

*Essentials of
Polymer Science and Engineering*

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Essentials of

Polymer Science
and **Engineering**

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Preface

We have written books before, but this one may be our farewell performance, our swan song. According to legend, the Mute Swan (*Cygnus olor*) is mute during its lifetime, but sings a single, heartbreakingly beautiful song just before it dies. Of course, your authors have been compared to many things, but the list does not include swans. Also, a polymer science textbook is anything but heartbreakingly beautiful, although we've attempted to tart this one up by making it in living color. The problem is that we're aging fast and perhaps there's not another book in us.

**Old age is when you resent the swimsuit issue of Sports Illustrated
because there are fewer articles to read.**

George Burns

We are finding that holding a collection of facts and ideas in one's mind in order to organize them in some logical, thematic fashion gets harder.

**There are three things an aging golfer loses.
His nerve, his memory and I can't remember the third thing.**

Lee Trevino

Seemingly minor tasks like proof reading become more difficult.

Always proof-read carefully to see if you any words out.

Author Unknown

And without some rules we learned long ago, we would forget how to spell important, everyday words.

Remember: 'i' before 'e', except in Budweiser.

Author Unknown

But there are compensations. We can look back over a subject and thanks to those years of experience and effort find a depth of understanding that eluded us as young men.

**I had a feeling once about Mathematics, that I saw it all—
Depth beyond depth was revealed to me—the Byss and the Abyss.
I saw, as one might see the transit of Venus—
a quantity passing through infinity and changing its sign from plus to minus.
I saw exactly how it happened and why the tergiversation was inevitable:
and how the one step involved all the others.
But it was after dinner and I let it go.**

Winston Churchill

This, too, is perhaps an illusion and things just don't add up to us anymore.

Two thirds of Americans can't do fractions. The other half, just don't care.

Author Unknown

But our recreation is golf and gardening, so what are we to do in the depths of a Pennsylvania Winter? Might as well write another book. So here it is. It covers much of the same ground as our previous textbook, including the usual topics of polymer organic synthesis;

**Organic chemistry is the study of organs;
inorganic chemistry is the study of the insides of organs.**

Max Shulman

and some basic polymer physics and physical chemistry.

**Physical Chemistry is research on everything for which
the negative logarithm is linear with 1/T.**

D.L. Bunker

We also included two new topics, on natural polymers;

**Rubber looks good but it doesn't do anything for me.
No, let's have the real thing—give me some leather gear.**

Cat Deeley

and on polymer processing.

**You know you've made it when you've been molded in miniature plastic.
But you know what children do with Barbie dolls—it's a bit scary, actually.'**

Cate Blanchett

But, dear reader, this one got hard, particularly towards the end and without the loving support and encouragement of our wives we may never have completed it.

Why don't you write books people can read?

Nora Joyce to her husband James (1882–1941)

We just hope that you feel the same way as Francis Bacon when it comes to things that are getting old.

**Age [and retirement] appear to be best in four things — old wood best to burn,
old wine to drink, old friends to trust, and old authors to read.**

Francis Bacon

PAUL PAINTER AND MIKE COLEMAN

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Most of the superior figures in this book would not have been produced without the support of the National Science Foundation, through grants from the Advanced Technological Education Program, the Course, Curriculum and Laboratory Improvement Program and the Polymers Program. Any figure that displays any semblance of artistic talent or technical skill was almost certainly produced by Mike Fleck or Alex Bierly. Many of the ideas for the original figures in the chapter on processing originated with our colleagues at Penn College, Tim Weston and Kirk Cantor. Kirk also wrote the original version of the chapter on processing, which we subsequently mangled into its present form. Thanks, guys, you will get your reward in heaven, because we're too cheap to give you a share of the royalties!

Introduction

PRELIMINARY RANT

This is a textbook about polymer science, a field your authors have studied and labored in for most of their professional lives. We recall that it was not that long ago, when we were just getting started in this subject, that polymers were regarded as an unalloyed blessing and a boon to mankind. (OK, on second thought, maybe it was that long ago.) Then, sometime in the 1960s, there was a turning point in popular culture, first reflected in the disdain expressed by the writer, Norman Mailer (see quotes). For our money, though, the real tipping point came with the one-word advice, "*Plastics!*" given to Dustin Hoffman in the movie *The Graduate*. Hearing this, shudders of disgust and nausea would pass like a wave through the audience. Plastics were no longer cool.

We beg to disagree. First, we think that the subject of polymer science and engineering is so broad and diverse that scientists and engineers of every stripe can find topics that have an engaging richness and depth. This is reflected in the history of the subject, which includes not only the usual list of Nobel Prize-winning scientists of the highest caliber, but also many interesting characters and even some outright scoundrels. We also believe that a feel for the history of this subject and some of the controversies surrounding the use of certain polymer materials can help bring the subject alive to many students. Accordingly, in writing

"I am inclined to think that the development of polymerization is, perhaps, the biggest thing that chemistry has done, where it has the biggest effect on everyday life."

Lord Todd
President, Royal Society of London

"I sometimes think there is a malign force loose in the universe that is the social equivalent of cancer, and it's plastic."

Norman Mailer

"We divorced ourselves from the materials of the earth, the rock, the wood, the iron ore. We looked to new materials, which were cooked in vats, long complex derivatives of urine, which we call plastic."

Norman Mailer

"From packaging materials, through fibers, foams and surface coatings, to continuous extrusions and large-scale moldings, plastics have transformed almost every aspect of life. Without them, much of modern medicine would be impossible and the consumer electronics and computer industries would disappear. Plastic sewage and water pipes alone have made an immeasurable contribution to public health worldwide."

Dr. N. C. Billingham

this textbook we have sought to do things a little differently than in many conventional texts (including our previous efforts). We will discuss the usual topics, polymer synthesis, structure and morphology, etc., but here and there you will also find what we will call *Polymer Milestones*, brief summaries of the contributions of some great scientists and interesting characters. In addition, books such as this, which are largely concerned with general principles, often do not give students a feel for the nature and use of specific polymers, so we will also sprinkle in some brief reviews of *Fascinating Polymers*. These reviews are not intended to be comprehensive, but are aimed at just giving you a feel for the depth of this field and its rich history. (Those of you who like this stuff and want to explore it in more detail, may want to check out our CD, *The Incredible World of Polymers: Tales of Innovation, Serendipity and Perseverance*, also published by DEStech.) In order to set this up, the rest of this chapter will briefly review the early history of polymer materials, so as to provide a context for our *Polymer Milestones*, together

with our view of some of the controversies surrounding the role of polymers in modern society, just to get you worked up and into the spirit of the thing when we get to certain topics in our *Fascinating Polymers* sections. But first, for those of you who have wandered into polymers from other disciplines, we'll provide some basic definitions.

What Is a Polymer?

If you are new to this field, the first thing you are probably wondering after reading our preliminary rant is "what's the difference between a plastic and a polymer, or are they the same thing?" A plastic is a type of material, whereas a polymer is a type of molecule, a very, very large molecule (Figure 1-1)! The word plastic comes from the Greek, *plastikos*, meaning shapeable. The word polymer also comes from the Greek, meaning many parts. Plastics are polymers, but so are many other things, as we will mention below under "classification." For now we will just note that all disciplines develop their own ways of abusing the English language. Some, psychology and sociology come to mind, seem to take pleasure in describing the obvious in complex terms that appear to be simply designed to impress and confuse those unfamiliar with their subject. But, we digress, and before our friends in the sociology department start to get too upset, let's come to the point and consider some plain, common or garden, polymer nomenclature. Some of the most common terms are listed in the boxes opposite and we believe these definitions are essentially self-evident.

POLY.....MER

Many Units

-M-M-M-M-M-M-M-

or

-(M)_n-

SOME BASIC NOMENCLATURE.

POLYMER—a large molecule made up of smaller building blocks

MONOMER—the building blocks

HOMOPOLYMER—when all the monomers are the same

COPOLYMER—a polymer composed of different monomers

BLENDS—a mixture of polymers

How Big Are Polymers?

It would be nice if we could assume that anyone with a high school diploma would be familiar with the molecular structure of say, water or benzene (Figure 1-2). But, to our jaundiced eye, the current staple of many high school science curriculums seems to be "Saving the Rainforest" and molecular science appears to be largely an afterthought. But that's a different rant. The point we wish