circle (along its axis), or as a rectangle (on its side).

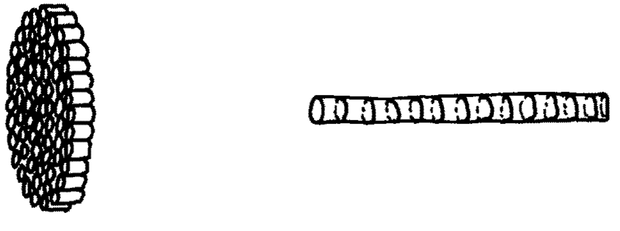


If one sticks close to one of these views, the cylinder will appear little different from a circle or a rectangle. Of course, these points of view do not overlap, so that there is no contradiction in these descriptions ("complementarity"), and they suffice in principle to reconstruct the entire object ("duality"). It is clear, however, that, from a _general_ point of view, the cylinder will not reduce to one or the other of these pictures. The situation is much the same for a quantum object. It is only under very specific circumstances that either a particle, or a wave description will exhaust its appearance. Only in definite experimental setups where the superposition principle is crucial, such as for diffraction effects, will the wave aspect prevail, while the particle aspect will impose itself for instance in collision experiments where the discrete nature of quantons is essential. Any non-specific situation, such as the one of the electron in the hydrogen atom for instance, can only be analysed by using the full conceptual apparatus of quantum theory, as I have already stressed.

Case 2), conversely, concerns the general description of specific objects. Consider, for instance, a very flat cylinder or a very long one :



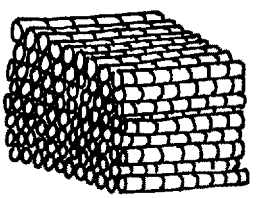
In the first case, a description of the circular faces almost exhausts the appearance of the object, while in the second the side surface only can easily be seen, from practically any point of view. The situation is reversed : one has to adopt a very specific point of view for the rectangular side of the flat cylinder or the circular end of the long one to appear prominently. Similarly, most macroscopic objects, will usually appear either as discrete, localized, chunks of matter ("particles" : pieces of solid material), or as continuous, extended fields (waves", as for the electromagnetic field). If one considers the above flat and long cylinders to be special arrangements of "elementary" cylinders :



exactly as solids or fields are built out of quantons, the analogy is complete.

Of course, it is the very prevalence in our macroscopic world of these rather specific objects which led us to build the naive ideas sufficient to describe them. As long as there seems to be only very flat or very long cylinders, the ideas of circles and rectangles are sufficient. As long as quantons only show up in large amounts with either wave or particle properties, it is not possible to build concepts pertaining to the description of more general situations ! Also, this explanation of the approximate validity of wave or particle ideas in case 2) has a bearing upon the explanation in case 1). It is because of the macroscopic nature of most experimental apparatus and their ensuing "wave" or "particle" character, that the corresponding specific points of view appear as the most natural ones even when looking at quantum systems in general. In other words, most experimental situations, up to rather recent times, automatically selected particular "windows" through which quantons usually only showed either their wave, or their particle sides.

An important question remains, though : how comes that most macroscopic objects look either as waves, or as particles ? How comes that arrangements of the small cylinders which are not either very long or very flat



are so uncommon ? Of course, we now know how to build macroscopic systems which exhibit major quantal properties and do not reduce to a classical wave or particle description : a vessel full of superfluid helium or a laser beam are but two examples. Still, all the more so, the question is certainly not a trivial one and much work yet remains to be done before a satisfying answer exists, showing why classical theories (particle mechanics and field theory) give such a good approximation to quantum theory (see a discussion of some recent work in ref. 2).

In other words, while we now have a good grasp, practical and conceptual, of quantum physics, it is classical physics which requires a better understanding...

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