Chapter 1. What is Condensed matter physics?

In science classes high school students are often taught that there are only three states of matter: solid, liquid, and gas. However, this is quite misleading as there are many more different states of matter. For example, what are the ``liquid crystals'' that are the basis of LCDs (Liquid Crystal Displays) in the screens of televisions, computers, and smart phones? How can something be a liquid and a crystal (solid)? Furthermore, solids can be found in many different states. Ice is solid water, but there are actually eighteen different states of solid water, depending on the pressure and temperature. Each state of matter has distinctly different physical properties. All these different states we refer to as condensed phases of matter. We use the word ``condensed'' in the same sense as that steam condenses into liquid water. Condensed matter physics is concerned with characterizing and understanding all these diverse states of matter.

In order to understand what a specific academic discipline is there are a series of different questions one can ask. What are the objects of study? What are the big questions that the discipline aims to answer? What techniques are used by the discipline? How is the discipline related to other academic disciplines? What are the key concepts and ideas in the discipline? What are the major achievements of the discipline? What is the history of the discipline? Why is the discipline important? How is the discipline ``useful'' in the sense of enhancing human life? What are major outstanding challenges that the discipline faces? In this *Very Short Introduction* I will aim to at least partially answer all of these questions about Condensed Matter Physics (CMP). However, I will mostly focus on introducing the reader to the key concepts because I believe they embody why CMP is so important, is so useful, and is intellectually rich, exciting and challenging.

The Big Question

In order to introduce the main question that CMP addresses I now introduce a concrete example. Consider graphite and diamond. Both are composed solely of carbon and both are solids. Graphite is commonly found in lead pencils, whereas diamond is found in jewelry. However, although both are solid carbon, they have distinctly different properties. Graphite is common, black, soft, and conducts electricity and heat moderately well. In contrast, diamond is rare, transparent, hard, and conducts electricity and heat very poorly. What is the origin of these distinctly different physical properties of graphite and diamond? CMP has shown that the answer lies in the fact that the carbon atoms have a distinctly different geometric arrangement in these two solid states (see Figure 1).

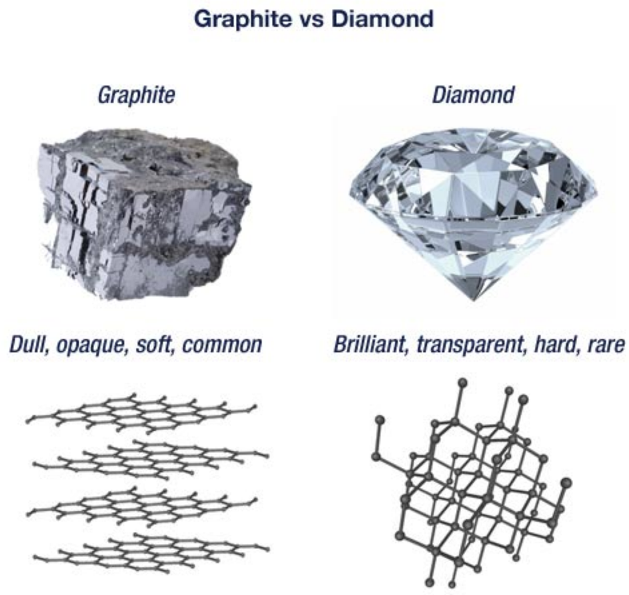

Figure 1. Comparison of the different properties of graphite and diamond. The lower figures show the arrangement of the individual atoms in the solid. Each circle represents a single carbon atom and each solid line represents a chemical bond.

In diamond every carbon atom is next to four other carbon atoms. In graphite every carbon atom is next to only three other carbon atoms and they form layers with a honeycomb pattern. These layers are then stacked on top of each other. The question that CMP has been able to answer is: how do the distinct properties of graphite and diamond *emerge* from their distinct properties at the atomic scale? This is a specific example of the central question that CMP seeks to address:

How do the properties of a distinct phase in a material emerge from the interactions between the atoms of which the material is composed?

A major ongoing scientific challenge is to understand such collective phenomena. How do the many atoms in a material interact with one another in order to act collectively to produce a particular property? In different words CMP aims to find a connection between the *microscopic* and *macroscopic* properties of a system. The microscopic properties are those on the atomic scale, such as the type of atoms or molecules in the material, their geometric arrangement, and how they interact with each other. We cannot see the atoms with the naked eye but need probes such as x-rays. Macroscopic properties occur on the scale of everyday experience, i.e. we can see or experience them, for example we can feel that diamond is hard and see that it is transparent. We can measure the electrical conductivity of a solid with an electrical multi-meter. Macroscopic properties can be determined without any knowledge of the microscopic properties of the material. For example, we can measure the density, temperature, and pressure a gas without knowing anything about what kind of atoms or molecules the gas is composed of. Macroscopic properties can be viewed as collective or emergent phenomena. They do not have any meaning at the atomic scale. The hardness, colour, or conductivity of a single carbon atom has no meaning.

CMP uses a diverse range of techniques: chemical, experimental, theoretical, and computational to address the central question above. To appreciate the diversity of techniques and the need for this diversity it may be helpful to consider something readers might be more familiar with, the collective social phenomena of standing ovations.

The standing ovation problem

Reflect on your experience on attending concerts, lectures, and speeches. Some received a standing ovation and others did not. Why? Consider how with time a standing ovation develops or does not develop. First, a few enthusiastic people may instantly stand at the end of the performance. Gradually, others will stand. Others will not. Why? It is not simply a matter of what people thought about the performance. There is an element of social pressure. Be honest. If everyone around you is standing or seated that will have some influence on what you do, regardless of what you thought of the performance. Furthermore, without turning around you can only see the people in front of you. You may not be able to see the people on the balcony above you.

There are many questions we can ask about this collective social phenomenon? What is the time scale on which standing ovations develop or die out? What are the spatial patterns associated with the development of ovations? For example, do ovations develop from groups of individuals standing together and the size of that standing group growing outwards? What is the relative importance of what people thought about the performance compared to what others thought? Are there any common features to all standing ovations? What would be the simplest possible computer model that might simulate the phenomena? What are the key variables and parameters? Does this problem have similarities and provide insight into some other social phenomena where the behavior of individuals is influenced by those around them? Some examples include spread of crime in a neighbourhood, emergence of a riot, whether parents vaccinate their children, or outbreak of a drug epidemic.

Arguably, a good approach to understanding this collective social phenomenon may be a multi-disciplinary approach that brings together psychologists, sociologists, acoustics experts, and computer scientists. The best investigative techniques may include a mix of experiment (gathering and analysis of data), interviews of audience members, video and sound recording of audience responses, model building, and computer modelling. There is also a set of scales associated with the problem: size of the audience, size of standing groups, time scales, length scales, and level of diversity in the audience. However, it is debatable what relative importance and resources should be given to the different disciplines, to the different techniques, and the different scales of the problem. A good balance will only become apparent after doing some investigations and seeing what is fruitful, what is not fruitful, and how the knowledge gained can be integrated into a coherent picture.

A multi-faceted approach

Now, back to condensed matter physics: what are effective strategies and techniques for understanding the collective phenomena associated with a specific material, class of materials, or state of matter? Just like for the standing ovation problem a diverse range of techniques and approaches is needed, including those that address the phenomena at different scales. Similarly, there is always debate about what is the best mix of techniques and approaches. Broadly, I will divide the techniques used in CMP into the following categories: chemical synthesis, sample characterization, measurement of physical properties, measurement of atomic scale properties, theory, computation, comparison, and intellectual synthesis. All of these turn out to be important and scientifically challenging. Some scientists spend their whole career just working on one of these approaches. It may be helpful to illustrate these different approaches for the specific case of graphite with a view to working towards an answer to our basic question of why graphite and diamond are so different?

We want to quantify the properties of graphite such as how well it conducts electricity in order to test theories of its properties. In order to do this, we first need a good sample of graphite, i.e. we want a sample that is chemically pure and preferably a single crystal. The graphite found in lead pencils is not good enough because it contains lots of impurities, i.e. it is not just carbon. Impurities can have a significant effect on properties. Thus, we need to either find a highly pure sample in nature or have a good solid-state chemist *synthesize* a pure sample. But how do we know if they have done a good job? There are sophisticated chemical and physical checks one can make to *characterize* the sample and see if it is a good enough sample for our purposes. We also may want to cleave off a single crystal. Next some *fabrication* will be involved to connect small electrical wires to the sample so we can measure the electrical conductivity of the sample. Here, the quality of the surfaces and the electrical contacts can matter a lot. We might *measure* the conductivity as a function of several external control variables such as temperature, pressure, and magnetic field. But, we also want to know the physical properties of the graphite at the atomic scale. One approach to determine this is to scatter x-rays off a crystal (X-ray crystallography, to be discussed in chapter 3). This allows determination of the relative positions of the carbon atoms in the crystal.

If we know the microscopic and the macroscopic properties then the challenge for *theory* is to provide a bridge between them. Specifically, a good theory can take the details about the arrangement of the carbon atoms and calculate what the conductivity is as a function of external parameters. The relative merits of different theories can be determined by comparing how the properties calculated by the different theories compare with the macroscopic measurements. However, calculation of the properties of a theory often requires supercomputers. Thus, there is a whole *computational* subfield that takes the equations of the theory and designs and tests algorithms to solve the equations on the computer. However, we don't want just a theory of graphite but also of diamond, and in fact many other materials. We don't want a different theory for every different material. Rather we want a *unifying* theory that can explain and describe properties of broad classes of materials. So, we contrast and *compare* the properties of graphite with other classes of material. Finally, ultimately, we want a few unifying *concepts* and organizing principles that can help us understand and describe the properties of all states of matter. The major goal of this VSI is to introduce some of these unifying concepts.

In summary, CMP involves a multi-faceted approach and a diverse toolbox of techniques. There is a complementarity and synergy between the different techniques used. Success really depends on using all of them in order to get a complete picture. However, the relative importance or value of the different techniques is often hard to anticipate and can vary significantly depending on the material system or phenomena of interest. One key idea that does emerge is that of the *many scales* of the problem. There are often unanticipated scales that are intermediate between the atomic scale and the macroscopic scale. These can be scales of length, time, and energy. Hence, one needs different experimental probes that are relevant to the scale of the phenomena. For example, there are many different forms of electromagnetic waves: microwaves, infrared, visible light, ultraviolet, and x-rays. They have quite different wavelengths and frequencies. Hence, to study and probe a phenomena that occurs on a particular scale it is necessary to ``shine light'' with the appropriate wave length. X-rays will reveal the atomic structure, whereas infrared with elucidate the dynamics of the electrons responsible for electrical conductivity. Similarly, one can develop theories that are appropriate for different scales. Finding the relationship between the different theories for the different scales is a challenge.

Why is CMP so rich and exciting?

One reason is that it is so full of surprising new discoveries: new materials and new phenomena. It is hard to anticipate what will be discovered next. This is arguably because it is very hard to predict emergent phenomena in complex systems. Throughout this VSI I will provide examples of exciting discoveries, many of which received Nobel Prizes. Here, I will give one example: the discovery of graphene in 2004. Going back to graphite, in Figure 1, we see how it is composed of layers of carbon atoms, where in each layer the atoms form a honeycomb structure. This was known since 1924. Given that the individual layers are only weakly bonded to each other an interesting question is whether it would be possible to ``peel off'' a single layer which is called graphene. Figure 2 shows the atomic structure of graphene. The electronic properties of graphene were studied theoretically in 1947 by P.R. Wallace. However, it was not until 2004 that graphene was isolated, characterized, and studied, by a group at the University of Manchester led by Andre Geim and Konstantin Novoselov. What is fascinating and surprising is the simple “low-tech” technique that they used to produce the single layers of carbon atoms. They did not use expensive state-of-the-art scientific equipment, but rather a common household item. They simply took some graphite and used sellotape (also known as sticky tape or scotch tape) to peel off single atomic layers. They were able to determine their electronic properties, such as how well the layers conducted electricity or reflected light. They found that the electronic properties were significantly different from those of most materials. For example, it turns out that the electrons in the graphene that conduct electricity behave in a manner more characteristic of light particles (which have no mass) than isolated electrons (which do have mass). Fans of the TV show, *The Big Bang Theory* may recall how Sheldon Cooper spent a whole episode obsessing about this question.

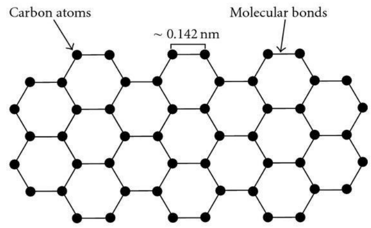

Figure 2. The atomic scale structure of graphene.

Why is CMP ``useful"?

It is central to technology we use and take for granted. Examples include transistors in computer chips, solid state lighting, photovoltaic cells, liquid crystal displays, optical fibres, micromagnets in computer memories, and superconducting magnets in MRI (Magnetic Resonance Imaging) machines. Hence, given the diversity of possible states of matter and so many technological applications it is not surprising that CMP is the largest sub-field of physics. This size is reflected in the relative numbers of physicists, journal articles, citations to journal articles, and Nobel Prizes.

What is the relationship of CMP to other academic disciplines?

CMP does not have clear boundaries. CMP is a rich source of ideas, concepts, and techniques that have cross-fertilised with other sub-fields of physics and scientific disciplines (chemistry, biology, computer science) and engineering (materials and chemical). Indeed, in the last two decades, eight condensed matter physicists have been awarded a Nobel Prize in Chemistry. One way to contrast and compare CMP to two "fundamental" sub-fields of physics, cosmology and elementary particle physics, is the following. Cosmology is concerned with the *infinitely large*: the scale and history of the whole universe. Elementary particle or high energy physics is concerned with the *infinitely small*: finding the elementary building blocks of all matter (quarks, electrons, the Higgs boson) and the forces between them. In contrast, CMP is concerned with the *infinitely complex*: how extremely large numbers of atoms or molecules behave when they interact with one another. At different points in this VSI I will provide specific examples of cross-fertilisation with other disciplines.

Overview of this Very Short Introduction

I now give a brief overview of each chapter that follows, highlighting the key ideas that will be described. The next chapter introduces some of the multitude of different phases of matter that have been discovered. Transitions between distinct phases are defined by discontinuities in properties. Phase diagrams encode what phase is stable under specific external conditions such as temperature and pressure.

Chapter 3 describes how the unifying concept of distinct changes in symmetry enables one to classify and distinguish different phases. In the following chapter we see how the qualitative change associated with a phase transition can be quantified in terms of just a few numbers (known as an order parameter) that quantify the change in symmetry and the ordering of the components of the system.

Chapter 5 discusses how confining a material to one or two dimensions can lead to new states of matter. Furthermore, imagining a world of variable dimension can actually lead to a better understanding of materials in our three-dimensional world.

Chapter 6 describes how at a specific value of the temperature and pressure the transition between two different phases is not associated with discontinuous properties. Near this critical point in the phase diagram one observes a surprising universality: very different material systems can have the same properties. This arises because of the many length scales that emerge in the system.

Chapter 7 introduces the weirdness of quantum theory, something that is most commonly manifest at the level of single atoms and molecules. Surprisingly, quantum effects can also be seen "with the naked eye" in states of matter such as superconductors and superfluids.

Chapter 8 considers how some abstract ideas about shapes (what is the difference between a donut and pretzel?) help understand new states of quantum matter and the kinds of `defects' found in many states of matter.

Chapter 9 discusses how CMP is essentially about emergence, i.e. how the whole is greater than the sum of the parts. This connects to some broader philosophical questions and to the relationship between different scientific disciplines.

The last chapter reviews the main ideas, discusses scientific challenges that remain for CMP, and what lessons CMP may have for other academic disciplines.

In review, CMP is concerned with studying and understanding material systems composed of large numbers of interacting atoms. The main question is how do the properties of the system and new states of matter emerge from the properties of the constituent atoms and the interactions between them? CMP involves a multi-faceted approach and a diverse range of experimental and theoretical techniques. This diversity is required because there are a range of different scales associated with the problem. Moreover, in spite of the incredible diversity of materials and different states of matter, CMP involves a unifying set of concepts.

We now turn to the following questions. How do we know if we have discovered a new state of matter? How do we codify and classify the diverse states of matter that exist?