Discurso de investidura como Doctor "Honoris Causa" del Excmo. Sr. Anthony J. Leggett

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Excelentísimo Sr. Rector, Autoridades Universitarias, Profesores, Señoras y Señores:

It is a great honor and pleasure for me to be receiving an honorary doctorate from the Universidad Complutense, one of the most ancient and distinguished in Europe and indeed in the world. I recall that when I started my research career in 1961, physics in Spain, despite the efforts of a heroic few, was scarcely a blip on the radar; over the last half-century it has been very satisfying for me to watch it blossoming and taking its rightful place on the European and world scene, and since the late eighties, thanks in particular to my association with Dr. Fernando Sols who is now on your faculty, I have been able to make repeated and very fruitful visits to this country. So it is indeed a pleasure to address you here today.

Actually, my own entry into physics was far from conventional; as a schoolboy I certainly did not fit the stereotype of the budding scientist who takes the radio apart to see how it works (had I done so, I could certainly never have put it back together again!). In fact, until my early twenties I scarcely had contact with science at all; my original undergraduate degree was the Oxford Greats degree (classical literature, ancient history and philosophy), and it was indirectly through my interest in philosophy that I eventually migrated into physics. So you might suppose, first, that throughout my career I would maintain an interest in the philosophical issues posed by physics, and secondly that this would automatically draw me towards those areas of the subject which are conventionally characterized as "fundamental", namely elementary particle physics and cosmology. The first supposition is correct, but the second is not; in fact, while I have maintained a strong interest in truly foundational issues such as the quantum measurement problem (on which more below), the "technical" area of physics on which I have spent most of my time and effort over the last 50 years is that which is nowadays known as "condensed matter physics". In the next few minutes I want to tell you why.

What exactly is "condensed matter physics"? One can think of a range of possible definitions, ranging from the very narrow (essentially, what used to be called "solid state" physics) to the all-encompassing (the study of any system of many interacting objects, up to and including the cosmos and the stock market). For present purposes let's make the following somewhat arbitrary definition: Condensed matter physics is the study of any system of physical particles whose mutual interactions are not negligible, at any level above that of single atoms but below that of the universe. This then includes not only the subject-matter of traditional solid- and liquid-state physics but also most of astrophysics, biophysics and chemical physics; more generally, it almost automatically includes any physics which is likely to be relevant at the human scale.

Why is this kind of physics interesting? The first and most obvious answer is that any physics-based technological advance which is likely to be directly relevant to practical human concerns has to occur at the human scale, and is therefore automatically the province of condensed matter physics; think of transistors, light-emitting diodes, liquid-crystal displays, magnetocardiac detectors... But important as this consideration is, it is not what drew me into the field; rather, it was the purely intellectual challenge, and it is this latter that I want to address.

Let me start with a bit of devil's advocacy. Here are a couple of quotes from distinguished elementary particle theorists which reflect a widely held view of the relative interest and importance of different areas of physics:

“Important theories do emerge in other sciences [than elementary particle physics and cosmology]... How truly fundamental are they? Do they not result from a complex interplay among many atoms, about which Heisenberg and his friends taught us all that we need to know long ago?” [S. Glashow, Physics Today, Feb.1986, p.11]

“No one thinks that the phenomena of phase transitions and chaos...could have been understood on the basis of atomic physics without creative new scientific ideas, but does anyone doubt that real materials exhibit these phenomena because of the properties of the particles of which the materials are composed?” [S. Weinberg, Nature 330, 435 (1987)]

Now the interesting thing about these quotations is that both are framed as rhetorical questions; and while I may no doubt be unduly cynical, to me the use of a rhetorical question very often conceals the fact that at a deep subconscious level, the speaker is not quite as certain of the answer as he or she would like us to believe. I will now attempt to make two counter-arguments to the above point of view; the first is to some extent in the spirit of remarks made by other condensed matter theorists such as Anderson and Laughlin, while the second is much more radical and personal.

First, let's grant that were the properties of atoms very different from what we know them to be, then the behavior of the macroscopic (everyday-level) objects composed of them would also be quite different. But the converse is also true! So in what sense does the behavior of the macroscopic objects “result from” that of the atoms rather than vice versa? Why do we implicitly assume that since large objects are made of small objects, the properties of the latter <u>cause</u> those of the former? I wonder if it is not at least partly because we subconsciously remember (some of us!) our childhood experience of taking that radio apart to “see how it works”. But the radio works the way it does precisely because some human agent started with the component parts and deliberately put them together in a particular way and for a particular purpose; by contrast, the overwhelming majority of systems studied in condensed matter physics involve no such Aristotelian “final cause”.

Of course, it is true that most condensed matter physicists believe that “in principle” we should be able to derive the behavior of complex macroscopic objects from a description which refers only to the individual component atoms and (usually) their pairwise interactions. So what? Does that mean that the consequences of these interactions are less "fundamental" than the atoms themselves? Let me try to illustrate this point with an analogy from the social sciences: Suppose that a sociologist were to propose that by studying the behavior of a sufficient number of pairs of people confined on desert islands, she could "in principle" infer the economic performance or political behavior of nation-states. I think she would be laughed out of court, and rightly so, because it is a matter of common experience that the interaction between any two individuals is itself profoundly influenced by the social setting in which it occurs. So the claim that economics and politics work the way they do “because of” the properties of individual humans and their pairwise interactions, while perhaps at the most literal level formally true, is essentially vacuous. Why do we (most of us) take a different view when it comes to physics?

To elaborate the analogy with the situation in the social sciences further, just as “economics” or “politics” can scarcely be even defined at the level of pairwise interactions, so there are many phenomena which occur in condensed matter systems which simply have no analog for single atoms or small collections of them. (This kind of consideration is sometimes lumped with a number of related ones under the catch-all buzzword "emergence", though I do not myself feel that the word adds anything much). Let me try to give one example, although it is perhaps somewhat technical: Generally speaking, an electron circling an atom is not in its equilibrium state (which is non-circulating), and will therefore return to that state rather rapidly (typically in about a billionth of a second). As far as we know, the same would happen for a single electron, or for that matter a single atom, circulating in a large doughnut-shaped container (although the experiment would be difficult to do). If however we fill such a container with liquid helium at a temperature below 2 degrees absolute and set the helium into rotation, it will not relax but will continue to circulate for as long as we care to look at it! (This is part of the complex of phenomena we call “superfluidity”). Let me try to sketch the essentials of the explanation using the following analogy: Imagine you take some doughnut-shaped object (a hula hoop, a bicycle inner tube...), wind a string around it a certain number of times (call it n) and then tie the ends of the string back together. You can easily convince yourself (or verify by experiment!) that provided you are not allowed to cut either the string or the hoop, no matter how much you shuffle the string you can never change the “winding number” n; this is a simple example of what in physics is called a topological conservation law. Now it turns out (I won't go into the technical details) that an electron in an atom, or an atom in the doughnut-shaped container, is described by something like the string; a winding number of zero corresponds to a non-circulating state, while a nonzero value corresponds to a circulatory motion. The important difference between the single atom and the myriad of atoms constituting the liquid helium is that in the former case it is relatively easy to “cut the string”, while in the latter case, as a result of the collective behavior of the atoms, it is virtually impossible. So the atom relaxes easily to the equilibrium (non-circulating) state while the helium remains circulating for ever. No calculation based on single atoms or even small collections of interacting atoms could have predicted this.

This state of affairs (which has been understood, at least qualitatively, for many years) is a rather simple example of the way in which collective (“many-body”) effects can produce behavior which is qualitatively different from that of single atoms or small groups of them. An even more intriguing possible example relates to the topic of “topological quantum computing”; it is believed that by exploiting the subtle properties of quantum mechanics applied to many-particle systems (properties which really have no analog at all at the level of single atoms), it may be possible to build a computer which not only operates on intrinsically quantum-mechanical principles (thereby gaining many orders of magnitude in the speed with which it can perform certain types of operation) but, unlike previous proposals for such a device, is guaranteed to be error-free. Although this idea is still on the theoretical drawing-board, it is a fascinating example of the way in which quantum mechanics and condensed matter physics can intersect to produce a totally novel state of affairs.

I turn now very briefly to my second counter-argument to the point of view embodied in the two quotations I have given you above. Is it in fact the case that all physics at the level of everyday life can be accounted for, even in principle, in terms of the laws describing single atoms (etc.)? This seems to be the “default” point of view, and I would have no particular difficulty in accepting it were it not for a single major stumbling-block, namely the so-called quantum measurement paradox. This paradox goes roughly as follows: If we believe (as almost all physicists, including the present speaker, do) that matter at the level of single electrons or atoms is completely described by the laws of quantum mechanics, then it seems prima facie to follow that an electron or atom faced with two or more different courses of action does not have to select one or the other but can as it were explore both possibilities in parallel. But if objects at the everyday level are (as again almost everyone believes) composed of electrons and atoms, then the same should follow for such objects, and as was shown in a famous 1935 paper by Erwin Schrödinger, one should be able to set up situations in which a cat inside a closed box is in some sense neither alive nor dead but manages to explore both possibilities in parallel. Clearly this flies in the face of our everyday common sense (since our overwhelming expectation is that when we open the box and inspect the cat, she will be either alive or dead). While there have been literally thousands of papers in the physics literature over the past 75 years which have claimed to resolve this paradox, my personal opinion is that none of them have been successful; and I would therefore take it as a very real possibility that there truly are new laws of physics which come into play at some point between the level of the atom and that of the cat. Should this turn out to be so, no-one will any longer be able to maintain that condensed matter physics is merely a “derivative” and non-fundamental area of physics! Much of my research over the last 30 years has been devoted to exploring ways of testing experimentally whether or not this is so.

At any rate, I hope what I have said in the last few minutes helps to explain why I have made condensed matter physics my life's work. It just remains for me to thank you for the honor you are bestowing on me and to wish the Universidad Complutense a happy and prosperous future.