CHAPTER

29

THE FUTURE OF VAN DER WAALS FORCE-ENABLED TECHNOLOGY TRANSFER INTO THE AEROSPACE MARKETPLACE

Fabrizio Pinto

Department of Aerospace Engineering, Faculty of Engineering, Izmir University of Economics, Izmir, Republic of Turkey

CHAPTER OUTLINE

Nanotube Superfiber Materials. https://doi.org/10.1016/B978-0-12-812667-7.00029-X

1 INTRODUCTION

A proper appreciation of potential technological applications of intermolecular forces demands awareness that the mutual attraction of smooth marble surfaces had been firmly established experimental knowledge for centuries before the fascinating discoveries of the past few decades. “The fact that such surfaces displayed spontaneous cohesion was not in doubt; the proper explanation of that cohesion… was, however, intensely debated” [1]. Furthermore, electrically neutral conductors representing a good approximation to perfectly conducting plates were already well known in the early 19th century to display a strong attractive force [2, 3]. Although this may not have been—nor is even today—common knowledge in the rarefied atmosphere of some theoretical physicists’ circles, Johansson steel gauge blocks commonly employed for length measurements in precision mechanical workshops can be “wrung” so as to adhere to one another so strongly that they may require hundreds of pounds of force to later be pulled apart. In some cases, they may just become inseparable [4–7]. Physics Nobelist Richard Feynman, renowned for his unmatched ability to connect abstract theories to common experience, mentions the use of “Johansen [*sic*] blocks… which we use in accurate machine work” in his foundational talk “There’s plenty of room at the bottom,” given at Caltech in 1959 [8]. Just a few years later, we again read about “Johansson blocks… providing a stunning demonstration of the direct attraction between the atoms on one block for the atoms on the other block” in the section on molecular forces of *Feynman’s Lectures on Physics* [9].

Interatomic forces, explored by van der Waals on thermodynamical grounds [10–12], were later correctly described by London within the framework of nonrelativistic quantum mechanics. London stated: “Though it is of course not possible to describe this interaction mechanism in terms of our customary classical mechanics, we may still illustrate it in a kind of semi-classical language. If one were to take an instantaneous photograph of a molecule at any time, one would find various configurations of nuclei and electrons, showing in general dipole moments. In a spherically symmetrical rare gas molecule, as well as in our isotropic oscillators, the average over very many of such snapshots would of course give no preference for any direction. These very quickly varying dipoles, represented by the zero-point motion of a molecule, produce an electric field and act upon the polarisability of the other molecule and produce there induced dipoles, which are in phase and in interaction with the instantaneous dipoles producing them. The zero-point motion is, so to speak, accompanied by a synchronised electric alternating field, but not by a radiation field: The energy of the zero-point motion cannot be dissipated by radiation” [13]. Therefore, “although the atoms or molecules under consideration are electrically neutral and symmetrical on the whole over a given period of time, the continually changing dipoles induce dipoles in other neighboring atoms and vice versa, in such a way that at each moment an attractive force results from the reciprocal action between the induced and the inducing dipoles” [14].

Working within the framework of London’s theory, detailed predictions of the stability of lyophobic colloids were formulated at the Philips Natuurkundig Laboratorium in Eindhoven by Verwey and Overbeek [15] employing computations of adhesive forces between particles by Hamaker [16] and de Boer [14]. However, “Overbeek… found that a suspension of quartz particles was more stable than was to be expected from his formulæ” [17]. In 1948, Hendrik Brugt Gerhard Casimir, also at Philips, approached the problem by pursuing what he would much later describe as a “stroke of genius” [18]. Overbeek had suggested that “at large distances… the interaction must decrease more rapidly… and he suggested that this might be due to retardation effects” [17]. According to this qualitative, semi-classical argument couched in the same language as that of London and de Boer as previously stated, the fact that the speed of light is finite should be expected to cause “a phase lag between the circulating electron in the first atom and the dipole induced in the second atom. There will also be double that phase lag between the circulating electron and the field of the induced dipole that acts on this electron. This reduces the interaction energy” [18]. In his own characteristically modest words, Casimir followed this argument and carried out “rather clumsy” [18] calculations, in collaboration with Dirk Polder, “by taking the usual van der Waals-London forces as a starting point and correcting for retardation effects” [19]. From this earlier effort there emerged the result for the fully retarded force between two polarizable atoms, now referred to as the Casimir-Polder force, which led to a theory fully confirmed by experiments along the lines first suggested by Overbeek’s intuition.

Although “Casimir’s papers on vacuum forces and the van der Waals interaction are not easy reading” [20], the result obtained by Casimir and Polder was, mathematically speaking, “very simple” [19]. This intriguing feature led Casimir to a famous conversation with Niels Bohr: “In retrospect, I think it was a remark by Bohr that put me on a new track. During a visit to Copenhagen—I do not remember exactly when—I explained to Bohr what I had been doing about Van der Waals forces. “That is nice,” said Bohr. “That is something new.” I then told him I was still looking for a simple explanation of the simple formulæ. “Must have something to do with the zero-point energy of the vacuum,” he muttered. As far as I remember, that was the extent of our conversation on this subject. Just a few words, but they were enough”[1] [18].

In short order, Casimir recovered the expression of the Casimir-Polder force between two atoms by means of the new zero-point-energy arguments [21, 27]. He then proceeded to apply that same approach to the problem of the force between two macroscopic perfectly conducting plates presenting his results in a two-and-a-half page paper published in the *Proceedings of the Royal Netherlands Academy of Arts and Sciences* [19]. In that seminal communication, contradicting expectations from basic electrostatics usually deemed to be “intuitive,” Casimir proved that two perfectly smooth, flat, electrically neutral, ideally conducting plates, facing parallel to each other across an empty gap of width much smaller than their lateral dimensions, experience a mutually attractive force. This phenomenon—the Casimir effect—was, several years later, considered surprising enough to be described by physics Nobel prize winners and other world-class experts as “one of the least intuitive consequences of quantum electrodynamics” [28] (QED) and a “crazy idea” [29].

---

[1] The quote is from Casimir’s own recollection, in 1998, published in the *Essays in Honour of Victor Frederick Weisskopf*. A slightly different version is given by Milonni (later cited as a preprint in Casimir’s own essay [18]), who quotes from a letter to him dated March 12, 1992. In that account, Casimir states: “Summer or autumn 1947 (but I am not absolutely certain that it [was] not somewhat earlier or later), I mentioned my results to Niels Bohr, during a walk. ‘That is nice,’ he said, ‘That is something new.’ I told him that I was puzzled by the extremely simple form of the expressions for the interaction at very large distance and he mumbled something about zero-point energy. That was all, but it put me on a new track.” (matter in square brackets in the original) [21] Although the two narratives historically complement each other without mutual contradictions, the later one explicitly has zero-point energy *of the vacuum* (my italics) This is critical to the retarded formulation as the zero-point energy *of the atoms* is discussed by London as already playing a role in the earlier nonrelativistic theory of van der Waals forces (see Ref. [13], §4). For completeness, we mention that these events were narrated by Casimir on three other occasions known to this author. In the first, “he muttered ‘it must be a manifestation of zero-point energy.’ As far as I remember that was the whole of our conservation [*sic*] on this problem, but it led into a new direction” [22]; in the second, “Bohr thought this over, then mumbled something like ‘must have something to do with zero-point energy.’ That was all but in retrospect I have to admit that I owe much to this remark” [23]. Milton references this latest citation but introduces a subject absent in the original: [“…the van der Waals force] must have something to do with zero-point energy” [24], whereas context indicates “a simple and elegant derivation of my results” was meant by Casimir (see also [25]); in the third, reported by Lamoreaux, “Bohr mumbled something about zero-point energy” [26].

Throughout his few personal accounts, Casimir consistently stressed the connection between his discovery and the “zero-point-energy of the vacuum” interpretation, even jokingly referring to this concept as “poor man’s QED” in his essay written in honor of Victor Weisskopf [18]. The unparalleled insight of that contribution—and the accompanying controversy that endures to this day [30]—were, therefore, connected to having explained by means of new techniques the existence of known forces between neutral bodies and *not* due to any announcement of their existence. Indeed, we read in his work of reminiscences that, in 1951, a heated conversation with Wolfgang Pauli during a boat excursion on the Neckar River at Heidelberg focused on Casimir’s “results on the Van der Waals forces and their relation to field fluctuations in empty space.” Pauli bluntly defined that approach as “all nonsense” before being amused and finally won over by Casimir’s unrelenting arguments [31]. As noted by Milonni (see Ref. [32], p. 240, footnote 20) and as documented in a letter by Otto Stern to C. P. Enz, this account is consistent with Pauli’s very early opinion about the “zero-point energy against which he had the gravest hesitations” [33]. An additional intriguing finding, also noted by Casimir, was proof of the existence of a “universal force—that is, independent of the properties of the metals as long as they are good conductors” [31]. In other words, this force between two parallel surfaces in the ideal limit of perfect conductivity—the Casimir force—remarkably only depends on the interboundary distance and two natural constants, the speed of light in vacuo and Planck’s constant.

In the seven decades since Casimir’s quantum field theoretic description of the electrodynamical pressure between two electrically neutral boundaries, our understanding of the technological potential of dispersion forces has undergone a radical and fascinating transformation. On the one hand, partly influenced by Casimir’s own initial assessment, the Casimir force was for a long time variously regarded by some as a “tiny,” “barely detectable” and “weak” interaction. On the other hand, already in Feynman’s memorable talk—“There’s Plenty of Room at the Bottom”—van der Waals forces were identified as a fundamentally detrimental roadblock and caricatured as molecular scale “molasses”—a forewarning of the failure mechanism we now refer to as “stiction” (sticking friction) [34], “a term borrowed from the magnetic recording media industry” [35]. Commencing in the 1980s, new ideas emerged explicitly challenging both conflicting views that dispersion forces are either technologically irrelevant and even difficult to detect or that they are an obstacle to be carefully avoided in microelectromechanical system fabrication and operation.

Suggestions that Casimir forces represent a remarkable—specifically, disruptive—technological opportunity either to enhance the performance of existing devices or even to introduce capabilities entirely inaccessible to traditional approaches were initially received with caution and even skepticism, particularly by some within the theoretical physics community. In historical perspective, however, the concept that van der Waals forces may enable breakthrough applications should have been far from controversial. Indeed, it had been a primarily industrial problem—the stability of colloids used in manufacturing—to lead Casimir and Polder to their groundbreaking analyses. For a variety of reasons, including a predictable but somewhat indiscriminate and overreaching reaction against research directions deemed by some to be excessively speculative, such a vision was not immediately embraced. Therefore, widespread recognition of the enabling role of dispersion forces in nanotechnology had to wait till the turn of the present century. Even through uncertainty and confusion regarding the potential for technological applications, however, the subject of Casimir force research in all of its multifaceted ramifications has been growing explosively in the last few decades. The anticipated future of a subset of such activities holding great promise for space technology applications is the subject of this chapter.

Due to our specific focus, here we shall neither comprehensively review theoretical, computational, and experimental Casimir force physics nor analyze the historical circumstances leading to the present process of early dispersion force know-how deployment into the market place. Concerning the former issues, a pedagogical overview of the fundamental scientific issues was recently presented, with references, including also a discussion of the role of classical fields in dispersion force theory within the context of the development of Maxwell's equations [63]. Furthermore, epistemological and ontological implications of the existence of classical schemes for the description of the linearized gravitational zero-point-field were discussed [30, 36]. An informative account of many such issues at an introductory level aimed at a wide readership is also available [37]. As to the latter issues, an extensive analysis of the emergence of dispersion force-enabled technologies in the last 150 years will appear [64].

In what follows, we pursue two lines of attack. On the one hand, after a short introduction to establish fundamental concepts, we illustrate the path from concept to the marketplace taken by early, illustrative dispersion force-enabled applications. Then we define the novel field of "dispersion force engineering" and discuss its promising trajectory with a particular focus on potential benefits to the aerospace industry in the medium- to long-term future and including remarkable challenges in the process of technology transfer, initial fundraising, and product entry to market. Building upon such narratives and experience, we discuss reasonable models of the impact of advanced dispersion force-enabled technologies particularly on spacecraft design and performance of the future. As is typical of progress achieved in aerospace technologies, it will become apparent that the applications we shall consider have the potential to greatly improve quality of life and knowledge of our universe on the ground [38–42].

In addition to such standard-format presentation about intrinsically exciting topics, the present chapter also aims to outline the business opportunity presented by dispersion force engineering so as to serve as an open "invitation to act" for both government agencies and private investors. The message to the investment manager and research planning communities within academia, private industry, and public administration consists of straightforwardly proposing the explosively developing field of dispersion force engineering as an emerging enabling general-purpose technology (EEGPT), thus well worthy of serious due diligence because of its anticipated benefits to society, its role in stimulating future industrial growth, and its potential financial returns. In this sense, this chapter provides an updated and much expanded view of observations on "*The Economics of van der Waals Force Engineering*" first presented almost a decade ago [43], and now based on two decades of intense experience by this author in communicating this largely undetected or often misunderstood business opportunity. Our emphasis will be on *not* keeping readers from reality and the language may appear as jarring and even petulant, but only because that is what is experienced whenever change faces incumbent ideas and interests. The written word is an important part of the story and we shall devote some observations to the corruption of quotations and facts as they are related within the scientific community.

The author recognizes that this latter perspective may be perceived as engaging in self-serving "overclaiming" (Ref. [44], Section 4.4). It is impossible to eliminate the possibility of such an appearance beyond disclosing it and attempting to control any potential biasing effects. A rich genre of scientific literature developed over a period of centuries exists authored either by scientist-inventors or by investors aggressively pursuing high-risk, high-reward technologies at the cutting edge of their times, presenting their best case for novel, possibly controversial concepts that could, did—or failed to—benefit not only society but, clearly, also those proposers. Whether motivated by skillful "self-promotion" [45] as in

Galileo's *Sidereus Nuncius* (traditionally rendered into English as *Starry Messenger*) [46] or motivated by a possible doomsday scenario as in Elon Musk's very recent call to "*Making Humans a Multi-Planetary Species*" [47], the desire and ability to articulate a vision and to formulate a clear call-to-action is a mandatory skill in the toolbox of anyone wishing to inspire decision makers to provide necessary resources to translate an abstract idea or a crude proof-of-concept into a viable product to enhance the quality of human life. We present our reflections on the future of industrial applications of dispersion force engineering to space technology in this same unapologetic spirit.

2 ELEMENTS OF DISPERSION FORCE ENGINEERING

In this section, we introduce issues relevant to the technological application of dispersion forces by means of qualitative, nonmathematical language. Our present goal is to provide the links of a logical chain leading to the executive summary following (Section 2.2), aimed at informing potential entrepreneurs and decision makers, and supported by the evidence presented in the rest of this chapter. Readers unfamiliar with the subfield may benefit from a recent informative introduction by this author in *American Scientist* [37]. Proposing a full listing of reviews, let alone of the relevant literature cited therein, has become a daunting task. As commented by Babb [48] quoting Bonin and Kresin, even authors of works highly focused either by subject or by time frame have to deal with "a mountain of available information" (Ref. [49], p. 185). Without any pretense of completeness, in addition to the several references cited throughout this chapter, relatively recent overviews from very different standpoints are available [50–59]. Technical reviews of van der Waals forces in the unretarded regime as applied to spacecraft nanopropulsion [60] and to energy storage [61] by means of dispersion force manipulation in nanotubes [62] were presented by this author. Additional technical introductions, enhanced by examples in the *Mathematica* language, are forthcoming, partly in the Proceedings of the 2017 NATO International School of Atomic and Molecular Spectroscopy—Quantum Nano-Photonics held at Erice, Italy [63], and partly in a historical review in *Progress in Aerospace Sciences* [64].

2.1 PHYSICAL CONSIDERATIONS

To provide an immediate intuition for the existence of interactions between electrically neutral surfaces, here we shall commence—for maximum simplicity—from the completely classical perspective provided by the so-called *acoustic* Casimir effect, which, in addition to its intrinsic interest, represents a powerful analogy with the electrodynamical Casimir effect (Ref. [65, 66], Section 4.6).

Our first logical link is the observation that acoustic radiation reflected by an object exerts a force on that object, usually "very weak in comparison to gravity," although this is, obviously, deemed to have potentially important applications in microgravity environments. Acoustic radiation pressure [67] "has been studied by many researchers, with differing results…because the phenomenon is such a subtle nonlinear effect…" [68] but we shall concentrate on the standard case of plane waves incident upon a perfectly reflecting wall, first dealt with by John William Strutt (3rd Baron Rayleigh) [69, 70]. The reflector can be imagined to be, for instance, a circular plate held within a much larger container and far away from its walls whereas noise sources, such as compression drivers, generate a random acoustic field whose spectral characteristics are arbitrarily determined by the experimenter. With this geometry, radiation evidently strikes both sides equally and the net force acting on the plate vanishes. Let us now introduce another, identical, perfectly reflecting circular plate positioned parallel to the first so that their surfaces exactly superimpose while being separated by a gap much smaller than their radius (here we are not considering additional structures needed to hold the plates in position). Importantly, within the gap, not all modes of oscillation of the acoustic field are allowed, since perfect reflection requires the amplitude of the pressure waves to vanish at the boundaries (Ref. [71], Section 7.7). Hence the outward contribution of the radiation pressure due to modes within the gap will not, in general, equal the inward pressure due to the modes outside the gap and the two plates will experience a net force, referred to as the *acoustic Casimir force* [65, 72–74]. In practice, the resulting mutual force between the two plates due to broadband noise can be measured by a precision scale.

It is interesting to notice that, depending on the details of the arbitrary noise spectrum, such a force may be either repulsive or attractive or even vanish, and it may also oscillate as a function of the gap width. However, if the intensity of acoustic noise is constant over the required spectral band, and if all wavelengths between zero and infinity are present (obviously an idealized limit), the resulting acoustic Casimir force is found to always be attractive and to decrease in a manner inversely proportional to the gap width so that, for instance, if the gap width doubles, the force is reduced to one-half. Reported experimental data have confirmed calculations based on this theoretical framework including the appearance of the repulsive Casimir force [65, 72, 73], leading to suggestions that such an interaction may offer a strategy to remedy the problem of stiction in nanoelectromechanical systems (NEMS) [75, 76]. Of great interest is the fact that the acoustic Casimir force can be altered, shaped, or more generally *engineered* not only by acting on the acoustic noise spectrum [65, 72, 73], but also on the reflectivity of the materials and on the shape of the interacting boundaries [74]. Furthermore, the fact that the force appears at macroscopic plate separations makes it ideally suited for demonstrations designed to make the Casimir effect as “obvious” as possible, such as in the classroom or in a business presentation setting [65]. In the acoustic Casimir effect, the driver of the plate-plate interaction process is clearly the arbitrary random noise field. Let us now consider two ideal mirrors, that is, two perfect optical reflectors, and let us investigate the possibility of introducing a *classical* electromagnetic field to generate an *electrodynamical Casimir effect*. As we shall see in this chapter, systems of this type were studied by Boyer in his efforts to recover results deemed inherently of a quantum nature by means of appropriate classical stochastic fields (Sections 3.3 and 3.5). This point of view has been extremely successful and, indeed, the starting point of the work by Larraza et al. on the acoustic Casimir effect had been the interpretation of the electrodynamical Casimir effect as a “Radiation pressure from the vacuum,” in turn inspired by an explicit suggestion by Casimir (Ref. [30], footnote 5; Ref. [63]). However, in this case, the stochastic field cannot be not deemed to be completely arbitrary as it must satisfy some specific requirements of Lorentz invariance first discovered by Marshall [32, 77, 78]. With this restriction, the original result by Casimir [19] can be recovered without the need for field quantization. The difference between the classical and quantum interpretations of the Casimir effect lie with the ultimate reason for the existence of the driving field. In QED, quantization leads to the appearance of the zero-point-field [79], whereas in stochastic electrodynamics (SED) a Lorentz-invariant random field is introduced as a nonvanishing solution of the homogeneous Maxwell equations, both leading to the same predictions. Fascinatingly, in recent times, the manipulation of dispersion forces, demonstrated in acoustics by imposing an arbitrary classical noise field, has been observed also in the electrodynamical case by Brugger et al. by explicitly making use of the work by Boyer [80].

Two spherically symmetrical classical atoms cannot interact electrostatically as their dipole-dipole forces average to zero—indeed this was the reason that a rigorous explanation for the existence of van der Waals forces, first by Wang [81] and then by Eisenschitz and London [82], had to wait till the invention of quantum mechanics to be secured [12]. As seen in the Introduction, this was qualitatively illustrated by London with lucidity that has stood the test of time by an appeal to the concept of zero-point energy of the two atoms modeled as harmonic oscillators [13]. This is because, as understood relatively early on [83], the ground energy of a harmonic oscillator can be computed from simple considerations by *assuming* the uncertainty principle as a fundamental postulate without any need to even solve the Schrödinger equation. According to the uncertainty principle, in quantum mechanics there exist pairs of quantities that cannot *both* be measured with infinite precision *at the same time* regardless of equipment quality or cleverness of the experiment. In particular,[2] "The uncertainties in the position and momentum of a particle at any instant must have their product greater than or equal to half the reduced Planck constant" (Ref. [9], Vol. III, Section 1.8).

Qualitatively, the energy of an atom in its lowest energy (ground) state is determined by the sum of two terms: the former, referred to as the *kinetic* energy, is proportional to the speed of the oscillator squared; the latter, referred to as the *potential* energy, is proportional to the displacement from the position of equilibrium squared. In classical mechanics, both the speed and the displacement can possibly vanish at the same time if the oscillator is at rest and at its position of equilibrium, which corresponds to a state of zero energy. However, in quantum mechanics, position and momentum are "incompatible" variables (Ref. [84], Ch. III, Section 6)—a small average speed demands a large average displacement from the position of equilibrium because of the uncertainty principle. This means that the total energy can be expressed in terms of the average position *alone* and that there exists a position at which the total energy has a minimum. By computing this average position and its corresponding energy, one quickly shows that the lowest energy of a quantum harmonic oscillator has a nonzero initial value, referred to as its zero-point energy [85]. Similar considerations can be made regarding the ground state energy and size of atoms (Ref. [9], Section 2.4 and Ref. [84], Chapter 1, Complement C_1).

As London observed, since the average displacements of the electrons from their position of equilibrium vanish, so would also the average atomic dipole moments, and "*Classically* the two systems in their positions of equilibrium would not act upon each other… However, in *quantum mechanics*, as is well known, a particle cannot lie absolutely at rest on a certain point. That would contradict the uncertainty relation. According to quantum mechanics our isotropic oscillators, even in their lowest states, make a so-called zero-point motion which one can only describe statistically, for example, by a probability function which defines the probability with which any configuration occurs…" (italics in the original). In other words, the van der Waals force is "…a consequence of the uncertainty principle for particles" [86].

This *unretarded* treatment is valid so long as the distance between the atoms is not so large as to make the travel time of electromagnetic signals appreciable compared to the time scales of characteristic atomic transitions. However, as also discussed in the Introduction, the decay of van der Waals forces at relatively large distance range predicted from the preceding simple electrostatic considerations was found to follow a different power law than that observed experimentally. This *retarded* regime, first explored by Casimir and Polder [87, 88], has been more recently elucidated by Spruch by introducing a stochastic electromagnetic field that causes the two atoms to become randomly polarized

---

[2] In this case, the momentum can be assumed to be the product of the mass of the oscillating particle by its velocity; the reduced Planck constant is the Planck constant divided by 2π.

and to interact with each other *classically*—"a result that Maxwell could have derived, and perhaps did" [86]. Although the existence of a classical field driving interatomic forces was never fully accepted even just as a much-needed pedagogical device [89–91], this image provides a very powerful visualization of interatomic forces [63]. The obvious consequence of this model is the possibility of radically modifying such interactions by means of external fields as further explored by Milonni and Smith [92].

In quantum field theory, however, the uncertainty principle must be applied to the electric and magnetic fields just as it is applied to particle position and momentum. Consequently, space devoid of matter, just as a harmonic oscillator in its ground state, is not devoid of energy due to the existence of a *zero-point field*. The response of individual atoms to such an external field is described by their polarizability, which, in turn, is connected to the dielectric constant of a solid by the Clausius-Mossotti equation [93]. This leads to a simple explanation of the dispersion force[3] "…as having its origins in vacuum fluctuations, that is, in the uncertainty principle for the electromagnetic fields" [86]. Finally, since the zero-point energy is a consequence of the uncertainty principle [32], it is impossible to naively "switch off" dispersion forces, whether retarded or unretarded—a fundamental fact with pervasive consequences in applications.

A completely different point of view, as first showed by Lifshitz, is to describe the dispersion force between two slabs macroscopically by "the introduction into the Maxwell equations of a 'random' field" [94] following Rytov [95]. Therefore, analogously to the acoustic case (which of course was discovered much later), the Casimir force between two slabs in the real case of nonideal reflectors depends on the reflectivity properties of the interacting boundaries, which are described in terms of dielectric functions. The Lifshitz theory has been extraordinarily successful in unifying all existing results in particular known cases [32]. In the appropriate limit, it recovers the unretarded London theory of van der Waals forces and, without any ad hoc assumptions, it describes the Casimir-Polder force, that is, the retarded regime of interatomic interactions. Also, without assuming pairwise *additivity*, it yields the dispersion interaction between macroscopic boundaries in the unretarded regime and in the retarded regime of the Casimir force. In its later extension [96, 97], the theory also predicts that the force can be made repulsive by introducing an appropriate third medium in the gap between two unequal reflectors (Section 4.5). It is important to point out to the nonspecialized readership that usage of the preceding terminology in the technical literature is completely inconsistent. Such a term as, for instance, the "van der Waals force" may be used by an author to mean various possible dispersion interactions, including in the retarded regime of the interatomic Casimir-Polder force or the interboundary force of the Lifshitz theory, whose retarded limit is of course the Casimir force. Therefore, although, by a rigorous definition, use of the term "van der Waals force" should be restricted to the unretarded regime, it is extremely common to find it employed also in the retarded regime.

An exploration of the dependence of dispersion forces on the dielectric function of truly historic importance to technological applications [37] was first carried out by Arnold, Hunklinger, and Dransfeld [98]. In that experiment, it was shown that, by irradiating a semiconducting surface to alter its free

---

[3] The term *dispersion effect* was first introduced by London to indicate that van der Waals forces depend on the spectral response of interacting molecules (see Ref. [13], §5). Although "dispersion forces, together with the orientation and induction forces of Keesom and Debye, are now regarded as three general types of van der Waals forces" [32], unless otherwise specified, hereinafter "we shall presume that this type of force, which is not conditioned by the existence of a permanent dipole or any higher multiple, will be responsible for the van der Waals attraction…." [13].

charge number density, the van der Waals force changes as a function of illumination level, thus demonstrating the critically enabling attribute of time-modulation. Although the experimental results offered some interpretative challenges, a much later experiment carried out with the atomic force microscope (AFM) was reported to fully confirm expectations from the Lifshitz theory [99].

The discovery of the implications of the existence of dispersion forces in nanotechnology applications has a long and intricate history, which we explore, in part, in this chapter. Possibly one of the earliest steps was the bold suggestion by Robert Forward that potential energy can be stored in the dispersion force field and that such energy can be later released as an electric current [100]. Although the idealized device Forward discussed is not competitive by many orders of magnitude, his explicit suggestion that energy associated to the Casimir force can be transformed from and into electrical energy remains an extremely powerful inspiration. The importance of dispersion forces in NEMS dynamics was first outlined in a widely cited paper by Serry, Walliser, and Maclay, who concluded, that "it appears that the attractive force between parallel surfaces may not always have to be dealt with as a nuisance; rather, it may be manipulated to perform useful tasks just as capillary forces have been utilized to actuate MEMS components" [101]. The remarkable foresight of this statement can be best appreciated from the fact that no leading reviews on nanorobotic actuation of the period, regardless of the breadth of their visions, mentioned van der Waals forces as an actuation tool [102–106].

2.2 EXECUTIVE SUMMARY

Given the preceding background, the following overarching question has been advanced by the present author over the last two decades: "What space technology applications are enabled by the fact that two neutral polarizable objects strongly interact with each other at submicrometer separations and that such interactions can be manipulated in both space and time?" [107] This issue was initially explored by building upon a synergy of the previous ideas on energy conversion and MEMS actuation introduced, respectively, by Forward and by Maclay and collaborators, and from the perspective of dispersion force control implied by the experiment carried out by Arnold, Hunklinger, and Dransfeld. As a first step in this direction, the existence of thermodynamical engine cycles was shown, in which the van der Waals pressure plays a role analogous to that of gas pressure in an idealized steam engine.[4] Since energy can be drawn from (released to) the environment to increase (decrease) the magnitude of the van der Waals pressure in semiconductors, the possibility exists to transform part of such irradiated energy into, for instance, mechanical work thus "…achieving optical control of Casimir force actuated devices, in close analogy with already existing technologies for the control of semiconductor microactuators. As the Casimir force acts on components on any scale, this technology could allow for the direct dynamical manipulation and control of semiconducting nanostructures" [108]. Such idealized engine cycles can be applied to macroscopic slabs as well as to individual molecules [37]. For instance, actuation of membranes [109, 110], microswitches [111], adaptive optics [112], and optically driven parametric amplifiers [36] were suggested. The present author has also shown that the interlayer van der Waals force in nanotubes can be modulated by irradiation [62]. This leads to consideration of engine cycles to control shuttle dynamics in telescoping nanotubes employed as nanoaccelerators [60] and nonchemical energy

---

[4] Notice that ordinary gas pressure is positive whereas the van der Waals pressure is quite often, though not always, negative. Hence engine cycles leading to positive mechanical work done on the environment may take place in a *clockwise* fashion in an ordinary (P, V) diagram [108].

storage devices—an approach that holds promise to deliver energy and power densities capable of outperforming traditional devices such as electrochemical batteries and supercapacitors [61]. More broadly, as explored in one related example in Section 4.4, the properties of nanotube superfibers are expected to be not only affected but possibly also both manipulated and modulated by an appropriate management of dispersion force interactions.[5] Casimir force modulation in nanotubes [62] represents one further key step forward in this developmental process [113].

In the rest of this chapter, we analyze several threads of the rapidly accelerating transfer of dispersion force physics into the technology marketplace with an emphasis on the economic significance of such momentous developments and on crucial challenges likely to be met on the ground as this process unfolds.

3 INDUSTRY, SCIENTISTS, THE NEWS, AND CAPITAL

Although our plan of action is clear, an unusual, yet major, obstacle lies immediately in our path. This is presented by a rather widespread perception among several well-informed decision makers that the scientific risk of adopting dispersion force-enabled solutions is in fact *not* being reduced even after decades of explosively growing laboratory, theoretical, and computational activities. As witnessed by this author on multiple occasions, several factors contribute to creating this additional challenge.

3.1 SURPRISING AND WEAK

A first cause is the continued belief or claim, even by some professional scientists and quickly magnified by media coverage, that Casimir forces are “surprising” as well as “weak.” In the two-decade experience of this author so far spent actively pursuing industrial applications of the Casimir force, such easy cliches and inaccurate characterizations have been consistently found to unnecessarily inhibit that profound “meeting of the minds” with potential investors and public administrators that is an absolute precondition on even attempting to cross the yawning chasm [114] between the chalkboard (or whiteboard) and the advanced technology marketplace. In practice, media outlets and science magazines aimed at a general audience, inspired by interview material or official research laboratory press releases, often market the Casimir effect as “mysterious” [115, 116] and, if this were possible, even “more mysterious” [117]. From the quantitative standpoint, the Casimir force is sometimes authoritatively described as “barely detectable” [20] and “…a very weak effect that can only be measured at smallest distances of the plates, typically of the order [of] nanometers” [118].

As regards commentary on the Casimir effect as “surprising,” a careful examination of the scientific and broader historical contexts reveals that, at the time of its announcement, that contribution was *not* perceived to be, as often erroneously stated, the discovery that “a pair of electrically neutral conductors should attract one another” [29]. Such adhesion phenomena had been known for centuries in marble and glass surfaces and for over one century in polished metals. One decade earlier than Casimir’s paper, Hamaker, also at Philips, had given as his leading motivating factor the fact that “frequently we experience the existence of adhesive forces between small particles of any substance or between a particle

---

[5] It was proposed by this author that, in analogy with the transistor, devices based on this principle be referred to as TRANSVACER devices, as the acronym of TRANSducer of VACuum enERgy.

and a surface" [16]. Indeed, speaking from the standpoint of quantum electrodynamics, Milonni clearly commented: "Whether the Casimir force should be regarded as startling or nonintuitive is, of course, arguable. If we regard it as a macroscopic manifestation of van der Waals forces between molecules, there is hardly any reason for surprise" [32]. In that discussion, quantitative arguments based upon the additive approximation and the Clausius-Mossotti equation were presented showing that, if a *retarded* (Casimir-Polder) interatomic force is postulated, a macroscopic force between perfectly conducting plane boundaries correct to within 80% of Casimir's result follows as an immediate consequence. This is an extension of earlier arguments developed by Hamaker [16] and de Boer [14] to calculate the van der Waals force between dielectric boundaries within the framework of London's theory of *unretarded* forces.

Of course, such a view only shifts the "mystery" to that of the existence of forces between individual atoms. Within the context of quantum theory, even only considering unretarded forces, it is difficult to go beyond the highly suggestive teachings by London quoted in the Introduction. As recently discussed by the present author [63], arguments based on classical stochastic fields greatly aid in removing the perceived clash with the widespread doctrine that neutral conductors do not interact. The only responsible, long-term approach to address "surprise" and misperceptions about the existence of the Casimir effect is to redesign the basic pedagogical analysis of Coulomb's law to include an unambiguous statement that only *nonpolarizable* neutral particles are expected to not interact, whereas any *polarizable* particles, even including neutrons [119, 120], *always* interact. This is not in contradiction with classical electrodynamics as indeed shown by a careful reading [63] of Maxwell's *Treatise on Electricity and Magnetism* [121]. Feynman's reported—nowadays hardly known—"stunning demonstration" [9] of molecular forces by means of the Johansson blocks can provide an unequivocal visual experience that the acquired "intuition" of noninteracting neutral conductors is based on a dogma in stark conflict with physical reality.

As regards the alleged nearly negligible magnitude of the force, such comments are also rather common—again especially within or originating from the theoretical physics community—despite their being in striking conflict with Feynman's early warning about stiction and also not based on physical fact. Indeed, as one can quickly verify from Casimir's result, the idealized Casimir pressure for such an extremely small experimental plate separation as $s = 1\,\text{nm}$ (mentioned in Ref. [118]) is $\sim 10^4$ atm, whereas a realistic order of magnitude for real materials at a separation $s = 4\,\text{Å}$ yields a pressure $\sim 10^3$ atm or "…of the order of the tensile strength of solids" [122]—thus not only "detectable" but indeed dominant.

3.2 INTERNECINE STRIFE

A third factor introducing doubts about dispersion forces as a viable path to disruptive technologies in the minds of decision makers is the unusually confrontational interaction among several leading practitioners, which is also amply documented and sometimes caricatured in the international media. One early source of conflict was a very public clash over the issue of "zero-point-energy extraction," typically in engines with a variable gap between plates interacting via the Casimir effect (Section 2), which erupted in the aftermath of the 1997 NASA Breakthrough Propulsion Physics Workshop (for instance, see papers by Forward and by Puthoff in Ref. [123]) also including independent work by the present author [108]. This debate is logically connected to earlier and, to some, equally controversial research [63, 124] into alternative formulations of electrodynamics—referred to as random or stochastic electrodynamics

(SED)—capable of producing correct predictions *classically* and without any need to introduce quantization schemes [32, 77, 78, 125–129]. In these approaches, provocatively, the now mainstream idea of quanta becomes a "subterfuge" [130]—the same appellative later used to describe stochastic electrodynamics [131]. Although, as stated elsewhere [37], objections to predictions of energy conservation violations by a *Gedankenexperiment* by this author are well-posed and may be correct [132], the nearly total disappearance of this issue from the refereed record indicates an instance of what Collins and Pinch refer to as "implicit" rejection, which, in contrast to "explicit" rejection, "operates when rival knowledge claims are ignored by orthodoxy" [133]. Marco Scandurra offered the following important commentary on this scientific practice in arXiv: "The silence of the 'orthodox' part of the community expresses the deep scepticism on such developments. However the policy of ignoring publications does not contribute to the progress of science. Discussion is always positive as long as it remains on the track of scientific argumentation. We also point out that a rigorous quantum field theoretical analysis of the ideas lying at the basis of the proposed machines is still lacking. This subject gives the opportunity to investigate the thermodynamics of the quantum fluctuations of the vacuum. More exactly we would like to address the question: does any thermodynamics in the vacuum exist?" [132]

Juxtaposed to such an agreeable and professionally stated plan of action, leading science news outlets had reported that some within the majority of orthodox physicists disdainfully branded any investigation in this direction as nothing but "pseudoscience that could leech funds from legitimate research" [134]. Reaction by the "orthodoxy" against any contrary view is so strong that one might be justified to not include this debate within a section titled "Internecine strife," as "Outward strife" might be more correct. The justification often repeated in the media to show energy conservation in the standard Casimir force system of two parallel planes is that "The effect cannot be tapped as a continuous power source, though, since pulling the plates apart takes as much energy as is released when they come together" [135] (a nearly identical statement also appears in Ref. [134]). As we have seen (Section 2.1), this key statement is easily shown to be in conflict with both theoretical understanding and experimental fact (Section 2). In fact, as shown by the same *Gedankenexperiment* proposed by this author, "thermodynamics in the vacuum" leads to a clear prescription for the realization of a thermodynamical engine cycle by means of semiconductors, which is necessary for the design and operation of dispersion force-enabled nanomachines capable of exchanging energy with the environment in the full respect of the laws of thermodynamics [37, 108].

It is probably correct to state that the present status of understanding of the so-called "zero-point-energy extraction" debate by the orthodox majority is that extraction is impossible in theory [134] and that experimental data are consistent with null results according to reputed laboratory workers [136]. However, such outcome has been misconstrued by some and misunderstood by others as implying that *any* applications of the Casimir force involving energy exchange, including both ordinary energy storage and energy transfer and conversion in engines, must be disbelieved on fundamental thermodynamical grounds. In part, this deafening silence and misinformation regarding scientifically legitimate issues might be explained as a manifestation of deep cultural differences, as extensively articulated by Collins in terms of *open* and *closed evidential cultures* (see Ref. [137], Chapter 22 and Fig. 22.1). For instance, discussing the tensions between the Frascati and Louisiana gravitational wave detection groups in dealing with controversial experimental data on supernova SN1987A, attitudes in favor of or against publication were attributed to an *experimental animus* or a *mathematical animus*. Collins comments: "These are useful labels in this case, because of the *current role of theory in holding back speculation*… the Frascati team believed this data should be published and looked at by the rest of the community; as far as they were concerned, something had been found, and it could not be wished away. In contrast, the mathematical animus, *taking experiment to be servant of theory*, would have suppressed the data" [137] (my italics). Although the present author accepts formulating such explanations in the language of social science, in practice, as we shall explore below, the issue is one of calculated information control in the service of agendas designed to advance some interests to the detriment of others. In this case, in the direct experience of this author, *any* proposal to exploit dispersion force manipulation in NEMS may encounter an abnormal, wholly unjustified degree of skepticism regarding the legitimacy of its very physical foundations.

Unlike wishful thinking to the contrary, such exchanges do not only occur at the clash line that the "kook community" [134] joins battle with practitioners [138] valiantly defending the orthodoxy from "cranks" [124]. Indeed, far fiercer confrontations have repeatedly involved established groups within the mainstream providing telling snapshots of international level academic interactions sadly not measuring up to the idyllic harmony of the breathtaking *School of Athens*, in which Raphael had "portrayed all the wise men of the world presenting different arguments" [139]. Some debates, such as that on the "finite temperature correction" [54, 140–142], although actually focused upon issues very substantive to theoretical physics, are generally perceived as too esoteric to be central to venture capital boardroom decisions about funding disruptive technologies. However, it is a simple matter to pierce the thin appearance of civility and find sociologists in fact studying such issues as "Controversies in the Casimir effect" (*Controversias en el Efecto Casimir*) [143] after having left the field as physicists specializing in the same area [124] or even mainstream physicists unusually announcing the end of their own work in the field [54]. Certainly more transparent to informed, interested readers are the loudly voiced doubts regarding even the meaning of experiments "that claim 1% accuracy" [144] and delivered with language leaving little to the imagination: "…in the surface-surface Casimir force measurement field, there have been more than a few 'Comments' on various papers; the interested reader would do well to ignore most, but not all, of these 'Comments' as they are confusing, if not bogus, but certainly inflammatory" [144]. This particular broadside attracted literary return fire in a paper with such a revealing title as "What is credible and what is incredible in the measurements of the Casimir force" [145]. Extremely devastating in the latter, sanguineous counter-strike is the claim that, in practice, one of the most celebrated experiments in the history of Casimir force studies [146] would be "fundamentally flawed" [145], followed by an entire section devoted to a list of "Technical mistakes" allegedly committed by the opposing practitioner.

Another well-documented exchange involving two different groups was caused by a disagreement over the existence of "quantum friction"—the drag-like force expected to oppose relative motion of the two standard Casimir system plates parallel to each other, that is, while maintaining a constant gap width. The opening salvo was a paper unambiguously titled "No quantum friction between uniformly moving plates" [147]. Interestingly, along with technical quantum electrodynamical calculations showing that quantum friction does not exist, a simple thought experiment was also introduced showing that the existence of such a drag-force would lead to a violation of the conservation of energy so that the friction force must *not* exist on fundamental grounds.[6]

---

[6] This second argument is logically faulty as shown by the present author by means of elementary mechanics calculations [63].

The competing group replied with their own provocative title, reading like the opening verse of a scoffing epigram, "Quantum friction—fact or fiction?" [148] This criticism in turn led to more heated exchanges published as Comments [149, 150], prompting Chris Lee to publish a story aptly titled "A fraction too much friction causes physics fisticuffs" [151], commenting, "If we hurry, we should catch the end of round three," and illustrated by a photo of one individual punching another.

Although, as Collingridge authoritatively stated, it is a reality of science that "experts can be expected to disagree" [152], unusually bitter, well-documented confrontations are not rare occurrences in Casimir force physics, involving even groups continuously feuding over multiple issues. This landscape is fundamentally different from random ego clashes that erupt at times in any profession such as, for instance, the unforgettable—but personal and time-limited – exchange between Neal Koblitz and Economics Nobel Prize winner Herbert A. Simon [153–155]. It is also a peculiar phenomenon considering that there now exists a sophisticated genre of pedagogical literature devoted to teaching proper, nonconfrontational English-language academic writing techniques [156] and that a subfield of modern linguistics research is, somewhat ironically, devoted to the study of "hedges" and "politeness" in professional research writing [157, 158].

It would also be erroneous to dismiss this assessment by stating that such clashes in dispersion force research are not a recent development. One example of a much earlier disagreement is the historic first face-to-face encounter between Derjaguin on one side and Verwey and Overbeek on the other at the 18th Discussion of the Faraday Society held in Sheffield in 1954 [159]. In a detailed footnote, Derjaguin indeed observed the lack of proper citation of his important work[7] with Landau [160] by Verwey and Overbeek in their famous *Theory of the stability of lyophobic colloids* [161]—still in print today—describing it as "the fallacy of the critical remark… with no reference to our paper" [162]. However, in the general discussion following that session, Verwey and Overbeek stated: "We admit to these facts and we want to express our great regret that we have overlooked these papers in writing our monograph," even admitting to Derjaguin's priority in the specific issue at hand. In response, Derjaguin reported his full satisfaction and congratulated Verwey and Overbeek for the "exceptionally clear and systematic form" in the presentation of their discoveries (Ref. [162], pp. 180–181). Such a resolution represents an exceptional degree of professionalism displayed by all involved and it stands as an egregious counterexample to embarrassing contemporary events.

3.3 ENTERTAINMENT AND FICTION

Finally, as also occurs for nanotechnology [105, 163], factors to play a role in discussions on funding dispersion force engineering business plans have been the entertainment industry and literary fiction [164]. In the experience of this author, even in conversations at the highest level, it was found that science fiction was "not an external but an internal aspect" [165] of the Casimir force-enabled technology discourse. Since descriptions of the Casimir effect quite typically appeal to the concept of zero-point-energy (Section 2), exchanges with decision makers were often found to drift into "free energy" speculations and related concepts popularized by nonscientists or by scientists writing fiction. Among many examples, awareness in space technologist circles of *Encounter with Tiber*, by Buzz Aldrin and

---

[7] On August 10th, 1987, the same paper became a "Citation Classic" in the Acta Physicochimica URSS as the "most cited paper for this journal" (see Acta Physicochim. URSS, 32, 22).

John Barnes, with scientific assistance from Robert Forward and other experts, was already reported [43]. In this highly acclaimed 1996 science fiction novel based on an alien contact plot, Engineer's Assistant Krurix, "a Palathian male," provides detailed descriptions of zero-point-energy extraction via the Casimir effect (Ref. [166], pp. 440–441). Indeed, in the foreword, such an argument is raised by none other than Arthur C. Clarke citing an oft-repeated estimate of zero-point-energy density by Richard Feynman. The Casimir effect also makes an unlikely appearance as "a free lunch" in the play *An Immaculate Misconception* by the late Carl Djerassi of Stanford University, "father of the birth control pill" [167] and it is a *Physics Bowl* answer in the "*The Bat Jar Conjecture*" episode of the ever-popular sitcom *The Big Bang Theory* [168, 169]. However, probably no other work contributed more to spreading Casimir effect-related ideas into Silicon Valley circles than Syndrome's "zero-point energy beam" [170] in the animated feature *The Incredibles* [171].

As might be expected, the effect of such a broad presence of Casimir force–related concepts within fictional works is two-fold. On the one hand, it facilitates "breaking the ice" and establishing a communication line with an extremely diverse pool of potential recipients of the message by taking advantage of a potential common experience, whether literary or visual. On the other hand, it contributes to further exacerbating follow-up skepticism, as it is natural for a professional decision maker, though curious at first, to then disbelieve information acquired from works of science fiction, television entertainment, or cartoons. An exception to this assessment is the role of speculative, but not necessarily incorrect, Casimir force concepts in such areas as cosmology and metaphysics. This is the case, for instance, with the mention of "Creation—namely, generation of the universe from vacuum fluctuations" [20], closely connected to an earlier, uncited paper by Tryon [172], which, however, offers little opportunity for technological development beyond fascinating conjectures.

3.4 QUASI-HISTORY AND MYTHS

The consequences of all challenges briefly outlined in this section are as complex to assess as they are multilayered and real. As already previously reported, among factors of critical importance and in need of deeper study, existing irreconcilable disagreements result in improper, incomplete, and self-serving citation strategies [43], which produce a distorted description of the role of various authors in the history of the field and, critically, of the development of the present state of the art. Such phenomena have been known for decades and are the subject of intense coverage too lengthy to cite comprehensively here (several early examples and commentary are given in Ref. [173]). Unlike the highly idealized "inflexible etiquette in scientific publications that authors should refer to all previous findings" [174], several years ago David Jones graphically reported: "Performance indicators abound—impact factors, citation counts, publications per head or per grant dollar, and so on. Mutual backscratching cliques cite each other furiously in all their papers; journals parasitized by such publications proudly proclaim their impact factors; grant money flows to individuals and organizations who can show the best performance indicators" [175]. Such an apparently injurious description certainly lends credence to a view of science not as the "product of contemplation," but in relation to "interests" [176], which "can be thought of in terms of a stake in money, power, status, privilege, or other advantages" [177]. Although such a jarring realization is far from new, it also naturally leads to the expectation that researchers conduct themselves as any other corporate entity, in particular, reacting with hostility to any challenge to their status. Here we do not intend to take a philosophical position as to the vast question of the ultimate nature of knowledge. Instead, we intend to propose an issue of interest even within the provocative framework that "science has now become as oppressive as the ideologies it had once to fight" and that "it inhibits freedom of thought" [178]. The question is: Are such well-known practices, along with all phenomena briefly mentioned in this section, undermining economic development by inhibiting early-stage investment?

For instance, exploratory studies by this author lead to hypothesizing that the delineation of the field of dispersion forces and mapping of contributing groups as functions of time as shown by citation practices in publications, which are voluntary, may not match those obtained from patent citation practices, which reflect regulation by law and are chosen by the patent examiner (different procedures between the USPTO and the EPO are discussed in Ref. [179]). This is far from a novel idea. Although indeed "inventors are mostly scientists" [180], the description of this emerging technology by practitioners acting in compliance with the regulated environment of patent law may be different than that provided by the same practitioners creating their own narrative in refereed journals [181].

Typically, the creation of quasi-history by "textbook writers and the science community at large" [182, 183] is studied for its negative pedagogical consequences and its potential impact on bona fide historical research. It is also clear from the few examples listed so far—and the many others available—that some practitioners within the disharmonious dispersion force research community have both the motives and the opportunities to dominate perception of the field by injecting quasi-history into the narrative. The outstanding question is the reason that facts so relatively simple to disprove are not more carefully scrutinized by the majority of practitioners and they are uncritically repeated. In addition to the mischaracterization of the Casimir force as "weak," the present author documented a simple instance of myth-in-the-making [184] introduced to provide credible but demonstrably nonexisting support to an otherwise quite possibly valid physical model for a proposed maritime Casimir effect [185], which later evolved into widespread belief by the orthodox scientific community because of such relaxed fact-checking. In a section titled "Propaganda and myth," Whitaker concludes that "it is an extremely difficult task to decide from written evidence what was really believed at a certain time, but also that, after many years of propagation of quasi-history/myth, even those involved in the events may come to believe it" [182]. Such a matter-of-fact statement challenges the naive view of science as yielding the truth [152] and is strongly mindful of the lengthy debate about the ultimate meaning of historical understanding prompted by the concept of contextual archaeology [186, 187] developed by Ian Hodder [188–190]. Fascinatingly, scientific interpretations and media reflections on the Casimir effect and its potential technological role conform, *mutatis mutandis*, to Hodder's assessment that "In archaeology, there is a spectrum of positions on meaning, ranging from the idea that meaning is inaccessible to the idea that meaning is accessible and multiple" (Ref. [191], p. 162).

Such confusion may appear surprising since, unlike the case of a typical archaeological site, Casimir force research activities are a contemporary occurrence and most actors involved are professionally active. However, such a variety of multiple opinions is typical as "anomalies" [192] emerge and it also reflects the "uncertainty and ambiguity" that accompany the appearance of disruptive technologies [44] (Section 4). In addition to these mechanisms well known to be operating throughout the practice of scientific endeavor, the specific manner in which QED reaches a quantitatively highly accurate explanation of reality—renormalization—was challenged for its philosophical implications (Ref. [193], p. 46 and Footnote 20). Mathematically, also in the Casimir effect, this entails extracting a finite result from the difference between two infinite values, as Dowling entertainingly shows [194]. Physically, in our particular case, "many ways to describe the effect" are known, also without resorting to zero-point-energy but by means of source fields, "in which, contrary to prevailing ideas, there are no nontrivial vacuum fields" [32]. Such factors surely make plausible the alluring myth that the prediction of forces between neutral conductors was "dismissed…as patent nonsense" [194]. However, as we have already seen in the Introduction, such was absolutely not the case as the "nonsense," according to Pauli, was *not* the existence of the effect but its physical interpretation in terms of zero-point energy.

3.5 THE "FRINGE"

It is now appropriate to offer a few comments about the effect of the presence of a so-called "kook community" of "pseudoscientists" on the dynamics of scientific due diligence of Casimir force-enabled inventions alleged to be siphoning off funds, "perhaps governmental" [134], that might otherwise be devoted to legitimate research. An already cited very recent effort aimed at characterizing "fringe science as opposed to the mainstream" [138], coauthored by a social scientist with Casimir force research experience, also offers a review of the problem and useful operating definitions. Without attempting to adapt that general discussion to the specific case of "zero-point energy extraction," we point out that those who would likely be declared to come from the so-called fringe of this particular subfield belong to two very different communities.

On the one hand, "a small but active group of researchers" [32] is motivated by their own interest in determining whether successful theoretical predictions typically attributed to the development of quantum mechanics, including the existence of dispersion forces [125, 128], can instead be reached by exclusively classical or semiclassical methods [78, 128, 129]. In this approach, referred to earlier (Section 3.3) as "stochastic electrodynamics" (SED), the starting point is provided by the classical Maxwell equations for which the existence of a fluctuating field is posited as the homogeneous solution in the absence of charges and currents. Consequently, "The appearance of $\hbar$ in this modification of classical electrodynamics implies no deviation from conventional classical ideas, for $\hbar$ is regarded as nothing more than a number chosen to obtain consistency of the predictions of the theory with experiment" [32]. Providing a calculation leading to predictions of the physical parameters of this hypothetical random field, though obviously interesting, is no more necessary to this approach than the "considerable numerology" [195, 196, 197] surrounding attempts to heuristically compute Planck's constant of quantum mechanics from other a priori assumptions. Indeed, theory and experiment have shown that "dispersion forces between small colloidal particles can also be induced and controlled using artificially created fluctuating light fields" [80], as was also previously proven to be possible by means of broadband noise in the acoustic Casimir effect [73]. As Boyer reported, "Some readers of this classical electromagnetic analysis are distressed, even indignant at the idea of a "classical" electromagnetic zero-point radiation. They insist that zero-point radiation is a "quantum" idea which can not be used as part of classical physics. However, surely this objection is without merit" [129]. In the experience of the present author, the impressive record of publications of this community is often ignored,[8] misconstrued, disparaged and even shamed by "orthodox" practitioners, including, remarkably, present editors of those journals deemed as among the most prestigious by the same orthodoxy and in which SED results were very extensively featured in the past. The reaction by some mainstream scientists towards the undeniable "successes of SED" [32], is quite often vitriolic, even if the only aim

---

[8] One of many possible examples is provided by David L. Rosen in a letter [198] to *Physics Today* pointing out the striking absence of any mention of SED in a recent article devoted to the classical atom [199]. Unsurprisingly in light of our previous comments [133], that letter went without any reply from the original authors.

of such efforts be an exercise “to save the phenomena” [200]. This can be understood in terms of the anthropological processes described by Th´er‘ese and Martin in their paper unforgettably titled “Shame, scientist! Degradation rituals in science” [201]. In fact, despite those blatantly unscientific positions, the question Scandurra asked [132]—“does any thermodynamics in the vacuum exist?”—can obviously be investigated in relation to thermodynamical engine cycles involving dispersion force manipulation achieved by energy exchange with any fields [108], whether, for instance, electrodynamic or acoustic, stochastic or quantum, artificial or genuinely “zero-point,” such as those reported previously [73, 80]. Such investigations are not only legitimate but ongoing and technologically very promising [107].

Next to these SED workers, who regularly publish in journals held in high repute even by the orthodoxy, a second group exists that one might reasonably characterize as belonging to a “fringe” [138], sometimes inspired by fiction and conspiracy theories. The stories surrounding this community range through the entire spectrum between relatively unconventional and daring, but legitimate, mainstream research all the way to accounts of alleged UFO technologies and antigravity as entertainingly told, for instance, in *The Hunt for Zero Point* by Nick Cook [202]—rebuffed point-by-point by mainstream authors as in *Voodoo Science* by Robert Park [203] and “*Did Adam and Eve have navels?*” by Martin Gardner (Ref. [204], Chapter 4).

Although it is quite typically believed by practitioners that “You instantly know if a paper is junk” [138], the situation is far from clear-cut from the standpoint of technological investment decisions. For instance, mainstream physics is affected by internal debates regarding whether testability should even be a prerequisite or whether “elegance will suffice” so that it is now feared that “theoretical physics risks becoming a no-man’s land between mathematics, physics and philosophy that does not truly meet the requirements of any” [205]. In parallel developments, a “reproducibility crisis” [206] is widely reported and accompanied by a corresponding debate as to whether irreproducibility as well should just become the new norm [207, 208]. In connection with this latter issue, direct experiences of this author—consistent with far broader findings [209]—have shown that demonstrably incorrect papers in Casimir force research published in a high impact factor journal are nearly impossible to correct even after multiple attempts and appeals, at most resulting in very limited admissions of error [63, 210, 211]. These latter cases are far more treacherous to the process of scientific due diligence because, in papers written fully conforming to orthodox practices, “Mathematical verbiage is being used like a witch doctor’s incantation, to instill a sense of awe and reverence in the gullible or poorly educated” [153]. Plainly, it is far easier to weed out a business proposal alleging to be based on “alien technology” than one based on discoveries published in some of the most revered scientific journals in the world, although they might both be equally unsound if not fraudulent [212]. Intriguingly, although it was confidently stated that “retired engineers seem to be prone to this grandiosity” [138], announcements at first sight just as offensive, also connected to quantum vacuum physics, but made under the umbrella of powerful sponsors [213–215], fail to trigger the expected “ritualized degradation” before the “assembled audience” of mainstream science [201]. Of course, this is not the place for an analysis of this phenomenon except to remark that, commencing at least with Martin Gardner’s decades-old devastating comments about “stupid, ignorant, almost illiterate men” [216], this latter “kook community” [134] has in practice been marginalized and neutralized by attacks at least as brutal as those mainstream Casimir force practitioners openly reserve for one another. Unfortunately, the same cannot confidently be said for the historic “…impositions that have been practiced in science… of hoaxing, forging, trimming, and cooking” [217]. It is important to frankly acknowledge that declaring untimely physics breakthroughs, publishing fraudulent data, and misrepresenting the work of others through unethical citation practices is no longer just a grotesque symptom of belonging to the fringe but also a systemic malaise of the mainstream that has led to an explosively growing lack of credibility in science by the community of nonscientists.

3.6 OVERALL EFFECT ON SCIENTIFIC DUE DILIGENCE

Twenty years after serious concerns about "leeching" of public funds were raised in Philip Yam's *Scientific American* article, it would be naive, if not irrational, to not hypothesize that, applying to this field the candid words by David Jones in *Nature*, "mutual backscratching cliques" entirely embedded within the official "orthodoxy," often openly warring against one another, ruthlessly control the narrative thus ensuring continued publication success in "parasitised journals," and, consequently, the flow of "grant money." This vicious dynamics manifests itself by an often grotesque absence of "good manners" in citation practices [218] thus erasing the very existence [43] of workers deemed as threats or as unserviceable article references. The end product is an "incomplete and tainted record" [219], or, actually, a plurality of multiple, incompatible records, to severely cripple the ability of even highly qualified experts to "extract meaning against the grain of the documentation" [220], as in Raphael Samuel's famous phrase quoted by John Tosh (Ref. [219], p. 179). In addition, the enduring culture of "mystery" associated with the Casimir effect encourages a particular variety of "manufacturing doubt" [221]—begging for a resolution by "appropriate" research actors, marketed as an engaging story in newspapers and popular science publications, and adopted as a thrilling element in deservedly successful fictional plots. Among the standard tools to succeed, it is now matter-of-factly accepted that "Being a good scientist is half science and half marketing" and that "Of course, to get a proposal funded, we need to market our work" [222].

The fact that taking control of the narrative of scientific and technological progress enables control of public research funding is so transparently clear that such a mechanism is taught as one of the "kinds of power in science" to be understood in order to be "winning the games scientists play" [223]. Among others, Sindermann lists the "power possessed by the principal administrative officers of granting agencies, government or private"; "power possessed by journal editors"; and "power possessed by scientific peers." For instance, regarding the last type, "peers examine and comment on research proposals and manuscripts; peers decide whether or not they will cite published work; and peer discussions result in informal but very important evaluations of research." (Ref. [223], pp. 180–182) The detailed analysis of the science funding machine with its many moving parts provided therein makes it clear that the stakes could not be higher in executing a strategy resulting in effective management of the interaction with editors, agency administrators, and peers.

These complex mechanisms directly and indirectly affecting grant proposal scoring are not only active in determining public research funding allocation. On the contrary, companies at any stage of development undergo a thorough audit to determine the accuracy of the information upon which a critical transaction decision, such as a merger and acquisition (M&A) or an investment, is made. Such is the scenario, for instance, of a startup company seeking angel or institutional venture capital funding to develop an invention into a profitable product. This inquiry into all aspects of the company, referred to as *due diligence* [224–227], has been generally characterized as "a reality check with an in-built veto" [228]. It is deemed by practitioners to be "*imperative* to perform due diligence on all new plants or processes that utilize either *new* or *emerging* technologies" [229] (italics in the original).

This particular phase of the investigation is referred to as *scientific*, *technical*, or *technological* due diligence. A first well-known difficulty with competently executing such a check of any scientific claims underlying a business proposition is that "Sourcing the right expertise can be difficult and knowing how to upscale the technology can also be complex" [230]. A second obstacle is that "Visualising the opportunities is beyond many investors without significant investment in technological and scientific due diligence, which is all too often derailed by large upfront fees" [231]. This latter problem is especially felt in the case of angel investing in startup companies, which cannot be expected to face burdensome costs [226]. However, if this problem can be addressed, it is often possible to locate highly qualified due-diligence firms that specialize in particular industries, such as clean tech [230] or sustainable energy [232].

Unlike better-understood subfields, as we shall see in the following discussion, investment opportunities based on Casimir force-enabled technologies display a "perfect storm" from the standpoint of scientific-technical due diligence. The science—both theoretical and experimental—and the mathematics involved require an advanced degree of general knowledge applied to a subject with a notoriously steep learning curve; qualified expertise in this area is not widely available; and companies seeking funding for related applications are often, though not always, startups. Typically, if the business proposition presented in a formal business plan survives its first screening, perspective angel investors or institutional venture capital fund managers will reach out to a trusted technical consultant to receive an opinion on technological feasibility. Such consultants may or may not have present or past association with academia and may widely vary in personal career achievements, ranging from Nobel laureates to versatile, self-made experts without an advanced degree in a scientific field. At this early stage, an attempt is probably made to analyze any claims that appear "too good to be true." Because concepts based on Casimir forces are, by the nature of the applications designed to involve them, disruptive, the proposition described in a business plan is likely to highlight the possibility of generating very attractive returns by the introduction of breakthrough technologies in such remunerative markets as energy and medical technology. However, a technical expert will naturally approach such claims with an understandable degree of professional skepticism.

On the one hand, for inventions relying on exploiting the adhesion between two surfaces by strategies based on nontrivial geometries or gap media, a consensus can relatively quickly be reached that no fundamental laws are violated. Cases of this type include, for instance, the historically important Johansson blocks to be discussed later (Section 4.1), "gecko glue" [233] concepts, and even some nanoelectromechanical systems (NEMS), such as the carbon nanotube-based nonvolatile random access memory [234]. On the other hand, inventions involving the interplay of a time-modulated Casimir force, and possibly simultaneously of electrostatic forces, are based on thermodynamical transformations involving energy transfers with the surrounding environment [37]. Unfortunately, consideration of issues relating to such engine cycles is often tainted by impressions gleaned from reports surrounding the fierce debates about "free energy" (Section 3.3) likely leading a cautious expert to raise a "red flag." In these cases, scientific due diligence may either just yield a disappointing quick veto recommendation, or continue with the same expert, or more specialized consultants may be recruited to provide a final opinion. If the second outcome materializes, one of many possible follow-up directions may include a highly technical discussion of supporting experiments proving that Casimir forces have indeed been manipulated by means of illumination in the laboratory. However, earlier results failed to conform in detail with expectations from the Lifshitz theory [98] whereas more recent data [99], which do conform, fall under a shadow of doubt given the mutual credibility allegations previously discussed.

Furthermore, it must be considered that such discussions take place in person—more rarely on the telephone or on teleconferencing connections—in high-stakes meetings under the pressure of time during which any concern, even though minor, may lead an expert to recommend opting out of the opportunity. Given the aforementioned common characterizations of the Casimir force as weak and mysterious and the levels of public, mutual discrediting of experimental and theoretical results found in the refereed literature, a consultant unfamiliar with the field may well decline recommending an investment until the scientific landscape becomes less contentious. If the third outcome occurs, more voices, often in part drawn from or heavily influenced by academia, are added to the scientific due diligence team. In this case, in the experience of this author, the typical outcome is that "experts can be expected to disagree" [152]. This is a natural consequence of bringing the highly confrontational academic Casimir force research community subculture into the boardroom. Doubt does not well harmonize with the aim to determine whether the technological risk has been eliminated, or at least reduced, from the business proposition so that a negative recommendation is likely.

The relative immunity of the investment community from errors due to uncritically accepting inventions based on "fringe" claims can be attributed to the very existence of the technological due diligence process. More challenging during this delicate phase is the effect of inconsistent assessments regarding a "weak" and "mysterious" Casimir force often repeated by an influential subset of science news coverage reiterating the stereotype of the Casimir force as exotic but technologically inconsequential and physically ill-understood. In some cases, as already noticed [37], the outcome of such statements, demonstrably incompatible with physical reality, are confusing news reports, exemplified by a *New York Times* article inexplicably titled "*A Tiny Force of Nature is Stronger Than Thought*" [135]. In the experience of this author, *neither* the irrelevant "kook community" *nor* deprecated SED practitioners have had a significant chilling effect on privately held capital decision makers. This is instead due to these types of mischaracterizations, to a general degradation of scientific ethics and questionable publishing practices, and to the widespread negative interactions both radiating from and within the Casimir force research mainstream, all engendering mistrust in results published even in the most highly reputed scientific journals.

3.7 INNOVATION AND RISK AVERSION

It has been long recognized that two sources of motivation exist that affect commitment to innovative technologies, that is, technological-push and market-pull, or market demand. On the one hand, "Technological push forces stem from a recognition of a new technological means for enhancing a firm's performance" [235]. On the other hand, "The market demand school of thought suggests that organizations innovate based on market needs… Collectively, empirical research studies on technological innovation are inconclusive regarding this technology-push, demand-pull (TPDP) debate" [236]. As should be expected, the landscape is more nuanced than would appear from those two distant alternatives and much research has been devoted to the interplay or even the planned integration of these two development drivers [235], including specifically in startup firms [237]. A further important refinement concerns market-pull forces, which "… can be conceptualized as occurring along two fronts: 1) marketing performance deficiencies that stem from manufacturing and/or 2) perceived marketing opportunities that could be explored because of enhancements to the manufacturing process. The former tends to put management in a defensive or reactive mode (e.g., the competitive inroads made by the competitors force the firm to become more cost efficient) while the latter is more opportunistic or proactive. While both of these forces can be operative, it is likely that one would be more dominant in management's view" [235]. From the standpoint of physics entrepreneurship, it is stated that "The technology push companies are the riskiest in terms of survival, but they also offer the greatest likelihood of creating breakthrough technologies. Market pull companies, on the other hand, can create important refinements or improvements in existing technologies" [238].

As stated earlier, the most widely popularized applications of quantum vacuum-enabled technologies at or just beyond the horizon tend to be highly disruptive and could quite reasonably be viewed as resulting from technological-push forces. However, for instance, since "The demand for reliable anti-stiction methods of MEMS and NEMS structures is essentially unlimited" [239], inventions designed to engineer Casimir forces so as to make them repulsive [240, 241] with the aim to control both manufacturing and device operation stiction (Section 4.5), could be considered as the result of market-pull forces to remedy this "dominant source of yield loss in MEMS" [242].

In order to fairly judge all negative effects on the transfer to the marketplace of Casimir force-enabled technologies—especially if developed by startups—we should also consider factors leading to the overall steady decrease in both angel and institutional venture investment capital available in the United States. Because "The market… remains the final arbiter of success or failure" [238], this in turn requires an understanding of the dynamics of opposition to innovative manufacturing by industry managers, which is often, though not always, determined by a perception of risk associated with such change [243, 244]. Butler and Anderson conclude: "…reducing risk has become a major feature of high-tech entrepreneurship. Since the mid 1990s, venture capitalists have been reducing their investments in seed and early-stage companies and have focused instead on later-stage companies ready to bring products to the market. As a result, in order to establish proof of concept and fund early development, early-stage entrepreneurs have turned to alternative sources of funding, including angel investors and especially the SBIR and STTR programs. The innovators thereby retain control of their technology, at least until products are ready for the market; that move appears to reduce risks" [238].

The main point of this section has been that various factors presently send a powerful—though completely inappropriate—signal to sophisticated investors that dispersion force engineering still displays an amount of technological uncertainty even at the most basic scientific level that is incompatible with the present risk-averse atmosphere. It is important for such decision makers to realize that the cumulative effect of all such negative factors could be negotiated by the adoption of novel management tools suited to properly identifying and funding truly promising breakthrough technology projects. Ironically, some such approaches for risk reduction were developed by Marc Millis [123, 134, 245] during and in the aftermath of the highly controversial 1997 NASA Breakthrough Propulsion Physics Workshop mentioned earlier (Section 3.3). This methodology is now relatively sophisticated [246], it was applied to propulsion science [247], and was presented literally within a short walk of Sand Hill Road in the heart of Silicon Valley [248]. As a first work in progress in this direction, a traceability map describing technology transfer of dispersion force engineering applications, adapted from the ones proposed by Millis for NASA Breakthrough propulsion physics, was recently proposed by the present author [249].

As stated previously, in addition to lack of funding for early stage startup companies due to investor risk aversion, lack of investments affects developmental programs to transfer already acquired know-how to the marketplace. Many factors are at play both domestically and internationally, which are beyond the scope of this chapter. This includes, for instance, a dramatic weakening of intellectual property rights of independent inventors in the United States [250] through the recent patent reform, which, according for instance to IEEE-USA, serves as "…a disincentive to inventiveness, and stifles new businesses and job growth by *threatening the financial rewards available to innovators* in U.S. industry" [251] (my italics). Also cited factors are dysfunctional or at least ineffective interactions within and between academia and industry due to [252]: an overall ineffectiveness by academia to communicate results with a commercial potential to industry because "most research papers are written in a format that is not easy for industry to consume"; cultural friction caused, for instance, by the fact that academic "focus is on generating findings that are reviewed by academic peers, universities don't consider commercialization when granting tenure"; and "lack of long-term relationships. Most current engagements between universities and manufacturers are transactional…" It is impossible to not view this list partly as a consequence of lack of entrepreneurship education on the side of academics [253], and partly as a consequence of the interconnected hidden interests exemplified by the "*wired*" government grant decisions alleged by David Jones [175], which artificially determine winners and losers well before the market is allowed to have its ultimate say. The academic goal—obtaining a never-ending string of grants—can be achieved with powerful alliances, whereas the commercial goal—winning in the marketplace and never a foregone conclusion for anyone regardless of connections—is not considered as a factor when granting tenure. Although this academic culture is very slowly evolving [254, 255], opposition to science commercialization is still strong on grounds that "Promoting spin-offs relative to patenting or licensing may unintentionally jeopardize the university's research and educational missions" [256].

More broadly, however, opposition to and mismanagement of the apparently ever-increasing pace of change in all areas of company activities may also explain hostility towards accepting disruptive technologies regardless of the possibility of returns—a phenomenon sometimes referred to as "change fatigue" [257]. Indeed, available data suggest that lack of funding is *not* the leading obstacle to the successful execution of "change initiatives" as opposed to a "lack of clearly defined milestones and objectives" and "lack of commitment by senior management" [258]. As a final environmental element surrounding the search for funding, "many experts contend that America's inventive spirit is already flagging. As the Silicon Valley venture capitalist Peter Thiel put it to me in an interview, American innovation in recent decades has been remarkably narrowly based. "It has been confined largely to information technology and financial services" [259]. This assessment is perhaps best reflected by the front-page headline, "You promised me Mars Colonies. Instead I got Facebook," accompanying an article titled "*The Imperative to Explore*" by Buzz Aldrin in the *MIT Technology Review* [260].

These mitigating circumstances are extremely important to consideration of the possibility of successfully funding any startup in the United States at this time. However, lacking a concerted effort to provide a truthfully reassuring picture of gradual technological risk elimination, the road to realizing attractive return opportunities based on investments in dispersion force-enabled products has been further unnecessarily blocked. Therefore, the creation of an entirely new industry potentially capable of contributing thousands of high tech manufacturing jobs has been lamentably forestalled.

4 DISPERSION FORCE ENGINEERING: AN EMERGING ENABLING GENERAL-PURPOSE TECHNOLOGY

In what follows, we shall use the Johansson blocks as the archetypal application of a novel technology we have been referring to as *dispersion force engineering* [37, 43, 60, 61]. By dispersion force engineering, here we shall mean any technology to control dispersion forces, or, more formally, *manipulating dispersion forces to achieve a causally quantifiable success*. Dispersion force control technologies are extremely varied and range, for instance, from surface manipulation as simple as polishing to time modulation of optical properties of the interacting bodies by illumination in semiconductors [98]. In this sense, we shall see that the invention of the Johansson blocks reveals possibly the earliest manifestation of planned manipulation of naturally existing surface forces for the purpose of achieving a specific technological goal.

Rotolo, Hicks, and Martin (RHM) have recently proposed "five attributes that feature in the emergence of novel technologies: These are: (i) radical novelty, (ii) relatively fast growth, (iii) coherence, (iv) prominent impact, and (v) uncertainty and ambiguity" [44]. Commencing with the evolution of the Johansson blocks as a market product—our archetype[9]—it will become apparent that dispersion force control technology embodies such five features. Therefore, on the strength of the evidence provided herein, we shall argue that *dispersion force engineering is an emerging technology*. To clarify, we are obviously *not* proposing that Johansson blocks should be identified as an emerging technology. Even at the time of most rapid adoption, they probably failed to meet the requirement of "prominent impact" in the same sense as, for instance, steam or electricity. As far as the present time, it has been stated that "gauge blocks should be dead and gone" [6]—surely a breakthrough in early 20th century precision manufacturing tool development but no longer satisfying the requirement of "radical novelty." Of course, we also do not claim that dispersion forces are an emerging technology since they are, in the absence of a planned activity to control them, only a natural force in the same sense as gas pressure inside a cylinder-piston system. However, dispersion force engineering certainly enabled Johansson blocks to "achieve a causally quantifiable success." The delivery of market products—initially, Mauser rifles—in large numbers was the result of a revolution in high-precision manufacturing made possible by another market product, the Johansson blocks, in turn enabled by emerging dispersion force engineering technology. Hypothetically, if for any reason dispersion forces could not have been brought to bear as a technological solution, the Johansson blocks would have been only useful as a more versatile type of "fixed-limit gauges" but far from a radical novelty. Therefore we shall use information about the evolution of derivative products enabled by dispersion forces, if such information and products are available, as a "tracer" of dispersion force attributes acting as an enabling technology. We consciously choose the term *tracer* over *marker* to imply that the derivative technologies are not simply "mixed" [262] with dispersion force engineering so as to share their evolutionary path but they are an active part—indeed one of the fundamental enabling factors—of that evolution. For this reason, we shall further argue that dispersion force engineering is an *emerging enabling technology*—a class of emerging technologies expected to "make currently unachievable system concepts realizable in the coming decades" (see Ref. [263], pp. 40–41; also Ref. [264]).

As also observed by RHM speaking from the standpoint of the fourth attribute—*prominent impact*—"the concept of emerging technologies becomes very close to that of 'general purpose technologies' and so excludes technologies prominent within a specific domain" [44]. According to Bresnahan and Trajtenberg [265], general-purpose technologies (GPTs) are defined "as having three key characteristics: pervasiveness, technological dynamism, and innovational complementarities" [266]. According to Lipsey and collaborators, on the other hand, a general-purpose technology is "a technology that initially has much scope for improvement and eventually comes to be widely used, to have many uses,

---

[9] The use and meaning of this term as applied to the pursuit of scientific knowledge was clarified by Pauli in his study "*The Influence of Archetypal Ideas on the Scientific Theories of Kepler*" (Ref. [261], Ch. 21).

and to have many Hicksian and technological[10,11] complementarities" [266]—although "wide dissemination…is often considered a logical consequence of the other three attributes" [269].

Interestingly, Lipsey and collaborators also devoted themselves to the analysis of *emerging* general-purpose technologies providing a most relevant example from our own present perspective: "…if one is told that a new technology will allow for the rearrangement of matter at the molecular level to enable the construction of almost any product or material, whatever its engineering specifics (i.e. mature nanotechnology), it can be confidently said that the technology has a clear potential to develop into a GPT. No one can predict how such technologies will evolve in detail, or whether they will encounter insurmountable cost obstacles to their commercialization, but they are prime candidates for close attention as potential GPTs" [270]. Although only able to conclude that "there is a growing body of work that considers nanotechnology a GPT," later analyses have undertaken to study in somewhat greater detail the intricate nanotechnology value chain [271–274]. This has led to the identification of sample sequences moving from such technological discoveries as the atomic force microscope (AFM), to intermediate goods such as nanorobotic systems and nanomechanical devices, and finally flowing into potentially widespread market products [269]. It is of critical significance that these latter authors recognized the existence of "families of nanotechnologies" since any activity aimed at "the rearrangement of matter at the molecular level" must be expected to be vastly more complex and interdisciplinary [180, 275] than such historical candidates for general-purpose technologies as electricity or steam [266, 270, 276, 277]. A manifestation of this complexity is provided by research on nanotechnology publication and citation counts, reporting that "the basic first search term 'nano*' yielded about half the total. Results were augmented by additionally searching for variants on quantum, self-assembly, molecular manipulations, microscopy, and other terms (such as NEMS, quasi-crystal or sol-gel)" [278]. A more recent study of nanotechnology patenting activity "finds evidence from a broader sample that nanotechnology itself appears to display the three characteristics of growth, pervasiveness and improvement of a GPT" [279].

The connection between these broad economic studies and the present analysis is provided by our further thesis that *dispersion force engineering is an emerging enabling general-purpose technology* (EEGPT) [280]. Because of the previously discussed enduring misperceptions (Section 3.6), lacking a "big picture" and despite supporting evidence—which we attempt to provide herein—such a statement might be considered as surprising or bold to nonspecialists and even to skeptical experts. Nevertheless, we shall argue this is a straightforward consequence of physical law and of engineering developments occurring since the early 19th century.

A starting point to rationalize both the logical justification and the temporal evolution of the supporting evidence is again the work of Bresnahan and Trajtenberg, who provided examples readily applicable to dispersion force engineering: "Most GPT's play the role of 'enabling technologies', opening up new opportunities rather than offering complete, final solutions. For example, …the users of microelectronics are among the most innovative industries of modern economies, and they benefit from the surging power of silicon by wrapping around the integrated circuits their own technical advances. This phenomenon involves what we call 'innovational complementarities' (IC), that is, the productivity of

---

[10] "Hicksian complementarities involve lower factor prices driving substitutions and technological complementarities occur whenever one technological change requires a redesign or reorganization of other production systems" [267].

[11] I am grateful to Mark J. Schulz for reminding me of Thomas Jefferson's statement that "…every science is auxiliary to every other" [268].

R&D in a downstream sector increases as a consequence of innovation in the GPT technology. These complementarities magnify the effects of innovation in the GPT, and help propagate them throughout the economy" [265].

Perhaps the most lucid general observation on the role of complementarities potentially translatable to dispersion force engineering as a nanotechnology enabler—a complementary technology to nanotechnology—is provided by Rosenberg: "Inventions hardly ever function in isolation. Time and again in the history of American technology it has happened that the productivity of a given invention has turned on the question of the availability of complementary technologies. Often these technologies did not initially exist, so that the benefits potentially flowing from invention A had to await the achievement of inventions B, C, or D. These relationships of complementarity therefore make it exceedingly difficult to predict the flow of benefits from any single invention and commonly lead to a postponement in the flow of such expected benefits. Technologies depend upon one another and interact with one another in ways which are not apparent to the casual observer, and often not to the specialist" (see Ref. [281] and also Ref. [265], p. 84, Note 2). This exceedingly important statement captures the essence of the thesis of this chapter as subtitled by Feynman's visionary talk: "There is the problem that materials stick together by the molecular (Van der Waals) attractions. It would be like this: After you have made a part and you unscrew the nut from a bolt, it isn't going to fall down because the gravity isn't appreciable; it would even be hard to get it off the bolt. It would be like those old movies of a man with his hands full of molasses, trying to get rid of a glass of water. There will be several problems of this nature that we will have to be ready to design for" [8]. This statement is usually interpreted as a remarkable prediction of the "fundamental catastrophic failure in microelectromechanical systems (MEMS)" [239] later referred to as *stiction*. Notice that, in Feynman's brilliant intuition, the fact that materials stick together because of van der Waals forces is described as a problem "to be ready to design for," that is, to avoid. From our perspective, instead, we shall frame Feynman's prediction of stiction by paraphrasing Rosenberg's words to mean that the "benefits potentially flowing from nanotechnology had to await the achievement of dispersion force engineering" (among other complementary technologies).

In a little quoted statement just a few years later, Casimir himself commented on the experience at Philips with "qualitative evidence …by another group of our laboratories when they had to approach a metal surface with very thin wires ending in a little sphere …Also I should like to point out that there exists now a tendency to make smaller and smaller objects. If we ever learn to manipulate dimensions and distances of a few tenths of a micron then forces between metals might have a dominating influence" [17]. This attests to a dramatic evolution in Casimir's opinion of the technological importance of the submicrometer scale of the effect he discovered when contrasted with his earliest, most often quoted assessment, that "Although the effect is small, an experimental confirmation seems not unfeasable [*sic*] and might be of a certain interest" [19]. As we shall see, this wavering between "small" and "dominant" is characteristic of the reported understanding of dispersion forces in nanotechnology to this day—a manifestation of the attributes of "uncertainty and ambiguity" identified by RHM.

As we have mentioned, Casimir's approach involved two perfectly conducting planes and it focused on the zero-point energy of the electromagnetic field in the empty space both within and without the plates. Such a space is customarily referred to as the "quantum vacuum" [32] and altering dispersion forces could be viewed as acting on the properties of such a quantum vacuum. Hence this author has in the past referred to dispersion force engineering also as "quantum vacuum engineering." In fact, that terminology was inspired by a rather sibylline statement by physics Nobel Prize laureate T.D. Lee: “If indeed we are able to alter the vacuum, then because the vacuum is ever present and everywhere, our microscopic world of elementary particles would become inextricably connected to the macroscopic world of the cosmos” [282]. Although the present author found such words extremely motivating, what exactly Lee had in mind when he included a section perplexingly titled “*Possibility of vacuum engineering*” in the “Outlook” chapter of his textbook on elementary particles is not entirely clear. It is perhaps worth remembering the oft-quoted words by Dyson published approximately one year before Feynman spoke at Caltech: “When the great innovation appears, it will almost certainly be in a muddled, incomplete and confusing form. To the discoverer himself it will be only half-understood; to everybody else it will be a mystery. For any speculation which does not at first glance look crazy, there is no hope” [283].

4.1 THE JOHANSSON BLOCKS AS AN ARCHETYPE

The remarkable attraction between highly polished metallic surfaces in Johansson blocks, so noticeable as to be adopted by Feynman for pedagogical purposes, had actually been reported much earlier in a paper read in 1840 at the British Association in Glasgow describing the Whitworth Measuring Machine, which led to a technological leap in the manufacture of “mechanical true planes” [2]. Whitworth remarked in a footnote that “a simple and interesting experiment may be tried with a pair of true surface plates. If one of them be allowed to slide on the other so as to exclude the air, the two plates are caused to adhere together with considerable force, by the pressure of the atmosphere.” Such adhesion between two surfaces, if “…perfectly dry, proves a high degree of truth, rarely attained” [3]. Since “it has been well said that ‘a true plane is the foundation and source of all truth in mechanisms’” [2], Whitworth’s intriguing observation appears to be the first conscious instance of a surface interaction between neutral plates neither merely observed as a curiosity nor reported as a complication but instead put forth as a test to monitor the “truth” of two plane surfaces being prepared in a highly accurate mechanical manufacturing process.

The explanation provided by Whitworth for strong adhesion explicitly appealed, without further proof, to the expulsion of the air cushion between the surfaces and to atmospheric pressure. That view, of course, came from the authority of none other than Robert Boyle, the inventor of the vacuum pump [1]. Boyle recalled that “it has been admired by very ingenious men that if the exquisitely polished surfaces of two flat pieces of marble be so congruous to each other, that from their mutual application there will result an immediate contact, they will stick so fast together, that he, that lifts the uppermost, shall, if the undermost be not exceeding heavy, lift up that too, and sustain it aloft in the free air” [284]. Such experiments on cohesion were also known to Newton, who commented that “two polish’d Marbles, which by immediate Contact stick together, are difficultly brought so close together as to stick” [285]. As vividly described by Shapin and Shaffer in *Leviathan and the Air-Pump* within the complex context of the fierce philosophical debate with Hobbes, Boyle conjectured that cohered marbles placed within his vacuum chamber would “fall apart as the air’s pressure diminished” [1]. In order to test his theory, he assembled an experiment still appealing even to modern eyes [286] in which a pair of already cohered marble disks were lowered into the vacuum hanging from a string while the chamber was being evacuated and he waited for the bottom marble to just fall off. Despite the presence of an additional weight attached to the bottom marble, “to facilitate its falling off,” the marbles did *not* separate. Importantly, Boyle did not conclude that adhesion is due to forces between the surfaces independent of air pressure. As with other famous observations contradicting an experimenter's prejudicial expectations throughout the history of science, Boyle concluded that his own remarkable experiment had actually failed due to the presence of residual air caused by a leakage.

Two hundred years after Boyle, the role of atmospheric pressure was explicitly disproven by John Tyndall as reported to the Royal Institution of Great Britain on 4 June, 1875. In his experiment, "two exceedingly accurate hexagonal Whitworth planes remained adherent in the best vacuum obtainable by a good air-pump…The lower plate weighed 3 lbs., and to it was attached a mass of lead weighing 12 lbs. Though the pull of gravity was here thirty times the pressure of the atmosphere, the weight was supported. Indeed, it was obvious when an attempt was made to pull the plates asunder, that had a weight of 100 lbs. instead of 12 lbs. been attached to the lower hexagon, it would also have been sustained by the powerful attraction of the two surfaces" [287]. Just as Newton had observed the varying colors emerging from two glasses pressed together [285] (Book II, Obs. 4), Tyndall caused two very smooth glasses to cohere similarly to metallic Whitworth plates and he pressed them together with calipers. Upon illuminating the stack with bright light, colors reflected on a white screen "passed through various changes. When monochromatic light was employed, the succession of light and darkness were numerous and varied, producing patterns of great beauty." From these observations, he concluded that "…though in such close mechanical contact, the plates were by no means in optical contact, being separated by distances capable of embracing several wave-lengths of the monochromatic light" [287]. This may have been the first report of interferometric methods being used to monitor the distance between two boundaries in a surface force experiment.

The technological background at the end of the 19th century was one of significant evolution driven by the requirements of a few industries in need of high-precision machinery, particularly small arms manufacturers [288]. At this time, Carl Evard Johansson, at the Eskilstuna rifle factory in Sweden, developed the gauge blocks for which, in 1898, he filed for his first Swedish patent, whose granting in 1908 required the personal intervention of the Swedish royal family (No. 17017, "*Gauge Block Sets for Precision Measurement*"). That invention consisted of a set of 102 accurately machined steel blocks that could be arranged in any combination to yield 20,000 different measurements between 1 mm and 201 mm in increments of 0.01 mm [7, 289]. The idea of a "combination gauge block set" capable of yielding a very large number of lengths with a small number of gauges was of critical importance during the transition from manufacturing the Remington rifle to tackling the more complex 6.5 mm Mauser rifle, which Johansson had seen required thousands of gauges at the Mauser works in Oberndorf. That first patent made no mention of wringing the gauges together, a phenomenon that Johansson may have first experienced only in 1900 when he found that "two lapped gauges that were tightly stuck together would not separate when they were accidentally dropped" [7]. However, "the fact that finely lapped gage blocks adhere, or 'wring,' made the system both possible and practical" [4]. The importance of this later development is perhaps best captured by a stunning demonstration given by Johansson at an engineering conference in Stockholm in 1917. A photo from the event shows a string supporting two gauge blocks wrung together and two large 100-lb lead weights hanging from the lower block [7] (Fig. 2, therein).

This facet of the Johansson gauge block story represents a first important thread to analyze the technological role of dispersion forces. Possibly for the first time in the history of technology, a new device was made "both possible and practical" by the judicious inclusion of surface forces as part of its design. As documented in many remarkable photos since the early days of this invention till the present, the enduring success of Johansson's idea entirely depends on the fact that, in capable hands, even two dozen gauge blocks can be connected together in one stable unit for as long as needed to provide an extremely accurate measure of length. This fact is neither a trivial scientific curiosity nor an inconvenience to be avoided. On the contrary, "the primary attribute of gauge blocks is that they wring together" [6]—a unique, advantageous feature made possible by a conscious application of dispersion forces to the solution of a specific engineering problem. As such, dispersion forces, engineered to be an integral part of the Johansson block set, represented a "radical novelty" as defined by RHM.

A second thread worthy of our attention is the fact that, although the surface forces involved are central to Johansson gauge block operation, they were—and are—not yet completely understood from the fundamental physical standpoint. The studies by Tyndall were the beginning of a long and still ongoing effort [290–292] to fully clarify the contributions of the various mechanisms believed to lead to the adhesion of gauge blocks, whose longevity as an international length standard has caused them to be recently referred to as a "zombie technology" [6]. For instance, the role of liquid films on the facing surfaces was first highlighted by Budgett, who, in 1912, concluded that film interaction completely dominates over direct intermolecular forces between metallic surfaces [293, 294]. Indeed, in the footsteps of Robert Boyle's moistening the facing surfaces with alcohol [1], Rolt and Barrell chose to define "wringing" as "the operation of bringing two surfaces into intimate contact with the aid of a minute trace of liquid" [295]. However, attempts to measure the thickness of the "wringing film" yielded a *negative* value [296] thus indicating that "the actual metal surfaces come into contact" and "there is no liquid film effectively separating the surfaces" [297]. Despite the use of interferometry [298] and atomic force microscopy [299] to solve the problem, probably the best characterization of the present status of research comes from a recent assessment by Doiron and Beers (NIST): "Unfortunately for those wishing tidy solutions, the field has not progressed much since 1912. The work since then has, of course, added much to our qualitative understanding of various phenomena associated with wringing, but there is still no clear quantitative or predictive model of wringing film thickness or its stability in time" [5]. This lack of full theoretical understanding, however, did *not* stop the market success of Johansson's invention. In general, "for retrospective analyses, the evaluation of uncertainty and ambiguity remains largely unexplored in scientometric studies" [44] but we shall argue that the evidence from literature of dispersion force engineering displays this attribute in all applications as exemplified in this archetype.

Although here we do not devote ourselves to a full review of gauge block market evolution since the patenting and introduction of this product, all available historical information supports the claim that the adoption of gauge blocks took place at a relatively high growth rate [4, 6, 7]. As we shall see, other market products—so far relatively few—enabled by dispersion force engineering have shared similar qualitative evolutions and the pace of inclusion of dispersion forces within existing or proposed products displaying radical novelty and prominent impact is rapidly growing. Evidence that dispersion force engineering displays the attribute of coherence will be presented in connection, where possible, with similar evidence for its tracer products [300].

4.2 THE ATOMIC FORCE MICROSCOPE

A remarkably significant example of the enabling characteristics of dispersion force engineering in modern times is represented by the atomic force microscope (AFM, see Ref. [301], Part C), which earned Binnig and Rohrer a share of the physics Nobel prize in 1986 [302]. Unlike the scanning tunneling microscope (STM)—based on electron current tunneling between a tip and the sample

[303, 304]—the AFM is based on tip-sample forces. Although initially operated mainly in static contact-mode [302, 305, 306], noncontact-mode AFM techniques were quickly introduced along with the need for realistic modeling of long-range van der Waals forces and probe geometry, which play a key role in tip-sample interactions [307–311]. The AFM—employed, for instance, in dynamic amplitude- or frequency-modulated mode (AM-AFM or FM-AFM)—operates in the presence of long-range atomic forces, which represent a limiting performance factor [306]. Therefore "manipulating dispersion forces to achieve a causally quantifiable success" (Section 4) becomes imperative to an effective operation of the AFM. Given the breadth of the subject, here we just provide a few elements pointing into the direction of future investigations into scanning probe microscopy applications as embodiments of this emerging enabling technology. An explicit statement of that role is that by Hutter and Bechhoefer, who stated that "If only short-ranged forces existed, the AFM would operate exactly as the STM does—through a single atom—and one would expect to achieve the same resolution (without the STM's restriction to conducting and semi-conducting surfaces). However, the presence of long-ranged interactions such as the van der Waals (vdW) force, leads to a very different imaging scenario in which the macroscopic tip radius controls the imaging resolution" [312]. From this point of view, fascinatingly, the AFM represents a microcosm of the overall history of dispersion force engineering. On the one hand, since "the van der Waals forces cannot be switched off" [306], "the undesired effects of long-ranged forces" must be negotiated. On the other hand, "vdW forces can be measured using an AFM" [312], thus foreshadowing the role transformation of dispersion forces from a limitation to an enabling opportunity stressed throughout this chapter.

The observation that the AFM, originally conceived for surface imaging, can serve as a unique tool for the measurement of dispersion forces goes back at least to the original paper by Martin, Williams, and Wickramasinghe, who concluded that "simultaneous measurement of the peak van der Waals force and profiling has been demonstrated" [307] and indeed Albrecht and Quate stated that "Since its invention in 1985, AFM has been used to study attractive van der Waals forces …" [313]. Pursuit of this suggestion proceeded at an accelerated pace throughout the decade following the invention of the STM and AFM [307, 312, 314–321]. It is within this background that we must frame the presentation by Jordan Maclay et al.—intriguingly, at the aforementioned 1997 NASA Breakthrough Propulsion Physics Workshop (Section 3.3)—of a paper titled "Use of AFM (Atomic Force Microscope) methods to measure variations in vacuum energy density and vacuum forces in microfabricated structures."[12] In that contribution, the authors explicitly justify the use of the AFM for Casimir force studies in different geometries and presage many of the challenges identified later for such an approach. They state: "Previous experimenters have relied on custom-made instrumentation, with relatively large components to make measurements of the Casimir force in the parallel plane configuration. With very few attempts made at measuring Casimir forces in other geometric configurations, much of the theory remains unsubstantiated …The Atomic Force Microscope (AFM) integrates a number of features essential for measurements of Casimir forces in the parallel-plate and

---

[12] The 1997 NASA Breakthrough Propulsion Physics Workshop was held 12–14 August 1997 (NASA/TM 1998–208400, p. 5, see also Ref. [322]). Since Maclay's contribution was not an invited paper (see Sec. 5.1 therein), it is not listed in that same Report. However, the paper is listed in the Preliminary Report (NASA/TM–97-206241, Poster Papers, p. 4), dated November 1997, and it appears in full in the Proceedings (NASA/CP–1999-208694, pp. 247–256). Notice that the front page of this latest document, dated January 1999, incorrectly indicates the Workshop was held on 12–14 August 1998, one year later than the correct date [123].

in many other configurations" [123]. Shortly afterwards, the first data by Mohideen and Roy confirming the Casimir force in the plate-surface geometry by means of an AFM appeared—the beginning of a lasting effort in this area by that group [323]. Working at 50 mTorr pressure and at room temperature, those authors reported that "the root mean square average deviation of 1.6 pN between theory and experiment corresponds to 1% deviation at smallest separation" [324], as previously discussed (Section 3.3).

The lack of mutual citation among various actors in these developments is so total as to be impossible to ignore and, in part, has already been noticed. Kim and Schwarz, speaking of noncontact AFM (NC-AFM) and Casimir force research practitioners, remarked: "…there has been no tangible effort thus far to bring together the two communities in a science meeting for discussions on the unified theme. This divergence, which grew rampantly over the past decade, is most likely to stem from a stark difference in attitude toward the core subject matter—a microscopic, materialistic approach adopted by the NC-AFM community versus a macroscopic approach favored by the Casimir community, which is geared toward a verification of quantum vacuum phenomena that are referred to as the 'Casimir effect'" [325]. However, this hardly explains the fact that, to the best of this author's knowledge, the paper by Maclay et al. seems unknown to authors of Casimir force measurements (it only appears cited by De Los Santos; see, for instance, Ref. [326]) including, particularly, Mohideen and Roy. This silence is all the more surprising, indeed ironic, as it was confidently reported about the 1997 NASA Breakthrough Propulsion Physics Workshop that "More conventional scientists decried the channeling of NASA funds to a meeting where real science was lacking" [134]—a blanket negative assessment that should imply deep awareness by the mainstream of all presentations made at that controversial event. Characteristically, however, that same paper by Maclay et al. cites no literature about the AFM including, of course, AFM applications to van der Waals force measurements. Unsurprisingly, as one would expect from the observation of Kim and Schwarz, Mohideen and Roy make no effort to mention even the existence of a state of the art in van der Waals force measurements with the AFM at the time of their first publication. This approach applies also to later extensive, chapter-length reviews written over a decade after the first paper by that group (see Ref. [323], Section 19.2, which preserves the same language as in their earlier review, Ref. [327], Section 6.4). Finally, as already mentioned herein and previously [43], the 2007 review by Lamoreaux covering 60 years of theoretical and experimental work in Casimir force physics bears no sign of any AFM activity despite earlier mentions by the same author (see for instance Ref. [328]).

Overall, it is only through laborious historical research conducted by this author to "extract meaning against the grain of the documentation" [220], that these complex, contradictory, and misleading fragments of information emerged. As already remarked in the past by the present author, Parsegian displayed "remarkable acumen" [43], when he observed: "The van der Waals interaction story is an excellent subject for scientific historians. Think of the elements…Disjunction among disciplines: Physicists with their 'Casimir Effect,' chemical engineers and physical chemists with their 'DLVO theory' and terror in many of tackling abstruse physics, lack of interest by most parties in each others' motivating questions (DLVO = Derjaguin, Landau-Verwey-Overbeek)." (Ref. [329], p. 349) Both Parsegian and Kim and Schwarz choose to describe these events in abstract terms attributing them to "divergence" or "disjunction," among disciplines. However, one must question to what extent such breath-taking noncitation practices are due to lack of knowledge of the state-of-the-art in one's own field, or to the natural effect of scientific subcultures impermeably insulated from one another, or to individual strategic choices aimed at controlling the narrative of discovery (Section 3.6).

The most recent evolutionary stage in the unfolding story of dispersion force engineering as an EEGPT applied to the AFM is the appearance of applications in which van der Waals forces become critical not just to surface imaging or fundamental metrology but to actual manipulation on the atomic scale. As lucidly articulated, for instance, by Fukuda, Arai and Dong: “Nanomanipulations were enabled by the inventions of scanning tunneling microscopes (STMs), AFMs, and other types of scanning probe microscopes (SPMs) …The main problem is how to achieve the control of the interactions between the tool and object and between the object and substrate.” One strategy “…is to modify the van der Waals and other intermolecular and surface forces between the object and the substrate. For the former one, an AFM cantilever is ideal …” [330].

While again leaving a more detailed analysis of this phase to later work for reasons of space, progress in this new subfield has been extremely rapid [331]. As early as 1990, the possibility to position individual atoms by exploiting van der Waals and electrostatic tip-sample forces in an STM was famously demonstrated by writing the acronym IBM with precisely arranged xenon atoms on a nickel surface [332]. Avouris describes the approach: “The forces, even the weak van der Waals force, between tip and sample can be controlled and used to move atoms or molecules laterally on a surface. This process is usually referred to as “atom sliding” [333]. The challenges of manipulation on the nanoscale had already been predicted by Feynman (Section 1): “After you have made a part and you unscrew the nut from a bolt, it isn’t going to fall down because the gravity isn’t appreciable; it would even be hard to get it off the bolt. It would be like those old movies of a man with his hands full of molasses…” [8]. Such a vision is now stunningly being rediscovered by direct experience: “When handling a micro object with a gripper, it is easy to pick up by gripping, but the release process will often be disturbed by adhesion. When designing a microgripper for handling micro objects, the van der Waals forces should be considered carefully…” [334]. Just as illustrative examples, we recall that the AFM has been used to manipulate multiwalled carbon nanotubes (MWCNTs): “Specifically we can bend, straighten, translate, rotate, and—under certain conditions—cut nanotubes, …” in which case “The interaction between nanotubes and the surface is crucial” [335]. Successful nanostructure assembly based on combining use of the AFM (possibly along with scanning electron microscope, SEM) with dispersion force engineering strategies, typically within the additive approximation, has been reported [334, 336, 337]. Applications include, for instance, controlled placement of individual nanotubes [338], nanotube nanotweezers [339, 340], “pick-and-place” polystyrene beads and nanotube picking and bending [341], nanorobotic haptic interfaces [342, 343], use of dispersion forces as a bonding agent in various connecting configurations [344], MWCNT shell extraction [345, 346], and adenovirus manipulation on solid surfaces in nanomedicine [347]. Also, MWCNTs were “stretched using a microprobe system in a scanning electron microscope…and fabricated into atomic force microscopy probes.”

As engagingly told by Mody, the epilogue of this remarkable story is that “Today, the scanning tunneling microscope and the atomic force microscope are the multimillion dollar darlings of the nanotechnology boom” [348, 349]. Although far more forensic research is needed to tease out the fraction of that market value directly or indirectly connected to the enabling role of dispersion force engineering, it is clear that such a share will dramatically increase due to future uses of the AFM. An interesting example is the recent report of a microelectromechanical system (MEMS) implementation of the AFM [350, 351, 352] available as a commercial product under the name of nGauge AFM from ICSPI [353], a spinoff of the University of Waterloo in Canada, which represents one significant next step towards the full integration of traditionally macroscopic instrumentation into the nanoscale domain. Developments such as this are consistent with the view that MEMS AFM approaches, on-chip Casimir force experimentation, and nanorobotic actuation are on a rendezvous course to enable future applications made possible by dispersion force engineering, which would otherwise be inaccessible [57, 58, 241, 354–361].

4.3 GECKO GLUE PRODUCTS

One of the most spectacular demonstrations of dispersion force engineering as an EEGPT to ever emerge is that of adhesives, variously referred to as gecko glue or gecko-inspired glue. These adhesives were developed in the aftermath of the discovery that the remarkable climbing abilities of the tokay gecko (*Gekko gecko*) are due to van der Waals forces between the hairlike structures on the gecko toe pads, referred to as *setæ*, and the climbing surface [233]. As popularized by Autumn in a beautifully illustrated article in *American Scientist*, "Theoretically, the 6.5 million setæ on a tokay gecko could generate 1,300 newtons of shear force—enough to support the weight of two medium-sized people—based on measurements from single setæ" [362]. Additionally, structure geometry and hierarchy play a critical role in the self-cleaning and quick release properties of the gecko pads that allow for continued *directional* adhesion effectiveness and extremely high speed in vertical climbing [363]. Autumn et al. concluded: "Although manufacturing small, closely packed arrays mimicking setæ are [*sic*] beyond the limits of human technology, the natural technology of gecko foot-hairs can provide biological inspiration for future design of a remarkably effective adhesive" [233]. Two decades later, the progress made in successfully fabricating gecko-inspired directional adhesives based on sophisticated artificial nanostructures [364–368] is well illustrated by large weights hanging from very small adhesive pads attached to vertical surfaces [369]—a contemporary reminder of the capabilities of Johansson's blocks demonstrated early in the 20th century (Section 4.1).

Two observations on the existing literature in this field are in order. Firstly, yet another example of the casual manner in which the integrity of literary evidence is silently, slowly eroded in scientific circles to eventually fit it into a desirable narrative is the text quoted [370, 371] by Autumn et al. and attributed to Aristotle in his *History of Animals*, in the translation by Thompson. They state: "Over two millennia ago, Aristotle commented on the ability of the gecko to 'run up and down a tree in any way, even with the head downwards'" [371]. Actually, Thompson has: "The woodpecker does not squat on the ground, but pecks at the bark of trees to drive out from under it maggots and gnats; when they emerge, it licks them up with its tongue, which is large and flat. It can run up and down a tree in any way, even with the head downwards, like the gecko-lizard" (Ref. [372], Book IX, Part 9). Substantially identical words (" …like the gecko") are used in the translation by Cresswell (Ref. [373], Book The Ninth, Chapter X), also confirmed by the Greek original. In this case, this unnecessary misquotation[13] reinforces the image that Aristotle would have devoted significant effort to elucidating the mysterious climbing abilities of the gecko, whereas in fact those were only used in passing as a term of comparison with the agility of the woodpecker. Furthermore, since the woodpecker achieves his climbing feats by ordinary anatomical means, as do most lizards, this text actually indicates that Aristotle attributed the climbing abilities of the gecko to smaller-scale features similar to those of the

---

[13] Although this criticism may appear fastidious and the quoted version may even feel "improved" to some, the *Chicago Manual of Style* states (11.6): "*Accuracy*. It is impossible to overemphasize the importance of meticulous accuracy in quoting from the works of others" [374]. Recommendations on this issue in the *The MLA Handbook for Writers of Research Papers* [375] and the *Publication Manual of the American Psychological Association* are even stricter [376].

woodpecker and not to surface forces. Indeed, notice that still in recent times, even after the conclusive discoveries by Autumn et al., the setæ have been incorrectly described as "hooklike" (Ref. [377], footnote 2 therein). Even more importantly, the connection between this text and any modern understanding of interatomic forces must reckon with the fact that Aristotle was, at least apparently, not an atomist although this subject is quite complex from the interpretative standpoint [378–380]. Hence the unspoken suggestion that Aristotle would have had any early intuition of adhesion mechanisms in geckos is absolutely unjustified, as shown by the fact that all other references to that species in the *History of Animals* do not discuss this issue. Some careful science and technology authors have detected this discrepancy and restored Thompson's exact words and textual intent by accurately stating only that "the Greek philosopher Aristotle first coined the phrase ' …like the Gecko-lizard'" [363]. Of course, the climbing abilities of geckos and lizards in general were well known earlier than Aristotle and are a frequent, highly symbolic feature in surviving classical art [381].

Secondly, an analysis of the typical descriptions of gecko toe pad adhesion physics at the foundations of these novel nanomaterials quickly reveals the persistent confusing contradictions already discussed (Section 3.1) [135]. For instance, Autumn and his group never once use the adjective *weak* in reference to van der Waals forces in the works cited herein [233, 362, 370, 371]. On the other hand, one does not have to look far to rediscover such a term elsewhere. For instance, Valdes states that spatulæ "…are held to surfaces by van der Waals attractions, generally considered to be fairly weak intermolecular forces" [382]. Similarly, Greiner comments, "However, as the van der Waals forces are about as weak as they are omnipresent, the gecko must rely on having between 50 and 500 million spatulae on each toe pad" [363]. Kundu elaborates: "On an individual level, each of these hairs weakly interacts with any surface through a small short-range electrostatic force known as a Van der Waals force. Working alone, one hair would be attracting the gecko's foot to the surface with such a small force of attraction that it would fall straight off the ceiling. However in vast numbers, the individual weak attractive forces between the hairs and the surface, and the inherent increased surface area of interface between the gecko hairs and the surface add up to create a mighty grip for the gecko" [383].

These comments may point to confusion between the concepts of force and pressure.[14] Autumn describes his estimate of the maximum potential sheer force cited earlier as "based on measurements from single setae" [362]. Hence the pressure is not at all small regardless of the "small force of attraction" mentioned by Kundu. In practice, it is absurd to insist on being surprised and on characterizing a sheer force able "to support the weight of two medium-sized people" as "weak." The pressure is relatively very large and, multiplied by the effective area, the macroscopic force is large. There is no mystery. These unhelpful mischaracterizations are again reminiscent of the confusing title of the cited *New York Times* article, "*A Tiny Force of Nature Is Stronger Than Thought*" [135].

Further proof of the dominance of dispersion forces in appropriate regimes is that, just as Autumn had foreseen [362], the availability of dry adhesives has led to the development of robots, such as Stickybot and Waalbot, shown effortlessly climbing vertical glass surfaces [389–392]. A stunning

---

[14] It is important to point out the existence of inconsistent definitions in the literature of the van der Waals force as both long range [384, 385] and short range [386, 387]. Indeed French et al. explicitly commented that "…the distinction between long and short ranged nanoscale interactions is blurred and to some extent idiosyncratic, manifesting itself clearly only at the upper end of the nanoscale or even after entering the mesoscale, with a consequence that on the nanoscale long and short ranged interactions appear to be equally important and difficult to distinguish. Thus here too what constitutes a long range as opposed to short range interaction depends primarily on the specific problem under investigation" [388].

achievement has been the development of "…adhesive bearing structures …enabling a human to climb vertical glass using an area of adhesive no larger than the area of a human hand" [393]. This remarkable demonstration was quickly connected in international media coverage to the 2011 movie *Mission: Impossible—Ghost Protocol* (Section 3.3), in which Tom Cruise climbs Dubai's Burj Khalifa with a pair of gloves [394]. Most significant from the standpoint of this chapter is the goal now in sharp focus to employ dry adhesives in various space mission roles [395]. Possible applications include, for instance, robot anchors to spacecraft for repairs or in unsafe environments [396–398], uncooperative space junk grappling [399], general object manipulation in microgravity [400], rendezvous and docking, astronaut extravehicular activity (EVA), and in-space assembly [401].

Although dry adhesive technologies enabled by dispersion forces are a relatively new development, the pace of technology transfer into the marketplace of products derived from these inventions is accelerating. For instance, the just-cited article by Kundo in *Forbes* reports on Setex, described as "leading the charge in dry adhesive technology," aimed at a wide set of applications ranging from packaging to medical prosthetics, and marketed by nanoGriptech, a spin-off company from Carnegie Mellon University [383]. This chapter is not the venue for a review of trends in this industry, but all available information indicates that more actors will enter this specialized subfield planning to capture a fraction of the attractive international adhesive market value. Of special interest is the fact that dispersion force-enabled adhesives are not based on chemicals—although they require chemicals for nanofabrication—so that environmental impact considerations are not an obstacle to their adoption and they are not degraded in harsh environments such as outer space.

4.4 NONVOLATILE NEMS MEMORY ELEMENTS

A disruptive application now approaching market entry is the so-called nanotube-based nonvolatile random access memory (NRAM), in which the attribute of nonvolatity is entirely enabled by a straightforward, yet elegant, dispersion force engineering strategy. In the originally proposed architecture [234], equally spaced, parallel single-walled nanotubes (SWNTs) are in equilibrium suspended over an identical grid of parallel nanotubes arranged perpendicularly to the former and resting upon a dielectric substrate. By charging any two nanotubes, each belonging to one of the two grids, so as to produce a mutually attractive electrostatic force, the suspended nanotube is deformed towards the other perpendicular to it till it falls within the van der Waals attractive potential to a second position of equilibrium and the two stick together, forming a junction point. This nanotube connection, which creates a drastically lower value of the junction resistance, corresponds to an ON state that can be electronically read. Upon producing a repulsive electrostatic force capable of overcoming the van der Waals attraction, the two nanotubes become again separated under the effect of their restoring tensile strain and the junction resistance increases by several orders of magnitude, thus yielding an OFF state. Rueckes, cofounder of Nantero, Inc. in 2001 [402], clearly explains in his PhD dissertation: "Qualitatively, bistability can be envisioned as arising from the interplay of the elastic energy, which produces a potential energy minimum at finite separation (when the upper nanotube is freely suspended), and the attractive van der Waals (vdW) energy, which creates a second energy minimum when the suspended SWNT is deflected into contact with the lower nanotube. These two minima correspond to well-defined OFF and ON states, respectively; that is, the separated upper-to-lower nanotube junction resistance will be very high, while the contact junction resistance will be orders of magnitude lower" [234, 403].

Critically for our purposes in this chapter, “Once electromechanically switched, the SWNT fabric is held in contact (and electrically connects) with the underlying electrode and van der Waals interactions ensure that the switched bit state is stored. van der Waals interactions occur between any two materials in close nanoscopic proximity and are independent of external or internal electrical power. For this reason, NRAM is an intrinsically nonvolatile memory technology.” Also, “The memory elements are naturally radiation hard, since energetic particles can not disturb the stored data. Moreover, the microscopic mass of the fabric elements themselves make them highly resistant to mechanical shock and vibration. In addition, the devices have experimentally exhibited a wide range of temperature operation—from below room temperature to in excess of 200°C” [404].

Without specifically reviewing the merits of this particular nanoelectromechanical approach to memory devices [405], here we mention three additional points. Firstly, the tortuous journey of the NRAM from concept to the marketplace is an object lesson in the harsh realities of any such technology transfer initiative [406]. Technologically, this has included the uphill battle to scale a fascinating single memory cell experiment [234, 403] up to practical level densities [407, 408]. From the business standpoint, the Nantero story—a veritable odyssey [409] stretching over almost two tormented decades [402]—has been summarized as follows by Chris Spivey: “The long runway for NRAM and Nantero can be seen as a feature and not a bug.” (quoted in Ref. [409]). Secondly, the trajectory followed by Nantero and its proprietary technologies was detected relatively early and followed through scientometric methods [406, 410], thus yielding an increased understanding of the manner in which to apply such novel techniques to describe the evolution of dispersion force engineering as presently being pursued by the present author.

Finally, purely from the classical mechanics standpoint, the fact that “a revolutionary approach” and “an unconventional memory architecture” [403] could be conceived by building upon the interplay of dispersion, elastic, and electrostatic forces should be considered within the more general context of a wide class of dispersion force-enabled systems that, although in very different physical implementations and on vastly different length scales, display analogous behaviors. For instance, as far back as 1983, in a qualitative analysis of the dynamics of his well-known, idealized charged “spiral” under the action of those same three forces, Robert Forward had noticed that “This electrostatic suspension system is unstable” (Ref. [100, 411] and discussion in Ref. [61], Section 27.2). Over a decade later, in their widely cited analysis of a harmonic oscillator under the effect of an additional Casimir force (anharmonic Casimir oscillator, ACO), Serry, Walliser, and Maclay identified two positions of equilibrium for the system—one stable, at relatively large separation between the interacting bodies, and a latter one unstable, at closer range and leading to surface contact, respectively [101]. The authors commented that “Any separation state, along with the contact state of an ACO device, may define an ‘open’ and the ‘closed’ states, respectively, of a Casimir switc. [*sic*] The switching of an ACO device between its open and closed states may be accomplished by…introducing additional forces into the system… The additional forces may be electrostatic, mechanical, pneumatic, etc.” Interestingly, they later concluded that “…at least one of the two switch positions in a functional Casimir switch may be maintained with no electric power required” [101]. These statements foreshadow the use of electrostatic forces to switch between the ON and OFF states in the NRAM and the assessment that “the nonvolatile nature of our devices is preferable from the standpoint of power consumption and corresponding heat dissipation as compared to dynamic RAM, which must be continually refreshed” [234]. Indeed, the principle of this invention cleverly turns a particular mechanism of nanostructure stiction, typically described as undesirable, into a key strategy without which the device could not operate as designed.

A related system is that of an AFM cantilever [412–414], under the simultaneous action of the same two forces as in the ACO, which also displays bistability with equilibrium positions at different ranges between the probe and the surface (see Ref. [415], Fig. 5, and Ref. [416]). The additional effect of electrostatic forces on cantilever dynamics has been extensively considered [417–419] also in view of its effect in properly interpreting AFM data in Casimir force experiments [420].

4.5 REPULSIVE CASIMIR FORCES

The model inventions discussed so far can arguably be considered as technology-push applications of dispersion force engineering within their respective historical frameworks. In the last two sections, we analyze the implementation of—primarily—market-pull applications in the sense defined previously (Section 3.7) of a "new technological means for enhancing a firm's performance" [235] and a new approach to "create important refinements or improvements in existing technologies" [238]. As our first example, the leading R&D motivation is the goal of drastically reducing the magnitude of dispersion forces or even to transform them from attractive to repulsive as an obvious "anti-stiction" strategy [239]. Some additional reflections on potential technology-push applications in this area are also presented.

Historically, realization that, unlike suggested by common experience with adhesion, dispersion forces can be repulsive emerged from independent lines of inquiry corresponding to different physical mechanisms behind this phenomenon. Possibly the earliest suggestion in the literature goes back to none other than Hamaker who—well before the developments by Casimir and Polder—predicted that repulsion in the unretarded regime might result from the interplay of properties in the case of two different interacting materials immersed in yet a different fluid: "The London–van der Waals forces between two particles of the same material embedded in a fluid is always attractive, provided there is no marked orientation of the fluid molecules. If the particles are of different composition, the resultant force may be a repulsion." (Ref. [16], p. 1069) A second mechanism emerged a few years later—again before the development of the theory of retarded dispersion forces—as Axilrod and Teller proved that three identical atoms, although interacting pairwise via the ordinary attractive unretarded van der Waals interaction, can experience repulsive forces depending on their mutual geometrical position—a clear demonstration of the nonadditivity of such interactions [421]. Finally, a third system in which unretarded repulsive van der Waals forces were found to appear is that of an electrically polarizable atom interacting with a magnetically polarizable one [422–424].

Corresponding behaviors can be identified within the retarded regime. For instance, after the Lifshitz theory [94] was generalized to two semiinfinite slabs separated by a liquid gap medium, Dzyaloshinskii, Lifshitz, and Pitaevskii—while acknowledging and critiquing some of Hamaker's conclusions (see Ref. [96], footnote on p. 164)—again pointed out that if, and only if, the two slab media are different, under some simple conditions to be satisfied by the dielectric functions of all media, the dispersion force can be repulsive [96, 97]. As regards the role of geometry, fascinating results were later discovered—to Casimir's enduring disappointment [32]—as the self-stress of a perfectly conducting shell was proven by Boyer to be positive [425]. This conclusion invalidated Casimir's own "admittedly very crazy" [426] model of the electron, speculated to be held together against self repulsion by attractive Casimir forces, which instead turned out to be repulsive. As regards our third system, Farina et al. have recently pointed out that, as a consequence of the unretarded repulsive force between an electrically and a magnetically polarizable atom, "two macroscopic bodies, one made of an electrically polarizable material and the other made of a magnetically polarizable one, will repel each other" [423]. Indeed the repulsive interaction between an infinitely conducting and an infinitely permeable slab had been first calculated by Boyer by a remarkable application of SED methods stimulated by correspondence with Casimir himself (Ref. [427], see also Ref. [428]).

This unpredictability of even such a basic feature as the algebraic sign of dispersion forces was cited by Elizalde and Romeo, in a section of their paper titled "The mystery of the Casimir effect," (see Section 3.1 herein for more on the Casimir effect as a "mystery") as one fundamental reason that the Casimir effect is "…less understood now than it was 40 years ago." Those authors, writing in 1990, unequivocally state that "Unlike the van der Waals forces, *which are always attractive*, the ones appearing in the Casimir effect can be either attractive or repulsive." (my italics, Ref. [429]) This curious statement, obviously wrong in light of the many results in the unretarded regime already known at that time, may be understood within its historical context by an observation made less than a decade earlier by Visser: "Still, the idea of repulsive van der Waals forces has not generally been accepted… The main reason why people did not immediately accept the idea of negative Van der Waals forces or, in terms of material properties only, the concept of negative Hamaker constants, is the difficulty to visualize the concept and the lack of clear experimental evidence" [430]. Somewhat ironically, the same three-body system introduced by Axilrod and Teller [421] was later employed by Farina, Santos, and Tort in their pedagogical paper, *A simple way of understanding the nonadditivity of van der Waals dispersion forces*. Again working in the unretarded regime, they concluded that their result, "depending on the geometrical arrangement of the oscillators, may yield an attractive or a repulsive contribution" [431].

In fact, studies in the field advanced so rapidly as to warrant the Symposium on Negative Hamaker Coefficients and Repulsive van der Waals Interactions held in Las Vegas in 1980 [430] and a two-part follow-up review by Visser that appeared as early as 1981–1983. In the first part of that report, the author claimed that, although Hamaker had indeed made the comment we quoted previously, he had not derived any detailed quantitative conditions for repulsive forces to occur[15] and that, "after a detailed study of van der Waals forces in general, the author came to the conclusions [*sic*] that in the case of a three-component system, the corresponding Hamaker constant A_{132} could attain a negative value" [430]. Visser related that, after his own first report on the subject [433], he had learned of the earlier specific theoretical prediction of a negative Hamaker constant for the (PTFE)-glycerol-iron system[16] by Fowkes [435] although he claims to have announced the first experimental observation in PTFE-water-graphite secured by Smith on Visser's request, which, however, appears to have remained unpublished [430, 436]. Such early discoveries were then followed by systematic theoretical and experimental studies by Neumann, Omenyi, and van Oss [437, 438].

Experimental evidence during this early phase was unavoidably indirect and connected to observations of such macroscopic properties as stability of suspensions and contact angles [439–443]. However, writing with van Oss, Absolom, Omenyi, and Neumann in 1983, Visser could state matter-of-factly that "There are many applications in which, knowingly or (often) unknowingly, one uses negative Hamaker coefficients to achieve separation" [444]. The invention of the AFM (Section 4.2)

---

[15] Milling later stated that Visser "derived an equation (implicitly mentioned by London) …" [432] although Visser appears to consistently attribute [430] that early statement, also quoted herein, to Hamaker [16].

[16] A well-known trade name for polytetrafluoroethylene (PTFE)-based formulas is Teflon [434].

changed everything by making it possible for the first time to directly demonstrate the occurrence of repulsive dispersion forces at near range [432, 445–447].

As an indication of the market-push attribute of these activities (Section 3.7), it is appropriate to notice that those latest developments were followed by an informative article in *The Economist* in May 2008 devoted, in part, to "the idea that the Casimir effect may sometimes be repulsive. That would knock the problem of stiction firmly on the head…" At press time, the Casimir force was reported to only have been reduced but not reversed in sign, which "would be very good news for MEMS indeed" [448]. In September 2008, a DARPA Broad Agency Announcement—somewhat confusingly titled "*Casimir Effect Enhancement (CEE)*"—appeared with the "primary goal …to determine if it possible to manipulate and to neutralize the Casimir force in an experimental system" [449]. More generally, the aim of the program was "…to develop new methods to control and manipulate attractive and repulsive forces at surfaces based on engineering of the Casimir Force."

In January 2009, a Letter in *Nature* reported that, again via an AFM approach, earlier results had been extended to the retarded regime by Munday and Capasso with the successful measurement of the Casimir-Lifshitz (C-L) force between a gold sphere and a silica surface submerged in bromobenzene [240, 241]. Furthermore, strategies were discovered involving boundaries with nontrivial geometries separated by empty space, that is, without the need to involve a third medium in the gap. In June 2008, following up on earlier studies of the Casimir force between corrugated surfaces [450, 451], an approach based on a "zipperlike, glide-symmetric structure formed of interleaved metal brackets attached to parallel plates" was predicted to yield both attractive and repulsive forces depending on the distance between the interacting surfaces [241, 452].

4.6 CASIMIR FORCE COMPUTATIONAL TOOLS

As a second example of a market-pull application, we consider the ongoing development of software products aimed at enabling the user to characterize the effect of dispersion forces in arbitrary physical systems, including of course those at the core of realistic micro- and nanomachines with a potential role in the marketplace. This brief introduction serves not only as an illustration of the evolution of this potential market but also as an initial orientation aimed at applied scientists and engineers working in different fields who may need to employ dispersion force engineering in their own realistic applications. In keeping with the approach followed in this chapter, the discussion will be nonmathematical although the references provided range from secondary school to a highly technical level.

The overarching motivation for work in this field is exemplified in a statement by the very authors reporting the latter achievement described in the previous section: "Until recently, however, predictions of Casimir forces in geometries very different from parallel plates have been hampered by the lack of theoretical tools capable of describing arbitrary geometries, but this difficulty has been addressed (in principle) by recent numerical methods" [452]. This is an extremely important observation showing the critical role now played in R&D by this novel software engineering subfield, which we refer to herein as *computer-aided dispersion force engineering* (CADFE).

In order to understand the fundamental role played by such computer-aided analysis tools, let us recall that, in both scientific and engineering practice, the need is ever present to quantitatively model the behavior of any system under study before it is manufactured and deployed [453, 454]. Such a process, which often involves vastly different areas of physics interacting simultaneously to determine device performance [455], ultimately consists of finding accurate solutions to a possibly very large number of potentially demanding mathematical problems. It is sometimes not sufficiently appreciated that, even for relatively simple systems, it is rare to be able to exhibit *analytical* solutions to realistic problems, that is, *exact* expressions capable to yield all dependent, unknown variables for any given arbitrary values of the independent variables. If providing an analytical solution is either impossible or impractical, a *numerical solution* may be sought.[17]

A wonderfully entertaining, short introduction to numerical strategies is provided in *Feynman's Lectures on Physics*, wherein it is shown that an approach, now referred to as the leapfrog method [460], recovers already known analytical solutions for the elementary mass-spring system, in which the elastic force is linearly proportional to displacement (Refs. [461, 462], Ch. 19, and [463], Ch. 15), and for an interesting gravitational two-body problem—the motion of an object around the Sun (Ref. [9], Sections 9.5–9.7; also reproduced in Ref. [464], Chapter 9, Advanced Topic 2). These are examples of *initial value* problems [465], that is, the determination of the position and velocity of the moving mass at any required final time if the position and velocity at an initial time are given. In the simplest possible terms, the algorithm in these two dynamical examples is based on dividing the time span between the initial and the final time into relatively small time steps (time discretization) during which the force on every planet due to all other planets and the Sun, and therefore its acceleration, are assumed to be constant (as in the standard case of a projectile in free-fall near the ground). The system is then advanced by a time step, after which velocities and positions are recomputed. This allows the forces and accelerations to be updated at the new positions, and the process continues till the final time. After such a consistency check based on comparisons with known analytical solutions, the *Lectures* challenges the reader to leap into the unknown—armed only with a slide rule [466]—by calculating the actual trajectories of the planets considering all mutual perturbations—an example of the fascinating *gravitational N-body problem* first attacked, unsuccessfully, by Newton and for which exact analytical solutions are very few and rarely applicable to realistic cases [467].

As an alternative strategy, *approximate analytical methods* can be employed. As an elementary example, let us again consider the mass-spring system but including also additional forces, referred to as *perturbations*. These might be, for instance, forces describing friction depending on higher powers of the speed of the moving mass through air or driving forces such as those caused by a child moving her legs while sitting in a swing [468]. In all such cases, it may be possible to approximately solve the problem in the assumption that the perturbation be, in some sense, "small" with respect to the elastic force due to the spring, or that the time interval considered be not too "long." The solution obtained from this approach is again analytical—it provides an exact rule associating a position and a velocity of the moving mass to a final time. However, the problem solved is not the original problem but another that approximates it, sometimes improved by iteration (Ref. [469], Section 3.7), and that converges to it in the limit in which the perturbation is negligible. Important questions to be addressed are whether the approximate analytical solution well represents the solution of the original problem, the relationship between numerical solutions of the exact problem and approximate analytical solutions, and estimates of the "*error*" associated with either approach [459].

---

[17] A secondary school level example of such a situation is the quadratic equation, $ax^2+bx+c=0$, whose two solutions are well known to be given by the exact expression, $x_{1,2}=(1/2a)(-b\pm\sqrt{b^2-4ac})$ [456]. If the highest power n of the unknown, x^n, is higher than $n=2$, the process of exhibiting the algebraic solutions [457] is more laborious so that one often prefers seeking a numerical solution even just for cubic equations ($n=3$) [458]. For instance, if seeking real roots (i.e., without imaginary part), this may be achieved by locating the intersections of the polynomial function with the x-axis (Ref. [459], Sec. 5.6).

Although both numerical and perturbation methods may appear as only mere machinery to extract answers to difficult problems, as the available technological resources rapidly improved in the 20th century, it became understood that computing can, in itself, also represent a means for discovery. The turning point in the development of the practice of "numerical experiments" is considered the study by Fermi, Pasta, Ulam, and Tsingou (FPUT) [470] of a long chain of masses linked by springs with forces not trivially linear as described in the *Lectures* but including also a weak nonlinear term (Ref. [471], p. 565). The behavior of the FPUT system as elucidated by means of the then new MANIAC I computer at Los Alamos was very surprising and it represented possibly the earliest example of scientific discovery enabled by simulations [472, 473]. Following usage of the term "synergesis" later famously introduced by Ulam [474], this spurred research into the meaning of "computational synergetics" [475], that is, "synergetic cooperation between a physicist and a computer" [476].

In addition to the initial value problem represented by Newton's second law of motion with Newton's law of gravitation, there exist so-called *boundary value* problems [465], typical, for instance, in classical electrostatics. A delightful introduction to these problems is the calculation of the electric field of two square conductors kept at different potential and nested within each other provided in the timeless *Electricity and Magnetism* volume of the *Berkeley Physics Course*. In this case, space is discretized by an appropriate choice of grid points and the potential at any point is determined by simply iterating the process of averaging the potential values at the four nearest points to every point, updating such values—unless they belong to the two conducting boundaries—and repeating the process till satisfactory convergence is reached "using nothing but arithmetic" (Ref. [477], Exercise 3.76). Although this *method of relaxation* was described by Gauss to Gerling as "a pleasant entertainment" that "…can be done while half asleep, or while thinking about other things" [478], much can be done to further improve the speed of convergence (Refs. [459], Section 19.5, [477], Exercise 3.77, and [479]), as also pointed out by Gauss himself [480].

Despite the existence of a very extensive set of approximate analytical and numerical methods and of hardware of ever-improving performance, a fundamental difference with respect to the problems just described made dispersion force computations nearly impossible until very recently. This is due to the nature of existing theoretical expressions for dispersion forces, which did not appear to simply allow for numerical approaches. In general, the computation of the Casimir force between two boundaries is an extremely complex mathematical endeavor allowing for exact analytical expressions only in a relatively small number of cases not easily generalized to geometries of actual technological interest, including, of course, the standard case of two perfectly conducting, infinite parallel planes first analyzed by Casimir [19]. The situation changed in 2007 with the remarkable announcement of "a method of computing Casimir forces for arbitrary geometries, with any desired accuracy, that can directly exploit the efficiency of standard numerical-electromagnetism techniques" [481]. This development has completely revolutionized the process of exploration of Casimir forces between objects in arbitrary geometries, leading to discoveries that likely would have been impossible to make by means of approximate analytical methods. Although the details are well beyond the scope of this review, since this approach leverages standard numerical-electromagnetism techniques, it is important to notice that discretization is central to the resolution algorithm [481–483]. The connection between Casimir forces and classical electromagnetism, however, is far deeper and it has been suggested that "…one approach for discovering 'interesting' geometric Casimir effects is to first find an interesting electrostatic interaction, and then seek an analogous Casimir system" [484]. Finally, we remark that, as already discussed, both exact and approximate analytical methods still have much to contribute to elucidating the behavior of dispersion forces in nontrivial geometries [329, 485, 486].

The interest of the present author has focused on developing techniques that reflect the transparency of the approaches exemplified by the pedagogical treatments presented in the *Lectures* and in *Electricity and Magnetism* extended to the computation of Casimir forces. This research program consists of identifying the "simplest" numerical algorithms able to converge to known analytical solutions (historical details are in Refs. [487, 488]) also implemented in the MATHEMATICA system [489], and to use such tools for further exploration [63, 490].

Future advances in this field from the standpoint of CADFE software development will likely focus on the integration of the most sophisticated Casimir force numerical computation algorithms available within existing or novel commercial M(N)EMNS design packages [491]. This applies not only to the obvious need for stiction remediation but also to the deployment of strategies for the "direct dynamical manipulation and control of semiconducting nanostructures" [108] based on employing Casimir forces instead of, or in addition to, electrostatic interactions [492].

Early illustrations of the immense, largely untapped potential of CADFE as synergic tools for scientific discovery applicable to future nanodevices—in the sense introduced by Ulam—are computations showing geometries for which the Casimir force becomes repulsive, as already discussed in the previous section [241, 452]. Research in carbon nanotube (CNT) modeling by the finite-element method (FEM)—already in wide use in engineering—has focused on multiwalled nanotubes (MWNTs) and "Results suggest that the van der Waals forces play an essential role in the interaction of CNTs, especially for MWNTs" [493]. The present author has pointed out several potential applications of dispersion force engineering in nanotubes emerging from a combination of appropriate geometry and modulation strategies [60–62].

The strategic importance in the development of CADFE tools for R&D leading to the design of competitive nanomachines is obvious [494] and some additional comments are offered in the next section.

4.7 VALUE CHAIN ANALYSIS, PROFIT POOLS, AND CHOKE POINTS

The representative inventions described so far naturally introduce us to value chain and profit pool analysis of companies manufacturing products potentially either enabled or enhanced by deploying dispersion force engineering solutions. Although a full treatment of this novel strategic application is well beyond the scope of this chapter, as a first step in this direction, it is useful to start from the definition of value chain first introduced by Michael Porter in 1985: "Every firm is a collection of activities that are performed to design, produce, market, deliver and support its product. All these activities can be represented using a value chain…A firm's value chain and the way it performs individual activities are a reflection of its history, its strategy, its approach to implementing its strategy, and the underlying economics of the activities themselves" (Ref. [495], p. 36). In 1998, Gadiesh and Gilbert introduced the strategy analysis concept of "profit pool, …which can be defined as the total profits earned in an industry at all points along the industry's value chain" [496]. To produce a profit pool map, those authors outlined a four-step process [497] commencing with vertically disaggregating the industry and ending with a graphical representation of its profitability structure [498]. In a typical map, such as "*The U.S. Auto Industry's Profit Pool*," all pertinent value chain activities are arranged sequentially along the x-axis as segments of length corresponding to their relative share of industry revenue whereas, along the y-axis, each block has a height proportional to their operating margin (Ref. [496], p. 142; see also Ref. [498], p. 113). For instance, this representation quickly reveals that, although "From a revenue standpoint, car manufacturers and dealers dominate the industry, accounting for almost 60% of sales," in fact "Auto leasing is by far the most profitable activity in the value chain" [496].

Our goal in introducing this tool in this chapter is twofold. On the one hand, "The profit-pool lens can be particularly illuminating in industries undergoing rapid structural change. Such change, whether triggered by deregulation or *new technology* or new competitors, always results in a shift in the distribution of profits along the value chain" [496] (my italics). Therefore, in reference to the cases discussed herein, the adoption of dispersion force engineering is expected to be a strategic choice within the framework of the industrial developmental stage at the time that particular invention was, or will shortly be, introduced. This hypothesis can be supported by historical value chain analysis comparing the performance of different firms and markets also as a function of time, as already demonstrated in follow-up studies [273, 499], to an oft-cited report by Lux Research [500], a research and consulting company. On the other hand, on the strength of the evidence this strategy has paid attractive dividends in the past, we intend to lay the foundations of a framework to show the adoption of dispersion force engineering is a credible and promising winning strategy in several possible future applications. Of particular interest in support of both aims is the concept, also introduced by Gadiesh and Gilbert, of profit pool *choke points*, "particular business activities that control the flow of profits throughout an industry" [496].

Especially applicable to our present treatment are three further clarifications also provided by Gadiesh and Gilbert. Firstly, a choke point may arise, among other reasons, due to "the granting of a patent for a core component of a product." Secondly, "choke points can take many different forms …in the personal computer business, Intel's dominance of microprocessors has become an important choke point." Finally—and quite critically—"Choke points, it should be noted, do not always represent major sources of profit in and of themselves, but they do always hold enormous strategic importance. A company that controls a choke point can influence the distribution of profits among its direct competitors and even among other, more distant value-chain participants. Much of Microsoft's business is built on the control of choke points. Its Windows operating system is a choke point for the computer industry, and its Explorer browser is emerging as a choke point for electronic commerce" [496].

As a sketch of this approach applied to our archetype, one might conjecture that owning the patent portfolio and know-how to manufacture wringing-capable Johansson blocks created a choke point in the gauge industry. Although, to the best of this author's knowledge, research must still be carried out to extract historical data enabling one to build up gauge industry value chain and profit pool maps as functions of time for various companies operating in the early 20th century, it is a reasonable working assumption that the introduction of dispersion force engineering into the process of Johansson blocks manufacturing led the company owning such intellectual property to being able to "control the flow of profits" throughout that industry. As a purely general comparison, one might argue that revolutionary Johansson blocks enhanced by dispersion forces represented the same strategic value to the companies involved as microprocessors did for Intel and the Windows operating system for Microsoft.

In the case of nanotechnology, a global analysis is obviously extremely complex including both inter- and intrafirm links [274], but extensive results are available such as in the already mentioned report [500] by Lux Research [501]. In that study, products are classified into four segments: nanomaterials, nanointermediates, nano-enabled products, and nanotools [273, 499]. Within this very high-level classification, for instance, the AFM can be considered as a nanotool enabling the manufacture of nanoproducts, as we already mentioned (Section 4) in relationship to the study by Youtie, Iacopetta, and Graham [269], also citing the Lux Research report. If just considering the AFM, market segmentation can then be represented at a much higher resolution by means of various sources of information

[348] and the question can be properly posed as to what activities "are performed to design, produce, market, deliver and support" a particular type of AFM. In terms of the Lux product classification, nanotools include "Inspection tools, Fabrication tools, and modeling software," and they encompass "Capital equipment and software used to visualize, manipulate, and model matter at the nanoscale" [500]. As far as our own focus, this might include value-added processes specifically making use of dispersion force engineering, such as force models implemented in data analysis software or proprietary cantilever probe know-how. As stated by Gadiesh and Gilbert, although such factors may not "represent major sources of profit," substantial progress in these areas may have offered the opportunity to secure a profit pool choke point in that industry. In broader historical perspective, it is useful to again recall the statement by Hutter and Bechhoefer that "If only short-ranged forces existed, the AFM would operate exactly as the STM does" [312], so that the very invention of the AFM, including the key role played by dispersion force engineering, may be considered as the creation of a choke point within the nanotool chain.

Such brief and introductory considerations, both on the smaller scales of the industry to which an invention belongs and on the larger ones of the broader markets that any such invention can disrupt, can be adapted to the cases of newly available gecko glue products and of the presently developing NRAM marketplace, both of which could be described as "turbulent industries" in the sense of Gadiesh and Gilbert [496]. A useful analogy is provided by recalling (Section 4) that "Intel's dominance of microprocessors" [496] was in turn enabled by "the surging power of silicon" magnified "by wrapping around the integrated circuits their own technical advances" [265]. Hence the strategic value offered by microprocessors as a choke point was enabled by the development of semiconductor physics. Similarly, the choke points represented, historically, by the Johansson blocks and the AFM and, in the near future, by gecko glue and the NRAM are enabled by our developing understanding of dispersion force physics. Therefore the acquisition of dispersion force engineering intellectual property, know-how, and processes becomes a *sine qua non* condition to secure corresponding choke points on all market scales. An analysis of this type can be carried out by entrepreneurs during business plan preparation as well as by investors or company managers in need of actionable information to reach a decision about the strategic value of an investment in a potential dispersion force engineering enabled technology (Section 3.7). It is to be expected that, for companies such as the Eskilstuna rifle factory (Section 4.1), products closely linked to dispersion force engineering may, by themselves, be identified as major sources of profit; for other companies, on the other hand, profit flow control may be achieved by occupying choke points created, as suggested by Gadiesh and Gilbert, through the creation of intellectual property creation later available for licensing—the strategy reportedly being executed by Nantero [409].

5 AEROSPACE APPLICATIONS: THE FUTURE

Niels Bohr is famously reported to have stated that "It's hard to make predictions, especially about the future."[18] It is with this aphorism in mind that we consider, from an admittedly personal perspective, the ways in which future dispersion force engineering-enabled space travel in general, and dispersion force engineering-enabled spacecraft in particular, might affect the evolution of human activities matured from traditional technologies over the last six decades.

---

[18] This quote has a very long history of varied attributions with minor variations of form [502].

First of all, the process of R&D in dispersion force-enabled devices is hampered by computing challenges. Although great progress has been made in reducing the problem to such a form that classical electromagnetic approaches can be successfully employed [487], one is left speculating whether we truly have the best possible algorithms for dispersion force computation. Substantial mathematical advances in this field would in turn enable the rapid exploration of completely unknown regions in parameter space.

An enduring need in space technology is that of greatly improved inertial navigation sensors, which are critical to the smart, self-navigating spacecraft of the future—whether deployed too far to receive timely information from Earth or exploring the underground oceans of a remote moon. Progress in this arena would also benefit such aspects of life on Earth as, for instance, search and rescue in GPS-denied environments. From the business standpoint, it is rather straightforward to make the case that a breakthrough in this area should be reasonably expected to generate attractive returns. Although it is quite likely that any such sensors would operate on the nanoscale, the question is whether dispersion forces can enable the desired disruptive performance improvements in such devices. The dependence of dispersion forces on a high power of the gap width is often cited as a reason for such an expectation [300] but no disruptive products have yet been introduced that exploit this fundamental physics to achieve revolutionary performance gains.

The issue of the relationship between energy and dispersion force physics is likely to remain critical [61]. Without assuming any energy conservation violations, the possibility to store energy at extremely high density does not appear to contradict other fundamental laws. Storing energy in the dispersion force field neither requires exotic nor expensive chemicals but only, apparently, a clever management of the geometry. Also, the interplay between electrostatic and dispersion forces typical of this approach ensures that the process of discharge and recharge is not determined by chemical processes but is managed by the user and that high-power densities can be achieved. Dispersion force manipulation on the nanoscale also enables the actuation of nanotube cores, which is often cited as a critical element to drive next-generation, gigahertz oscillators and nearly friction-free nanorobotic pistons.

As shown by the example of the AFM on a chip and the NRAM, the potential for unprecedented integration of computing power, artificial intelligence (AI), robotics, ultrahigh energy storage, and breakthrough inertial sensing on the nanoscale appears to be naturally enabled by dispersion force engineering. Indeed, a nano-spacecraft embodying all such attributes, referred to as a “starchip,” has been recently suggested as a realistic vehicle to achieve the dream of interstellar travel [503].

The inspiration provided by the few comments in this final section should make it clear that dispersion forces should no longer be described either as “weak” or as “a crazy idea.” The remarkably enduring characterization of the Casimir effect as a “bizarre theoretical prediction” [504], already inconsistent with experimental fact in the times of Boyle and Newton, is spectacularly contradicted by recent footage of a human climbing vertically on glass; in addition, it does not reflect electrodynamics as presently understood and it obscures the breathtaking, as yet largely untapped, technological potential of dispersion force engineering, which we have explored in this chapter.

ACKNOWLEDGMENTS

I am deeply grateful to Mark J. Schulz for his kind invitation to contribute to this volume and for several useful suggestions regarding topic selection and relevant questions covered in this chapter. During my experiences as a physicist entrepreneur, I was fortunate to receive patient advice in widely different areas from Stephen G. Eichenlaub, Matt Kirmayer, Edoardo LaPorta, and Michael L. Oddenino. I am grateful to Wayne S. Breyer for his many explanations regarding patent law and for contributing to the definition of dispersion force engineering given in Section 4. It is my pleasant duty to gratefully acknowledge Kristin Buxton (Caltech Library), Andrea Merkel (ETH Zurich, ETH-Bibliothek), and Marlies van Leersum (Unilever Archives & Records Management) for their indispensable help in obtaining copies of some of the resources cited herein.

This chapter is dedicated to the memory of my father, Italo Pinto (1928–2017), who believed in a small child interested in astronomy.

REFERENCES

[1] S. Shapin, S. Schaffer, Leviathan and the Air Pump: Hobbes, Boyle, and the Experimental Life, Princeton University Press, Princeton, 1985.

[2] T.M. Goodeve, C.P.B. Shelley, The Whitworth Measuring Machine, Longmans, Green, and Co, London, 1877.

[3] J. Whitworth, Miscellaneous Papers on Mechanical Subjects, Longman, London, 1858.

[4] W.R. Moore, Foundations of Mechanical Accuracy, The Moore Special Tool Company, Bridgeport, CT, USA, 1970.

[5] T. Doiron, J. Beers, The Gauge Block Handbook (NIST Monograph 180 with Corrections), Dimensional Metrology Group, US National Institute of Standards and Technology, USA, 2005.

[6] T. Doiron, Gauge blocks—a zombie technology, J. Res. Natl. Inst. Stand. Technol. 113 (3) (2008) 175–184.

[7] T. Kosuda, The History of Gauge Blocks, Mitutoyo Corporation, Kanagawa, Japan, 2013.

[8] R. Feynman, There's plenty of room at the bottom, J. Microelectromech. Syst. 1 (1) (1992) 60–66.

[9] R. Feynman, R.B. Leighton, M. Sands, Feynman's Lectures on Physics, Caltech, Pasadena, 1963.

[10] J.D. van der Waals, The equation of state for gases and liquids, in: Nobel Lectures, Physics 1901–1921, Elsevier Publishing Company, Amsterdam, 1967, pp. 254–265.

[11] J.S. Rowlinson, Legacy of van der Waals, Nature 244 (1973) 414–417.

[12] J.S. Rowlinson, Cohesion – A Scientific History of Intermolecular Forces, Cambridge University Press, Cambridge, 2002.

[13] F. London, The general theory of molecular forces, Trans. Faraday Soc. 33 (1937) 8–26.

[14] J.H. de Boer, The influence of van der Waals forces and primary bonds on binding energy, strength and special reference to some artificial resins, Trans. Faraday Soc. 32 (1936) 10–37.

[15] E.J.W. Verwey, J.T.G. Overbeek, Long distance forces acting between colloidal particles, Trans. Faraday Soc. 42 (7) (1946) B117–B123.

[16] H. Hamaker, The London-van der Waals attraction between spherical particles, Physica 4 (10) (1937) 1058–1072.

[17] H.B.G. Casimir, Some main lines of 50 years of Philips research in physics, in: H.B.G. Casimir, S. Gradstein (Eds.), An Anthology of Philips Research, N. V. Philips' Gloeilampenfabrieken, Eindhoven, 1966, pp. 81–92 (Chapter 4).

[18] H.B.G. Casimir, Van der Waals forces and zero point energy, in: Essays in honour of Victor Frederick Weisskopf (Physics and Society), Springer-Verlag, New York, 1998, pp. 53–66.

[19] H.B.G. Casimir, On the attraction between two perfectly conducting plates, Proc. Kon. Ned. Akad. Wetenshap 51 (1948) 793–795.

[20] D. Kleppner, With apologies to Casimir, Phys. Today 43 (10) (1990) 9–11.

[21] P.W. Milonni, M.-L. Shih, Casimir forces, Contemp. Phys. 33 (5) (1992) 313–322.

[22] H.B.G. Casimir, Van der Waals forces and zero point energy, in: W. Greiner (Ed.), Physics of Strong Fields, Springer, USA, 1987, pp. 957–964.

[23] H.B.G. Casimir, Some remarks on the history of the so-called Casimir effect, in: M. Bordag (Ed.), The Casimir Effect 50 Years Later: Proceedings of the Fourth Workshop on Quantum Field Theory Under the Influence of External Conditions, 14–18 September 1998, Leipzig, Germany, World Scientific Publishing Co. Pte. Ltd., Singapore, 1999, pp. 3–9

[24] K.A. Milton, The Casimir Effect: Physical Manifestations of Zero Point Energy, World Scientific, Singapore, 2001.

[25] H. Rechenberg, Hendrik Brugt Gerhard Casimir (1909–2000). The physicist in research, industry and society, Eur. J. Phys. 22 (2001) 441–446.

[26] S.K. Lamoreaux, Casimir forces: Still surprising after 60 years, Phys. Today 60 (2) (2007) 40–45.

[27] H.B.G. Casimir, Sur les forces van der Waals-London, J. Chim. Phys. 46 (1949) 407–410.

[28] J. Schwinger, L.L. DeRaad, K.A. Milton, Casimir effect in dielectrics, Ann. Phys. (N. Y.) 23 (1978) 1–23.

[29] B.S. DeWitt, The Casimir effect in field theory, in: A. Sarlemijn, M.J. Sparnaay (Eds.), Physics in the Making, Elsevier Science Publishers, Amsterdam, 1989, pp. 247–272 (Chapter 9B).

[30] F. Pinto, Gravitational Casimir effect, the Lifshitz theory, and the existence of gravitons, Class. Quantum Grav. 33 (2016) 237001.

[31] H.B.G. Casimir, Hapharzard Reality: Half a Century of Science, Harper Colophon Books, New York, 1983.

[32] P.W. Milonni, The Quantum Vacuum, Academic Press, San Diego, 1994.

[33] C.P. Enz, Is the zero-point energy real? in: C.P. Enz, J. Mehra (Eds.), Physical Reality and Mathematical Description, D. Reidel Publishing Company, Dordrecht-Holland, 1974, pp. 124–132.

[34] W.M. van Spengen, R. Modlinski, R. Puers, A. Jourdain, Failure mechanisms in MEMS/NEMS devices, in: B. Bhushan (Ed.), Handbook of Nanotechnology, Springer, New York, 2007 (Chapter 52).

[35] R. Maboudian, R.T. Howe, Critical review: adhesion in surface micromechanical structures, J. Vac. Sci. Technol. B 15 (1997) 1–20.

[36] F. Pinto, Gravitational-wave response of parametric amplifiers driven by radiation-induced dispersion force modulation, in: M. Bianchi, R.T. Jantzen, R. Ruffini (Eds.), Proceedings of the Fourteenth Marcel Grossmann Meeting on General Relativity, World Scientific, Singapore, 2017, pp. 3175–3182.

[37] F. Pinto, Engines powered by the forces between atoms, Am. Sci. 102 (2014) 280–289.

[38] S.E. Doyle, Benefits to society from space exploration and use, Acta Astronautica 19 (9) (1989) 749–754.

[39] IOP, Space: Exploration and exploitation in a modern society, Tech. rep. (2009).

[40] ISECG, Benefits Stemming from Space Exploration, Tech. rep, International Space Exploration Cordinaation Group, 2013.

[41] I.A. Crawford, The long-term scientific benefits of a space economy, Space Policy (July) (2016) 1–4.

[42] R.S. Jakhu, The role of space in long-term economic development on earth, in: R. Jakhu, J. Pelton (Eds.), Global Space Governance: An International Study, Springer, 2017, pp. 519–540 (Chapter 20).

[43] F. Pinto, The economics of van der Waals force engineering, in: M.S. El-Genk (Ed.), Space Technology and Applications Int. Forum (STAIF-2008), AIP Conf. Proc., 969, AIP, Melville, New York, 2008, pp. 959–968.

[44] D. Rotolo, D. Hicks, B.R. Martin, What is an emerging technology? Res. Policy 44 (2015) 1827–1843.

[45] E.B. Davies, Why Beliefs Matter, Oxford University Press, Oxford, 2014.

[46] F. Pinto, Giant's talk, Griffith Observer 1992 (9) (1992) 2–18.

[47] E. Musk, Making humans a multi-planetary species, New Space 5 (2) (2017) 46–61.

[48] J.F. Babb, Casimir effects in atomic, molecular, and optical physics, in: Advances in Atomic, Molecular, and Optical Physics, vol. 59, Elsevier Inc., 2010, pp. 1–20 (Chapter 1).

[49] K.D. Bonin, V.V. Kresin, Electric-Dipole Polarizabilities of Atoms, Molecules and Clusters, World Scientific, Singapore, 1997.

[50] G.L. Klimchitskaya, V.M. Mostepanenko, Casimir and van der Waals forces: advances and problems, in: Proceedings of Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia, 2015, pp. 41–65.

[51] L.M. Woods, D.A.R. Dalvit, A. Tkatchenko, P. Rodriguez-Lopez, A.W. Rodriguez, R. Podgornik, A materials perspective on Casimir and van der Waals Interactions, arXiv (2015) 1–54.

[52] D.L. Andrews, D.S. Bradshaw, The role of virtual photons in nanoscale photonics, Ann. Phys. (Berlin) 186 (3) (2014) 173–186.

[53] W.M. Simpson, Ontological aspects of the Casimir Effect, Stud. Hist. Philos. Modern Phys. 48 (2014) 84–88.

[54] S.K. Lamoreaux, The Casimir force and related effects: the status of the finite temperature correction and limits on new long-range forces, Annu. Rev. Nucl. Part. Sci. 62 (2012) 37–56.

[55] K.A. Milton, Resource letter VWCPF-1: van der Waals and Casimir-Polder forces, Am. J. Phys. 79 (7) (2011) 697–711.

[56] J.N. Munday, F. Capasso, Repulsive Casimir and van der Waals forces: from measurements to future technologies, Int. J. Mod. Phys. A 25 (11) (2010) 2252–2259.

[57] C. Genet, A. Lambrecht, S. Reynaud, The Casimir effect in the nanoworld, Eur. Phys. J. Spec. Top. 160 (1) (2008) 183–193.

[58] F. Capasso, J.N. Munday, D. Iannuzzi, H.B. Chan, Casimir forces and quantum electrodynamical torques: physics and nanomechanics, IEEE J. Sel. Top. Quant. Electron. 13 (2) (2007) 400–414.

[59] S.A. Ellingsen, Casimir effect in plane parallel geometry, Ph.D. thesis, Norwegian University of Science and Technology, 2006.

[60] F. Pinto, Nanopropulsion from high-energy particle beams via dispersion forces in nanotubes, in: 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference (JPC) & Exhibit, no. July, AIAA, Atlanta, 2012, pp. 1–31.

[61] F. Pinto, Energy storage from dispersion forces in nanotubes, in: M. Schulz, V.N. Shanov, Y. Zhangzhang (Eds.), Nanotube Superfiber Materials: Changing Engineering Design, Elsevier, New York, 2014, pp. 789–806 (Chapter 27).

[62] F. Pinto, Reflectance modulation by free-carrier exciton screening in semiconducting nanotubes, J. Appl. Phys. 114 (2013) 24310.

[63] F. Pinto, Casimir forces: Fundamental theory, computation, and nanodevices applications, in: Quantum Nano-Photonics, NATO Science for Peace and Security Series B: Physics and Biophysics, Springer, Nature B. V., Dordrecht, 2018, pp. 149–180 (Chapter 8).

[64] F. Pinto, The development of dispersion force engineering and its future aerospace industry applications: sensing, nano-actuation, energy-storage and advanced propulsion, Progr. Aerospace Sci. (2018). in preparation.

[65] A. Larraza, A demonstration apparatus for an acoustic analog of the Casimir effect, Am. J. Phys. 67 (11) (1999) 1028–1030.

[66] D. Dragoman, M. Dragoman, Quantum-Classical Analogies, Springer, Heidelberg, 2004.

[67] C.P. Lee, T.G. Wang, Acoustic radiation pressure, J. Acoust. Soc. Am. 94 (1993) 1099–1109.

[68] T.G. Wang, C.P. Lee, Radiation pressure and acoustic levitation, in: M.F. Hamilton, D.T. Blackstock (Eds.), Nonlinear Acoustics, Academic Press, San Diego, 1998, pp. 177–205 (Chapter 6).

[69] L. Rayleigh, On the pressure of vibrations, Phil. Mag. 3 (ser 6) (1902) 338–346.

[70] L. Rayleigh, On the momentum and pressure of gaseous vibrations, and on the connexion with the virial theorem, Phil. Mag. 10 (ser 6) (1905) 364–374.

[71] D.R. Raichel, The Science and Application of Acoustics, Springer-Verlag, New York, 2000.

[72] A. Larraza, B. Denardo, An acoustic Casimir effect, Phys. Lett. A 248 (5) (1998) 151–155.

[73] A. Larraza, C.D. Holmes, R.T. Susbilla, B.C. Denardo, The force between two parallel rigid plates due to the radiation pressure of broadband noise: an acoustic Casimir effect, J. Acoust. Soc. Am. 103 (1998) 2267–2272.

[74] J. Barcenas, L. Reyes, R. Esquivel-Sirvent, Acoustic Casimir pressure for arbitrary media, J. Acoust. Soc. Am. 116 (2) (2004) 11.

[75] G. Palasantzas, Pull-in voltage of microswitch rough plates in the presence of electromagnetic and acoustic Casimir forces, J. Appl. Phys. 101 (6) (2007) 63548.

[76] R. Esquivel-Sirvent, L.I. Reyes, Pull-in control in microswitches using acoustic Casimir forces, EPL 84 (2008) 48002.

[77] T.W. Marshall, Random electrodynamics, Proc. Royal Soc. A: Math. Phys. Eng. Sci. 276 (1367) (1963) 475–491.

[78] T.W. Marshall, Statistical electrodynamics, Proc. Cambridge Phil. Soc. 61 (1965) 537–546.

[79] I.J.R. Aitchison, Nothing's plenty. The vacuum in modern quantum field theory, Contemp. Phys. 50 (2009) 261–319.

[80] G. Brugger, L.S. Froufe-Perez, F. Scheffold, J.J. Saenz, Controlling dispersion forces between small particles with artificially created random light fields, Nat. Commun. 6 (2015) 7460.

[81] S.C. Wang, Die gegenseitige Einwirkung zweier Wasserstoffatome, Phys. Z. 28 (1927) 663–666.

[82] R. Eisenschitz, F. London, Uber das Verhaltnis der van der Waalsschen Krafte zu den homoopolaren Bindungskraften, Z. Phys. 60 (1930) 491–527.

[83] R.A. Newing, Uncertainty principle and the zero-point energy of the harmonic oscillator, Nature 136 (1935) 395.

[84] C. Cohen-Tannoudji, B. Diu, F. Laloe, Quantum Mechanics (two volumes), John Wiley & Sons, New York, 1977.

[85] L.S. Levitt, Derivation of the zero-point energy from the uncertainty principle, J. Chem. Phys. 39 (1962) 520–521.

[86] L. Spruch, Retarded, or Casimir, long-range potentials, Phys. Today 39 (11) (1986) 37–45.

[87] H.B.G. Casimir, D. Polder, Influence of retardation on the London-van-der-Waals forces, Nature 158 (1946) 787–788.

[88] H.B.G. Casimir, D. Polder, The influence of retardation on the London-van der Waals forces, Phys. Rev. 73 (4) (1948) 360–372.

[89] M. Cooper, Why ask why? J. Chem. Ed. 92 (2015) 1273–1279, https://doi.org/10.1021/acs.jchemed.5b00203.

[90] N. Becker, K. Noyes, M. Cooper, Characterizing students' mechanistic reasoning about London dispersion forces, J. Chem. Ed. 93 (2016) 1713–1724.

[91] S.M. Underwood, D. Reyes-gastelum, M. Cooper, When do students recognize relationships between molecular structure and properties? A longitudinal comparison of the impact of traditional and transformed curricula, CERP 17 (2016) 365–380.

[92] P.W. Milonni, A. Smith, van der Waals dispersion forces in electromagnetic fields, Phys. Rev. A 53 (5) (1996) 3484–3489.

[93] J.H. Hannay, The Clausius-Mossotti equation: an alternative derivation, Eur. J. Phys. 4 (1983) 141–143.

[94] E.M. Lifshitz, The theory of molecular attractive forces between solids, Sov. Phys. JETP 2 (1) (1956) 73–83.

[95] S.M. Rytov, Theory of Electric Fluctuations and Thermal Radiation, Armed Services Technical Information Agency, Rep. AFCRC-TR-59-162, Air Force. Cambridge Research Center, Bedford, MA, Arlington, VA, 1959.

[96] I. Dzyaloshinskii, E.M. Lifshitz, L.P. Pitaevskii, Van der Waals forces in liquid films, Sov. Phys. JETP 37 (1960) 161–170.

[97] I. Dzyaloshinskii, E.M. Lifshitz, L.P. Pitaevskii, The general theory of van der Waals forces, Adv. Phys. 10 (38) (1961) 165–209.

[98] W. Arnold, S. Hunklinger, K. Dransfeld, Influence of optical absorption on the Van der Waals interaction between solids, Phys. Rev. B 21 (4) (1980) 1713.

[99] F. Chen, G.L. Klimchitskaya, V.M. Mostepanenko, U. Mohideen, Demonstration of optically modulated dispersion forces, Opt. Express 15 (8) (2007) 4823–4829.

[100] R.L. Forward, Extracting electrical energy from the vacuum by cohesion of charged foliated conductors, Phys. Rev. B 30 (4) (1984) 1700–1702.

[101] F.M. Serry, D. Walliser, G. Maclay, The anharmonic Casimir oscillator (ACO)-the Casimir effect in a model microelectromechanical system, J. Microelectromech. Sys. 4 (4) (1995) 193–205.

[102] W.S.N. Trimmer, Microrobots and micromechanical systems, Sens. Actuators 19 (1989) 267–287.

[103] W. Trimmer, R. Jebens, Actuators for micro robots, in: 1989 IEEE International Conference on Robotics and Automation, Scottsdale, AZ, USA, 1989, pp. 1547–1552.

[104] I. Shimoyama, Scaling in microrobots, in: Proc. 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots, 2, 1995, pp. 208–211.

[105] T. Hayashi, On micromechanisms and their researches and developments, in: A. Morecki, G. Bianchi, K. Jaworek (Eds.), Proc. of the Ninth CISM-IFToMM Symposium on Theory and Practice of Robots and Manipulators, 187 Springer-Verlag, London, 1993, pp. 1–12.

[106] T. Hayashi, Research and development of micromechanisms, Ultrasonics 38 (1-8) (2000) 6–14.

[107] F. Pinto, Casimir forces in relativistic metrology: Fundamental physical tests and aerospace applications, in: Third IEEE International Workshop on Metrology for Aerospace, IEEE, Florence, Italy, 2016. p. (Paper ID: 4292221).

[108] F. Pinto, Casimir forces in relativistic metrology: Fundamental physical tests and aerospace applications, in: Third IEEE International Workshop on Metrology for Aerospace, IEEE, Florence, Italy, 2016. p. (Paper ID: 4292221).

[109] F. Pinto, Membrane nano-actuation by light-driven manipulation of van der Waals forces: a progress report, in: M.S. El-Genk (Ed.), Space Technology and Applications Int. Forum (STAIF-2008), AIP Conf. Proc. 969, no. 626, AIP, Melville, New York, 2008, pp. 1111–1119.

[110] F. Pinto, Demonstration of biased membrane static figure mapping by optical beam subpixel centroid shift, in: A. Al-Kamli (Ed.), Proceedings of the Fifth Saudi International Meeting on Frontiers of Physics (SIMFP2016) – AIP Conference Proceedings, 1742, AIP, Gizan, Saudi Arabia, 2016, p. 030014.

[111] F. Pinto, Membrane actuation by Casimir force manipulation, J. Phys. A 41 (2008) 164033.

[112] F. Pinto, Adaptive optics actuation by means of van der Waals forces: a novel nanotechnology strategy to steer light by light, in: Y. Otani et al., (Ed.), Optomechatronic Technologies 2008, 7266, SPIE, San Diego, 2008, p. 726616.

[113] M.J. Schulz, Speeding up artificial muscles, Science 338 (2012) 893–894.

[114] G.A. Moore, Crossing the Chasm, HarperCollins, New York, 2006.

[115] L. Hardesty, Mysterious quantum forces unraveled, MIT News, 2010.

[116] PPhysorg, Researchers harness mysterious Casimir force for tiny devices, (2017).

[117] LabTalk, The Casimir force becomes more mysterious, J. Phys: Condens Matt. http://iopscience.iop.org/journal/0953-8984/labtalk/article/61235.

[118] S. Hossenfelder, The Casimir Effect, Backreaction, 2007.http://backreaction.blogspot.com.tr/2015/03/can-we-prove-quantization-of-gravity.html.

[119] F. Hagelstein, R. Miskimen, V. Pascalutsa, Nucleon polarizabilities: from Compton scattering to hydrogen atom, Prog. Part. Nucl. Phys. 88 (2016) 29–97.

[120] J.F. Babb, R. Higa, M.S. Hussein, Dipole-dipole dispersion interactions between neutrons, Eur. Phys. J. A 53 (2017) 126.

[121] J.C. Maxwell, A treatise on electricity and magnetism, second ed., vol. I & II, Dover Publications, Inc., New York, 1954.

[122] H. Krupp, Particle adhesion: theory and experiment, Advan. Colloid Interface Sci. 1 (1967) 111–239.

[123] M.G. Millis, NASA breakthrough propulsion physics program, in: M.G. Millis (Ed.), NASA Breakthrough Propulsion Physics NASA/CP-1999-208694, NASA Technical Information Service, Cleveland, OH, 1999, pp. 1–416.

[124] L.I.R. Galindo, The Sociology of Theoretical Physics, Ph.D. thesis, Cardiff University, 2011.

[125] L.L. Henry, T.W. Marshall, A classical treatment of dispersion forces, Il Nuovo Cimento B XLI (2) (1966) 188–197.

[126] L. de la Pena, Stochastic electrodynamics: its development, present situation and perspectives, in: B. Gomez, S.M. Moore, A.M. Rodriguez-Vargas, A. Rueda (Eds.), Stochastic Processes Applied to Physics and other Related Fields – ACIF Series, I, World Scientific, Singapore, 1983, pp. 428–581.

[127] L. de la Pena, A.M. Cetto, The physics of stochastic electrodynamics, Il Nuovo Cimento 92 (1986) 189–217.

[128] T.H. Boyer, Casimir forces with and without zero-point energy: some historical comments, in: A.V.S. D. Han, Y.S. Kim, B.E.A. Saleh, M.C. Teich (Eds.), Squeezed States and Uncertainty Relations, held at Boston University, Boston, USA, June 4–8 (2001), Boston, USA, 2001, pp. 1–6.

[129] T.H. Boyer, Blackbody radiation and the scaling symmetry of relativistic classical electron theory with classical electromagnetic zero-point radiation, Found. Phys. 40 (8) (2010) 1096–1098.

[130] T.H. Boyer, Classical statistical thermodynamics and electromagnetic zero-point radiation, Phys. Rev. 186 (1969) 1304–1318.

[131] P.W. Milonni, Semiclassical and quantum-electrodynamical approaches in nonrelativstic radiation theory, Phys. Rep. 25 (1976) 1–81.

[132] M. Scandurra, Thermodynamic properties of the quantum vacuum, (2008), pp. 1–15. arXiv:abs/hep-th/0104127.

[133] H. Collins, T. Pinch, The construction of the Paranormal: nothing unscientific is happening, in: R. Wallis (Ed.), The Sociological Review Monograph No. 27: On the Margins of Science: The Social Construction of Rejected Knowledge, Keele University Press, Keele, 1970, pp. 237–270.

[134] P. Yam, Exploiting zero-point energy, Sci. Am. 277 (December) (1997) 82–85.

[135] K. Chang, A tiny force of nature is stronger than thought, Friday, February 9, 2001, New York Times A17 (2001).

[136] E.W. Davis, V.L. Teofilo, B. Haisch, H.E. Puthoff, L.J. Nickisch, A. Rueda, D.C. Cole, Review of experimental concepts for studying the quantum vacuum field, in: Space Technology and Applications International Forum AIP Conference Proc. STAIF 2006, vol. 813, AIP, 2006, pp. 1390–1401.

[137] H. Collins, Gravity's Shadow, The University of Chicago Press, Chicago, 2004.

[138] H. Collins, A. Bartlett, L. Reyes-galindo, H. Collins, L. Reyes-galindo, Demarcating fringe science for policy, Perspectives on Science 25 (4) (2017) 411–438.

[139] J. Conaway Bondanella, P. Bondanella, Giorgio Vasari: The Lives of the Artists, Oxford University Press, New York, 1991.

[140] G.L. Klimchitskaya, M. Bordag, V.M. Mostepanenko, Comparison between experimental and theory for the thermal Casimir force, Int. J. Mod. Phys. Conf. Ser. 14 (2012) 155–170.

[141] G.L. Klimchitskaya, V.M. Mostepanenko, Low-temperature behavior of the Casimir free energy and entropy of metallic films, Phys. Rev. A 95 (2017) 12130.

[142] G. Bimonte, G.L. Klimchitskaya, V.M. Mostepanenko, Universal experimental test for the role of free charge carriers in the thermal Casimir effect within a micrometer separation range, Phys. Rev. A 95 (2017) 52508.

[143] L.I.R. Galindo, Controversias en el Efecto Casimir, Master's thesis, Universidad Nacional Autonoma de Mexico, 2007.

[144] S.K. Lamoreaux, Progress in experimental measurements of the surface-surface Casimir force: electrostatic calibrations and limitations to accuracy, in: Casimir Physics, Springer Lecture Notes in Physics, vol. 834, Springer, Heidelberg, 2011, pp. 219–248 (Chapter 7).

[145] G.L. Klimchitskaya, V.M. Mostepanenko, What is credible and what is incredible in the measurements of the Casimir force, in: 8th Alexander Friedmann International Seminar – International Journal of Modern Physics: Conference Series, vol. 3, World Scientific, 2011, pp. 541–554.

[146] S.K. Lamoreaux, Demonstration of the Casimir force in the 0.6 to 6 μm range, Phys. Rev. Lett. 78 (1) (1997) 5–8.

[147] T.G. Philbin, U. Leonhardt, No quantum friction between uniformly moving plates, New J. Phys. 11 (3) (2009) 33035.

[148] J.B. Pendry, Quantum friction – fact or fiction? New J. Phys. 12 (3) (2010) 33028.
[149] U. Leonhardt, Comment on 'Quantum friction – fact or fiction?', New J. Phys. 12 (6) (2010) 68001.
[150] J.B. Pendry, Reply to comment on 'Quantum friction – fact or fiction?', New J. Phys. 12 (6) (2010) 68002.
[151] C. Lee, A fraction too much friction causes physics fisticuffs, Ars Technica 11 (3) (2009).
[152] D. Collingridge, C. Reeve, Science Speaks to Power, St. Martin's Press, New York, 1986.
[153] N. Koblitz, A tale of three equations; or the emperors have no clothes, Math. Intell. 10 (1) (1988) 4–10.
[154] H.A. Simon, Unclad emperors: a case of mistaken identity, Math. Intell. 10 (1) (1988) 11–14.
[155] N. Koblitz, Reply to unclad emperors, Math. Intell. 10 (1) (1988) 14–15.
[156] E. Hinkel, Objectivity and credibility in L1 and L2 academic writing, in: E. Hinkel (Ed.), Culture in Second Language Teaching and Learning, Cambridge University Press, 1999, pp. 1–40.
[157] G. Myers, The pragmatics of politeness in scientific articles, Appl. Linguist. 10 (1) (1989) 1–35.
[158] A. Okamura, Politeness in scientific research articles revisited: the use of ethnography and corpus, in: A. Ryan, A. Wray (Eds.), British Studies in Applied Linguistics: Evolving models of Language, Multilingual Matters, Clevedon, 1997, pp. 84–99.
[159] B. Vincent, Colloids, in: 100 Years of Physical Chemistry, The Royal Society of Chemistry, 2003, pp. 207–209.
[160] B.V. Derjaguin, L.D. Landau, Theory of the stability of strongly charged lyophobic sols and of the adhesion of strongly charged particles in solutions of electrolytes, Acta Physicochim. URSS 14 (1941) 633–662.
[161] E.J.W. Verwey, J.T.G. Overbeek, Theory of the Stability of Lyophobic Colloids, Elsevier Publishing Company, Inc, New York, 1948.
[162] B.V. Derjaguin, A.S. Titijevskaia, I.I. Abricossova, A.D. Malkina, Investigations of the forces of interaction of surfaces in different media and their application to the problem of colloid stability, Discuss. Faraday Soc. 18 (1954) 24–41.
[163] C. Selin, Expectations and the emergence of nanotechnology, Sci. Technol. Hum. Values 32 (2007) 196–220.
[164] M. Appel, S. Krause, U. Gleich, M. Mara, Meaning through fiction: science fiction and innovative technologies, Psychol. Aesthet. Creativity Arts 10 (4) (2016) 472–480.
[165] J. Lopez, Bridging the gaps: science fiction in nanotechnology, HYLE – Int. J. Philos. Chem. 10 (2) (2004) 129–152.
[166] B. Aldrin, J. Barnes, Encounter with Tiber, Warner Books, New York, 1996.
[167] C. Djerassi, An immaculate misconception, http://www.djerassi.com/icsi/immaculate.html, 2005.
[168] M. Cendrowski, The Bat Jar Conjecture, Warner Bros. Television, 2008.
[169] D.A. Kowalski, The Big Bang Theory and Philosophy: Rock, Paper, Scissors, Aristotle, Locke, John Wiley & Sons, Inc., Hoboken, NJ, 2012.
[170] J. Egan, 1000 Facts About Animated Films, lulu.com, (2017).
[171] B. Bird, The Incredibles, Pixar Animation Studios – Walt Disney Pictures, 2004.
[172] E.P. Tryon, Is the universe a vacuum fluctuation? Nature 246 (1973) 396–397.
[173] L.B. Ebert, Intersection of science and law, Tech. rep.(1998).
[174] N. Wade, No Nobel Prize This Year? Try Footnote Counting, (1997).
[175] D. Jones, A science futures market, Nature 387 (1997) 763.
[176] B. Barnes, Interests and the Growth of Knowledge, Routledge, New York, 1977.
[177] B. Martin, Strategies for dissenting scientists, J. Sci. Explor. 12 (4) (1998) 605–616.
[178] P. Feyerabend, How to defend society against science, in: H. Klemke et al., (Ed.), Introductory Readings in the Philosophy of Science, third ed., 1998, pp. 54–65 (1975).
[179] L. Leydesdorff, Patent classifications as indicators of intellectual organization, JASIST 59 (10) (2008) 1582–1597.
[180] M. Zitt, E. Bassecoulard, Delineating complex scientific fields by an hybrid lexical-citation method: An application to nanosciences, Inform. Process. Manag. 42 (2006) 1513–1531.

[181] M. Meyer, What is special about patent citations? Differences between scientific and patent citations, Scientometrics 49 (2000) 93–123.

[182] M.A.B. Whitaker, History and quasi-history in physics education. I, Phys. Educ. 14 (1979) 108–112.

[183] M.A.B. Whitaker, History and quasi-history in physics education – part 2, Phys. Educ. 14 (1979) 239–242.

[184] P. Ball, Popular physics myth is all at sea, News@Nature 2006 (2006) 2006–2008.

[185] S.L. Boersma, A maritime analogy of the Casimir effect, Am. J. Phys. 64 (5) (1996) 539–541.

[186] H. Johnsen, B. Olsen, Hermeneutics and archaeology: on the philosophy of contextual archaeology, Am. Antiq. 57 (3) (1992) 419–436.

[187] A. Marciniak, Setting a new agenda: Ian Hodder and his contribution to archeological theory, Archeologia Polona 35 (1997) 409–426.

[188] I. Hodder, The contextual analysis of symbolic meanings, in: I. Hodder (Ed.), The Archaeology of Contextual Meanings, Cambridge University Press, 1985, pp. 1–11 (Chapter 1).

[189] I. Hodder, Interpretive archaeology and its role, Am. Antiq. 56 (1) (1991) 7–18.

[190] I. Hodder, Theory and Practice in Archaeology, Routledge, London and New York, 1995.

[191] I. Hodder, S. Hutson, Reading the Past, third ed., Cambridge University Press, Cambridge, 2003.

[192] T.S. Kuhn, The Structure of Scientific Revolutions, second ed., vol. I and II, The University of Chicago Press, Chicago, 1970.

[193] P. Feyerabend, Against Method, fourth ed., Verso Books, New York, 2010.

[194] J.P. Dowling, The mathematics of the Casimir effect, Math. Magaz. 62 (5) (1989) 324–331.

[195] G.B. Lubkin, A mathematician's version of the fine-structure constant, Phys. Today 24 (8) (1971) 17.

[196] A.O. Barut, The creation of a photon: a heuristic calculation of Planck's constant hbar of the fine structure constant, Zeitschrift für Naturforschung A 33 (8) (1978) 993–994.

[197] D.C. Chang, Physical interpretation of the Planck's constant based on the Maxwell theory, Chin. Phys. B 26 (4) (2017) 40301.

[198] D.L. Rosen, Beyond the classical view of atoms, Phys. Today 66 (5) (2013) 19–21.

[199] P. Gruji´c, N. Simonovi´c, Insights from the classical atom, Phys. Today 65 (5) (2012) 41–46.

[200] P. Duhem, To Save the Phenomena, University of Chicago Press, Chicago, 1969.

[201] S. Therese, B. Martin, Shame, scientist! Degradation rituals in science, Prometheus 28 (2010) 97–110.

[202] N. Cook, The Hunt for Zero Point, Broadway Books, New York, 2002.

[203] R. Park, Voodoo Science, Oxford University Press, Oxford, 2000.

[204] M. Gardner, Did Adam and Eve have navels? W. W. Norton & Company, New York, 2000.

[205] G. Ellis, J. Silk, Defend the integrity of physics, Nature 516 (2014) 321–323.

[206] M. Baker, Is there a reproducibility crisis? Nature 533 (2016) 452–454.

[207] J. Horvath, The replication myth: shedding light on one of science's dirty little secrets, Sci. Am. Guest Blog (2013).

[208] S. Hossenfelder, Are irreproducible scientific results okay and just business as usual?, Backreaction, 2013. http://backreaction.blogspot.com.tr/2013/12/are-irreproducible-scientific-results.html.

[209] D.B. Allison, A.W. Brown, B.J. George, K.A. Kaiser, A tragedy of errors, Nature 530 (2016) 27–29.

[210] J.Q. Quach, Gravitational Casimir Effect, Phys. Rev. Lett. 114 (8) (2015) 81104.

[211] J.Q. Quach, Erratum: gravitational Casimir Effect, Phys. Rev. Lett. 118 (2017) 139901.

[212] D.S. Kornfeld, S.L. Titus, Stop ignoring misconduct, Nature 537 (2016) 29–30.

[213] H. White, J. Vera, P. Bailey, P. March, T. Lawrence, A. Sylvester, D. Brady, Dynamics of the vacuum and Casimir analogs to the hydrogen atom, J. Mod. Phys. 6 (2015) 1–9.

[214] H.S. White, A discussion on characteristics of the quantum vacuum, Phys. Essays 4 (October) (2015) 496–502.

[215] H. White, P. March, J. Lawrence, J. Vera, A. Sylvester, D. Brady, P. Bailey, Measurement of impulsive thrust from a closed radio-frequency cavity in vacuum, J. Propul. Power (2016) 1–12.

[216] M. Gardner, Fads and Fallacies in the Name of Science, Dover Publications, Inc, New York, 1957.

[217] C. Babbage, Reflections of the Decline of Science in England, and on Some of its Causes, B. Fellowes, London, 1830.

[218] J. Maddox, Restoring good manners in research, Nature 376 (1995) 113.

[219] J. Tosh, The Pursuit of History, fourth ed., Pearson Longman, London, 2006.

[220] R. Samuel, People's History and Socialist Theory, Routledge, New York, 1981.

[221] M. Weinel, Paper 120: Counterfeit scientific controversies in science policy contexts, SSRN Electron. J. (2008) 1–21.

[222] M.J. Kuchner, Marketing for Scientists, Island Press, Washington, D.C., 2012.

[223] C.J. Sindermann, Winning the Games Scientists Play, Perseus Publishing, Cambridge, Massachusetts, 2001.

[224] M.G. Harvey, R.F. Lusch, Expanding the nature and scope of due diligence, J. Bus. Ventur. 10 (1995) 5–21.

[225] M. Van Osnabrugge, R.J. Robinson, Angel Investing, Jossey-Bass, San Francisco, 2000.

[226] G.A. Benjamin, J. Margulis, The Angel Investor's Handbook, Bloomberg Press, New York, 2001.

[227] S.L. Preston, Angel Financing for Entrepreneurs, John Wiley & Sons, Inc, San Francisco, 2007.

[228] P. Douglas, Due Diligence: The Hard Edge of a Soft Science, Eurekaedge, 2004.

[229] J.F. Wright, Technical Due Diligence, Errors & Uncertainty, Tech. rep.(2002).

[230] ECN, Technology due diligence, Tech. rep., ECN, The Netherlands.

[231] A. Miller, Bridging the valley of death: improving the commercialization of research, in: Eighth Report of Session 2012-13, Volume II Additional written evidence Ordered by the House of Commons to be published 22 February 2012, 18 April 2012 and 25 April 2012, Published on 13 March 2013 by authority of the House of Commons London: The Stationery Office Limited, 2012.

[232] N. Winterton, Scalability and scientific due diligence, Clean Technol. Environ. Policy 13 (2011) 643–646.

[233] K. Autumn, Y.A. Liang, S.T. Hsieh, W. Zesch, W.P. Chan, T.W. Kenny, R.S. Fearing, R.J. Full, Adhesive force of a single gecko foot-hair, Nature 405 (June) (2000) 681–684.

[234] T. Rueckes, K. Kim, E. Joselevich, G.Y. Tseng, C.-L. Cheung, C.M. Lieber, Carbon nanotube-based non-volatile random access memory for molecular computing, Science 289 (2000) 94–97.

[235] H. Munro, H. Noori, Measuring commitment to new manufacturing technology: integrating technological push – and marketing pull concepts, IEEE Trans. Eng. Manag. 35 (2) (1988) 63–70.

[236] S.R. Chidamber, H.B. Kon, A research retrospective of innovation inception and success: the technology-push, demand-pull question, Int. J. Technol. Manag. 9 (1) (1994) 94–112.

[237] S. Lubik, S. Lim, K. Platts, T. Minshall, S. Lubik, S. Lim, K. Platts, T. Minshall, Market-pull and technology-push in manufacturing start-ups in emerging industries, JMTM 24 (1) (2012) 10–27.

[238] O.R. Butler, R.J. Anderson, Risky business: a study of physics entrepreneurship, Phys. Today 65 (12) (2012) 39–45.

[239] Z. Yapu, Stiction and anti-stiction in MEMS and NEMS, Acta Mechanica Sinica 19 (2003) 1–10.

[240] J.N. Munday, F. Capasso, V.A. Parsegian, Measured long-range repulsive Casimir-Lifshitz forces, Nature 457 (January) (2009) 170–173.

[241] A.W. Rodriguez, F. Capasso, S.G. Johnson, The Casimir effect in microstructured geometries, Nat. Photonics 5 (2011) 211–221.

[242] C. Mastrangelo, Adhesion-related failure mechanisms in micromechanical devices, Tribolol. Lett. 3 (1997) 223–238.

[243] S.F. Cohn, Adopting innovations in a technology push industry, Res. Manag. 24 (1981) 26–31.

[244] R.W. Zmud, An examination of 'Push-Pull' theory applied to process innovation in knowledge work, Manag. Sci. 30 (6) (1984) 727–738.

[245] M.G. Millis, Breakthrough Propulsion Physics Project: Project Management Methods/TM-2004-213406, Tech. rep.NASA, Cleveland, OH, 2004.

[246] M.G. Millis, Managing for revolutionary gains, Glob. Perspect. Eng. Manag. 2 (1) (2013) 11–20.

[247] M.G. Millis, E.W. Davis, Frontiers of Propulsion Science (Progress in Astronautics and Aeronautics, Book 227), AIAA, Reston, VA, 2009.

[248] M.G. Millis, Breakthrough Managing High-Risk/High-Gain Research, in: 2005 Design for Breakthrough Research in an Academic Setting, Stanford, CA, 2005, pp. 1–40.

[249] F. Pinto, The Casimir effect and its role in nanotechnology applications, in: Materials Today: Proceedings, 5, (2018) pp. 15976–15982.

[250] P. Choate, Testimony of Pat Choate, Hearing on Intellectual Property Rights Issues and Dangers of Counterfeited Goods Imported into the United States, (2006).

[251] J. Meredith, Letter to Speaker of the House Nancy Pelosi and Senate Majority Leader Harry Reid: IEEE-USA Opposes the Patent Reform Act, 2007, p. (2007).

[252] H.L. Sirkin, J. Rose, R. Choraria, An Innovation-Led Boost for US Manufacturing, Tech. rep.BCG The Boston Consulting Group, 2017.

[253] D.N. Arion, Things your adviser never told you: entrepreneurship's role in physics education, Phys. Today 66 (8) (2013) 42.

[254] P.R. Sanberg, M. Gharib, P.T. Harker, E.W. Kaler, R.B. Marchase, T.D. Sands, Changing the academic culture: valuing patents and commercialization toward tenure and career advancement, PNAS 111 (2014) 6542–6547.

[255] V. McDevitt, J. Mendez-Hinds, D. Winwood, V. Nijhawan, T. Sherer, J.F. Ritter, P.R. Sanberg, More than money: the exponential impact of academic technology transfer, Technol. Innov. 16 (1) (2014) 75–84.

[256] A.A. Toole, D. Czarnitzki, A.A. Toole, D. Czarnitzki, Commercializing science: is there a university "brain drain" from academic entrepreneurship? Manag. Sci. 56 (2010) 1599–1614.

[257] P. Keenan, J. Bickford, A. Doust, J. Tankersley, C. Johnson, J. McCaffrey, J. Dolfi, G. Shah, Strategic Initiative Management, Tech. rep.Boston Consulting Group, 2013

[258] The Economist Intelligence Unit, A change for the better, (2008).

[259] E. Fingleton, America the Innovative?, (2013).

[260] B. Aldrin, You promised me Mars colonies. Instead, I got Facebook, MIT Technol. Rev. 115 (6) (2012) 70.

[261] W. Pauli, Writings on Physics and Philosophy, Springer-Verlag, Berlin, 1994.

[262] R. Turner, T. Jones, Techniques for imaging neuroscience, Br. Med. Bull. 63 (September) (2003) 3–20.

[263] NRC, Technology for the United States Navy and Marine Corps, 2000-2035 Becoming a 21st-Century Force, vol. 7, Undersea Warfare, National Academy Press, Washington, D.C., 1997.

[264] L. Mainetti, L. Patrono, M.L. Stefanizzi, R. Vergallo, A Smart Parking System Based on IoT Protocols and Emerging Enabling Technologies, in: 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT), 2015, p. 15729117.

[265] T.F. Bresnahan, M. Trajtenberg, General purpose technologies: "engines of growth" J. Econometr. 65 (1995) 83–108.

[266] R.G. Lipsey, C. Bekar, K. Carlaw, What requires explanation? in: E. Helpman (Ed.), General Purpose Technologies and Economic Growth, The MIT Press, Cambridge, MA, 1998, pp. 15–54 (Chapter 2).

[267] P.W.B. Phillips, Governing Transformative Technological Innovation: Who is in Charge? Edward Elgar Publishing, Cheltenham, UK, 2007.

[268] T. Jefferson, B.F. Woods, Diplomatic Correspondence, Algora Publishing, Paris, 2016, pp. 1784–1789.

[269] J. Youtie, M. Iacopetta, S. Graham, Assessing the nature of nanotechnology: can we uncover an emerging general purpose technology? J. Technol. Transf. 33 (2008) 315–329.

[270] R.G. Lipsey, K.I. Carlaw, C.T. Bekar, Technology and technological change, in: Economic Transformations: General Purpose Technologies and Long-Term Economic Growth, Oxford University Press, Oxford, 2005, pp. 1–656 (Chapter 4).

[271] A. Jamting, J. Miles, Metrology for nanotechnology, in: International Conference on Nanoscience and Nanotechnology (ICONN 2008), IEEE, 2008, pp. 56–58.

[272] S. Frederick, A value chain research approach to nanotechnology: a framework for competition and collaboration, in: CNS Seminar Speaker Series, 2 March, 2011.

[273] G. Wang, J. Guan, Value chain of nanotechnology: a comparative study of some major players, J. Nanopart. Res. 14 (2012) 702.

[274] A.R. Ungureanu, Competitive advantages in a nanotechnology value chain, SEA: Pract. Appl. Sci. III (1) (2015) 573–580.

[275] J. Schummer, Multidisciplinarity, interdisciplinarity, and patterns of research collaboration in nanoscience and nanotechnology, Scientometrics 59 (3) (2004) 425–465.

[276] N. Crafts, Steam as a general purpose technology: a growth accounting perspective, Econ. J. 114 (75) (2004) 338–351.

[277] P. Moser, T. Nicholas, T.O.M. Nicholas, Was electricity a general purpose technology? Evidence from historical patent citations, Am. Econ. Rev. Pap. Proc. 94 (2) (2015) 388–394.

[278] J. Youtie, P. Shapira, A.L. Porter, Nanotechnology publications and citations by leading countries and blocs, J. Nanopart. Res. 10 (2008) 981–986.

[279] C.M. Shea, R. Grinde, B. Elmslie, Nanotechnology as general-purpose technology: empirical evidence and implications, Technol. Anal. Strateg. 23 (2011) 175–192.

[280] D. Meissner, Instruments to measure foresight, in: D. Meissner, L. Gokhberg, A. Sokolov (Eds.), Science, Technology and Innovation Policy, Springer-Verlag, Berlin, Heidelberg, 2013, pp. 43–62 (Chapter 4).

[281] N. Rosenberg, Technological interdependence in the American Economy, Technol. Cult. 20 (1) (1979) 25–50.

[282] T.D. Lee, Particle Physics and Introduction to Field Theory, first ed., Harwood Academic Publishers, Chur, 1990.

[283] F.J. Dyson, Innovation in Physics, Sci. Am. 199 (3) (1958) 74–83.

[284] R. Boyle, A Continuation of New Experiments, Henry Hall printer to the University, Oxford, 1669.

[285] I. Newton, Opticks, Sam. Smith and Benj. Walford, Printers to the Royal Society, at the Princes Arms in St Paul’s Churchyard, 1704.

[286] M.J. Sparnaay, The historical background of the Casimir effect, in: A. Sarlemijin, M.J. Sparnaay (Eds.), Physics in the Making, Essays on Developments in 20th Century Physics in Honour of H.B.G. Casimir, North-Holland, Amsterdam, 1989, pp. 235–246.

[287] J. Tyndall, On Whitworth’s plates, standard measures, and guns, Proc. R. Inst. Great Brit. 7 (1875) 524–539.

[288] N. Rosenberg, Technological change in the machine tool industry, 1840–1910, J. Econ. Hist. 23 (4) (1963) 414–443.

[289] T.K. Althin, E. Carl, Johannson 1864–1943. The Master of Measurement, Nordisk Rotogravyr, Stockholm, 1948.

[290] G.J. Siddall, P.C.T. Willey, Flat-surface wringing and contact error variability, J. Phys. D: Appl. Phys. 3 (1970) 8–28.

[291] H. Matsumoto, L. Zeng, Simple compensation method for wringing errors in the interferometric calibration of gauge blocks, Metrologia 33 (1996) 1–4.

[292] D.R. Lide, A Century of Excellence in Measurements, Standards, and Technology (NIST Spec. Publ. 958 – U. S. Government), CRC Press, Boca Raton, FL, 2002.

[293] H.M. Budgett, The adherence of flat surfaces, Proc. Roy. Soc. A 86 (1912) 25–36.

[294] H.M. Budgett, The Adherence of Flat Surfaces, Sci. Am. 73 (1912) 30–31. Suppl 1880.

[295] F.H. Rolt, H. Barrell, Contact of flat surfaces, Proc. Roy. Soc. (London). Ser. A 116 (1927) 401–425.

[296] A. P´erard, L. Maudet, Etudes sur les Etalons a Bouts, Trav. et Mem. Bur. Int. 17 (5) (1927) 1–97.

[297] C.F. Bruce, B.S. Thornton, Adhesion and contact error in length metrology, J. Appl. Phys. 27 (1956) 853–859.

[298] C.G. Peters, H.S. Boyd, Interference mthods for standardizing and testing precision gage blocks, Sci. Pap. Bureau Stand. 17 (1922) 677–713.

[299] R.K. Vegesna, R.J. Hocken, A study of gage block wringing, in: Proceedings of the American Society for Precision Engineering, 9–14 October, 2005, Norfolk, VA, vol. 37, 2005, pp. 37–40.

[300] F. Pinto, Nanomechanical sensing of gravitational wave-induced Casimir force perturbations, Int. J. Mod. Phys. D 23 (12) (2014), 1442001.

[301] B. Bhushan (Ed.), Handbook of Nanotechnology, Springer, New York, 2007.

[302] G. Binnig, H. Rohrer, The scanning tunneling microscope, Sci. Am. 253 (1985) 50–56.

[303] G. Binnig, H. Rohrer, C. Gerber, E. Weibel, Surface studies by scanning tunneling microscopy, Phys. Rev. Lett. 49 (1) (1982) 57–61.

[304] G. Binnig, H. Rohrer, C. Gerber, E. Weibel, Tunneling through a controllable vacuum gap, Appl. Phys. Lett. 40 (1982) 178–180.

[305] G. Binnig, C.F. Quate, Atomic force microscope, Phys. Rev. Lett. 56 (9) (1986) 930–933.

[306] F.J. Giessibl, Advances in atomic force microscopy, Rev. Mod. Phys. 75 (2003) 949–983.

[307] Y. Martin, C.C. Williams, H.K. Wickramasinghe, Atomic force microscope—force mapping and profiling on a sub 100-A scale, J. Appl. Phys. 61 (1987) 4723–4729.

[308] H.K. Wickramasinghe, Scanned-probe microscopes, Sci. Am. 261 (4) (1989) 98–105.

[309] R. Wiesendanger, Scanning Probe Microscopy and Spectroscopy, Cambridge University Press, Cambridge, 1994.

[310] D. Sarid, Exploring Scanning Probe Microscopy with Mathematica, John Wiley & Sons, Inc, New York, 1997.

[311] D. Bonnell (Ed.), Scanning Probe Microscopy and Spectroscopy, Wiley-VCH, New York, 2001.

[312] J.L. Hutter, J. Bechhoefer, Manipulation of van der Waals forces to improve image resolution in atomic-force microscopy, J. Appl. Phys. 73 (9) (1993) 4123–4129.

[313] T.R. Albrecht, C.F. Quate, Atomic resolution with the atomic force microscope on conductors and nonconductors, J. Vac. Sci. Technol. A 6 (1988) 271–274.

[314] U. Durig, J.K. Gimzewski, D.W. Pohl, Experimental observation of forces acting during scanning tunneling microscopy, Phys. Rev. Lett. 57 (1986) 2403–2406.

[315] A.L. Weisenhorn, P.K. Hansma, T.R. Albrecht, C.F. Quate, Forces in atomic force microscopy in air and water, Appl. Phys. Lett. 54 (1989) 2651–2653.

[316] N.A. Burnham, D.D. Dominguez, R.L. Mowery, R.J. Colton, Probing the surface forces of monolayer films with an atomic-force microscope, Phys. Rev. Lett. 64 (16) (1990) 1931–1934.

[317] W.A. Ducker, R.F. Cook, Rapid measurement of static and dynamic surface forces, Appl. Phys. Lett. 56 (1990) 2408–2410.

[318] W.A. Ducker, T.J. Senden, R.M. Pashley, Measurement of forces in liquids using a force microscope, Langmuir 8 (1992) 1831–1836.

[319] H.-J. Butt, A technique for measuring the force between a colloidal particle in water and a bubble, J. Colloid Interface Sci. 166 (1994) 109–117.

[320] M. Pierce, J. Stuart, A. Pungor, P. Dryden, V. Hlady, Adhesion force measurements using an atomic force microscope upgraded with a linear position sensitive detector, Langmuir 10 (9) (1994) 3217–3221.

[321] C. Argento, R.H. French, Parametric tip model and force–distance relation for Hamaker constant determination from atomic force microscopy, J. Appl. Phys. 80 (11) (1996) 6081–6090.

[322] M.G. Millis, NASA breakthrough propulsion physics program, Acta Astronautica 44 (216) (1999) 175–182.

[323] M. Bordag, G.L. Klimchitskaya, U. Mohideen, V.M. Mostepanenko, Advances in the Casimir Effect, Oxford University Press, Oxford, 2009.

[324] U. Mohideen, A. Roy, Precision measurement of the Casimir force from 0.1 to 0.9 μm, Phys. Rev. Lett. 81 (1998) 4549–4552.

[325] W.J. Kim, U.D. Schwarz, Potential contributions of noncontact atomic force microscopy for the future Casimir force measurements, J. Vac. Sci. Technol. B 28 (2010) C4A1.

[326] H.J.D.L. Santos, Nanoelectromechanical quantum circuits and systems, Proc. IEEE 91 (11) (2003) 1907–1921.

[327] M. Bordag, U. Mohideen, V.M. Mostepanenko, New developments in the Casimir effect, Phys. Rep. 353 (2001) 1–205.

[328] The Casimir force: background, experiments, and applications, Rep. Prog. Phys. 68 (2004) 201–236.

[329] V.A. Parsegian, Van der Waals Forces, Cambridge University Press, Cambridge, 2006.

[330] T. Fukuda, F. Arai, Assembly of nanodevices with carbon nanotubes through nanorobotic manipulations, Proc. IEEE 9 (11) (2003) 1803–1818.

[331] B.J. Nelson, L. Dong, Nanorobotics, in: B. Bhushan (Ed.), Handbook of Nanotechnology, Springer, New York, 2007 (Chapter 49).

[332] D.M. Eigler, E.K. Schweizer, Positioning single atoms with a scanning tunnelling microscope, Nature 344 (1990) 524–526.

[333] P. Avouris, Manipulation of matter at the atomic and molecular levels, Acc. Chem. Res. 28 (3) (1995) 95–102.

[334] L. Sun, L. Wang, W. Rong, L. Chen, Considering van der Waals forces in micromanipulation design, in: 2007 IEEE International Conference on Mechatronics and Automation, IEEE, Harbin, China, 2007, pp. 2507–2512.

[335] T. Hertel, R. Martel, P. Avouris, Manipulation of individual carbon nanotubes and their interaction with surfaces, J. Phys. Chem. B 102 (6) (1998) 910–915.

[336] F. Arai, D. Ando, T. Fukuda, Y. Nonoda, T. Oota, Micro manipulation based on micro physics, in: Proceedings of 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots, IEEE, Pittsburgh, PA, USA, 1995, pp. 236–241.

[337] L. Zhang, J. Cecil, D. Vasquez, J. Jones, B. Garner, Modeling of van der Waals forces during the assembly of micro devices, in: 2006 IEEE International Conference on Automation Science and Engineering, IEEE, Shanghai, China, 2006, pp. 484–489.

[338] P.a. Williams, S.J. Papadakis, M.R. Falvo, A.M. Patel, M. Sinclair, A. Seeger, A. Helser, R.M. Taylor, S. Washburn, R. Superfine, Controlled placement of an individual carbon nanotube onto a microelectromechanical structure, Appl. Phys. Lett. 80 (14) (2002) 2574.

[339] P. Kim, Nanotube nanotweezers, Science 286 (5447) (1999) 2148–2150.

[340] S. Akita, Y. Nakayama, S. Mizooka, Y. Takano, T. Okawa, Y. Miyatake, S. Yamanaka, M. Tsuji, T. Nosaka, Nanotweezers consisting of carbon nanotubes operating in an atomic force microscope, Appl. Phys. Lett. 79 (11) (2001) 1691–1693.

[341] L. Dong, F. Arai, T. Fukuda, 3D nanorobotic manipulation of nano-order objects inside SEM, in: Proceedings of 2000 International Symposium on Micromechatronics and Human Science (MHS2000) (Cat. No.00TH8530), IEEE, Nagoya, Japan, 2000, pp. 151–156.

[342] A. Ummat, A. Dubey, G. Sharma, C. Mavroidis, Nanorobotics, IEEE Trans. Nanobiosci. 4 (2005) 133–140.

[343] M. Calis, M. Desmulliez, Haptic sensing for MEMS with application for cantilever and Casimir effect, in: 2008 Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS, no. April, IEEE, 2008, pp. 80–84.

[344] L. Dong, F. Arai, T. Fukuda, 3D nanoassembly of carbon nanotubes through nanorobotic manipulations, in: Proceedings of 2002 IEEE International Conference on Robotics and Automation (Cat. No.02CH37292), vol. 2, IEEE, Washington, DC, 2002, pp. 1477–1482.

[345] M.-f. Yu, B.I. Yakobson, R.S. Ruoff, Controlled sliding and pullout of nested shells in individual multiwalled carbon nanotubes, J. Phys. Chem. B 104 (37) (2000) 8764–8767.

[346] B.H. Hong, J.P. Small, M.S. Purewal, A. Mullokandov, M.Y. Sfeir, F. Wang, J.Y. Lee, T.F. Heinz, L.E. Brus, P. Kim, K.S. Kim, Extracting subnanometer single shells from ultralong multiwalled carbon nanotubes, Proc. Natl. Acad. Sci. USA 102 (40) (2005) 14155–14158.

[347] M. Falvo, R.M.I. Taylor, S. Washburn, Nanomanipulation: buckling, transport, and rolling at the nanoscale, in: W.A.I. Goddard, D.W. Brenner, S.E. Lyshevski, G.J. Iafrate (Eds.), Handbook of Nanoscience, Engineering, and Technology, CRC Press LLC, Boca Raton, FL, 2003 (Chapter 13).

[348] C. Mody, Crafting the tools of knowledge: The invention, spread, and commercialization of probe microscopy, 1960-2000, Ph.D. thesis, Cornell University, 2004.

[349] C.C.M. Mody, Instrumental Community: Probe Microscopy and the Path to Nanotechnology, The MIT Press, Cambridge, MA, 2011.

[350] M.G. Ruppert, A.G. Fowler, M. Maroufi, S.O.R. Moheimani, On-chip dynamic mode atomic force microscopy: a silicon-on-insulator MEMS approach, J. Microelectromech. Syst. 26 (1) (2016) 215–225.

[351] M. Maroufi, S.O.R. Moheimani, An SOI-MEMS piezoelectric torsional stage with bulk piezoresistive sensors, IEEE Sens. J. 17 (10) (2017) 3030–3040.

[352] M.B. Coskun, A.G. Fowler, M. Maroufi, S.O.R. Moheimani, On-chip feedthrough cancellation methods for microfabricated AFM cantilevers with integrated piezoelectric transducers, J. Microelectromech. Syst. 26 (6) (2017) 1287–1297.

[353] M. Rice, The Single-Chip Atomic Force Microscope, (2016).

[354] H.B. Chan, V.A. Aksyuk, R.N. Kleiman, D.J. Bishop, F. Capasso, Quantum mechanical actuation of microelectromechanical systems by the Casimir force, Science 291 (2001) 1941–1944.

[355] H. Chan, V. Aksyuk, R. Kleiman, D. Bishop, F. Capasso, Nonlinear micromechanical Casimir oscillator, Phys. Rev. Lett. 87 (21) (2001) 21–24.

[356] T.W. Kenny, Nanometer-scale force sensing with MEMS devices, IEEE Sens. J. 1 (2) (2001) 148–157.

[357] D. Lopez, R.S. Decca, E. Fischbach, D.E. Krause, MEMS-based force sensor: design and applications, Bell Labs Tech. J 10 (3) (2005) 61–80.

[358] E.L. Carter, M. Ward, C. Anthony, Design and fabrication of novel devices using the Casimir force for non-contact actuation, in: 2009 IEEE Sensors, 2009.

[359] C. Yamarthy, S. McNamara, Design of a MEMS sensor to detect the Casimir force, in: 2009 4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, IEEE, Shenzhen, China, 2009, pp. 645–648.

[360] R. Ardito, B.D. Masi, A. Frangi, A. Corigliano, An on-chip experimental assessment OF Casimir force effect in micro-electromechanical systems, in: 11th International Conference on Thermal, Mechanical and Multiphysics Simulation and Experiments in Micro-Electronics and Micro-Systems, EuroSimE2010, Proceedings of a Meeting Held 26–28 April 2010, Bordeaux, France, IEEE, Bordeaux, France, 2010, pp. 1–8.

[361] H. Xie, C. Onal, S. Regner, M. Sitti, Atomic Force Microscopy Based Nanorobotics: Modelling, Simulation, Setup Building and Experiments, 2012th ed., Springer Tracts in Advanced Robotics, vol. 71, Springer-Verlag, Berlin, Heidelberg, 2012.

[362] K. Autumn, How Gecko Toes Stick, Am. Sci. 94 (March-April) (2006) 124–132.

[363] C. Greiner, Gecko inspired nanomaterials, in: C.S.S.R. Kumar (Ed.), Nanomaterials for the Life Sciences Vol. 7: Biomimetic and Bioinspired Nanomaterials, first ed., Wiley-VCH, Weinheim, 2010, pp. 1–39 (Chapter 1).

[364] E.P. Chan, C. Greiner, E. Arzt, A.J. Crosby, Designing model systems for enhanced adhesion, MRS Bull. 32 (2007) 496–503.

[365] A. del Campo, E. Arzt, Design parameters and current fabrication approaches for developing bioinspired dry adhesives, Macromol. Biosci. 7 (2007) 118–127.

[366] A. Mahdavi, L. Ferreira, C. Sundback, J.W. Nichol, E.P. Chan, D.J.D. Carter, C.J. Bettinger, S. Patanavanich, L. Chignozha, E. Ben-Joseph, A. Galakatos, H. Pryor, I. Pomerantseva, P.T. Masiakos, W. Faquin, A. Zumbuehl, S. Hong, J. Borenstein, J. Vacanti, R. Langer, J.M. Karp, A biodegradable and biocompatible gecko-inspired tissue adhesive, Proc. Natl. Acad. Sci. USA 105 (7) (2008) 2307–2312.

[367] E.H. Jeong, K.Y. Suh, Nanohairs and nanotubes: efficient structural elements for gecko-inspired artificial dry adhesives, Nano Today 4 (2009) 335–346.

[368] M.D. Bartlett, A.B. Croll, A.J. Crosby, Designing bio-inspired adhesives for shear loading: from simple structures to complex patterns, Adv. Funct. Mater. 22 (2012) 4985–4992.

[369] D.R. King, M.D. Bartlett, C.A. Gilman, D.J. Irschick, A.J. Crosby, Creating Gecko-like adhesives for "real world" surfaces, Adv. Mater. 26 (2014) 4345–4351.

[370] K. Autumn, M. Sitti, Y.a. Liang, A.M. Peattie, W.R. Hansen, S. Sponberg, T.W. Kenny, R.S. Fearing, J.N. Israelachvili, R.J. Full, Evidence for van der Waals adhesion in gecko setae, Proc. Natl. Acad. Sci. USA 99 (19) (2002) 12252–12256.

[371] K. Autumn, N. Gravish, Gecko adhesion: evolutionary nanotechnology, Phil. Trans. R. Soc. A 366 (1870) (2008) 1575–1590.

[372] Aristotle, History of Animals, Translated by D'Arcy Wentworth Thompson, (1910).

[373] Aristotle, History of Animals, George Bell & Sons, London, 1883.

[374] M.D.F. Mahan, The Chicago Manual of Style, 15th ed., The University of Chicago Press, Chicago, 2003.

[375] R.G. Feal, MLA Handbook for Writers of Research Papers, seventh ed., The Modern Language Association of America, New York, 2009.

[376] G.R. VandenBos, Publication Manual of the American Psyhological Association, sixth ed., American Psychological Association, London, 2010.

[377] J.M. Hurwit, Lions, lizards, and the uncanny in early Greek art, Hesperia 75 (2006) 121–136.

[378] J.E. Murdoch, Aristotle on Democritus's argument against infinite divisibility in De generatione et corruptione, in: The Commentary Tradition on Aristotle's 'De generatione et corruptione.' Ancient, Medieval and Early Modern, Brepols Publishers, 1999, pp. 87–102 (Book I, Chapter 2).

[379] M. Cresswell, On some of Aristotle's arguments against atomism, Prudentia 32 (2000) 99–117.

[380] P.S. Hasper, Aristotle's diagnosis of atomism, Apeiron 39 (2006) 121–156.

[381] O. Keller, Die antike Tiervelt, vol. 2, Verlag von Wilhelm Engelmann, Leipzig, 1913.

[382] E.R. Valdes, Bio-inspired materials and operations, in: R.E. Armstrong, M. Drapeau, C.A. Loeb, J.J. Valdes (Eds.), Bio-inspired Innovation and Bio-inspired Innovation and National Security, National Defense University Press, Washington, DC, 2010, pp. 139–154 (Chapter 9).

[383] S. Kundu, Dry adhesive inspired by geckos now on the market, Forbes (2015) 3–4.

[384] B.W. Ninham, Long-range vs. short-range forces. The present state of play, J. Phys. Chem. 84 (12) (1980) 1423–1430.

[385] Y. Chen, H.J. Busscher, H.C.V.D. Mei, W. Norde, Statistical analysis of long- and short-range forces involved in bacterial adhesion to substratum surfaces as measured using atomic force microscopy, Appl. Environ. Microbiol. 77 (15) (2011) 5065–5070.

[386] M. Kunitski, Observation of the Efimov state of the helium trimer, Science 348 (2015) 954–959.

[387] P. Naidon, S. Endo, Efimov physics: a review, Rep. Prog. Phys. 80 (2017) 056001.

[388] R.H. French, V.A. Parsegian, R. Podgornik, R.F. Rajter, A. Jagota, J. Luo, D. Asthagiri, M.K. Chaudhury, Y.M. Chiang, S. Granick, S. Kalinin, M. Kardar, R. Kjellander, D.C. Langreth, J. Lewis, S. Lustig, D. Wesolowski, J.S. Wettlaufer, W.Y. Ching, M. Finnis, F. Houlihan, O.A. Von Lilienfeld, C.J. Van Oss, T. Zemb, Long range interactions in nanoscale science, Rev. Mod. Phys. 82 (2) (2010) 1887–1944.

[389] K. Autumn, M. Buehler, M. Cutkosky, R. Fearing, R.J. Full, Robotics in scansorial environments, in: G.R. Gerhart, C.M. Shoemaker, D.W. Gage (Eds.), Proc. SPIE, Unmanned Ground Vehicle Technology VII, Bellingham, WA, vol. 5804, 2005, pp. 291–302.

[390] S. Kim, M. Spenko, S. Trujillo, B. Heyneman, D. Santos, M.R. Cutkosky, Smooth vertical surface climbing with directional adhesion, IEEE Trans. Robot. 24 (1) (2008) 65–74.

[391] J. Socha, J. Gubich, Biomechanically inspired robotics, in: R.E. Armstrong, M. Drapeau, C.A. Loeb, J.J. Valdes (Eds.), Bio-inspired Innovation and Bio-inspired Innovation and National Security, National Defense University Press, Washington, DC, 2010, pp. 195–206 (Chapter 13).

[392] M. Henrey, J. Krahn, A. Ahmed, K. Wormnes, C. Menon, Climbing with structured dry adhesives: sticky robots for scaling smooth vertical surfaces, in: 12th Symposium on Advanced Space Technologies in Robotics and Automation ASTRA 2013, ESA/ESTEC (15–17 May), Noordwijk, The Netherlands, 2013, pp. 1–6.

[393] E.W. Hawkes, E.V. Eason, D.L. Christensen, M.R. Cutkosky, Human climbing with efficiently scaled gecko-inspired dry adhesives, J. R. Soc. Interface 12 (102) (2015) 20140675.

[394] B. Newman, Stanford University students create 'gecko gloves' that allow humans to scale glass walls, http://www.smh.com.au/technology/sci-tech/stanford-university-students-create-gecko-gloves-that-allow-humans-to-scale-glass-walls-20141226-12dx31.html, 2014.

[395] C. Menon, M. Murphy, M. Sitti, N. Lan, Space exploration – towards bio-incpired climbing robots, in: M.K. Habib (Ed.), Bioinspiration and Robotics: Walking and Climbing Robots, InTech, Rijeka, Croatia, 2007, pp. 261–278 (Chapter 16).

[396] A. Parness, Micro-structured adhesives for climbing applications, Ph.D. thesis, Stanford University, 2009.

[397] M. Henrey, Climbing in space: Design and implementation of a hexapod robot using dry adhesives, Ph.D. thesis, Simon Fraser University, 2013.

[398] M. Henrey, K. Wormnes, L. Pambaguian, C. Menon, Sticking in space: manufacturing dry adhesvies and testing their performance in space environments, in: 12th Symposium on Adv. Space Technologies in Robotics and Automation, 2013, pp. 1–7.

[399] H. Jiang, E.W. Hawkes, V. Arutyunov, J. Tims, C. Fuller, J.P. King, C. Seubert, H.L. Chang, A. Parness, M.R. Cutkosky, Scaling controllable adhesives to grapple floating objects in space, in: IEEE International Conference on Robotics and Automation (ICRA), IEEE, Seattle, Washington, 2015, pp. 1–8.

[400] H. Jiang, E.W. Hawkes, C. Fuller, M.A. Estrada, S.A. Suresh, N. Abcouwer, A.K. Han, S. Wang, C.J. Ploch, A. Parness, M.R. Cutkosky, A robotic device using gecko-inspired adhesives can grasp and manipulate large objects in microgravity, Sci. Robot. 2 (2017). eaan4545.

[401] A. Parness, T. Hilgendorf, P. Daniel, M. Frost, V. White, B. Kennedy, Controllable ON-OFF adhesion for Earth orbit grappling applications, in: 2013 IEEE Aerospace Conference, IEEE Comput. Soc, Big Sky, MT, 2013, pp. 1–11.

[402] M. Tomczyk, Nanoinnovation, Wiley-VCH, Germany, 2014.

[403] T. Rueckes, Mechanical and electromechanical studies toward the assembly of carbon nanotube-based non-volatile random access memory, Ph.D. thesis, Harvard University, 2001.

[404] J.W. Ward, M. Meinhold, B.M. Segal, J. Berg, R. Sen, R. Sivarajan, D.K. Brock, T. Rueckes, A non-volatile nano-electromechanical memory element utilizing a fabric of carbon nanotubes, in: Proceedings of Non-Volatile Memory Technol. Symp. 15–17 November 2004, IEEE, 2004, pp. 34–38.

[405] M.F.L. De Volder, S.H. Tawfick, R.H. Baughman, A.J. Hart, Carbon nanotubes: present and future commercial applications, Science 339 (2013) 535–539.

[406] O. Kuusi, M. Meyer, Anticipating technological breakthroughs: using bibliographic coupling to explore the nanotubes paradigm, Scientometrics 70 (3) (2007) 759–777.

[407] Y. Zhang, Carbon nanotube based nonvolatile memory devices, Int. J. High Speed Electron. Syst. 16 (4) (2006) 959–975.

[408] B.R. Karam, R. Puri, S. Ghosh, S. Bhunia, Emerging trends in design and applications of memory-based computing and content-addressable memories, Proc. IEEE 103 (2015) 1311–1330.

[409] D. Johnson, Carbon nanotube memory company's ship may finally come in, IEEE Spectrum (2017) 1–4.

[410] R.O. van Merkerk, H. van Lente, Tracing emerging irreversibilities in emerging technologies: the case of nanotubes, Technol. Forecast. Soc. Change 72 (2005) 1094–1111.

[411] R.L. Forward, Alternate Propulsion Energy Sources, Final Report for the period 3 March 1983 to 21 September 1983, AFRPL TR-83-067, Tech. rep.Edwards Air Force Base, Air Force Rocket Propulsion Laboratory, 1983

[412] R. García, A. San Paulo, Attractive and repulsive tip-sample interaction regimes in tapping-mode atomic force microscopy, Phys. Rev. B 60 (7) (1999) 4961–4967.
[413] A. Raman, J. Melcher, R. Tung, Cantilever dynamics in atomic force microscopy, Nanotoday 3 (1) (2008) 20–27.
[414] H.V. Guzman, P.D. Garcia, R. Garcia, Dynamic force microscopy simulator (dForce): a tool for planning and understanding tapping and bimodal AFM experiments, Beilstein J. Nanotechnol. 6 (2015) 369–379.
[415] S.I. Lee, S.W. Howell, A. Raman, A. Reifenberger, Nonlinear dynamics of microcantilevers in tapping mode atomic force microscopy: a comparison between theory and experiment, Phys. Rev. B 66 (2002) 115409.
[416] K. Yagasaki, Nonlinear dynamics of vibrating microcantilevers in tapping-mode atomic force microscopy, Phys. Rev. B 70 (2004) 245419.
[417] S. Hudlet, M.S. Jean, C. Guthmann, J. Berger, Evaluation of the capacitive force between an atomic force microscopy tip and a metallic surface, Eur. Phys. J. B 2 (1998) 5–10.
[418] B.M. Law, F. Rieutord, Electrostatic forces in atomic force microscopy, Phys. Rev. B 66 (2002) 035402.
[419] S. Guriyanova, Cantilever contribution to the total electrostatic force measured with the atomic force microscope, Meas. Sci. Technol. 21 (2010) 025502.
[420] G.V. Dedkov, A.A. Kanametov, E.G. Dedkova, Electrostatic and van der Waals forces in the air contact between the atomic force microscope probe and a conducting surface, Tech. Phys. 54 (12) (2009) 1801–1807.
[421] B.M. Axilrod, E. Teller, Interaction of the van der Waals type between three atoms, J. Chem. Phys. 11 (6) (1943) 299–300.
[422] G. Feinberg, J. Sucher, General theory of the van der Waals interaction: a model-independent approach, Phys. Rev. A 2 (6) (1970) 2395–2415.
[423] C. Farina, F.C. Santos, A.C. Tort, A simple model for the nonretarded dispersive force between an electrically polarizable atom and a magnetically polarizable one, Am J. Phys. 70 (2001) 421–423.
[424] C. Farina, F.C. Santos, A.C. Tort, On the force between an electrically polarizable atom and a magnetically polarizable one, J. Phys. A: Math. Gen. 35 (2002) 2477–2482.
[425] T.H. Boyer, Quantum electromagnetic zero-point energy of a conducting spherical shell and the Casimir model for a charged particle, Phys. Rev. 174 (5) (1968) 1764–1776.
[426] H.B.G. Casimir, Introductory remarks on quantum electrodynamics, Physica 19 (1953) 846–849.
[427] T.H. Boyer, Van der Waals forces and zero-point energy for dielectric and permeable materials, Phys. Rev. A 9 (5) (1974) 2078–2084.
[428] V. Hushwater, Repulsive Casimir force as a result of vacuum radiation pressure, Am. J. Phys. 65 (5) (1997) 381–384.
[429] E. Elizalde, A. Romeo, Essentials of the Casimir effect and its computation, Am. J. Phys. 59 (8) (1991) 711–719.
[430] J. Visser, The concept of negative Hamaker coefficients. I. History and Present Status, Adv. Coll Interf. Sci. 15 (1981) 157–169.
[431] C. Farina, F.C. Santos, A.C. Tort, A simple way of understanding the nonadditivity of van der Waals dispersion forces, Am. J. Phys. 67 (4) (1999) 344–349.
[432] A. Milling, P. Mulvaney, I. Larson, Direct measurement of repulsive van der Waals interactions using an atomic force microscope, J. Colloid Interface Sci. 465 (1996) 460–465.
[433] J. Visser, Colloid and surface chemistry, Rep. Progr. Appl. Chem. 53 (1968) 714.
[434] D.B. Hough, L.R. White, The calculation of Hamaker constants from Lifshitz theory with applications to wetting phenomena, Advan. Colloid Interface Sci. 14 (1980) 3–41.
[435] F.M. Fowkes, Intermolecular and interatomic forces at interfaces, in: J.J. Burke, N.L. Reed, V. Weiss (Eds.), Proc. Sagamore Army Mater. Res. Conf. 13th 1966, vol. I, Syracuse University Press, Syracuse, NY, USA, 1967, pp. 197–224.

[436] J. Visser, On Hamaker constants: a comparison between Hamaker constants and Lifshitz – van der Waals constants, Adv. Colloid Interface Sci. 3 (1972) 331–363.
[437] A..W. Neumann, S.N. Omenyi, C. van Oss, Negative Hamaker coefficients I. Particle engulfment or rejection at solidification fronts, Colloid Polym. Sci. 257 (1979) 413–419.
[438] C.J. van Oss, S.N. Omenyi, A.W. Neumann, Negative Hamaker coefficients II. Phase separation of polymer solutions, Colloid Polym. Sci. 257 (1979) 737–744.
[439] F.M. Fowkes, Attractive forces at interfaces, Ind. Eng. Chem. Res. 56 (1964) 40–52.
[440] D. Blake, Investigation of equilibrium wetting films of n-alkanes on α-alumina, J. Chem. Soc. Faraday Trans. 1 (71) (1975) 192–208.
[441] M.L. Gee, T.W. Healy, L.R. White, Ellipsometric studies of alkane adsorption on quartz, J. Colloid Interface Sci. 131 (1) (1989) 18–23.
[442] Y. Pomeau, E. Villermaux, Two hundred years of capillarity research, Phys. Today 59 (3) (2006) 39–44.
[443] R.J. Hunter, Foundations of Colloid Science, second ed., Oxford University Press, Oxford, 2009.
[444] J. Visser, The concept of negative Hamaker coefficients. II. Thermodynamics, experimental evidence and applications, Adv. Colloid Interface Sci. 18 (1983) 133–148.
[445] A. Meurk, P.F. Luckham, L. Bergström, Direct measurement of repulsive and attractive van der Waals forces between inorganic materials, Langmuir 13 (13) (1997) 3896–3899.
[446] S. Lee, Repulsive van der Waals forces for silica and alumina, J. Colloid Interface Sci. 243 (2) (2001) 365–369.
[447] B. Young, K. Cho, R. Wartena, S.M. Tobias, Y.-m. Chiang, Self-assembling colloidal-scale devices: selecting and using short-range surface forces between conductive solids, Adv. Funct. Mater. 17 (2007) 379–389.
[448] Much ado about nothing, May 24th-30th, 2008, Economist, 2008, 105.
[449] T.W. Kenny, Casimir Effect Enhancement (CEE), Broad Agency Announcement (DARPA-BAA-08-59), DARPA, Arlington, VA, 2008.
[450] F. Chen, U. Mohideen, G.L. Klimchitskaya, V.M. Mostepanenko, Experimental and theoretical investigation of the lateral Casimir force between corrugated surfaces, Phys. Rev. A 66 (2002) 032113.
[451] F. Chen, U. Mohideen, G.L. Klimchitskaya, V.M. Mostepanenko, Demonstration of the lateral Casimir force, Phys. Rev. Lett. 88 (2002) 101801.
[452] A.W. Rodriguez, J.D. Joannopoulos, S.G. Johnson, Repulsive and attractive Casimir forces in a glide-symmetric geometry, Phys. Rev. A 77 (2008) 062107.
[453] H. Van Der Auweraer, J. Anthonis, S. De Bruyne, J. Leuridan, Virtual engineering at work: the challenges for designing mechatronic products, Eng. Comput. 29 (2013) 389–408.
[454] H.G. Lemu, Virtual engineering in design and manufacturing, Adv. Manuf. 2 (2014) 289–294.
[455] P. Lethbridge, Multiphysics analysis, Ind. Phys. (2005) 28–31.
[456] G. Chrystal, Algebra: An Elementary Text-Book, seventh Edition, AMS Chelsea Pub, 1964.
[457] G. Brookfield, Factoring quartic polynomials: a lost art, Math. Magaz. 80 (1) (2007) 67–70.
[458] W. Squire, Landen's solution of the cubic, Am. J. Phys. 55 (1987) 374–375.
[459] W.H. Press, S.A. Teukolski, W.T. Vetterling, B.P. Flannery, Numerical Recipes in FORTRAN, 2nd ed., Cambridge University Press, Cambridge, 1992.
[460] P. Hut, J. Makino, S. McMillan, Building a better leapfrog, Astrophys. J. 443 (1995) L93–L96.
[461] C. Gauld, Pendulums in the physics education literature: a bibliography, Sci. Educ. 13 (2004) 811–832.
[462] P.G. Hewitt, Conceptual Physics, 10th ed., Addison-Wesley, San Francisco, 2006.
[463] R.A. Serway, J. Jewett, W. John, Physics, seventh ed., Thomson Brooks/Cole, Belmont, CA, 2008.
[464] C. Kittel, W.D. Knight, M.A. Ruderman, Berkeley Physics Course Vol. 1 (Mechanics), second ed., McGraw Hill Book Company, New York, 1965.
[465] W. Kaplan, Advanced Calculus, fifth ed., Addison-Wesley, Boston, 2003.
[466] C. Stoll, When slide rules ruled, Sci. Am. 294 (2006) 80–87.

[467] B. Hayes, The 100-billion-body problem, Am. Sci. 103 (2015) 90–93.
[468] F. Pinto, Parametric resonance: an introductory experiment, Phys. Teach 31 (1993) 336–346.
[469] G.L. Fowles, G.L. Cassiday, Analytical Mechanics, Thomson Brooks/Cole, Belmont, CA, 2005.
[470] E. Fermi, J. Pasta, S. Ulam, Studies of Nonlinear Problems, Los Alamos Scientific Laboratory report LA-1940, Los Alamos, NM, 1955.
[471] D. Dubin, Numerical and Analytical Methods for Scientists and Engineers Using Mathematica, Wiley-Interscience, Hoboken, NJ, 2003.
[472] T. Dauxois, M. Peyrard, S. Ruffo, The Fermi-Pasta-Ulam ’numerical experiment’: history and pedagogical perspectives, Eur. J. Phys. 26 (2005) S3–S11.
[473] T. Dauxois, Fermi, Pasta, Ulam, and a mysterious lady, Phys. Today 61 (2008) 55–57.
[474] S.M. Ulam, A Collection of Mathematical Problems, Wiley-Interscience, New York, 1960.
[475] N.J. Zabusky, Computational synergetics and mathematical innovation, J. Comp. Phys. 43 (1981) 195–249.
[476] G.P. Berman, F.M. Izrailev, The Fermi - Pasta - Ulam problem: Fifty years of progress, Chaos 15 (2005) 015104.
[477] E.M. Purcell, D.J. Morin, Electricity and Magnetism, third ed., Cambridge University Press, New York, 2013.
[478] G.E. Forsythe, Gauss to Gerling on Relaxation, Math. Tables Other Aids Comput. 5 (36) (1951) 255–258.
[479] F. Pinto, Discrepancy between published Laplace difference equations on cylindrical dielectrics, Am. J. Phys. 75 (6) (2007) 513–519.
[480] A.M. Ostrowski, On Gauss’ speeding up device in the theory single step iteration, Math. Tables Other Aids Comput. 12 (1958) 116–132.
[481] A.W. Rodriguez, M. Ibanescu, D. Iannuzzi, F. Capasso, J.D. Joannopoulos, S.G. Johnson, Computation and visualization of Casimir forces in arbitrary geometries: nonmonotonic lateral-wall forces and the failure of proximity-force approximations, Phys. Rev. Lett. 99 (8) (2007) 080401.
[482] A.W. Rodriguez, M. Ibanescu, D. Iannuzzi, J.D. Joannopoulos, S.G. Johnson, Virtual photons in imaginary time: computing exact Casimir forces via standard numerical electromagnetism techniques, Phys. Rev. A 76 (3) (2007) 032106.
[483] S.G. Johnson, Numerical Methods for Computing Casimir Interactions, in: D. Dalvit et al., (Ed.), Casimir Physics, Lecture Notes in Physics, vol. 834, Springer-Verlag, Heidelberg, 2011, pp. 175–218.
[484] M. Levin, A. McCauley, A.W. Rodriguez, M. Reid, S.G. Johnson, Casimir repulsion between metallic objects in vacuum, Phys. Rev. Lett. 105 (9) (2010) 090403.
[485] S.A. Ellingsen, Casimir attraction in multilayered plane parallel magnetodielectric systems, J. Phys. A 40 (2007) 1951–1961.
[486] M.F. Maghrebi, S. Jamal, T. Emig, N. Graham, R.L. Jaffe, M. Kardar, Analytical results on Casimir forces for conductors with edges and tips, PNAS 108 (17) (2011) 6867–6871.
[487] F. Pinto, Improved finite-difference computation of the van der Waals force: one-dimensional case, Phys. Rev. A 80 (2009) 042113.
[488] F. Pinto, Finite difference computation of Casimir forces, J. Phys.: Conf. Ser. 738 (2016) 012134.
[489] Wolfram Research, Inc., Mathematica (2018).
[490] F. Pinto, Casimir force computations in non-trivial geometries using Mathematica, in: International Mathematica User Conference 2008, Champagne, IL, USA, 2008.
[491] I. Mirman, D. Flanders, Leveraging mainstream design and analysis tools for MEMS, in: 2004 IEEE/SEMI Advanced Semiconductor Manufacturing Conference and Workshop (IEEE Cat. No. 04CH37530), 2004, pp. 187–192.
[492] R.C. Batra, M. Porfiri, D. Spinello, Review of modeling electrostatically actuated microelectromechanical systems, Smart Mater. Struct. 16 (6) (2007) R23–R31.
[493] A. Pantano, D. M. Parks, M.C. Boyce, Mechanics of deformation of single- and multi-wall carbon nanotubes, J. Mech. Phys. Solids 52 (4) (2004) 789–821.

[494] L. Tang, M. Wang, C.Y. Ng, M. Nikolic, C.T. Chan, A.W. Rodriguez, H.B. Chan, Measurement of non-monotonic Casimir forces between silicon nanostructures, Nat. Photon. 11 (January) (2017) 97–102.
[495] M.E. Porter, Competitive Advantage, The Free Press, New York, 1985.
[496] B.Y.O. Gadiesh, J.L. Gilbert, Profit pools: a fresh look at strategy, Harvard Bus. Rev. 76 (5-6) (1998) 139–148.
[497] O. Gadiesh, J.L. Gilbert, How to map your industry's profit pools, Harvard Bus. Rev. 76 (5-6) (1998) 149–162.
[498] R.M. Grant, Contemporary Strategy Analysis, seventh ed., John Wiley & Sons, Ltd, Chichester, UK, 2010.
[499] M.S.M. Alencar, A.L. Porter, A.M.S. Antunes, Nanopatenting patterns in relation to product life cycle, Technol. Forecast. Soc. Change 74 (2007) 1661–1680.
[500] LuxResearch, Sizing Nanotechnology's Value Chain, 2004, Tech. rep.Lux Research, 2004.
[501] R. Kozarsky, How do you move nano to the market? Innovation (2012) 3–5.
[502] The perils of prediction, The Economist.
[503] Starchip Enterprise, The Economist. https://www.economist.com/news/science-and-technology/21696876-interstellar-travel-means-thinking-both-very-big-and-very-small-new-plan.
[504] M.W. Browne, Physicists confirm power of nothing, measuring force of universal flux, New York Times (1997).