Francesca Bonicalzi, Pietro Brighi

Matter today. Interview with a matter physicist

Pietro Brighi is a researcher in the field of quantum matter physics, working in Vienna at the Institute of Science and Technology (IST Austria), a recently founded but constantly growing fundamental research institute. We are asking him to help us get closer to what is the meaning of "matter" in contemporary physics. The discussion over matter has always suffered from common sense, which typically labels whatever has concrete appearance or can be perceived by our senses as matter. In modern thinking, matter and body merge into a unique concept and the relevant terminology remains affected throughout the nineteenth century, being opposed to spirit, soul, mind. Twentieth-century science, particularly since the period known as the scientific crisis marked by the work of notable scientists such as Einstein, Planck, Heisenberg, completely transformed our idea of matter.

Francesca Bonicalzi: As a first question, I would like to ask you to help us overcome the legacy of ordinary sensibility or common sense, and to become better acquainted with the idea of matter in contemporary physics. If possible, we would like you to try to explain, in a nutshell, what is meant by "matter" in the physics community nowadays. In that way we will have a common ground to start our discussion.

Pietro Brighi: I would say that the concept of matter in modern physics is manifold. Since this response may appear to evade your question, I will attempt to be more specific. On the one hand, we have branches of condensed-matter physics that study, both theoretically and experimentally, actual materials and their behavior in various conditions. I would call these branches "traditional condensed-matter physics". Those who work in this field, focus on explaining anomalous behaviors due to the interaction among electrons in particular conditions. A remarkable example, in my opinion, is the so-called "magic angle" in graphene: as you probably know, graphene is a very interesting material made of a single atomic layer of carbon atoms, yielding a truly two-dimensional material. As it turns out, taking two layers of graphene and tilting them to a very specific relative angle gives rise to superconductivity, while at all other angles the material behaves "normally". This phenomenon attracted a lot of attention and it is still, as of today, unexplained. This kind of questions, whose answer tends to be very hard to find, is mainly related to the interplay of interactions and geometry of the systems.

On a different line of research, we find so-called "artificial quantum matter". In this field, instead of using actual materials, researchers exploit modern technology to confine atoms in a lattice whose structure is highly tunable, therefore allowing for very precise control over the interactions among them. In this way, it is possible to explore phenomena which would not be visible in normal materials and to adapt experiments to specific theories that researchers are interested in, instead of the other way round. This allows for the study of very deep and fundamental questions, such as the issue of thermalization in closed quantum systems. Typical quantum systems reach thermalization through interaction with an external bath, which provides energy or particles necessary to reach thermal equilibrium. Studying what happens once we close a system, removing the bath, can therefore be very revealing on a fundamental level. It turns out that not all systems reach thermal equilibrium – a fact which can lead to profound insights into the mechanism of thermalization itself.

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Trying to wrap all of this up, and finally answer your question, let me say that "matter" today has a very broad meaning, including what we can see or imagine (such as pieces of metal or wood) but also systems we would not tend to describe as "matter" in a classical sense. In both cases, though, matter provides an optimal ground to explore phenomena we cannot yet fully explain, and to improve our understanding of the mechanisms that, although happening at a microscopic level, still have evident macroscopic effects.

F.B.: In your opinion, what issue or problem must be faced in order to obtain noteworthy progress in the physics of matter? What is the question that needs to be studied or, more properly, what is the theoretical bottleneck that must be overcome?

P.B.: This is a very tough question. Of course, there are many issues that are central relative to a particular sub-field (I am thinking, for instance, of the question of high critical temperature superconductors). On a more general ground, I think that the main obstacle is represented by the astonishing complexity of problems once interactions are taken into account, which is also what makes it such a rich field. Unfortunately, this is something intrinsic to each experimental context, so at the moment we are able to treat these topics only with the aid of approximations. In my opinion, the only *tool* within reach in the next decades is represented by *quantum computation*, which will, in principle, allow for an exact numerical study of many different systems.

F.B.: Do physicists and chemists, when they discuss the concept of "matter", speak the same language? Has the scientific community acquired a common understanding of matter, or does the high degree of specialization force different disciplines to make distinctions?

P.B.: Although from varying perspectives, physicists and chemists still speak a similar language when it comes to "matter" due to its shared commonality amid its many differences in usage. Surely, both chemists and physicists think of a typical material as a collection of atoms, or more generally ions, ordered in a particular way to form a lattice. On the other hand, the focus is very different given that the description which chemistry gives is much more connected, in my understanding, to the nature and behavior of a single atom or ion, while physicists tend to forget about the particularity of components and look at their collective behavior. Furthermore, the methods used can be very different, due to the different types of expertise required and displayed by the two disciplines. Generally speaking, I would say that on a deep and technical level it is very hard, even among physicists, to understand one another, due to their very high degree of specialization. Nevertheless, more phenomenological discussion is certainly possible and, in my opinion, beneficial between different sciences.

F.B.: Often, the terms "matter" and "materialism" are bound together; the latter, especially in the past centuries, has been related to a certain interpretation in science itself, besides history. Does it still make sense to talk about materialism? Does the materialistic approach still have epistemological power in today's physics, or does it no longer pertain to the physicist?

P.B.: Nowadays the term "materialism" does not come up very often in daily discussions among scientists, at least not in my experience. Nevertheless, I believe that the way each researcher approaches scientific production and science itself is often entangled with his or her philosophical ideas, and in that regard I would say that materialism still plays a role. While the concept of "matter" has no doubt changed considerably over the past century, it still guides many scientists in their work, and perhaps this is even more so in a branch such as the physics of matter.

F.B.: Gaston Bachelard is a twentieth-century epistemologist who proposed original and complex approaches. More than seeking a new definition of matter and materialism, his work aimed at asking and wondering about what types of experiences or mind structures produce matter as an epistemic effect (not to mention a poetic effect, which lies beyond the scope of our current discussion). In what ways can science keep being objective and material? What are the roles of experiment and mathematics?

P.B.: While the quantum mechanical revolution has shaken our understanding of what is objective, by highlighting the huge impact that the observer has on the phenomena that he or she is observing, there is still a way to define and understand science in an objective way. As an example, we could look at the particle-wave dualism. A naive analysis could summarily conclude that it is impossible to define objectively whether a particle is indeed a particle, or if it is a wave. However, I believe that such a conclusion would be erroneous, because the question itself is based on our ordinary life experience, which would naturally expect an object to be either wave or particle, but not both. The duality, being extremely counter-intuitive, cannot be fully understood with the lone experience of the world surrounding us, but it needs a change of perspective. So, to answer your first question, I think that to keep being *truly objective*, science needs to look for new perspectives and change its paradigms to be able to cope with the non-intuitive phenomena that scientific researchers encounter every day.

The way to do so lies in a strong collaboration among theorists and experimentalists, as both branches are absolutely essential to the progress of knowledge. Furthermore, it is fundamental that they communicate, in order to develop new ideas. From my perspective as a theoretical physicist, for instance, I could miss some details that an experimental scientist would instead grasp, and vice-versa. To delve more deeply into the subject, mathematics always offers a very good set of tools to get insights into the behavior of a system. Unfortunately, the great complexity of problems we study requires the use of a large number of approximations, whose accuracy can be more or less precise. Often, to be able to understand which approximation makes best sense in a given system, it is very useful to look at experimental data that can guide us in the correct direction. Conversely, the understanding of some intricate experimental data can come from predictions, perhaps made theoretically on much simpler grounds, but which still hold in the very complicated world of experimental physics. Both experimental research and mathematics (as applied in theoretical physics), pose very interesting questions to one another, and in my view – as in Bachelard's – it is exactly this *exchange of questions* from different branches that keeps our mind always ready to change its ideas on something, when disproved by either a theorem or an experiment.

F.B.: The reading of Bachelard's epistemological writings raises specific questions that I would like to raise: is matter an effect? Where is it found, or where is it produced?

P.B.: I think that whenever a new intuition about matter emerges so that a new concept is produced, it is certainly an *epistemic effect*, meaning that its experience through experiments or analytic studies comes as an aftermath of human intellect. With this I do not mean to claim that the existence of such phenomena is entirely related to our experience of them. I do believe that they would exist on their own. What I mean, perhaps, is that their existence *for us*, or in relation to us, happens through the observation of particular effects which we can acknowledge only through our intellectual activity.

F.B.: How does all this affect the individual, how can we talk about the profession of the scientist? In which way, in your opinion, does this new scientific work contribute toward the creation, or emergence, of a new and deeper aspect of humankind?

P.B.: The major feelings I have experienced when it comes to my job are curiosity and wonder. It was wonder, in the first place, that drove me to this particular field of research. The very idea that microscopic and quantistic phenomena can play such a fundamental role that they affect the macroscopic behavior of certain materials has always amazed me. Therefore, I would say that the scientist must be guided by these two forces, and that together with open-mindedness, they define the job itself. Unfortunately, this is not an easy or minor matter to explain and communicate to the non-scientific public. Sometimes some of the work that is done even seems pointless or completely detached from reality (this highlights the role of scientific communication, which is a crucial one, I believe). However, in my opinion, scientific research, when properly done, always produces advances in humankind. A deeper understanding of the world we live in (and how we come to know it) increases our awareness as human beings, and raises new questions whose impact can go, and have at times gone, beyond scientific knowledge.

F.B.: Bachelard's epistemological thinking is always entangled with the historic reality of science, understanding the route of a theory to success, what is the problem or experiment inspiring it, what it leaves behind and what changes in current knowledge it implies. Do you think this is relevant only with respect to didactic matters, or might history itself be an intrinsic factor in science?

P.B.: I believe that science or scientific work is highly influenced by its historical contour. The simplest way this happens is through funding: governments and companies fund the research they believe is most important or rewarding, and these decisions clearly affect the focus of science within a definite period of time. This first reason is maybe shallower, but it affects research at a very high level in its hierarchy, as it acts at the level of research groups, if not directly of departments or universities. On the other hand, I think that history acts in a deeper way on each individual who is involved in scientific research. In fact, the mainstream customs and ideas of a certain period affect everyone's way of thinking, and will therefore also condition the way research proceeds. For these reasons, I believe that a very strong link exists between the body of scientific research and the historical environment within which it was conducted.

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