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# Pigments, Extenders, and Particles in Surface Coatings and Plastics

Fundamentals and Applications to  
Coatings, Plastics and Paper Laminate  
Formulation

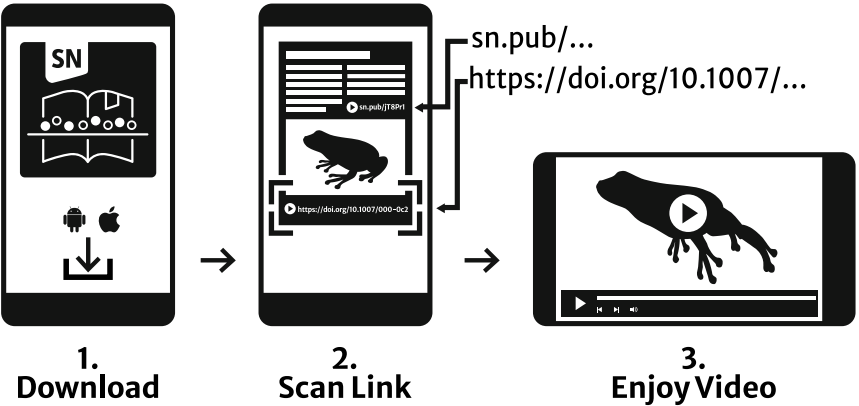
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Fundamentals and Applications to Coatings,  
Plastics and Paper Laminate Formulation



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# Preface

The goal of this book is to provide the reader with the knowledge necessary to effectively formulate paints, plastics, and décor paper for laminates. Our intention is that this book would be useful both as an introduction of concepts to the beginning formulator and as well as a review or reference for the experienced formulator.

Although books already exist that discuss many aspects of formulation, we find that these books primarily focus on the chemical nature of the raw materials rather than on their physical behavior as particles. For example, polymers are the topic of numerous books, but these books focus on the vast and rich chemistry of polymers, rather than their particulate properties. In a similar manner, books exist that discuss the extenders found in paint, plastics, and paper laminate applications, but these mainly focus on their mineral and chemical properties. Similarly, additives are also addressed in other books, but again the focus is on their chemistries.

By contrast, the interest of this book is the particulate aspects of the small particles found in paints, plastics, and paper laminates. In many ways, the contributions of these particles to the important properties of these materials are of equal or even of greater importance than that of the polymer or additives. As such, many of these important material properties, especially appearance properties, are best understood on a particle basis. For this reason, we believe that a book devoted entirely to the ways that the small particles encountered in these applications can affect and control the end-use properties of paints, plastics, and paper laminates is fully justified.

Our premise is that information alone does not provide this knowledge, but that understanding does. A book providing information only could be as short as a single sentence—“Systematically alter the concentrations and identities of the pigment, extender and resin particles until optimized”—perhaps with supplemental tables listing the various materials commonly available for these purposes. Clearly, such a book would be of little more value than a simple internet search of suppliers’ offerings.

Practical knowledge of formulation comes from understanding the effects of material selection, concentration, and manufacturing steps on the performance of the final product. Which materials are likely to give the desired properties? What undesired side effects might they cause? What gives these materials these properties, and how

might alternative materials perform differently? What other considerations must be taken into account? Such an understanding requires not only a significant investment of time and attention but also ready access to explanatory materials such as books, literature papers, patents, and manufacturers' brochures.

Our intention in writing this book is that it be a single source of these explanatory materials. Different aspects of much of this information are already available in a piecemeal way, but stitching this information together requires much labor, not only in finding it but also in weeding out incorrect or conflicting information and weaving the remainder into a consistent, complete, and coherent narrative. Our objective was to unify this material in just such a way.

In addition, we wanted this book to be as comprehensive as possible, which meant the inclusion of topics that do not fall directly within the category of small particle properties. For example, we do not limit our discussion of color pigments to simply their types and compositions but include aspects of how color is perceived, measured, and controlled. While color perception may seem far afield from the properties of small particles, it must be understood if the formulator is to truly master the use of these particles to their best advantage.

As for the subject matter itself: it may strike the reader as odd that the technologies of three very different industries—coatings, plastics, and paper laminates—would be discussed in one book. However, at a very basic level, these materials are essentially the same, differing only in details. They all consist of a continuous layer of polymeric resin into which are dispersed and embedded small particles—a sort of plum pudding, to borrow a phrase used over a century ago to describe a model of the atom.<sup>1</sup> Because of the fundamental similarity of these three materials, descriptions of certain important aspects of them overlap. If properly designed, expositions of these overlapping aspects can be of equal use to formulators in all three industries.

But what of the differing details? These fall into four categories. First, the concentration of particles within the polymer matrix varies by application. For some coatings, this can be significantly greater than 50% by volume, whereas for some plastics, this can be less than 1% by volume. Particle concentrations in paper laminates are intermediate between these, but closer to concentrated paints. Second, the typical thickness of these materials also varies widely according to application. Dry paint films are typically a few tens of microns thick, paper laminates on the order of 500 microns, and plastics can be as thin as coatings (plastics films) or as thick as several centimeters.

The third difference is the manner in which the particles are dispersed in the final product. In paints, particles are dispersed as a liquid slurry, and the final paint film is formed by evaporating the solvent (typically water) from the applied wet paint. In thermosetting plastics, the particles are dispersed in the molten polymer, which is then allowed to solidify, freezing the particles in place. Finally, in paper laminates, large agglomerates of particles are trapped in a paper fiber matrix, and then hot resin is pressed, under considerable pressure, into and throughout the paper, displacing

---

<sup>1</sup> Although this atomic model was later determined to be incorrect in the case of atomic structure, we believe that it is an appropriate and useful description of most coatings, plastics, and laminates.

the air voids within while maintaining the structure of the particles. Here again, the particles are frozen in place when the molten matrix solidifies.

Finally, the appearance of these materials can differ widely—not only between material types (coatings, plastics, or paper laminates) but also within a given type. The appearance differences are due to the two different ways that light can interact with a particle—it can be absorbed by the particle, or it can be deflected, or scattered, by it. The same particles are used to do this in all three material types. However, the details regarding how these particles are used, and their effect on the appearance properties of the final material, vary according to the material type.

Bearing in mind the similarities and differences between coatings, plastics, and paper laminates, we arranged our chapters according to topic, and arranged the topics such that they build on one another. This arrangement is shown in the table below.

Topic	Chapter Number and Description
Introduction to Small Particles	1. The Behavior of Small Particles
	2. The Physical Properties of Small Particles
Optical Properties	3. Light Scattering 1 - The Physics of Light Scattering
	4. Light Scattering 2 - Light scattering in Crowded Systems
	5. Color 1 - Seeing Color
	6. Color 2 - Measuring Color
Particle Types	7. White Pigments
	8. Color Pigments
	9. Extender Particles
	10. Resin Particles
Aspects of Formulation	11. Dispersion of Small Particles in Liquid Paints
	12. Dispersion Small Particles in Plastics
	13. Measuring the Optical Properties of Paints and Plastics
	14. Paint and Plastics Durability
Formulation	15. Formulating with Color
	16. Formulating Paints with Particles
	17. Formulating Plastics with Particles
	18. Application to Décor Paper for Use in Laminates
Future Looking	19. Issues and Trends

We believe such an ordering of chapters is the most logical way to develop the understanding necessary for successful formulation. With this arrangement we lay out the fundamentals that apply universally to the three material types in the first three sections, then have chapters specific to the formulation considerations of each material type. Finally, we describe specific formulation principles for each end use application. Our ambition is not that the entirety of these chapters be of interest to all readers, but that the entirety of the interests of any one reader be contained within a subgroup of the chapters.

An endeavor as broad as this one is beyond the abilities of a small group of people, and the authors are indebted to their colleagues and other experts in the industries discussed who have contributed to the creation of this book. These include, in chapter order:

Dr. Ebrahim Najafi, Ms. Heidi Huezo, and Mr. Roger Senigo, for the electron micrograph images found throughout the book.

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Dr. Hanne Blau, for reviewing the entirety of the book and providing us with the time and other resources necessary to produce it.

Our greatest debt of gratitude is owed to Dr. Austin H. Reid, Jr., who will be familiar to those in the plastics industry for his many contributions to it. The quality of this book was greatly improved by Dr. Reid's sharp editorial eye and keen technical observations, and it is no exaggeration to say that this book would not exist without his valuable input to the book as well as his kind and generous mentoring of the lead author throughout his career. For these, we are truly grateful.

Kallo, Belgium  
Newark, Delaware, USA  
January 2022

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**Part I**  
**Introduction to Small Particles**



# Chapter 1

## The Behavior of Small Particles



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### Introduction

We encounter objects of various sizes every day, some of which we can see with our naked eyes, while others are too small to resolve. For example, fish eggs and larvae can span sizes between 100 microns and 1 mm, placing them on the cusp of what we are able to observe visually. Even though they are too small for us to see, we know that materials such as soot, vehicle exhaust or pollen are also composed of particles, based on their characteristics and behaviors.

This book is concerned with the nature and effects that particles commonly found in paints, plastics, and paper laminates have on end-use properties. As a prerequisite to

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this, we must define precisely what, in our context, a particle is. The word “particle”, as it is commonly used, is quite general and, because of this, somewhat vague. In broad terms, we can define a particle as an object having a specific size and exhibiting both physical and chemical properties. For our purposes, we will define a particle as an object that is smaller than approximately 100 microns and will refer to materials larger than this as “macroscopic objects”. We will further divide particles into three size categories, with “large” particles being roughly 20 microns or larger, “small” particles spanning the range from 0.1 micron (100 nm) to 20 microns, and “nano” particles being smaller than this.

Our reason for dividing particles into these three groups is that many physical properties of particles are determined by their size, and the particles grouped according to these different size categories behave differently from one another in many very important ways. In our everyday life, we mainly deal with macroscopic objects—from grains of salt to carry-on luggage. In coatings, plastics, and paper laminates we deal predominantly with objects that are much smaller, with a range of characteristic sizes between roughly 0.2 and 20 microns—that is, objects that we defined as small particles in the paragraph above. Because most of our experiences are with large particles and macroscopic objects, and because the behaviors of large and small particles are very different from one another, as we will see, it is worthwhile to discuss the properties of small particles as a prelude to understanding their effects on many paints, plastics, and paper laminate properties.

## Physical Laws Governing Small Particles

We are familiar with the behaviors of objects that are large enough to hold in our hands. Objects of this size, such as grains of salt or ball bearings, flow easily and independently of one another, separate easily, are significantly acted on by gravity, and pack efficiently. However, the behaviors of objects that are smaller than this—objects that we defined as “small particles”—are much different. We rarely knowingly encounter small particles in everyday life and so are not familiar with many of these differences.

We will begin our analysis of small particle behavior with a review of the important forces that act on and between these particles.

### *The Forces of Nature*

Physicists have identified four fundamental forces from which all other forces are derived. These are the weak force, the strong force, electromagnetism<sup>1</sup>, and gravity.

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<sup>1</sup> As the name implies, the electromagnetic force can be split into two inter-related forces, the electrostatic force (which causes attraction and repulsion of charged species at rest) and the magnetic

Two of these forces are familiar to us in our everyday lives, and two, the weak force and the strong force, are quite foreign. We are unfamiliar with these two forces because their reach is subatomic—the strong force is important only at distances similar to those of the atomic nucleus, while the weak force operates at distances that are a small fraction (0.1%) of the size of an individual proton. The weak force is roughly a million times less intense than the strong force.

Electromagnetic forces and gravity operate over a much larger length scale than strong and weak forces. As an extreme, gravity can cause galaxies separated by distances of many millions of light-years to aggregate into galactic clusters. Both gravitational and electromagnetic forces decrease in strength as the square of distance, and the equations describing these forces are very similar:

$$F_{gravity} = G \frac{m_1 m_2}{r^2}, \text{ where } G = 6.67 \times 10^{-11} \frac{\text{Nm}^2}{\text{kg}^2} \quad (1.1)$$

$$F_{electrostatic} = k \frac{q_1 q_2}{r^2}, \text{ where } k = 8.99 \times 10^9 \frac{\text{Nm}^2}{\text{C}^2} \quad (1.2)$$

Note the large difference in the values of the constants in these equations ( $G$  and  $k$ ). Although we cannot equate coulombs to kilograms, we can say that these are convenient units to describe the number of electrons and quantities of mass with which we are accustomed to interacting. The difference in magnitude of these constants—20 orders of magnitude—suggests a very large difference in the relative strengths of these two forces. This is, in fact, the case. As a point of comparison, consider two electrons separated from one another by some distance  $d$ . These electrons will be attracted to one another by gravity and repelled from one another by charge repulsion. The electrostatic force of repulsion between these electrons is a remarkable  $4.17 \times 10^{42}$  times stronger than the attractive force of gravity [1].

The fact that gravity is by far the weakest of the four forces may come as a surprise since gravity plays such a dominant role in our everyday lives. However, if we look carefully, we can see indications that this force is, in fact, quite weak. For example, a relatively weak 10-gram magnet can easily pull a paperclip off of a table—in the process of completely overcoming the gravitational attraction of the  $5.972 \times 10^{24}$  kg mass of the Earth. Similarly, when rubbed on fur, a balloon can be attached to a ceiling, again overcoming the gravitational attraction of the Earth, in this case through electrostatic, rather than magnetic, interactions.

We may wonder why, if gravity is over forty orders of magnitude weaker than the electric force, it dominates our lives. There are two reasons that, together, explain this. The first is that there are two types of electric charges, positive and negative, and the interactions among them are both attractive and repulsive, unlike gravity, which operates solely on an attractive basis. The second reason is, paradoxically, that the electrical forces are so very strong.

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force (which arises from charged species in motion). These forces were united by Maxwell in the mid-nineteenth century.

The first of these reasons suggests a way that electrical forces can be minimized—charge cancellation. Because there are two opposing types of electrical charge, differently charged subatomic particles can balance one another. This is what occurs in free atoms and in molecules, where there are equal numbers of protons and electrons. Ions, on the other hand, are charged, but oppositely charged counterions are nearly always found in close proximity, again balancing the total charge of the system.

Not only can most electrical charges be balanced on a very small scale, they almost always are. This is explained by the second reason that the effect of gravitational force on Earth dominates that of the electric force. Both the attractive and repulsive forces are very strong between charged materials. The strength of the repulsive forces makes it difficult for unbalanced charges to build up in a given region of space, and the strength of the attractive forces assures that any buildup of charge will quickly be neutralized by charges of the opposing sign. The net effect is that, due to the high strength of attraction between oppositely charged materials, Nature will find a way to bring oppositely charged materials together, canceling their interactions with other materials or objects.

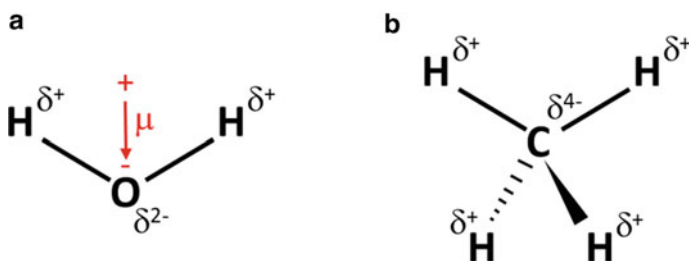
The net result of these factors is that the electrical charges are almost always balanced on a very small scale (on the order of a few nanometers), and so their influences do not typically extend beyond the molecular scale. Gravitational forces, on the other hand, are always attractive and so cannot be shielded or canceled in the same way as electrical forces. Gravitational forces instead always add onto one another, combining in a way that extends their influence to the galactic scale.

## *The Nature of Forces*

We are familiar with the most obvious ways that electrical energy reveals itself—the shock we get crossing a room on a low humidity day, the benefit we get from plugging appliances into electric outlets, the light we get by turning on a switch, and so forth. However, there are also manifestations of electrical energy that are not so obvious. One of these is the attraction of small particles to one another and to surfaces. These attractions are generally referred to as van der Waals forces, a term that includes three related types of interactions:

- those between permanent dipoles—the Keesom force,
- those between a permanent dipole and an induced dipole—the Debye force, and
- those between non-polar atoms or molecules arising from instantaneous dipoles—the London dispersion force.

Note that unlike electrical forces, which decrease as the square of distance, the magnitude of van der Waals forces decreases as the sixth power of surface separation distance and so recedes quite rapidly as touching particles move away from one another. They are therefore only important at distances of no more than a few nanometers.



**Fig. 1.1** Charge separation in molecules.  $\delta$  indicates a fractional charge. **a** Water. **b** Methane. Dipole moment in **(a)** indicated by arrow

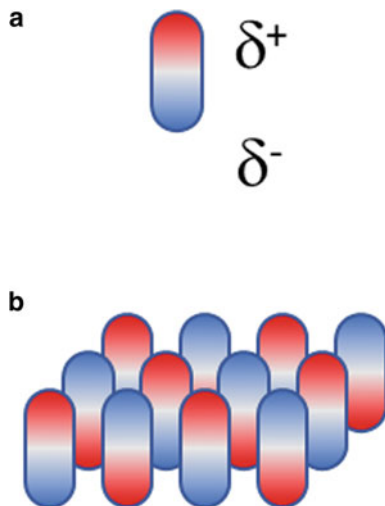
The three components of van der Waals forces arise from electric dipoles. Dipoles are atoms or molecules for which there is a slight separation of electric charge. Permanent dipoles are found in molecules when atoms of different electronegativities are bound to one another and the symmetry of the molecule is not high enough to balance these charges. For example, the hydrogen atoms in a water molecule are less electronegative than the oxygen atom. This generates a slight positive charge on the hydrogen atoms (designated as  $\delta^+$ ) and a negative charge double that on the oxygen atom ( $\delta^{2-}$ ). This is shown in Fig. 1.1a. Because the hydrogen atoms are on one side of the water molecule, and the oxygen atom on the other, there is a slight separation of electrical charges in the molecule. This separation is referred to as the dipole moment (designated as  $\mu$ ) and is shown in Fig. 1.1a as an arrow pointing to the negative part of the molecule. Molecules with dipoles are termed polar, and those without them are termed non-polar. As an example of the latter, there are slight charge separations in methane ( $\text{CH}_4$ ), just as in water, yet methane has no net dipole moment (Fig. 1.1b). This is because of the high (tetrahedral) symmetry of this molecule, which causes all vectors of charge separation to cancel.

When polar molecules are arranged in a liquid or solid, they align themselves to maximize attractive electrostatic forces and minimize repulsive attractive forces. This means that the positive end of one molecule aligns next to the negative end of another. This is shown pictorially in Fig. 1.2. These interactions result in a net attraction between the molecules and a net stabilization when molecules with dipoles assemble.

There is also a net attraction between molecules with a dipole moment (polar molecules) and those without one (non-polar molecules). In this case, as the molecules approach one another, the positive part of the polar molecule pulls towards it the electrons in the non-polar molecule, while the negative part of the polar molecule is aligned with the remainder of the non-polar molecule. Note that this remainder is partially positively charged because some electron density flowed from it towards the positive end of the polar molecule.

The separation of charge seen in a non-polar molecule that comes in contact with a polar one is called an induced dipole. While the interactions between polar and non-polar molecules are attractive, they are not as strong as the interactions between permanent dipoles.

**Fig. 1.2** Alignment of molecular dipoles **a** individual molecule. **b** Assembly of molecules. Red shading indicates areas of excess positive charge; blue shading indicates areas of excess negative charge



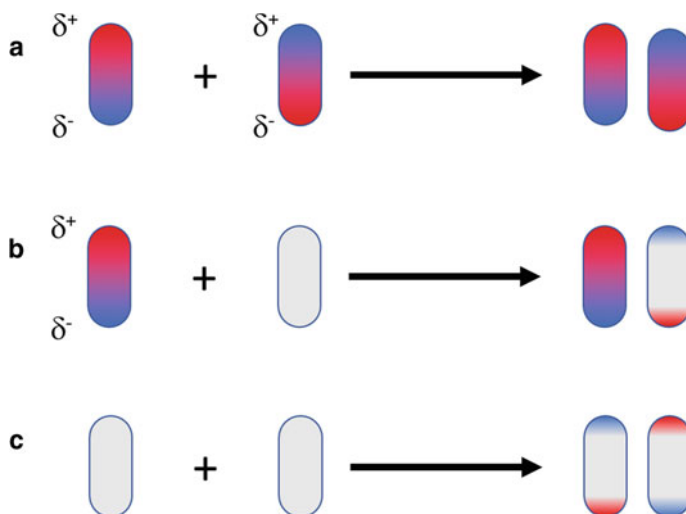
Finally, we have the situation where two non-polar molecules come close together. This, too, results in an attraction between them. The electrons within any molecule are in constant motion, and at any given instant they could be imbalanced—that is, there could be a net positive charge in one area of the molecule and a net negative charge in another. This charge separation occurs spontaneously and is temporary. This is referred to as an instantaneous dipole in the molecule.

When two non-polar molecules are in contact with one another, and one molecule develops an instantaneous dipole, an induced dipole is created in the second, much as occurs when a non-polar molecule is brought in contact with a polar molecule. As was the case with polar/polar and polar/non-polar interactions, instantaneous dipole moments cause an attraction between molecules. The attractions between non-polar molecules are, however, significantly weaker than the other two types of dipolar interactions.

The three ways that dipoles can align are shown in Fig. 1.3. Taken together, these forces are called the van der Waals forces, and they account for the assembly of atoms or molecules that are not chemically bound to one another (for example, they account for the liquification of methane at low temperatures).

In our discussion of Fig. 1.2, we noted that molecules in solids typically orient themselves in a way that maximizes the attractive electric forces and minimizes the repulsive forces. Because of this, the surfaces of these typically have alternating positive and negative patches. Other molecules coming into contact with these surfaces will generally align themselves according to these interactions. This explains the well-known phenomenon of the adsorption of a gas or a dissolved molecular species onto a particle surface.

This also explains the attraction particles have towards other particles. This attraction is a surface phenomenon—surface atoms act as shields and prevent the dipole



**Fig. 1.3** Dipolar interactions between molecules. **a** Permanent dipole–permanent dipole (Keesom force); **b** permanent dipole–induced dipole (Debye force); **c** Instantaneous dipole–induced dipole (London force)

charges from penetrating deeply into a particle. Because of this, we find the attraction strongest for particles with high specific surface areas.<sup>2</sup> Particles that have high specific surface areas are either porous or, more commonly, quite small. A sizeable fraction of the atoms and molecules within particles that are smaller than about half a micron are located at or near the particle surface, where they can participate in particle–particle interactions. The high proportion of surface atoms and molecules, and the sharp drop in interaction strength with distance, cause small particles to be more strongly attracted to one another (and to surfaces in general) than large particles.

### *The Balance of Forces in Large and Small Particles*

The differences in behaviors of large and small particles, on the one hand, and nanoparticles, on the other, are due to differences in the physical laws that they follow. Large and small particles follow what are considered the classical laws of physics—the laws discovered by scientists several centuries ago. As a group, we will call these Newtonian laws. These include, for example, the force law (force = mass times acceleration) and the law of gravity (see Eq. 1.1 above).

Nanoparticles, however, follow a different set of laws. These are the laws of quantum mechanics, where uncertainties in location and motion (momentum) are

<sup>2</sup> Specific surface area is the surface area of a particle divided by its weight. A collection of smaller particles has a higher specific surface area than a collection of the same weight of larger particles.

linked to one another. Quantum behavior is quite foreign to us, and the implications of quantum mechanics are difficult to perceive and understand at an intuitive level.

While nanoparticles follow quantum mechanical laws, both large and small particles follow the same laws (the Newtonian laws described above). As such we might expect their behaviors to be similar. This is not the case, however. Although large and small particles follow the same laws, the relative importance of the different laws is quite different between the two particle size regimes. As discussed above, large particles are governed primarily by gravity. Small particles, on the other hand, are governed primarily by surface forces.<sup>3</sup> These include friction and the natural attraction of one surface to another.

Gravitational forces scale as the volume of a particle ( $d^3$ , where  $d$  is the particle diameter), whereas surface forces depend on the surface area of a particle ( $d^2$ ). The relative importance of the two for a specific particle can be described by the ratio of the forces. This ratio ( $d^3/d^2$ ) changes linearly with particle size ( $d$ ). For large particles (large  $d$ ), gravitational forces ( $d^3$ ) are dominant, whereas for small particles (small  $d$ ), surface forces ( $d^2$ ) are dominant (Fig. 1.4). This can also be understood by comparing the fraction of molecules (or atoms) in a particle that are near the particle surface to the fraction of those in the bulk. Those molecules (or atoms) near the surface can be influenced by other surfaces, as discussed above, while those away from the surface are affected only by gravity.

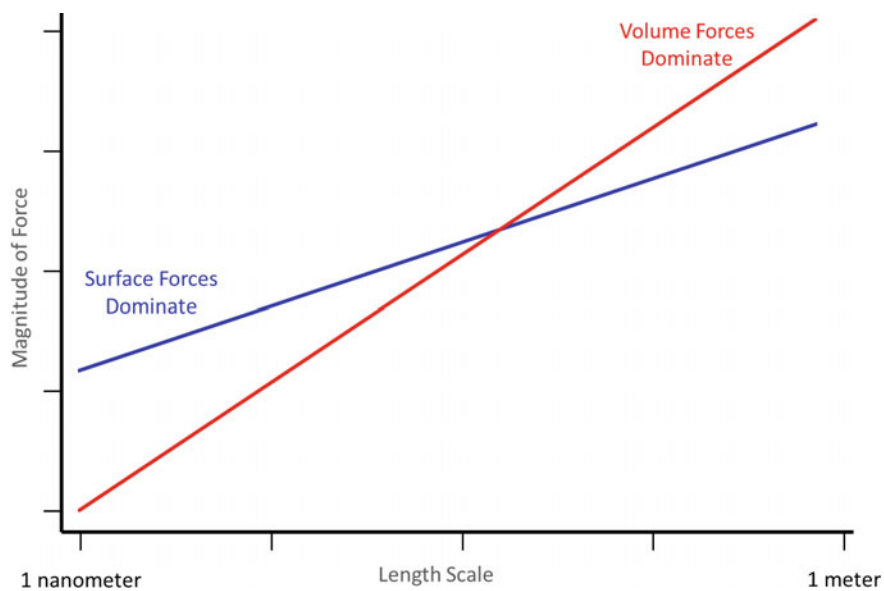
The remainder of this chapter will focus on comparing and contrasting the behaviors of large particles—behaviors that we are familiar with through our everyday lives—to those of small particles—which we rarely encounter. For many, the most common opportunity for interacting with small particles is in the kitchen, where many food staples are in powder form. These powders often exhibit small particle behavior, and an excellent point of reference for this chapter is the different behaviors of large and small particles of the same material—sugar. One can use granular sugar (a large particle) and powdered sugar<sup>4</sup> (a small particle) to show the similarities and differences between these two size regimes, and readers are encouraged to confirm the observations made below for themselves by using these forms of sugar as examples. Some of these differences are also demonstrated in the video associated with Fig. 1.5.

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<sup>3</sup> There is a second distinction between large and small particles that affects certain small particle behavior. This distinction applies when particles are so small as to approach the atomic or molecular dimensions. For macroscopic objects, we can ignore the fact that material is made up of indivisible units (atoms or molecules), but we sometimes cannot do so for small particles. Brownian motion is an example of this. Random imbalances of gas or liquid molecules striking a macroscopic object are much too slight for detection, while for small particles, such as grains of pollen, the imbalance is great enough to cause the particle to move. This is manifested as the random (Brownian) motion of these materials in air or water. An explanation of Brownian motion was one of Einstein's first contributions to physics, and the fact that it arises from a discontinuity in structure (i.e., the indivisibility of atoms) was determined by Perrin and was the basis for Perrin being awarded the Nobel prize in physics in 1908.

<sup>4</sup> Sometimes called confectioners' or 10X sugar. It is called icing sugar in the UK.





**Fig. 1.4** Schematic of the relative importance of volume and surface forces as a function of particle size (both axes are logarithmic)



**Fig. 1.5** Video demonstration of the behavior differences between granular and powdered sugars

## Properties of Small Particles

There are many properties common to all small particles that determine, in part or in whole, their physical behaviors. These properties can be broadly divided into two groups—physical properties and chemical properties. For the most part, chemical behaviors are determined by the chemical nature of the particle surface, since atoms below the surface are not available for chemical reaction. These behaviors can be altered by modification of the particle surface, usually through the adsorption of a small molecule or ion, or by the deposition of a new solid onto the particle surface.

By contrast, physical behaviors are determined by both the surface properties and the dimensional characteristics of the particle. Here, the chemical nature or elemental composition of the particle is not as important. Instead, aspects of the particle such as size, shape, weight, density, coefficient of friction, etc., control these properties. In this sense, we are concerned with the “object” characteristics of the particle rather than the reactivity characteristics.

We will discuss many of the properties of small particles, particularly those that have relevance to coatings and plastics. Before doing so, we note that, unless otherwise specified, we will typically refer to a property on the basis of a unit weight of particles, rather than on the basis of a single particle or a set number of particles. For example, a single large particle clearly has a higher surface area than a single small particle of the same shape. However, a gram of large particles will have a smaller surface area than a gram of small particles. Our reason for defining properties on a mass basis is that particles are formulated into paints, plastics, and paper laminates on a weight or volume basis, rather than on a number basis, and so it is on this basis that we will discuss their attributes.

### *Shape*

All particles, regardless of their size, have specific shapes. This can include roughly uniform shapes, such as a sphere, cube or block, irregular shapes, such as plates or rods, and all shapes in between. It is most convenient to classify shapes based on the number of dominant dimensions a particle has. We live in a three-dimensional world, and therefore there are three shape categories (Fig. 1.6). Three-dimensional, blocky shapes, such as a cube or a sphere, are roughly the same size in all directions. Plates can be considered two-dimensional—they extend in breadth and width but have very little thickness. Finally, needle-like or rod-shaped (acicular) particles extend in a single dimension (length), with negligible breadth and width.

Particles acquire a given shape in one of two ways. First, they can be formed with a preferred shape. This occurs when a small seed particle begins to grow. Growth typically occurs by the addition of “building blocks” to an existing particle. When building blocks are added to a growing crystal, they often do not attach to all faces equally. This is because some faces of the crystal are more energetic than others