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EVOLUTION OF THE CONCEPT OF FORCE IN MODERN NANOSCIENCE: THE PERSPECTIVES OF THE EXPERIENTIAL LEARNING IN RESEARCH AND TEACHING PROGRAMS

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ABSTRACT. Modern society requires to efficiently identify the new trends in sustainable development and their implications in future science, research and education. One of the major challenges in nanotechnology is the education and training of a new generation of skilled workers, that request the improvement of student understanding of the concept of force within the more broad scenery of modern nanoscience. The recent advancement in nanoscience and nanotechnology evidences the powerful methods of supramolecular approaches in modern nanoscience, which are based on the complex combinations of different forces acting both at the molecular and supramolecular levels. These forces represent the driving interactions for the efficient assembly of building blocks, and for the development of highly functional materials and devices with novel properties. Herein, a review of the evolution of the concept of force in connection with modern aspect of nanotechnology is presented. A special focus is devoted to the development of modern approaches taken from the academic research programs, that allows a fruitful understanding of the myriad of scientific discoveries that have characterized these last years. In this respect, the experiential learning method can be properly designed and delivered, with particular respect to the use of bio- and nanotechnology, and in ways that help the learners to efficiently develop the knowledge and skills needed in the modern age.

1. Introduction

The formation of graduate and post-graduate teaching programs in various field of modern science require a curriculum development oriented to the integration of modern approaches of nanoscience and nanotechnology (Roco 2003; Malsch 2014). As nanoscale science and technology have an increasing impact on many aspects in our lives, the opportunities for careers are expanding rapidly. Studying science or engineering with a particular focus to the developments of modern approaches of nanoscience can provide a solid foundation for a broad range of careers. Several studies have investigated both the industrial and academic European employers, with a special focus about their needs for workers with nanotechnology education and for nanotechnology training for their work project staff (Roco 2001). European union policies has been integrating nanotechnology education in its main programs since the 2004. The European Commission Communication "towards a European strategy for nanotechnology" (Commission 2004), highlighted several needs, including promoting the interdisciplinary education and training of R&D personnel together with a stronger entrepreneurial mindset [1]" (Feather and Aznar 2010).

Nanotechnology is an interdisciplinary field which investigates the basic laws and principles responsible for the formation of complex (higher-ordered) functional structures (nanomaterials) starting from their nano-sized building blocks, like atoms and (macro)molecules (Lehn 1995; Gale and Steed 2012; Calandra *et al.* 2015a; Lombardo *et al.* 2020b). In this respect, the self-assembly process of materials represents a key strategy for the development of nano-structured systems and has become a fundamental method for the construction of novel functional materials. Such a bottom up approach has successfully used the top down approach for the fabrication processes during the last decades. However, nature has always worked bottom up, where the principles of self-assembly lead to crystal growth in the inorganic world, and, via molecular self-assembly, to functional structures in biology (Calandra *et al.* 2015a; Lombardo *et al.* 2020b).

Herein, we review the evolution of the concept of the force, highlighting its importance in recent discoveries in the field of nanoscience and nanotechnology, with a special focus on the development of modern approaches in teaching and research program.

2. The newtonian mechanics and the basic concept of force

The concept of force in Newtonian (or Classical) mechanics represents a central topic in the study of physics and scientific disciplines within the (academic) teaching and research programs. Within the both graduate and post-graduate programs, the classical concept of force is initially introduced in the three mechanical Newtonian laws (so called, "laws of motion"), that Sir Isaac Newton first presented in 1686 in his book "Principia Mathematica Philosophiae Naturalis". More specifically, the second law states that: *the acceleration (a) of an object as produced by a net force (F) is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass (m) of the object*. This law is often considered as a Newtonian definition of force, in which the force F is strictly connected with the concept of mass (m) and of the acceleration (a). The basic Newtonian concept of force, then, is intimately connected with the main effect produced by the force itself, *i.e.*, the detection (and measurement) of a change of the mechanical state of an object during its motion (or quiet state). In this respect, the first low can be considered as a particular solution of the second law of Newton, as it describe the mechanical state of an object with respect to the absence the of a force: when the force is absent (*i.e.*, $F = 0$) then the acceleration is absent ($a = 0$), and the the velosity remain constant.

According to the Newtonian concepts of force, then, the main effect of the action of a force is to cause a change in the space-time configuration of the material system (*i.e.*, a point-like object that possess a mass m). Therefore, regardless of the type of force acting on the system, (be it one of the four fundamental forces such as gravity, electrostatic, nuclear, or a more complex one) its effect is a modification of a space-time "state". The force itself may depend on different parameters, like mass (*i.e.*, for gravity force), charge (*i.e.*, in electrostatic interaction), covalent bond strength (that may be approximated by a spring

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[1] European social funds in Italy (http://ec.europa.eu/esf/main.jsp?catId=386).

force) or more complex parameters (and properties) of the investigated system. But the final result of its action is always a change in the measurable quantities of space, time, (and matter), according the exact description (mathematical equation) of the interaction between (point-like) particles.

3. Interaction in nanoscience and generalization of the concept of force

As the inter-particle forces play a crucial role in determining the structure and architecture of nanomaterials assemblies, a detailed and comprehensive study of the inter-particles interactions represent, then, the first important stage for the understanding of the complex and cooperative behaviour of advanced nanomaterials (Calandra *et al.* 2000; Lehn 2002; Dill and Bromberg 2010; Mu *et al.* 2014). The study of the inter-particles interaction represent a fundamental aspect in the investigation of the complex physics phenomena in many-body systems. Moreover, self-assembly of nanoparticles and nanostructures is a major field of research in current nanoscience, due to the unique properties of the generated materials.

Various strategies can be adopted to efficiently effort this point, within a nanoscience-based approach. More specifically, the science teaching programs can be designed in a more flexible way, with the aim of going beyond the traditional science curricula. Traditional academic science programs, especially in the first years of the university courses, focus its main interest in treating the study of a limited number of simple forces (such as, gravitational, magnetic, electrostatic, elastic, friction force, and so on), (Figure 1A). Starting from an initial configuration of (point-like) interacting particles, it is possible to solve the problem by considering pairwise interactions (between two point-like objects), in order to obtain a final configuration of the collection of objects.

In the study of modern nanoscience and nanotechnology, many other relevant forces are present (supramolecular interactions). This circumstance require the assumption of a more general conceptual framework, as it is no more possible to treat the supramolecular forces as a simple “pairwise interactions” between “point-like particles” (Figure 1B). The new conceptual framework, to be adopted in modern academic curricula, should integrate the study of the interactions treated in traditional curricula (such as the gravitational, electrostatic, elastic forces) together with a number of relevant (complex and supramolecular) interactions encountered in modern nanotechnology, such as the screened coulombic interaction (DLVO) interaction, hydrophobic effect, steric repulsion, just to name a few (Lehn 1995; Gale and Steed 2012; Lombardo *et al.* 2020b). Within this conceptual framework, the Newtonian space-time change of the (individual) particles is substituted with a more general space-time evolution of the collective behaviour of a many-body systems (starting from their initial configuration) (Hamley 2000; Podgornik *et al.* 2000a; Shimomura and Sawadaishi 2001; Hamley 2003). In this case different sites of the same molecule are able to establish multiple interactions with other components of the material system.

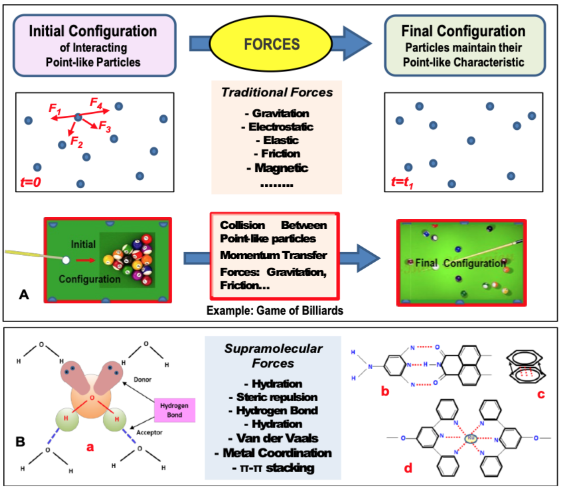


FIGURE 1. (A) Conceptual framework for the investigation of the main forces and interaction encountered in the traditional curricula of the academic disciplines in the field of condensed matter physics (practical example: game of billiard). (B) Main supramolecular forces and interaction encountered in the modern nanoscience and nanotechnology, including (multiple) hydrogen bonding (a, b), π-π stacking interaction (c) and metal coordination (d). In this case different sites of the same molecule are able to establish multiple interactions with other components of the material system.

4. Interaction and self-assembly: The objectives of an integration challenge in nanotechnology

Together with the concept of many-body interaction, the concept of self-assembly represents a central topic in modern nanoscience and nanotechnology. The combination of molecular interactions together with the ability to control both length scale and structural morphologies (Hamley 2000; Shimomura and Sawadaishi 2001; Lombardo *et al.* 2019a, 2020c), makes nanomaterials particularly interesting for the development of transdisciplinary teaching in academic research and teaching programs. The self-assembly process represents a strategy in which a disordered system with many components turns into an orderly and stable structure with a minimum energy configuration. Moreover, it represents one of the promising bottom-up methods for the design and construction of highly functional nanomaterials (Daoud and Williams 1999; Kiselev *et al.* 2001; Shimomura and Sawadaishi 2001; Lombardo *et al.* 2019a, 2020c) as well as a to test emerging properties of complex materials, as demonstarted in many investigations (Daoud and Williams 1999; Lesieur *et al.* 2000; Lombardo *et al.* 2004; Calandra *et al.* 2012; Khor *et al.* 2019; Lombardo *et al.* 2019b).

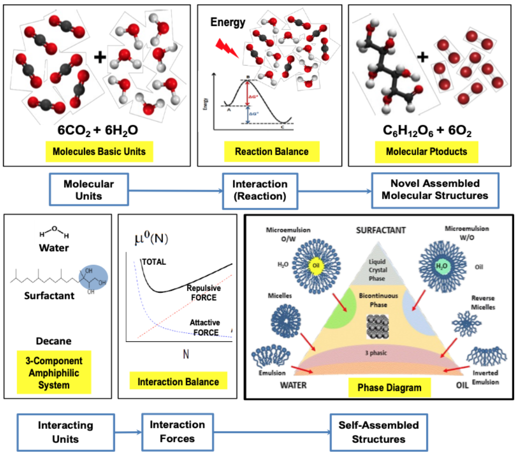


FIGURE 2. Example of two different self-assembly processes in multicomponent systems. The main features of a chemical reaction (A) shows strong similarity with the main features of a self-assembly process involving a 3 component amphiphile (sodium dodecyl sulphate - SDS).

It is possible to highlight the general aspect of the concept of self-assembly in nanoscience by making a similitude between a chemical reaction and the spontaneous formation of aggregates of amphiphilic molecules. Similarly to a chemical reaction, in fact, starting from an initial quantity of interacting basic units (initial compounds), we obtain a set of final products (aggregates), characterized by different morphologies that depends on the main system parameters (such as concentration and temperature). Moreover, it is important to point out the substantial differences, such as the reversibility/irreversibility of the two processes. In Figure 2 we compare the main steps of a chemical reaction (A) with the main features of the self-assembly process of a sodium dodecyl sulphate (SDS) amphiphile (B).

From an educational point of view, particularly interesting is the study of traditional amphiphiles such as the amphiphilic block copolymers. Together with the traditional amphiphiles, block copolymer systems represent the precursors of the molecular building blocks in modern nanotechnology and nanoscience. The possibility of molecular control by tuning the desired architecture (or polymer composition) makes these systems a versatile tool to study, in a convenient way, the rich and complex phenomenology in the field of nanoscience and nanotechnology (Alexandridis and Lindman 2000; Mallamace *et al.* 2001; Chen *et al.* 2002; Calandra *et al.* 2013; Stein *et al.* 2014; Calandra *et al.* 2015b; Bardik *et al.* 2020), and stimulates at the same time the rational design and engineering of materials with advanced desired properties (Trusso *et al.* 2011; Fong *et al.* 2012; Bonaccorsi *et al.* 2013b; Feng *et al.* 2017). This approach introduce a new way of treating the complex variety of topics within the nanoscience field, and stimulates the discovery of important links between physics, chemistry, material science and engineering, thus highlighting the interdisciplinary aspects of the scientific knowledge.

5. Nanotechnology and soft Interaction: beyond the pairwise forces between point-like particles

One of the the main characteristics of the self-assembly processes in nanoscience is the weakness of the involved forces (soft interactions) and their supramolecular character characterised by the involvement of a *multiplicity of interaction site*. These forces (due to their action on many-body systems) have some peculiar characteristics that distinguish them from the pairwise forces treated in traditional academic teaching programs. Despite the weakness of the interactions involved, the relevant number of these forces cause, in fact, an overall effect which is strong enough to hold together different molecular structures (building blocks) (Likos 2001; Whitesides and Lipomi 2009; Lombardo *et al.* 2016a). Those peculiar aspect of the soft interactions requires a substantial change (with respect to the traditional Newtonian framework), and a specific program that indicate how these new topics must be addressed within a science teaching program at both the undergraduate and graduate level. Detailed treatment of the main soft (non-covalent) forces acting in nanostructures self-assembly (such as the hydrogen bonding, hydrophobic effects, screened electrostatic interaction, steric repulsion and van der Waals forces) represents then an important and fundamental upgrade of modern approach in reseacrh and teaching curriculum. We give a brief overview of some of the peculiar characteristic of the main soft interaction which play a prominent role in the many-body systems in the field of nanotechnology.

The *hydrogen-bonding (H-bonding)* is an highly directional, specific interaction present in many organic molecules, and is responsible for supramolecular ordering in many biological and nanostructured systems (Magazù *et al.* 2012; Bagchi 2013; Głowacki *et al.* 2013; Magazù *et al.* 2016). The presence of hydrogen bonds (H-bond) makes nanostructured materials (such as biomolecules) substantially stronger upon forming a network (so called H-bond cooperativity effect) (Poole *et al.* 1994; Branca *et al.* 2002; Magazù *et al.* 2008). More specifically, the investigation of the properties of the structural and the functional water, represent a crucial step for the understanding of complex bio-processes in biological systems. This circumstance is essential for many important functions in biological systems and account for many biological processes such as the DNA base pairing, secondary and tertiary protein structure, carbohydrate hydration as well as a range of unusual properties of water (Chen *et al.* 2006; Magazù *et al.* 2007; Disalvo *et al.* 2008; Caccamo and Magazù 2016). Together with the hydrogen bond, the *hydrophobic effect* is another important driving force of the nanomaterial self-assembly into various supramolecular structures (Tanford 1973; Kiselev *et al.* 2008; Israelachvili 2010; Sánchez Iglesias *et al.* 2012; Kiselev *et al.* 2013). The hydrophobic effect plays an important role in many soft matter systems as it regulates the tendency of nonpolar (hydrophobic) molecules to self-aggregate. When non polar molecules are dissolved in water, the disruption of the H-bonding water network favourites a rearrangement of the water molecules around the nonpolar molecules. This effect correspond to an effective mutual attraction (hydrophobic interaction) between the non-polar molecules, caused by the disruption of the H-bonding water network around the hydrophobic component, followed by the rearrangement of new hydrogen bonds to form an ice-like cage structure. The hydrophobic effect plays a crucial role in the formation of amphiphilic micellar aggregates (Israelachvili and Wennerström 1996; Hu *et al.* 2014; Liveri *et al.* 2018; Caccamo *et al.* 2020; Lombardo *et al.* 2020a), as well as in a wide range of other biological processes in protein, bio-membranes and biological systems. Finally, the H-bond interaction and the hydrophobic effect represent important forces that, through their cooperative behaviour, stabilize the nanostructures in their solution environment.

There are three other important interactions that confer, through a spatially distributed action, a colloidal stability to the nanostructures in complex materials. These interactions are the *electrostatic stabilization* (or charge stabilization through an electrical double layer) (Podgornik *et al.* 2000b; Hunter 2001; Lombardo 2009, 2014), *steric stabilization* (obtained with adsorbed or chemically attached polymeric macromolecules to the nanoparticles surface) and *depletion stabilization* (obtained by inserting free polymer in the dispersion medium) (Marenduzzo *et al.* 2007; Semenov and Shvets 2015; González García 2019). In the last two cases the presence of the polymer that occupies a certain amount of space generate an "effective repulsion" due to both volume restriction and interpenetration effects of polymeric molecules (Marenduzzo *et al.* 2007; Semenov and Shvets 2015; González García 2019). The degree of the stability is strongly dependent on the amount of excluded volume and on the sizes and geometries of the excluded particles.

6. Many-body interaction: searching approximate solutions for unsolvable problems

A many-body system composed of multicomponent units interacting each other is impossible to solve exactly, except for very simple cases (such as in random field theory, 1D Ising model). However, the study of the behaviour of large and complex multicomponent system can be addressed by investigating simpler stochastic approximated models. Among them, one of the most widely used is represented by the mean-field approximation (MFA) (Chaikin and Lubensky 1995), also known as self-consistent field theory. In a mean field approach the effect on any given individual elements of all the remaining component units, within a nay-body system, can be approximated by a single averaged effect. The n-body system is then replaced by a 1-body problem, through the suitable choice of approximate external field that replaces the interaction of all the other particles to an arbitrary particle.

Another interesting approach for the solution of the problem of a many-body interacting system is given by solving the Ornstein-Zernike (O.Z.) integral equation, developed in the framework of liquid state theory (Belloni 1991; Hansen and McDonald 2013). The integral equations approach has been employed to study the range and strength of a wide range of interparticle interactions in different systems of nanoscience including dendrimers, amphiphiles, proteins, and lipid bilayer vesicles (Belloni 1991; Micali *et al.* 1998; Faunce and Paradies 2008). A classical theoretical approach that make use of the O-Z approach to determine the nanoparticles interaction is given by the so called D.L.V.O. theory (Hunter 2001). Within this approach the inter-particles interaction potential is determined by the balance between the Van der Waals (attractive) forces, and the screened Coulomb (repulsive) interaction. It is worth pointing that the application of the DLVO potential for the analysis of the interactions between nanoparticles evidenced the difficulty associated with having to rationalize the charge strength parameters in charged multi-components complex systems (Verwey 1947; Russel *et al.* 1989; Fritz-Popovski 2009; Lombardo *et al.* 2016b, 2018).

It is worth pointing that those approaches need a deep mathematical background preparation, as well as a proper analysis of the numerical solution methods. In this respect the teaching aspect should have its major emphasis on the methods that allow to approach the solution of specific many-body problems in the field of nanoscience. The lectures can be profitably organized as follows: various arguments of the program are first briefly introduced, and then specific problems are solved in full detail within the main aspects of the peculiar course of studies. In this case the main focus will be one's autonomy in the practice of specific theoretical approach, rather than in a systematic presentation of the well-established lessons covered by the course.

7. Multi-particles stepwise solution of the Newton's law: The molecular dynamic perspective

Molecular dynamic (MD) try to circumvents the problem of the many-body interacting system by numerically integrating Newton's equations of motion, by means of an iterative computational approach (Rapaport *et al.* 1996; Cagin *et al.* 1999). This approach represents a versatile method for the modelling of the nano-structured systems encountered in modern nanotechnology and may become a powerful tool for both of scientific research and teaching approaches. In multicomponent systems composed of many interacting particles, the forces between the particles are calculated using interatomic potentials or molecular force fields. In Figure 3 a schematic representation of the molecular dynamic approach is reported, together with the main approximated forces (force field) involved in multi-component system of nanoscience (Rapaport *et al.* 1996; Cagin *et al.* 1999).

Once the system is built in its initial configuration (the cell), the forces acting on every atom are obtained through the solution of the force-fields equations, during small integration time steps. In this case the potential energy is calculated starting from the initial molecular structure configuration. The form of the inter-particles interaction plays a crucial role in determining, with its mathematical expression, the numerical solution of the molecular dynamics simulation. This is a central point that allow a suitable solution to a problem that otherwise would have no solution.

The relative simplicity in the mathematical form of the force-field representation of the molecular interaction (such as springs for bond length and angles, periodic functions for bond rotations, Lennard–Jones potentials for van der Waals, and the Coulomb's law for the electrostatic interactions) (Rapaport *et al.* 1996; Cagin *et al.* 1999; Kremer 2006) assures that the energy and forces calculations are extremely fast even for large systems (Figure 3).

The performances of simulations has been increased by recent methodological advances and high performance computing facility. Moreover, molecular dynamics (MD) computer simulations can track the system complex behaviour across a vast space-time scales ranges, otherwise inaccessible with traditional experiments. Novel MD computational methods have assumed in the last decades an ever growing importance in the field of nanoscience and nanotechnology (Kremer 2006; Gelpí *et al.* 2015). It is worth pointing that in some specific cases the practices of MD simulation do not achieve the precision needed to predict complex structural description in many multicomponent systems. In these cases the support from experimental approaches are necessary. However, computational physics methods and molecular dynamic approaches in particular, are expected to significantly increase the investigation capacity in physics of many-body systems.

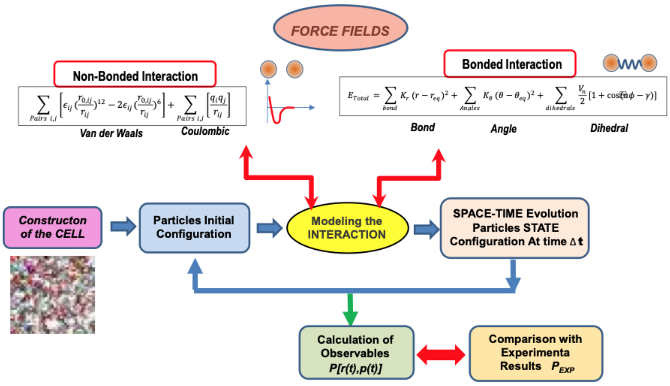


FIGURE 3. Schematic representation of the molecular dynamic approach and the main interactions (force fields) within a multi-component system of nanoscience.

The increase of the educational aspects of this field of investigation benefits from the ease of finding on the web many of the resources necessary for learners. For those reasons, we can expect that the molecular dynamics tools can accelerate the process of industrial and technological revolution with a strong impact in the development of appropriate teaching and research academic programs.

8. Supramolecular interaction: beyond the concept of pair-interaction

The use of the self-assembly processes allow the formation of highly functional structures through a spontaneous organization of the basic units (building blocks). This level, that represent the most advanced stage in modern approaches for of nanoscience, is based on the concept of supramolecular interaction which is established between building blocks. The construction of advanced materials are obtained by employing suitable driving forces (supramolecular forces), including hydrogen bonding, host–guest recognition, electrostatic forces, metal coordination and π-π stacking interaction (Lehn 2009; Wang *et al.* 2009).

The combination of the dynamic (and sometimes reversible) nature of non-covalent interactions with the new topological features and multi-functionality of building blocks provides a versatile strategy for preparation of novel, advanced (nanostructured) functional materials. Moreover, recent developments of supramolecular self-assembly allow to fabricate innovative well-defined nanomaterials by linking soft matter chemistry to hard matter sciences (Bonaccorsi *et al.* 2009; Lehn 2009; Wang *et al.* 2009; Bonaccorsi *et al.* 2013a; Quan 2018), by the suitable combination of approaches and techniques, to simultaneously detect the structure re-organization and dynamics at the nanoscale (Kiselev and Lombardo 2016; Caccamo and Magazù 2017a,b; Chen *et al.* 2017; Magazù *et al.* 2018).

This stage of the material evolution evidences how the reversible nature of the interactions may allow a dynamic switching of the generated nano-structures, with a modification of the morphology/function, in response to various external stimuli, such as pH, stress, temperature, electromagnetic radiation, magnetic field (Calandra 2020). For example the self-assembly nanostructures could disassemble upon the activation of an external stimulus such as ultraviolet (UV) electromagnetic radiation, or pH, and this process can be exploited for potential applications in the field of controlled drug delivery.

The analysis of the innovative aspects of the study of the supramolecular interactions encountered in the field of nanoscience suggests to adopt, for interdisciplinary and educational purposes, a conceptual scheme based on the following three stages: (see Figure 4):

- *Building Blocks*: They are not only atoms and molecules, but span a wide range of nano- and mesoscopic structures, with different chemical compositions, shapes and functionalities. Examples include hybrid units containing crystals, colloids, lipid bi-layers, cyclodextrins, charbohydrates and peptides.
- *Supramolecular Interaction*: It usually involves combination of different soft interaction between interacting sites. The interacting forces often occur between different sites of the building blocks and may present some dynamic switching, that may activate a structural response of the system to various external stimuli.
- *Functional Supramolecular Structure*: The self-assembled nano-structure are expected to have a high function/performance suitable for advanced nanotechnology application.

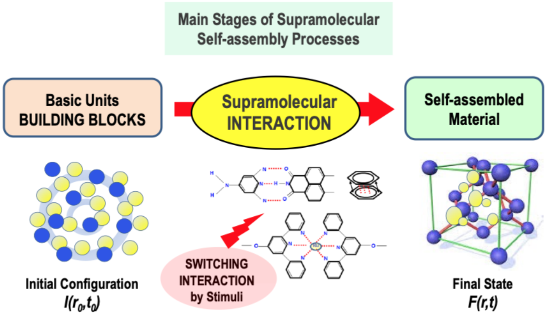


FIGURE 4. Conceptual framework for the study of supramolecular interactions in modern nanoscience and nanotechnology.

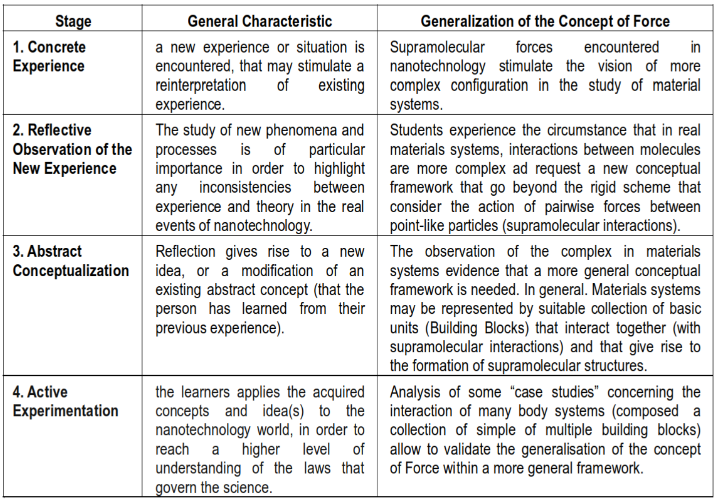
As an example, the molecular recognition processes of a host–guest system consisting of a receptor molecule (host) interacting with a ligand molecule (guest) through noncovalent interactions can be inserted in the more general framework of the supramolecular interactions. The construction of supramolecular nanostructures based on host–guest interaction provides, in fact, a flexible platform for the development of a wide range of novel smart nanomaterials and functional supramolecular devices (Shigemitsu and Hamachi 2017; Hatai *et al.* 2019; Pasqua *et al.* 2019).

9. The perspectives of the experiential learning in research and teaching programs

The development of modern teaching approaches within the academic research programs, allows a fruitful understanding of the large variety of scientific discoveries that have characterized the field of nanotechnology. In this respect the experiential learning (Dewey

1938; Kolb 1984) may be considered a valid approach for a strategic, active engagement of students in the opportunities to *learn through doing*. In this respect the laboratory classes represent an important stage as they introduces students to a critical cultural aspect of science and engineering, that all ideas need to be tested in a rigorous manner before it can be considered ’true’ (or valid). This stage also enable students to move from the concrete (specific observed phenomena) to the abstract (understanding the basic principles or theories). More specifically, there is a large variety of teaching models that aim to embed learning within real world (as well as in the scientific contexts), including: laboratory, workshop or studio work, apprenticeship, problem-based learning, case-based learning, project-based learning, inquiry-based learning, cooperative (work- or community-based) learning. In the Kolb’s experiential learning theory the impetus for the development of new concepts is provided by new experiences, by means of a four-stage learning cycle that involves the acquisition of abstract concepts that can be applied flexibly in a range of specific scientific problems and real life situations (Kolb 1984). In Table 1, we report the main stages of the experiential learning approach for the study of forces in modern research and teaching programs within the nanotechnology fields.

TABLE 1. Main stages of the experiential learning approach for the study of forces in modern nanotechnology.



Stage	General Characteristic	Generalization of the Concept of Force
1. Concrete Experience	a new experience or situation is encountered, that may stimulate a reinterpretation of existing experience.	Supramolecular forces encountered in nanotechnology stimulate the vision of more complex configuration in the study of material systems.
2. Reflective Observation of the New Experience	The study of new phenomena and processes is of particular importance in order to highlight any inconsistencies between experience and theory in the real events of nanotechnology.	Students experience the circumstance that in real materials systems, interactions between molecules are more complex ad request a new conceptual framework that go beyond the rigid scheme that consider the action of pairwise forces between point-like particles (supramolecular interactions).
3. Abstract Conceptualization	Reflection gives rise to a new idea, or a modification of an existing abstract concept (that the person has learned from their previous experience).	The observation of the complex in materials systems evidence that a more general conceptual framework is needed. In general. Materials systems may be represented by suitable collection of basic units (Building Blocks) that interact together (with supramolecular interactions) and that give rise to the formation of supramolecular structures.
4. Active Experimentation	the learners applies the acquired concepts and idea(s) to the nanotechnology world, in order to reach a higher level of understanding of the laws that govern the science.	Analysis of some “case studies” concerning the interaction of many body systems (composed a collection of simple of multiple building blocks) allow to validate the generalisation of the concept of Force within a more general framework.

Students experience the circumstance that the complex phenomena in nanotechnology are characterised by the complex interactions between molecules. This circumstance requests a new conceptual framework that go beyond the rigid scheme that consider the action of pairwise forces between point-like particles (supramolecular interactions). The observation of the complexity of the prcesses in materials systems evidences that a more general conceptual framework is needed. In general. Materials systems may be represented by suitable collection of basic *"Building Blocks"* that interact together (with supramolecular interactions) and that give rise to the formation of supramolecular structures. In this respect, kinematic events, chemical reactions or self-assembly processes can be considered as a result of the interaction between building block. Finally, the use of experiential learning for developing the knowledge and skills needed in a modern nanotechnology age, requests the best practices associated with the advanced teaching models.

10. Conclusion

The education and training of a new generation of skilled workers represent a key challenge for the efficient development of nanoscience and nanotechnology within the multidisciplinary perspectives of the rapid progress stimulated by the new nano-technologies. This require an (up to date) upgrade of the key concepts usually introduced and developed within the science and technology academic curricula. Modern society requires to identify in a efficient way the new trends in sustainable development and their implications in future science and research education. The synthesis of novel nano-structures as well as the efficient combination of soft and supramolecular forces allow for the design and development of novel materials with ordered morphologies. The assemblies of different nano-sized building blocks and their integrated actions favourite the activation of highly specific functions suitable for smart applications in material science and modern biotechnology.

The analysis of the force and interaction in the many-body materials systems present complex characteristics than that encountered in basic principles of traditional teaching programs. Multicomponent materials systems in nanoscience typically consist of a large number of interacting building blocks (such as macromolecules and/or nanoparticles). For this reason it is very difficult to identify, with high precision, the properties and performances of such complex material systems, by simply solving the corresponding set of equation of motion. Moreover most of the interactions involved go beyond concept of pairwise interaction between (point-like) particles, as they involve rather a distributed interaction between multiple sites. In this article, we review the concept of force and its evolution within the framework of the recent research and discoveries in the field of nanotechnology and biotechnology.

Finally, we propose a conceptual framework for an upgrade of the concept of force and (supramolecular) interaction within the modern approaches of academic scientific programs. In this respect, the experiential learning method can be properly designed and delivered in ways that help the students to efficiently develop the knowledge and skills needed in the modern teaching approaches of bio- and nanotechnology concepts.

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