Molecules: A Very Short Introduction

'a lucid account of the way that chemists see the molecular world … enriched with many historical and literary references, and accessible to the reader untrained in chemistry for whom it was written.'

Times Higher Education Supplement

'Ball's writing is sharp … and drolly intelligent … reliably good and often excellent.'

New Scientist

'In a society of chemical agnostics, it is a brave missionary who tries to reveal its mysteries, but that is what the author has attempted to do – and done remarkably well.… At no point does *Stories of the Invisible* sacrifice sound science for sound bites.'

Nature

'Almost no aspect of the exciting advances in molecular research studies at the beginning of the 21st Century has been left untouched and in so doing, Ball has presented an imaginative, personal overview, which is as instructive as it is enjoyable to read.'

Harry Kroto, Chemistry Nobel Laureate 1996

'A must for all those who wish to acquire a basic scientific culture while greatly enjoying it.'

Jean-Marie Lehn, Chemistry Nobel Laureate 1987

'A modern troubadour, [Ball] deftly and happily extols the magic of tiny leprechauns, furiously active in generating

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Preface

When Alexander Findlay wrote *Chemistry in the Service of Man* in 1916, there was an urgent need to advertise the benefits that chemistry had brought the world. Nine decades later, those writing about chemistry might hope to have been relieved of that burden. But it is not so. In spite of the single most dramatic contribution of chemical art to society – the increase in life span owing to chemotherapeutic health care – Findlay's words still have a familiar ring:

> The people as a whole, being ignorant of science, have mistrusted and looked askance at those who alone could enlarge the scope of their industries and increase the efficiency of their labours.

This same sternness of tone is often not far beneath the surface of efforts today by the chemical industry and its advocates to defend itself against public disdain and censure. One of the problems is that, while the good is taken for granted almost as soon as it is brought to market, the bad sticks in the mind for years. And there is no denying that the attempts by chemicals companies and governments to shirk responsibility for tragedies such as thalidomide and Bhopal, or near-catastrophes such as ozone depletion, have left them with severely diminished credibility to plead their case.

Thus we face the twenty-first century with a pervasive feeling that 'chemical' or 'synthetic' is bad, and 'natural' is good.

The traditional remedy is to list all the good things that chemistry has given us. This list is indeed long, and those who would demonize industrial chemistry probably enjoy many of its products. But I believe that 'chemistry in the service of man' is no longer what we need. For one thing, it perpetuates the impression of a monolithic scientific and technological enterprise universally committed to advancing its own cause. To outsiders, any culture looks monolithic and therefore potentially threatening. It will be a good day when there is more public recognition of how chemists argue furiously with one another about whether this or that product should be banned or restricted, or of the fact that some chemists work in military establishments while others join the blockade outside the gates. Maybe then we will start to see science as a human activity.

But, secondly, chemistry is not simply a thing to be tamed and commandeered into service. It is also what *makes* a man or woman, and the rest of nature too. The negative connotations of 'chemical' and 'synthetic' are hard now to shrug off; but 'molecules' have not yet acquired such colours. And it is by understanding our own molecular nature that we can perhaps begin to appreciate what chemistry has to offer, as well as perceiving why it is that some substances (natural and artificial) poison us and some cure us.

This is why I risk disapproval from some chemists by writing a guide to molecules that focuses to a large extent on the molecules of life – on biochemistry. What I have tried to show is that the molecular processes that govern our own bodies are not so different from those that chemists – I would prefer to say molecular scientists – are seeking to create. Indeed, the boundaries are becoming blurred: we are already using natural molecules in technology, as well as using synthetic molecules to preserve what we deem 'natural'.

In trying to tell these molecular tales, I have benefited greatly from the expert advice of Craig Beeson, Paul Calvert, Joe Howard, Eric Kool, Tom Moore, and Jonathan Scholey, to whom I extend my sincere thanks.

This book began its life as it will end it: as a contribution to OUP's Very Short Introduction series. I am very grateful to Shelley Cox for having sufficient belief in the text to offer it, for a time, an independent life.

Philip Ball

London
January 2001

Acknowledgements

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List of illustrations

Except where indicated, drawings are by the author

39 A polyhedral assembly made from DNA
Nadrian Seeman, New York University

40 Molecular logic

The publisher and the author apologize for any errors or omissions in the above list. If contacted they will be pleased to rectify these at the earliest opportunity.

Chapter 1
Engineers of the invisible: making molecules

The sergeant beckoned the waitress, ordered a barley wine for himself and a small bottle of 'that' for his friend. Then he leaned forward confidentially.

> – Did you ever discover or hear tell of mollycules? he asked.
>
> – I did of course.
>
> – Would it surprise or collapse you to know that the Mollycule Theory is at work in the Parish of Dalkey?
>
> – Well … yes and no.
>
> – It is doing terrible destruction, he continued, the half of the people is suffering from it, it is worse than the smallpox.
>
> – Could it not be taken in hand by the Dispensary Doctor or the National Teachers, or do you think it is a matter for the head of the family?
>
> – The lock, stock and barrel of it all, he replied almost fiercely, is the County Council.
>
> – It seems a complicated thing all right.

The shortest of short introductions to molecules has already been written, and is far more witty than mine. Flann O'Brien was a man who liked to serve up his erudition over a pint of Guinness, as though he were discussing the potato crop or the terrible state of the roads out of Dublin. We can benefit from some more of the wisdom that Sergeant Fottrell is sharing with Mick in the Metropole Hotel, on Dublin's main street:

> – Did you ever study the Mollycule Theory when you were a

lad? he asked. Mick said no, not in any detail.

– That is a very serious defalcation and an abstruse exacerbation, he said severely, but I'll tell you the size of it. Everything is composed of small mollycules of itself, and they are flying around in concentric circles and arcs and segments and innumerable various other routes too numerous to mention collectively, never standing still or resting but spinning away and darting hither and thither and back again, all the time on the go. Do you follow me intelligently? Mollycules?

– I think I do.

– They are as lively as twenty punky leprechauns doing a jig on the top of a flat tombstone. Now take a sheep. What is a sheep but only millions of little bits of sheepness whirling around doing intricate convulsions inside the baste.

What is a sheep? This simple question is (under many guises) more than enough to have kept scientists occupied for hundreds of years, and will continue to do so for many years to come. The science of molecules gives an answer embedded in a hierarchy of answers. It is concerned with the 'millions of little bits of sheepness', which are called molecules. A sheep is a blend of many kinds of molecule – tens of thousands of different varieties. Many of them appear not only in sheep but in humans, in the grass, in the skies and oceans.

But science, seeking deeper levels of understanding, does not leave things there. Are not a sheep's molecules made of atoms, and are not atoms made of subatomic particles such as electrons and protons, and are not those made of sub-subatomic particles such as quarks and gluons, and who is to say what *they* contain within their absurdly tiny boundaries?

– Mollycules is a very intricate theorem and can be worked out with algebra but you would want to take it by degrees with rulers and cosines and familiar other instruments and then at the wind-up not believe what you had proved at all. If that happened you would have to go back over it till you got a place where you could believe your own facts and figures as exactly delineated from Hall and Knight's Algebra and then go on again from that particular place till you had the whole pancake properly believed and not have bits of it half-believed or a doubt in your head hurting you like when you lose the stud of your shirt in the middle of the bed.

– Very true, Mick decided to say.

It is indeed an intricate business to work out what molecules are, if you want to begin on a lower (we should perhaps say deeper) rung of the ladder of science and climb upwards. That is necessary if one wishes fully to understand why molecules behave the way they do, and in consequence why matter – why a sheep or a rock or a pane of window glass – displays its characteristic gamut of properties. But many scientists who work with molecules do not need to bother with all the algebra, for its implications can be generally boiled down to rules of thumb about how molecules interact with one another. The chemical industry was a thriving enterprise before chemistry found its mathematics. Which is a way of saying that molecules need not, after all, make your head hurt.

Leaving the table

It is curious that, when Flann O'Brien reworked the conversation between Sergeant Fottrell and Mick from *The Dalkey Archive* into his most famous novel *The Third Policeman*, published after his death in 1966, he systematically replaced the 'Mollycule Theory' with the 'Atomic Theory'. Here then is the very item, the ambiguity about what things are made from. Is it atoms or molecules? Chemists give out mixed messages.

Their iconic cryptogram is the Periodic Table, a list of the ninety-two natural

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Elements: Primo Levi's *The Periodic Table*

There are the so-called inert gases in the air we breathe. They bear curious Greek names of erudite derivation which mean 'the New', 'the Hidden', 'the Inactive', and 'the Alien'. They are indeed so inert, so satisfied with their condition, that they do not interfere in any chemical reaction, do not combine with any other element, and for precisely this reason have gone undetected for centuries. As late as 1962 a diligent chemist after long and ingenious efforts succeeded in forcing the Alien (xenon) to combine fleetingly with extremely avid and lively fluorine, and the feat seemed so extraordinary that he was given a Nobel prize …

Sodium is a degenerated metal: it is indeed a metal only in the chemical significance of the word, certainly not in that of everyday language. It is neither rigid nor elastic; rather it is soft like wax; it is not shiny or, better, it is shiny only if preserved with maniacal care, since otherwise it reacts in a few instants with air, covering itself with an ugly rough rind: with even greater rapidity it reacts with water, in which it floats (a metal that floats!), dancing frenetically and developing hydrogen …

I weighed a gram of sugar in the platinum crucible (the apple of our eyes) to incinerate it on the flame: there rose in the lab's polluted air the domestic and childish smell of burnt sugar, but immediately afterward the flame turned livid and there was a much different smell, metallic, garlicky, inorganic,

indeed contra-organic: a chemist without a nose is in for trouble. At this point it is hard to make a mistake: filter the solution, acidify it, take the Kipp, let hydrogen sulphide bubble through. And here is the yellow precipitate of sulphide, it is arsenious anhydride – in short, arsenic, the Maculinum, the arsenic of Mithridates and Madame Bovary.

Primo Levi, *The Periodic Table* (1975)

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elements (supplemented by some unstable, artificial ones) arranged in a pattern that helps chemists make sense of them. The most famous book 'about' chemistry is the one that Italian chemist and writer Primo Levi named after this tabulation of matter's building blocks, and it reinforces the impression that chemistry begins with this irregularly shaped grid of symbols. At school I was encouraged to learn mnemonics encoding the elements in the first two rows of the table, which are the most important. For undergraduate chemistry it was required that one could recite the whole thing from memory, to know that iridium lies at the foot of cobalt, that europium is sandwiched between samarium and gadolinium. Yet I doubt that I shall ever set eyes on samarium (although europium shines out at us redly from our television screens).

But chemistry is only incidentally about the properties of the elements, and the science of molecules can afford to ignore many if not most of them. The Periodic Table really belongs to that realm where chemistry becomes physics, where we must wheel out the algebra and the cosines to explain why atoms of the elements form the particular unions called molecules. The table is one of the most beautiful and profound discoveries of the nineteenth century, but, until quantum mechanics was invented by physicists in the twentieth century, one could look