

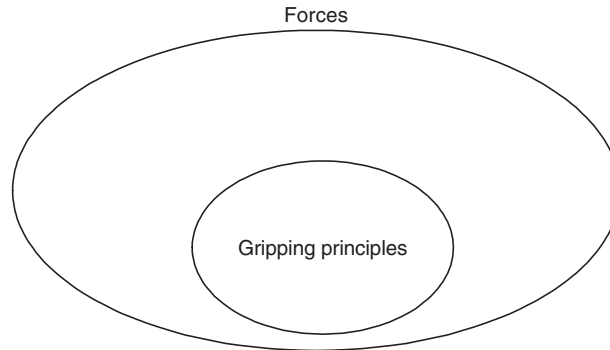
## Classification of Forces Acting in the Microworld

### 2.1 Introduction

When downscaled, volumic forces (e.g., the gravity<sup>1</sup>) tend to decrease faster than other kinds of forces such as the capillary force or the viscous force. Although they still exist on a macroscopic scale, these forces are often negligible (and neglected) in macroscopic assembly. A reduced system is consequently brought face-to-face with the relative increase of these so-called surface forces. According to the literature on microassembly, these forces are mainly the electrostatic forces, the van der Waals forces, the liquid bridge (also called capillary or surface tension) forces, the forces due to the mechanical clamping (contact forces) and deformation (pull-off forces), and viscous drag. The term surface force is misleading since all these forces does not really depend on the square of the characteristic length. Nevertheless, this term conveys the idea that these forces decrease more slowly than the weight, which leads to some cut-off sizes below which these forces disturb the handling task because they generate the sticking of the microcomponent to the tip of the gripper (the weight is no longer sufficient to overcome them and ensure release). There are several ways to tackle this problem: These forces can be reduced, overcome, or exploited as a gripping principle. The choice will be different according to the manipulation strategy (see Fig. 2.1): The parameters (materials, environment, geometries) will be chosen to maximize the force used as a gripping principle (for example by choosing hydrophilic materials in a manipulation based on the capillary force) and to minimize the disturbing forces (use of hydrophobic materials in a manipulation based on a mechanical gripper). This chapter presents some general classifications of the forces according to their range and introduces the most often cited forces in microassembly literature.

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<sup>1</sup> From one point of view, inertia forces also involve the mass of the component, but the possible high dynamics at small scales compensate this effect, as illustrated by the dynamical release proposed in [77].



**Fig. 2.1.** Forces and gripping principles: The force underlying in a gripping principle must be maximized, all the others should be decreased

## 2.2 Classification Schemes of the Forces

According to Lee [118], we go over the first simplified classification of the different forces in four main categories:

- Gravity, with an infinite range
- Electromagnetic force, with an infinite range
- Weak force, with a range smaller than  $10^{-18}$  m
- Strong force, with a range smaller than  $10^{-15}$  m

These last two forces are outside the scope of this work due to their very short range (inside the nucleus). Electromagnetic forces represent the source of all intermolecular interactions and their influence can be combined to that of gravity in some phenomena such as the rise of a liquid in small capillaries.

The interaction between atoms, molecules, and solids is characterized by the following:

- Chemical forces and covalent bonding, with a range over the order of an interatomic separation (typically 0.1–0.2 nm)
- Coulomb force and ionic (or partially ionic) bond

Moreover, the interaction between microscopic bodies also depends on the Lifshitz–van der Waals (VDW) forces, which can be classified into four categories:

- Dispersion forces, also called London forces [120], are due to a Coulomb interaction. They represent one third of the Lifshitz–van der Waals forces, are long range (more than 10 nm), can be attractive or repulsive, and act between all atoms and molecules, even between neutral ones. These forces are nonadditive, which means that the interaction between two molecules is affected by the presence of other bodies. The interaction energy of the dispersion forces decreases as a function of the separation distance to the sixth power ( $\frac{1}{r^6}$ )

- Orientation forces, also called Keesom forces, coming from the interaction between two permanent dipoles. Their energy also depends on the separation distance as  $\frac{1}{r^6}$
- Induction forces, also called Debye forces, due to the interaction between a permanent dipole and an induced dipole, with an energy decreasing as  $\frac{1}{r^6}$
- Retardation forces, described by Casimir and Polder, due to the non-negligible propagation time of the electromagnetic wave between the dipoles when their separation distance becomes higher than typically 10 nm. Because of this propagation time, the relative orientation of the dipoles are less favorable and the interaction energy decreases faster than for the other terms ( $\frac{1}{r^7}$ )

A detailed description of these four terms can be found in [118] (Table 3, p10) or in [88]. At this stage of reading, it seems that the fast decrease of the van der Waals with the separation distance put them aside as far as microsystems are concerned. However, a more subtle investigation shows that this decrease complies with another power law in the case of two macroscopic bodies interacting with each other [89]. Still mentioned in [118], the Coulomb and Lifshitz–van der Waals forces are not sufficient to explain the adhesion between two solids: the molecular interactions (also called donor–acceptor interactions by physicists or acid–base interactions by chemists) also play a role in adhesion, but as their range is limited to the interatomic separation (typically smaller than 0.3 nm), we will not consider them in what follows even if a more detailed study concerning the close contact of two bodies should probably involve their effects. Finally, we cannot conclude this section without mentioning the role of capillary forces [48], [80]. These forces play an important role in a lot of surrounding phenomena and applications: They allow children to build up sand castles and everyone to collect the crumbs more easily, provoke adhesion between microcomponents, cause reliability failure in MEMS<sup>2</sup> applications [104, 125, 176, 179, 184], and are of the utmost importance in microassembly. As a first conclusion, we propose the schematic summary presented in Table 2.1.

**Table 2.1.** Forces summary according to the interaction distance

INTERACTION DISTANCE	PREDOMINANT FORCE
Up to infinite range	Gravity
From a few nm up to 1 mm	Capillary forces
>0.3 nm	Coulomb (electrostatic) forces
0.3 nm < separation distance < 100 nm	Lifshitz–van der Waals
<0.3 nm	Molecular interactions
0.1–0.2 nm	Chemical interactions

<sup>2</sup> Micro Electro Mechanical System.

To make this first classification easier to use from a mechanical point of view, we have proposed [112] a different classification, making the distinction between forces at contact (forces including deformations – JKR, DMT, and related indicators,<sup>3</sup> interaction energy of two bodies, and friction) and forces at distance (surface forces including van der Waals forces, electrostatic forces, and capillary forces). This classification is valid for gaseous environment. On the other hand, the case of immersed environments is tackled in [64].

### 2.3 Conclusions

The problematics of microforces has already been described by several authors. Maybe the most cited surveys in the microassembly literature are the works given in [28], [58], and [89], which summarize the most important forces acting when dealing with microparts: the electrostatic forces, the van der Waals forces, the capillary forces, the gravity forces, and the viscous forces. Although the way these forces are involved in microassembly is not completely understood yet, it is now well established by the scientific community that these forces are no longer negligible when manipulating and assembling parts within the size of 0.1 mm and smaller. These effects are also experimented by a lot of industrials involved in the handling of components of watches or mobile phones [136]. Let us note that these disturbing side-effects are not limited to assembly but are also encountered in manufacturing by microstereolithography: The breakdown of small mechanical structures due to the collapsing induced by the capillary forces (the forces arise from the presence of a rinsing liquid after the polymerization phase of the process) is reported in [184].

Some authors suggest to assemble component in a liquid environment: Gauthier [64] has recently explained how the above mentioned forces were decreased in water<sup>4</sup>. This current research field on working in liquid media is beyond the scope of this book. In Chap. 3, it will be focused on the way these forces have been used through the literature as handling principles.

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<sup>3</sup> These models are extensions of the Hertz model, which takes adhesion into consideration. The Johnson–Kendall–Roberts model is more adapted for high adhesive or low stiffness contacts while the Derjagin–Muller–Toporov model is more adapted to low adhesive or stiff contacts.

<sup>4</sup> Capillary forces are totally suppressed since there is no longer a liquid/gas interface, van der Waals forces are decreased because the so-called Hamaker constant (which is proportional to the force) is usually smaller in liquid environments, and electrostatic forces are decreased since the dielectric constant  $\epsilon$  is 80 times larger for water than for vacuum.

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