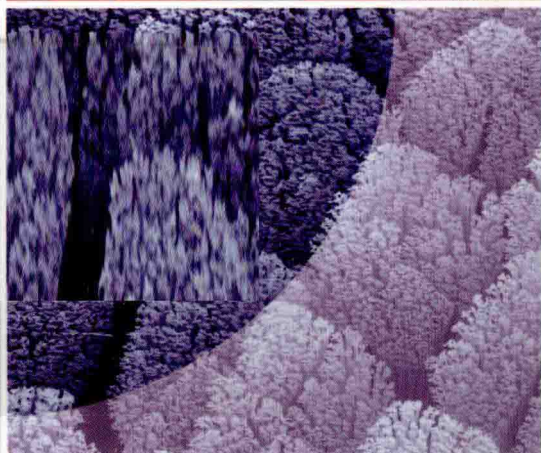
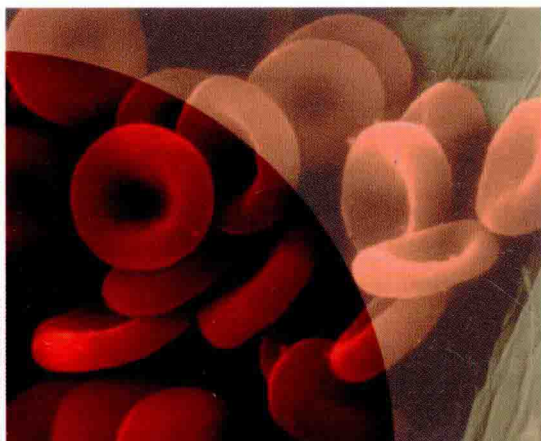
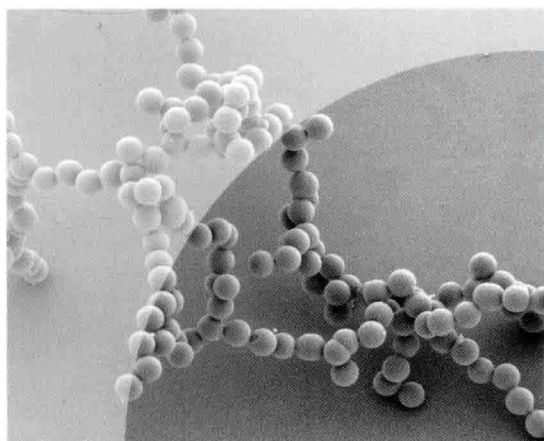


Hans-Jürgen Butt and Michael Kappl

 WILEY-VCH

# Surface and Interfacial Forces



*Hans-Jürgen Butt and Michael Kappl*

## Surface and Interfacial Forces



WILEY-VCH Verlag GmbH & Co. KGaA

## The Authors

### **Hans-Jürgen Butt**

Max-Planck-Institut für Polymerforschung  
Mainz, Germany  
butt@mpip-mainz.mpg.de

### **Michael Kappl**

Max-Planck-Institut für Polymerforschung  
Mainz, Germany  
kappl@mpip-mainz.mpg.de

### **Description of Cover-illustration:**

Top left: Scanning electron micrograph of clusters of silica particles deposited onto a silicon wafer. The particles have a diameter of 1.9  $\mu\text{m}$  and resemble an example of how surface force can dominate the behavior of small scale systems. Even though these structures look fragile, shaking such a sample could not deform them, since inertial forces will be smaller than the van der Waals forces between these particles. Top right: Scanning electron micrograph of red blood cells (courtesy of John Minarcik, Department of Laboratory Medicine & Pathology, University of Alberta). Bottom left: Photograph of a Tokay gecko (Gekko gecko) adhering to a glass plate. Bottom right: Scanning electron micrograph of the fine structure of the gecko foot. Each gecko toe consists of hundred thousands of small keratin hairs called setae. Each seta is further divided into several hundred subunits, the so-called spatulae with a diameter of about 200 nm. This structure allows the gecko to form intimate contact with surfaces and utilize van der Waals and capillary forces to adhere to surfaces. Both gecko images were kindly provided by S. Gorb, Max Planck Institute for Metals Research, Stuttgart.

All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

**Library of Congress Card No.:** applied for

### **British Library Cataloguing-in-Publication Data**

A catalogue record for this book is available from the British Library.

### **Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

© 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

**Typesetting** Thomson Digital, Noida, India  
**Printing and Binding** betz-druck GmbH, Darmstadt  
**Cover Design** Spieszdesign, Neu-Ulm

Printed in the Federal Republic of Germany  
Printed on acid-free paper

**ISBN:** 978-3-527-40849-8

*Hans-Jürgen Butt and  
Michael Kappl*

**Surface and Interfacial  
Forces**

## ***Related Titles***

Butt, H.J., Kappl, M.

### **Physics and Chemistry of Interfaces**

2006

ISBN: 978-3-527-40629-6

Friedbacher, G., Bubert, H. (eds.)

### **Surface and Thin Film Analysis**

**A Compendium of Principles, Instrumentation, and Applications**

2010

ISBN: 978-3-527-32047-9

Förch, R., Schönherr, H., Jenkins, A. T. A. (eds.)

### **Surface Design: Applications in Bioscience and Nanotechnology**

2009

ISBN: 978-3-527-40789-7

Tadros, T. F. (ed.)

### **Colloid Stability**

**The Role of Surface Forces - Part II / Colloids and Interface Science Vol. 2**

2007

ISBN: 978-3-527-31503-1

Brandrup, J., Immergut, E. H., Grulke, E. A. (eds.)

### **Polymer Handbook**

1999

ISBN: 978-0-471-16628-3

Evans, D. F., Wennerström, H.

### **The Colloidal Domain**

**Where Physics, Chemistry, and Biology Meet**

1999

ISBN: 978-0-471-24247-5

Garbassi, F., Morra, M., Occhiello, E.

### **Polymer Surfaces**

**From Physics to Technology. Revised and Updated Edition**

1998

ISBN: 978-0-471-97100-9

## Preface

Two decades have passed since the book by Jacob Israelachvili "*Intermolecular and Surface Forces*" appeared. During this period, our knowledge on interfacial forces has significantly improved partially due to new experimental tools and improved simulation capabilities. For example, the invention of scanning probe microscopy and the development of optical methods allow us to look at surface forces in much more detail.

Surface forces are relevant in a number of technologies, in particular eco-efficient technologies, for a sustained growth in the face of unbridled exploitation of natural resources, a growing world population, and the expected climate change. For example, a good understanding of particle dispersion is a prerequisite to improve mineral processing and adapt it to the increasing exploitation of raw materials. Food industry, facing a growing demand for healthy food, relies on a good understanding of the stability of emulsions and thus of the interaction of oil drops in water or oily liquids in water. The same is true for oil recovery and waste water treatment. The synthesis of polymers in aqueous emulsions allows an environment-friendly production; again, a good knowledge of the forces that keep the particles dispersed is required.

The number of papers published in journals on colloid and interface science has increased by about seven times during the past 20 years. We suppose that this increase is correlated with an increasing number of active researchers in the field. One reason for this increase is certainly the growth in the world population, the fact that a larger proportion of the world population takes part in the technological progress. Another reason is that several technologies rely more and more on processes at the small scale. One example is the increasing relevance of micro- and nanotechnology, including lab-on-chip technology, microfluids, and biochips. Objects in the micro- and nanoworld are dominated by surface effects rather than gravitation or inertia.

These developments motivated us to write this textbook. It is a general introduction to surface and interfacial forces. Though a basic knowledge of colloid and interface science is helpful, it is not essential because all important concepts have been explained. Certainly, no advanced level of mathematics is required. Looking

through the pages of this book, you will see a substantial number of equations. Please do not be scared! We preferred to explicitly give all transformations rather than writing “as can easily be seen” and stating the result.

A number of problems with solutions are included to allow private studies. If not mentioned otherwise, the temperature is assumed to be 25 °C. At the end of each chapter, the most important equations, facts, and phenomena are summarized.

This book certainly contains errors. Even after proofreading by different people independently, this is unavoidable. If you find any error, please write us a letter (Max Planck Institute for Polymer Research, Ackermannweg, 55128 Mainz, Germany) or an e-mail ([butt@mpip-mainz.mpg.de](mailto:butt@mpip-mainz.mpg.de)) so that we can correct it and do not confuse more readers.

We are indebted to several people who helped us collect information, prepare, and critically read this manuscript. In particular, we would like to thank Maria D’Acunzi, Günter Auernhammer, Clemens Bechinger, Elmar Bonaccorso, Derek Y.C. Chan, Vince Craig, Raymond Dagastine, Markus Deserno, Georg Floudas, Stanislav Gorb, Karina Grundke, Vagelis Harmandaris, Manfred J. Hampe, Manfred Heuberger, Katharina Hocke, Roger Horn, Naoyuki Ishida, Gunnar Kircher, Reinhard Miller, Maren Müller, Martin Oettel, Sandra Ritz, Tim Salditt, Tanja Schilling, Doris Vollmer, and Xuehua Zhang.

Mainz, August 2009

*Hans-Jürgen Butt and Michael Kappl*

## Symbols and Abbreviations

Many symbols are not unique for a certain physical quantity but are used two or even three times. We use the symbols as they are usually used in the relevant literature. Since the scope of this book includes many disciplines and thus different scientific communities, multiple usage of symbols is unavoidable. In molecular chemistry and physics, for instance,  $\mu$  is the dipole moment while in engineering  $\mu$  symbolizes the coefficient of friction.

$a$	contact radius (m), activity (mol/L)
$a_0$	Molecular radius (m)
$A$	Area (m <sup>2</sup> )
$A_H$	Hamaker constant (J)
$b$	Slip length, distance between grafting sites (m)
$c$	Number concentration (number of molecules per m <sup>3</sup> ) or amount concentration (mol m <sup>-3</sup> , or mol l <sup>-1</sup> = M), mean cosine of contact angles
$c_m$	Concentration in mass per unit volume (kg m <sup>-3</sup> )
$d_{cc}$	Center-to-center distance between two spheres (m)
$D$	Distance (m)
$D_d$	Diffusion coefficient (m <sup>2</sup> s <sup>-1</sup> )
$D_0$	Interatomic spacing used to calculate adhesion (m), typically 1.7 Å
$\tilde{D}$	Dimensionless normalized distance
$E$	Electric field strength (V m <sup>-1</sup> ), Young's modulus (Pa), surface elasticity (N m <sup>-1</sup> )
$E^*$	Reduced Young's modulus (Pa)
$F_{adh}$	Adhesion force (N)
$F_F$	Friction force (N)
$F_L$	Load (N)
$f$	Force per unit area (N m <sup>-2</sup> )
$f^*$	Different kinds of dimensionless correction functions
$G$	Gibbs energy (J)
$G_m, G_m^0$	Molar Gibbs energy and standard molar Gibbs energy (J mol <sup>-1</sup> )
$H$	Enthalpy (J)
$h$	Height of a liquid with respect to a reference level (m), Planck constant, film thickness (m)



$K$	Spring constant ( $\text{N m}^{-1}$ )
$K_c$	Spring constant of AFM cantilever ( $\text{N m}^{-1}$ )
$k_c$	Bending modulus of a membrane (J)
$k_s$	Segment elasticity ( $\text{N m}^{-1}$ )
$L$	Center-to-center distance between two spherical particles (m)
$L_c$	Contour length of a polymer chain (m)
$L_0$	Thickness of an undisturbed polymer brush (m)
$l_r$	Length of repeat unit in a polymer (m)
$l_s$	Segment length of polymer chain also called Kuhn length (m)
$M$	Torque (N m)
$M_w$	Molar mass ( $\text{kg mol}^{-1}$ )
$M_r$	Molar mass of repeat unit of a polymer ( $\text{kg mol}^{-1}$ )
$m$	Mass (kg), molecular mass (kg per molecule)
$N$	Number of molecules (dimensionless or mol), number of segments in a linear polymer chain
$n$	Refractive index, integer number
$P$	Pressure (Pa)
$P_c$	Capillary pressure caused by the curvature of an interface (Pa)
$P^V$	Equilibrium vapor pressure of a vapor in contact with a liquid with a curved surface (Pa)
$P_0$	Equilibrium vapor pressure of a vapor in contact with a liquid having a planar surface (Pa)
$Q$	Electric charge (A s), heat (J), quality factor of a resonator
$R$	Gas constant
$R_1, R_2$	Radii of spherical particles (m)
$R^*$	reduced radius (m)
$R_g$	Radius of gyration of a polymer (m)
$R_p$	Radius of a spherical particle (m)
$R_0$	Size of a polymer chain (m)
$r$	Radius (m), radial coordinate in cylindrical or spherical coordinates
$r_b, r_c, r_d$	Radius of a bubble, a capillary, and a drop, respectively (m)
$r_1, r_2$	Two principal radii of curvature of a liquid (m)
$S$	Entropy ( $\text{J K}^{-1}$ ), number of adsorption binding sites per unit area ( $\text{mol m}^{-2}$ ), spreading coefficient ( $\text{N m}^{-1}$ )
$T$	Temperature (K)
$T_\Theta$	Theta temperature (K)
$t$	Time (s)
$U$	Internal energy (J), applied or measured electric potential (V)
$V$	Volume ( $\text{m}^3$ ) or free energy of interaction between two molecules or particles (J)
$V_m$	Molar volume ( $\text{m}^3 \text{mol}^{-1}$ )
$v$	Velocity ( $\text{m s}^{-1}$ ), excluded volume parameter ( $\text{m}^3$ )
$v_0$	Sliding or rolling velocity ( $\text{m s}^{-1}$ )
$V^A$	Free energy for the interaction between two surfaces per unit area ( $\text{J m}^{-2}$ )
$W_{\text{adh}}$	adhesion energy per unit area ( $\text{J/m}^2$ )

$x, y, z$	Cartesian coordinates (m), reduced electric potential, and the reduced distance $y = x/(2L_0)$
$Z$	Valency of an ion
$\alpha$	Polarizability ( $\text{C m}^2 \text{V}^{-1}$ ), factor defined by Eq. (4.23)
$\gamma$	Surface tension ( $\text{N m}^{-1}$ ). Specifically, $\gamma_L$ , $\gamma_S$ and $\gamma_{SL}$ are the surface tensions of a liquid–vapor, a solid and solid-liquid interface, respectively
$\gamma^s$	Surface energy of a solid (J)
$\dot{\gamma}$	Shear rate ( $\text{s}^{-1}$ )
$\Gamma$	Grafting density of polymer ( $\text{mol m}^{-2}$ or $\text{m}^{-2}$ )
$\delta$	Thickness of the hydration layer (m), indentation (m)
$\epsilon$	Relative permittivity
$\zeta$	Zeta potential (V)
$\eta$	Viscosity (Pa s)
$\Theta$	Contact angle (deg)
$\kappa$	Inverse Debye length ( $\text{m}^{-1}$ ) (Eqs. (4.8) and (4.11))
$\kappa_c$	Capillary constant (m) (Eq. (5.7))
$\lambda$	Decay length or wavelength of light (m)
$\lambda_c$	Characteristic length scale, critical wavelength of fluctuations (m)
$\lambda_D$	Debye length (m)
$\lambda_K$	$= \gamma V_m / RT$ , Kelvin length (m)
$\lambda_{ev}$	penetration depth of evanescent wave (m)
$\mu$	Chemical potential ( $\text{J mol}^{-2}$ ), dipole moment (C m), friction coefficient
$\mu_k, \mu_s$	Dimensionless coefficient of kinetic and static friction, respectively
$\mu_r$	Coefficient of rolling friction (m)
$\mu_T$	Tabor parameter
$\mu_M$	Maugis parameter
$\nu$	Frequency (Hz), Poisson ratio (dimensionless)
$\Pi$	Disjoining pressure (Pa)
$\rho$	Mass density ( $\text{kg m}^{-3}$ )
$\rho_0$	Number density of molecules next to a wall (molecules per $\text{m}^3$ )
$\rho_n$	Molecular density (molecules per $\text{m}^3$ )
$\rho_e$	Electric charge density ( $\text{C m}^{-3}$ )
$\phi$	Volume fraction
$\sigma$	Surface charge density ( $\text{C m}^{-2}$ )
$\sigma_A$	Surface area per molecule ( $\text{m}^2$ )
$\xi$	Coordinate in the gap between two half-spaces (m)
$\xi_m$	Matsubara angular frequencies (Hz)

## Contents

Preface *XI*

Symbols and Abbreviations *XIII*

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Van der Waals Forces</b>	<b>5</b>
2.1	Van der Waals Forces Between Molecules	5
2.1.1	Coulomb Interaction	5
2.1.2	Monopole–Dipole Interaction	6
2.1.3	Dipole–Dipole Interaction	9
2.1.3.1	Keesom Interaction	10
2.1.3.2	Debye Interaction	11
2.1.3.3	London Dispersion Interaction	12
2.2	The Van der Waals Force Between Macroscopic Solids	14
2.2.1	Microscopic or Hamaker Approach	15
2.2.2	Macroscopic Calculation: Lifshitz Theory	19
2.2.2.1	Combining Relations for Hamaker Constants	27
2.2.3	Surface Energy and Hamaker Constant	31
2.3	The Derjaguin Approximation	32
2.3.1	The General Equation	33
2.3.2	Van der Waals Forces for Different Geometries	36
2.4	Retarded Van der Waals Forces	38
2.4.1	Screening of Van der Waals Forces in Electrolytes	40
2.5	Measurement of Van der Waals Forces	41
2.6	The Casimir Force	44
2.6.1	Casimir Forces Between Metal Surfaces	44
2.6.2	Critical Casimir Force	50
2.7	Summary	52
2.8	Exercises	53

<b>3</b>	<b>Experimental Methods</b>	<b>55</b>
3.1	Surface Forces Apparatus	56
3.1.1	Mica	58
3.1.2	Multiple Beam Interferometry	59
3.1.3	Friction Force Measurements	63
3.1.4	Surface Modification	63
3.2	Atomic Force Microscope	64
3.2.1	Force Measurements with the AFM	65
3.2.2	AFM Cantilevers	67
3.2.3	Calibration of the Spring Constant	68
3.2.4	Microfabricated Tips and Colloidal Probes	72
3.2.5	Friction Forces	73
3.2.6	Force Maps	75
3.2.7	Dynamic Modes	76
3.3	Optical Tweezers	76
3.3.1	Calibration	81
3.3.2	Multiple Traps	83
3.4	Total Internal Reflection Microscopy	83
3.5	Magnetic Tweezers	87
3.6	Summary	91
3.7	Exercises	92
<b>4</b>	<b>Electrostatic Double-Layer Forces</b>	<b>93</b>
4.1	The Electric Double Layer	93
4.2	Poisson–Boltzmann Theory of the Diffuse Double Layer	94
4.2.1	The Poisson–Boltzmann Equation	94
4.2.2	Planar Surfaces	96
4.2.3	The Full One-Dimensional Case	98
4.2.4	The Electric Double-layer Around a Sphere	101
4.2.5	The Grahame Equation	102
4.2.6	Capacity of the Diffuse Electric Double Layer	103
4.3	Beyond Poisson–Boltzmann Theory	104
4.3.1	Limitations of the Poisson–Boltzmann Theory	104
4.3.2	The Stern Layer	106
4.4	The Gibbs Energy of the Electric Double Layer	108
4.5	The Electrostatic Double-Layer Force	110
4.5.1	General Equations	110
4.5.2	Electrostatic Interaction Between Two Identical Surfaces	112
4.5.3	Electrostatic Interaction Between Different Surfaces	114
4.6	The DLVO Theory	116
4.7	Electrostatic Forces in Nonpolar Media	119
4.8	Summary	124
4.9	Exercises	125

<b>5</b>	<b>Capillary Forces</b>	127
5.1	Equation of Young and Laplace	128
5.2	Kelvin Equation and Capillary Condensation	131
5.2.1	Capillary Condensation	134
5.3	The Young's Equation	135
5.4	Capillary Forces Calculated with the Circular Approximation	136
5.4.1	Capillary Force Between a Sphere and a Plane	136
5.4.2	Two Different Spheres	140
5.4.3	Other Geometries	143
5.4.4	Assumptions and Limits	145
5.5	Influence of Roughness	147
5.6	Kinetics of Capillary Bridge Formation and Rupture	150
5.7	Capillary Forces in Immiscible liquid Mixtures and Other Systems	153
5.8	Lateral Forces Between Particles at a Fluid Interface	155
5.9	Summary	160
5.10	Exercises	160
<b>6</b>	<b>Hydrodynamic Forces</b>	163
6.1	Fundamentals of Hydrodynamics	163
6.1.1	The Navier–Stokes Equation	163
6.1.2	Laminar and Turbulent Flow	166
6.1.3	Creeping Flow	167
6.2	Hydrodynamic Force between a Solid Sphere and a Plate	168
6.2.1	Force in Normal Direction	168
6.2.2	Force on a Sphere in Contact with a Plate in Linear Shear Flow	174
6.2.3	Motion of a Sphere Parallel to a Wall	175
6.3	Hydrodynamic Boundary Condition	178
6.4	Gibbs Adsorption Isotherm	180
6.5	Hydrodynamic Forces Between Fluid Boundaries	182
6.6	Summary	186
6.7	Exercises	186
<b>7</b>	<b>Interfacial Forces Between Fluid Interfaces and Across Thin Films</b>	189
7.1	Overview	189
7.2	The Disjoining Pressure	192
7.3	Drainage	193
7.3.1	Vertical Foam Films	193
7.3.2	Horizontal Foam Films	196
7.4	Thin Film Balance	198
7.5	Interfacial Forces Across Foam and Emulsion Films	201
7.5.1	Shape of a Liquid Film	201
7.5.2	Quasiequilibrium	202
7.5.3	Rupture	205
7.6	Thin Wetting Films	208
7.6.1	Stability of Thin Films	212

7.6.2	Rupture of Thin Films	215
7.7	Summary	217
7.8	Exercises	217
<b>8</b>	<b>Contact Mechanics and Adhesion</b>	<b>219</b>
8.1	Surface Energy of Solids	220
8.1.1	Relation Between Surface Energy and Adhesion Energy	222
8.1.2	Determination of Surface Energies of Solids	224
8.2	Contact Mechanics	225
8.2.1	Elastic Contact for a Flat Punch	227
8.2.2	Adherence of a Flat Punch (Kendall)	229
8.2.3	Elastic Contact of Spheres: Hertz, Model	231
8.2.4	Adhesion of Spheres: JKR Theory	233
8.2.5	Adhesion of Spheres: DMT Theory	238
8.2.6	Adhesion of Spheres: Maugis Theory	240
8.3	Influence of Surface Roughness	244
8.4	Adhesion Force Measurements	246
8.5	Summary	249
8.6	Exercises	250
<b>9</b>	<b>Friction</b>	<b>251</b>
9.1	Macroscopic Friction	252
9.1.1	Dry Friction	252
9.1.1.1	Amontons' and Coulomb's Law	252
9.1.1.2	Sliding on Ice	257
9.1.1.3	Static, Kinetic, and Stick–Slip Friction	259
9.1.2	Rolling Friction	262
9.1.3	Friction and Adhesion	264
9.1.4	Techniques to Measure Friction	265
9.2	Lubrication	267
9.2.1	Hydrodynamic Lubrication	267
9.2.1.1	Elastohydrodynamic Lubrication	271
9.2.2	Boundary Lubrication	274
9.3	Microscopic Friction: Nanotribology	275
9.3.1	Single Asperity Friction	275
9.3.2	Atomic Stick–Slip	277
9.3.3	Velocity Dependence of Nanoscale Friction	284
9.3.4	Superlubricity	285
9.3.5	Thin Film Lubrication	288
9.4	Summary	290
9.5	Exercises	291
<b>10</b>	<b>Solvation Forces and Non-DLVO Forces in Water</b>	<b>293</b>
10.1	Solvation Forces	293
10.1.1	Contact Theorem	294

10.1.2	Solvation Forces in Simple Liquids	295
10.1.3	Solvation Forces in Liquid Crystals	298
10.2	Non-DLVO Forces in an Aqueous Medium	301
10.2.1	Hydration Forces	301
10.2.2	Hydrophobic Force	305
10.2.2.1	The Hydrophobic Effect	305
10.2.2.2	Hydrophobic Forces	307
10.3	The Interaction Between Lipid Bilayers	313
10.3.1	Lipids	313
10.3.2	The Osmotic Stress Method	315
10.3.3	Forces Between Lipid Bilayers	317
10.4	Force Between Surfaces with Adsorbed Molecules	322
10.5	Summary	324
10.6	Exercises	325

## **11 Surface Forces in Polymer Solutions and Melts 327**

11.1	Properties of Polymers	327
11.2	Polymer Solutions	332
11.2.1	Ideal Chains	332
11.2.2	Real Chains in a Good Solvent	334
11.2.3	Stretching Individual Chains	336
11.3	Steric Repulsion	339
11.4	Polymer-Induced Forces in Solutions	347
11.5	Bridging Attraction	352
11.6	Depletion and Structural Forces	356
11.7	Interfacial Forces in Polymer Melts	358
11.8	Summary	360
11.9	Exercises	361

## **12 Solutions to Exercises 363**

Chapter 2	363
Chapter 3	363
Chapter 4	365
Chapter 5	367
Chapter 6	369
Chapter 7	372
Chapter 8	373
Chapter 9	374
Chapter 10	375
Chapter 11	377

## **References 381**

## **Index 417**

## 1

## Introduction

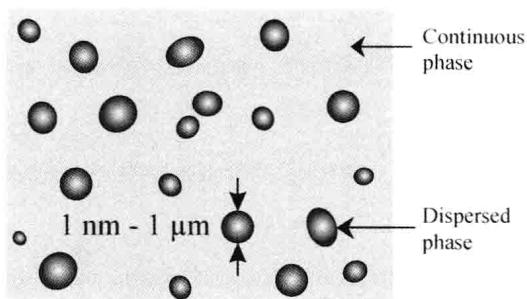
The topic of this book is forces acting between interfaces. There is no clear, unique definition of an interfacial force. One possible definition is as follows: Interfacial forces are those forces that originate at the interface. For example, electrostatic double-layer forces are caused by surface charges at the interface. Such a definition would, however, not include van der Waals forces. For van der Waals interaction, the surface atoms do not have a distinct role compared to the bulk atoms. Still, van der Waals forces substantially contribute to the interaction between small particles. One could define surface forces as all interactions that increase proportional to the interfacial area. Then, for certain geometries gravitation should also be included. Gravitation is, however, not described here. On the other hand, hydrodynamic interactions would be excluded because they depend on the specific shape of interacting interfaces and not only on the interfacial area.

We take a pragmatic approach and discuss all forces that are relevant in systems, that have a small characteristic length scale, and whose structure and dynamics are dominated by interfaces rather than gravitation and inertia. In this sense, this book is about the structure and dynamics of system with a small characteristic length scale. At this point we need to specify two terms: “Interface” and “characteristic length scale.”

An interface is the area that separates two phases. If we consider the solid, liquid, and gas phases, we immediately get three combinations of interfaces: the solid–liquid, the solid–gas, and the liquid–gas interfaces. The term surface is often used synonymously, although interface is preferred for the boundary between two condensed phases and in cases where the two phases are named explicitly. For example, we talk about a solid–gas interface but a solid surface. Interfaces can also separate two immiscible liquids such as water and oil. These are called liquid–liquid interfaces. Interfaces may even separate two different phases within one component. In a liquid crystal, for example, an ordered phase may coexist with an isotropic phase. Solid–solid interfaces separate two solid phases. They are important for the mechanical behavior of solid materials. Gas–gas interfaces do not exist because gases mix.

Often interfaces and colloids are discussed together. Colloid is a synonym for colloidal system. Colloidal systems are disperse systems in which one phase has dimensions in the order of 1 nm to 1  $\mu\text{m}$  (Figure 1.1). The word “colloid” comes from





**Figure 1.1** Schematic of a dispersion.

**Table 1.1** Types of dispersions.

Continuous phase	Dispersed phase	Term	Examples
Gas	Liquid	Aerosol	Clouds, fog, smog, hairspray
	Solid	Aerosol	Smoke, dust, pollen
Liquid	Gas	Foam	Lather, whipped cream, foam on beer
	Liquid	Emulsion	Milk, skin creams
	Solid	Sol	Ink, muddy water, dispersion paint
Solid	Gas	Porous solids <sup>a)</sup>	Partially sintered or pressed powders
		Foam	Styrofoam, soufflés
	Liquid	Solid emulsion	Butter
	Solid	Solid suspension	Concrete

a) Porous solids have a bicontinuous structure while in a solid foam the gas phase is clearly dispersed.

the Greek word for glue and was used the first time in 1861 by Graham.<sup>1)</sup> He applied it to materials that seemed to dissolve but were not able to penetrate a membrane, such as albumin, starch, and dextrin. A colloidal dispersion is a two-phase system that is uniform on the macroscopic but not on the microscopic scale. It consists of grains or droplets of one phase in a matrix of the other phase.

Different kinds of dispersions can be formed. Most of them have important applications and have special names (Table 1.1). While there are only 3 types of interfaces, we can distinguish 10 types of disperse systems because we have to discriminate between the continuous, dispersing (external) phase and the dispersed (inner) phase. In some cases, this distinction is obvious. Nobody will, for instance, mix up fog with a foam although in both cases a liquid and a gas are involved. In other cases, the distinction between continuous and inner phases cannot be made because both phases might form connected networks. Some emulsions for instance tend to form a bicontinuous phase, in which both phases form an interwoven network.

The characteristic length scale of a system can often be given intuitively. For example, for a spherical particle one would use the radius, for a thin film the thickness. For more complex systems, intuition, however, leads to ambiguous

1) Thomas Graham, 1805–1869. British chemist, professor in Glasgow and London.