CHAPTER 1

The quest for an understanding of matter

1.1 Welcome

People have wondered about the properties of matter for many centuries and have written many excellent books on the subject. Even books that were printed half a century ago are relevant today. The properties of matter, and our theories about matter, have changed relatively little in this time. This is not to say that new phenomena have not been discovered and explained: for example superfluidity and superconductivity have been exciting areas of advance in understanding. However, the laws of thermodynamics have not changed and the speed of sound in copper is the same as it was 100 years ago. The scientists who have worked during this century have left you, students of physics in the new century, a truly vast legacy of experimental results and theoretical analysis. Your mission, should you choose to accept it, is to acquaint yourselves with this legacy.

The study of the properties of matter is like an ancient party. Over millennia, it has at times been quiet, at times riotous. Famous figures have attended, but most of the people here are just like you and me. As I write today, the party is bustling after a century or so of explosive chitter chatter. What will happen next? I have no idea, but I expect it will be interesting. I hope you will stay to find out.

1.2 Personal experience

More than half a lifetime ago I was a student of physics. From the manner in which I was I taught the various elements that comprise the study of matter, I learned several lessons that it has taken me a long time to unlearn. Firstly, I learned that it was not necessary to actually know what the properties of matter were in order to debate them earnestly. This is, of course, rubbish. However, fear of my own ignorance prevented me from realising this earlier. Secondly, I learned to avoid thinking about awkward subjects. I imagined that cleverer people than myself had sorted these things out. This is rubbish too, but fear of my own ignorance still haunts me here.

In hoping that your experience will differ from my own, I would urge you develop your study of the properties of matter along the following lines. Firstly, ‘make friends’ with matter: become familiar with what the properties of matter actually are. These properties have been determined and tabulated for thousands of substances so it is not difficult. I believe that unless you are familiar with the properties of matter it is impossible ever to say that you understand them. Secondly, and also secondarily, try to think about why things are the way they are. Often the data seem perplexing, but they usually make sense eventually.

1.3 A historical perspective

1.3.1 Discovery and rediscovery

Before embarking on this contemporary study of the properties of matter, it is instructive to spend some time reviewing the historical context in which this study takes place.

In all aspects of my own work as a scientist, I am constantly reminded that ‘others have been here before’. That although I am discovering particular facts for the first time, these facts are leading me to re-discover the insights of previous generations of scientists. These scientists lacked the technical resources available today, but in their place used resourcefulness, dedication and imagination in a truly inspiring combination.

After overcoming my depression at the dimly retreating prospect of scientific stardom, I have realised that this process of rediscovery is not failure. Indeed it was – and is – the essential process through which the health of the scientific body is maintained. Further, I realise the process is not the work of a degree course, but of a lifetime. If you wish to learn about physics, the only way is to rediscover it for itself.

Unfortunately, rediscovery is as hard as discovery, but without the glory. In writing this book I have tried to ease your work of rediscovery of the properties of matter. I have written this book by collating data on the properties of matter, writing down a list of questions that occurred to me as I examined the data, and then trying to answer these questions on your behalf.

1.3.2 Familiarity and over-familiarity

The initial section of each topic in this book is a discussion of the data on that topic. Before discussing the theories about what happens, I wish you to become familiar with what actually happens. In this way I hope to allow you to rediscover some of the more striking properties of matter for yourself.

However in encouraging this familiarisation I encounter a severe problem. The problem of an improper over-familiarity with rather sophisticated theories about matter. For example, many of you reading this will have seen images of atoms: you will have heard or even taken part in discussions of their detailed structure. I would go so far as to say that many of you believe in atoms. However I would also venture that many of you believe in atoms not because of insights you have made yourself, but because you have been told that they exist and you have been told that they possess certain properties. I am sure your teachers have taught you well, but being told something is different from convincing yourself it must be so. This is the sense in which I would like you to embark upon the study of matter. Do not believe it until you have seen the data! I would like you to be sceptical about the data in this book, about the theories presented here, and most of all about your own credulity.

1.3.3 Consciousness lowering

In order to help get in the mood to rediscover the properties of matter, you may care to take part in an exercise in ‘consciousness lowering’.

Picture yourself in the late seventeenth century, look around you. The ‘stuff’ of the world – the matter – is diverse in its properties. You can probably see wood, metal, stone, paper and – most amazingly – animated flesh. Your task is to categorise these substances and their experimental properties. What do they have in common? How do they differ?

In other words, you must decide on a set of organisational principles which will allow you to found an understanding of matter. Notice that you cannot include references to concepts which we now accept such as atoms, or electric charge. These are concepts which you must develop by studying matter – categorising results, preparing hypotheses, worrying about exceptions – and trying to convince a sceptical group of colleagues that your insights are valid. I think you will find it extraordinarily difficult to know where to begin, and if you wish to see the task through, I should set aside a lifetime or so for the purpose. The bewildering variety of the properties of matter will provide exceptional cases for just about any scheme of categorisation you adopt.

And if you find this process of categorisation difficult, pity then people from earlier times who reflected on the nature of matter. They suffered both from a lack of reliable data, a lack of validated concepts for understanding the data, and the experimental equipment of the same type as a 13-year old might use in a modern teaching laboratory. I wonder how long it would have taken you to 'discover' atoms and determine their properties; to 'discover' that there are two types of electric charge; to 'discover' that heat is not a substantive fluid.

All your present clarity of vision, such as your wise belief in the existence of atoms, has been constructed on a foundation of centuries of sceptical enquiry.

1.3.4 Organisational principles

What the above exercise is intended to show is that it is not obvious what organisational principles we should use in attempting to categorise matter. And without the appropriate organisational principles, the properties of matter are bewilderingly diverse and explanations appear arbitrary and unconvincing. So, how should we choose to categorise matter?

Animate/inanimate

The first categorisation that suggests itself to me is that between animate and inanimate matter. Historically, division of the study of matter in this way allowed the emerging science of physics to appear successful at explaining and parameterising the simpler properties of inanimate matter. By contrast, the study of animate matter is still barely beyond the stage of naming and categorising.

Solids, liquids and gases

Considering the inanimate world, the next most apparent organisational scheme is the classification of matter into one of three categories: solid, liquid or gas. This rather natural categorisation is now seen as by no means exhaustive. (Indeed it never was: our own bodies are made from matter which is half-liquid and half-solid.) Liquid crystals for example disclose by their very name that the solid-liquid-gas categorisation is inadequate. Further, substances normally considered to be in one category (such as 'solid' rock) when viewed over geological time scales shows properties associated with the liquid state (such as flow and convection). However the solid–liquid–gas division is still a useful one, and forms the basis for the structure of this book.

The conceptual division of matter into distinct categories of solid, liquid and gas was historically extremely important. Once made, real progress became possible in understanding the properties of the simplest of the category of matter: the gaseous state. In studies of gases over the two hundred years from 1700 to 1900 an enormous number of ideas emerged and were tested. In particular the nature of four key concepts were distilled into a form somewhat similar to the one we hold today. The key concepts were descriptions of the properties of matter in terms of atoms, the nature of heat, electricity, and light As we examine the properties of gases in Chapter 5, bear in mind that with the exception of our reference to quantum mechanics, the study would not have been out of place a century ago!

1.4 The structure of this book

The structure of this book is shown in Figure 1.1. Chapters 1 to 3 provide respectively, the context of the book, a mini revision course on some relevant background theory, and a discussion of some aspects of the process of measurement. Chapters 4 to 11 comprise the main text of the book. Gases are discussed in Chapters 4 and 5, solids in Chapters 6 and 7, liquids in Chapters 8 and 9. The transitions between these states of matter are considered in Chapters 10 and 11. The first of each pair of chapters outlines relevant background theory, while the second considers the experimental data, and the extent to which they can be understood using the background theory. Where relevant, the theory is extended to understand the data.

Chapter 12 contains a set of 30 questions which are considerably more involved than the end of chapter exercises. They are arranged under the headings of gases, liquids, solids and phase changes.

The appendices contain detailed points of theory which are important, but which would tend to distract attention from the flow of the text if placed within the chapters.

At www.physicsofmatter.com

In any book there is a conflict between the desire to include more material, and the desire to prevent the book becoming unreadably large. In this second edition, I have attempted to improve on the compromise I chose for the first edition by placing additional material on the internet. This has allowed me to present additional material on several important topics that were briefly covered in the first edition, while simultaneously keeping the core text at the same size. All the extension topics are available for free download from the web site:

`http://www.physicsofmatter.com/`

At this site, you will find copies of all the figures and tables used in the text. You will also find copies of several of the data tables in a format which may be used with the spreadsheet programs available on most personal computers.

1.4.1 Data sources and bibliography

The data in this book has been compiled from a variety of sources. All the sources are secondary: that is they have already been compiled by somebody else from primary data in research literature. These secondary sources are enormously useful in all areas of physics and I would urge anyone contemplating a career in physics to buy them and treasure them. The main sources of data used in

Figure 1.1 The structure of this book.

In the text:

2	**Background theory**	
3	**Measurement**	
4	**Gases**	Background theory
5		Comparison with experiment
6	**Solids**	Background theory
7		Comparison with experiment
8	**Liquids**	Background theory
9		Comparison with experiment
10	**Changes of Phase**	Background theory
11		Comparison with experiment
12	**Questions**	
	Appendices	

At www.physicsofmatter.com:

W1	**Band theory of solids**
W2	**Magnetic properties of solids**

the compilation of this book are:

- G. W. C. Kaye and T. H. Laby, *Tables of Physical and Chemical Constants*: 14th, 15th and 16th Editions, published by Longman (Harlow) in the UK and Wiley (New York) in the USA. This is referred to as *Kaye & Laby* in the text.
- Weast *CRC Handbook of Chemistry and Physics:* 65th *Edition* [also known as the 'Rubber Bible'], published by Chemical Rubber Publishing Company (Chicago, Ill)
- John Emsley, *The Elements*, published by Clarendon Press / Oxford University Press (Oxford).

References to electromagnetic theory are to the excellent

- B.I. Bleaney and B. Bleaney, *Electricity and Magnetism* [two volumes] published by Oxford University Press (Oxford).

Other sources are given in the text. Where no reference is given in the text, the data have been compiled and cross-checked from several sources. I have tried, by several techniques, to eliminate erroneous data from my compilations. However, I cannot guarantee this, and you are referred to the original compilations and the references therein. The web site for the book also contains an up-to-date list of errata.

1.5 Exercise

Exercises marked with a P prefix are 'normal' exercises. Those marked with a C prefix are best solved numerically by using a computer program or spreadsheet. Exercises marked with an E prefix are in general rather more challenging that the P and C exercises. Answers to all the exercises can be found on the web at www.physicsofmatter.com

P1. Isaac Newton was (obviously!) unaware of developments in electromagnetism, quantum mechanics, genetics and evolutionary theory. However, in my opinion, his view of the world was undoubtedly 'modern'. Obtain a copy of Newton's work *Opticks* (New York: Dover) and read the final section marked 'Queries' (page 339 in the Dover edition). This consists of a number of questions over which Newton had puzzled, and to which he had arrived at tentative answers. After reading his 'Queries', carry out the following exercise.

Imagine that Newton were to return to life in our time, and it fell to you to explain to him the key developments in modern science since his death. Write the script of a half-hour conversation between the two of you. Remember, you haven't got long so (a) don't waste time telling him about what he already knows and (b) be sure to script Newton's part as well as your own. I imagine he would be rather ill-tempered and aggressive, but compulsively curious. So he would be sure to interrupt if he didn't understand the language you were using and would be sure to say things like 'Yes, yes, I suspected that all along'.