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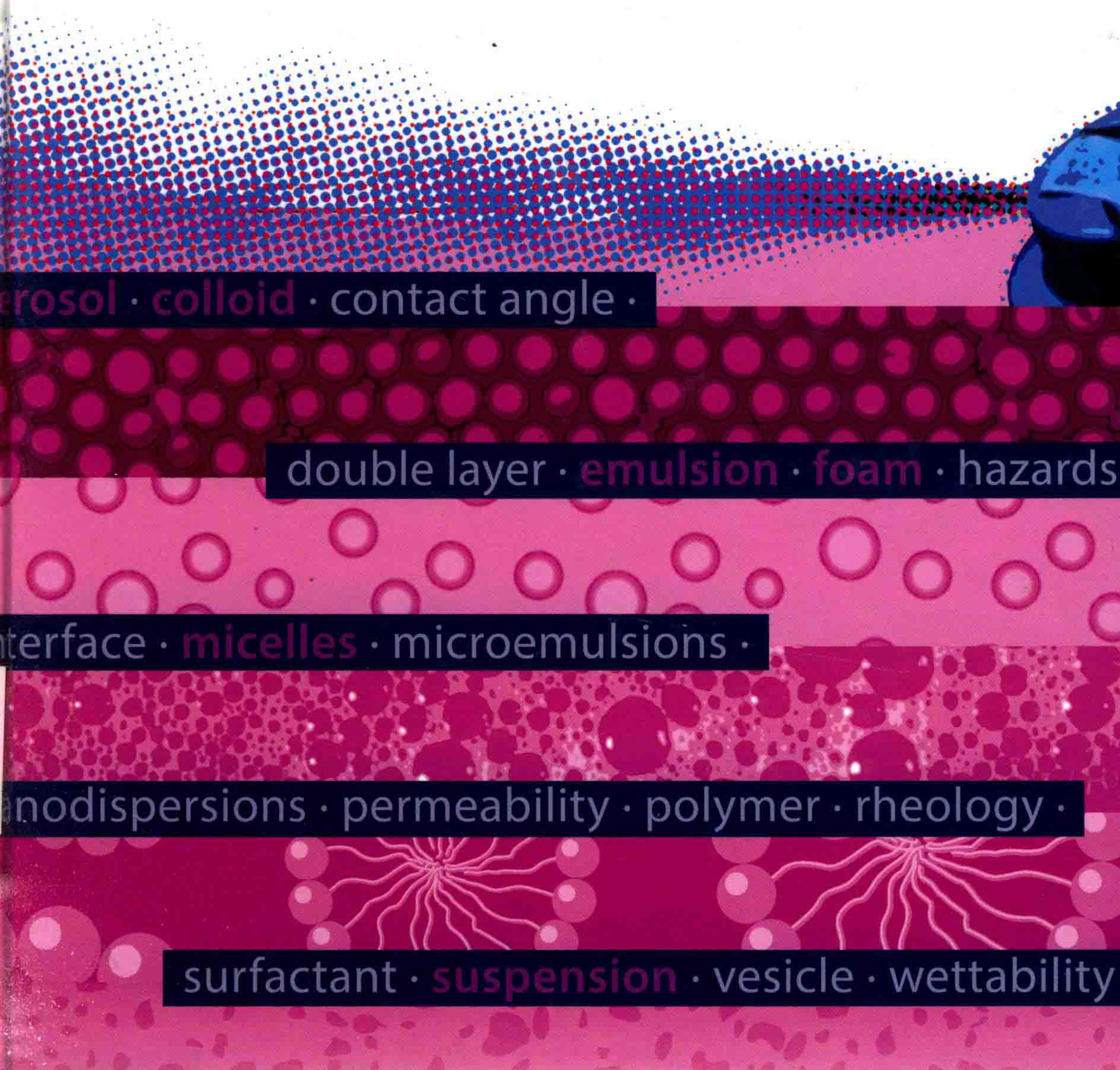
Laurier L. Schramm

Nano- and Microtechnology from A–Z

From Nanosystems to Colloids and Interfaces



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About the Author

Laurier L. Schramm has over 30 years of R&D experience spanning all four sectors: industry, not-for-profit, government, and academia. He is currently President and CEO of the Saskatchewan Research Council, and has previously served as Vice-President with the Alberta Research Council, and President and CEO of the Petroleum Recovery Institute. For much of this time he served in parallel as Adjunct Professor of Chemical and Petroleum Engineering, and before that Adjunct Professor of Chemistry, both with the University of Calgary. His research interests include applied colloid-, interface-, and nanoscience. His management interests include applied research, technology development and deployment, and innovation.

Dr. Schramm holds 17 patents and has published 10 other books, and over 400 other scientific publications or proprietary reports. Many of his inventions have been adopted into commercial practice. He was awarded one of the first NSERC-Conference Board Synergy Awards for Best Practices in University-Industry R & D Partnership, and his work on the development of oil-tolerant foams for enhanced oil recovery was judged to be a Milestone of Canadian Chemistry in the twentieth Century by the Canadian Society for Chemistry. He has received other national awards for his work and is a Fellow of the Chemical Institute of Canada and an honorary member of the Engineering Institute of Canada.

Among other community service contributions he has served for nearly two decades on numerous committees and panels of the Natural Sciences and Engineering Research Council of Canada and the Canada Foundation for Innovation, has been a member of several national or international expert advisory panels, and has served on the Boards of Directors or executive/management committees of numerous other organizations. He is also a cofounder of Innoventures Canada Inc. and a cofounder of Canada's Innovation School.

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I thank my colleagues who invested considerable time and effort reviewing earlier editions of this book and contributing comments and suggestions. There are too many such colleagues to list here but Randy Mikula, Elaine Stasiuk, Susan Kutay, and the late Karin Mannhardt and Loren Hepler were especially helpful. I also thank the staff of Wiley & Sons Inc. and Wiley-VCH, especially Darla Henderson, Karin Sora, Reinhold Weber, Stefanie Volk, and Natalie Wong.

Even in the modern electronic and Internet age there remains a need for major research libraries with substantive collections of scientific and engineering books and periodicals. In the preparation of this book, my work was greatly assisted by the collections of the libraries of the University of Calgary, Carleton University, Massachusetts Institute of Technology (MIT), University of Alberta, Memorial University, University of Saskatchewan, University of Regina, and the Canada Institute for Scientific and Technical Information (CISTI).

Because there are so many different, specialized references to aspects of colloidal systems, nano-, and microtechnology in industrial practice, some important terms will inevitably have been missed. I will greatly appreciate it if readers would take the trouble to inform me of any significant errors or omissions.

December 2013 *Laurier L. Schramm*

Contents

Introduction and Historical Evolution

Dispersions of one phase in another, such as glues and dyes, have been known to, and used by humans since circa 3000 to 2800 BC. However, systematic studies of dispersions as a classification of material did not occur until the late 1700s and early 1800s. In the late 1700s, Pierre Macquer studied the dispersions of finely divided gold particles in liquids, such as the gold tinctures of alchemy and medicine [1]. In the early 1800s, Thomas Graham studied the diffusion, osmotic pressure, and dialysis properties of a number of substances, including a variety of solutes dissolved in water (*see* References [2–4]). He noticed that some substances diffused quite quickly through parchment paper and animal membranes and formed crystals when dried. Other substances diffused only very slowly, if at all, through the parchment or membranes and apparently did not form crystals when dried. Graham proposed that the former group of substances, which included simple salts, be termed *crystalloids*, and that the latter group, which included albumen and gums, be termed colloids. Although colloidal dispersions had certainly been studied long before this time, and the alchemists frequently worked with body fluids, which are colloidal dispersions, Graham is generally regarded as having founded the discipline of colloid science.

The test of crystal formation later turned out to be too restrictive, the distinction of crystalloids versus colloids was dropped, and the noun colloid was eventually replaced by the adjective colloidal, indicating a particular state of dispersed matter: matter for which at least one dimension falls within a specific range of distance values. The second property that distinguishes all colloidal dispersions is the extremely large area of the interface between the two phases compared with the mass of the dispersed phase. Table 3 illustrates the wide range of dispersions concerned. It follows that any chemical and physical phenomena that depend on the existence of an interface become very prominent in colloidal dispersions. Interface science thus underlies colloid science.[1] In 1917, Wolfgang Ostwald, another founder of colloid science, wrote:

> *It is simply a fact that colloids constitute the most universal and the commonest of all the things we know. We need only to look at the sky, at the earth, or at ourselves to discover colloids or substances closely allied to them. We begin the day with a colloid practice – that of washing – and we may end it with one in a drink of colloid coffee or tea* [5].

Now, more than 300 years since Graham's time, a vast lexicon is associated with the study of colloid and interface chemistry because, in addition to the growth of the fundamental science itself, we recognize a great diversity of occurrences and properties of colloids and interfaces in industry and indeed in everyday life. The field has also become more generally referred to as *colloid and interface science* (not just chemistry) because so many other scientific disciplines become involved in the study and treatment of colloidal systems, and of course, each discipline has brought elements of its own special language. The most recent additions are the fields of nanoscience and nanotechnology.

In 1959, physicist Richard Feynman gave the first known lecture on nanotechnology

1) Following Graham's founding of colloid chemistry, the realization of the profound importance of the interface between the phases led to the broader term colloid and capillary chemistry (meaning colloid and interface chemistry).

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(without using that term) at the annual meeting of the American Physical Society [6], in which he proposed the idea that atomic manipulation could be used to build structures. The term nanotechnology itself was coined in 1974 by Norio Taniguchi, to describe processes at the nanometre scale.[2)] Significant interest, and work in, the areas of nanoscience and nanotechnology grew particularly rapidly following the publication of the book *Engines of Creation* by Eric Drexler in 1986 [7]. An illustration of the new way of thinking that is represented by nanotechnology has been given by B.C. Crandall:

> *We are distinct from all previous generations in that we have seen our atoms – with scanning tunneling and atomic force microscopes. But more than simply admiring their regular beauty, we have begun to build minute structures. Each atom is a single brick; their electrons are the mortar. Atoms, the ultimate in material modularity, provide the stuff of this new technology* [8].

Over the next two decades interest in nanoscience and nanotechnology grew exponentially, leading to a plethora of new terms. The "nano" regime (0.1–100 nm), by definition, overlaps heavily with the size range of colloid and interface science and technology (1–1000 nm). As a result, some of the literature now distinguishes between nanoscience and nanotechnology, and microscience and microtechnology, the latter referring to the 0.1–100 μm regime (the microscale). There has been an explosion of terms with the "nano" prefix[3)] [9] and the number of possible "nano" terms is virtually unlimited, especially when material types are included (Table 4 provides an illustrative listing and Table 2 shows the prefix nano in relation to other decimal prefixes in science and technology). For example, there are a wide range of types of nanorods, nanotubes, nanowires, nanobelts, and nanoribbons in nanoscale electronic circuit elements alone. Accordingly, some choices have had to be made regarding how many "nano" terms to include in this book.

Although some nanodispersions are simply colloidal dispersions under a new name, many other aspects of nanotechnology are genuinely new and distinct, such as transitive nanomaterials like carbon nanotubes and quantum dots. Quantum dots are an example of transitive nanoscale materials whose dimensions approach characteristic quantum wave function excitations, contributing quantum properties in addition to those contributed by chemical composition and structure. It has been suggested that the term nanotechnology be used to refer to the study of the nanoscale regime, and the term molecular nanotechnology to refer to the "nano approach," by which is meant the precise, controlled assembly of structures up from the molecular scale that are well organized. This is in contrast to the classical "top down" approach of making things by cutting, bending, and otherwise shaping structures from large starting pieces. In the dispersions area, an analogy would be the use of colloidal ink dispersions in robocasting to build near-nanometre-scale three-dimensional structures, as opposed to the formation of materials by subdividing bulk phases and then kinetically stabilizing their dispersions using emulsifiers and stabilizers.

Finally, as it becomes possible to more fully investigate the subatomic scale regime, new terms are also emerging in pico-, femto-, and atto-science and

2) The prefix nano to signify one-billionth was generally adopted in 1956. See the entry for Nano.
3) This is partly due to the widespread attention and excitement alone generated by this new and emerging field, to the extent that it has been reported that "Nanotechnology is a word you attach to things to attract funding" [9].

technology (such as Hollow Atom and Attoreactor). Tables 1, 2, and 5 provide some comparisons among the length scales in micro-, nano-, pico-, femto-, and atto-science and technology.

This book provides brief explanations for the most important terms that may be encountered in a study of the fundamental principles, experimental investigations, and industrial applications of nano-, colloid and interface-, and microscience. Even this coverage represents only a personal selection of the terms that could have been included were there no constraints on the size of the book.

I have tried to include as many important terms as possible, and cross-references for the more important synonyms and abbreviations are also included. The difficulty of keeping abreast of the colloid and interface science vocabulary, in particular, has been worsened by the tendency for the language itself to change as the science has evolved since the 1800s, just as the meaning of the word colloid has changed. Many older terms that are either no longer in common use, or worse, that now have completely new meanings, are included as an aid to the reader of the older colloid and interface science literature and as a guide to the several meanings that many terms can have. As emerging fields, the meanings of terms in nanoscience and nanotechnology are still somewhat in flux, although some standardization is beginning to occur.

Some basic knowledge of underlying fields such as physical chemistry, geology, and chemical engineering is assumed. Many of the important named colloids and phenomena (such as Pickering emulsions), equations, and constants are included, although again this selection represents only some of the terms that could have been included. I have also included a selection of brief biographical introductions to more than 120 scientists and engineers whose names are associated with famous named phenomena, equations, and laws in nano- and microscience and technology, and colloid and interface science (Table 27). Students first become aware of the people who have laid the foundation for a scientific discipline as they encounter these eponyms. By adopting the "students' view" of famous names in the field, it will be seen that in some cases the scientists are very famous, and biographies are readily found. In other cases, the scientists are not as well known. For those interested in this feature specifically, I have included an index of famous names in nano-, colloid and interface-, and microscience for easy searching (Table 27).

Specific literature citations are given when the sources for further information are particularly useful, unique, or difficult to find. For terms drawn from fundamental colloid and interface science, much reliance was placed on the recommendations of IUPAC (e.g., References [10, 11]. Numerous other sources have been particularly helpful in colloid and interface science (textbook references [12, 17]) and its subdisciplines and related, specialized fields (References [18–33]). I recommend these sources as starting points for further information. Similarly, for terms emerging in nanoscience and nanotechnology, much reliance was placed on the recommendations of ASTM Committee E56 on Nanotechnology [34] and the British Standards Institution Vocabulary on Nanoparticles [35]. Other helpful sources include [36–41]. Some richly illustrated descriptions of objects at the nanoscale are provided by Frankel and Whitesides [42]. For the famous names entries, I have drawn on a number of general references [43–48] and have also included numerous specific references for those interested in additional information. Finally, Table 28 provides a summary of common units and symbols in colloid and interface science, much of which crosses over into nanoscience.

Numeric

0-D Object

See Zero-Dimensional Object. *See also* Quantum Dot.

First-Generation Nanotechnology

See Generations of Nanotechnology.

Second-Generation Nanotechnology

See Generations of Nanotechnology.

Third-Generation Nanotechnology

See Generations of Nanotechnology.

Fourth-Generation Nanotechnology

See Generations of Nanotechnology.

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A

AAN

See Average Agglomeration Number.

Abbe Condenser

A condenser lens containing two or three lenses and used to adjust contrast in high-magnification (400× and higher) microscopy. By changing the size of an iris and/or moving the lens closer to or further away from the microscope stage, the diameter and the focal point of the cone of light illuminating the specimen under observation can be adjusted. References [1, 2]. *See also* Illuminating Lens.

Abbe, Ernst (1840–1905)

A German physicist and industrial scientist best known for his contributions to the field of optics, including his development of various lenses and optical instruments, such as refractometers. Eponyms include the Abbe condenser in microscopy, the Abbe sine condition in optics, and the Abbe crater on Earth's moon.

Aberration

In microscopy, an optical defect. *See* Spherical Aberration.

Ab Initio

In science and engineering, the Latin term *ab initio* generally refers to *developing models* and/or making calculations based on first principles; without experimental data (other than fundamental physical constants).

Ablation

The reduction of particles into smaller sizes due to erosion by other particles or the surrounding fluid. May also refer to the size reduction of liquid droplets due to erosion, as in the processing of an oil sand slurry in which the oil (bitumen) is very viscous.

Abrasion

The wearing down of a surface by erosion due to particles in the surrounding fluid.

Absolute Filtration Rating

The diameter of the largest spherical particle that will pass through a filter, under given test conditions, without deformation.

Absolute Viscosity

A term used to indicate viscosity measured by using a standard method, with the results traceable to fundamental units. Absolute viscosities are distinguished from relative measurements made with instruments that measure viscous drag in a fluid without known or uniform applied shear rates. *See* Viscosity and Table 11.

Absorbance

In optics, a characteristic of a substance whose light absorption is being measured. The Beer–Lambert law gives the ratio of transmitted (I) to incident (I_0) light as $\log(I/I_0) = alc$, where a is the absorptivity, l is the optical path length, and c is the concentration of species in the optical

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path. The logarithmic term is called the *absorbance*.

Absorbate

A substance that becomes absorbed into another material, or absorbent. *See* Absorption.

Absorbent

The substrate into which a substance is absorbed. *See* Absorption.

Absorber

(Aerosols) *See* Wet Scrubber.

Absorption

The increase in quantity (transfer) of one material into another or of material from one phase into another phase. Absorption may also denote the *process* of material accumulating inside another.

Acacia Gum

See Gum.

Accelerator

See Developer (Photography).

Accumulation Aerosol

An aerosol in which the primary particles or droplets have aggregated and/or coalesced into larger species or aggregates, typically in the size range of 50–1000 nm. *See also* Aerosol and Nucleation Aerosol.

Acheson, Edward (Goodrich) (1856–1931)

An American electrochemist and inventor known for his work in the electrical and electric lighting fields, and in abrasives. A contemporary of Thomas Edison, with whom he was at times a collaborator or a competitor, Acheson developed conducting carbon for Edison's electric light bulbs, and managed electric generating plants and lamp manufacturing factories in Europe and the United States. Acheson discovered silicon carbide, its practical application as an abrasive, and coined the name Carborundum. Acheson also developed pure graphite and colloidal graphite products and founded several companies for their manufacture. Two of Acheson's colloidal graphite products (suspensions in oil or water) were called *Oildag* and *Aquadag*. He was granted 70 patents on devices, techniques, and compositions of matter in the fields of mechanics, electricity, electrochemistry, and colloid chemistry.

Achromatic Lens

See Spherical Aberration.

Acicular Particle

A long, narrow particle, such as a "needle-shaped" particle. Example: pine needles.

Acid-Gas Scrubber

See Impingement-Plate-Tower Scrubber and Packed-Bed Scrubber.

Acid Number

See Total Acid Number.