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Inquiring functional materials in high-school labs: a route to key concepts in nanoscience and modern physics

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XXXII Ciclo

There are two ways in which science affects human affairs.
The first is familiar to everyone: directly, and to an even greater extent indirectly,
science produces aids that have completely transformed human existence.
The second way is educational in character-it works on the mind.
Although it may appear less obvious to cursory examination,
it is no less incisive than the first.

Albert Einstein

Abstract – en

Nanotechnologies are already part of everyday life. H2020 indicates them as fundamental key-enabling technologies for the scientific, economic and social development of EU. Indeed, EU has recommended the introduction of nanosciences and nanotechnologies in high school curricula since the beginning of the new millennium, due to their highly interdisciplinary character and their effectiveness in realizing hands-on activities. One of the most relevant goals of nanoscience is to design and synthesize novel materials with functional properties, the so-called functional materials, by fine-tuning their structure, chemical composition and morphology at the micro and nanoscale. Indeed, the microscopic characteristics of such materials strongly affect their macroscopic properties, often in highly surprising ways.

Several functional materials are nowadays easily purchased and they are used in the school labs to trigger pupils' curiosity and interest, exploiting the so-called wow-effect. The Unimore Nanolab project (www.nanolab.unimore.it) goes beyond this approach, designing fully quantitative experiments based on functional materials, which are aimed at introducing selected key-concepts ("big-ideas") in nanosciences.

In this PhD thesis work, as a part of the Nanolab project, I designed and test a few new teaching-learning sequences (TLS), developing a novel educational approach to experimental activities, inspired by ISLE (Investigative Science Learning Environment) and Instructional 5E models.

Tribology, i.e. the study of friction, wear and adhesion phenomena, is an extremely active field of research of paramount technological relevance. Achieving a comprehensive understanding of these phenomena at the nano- and meso-scale is currently an open issue. As far as education is concerned, friction has been considered a trivial topic which deserved little attention in traditional high-school curricula. In fact, it actually provides an appealing way to introduce fundamental interdisciplinary concepts, such as atomic and molecular interactions and their key role in determining the behaviour and properties of two surfaces in intimate contact.

In this work, I designed a TLS on friction and wetting, which inquires the properties of the Gecko Tape®, a micro-structured adhesive, bio-inspired by the gecko feet. The

TLS aims to convey one of nanoscience Big Ideas, i.e., “Structure is function” and the underlying strict connections between physics and chemistry.

The teaching sequence is intended to mimic the different steps of true scientific research, including results dissemination and discussion. This TLS has been validated with a few groups of students, with different backgrounds and levels of involvement, and also tested in a peer education set with very good results. A second TLS, addressing the Big Idea "Tools and Instrumentation" was also designed, exploiting Gecko Tape® as a flexible and deformable diffraction grating. This activity is part of a sequence focusing on optics and it is also a flipped-classroom approach. All the designed educational materials, including films and video tutorials, are available on-line and have been also used for in-service teachers' training activities, held in 2018 and in 2019, both deployed for a nation-wide basin by means of the SOFIA-MIUR platform.

Abstract - it

Le nanotecnologie sono ormai parte dell'esperienza quotidiana e rappresentano un pilastro fondamentale dello sviluppo tecnologico, economico e sociale futuro. In particolare, l'Unione Europea le considera fra le tecnologie chiave per lo sviluppo tecnologico ed ha messo in evidenza l'importanza di introdurne i principi base già nelle scuole superiori. L'introduzione delle nanoscienze nei curricula delle scuole superiori permette di collegare le diverse materie in un'ottica interdisciplinare e si presta ad attività "hands-on" di provata efficacia.

Le nanoscienze mirano a progettare e realizzare materiali con nuove proprietà, i cosiddetti materiali funzionali, controllandone struttura, composizione chimica e morfologia alla micro e nano scala. Le caratteristiche microscopiche di un maeriale si riflettono infatti sulle sue proprietà macroscopiche in modo spesso eclatante. Diversi esempi di materiali funzionali sono facilmente reperibili sul mercato e le loro proprietà possono efficacemente essere illustrate nei laboratori scolastici. Solitamente queste dimostrazioni d'aula sono pensate per accendere la curiosità degli studenti, utilizzando il cosiddetto "wow-effect". Il progetto Nanolab, di Unimore mira ad andare oltre questo approccio, proponendo protocolli sperimentali quantitativi, riproducibili e facilmente realizzabili per introdurre alcune idee-chiave delle nanoscienze.

In questo lavoro di tesi, che si inquadra nel progetto Nanolab, sono stati progettati alcuni nuovi protocolli e Teaching-Learning Sequence (TLS), sviluppando un approccio didattico originale all'attività sperimentale, che trova fondamento in letteratura nel modello ISLE (Investigative Science Learning Environment) e nell' Instructional Model "5E".

La tribologia, cioè lo studio dei fenomeni di attrito, è un settore delle scienze dei materiali di enorme rilevanza tecnologica. La comprensione delle origini microscopiche di questi fenomeni è a tutt'oggi oggetto di ricerca. Sebbene tradizionalmente i fenomeni di attrito siano piuttosto trascurati dai curricula scolastici, essi rappresentano invece l'occasione per introdurre concetti interdisciplinari estremamente importanti, quali le caratteristiche delle interazioni molecolari e il loro ruolo nel determinare le proprietà di superfici in contatto. Un contributo in questa direzione è fornito dalla prima TLS sviluppata in questa tesi. Essa si basa sullo studio del Gecko Tape®, un adesivo micro-strutturato e bio-ispirato alle zampe del Gecko, e collega fisica e chimica, introducendo l'idea-chiave "struttura è funzione". Il percorso proposto mima il mestiere dello scienziato nelle sue fasi di ricerca e di condivisione dei risultati con modalità simili a quelle di un congresso scientifico. La TLS è stata validata su alcuni gruppi di studenti, eterogenei per interesse e formazione, e testata anche in modalità peer-education, ottenendo sempre risultati molto positivi.

Una seconda TLS è legata all'idea-chiave "Metodi e strumentazione" e sfrutta il Gecko Tape® come reticolo di diffrazione, flessibile e deformabile, per l'apprendimento attivo dell'ottica. Viene proposta anche in flipped-classroom con materiali didattici appositamente preparati.

I materiali prodotti, tra cui filmati e video tutorial, sono disponibili sul sito, completamente rinnovato, www.nanolab.unimore.it, e sono la base per corsi di aggiornamento per insegnanti, di cui uno tenuto nel 2018, ed uno nel 2019, entrambi organizzati a livello nazionale con iscrizione sulla piattaforma SOFIA-MIUR.

List of abbreviations

AAPT American Association of Physics Teachers

AFM Atomic Force Microscopy

AMTA American Modeling Teachers Association

CL Cooperative Learning

COF Coefficient of Friction

CPS Collaborative Problem Solving

DBR Design-Based Research

DFPT Density Functional Perturbation Theory

DFT Density Functional Theory

EM Electron Microscopy

EQF European Qualifications Framework

ESEM Environmental Scanning Electron Microscope

F Female

FIM Fisica Informatica Matematica (University Department)

G-GT Glossy Gecko Tape®

GT Gecko Tape ®

HS Hard Skills

I-RAT Individual Readiness Assurance Test

IT information technology

KIC Knowledge and Innovation Community

M Male

MDF Medium-density fibreboard

NLGW National Learning Goal Workshop

NP nanoparticle

NSE Nanotechnology Science and Engineering

NSF National Science Foundation

OCSE Organizzazione per la cooperazione e lo sviluppo economico = OECD

OECD Organisation for Economic Co-operation and Development = OCSE

O-GT Opaque Gecko Tape®

PISA Program for International Student Assessment

PL “Peer Learning”

PLS “Piano Lauree Scientifiche” Project (Italian Ministry of Education)

PS Problem Solving

PTCO “Percorsi per le Competenze Transversali” – Soft skills training courses

QNQ “ Quadro Nazionale delle Qualificazioni” (Italian, referred to the EQF)

RAT Readiness Assurance Test

SP Sandpaper

SS Soft Skills

STEM Science Technology Engineering and Mathematics

TLS Teaching Learning Sequence

T-RAT Team Readiness Assurance Test

UE European Union

UPW understanding phenomena worksheet”

Contents

Introduction

Nanotechnologies (NTs) daily hit the media, being often referred to as the most relevant source for innovative technologies in life sciences, electronics, mechanical industry, etc. The EU program HO2020 considers NTs as one of the fundamental key-enabling technologies for our scientific, economic and social development.

One of the most relevant goal of nanosciences is to design and realize novel materials with peculiar functions, the so-called functional materials, by fine-tuning their structure, chemical composition and morphology at the micro and nanoscale. Indeed, the microscopic characteristics of such materials strongly affect their macroscopic properties, often in highly surprising ways.

Since the beginning of the new millennium, EU has recommended the introduction of nanoscience and nanotechnology in high school curricula [1], due to their highly interdisciplinary character and their effectiveness in hands-on activities [2]. Indeed, several functional materials are nowadays easily available off-the-shelf and can be used in the school labs to trigger pupils' curiosity and interest, exploiting the so-called wow-effect, i.e., in qualitative demonstrations. The Unimore Nanolab project [3] was born to go beyond this approach, designing fully quantitative experiments based on functional materials, which are aimed at introducing selected key-concepts ("Big-Ideas") in nanoscience [4].

During the three years of my PhD, a few further aspects has emerged, which slightly changed this initial perspective:

- The difficulties of secondary school teachers in managing strict time-schedules, to the detriments of time devoted to lab activities;
- The need to insert our work in a more general educational framework, and to develop effective tools to test our TLS.

In this PhD thesis work, as a part of the Nanolab project, I have designed and tested a few new teaching learning sequences (TLSs), developing a novel educational approach to experimental activities, inspired by ISLE (Investigative Science Learning Environment) [5] and Instructional 5E models [6]. Indeed, my work aims at leading students into scientific thinking and to develop problem solving and cooperative learning skills. These sequences have a strong multidisciplinary dimension, with particular reference to the connections between physics and chemistry. Flipped-classroom approach has been also proposed, as a way to effectively manage time.

All the designed TLS are based on the properties of the Gecko Tape® a structural adhesive bioinspired to the gecko feet, which represents a classical example of functional material. Practical cooperative activities aims at studying the properties of this functional material can be considered an effective way to introduce the physics of matter as a cornerstone of modern physics.

The thesis is organized as follows:

In **chapter one** I provide an overall perspective of different educational approach which are particularly suited for lab activities, such as, in particular, Peer Education, Cooperative Learning, the BSCS-5E instructional model and the Investigative Science Learning Environment (ISLE) methodology. The latter is specifically designed for the physical field and aimed to teach students both fundamental physics concepts and how to approach problems as a scientist. I also discuss the flipped-classroom approach, by introducing, in particular, Team Based Learning, a flipped education strategy which aims at both acquiring soft skills and achieving cognitive objectives, especially in basic training.

In **chapter two** I shortly introduce Nanoscience as one of the fastest-growing and most impactful fields in global scientific and technical research and development. The multidisciplinary aspect is an intrinsic feature of nanoscience which therefore represents an educational opportunity for STEM education synthesis, as well as a communicative challenge for different disciplinary areas. In this context, biomimetics is a fast-growing research domain, promoted by the wide technological possibilities offered by micro- and nano-fabrication to tailor the properties of materials.

In **chapter three** I introduce the field of tribology and discuss its presence in high-school curricula. Tribology, i.e., the study of friction, wear and adhesion phenomena, is an extremely active field of research of paramount technological relevance. Achieving a comprehensive understanding of these phenomena at the nano- and meso-scale is currently an open issue. As far as education is concerned, friction has been considered a trivial topic which deserved little attention in traditional high-school curricula. In recent years, this marginal role has been widely discussed in educational research. In fact, it actually provides an appealing way to introduce fundamental interdisciplinary concepts, such as atomic and molecular interactions and their key role in determining the behaviour and properties of two surfaces in intimate contact. In this chapter I briefly review the main didactic experimental approaches [7], [8], which in recent years aimed to bring tribological phenomena to the attention of STEM teachers.

In **chapter four** I describe the design and implementation - according to the Research-Based Design methodology, as described by Guiserola [9] - of a novel TLS on friction and wetting, which inquires the properties of Gecko Tape®. This TLS aims also at conveying one of nanoscience Big Ideas, i.e., "Structure is function", and to highlight the strict connections between physics and chemistry. The teaching sequence is intended to mimic the different steps of a genuine scientific research, including results dissemination and discussion. This TLS has been validated with a few groups of students, with different backgrounds and levels of involvement, and also tested in a peer education set with very good results.

In **chapter five** a further quantitative investigation of the adhesive behaviour of Geckotape® (GT) is proposed. It is devoted to the quantitative study of the stick-slip effect at the macroscopic level. By dragging a smooth wooden block on a GT-coated horizontal surface, due to the strong adhesive force exerted by GT on the block, a succession of phases in which the block sticks and phases during which quick slipping motion occurs, can be seen by eyes and video-recorded. Using an on-line acquisition system and Tracker video-analysis, a full description of the dynamical quantities (i.e. position, speed and frictional force exerted on the block) describing the system motion is obtained and discussed.

In **chapter six,** a second TLS, addressing the big ideas "Tools and Instrumentation" is presented, partially exploiting a flipped-classroom approach. It investigates the optical properties of GT and brings pupils to learn through experience both geometric and wave-optics and to understand the working principles of fundamental research tools, such as optical microscopy and diffraction.

Chapter 1: Education Perspectives

1.1 The Educational framework

The world is changing at the fastest speed ever. This evolution represents a huge challenge for education. In this regards, two main aspects can be identified:

- The demand for skills is migrating to non-routine cognitive and interpersonal skills, since many jobs are being lost to automation; **higher-level thinking skills** are indeed present in the labour market with a rapidly growing demand [1].
- Today technologies allow us to communicate with everyone around the world. The explosion of available information expands our perception of reality; the speed changes our physical and mental experiences, the world is just a click away, everything is faster, nearer and, for the most part, **quickly obsolete**.

As a result of this change of context, the educational focus must also change: if the challenge is to prepare kids for a world that has yet to be created, for jobs yet to be invented, and for technologies not yet imagined, a new instructional paradigm is required. In the "world of complexity", the focus strongly shifts from content to skills.

Future generations will increasingly need cognitive tools to solve pervasive complexity: the flexibility and the ability to face and solve new problems, to **find information and to manage relationships will become much more important to them than the acquisition of ever-changing content**.

In a rapidly changing world, education and training are called to play a key role in the acquisition of those skills and competencies which will be required to seize the work opportunities of tomorrow. Education and training are indeed pivotal in active policies all over the world. Online educational materials and an active-innovative approach for supporting the e-learning methodologies, can become a true resource to overcoming the actual educational challenges.

1.1.1 European Recommendation on Key Competences for Lifelong Learning

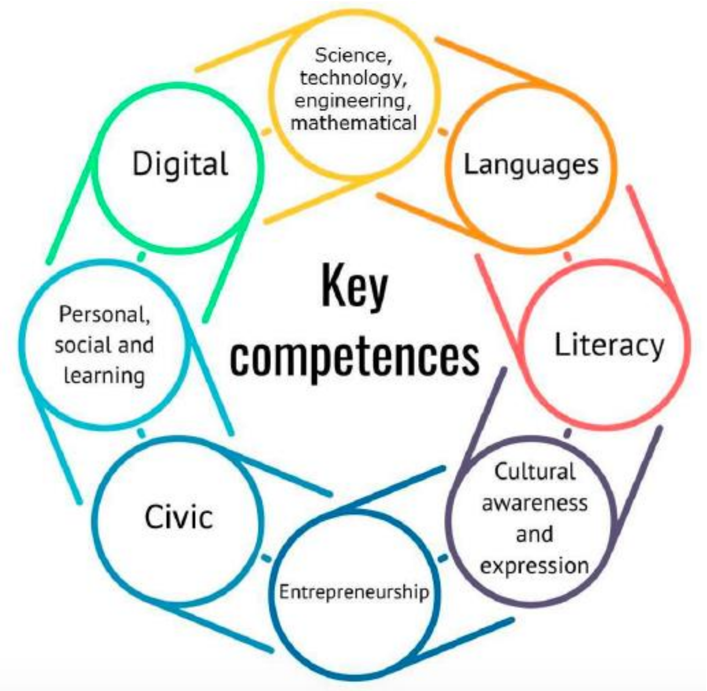


Figure 1-1: EU key competencies -march 2018-After[129].

In the Recommendation on Key Competences for Lifelong Learning (2006, revised in 2018) [10], the European Commission identifies eight key competences needed for personal fulfilment, a healthy and sustainable lifestyle, employability, active citizenship and social inclusion (**Figure 1-1**):

- Literacy
- Multilingualism
- Numerical, scientific and engineering skills
- Digital and technology-based competences
- Interpersonal skills, and the ability to adopt new competences (learn to learn)
- Active citizenship
- Entrepreneurship
- Cultural awareness and expression

Among these, we can distinguish between the so-called Hard Skills - or specific skills - and Soft Skills - or general skills. Hard skills are at the core of each professional requirement, they are directly related to specific knowledge and competences acquired during education and they are therefore easily assessed and quantified through academic records. Soft skills on the other hand, refer to thought, cognition and behavior processes. They play an essential role in the self-building process, in which students are actors of their own human, cultural, social and professional growth. The acquisition of soft skills allows students to enrich their personal assets, helping them in adopting the appropriate behavior for each situation, as well as learning and self-correction strategies. Soft skills are not specifically related to a job, rather they are closely related to personal attitudes. This makes them more difficult to quantify, to develop and, mostly, to teach. Soft skills are currently the subject of wide discussion in the international context by different authors and research entities, with different proposals for classifications, based on sometimes profoundly different assumptions.

For instance, according to the Transnational survey published in 2016 by Elena D'Amico [11] which aimed at understanding which skills companies require the most, twelve soft skills have been defined, which refer to three main areas:

Get ahead in the work-life: • Time management • Motivation • Adaptability and flexibility • Manage responsibilities (strictly connected to the identification of the objectives of work).

Master social skills: • Working in a team • Manage conflicts • Communication skills • Service orientation (understanding other people's needs).

Get results: • Solve problems • Creativity and innovation • Critical thinking • Making decisions.

Among these, **problem-solving** and **group-working skills** result to play a major role and are widely recognized as fundamental for modern life.

A problem is usually defined as a situation where a person cannot immediately and routinely achieve his or her goals due to some kind of obstacle or difficulty. The ability to solve problems is considered one of the most complex and sophisticated aspects of human cognition [12].

In order to accomplish the European Qualifications Framework for lifelong learning (EQF) request (see appendix A for details), Italy introduced in 2018 the so-called QNQ ("Quadro Nazionale delle Qualificazioni"). According to QNQ, at the end of the secondary school students are supposed to reach the fourth level ("livello 4") of competences, which, as far as soft skills are concerned, corresponds to:

- problem-solving
- ability to cooperate
- multitasking

As the problem-solving training is an educational challenge all over the world, we should ask ourselves which are the best strategies to effectively teach it. In particular, which among innovative teaching methods and instruments do teachers know and regularly apply? Can teachers find support and tools to implement this type of teaching? Are there disciplines more suitable for playing this fundamental role? Can physics in general and nanotechnology education in particular be a good candidate?

In the following of the chapter, I will provide a general - though not exhaustive - framework to answer these questions, with particular regards to the Italian situation.

1.1.2 The strategic role of Physics

Physics is both an experimental and a theoretical discipline, characterized by the rigorous observation and quantitative description of natural phenomena and, in general, of complex systems. Agreement with experiments obviously constitutes the final test of the validity of any scientific theory. Physical models, in particular, are rigorously described by mathematical equations and tools. Indeed, quantitative reasoning with numbers and units goes hand-in-hand with modelling and measurements, so that physics provides the foundation for quantitative methods in all scientific fields, and it stands as the first example of the scientific method.

Moreover, physics is the science most closely related to our basic perceptions of matter i.e., motion and light, and also provides a conceptual basis for many other disciplines (Chemistry, Biology, Geology, Computer Science, Engineering, Medicine, etc.). Indeed, all curricula in those fields include physics contents or courses.

The new ideas and discoveries in physics often have a large impact on our life. Many physics discoveries have led to relevant technological innovations and revolutions. Vice versa different technological innovations have enabled advancements in physics. Among these, information technology (IT) plays a distinct role, so much so that computational physics is sometimes regarded as the third branch of physics, besides experimental and theoretical one. Physics is often regarded as a 'hard' analytical science; however, it should be kept in mind that progress in physics inevitably requires imagination and creativity. Dealing with unanswered, profound questions, and finding new approaches to solve experimental or theoretical issues requires a great degree of flexibility. It is often the collaboration between physicists with different backgrounds and the exchange of ideas and techniques with people from other disciplines that have enabled the major physical and scientific discoveries of our days.

For all these reasons, the study of physics is a challenge for students and, consequently, it is an educational opportunity for teachers, called to untangle its complexity. Problem-solving strongly characterizes this domain, as a big part of students' efforts is to find and understand information, to organize and connect them, and to simplify and solve complexity. Physics appears therefore to be the eligible discipline to support modern education and training of future generations in the world of complexity. Indeed, this approach has been for instance pursued in the USA by the American Association of Physics Teachers (AAPT) and the American Modeling Teachers Association (AMTA) for nationwide implementation of STEM education reform (Hestenes2015) [13], which in 2002 adopted the so-called "Physics First" statement:

"...AAPT recognizes that teaching physics to students early in their high school education is an important and useful way to bring physics to a significantly larger number of students than has been customary. This approach—which we call "Physics First"—has the potential to advance more substantially the AAPT's goal of Physics for All, as well as to lay the foundation for more advanced high school courses in chemistry, biology or physics..."

In Europe the reference organization is the OECD[1] -PISA[2] Program, which examines not "*just what students know in: science, reading and mathematics, but also what they can do with what they know*". This organization states that the main objective of science education is to provide students with the basic skills to:

- Explain phenomena scientifically
- Evaluate and design scientific enquiry
- Interpret data and evidence scientifically [14]

As an example, some results of OECD PISA 2017 on Collaborative Problem Solving (CPS) [15] is shown in **Figure 1-2**, where the Italian performances in science, reading and mathematics falls below the OECD average.

[1] Organisation for Economic Co-operation and Development (OECD) or OCSE in Italy
[2] Program for International Student Assessment (PISA)

Countries/economies with a mean performance/relative performance above the OECD average
Countries/economies with a mean performance/relative performance not significantly different from the OECD average
Countries/economies with a mean performance/relative performance below the OECD average

	Collaborative problem solving					Index of valuing relationships	Index of valuing teamwork
	All students	Relative performance[1]	Boys	Girls	Gender difference (boys – girls)		
	Mean score	Score dif.	Mean score	Mean score	Score dif.	Mean index	Mean index
OECD average-32	500	3	486	515	**-29**	0.01	0.00
Singapore	561	16	552	572	**-20**	0.32	0.27
Japan	552	23	539	565	**-26**	-0.22	-0.03
Hong Kong (China)	541	15	523	559	**-36**	-0.04	0.05
Korea	538	20	522	556	**-33**	-0.02	0.14
Canada	535	10	516	555	**-39**	0.11	0.00
Estonia	535	8	522	549	**-27**	0.03	-0.10
Finland	534	7	511	559	**-48**	-0.08	-0.22
Macao (China)	534	11	515	553	**-38**	-0.15	0.01
New Zealand	533	20	513	553	**-41**	0.01	0.07
Australia	531	23	511	552	**-41**	0.09	0.01
Chinese Taipei	527	5	513	541	**-28**	0.22	0.37
Germany	525	14	510	540	**-30**	0.15	0.14
United States	520	22	507	533	**-26**	0.13	0.06
Denmark	520	14	509	530	**-21**	0.01	-0.12
United Kingdom	519	12	503	536	**-34**	-0.04	-0.04
Netherlands	518	8	504	531	**-27**	-0.18	-0.26
Sweden	510	9	489	531	**-42**	0.05	-0.19
Austria	509	13	498	521	**-24**	0.24	0.19
Norway	502	-5	487	518	**-30**	0.11	-0.23
Slovenia	502	-10	484	521	**-36**	-0.04	0.02
Belgium	501	-4	489	514	**-25**	-0.06	-0.11
Iceland	499	15	485	512	**-27**	-0.09	-0.20
Czech Republic	499	3	486	512	**-26**	-0.20	0.00
Portugal	498	-5	489	507	**-19**	0.37	0.32
Spain	496	-1	485	508	**-22**	0.19	0.15
B-S-J-G (China)*	496	-17	486	508	**-22**	0.01	0.39
France	494	-7	480	508	**-29**	-0.07	0.11
Luxembourg	491	2	478	504	**-25**	0.03	0.00
Latvia	485	-9	465	505	**-40**	-0.30	-0.14
Italy	478	-11	466	489	**-23**	-0.14	0.02
Russia	473	-22	460	486	**-25**	-0.25	-0.18
Croatia	473	-12	459	486	**-27**	0.01	0.21
Hungary	472	-10	459	485	**-26**	-0.03	-0.02
Israel	469	-11	459	481	**-22**	0.24	-0.03
Lithuania	467	-15	453	482	**-29**	0.16	0.33
Slovak Republic	463	-7	448	478	**-30**	-0.34	-0.12
Greece	459	-10	444	475	**-31**	0.03	0.18
Chile	457	-3	450	464	**-14**	0.08	0.21

Figure 1-2 Performance in collaborative problem solving and attitudes towards collaboration-OECD PISA 2017. Source OECD, PISA 2015 Database, Tables V.3.2, V.3.9a, V.4.3a and V.5.1. The original table has been cut for clarity, to show scores higher than 457. Italy's mean score performance is under OECD average score (500), but about half way through the rankings. The worst score is Tunisia's (382) (not shown). After [15].

In particular, problem-solving strategies are not systematically developed in Italian schools and show differences between high schools and technical/professional schools and by geographical area. The same document reports how students' participation in physical education class positively impacts the performances in collaborative problem-solving.

The Investigation analyzed also how performances depend on the number of days of practical training attended per week, considering also gender differences. As shown in **Figure 1-3**, students who attend physical education class once or twice per week had higher scores in collaborative problem solving than both students who attend between zero and three days, and of those who attend four or more days per week, proving the importance of a good balance between theory and practice.

"C*ollaboration skills can be taught and practiced in cognitive subjects, such as science, reading and mathematics: students can work and present in groups and can help each other learn the subject. However, much of the effort to master the material taught is typically made individually by the student. In contrast, collaboration is vital* *to many activities in physical education class, most obviously team sports, which require individuals to work together in groups to achieve a common goal*".

It is also interesting to note that females perform better than males in collaborative problem-solving in all countries, school levels, and disciplines.

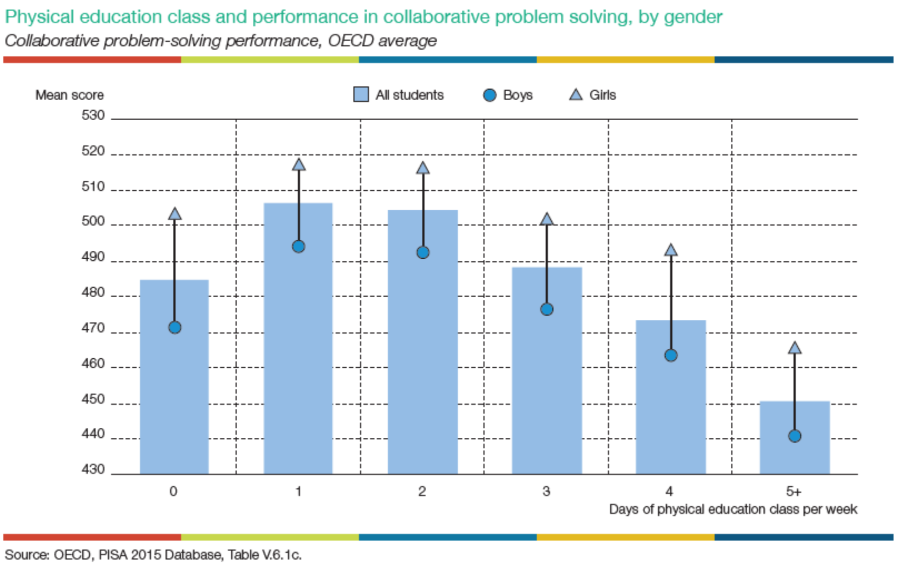


Figure 1-3 Performance in collaborative PS as a function of Physical education class attended per week. Gender differences are also shown. After [15].

1.1.3 The Specific Italian context

The General Lines and Competence Guidelines for "Nuovi Licei " curricula [16] established by Italian Ministry of Education (MIUR) in the context of the high school reform started in 2010-2011. Among the outcomes of the physics courses in high schools, the guidelines define that students must be able to:

- *"osservare e identificare fenomeni; affrontare e risolvere semplici problemi di fisica usando gli strumenti matematici adeguati al suo percorso didattico;*
- *avere consapevolezza dei vari aspetti del metodo sperimentale, dove l'esperimento e inteso come interrogazione ragionata dei fenomeni naturali, analisi critica dei dati e dell'affidabilità di un processo di misura, costruzione e/o validazione di modelli;*
- *comprendere e valutare le scelte scientifiche e tecnologiche che interessano la società in cui vive."*

The guidelines are focused on the acquisition of cognitive abilities of observation, on modelling construction, on problem-solving ability and communication skills. The acquisition of the scientific method is the ultimate goal of a physics course:

*"…nei primi anni si inizierà a costruire il linguaggio della fisica classica abituando lo studente a **semplificare e modellizzare situazioni reali**, a risolvere problemi e ad avere **consapevolezza critica** del proprio operato. Al tempo stesso, anche con un approccio sperimentale, lo studente avrà chiaro il campo di indagine della disciplina **ed imparerà ad esplorare fenomeni e a descriverli** con un linguaggio adeguato. Durante l'ultimo anno poi la dimensione sperimentale potrà essere ulteriormente approfondita con attività da svolgersi non solo nel laboratorio didattico della scuola, ma anche presso laboratori di Università ed enti di ricerca…".*

The connection with daily experience and innovation technology is also promoted, aims to increase students' motivation and making science closer to student's lives:

"…lo studente potrà approfondire tematiche di suo interesse, accostandosi alle scoperte più recenti della fisica (per esempio nel campo dell'astrofisica e della cosmologia, o nel campo della fisica delle particelle) o approfondendo i rapporti tra scienza e tecnologia (per esempio la tematica dell'energia nucleare), per acquisire i termini scientifici utili ad accostare criticamente il dibattito attuale, o dei semiconduttori, per comprendere le tecnologie più attuali anche in relazione a ricadute sul problema delle risorse energetiche, o delle micro- e nano-tecnologie per lo sviluppo di nuovi materiali)…" [17].

To these aims, several projects have been implemented by MIUR:

- **PLS** "Piano Lauree Scientifiche" (Scientific Degrees Project) aimed to engage young in science domain;
- **PNSD** "Piano Nazionale Scuola Digitale" (national digital school plan) started in 2008, aims to introduce digital breadboard (LIM), Wifi connection and digital infrastructure in every class, and supporting teachers' digital competencies through training, instrumentation and professional tutoring [18];
- **#scienza&tlab project** a science teacher training project aimed at "bringing the laboratory into classrooms";
- **PON for school 2014-2020** aims to train pupils, teachers, and adults (funded by the European Social Fund, ESF, for 2.2 billion euros), and to create a capillary innovation both in laboratory equipment and teaching skills (funded by the European Regional Development Fund, ERDF, for 800 million euros).

As far as the collaboration between schools and universities is concerned, the most interesting opportunity in the Italian panorama is the "Piano Lauree Scientifiche" (PLS) project [19], which has been aimed - since its starting in 2009 - at increasing scientific interest in high-school students. It directly involves almost all Italian universities offering educational projects addressing high-school students and teachers, respectively.

Two main objectives are in particular pursued:

- **Support students' interest and awareness**, **to promote enrolment in scientific faculties** (physics, chemistry, mathematics, biology, material science, etc.) and to reduce university dropout rates;
- **Offer training courses for secondary school teachers** and promote exchanges and collaboration between schools and universities.

In addition to these objectives, a few other outcomes have been also reported:

- Improved students' awareness about the strict link between real-life situations and science;
- teachers' increased opportunity to get to know new educational methodologies and evaluation instruments;
- Effective production of a collection of shared educational materials available at [20].

In this regard, it should be noted that most of these materials are concerned with chemistry and life sciences, while only a few focus on physics. Moreover, they are mainly "teacher-centered", and focused on laboratory techniques rather than on learning processes. Furthermore, among PLS activities a particularly relevant role is played by university training programs, which offers students the opportunity to train and test their vocations and resources.

In 2018, training programs for students have been extensively proposed in the framework of the so-called PTCO ("Percorsi per le Competenze Transversali" – soft skill training courses) guidelines [21]. The latter has been recently established by MIUR and aims to develop those transversal and technical-professional skills requested - according to the European Qualifications Framework for lifelong learning (EQF) - by both the labor market and higher education levels.

According to these guidelines, during the last three years of secondary school, students are expected to spend a significant fraction of time (ranging between 200 and 300 hours, checked during three years, and depending on the school type) in an active learning environment. The collaboration with companies, institutions, and, in particular, universities, represents therefore the focal point of PCTO. The training programs offered by universities typically run full-time for one- or two- weeks and may involve groups of students belonging to different schools. They represent therefore an ideal opportunity to test Teaching Learning Sequences, as in particular those designed in an experimental context.

1.2 Teaching methodologies to improve team working and problem solving skills

1.2.1 Teaching Role

The past teaching paradigm of the teacher as the possessor of knowledge is shifting to a new paradigm of the teacher as a facilitator or coach. This new teacher provides contextual learning environments that engage students in collaborative activities. This approach requires communications and access to information that only technology can provide. A qualified teacher, by using technological tools, provides a more effective learning environment, where students may challenge their new skills and create their new learning experiences. Teachers have to develop educational frameworks where students will be highly competent in solving new problems. Educators should promote “just in time” learning environments where students find solutions to real-world scenarios. To do that, only the recognized fundamental nuclei of knowledge must be transferred, starting from which, students can build their specific knowledge, acquiring, and training, appropriate cognitive tools [21].

These new teachers must also have a profound awareness of cognitive processes, educational frameworks, didactical instruments, and have to focus their work both in cognitive and soft skills.

1.2.2 Peer Education

In the Peer Education or Peer Learning methodology (PL in the following) the transmission of knowledge and experiences takes place among the members of a group of peers, within a project that foresees well-structured aims, times, roles, instructions, and tools.

Peer learning can be defined as “*the acquisition of knowledge and skill through active helping and supporting among status equals or matched companions, where both tutees* and tutors benefit from the transaction. *It involves people from similar social groupings who are not professional teachers helping each other to learn and learning themselves by so doing*”, Topping 2005 [22].

In this methodology, three different roles are envisaged: while the teacher operates as a coach, students may play both as peer educator or peer helpers (or tutors in the following) and as peer learners (or tutees or helped in the following). In former times, tutors were considered as a surrogate of teacher, in a linear model of the transmission of knowledge: from teacher to tutor and then to the tutees. For this reason, peer helpers were usually chosen amongst the "best students". The greater the difference in the ability or experience between helper and helped, the less cognitive conflict and the more scaffolding might be expected. However, in more recently studies, Topping 2017 [23]- Arendale 2014 [24], it appears clear that in such a situation the unequal levels of ability and interest could, actually, under-stimulate the helper and demotivate the peer learner.

It has been indeed realized that the peer helping interaction is qualitatively different from that between a professional teacher and young students; PL involves social and emotional interactions and promotes students' engagement because learners benefit from working in a protected environment, with a person who is considered closer to them. The affective component of PL and the trusting relationship with a peer who holds no position of authority has been proved very powerful [23] to facilitate self-disclosure of ignorance and misconception, thus supporting the subsequent diagnosis and correction. The correction may occur among peers or with the teacher's help; in this last case teachers, thanks to their coaching role, collect information on students' strategies and misconceptions, useful for continuous improvement of learning activities.

Reciprocal teaching allows students to increase and perfect their knowledge, study methods, and problem-solving skills. Both participants benefit from this teaching strategy as the tutor feels empowered by this role and consequently will develop an increasingly proactive behavior towards the school and the educational path.

In a well-designed activity, the asymmetry between helper and helped is reduced and all the students have the opportunity to help and to be helped, allowing the construction of a shared understanding between helper and helped [24]. As this "role reciprocation" occurs, both helper and helped give feedback to each other, implicitly and/or explicitly. Indeed, the implicit feedback is spontaneous, while the explicit ones, required by the teacher through a planned strategy guide, is recommended as educational instrument: it supports learning interaction and helps students to improve the effectiveness of their own learning strategies. In addition to this, the feedback provides the teacher with a collection of valuable information concerning the on-going learners' strategies and cognitive gains, for both tutors and tutees. The teacher may use this information both for students' assessment and for continuous improvement of learning activities.

According to K. Topping, pupils who receive explanations from other pupils learn more quickly and more in depth than those who work alone; similarly, for students who provide explanation: to face the commitment to explain a concept to a peer allows "student tutors" to strengthen their knowledge, to develop cognitive and communication skills, and to improve their learning strategies.
Peer tutoring is often implemented in the Cooperative Learning framework that I will shortly describe in the next section.

1.2.3 Cooperative learning

Cooperative Learning (CL) is more than "working together": as described by Slavin, [25] in his review of 1990, the CL core is "structuring positive interdependence in pursuit of a specific shared goal or output". It, therefore, involves the specification of goals, roles, task resources, and time scheduling. Students typically work in small groups of about three-to-six heterogeneous learners, to collectively carry out tasks. CL requires the teacher to master the interactive process to ensure equal participation.

Cooperative learning was born in the late eighteenth-century thank to Andrew Bell, a Scottish educator who pioneered the Madras education system [19]. Since the beginning of the 19th century, this system has taken hold in some European countries such as Great Britain, France, Spain, Italy, and in the United States. Fundamental contributions to this approach have been given by the pedagogue John Dewey, the psychologist Lewin, as well as Jean Piaget and Lev Vygotskij. The extent and range of this approach cannot be treated in detail in this context. It should however be said that since the sixties many other pedagogues, psychologists, and philosophers have developed CL, which is now considered an essential tool, not only within the school system but also within our entire system of social interactions. I briefly mention that in the "Learning Together" methodology of David and Roger Johnson, small groups of students learn group working, and learners' assessed is based on the group's progress [26]. Robert Slavin's CL assesses individual improvement relative to previous tests [27]. The structural approach of Spencer Kagan's promotes a strong positive interdependence concerning access to information and educational materials and ensures that "everyone knows everything"[28][29]. In Group Investigation of Y & S Sharan, students participate in the choice of content and process; this latest is articulated as a scientific investigation based on the interests of the students. The Group Investigations is the only model in which the criterion of the composition of heterogeneity groups is followed together, with the criterion of epistemic interest [30]. In Italy, Mario Comoglio can be considered the founder of Italian CL.[31].

All CL approaches are characterized by some fundamentals:

Positive interdependence. It is the essential, core element of CL [32]. It arises when each member of the group feels a link with others and with a commitment to pursuing a common goal. During CL activities, each group component has to perceive that they cannot be successful without the group, and, vice versa, that the group cannot be successful without the contribution of every single component;

Face-to-face promoting interaction. Students promote each other's success by sharing resources, supporting and praise each other's efforts to learn;

Social skills. These include, in particular, completing tasks, communicating, decision making, managing conflict, appreciating group members;

Individual and group accountability. Both the group as a whole and each member are accountable for achieving their goals and for contributing to this achievement. This means that the performance of each member must be assessed, and feedback must be provided to the group;

Group processing. It occurs when, aimed to improve the work effectiveness, the group discusses which actions were helpful and which need to be modified.

Teachers' role is to design the educational path and materials in such a way to foster this fruitful setting; to structure positive interdependence in a classroom, the teacher must first provide clear guidelines and instructions, aimed at achieving the common goal.

It is essential to pay attention to how to create an educational guide. Obviously, the choice of the task depends on what you want students to learn. When goals are abstract rather than factual, it is necessary to design a multi-skill activity, which should, as far as possible:

a) has more than one answer or more than one way to solve the problem
b) be interesting and rewarding in itself
c) allow different pupils to make different contributions
d) use multimedia tools
e) involve the five senses
f) require a variety of skills and behaviours

g) require both reading and writing
h) be challenging

1.2.4 The Investigative Science Learning Environment model

The "Investigative Science Learning Environment" (ISLE) methodology, is a learning model created by the group of prof. Eugenia Etkina during 30 years of working at the Reutgers University [33] [34]. Designed for the physics field, it has been applied mainly in high schools and universities, as well as in courses for pre-service teachers.

In the ISLE-based approach to STEM, students learn through experimental activities and are also engaged to design their experiments. By engaging pupils in processes similar to those used by scientists to construct new knowledge, ISLE teaches students both fundamental physics concepts and how to approach problems as a scientist. The scientific approach, i.e. "*the processes that mirror processes that physicists use to construct these concepts and laws* [35] "is the focus of detailed active learning experiences in which students get involved. Involving students in activities that allow them to retrace the knowledge building process, provides them with the opportunity to develop a wide set of soft and hard skills, such as:

- problem-solving, decision making, critical thinking, and creativity;
- the ability to cooperate, to manage conflicts and to communicate on a social level;

multitasking and time management.

The ISLE cycle

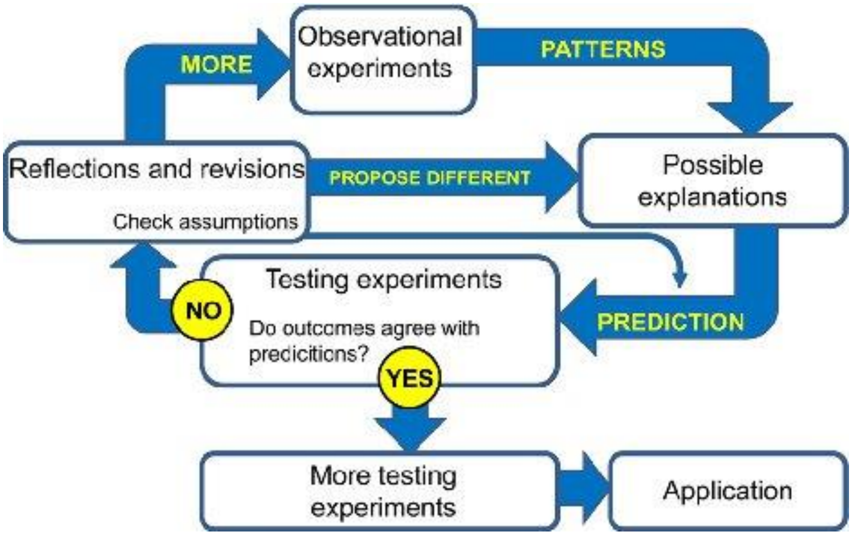


Figure 1-4 ISLE Cycle. After [5].

The effectiveness of this methodology increases if the activities are designed, implemented, and assessed following a cyclical path (the ISLE cycle- **Figure 1-4**) developed over a few days of time commitment.

The ISLE cycle [5] is articulated in five characteristic phases, as shown in**Figure 1-4**:

A) observation of a physical phenomenon and attempt to model it;

B) drawing-up a model which explains the observation;

C) use the model to predict the result of a test experiment;

D) understand if the test experiment validates or refutes the hypothesis that was made;

E) retract the hypothesis if necessary.

This scheme is applied as follows:

Phase A) an experiment is shown to students, which illustrate a particular phenomenon. These types of experiments are called observational. Often students do not know the explanation of the observed phenomenon. They are then guided in the observation through questions, in which they are asked to collect data and to give meaningful representations, to begin to identify what are, for instance, the regularities of the system.

Phase B) students discuss in small groups about the observation they made. The aim is to find an explanation for the phenomenon. They are stimulated to reason on the data they have collected, on the regularities they have found and on the information obtained from the experiment. They are asked to find a physical model underlying the phenomenon. At this stage, students do not know a priori the explanation and the teacher does not preclude any path, even those which may later prove to be wrong. It is important, for students, to reach this conclusion on their own, though their reasoning may be guided by questions and suggestions. The experiments proposed to students should be obviously formulated in such a way that data acquisition and hypothesis formulation are within their reach.

Phase C) students are asked to propose at least one prediction, based on the model they have developed with their classmates.

Phase D) students are asked to devise a new experiment to test their prediction. This experiment is called Test.

Phase E) the experiment designed by the students is performed, the results of data collection and analysis are then compared with prediction, so that the validity of the starting hypothesis can be assessed.

In some cases, an experiment called application is also designed, which is proposed after students have consolidated the knowledge of a law or a physical phenomenon. These types of experiments ask to apply this knowledge to a different situation or to solve a problem.

Unlike an experiment in which there is a formula to be verified through data collection, in this approach we start from data to arrive at the explanation.

One of the objectives of ISLE is to make students able to autonomously manage their own experimental investigation activity.

Teacher's role

If not correctly applied, this methodology could throw students off course. How the teacher can guide the path can be summarized in two key ideas: *scaffolding* and *coaching*.

Scaffolding provides that the teacher does not provide students with the information he is looking for in a prepackaged way, but tries to structure and guide their reasoning and their path to reaching a solution. This can be done, for example, by asking questions to students, to focus their attention on what are the experimental key issues, or to highlight the critical points of their reasoning.

Coaching, on the other hand, implies that the teacher participates in students' discussions, without providing the explicit solution to their questions, but making them think, emphasizing what may be the weak points of their reasoning, or directing them towards the correct ones. This teacher guidance should be gradually reduced so that students acquire more and more autonomy as the course proceeds.

1.2.5 The "BSCS-5E" instructional model

It should be first noted that while the ISLE methodology was developed in the specific area of physics, the 5E model has been proposed for a more general area; it has been widely used since the late 1980s as a model for the development of the STEM study at all school levels, as well as in the professional domain. Commonly called "BSCS-5E", the method is widespread worldwide. In 2006 R.W. Taylor, one of the leading American experts in the teaching domain, and R.W. Bybee, creator of the methodology, writing a report for the National Institute of Science Education regarding its diffusion, mention "*more than 97,000 examples in universities syllabi,…more than 131,000 example posted in teacher education programs,…more than 73,000 example of curriculum materials, …more than 235,000 lesson plans developed and implemented in 25 years of use …* " [36].

The 5E of the model represent the key points of the didactic planning:

Engage. Stimulate students' interest by introducing new concepts through the use of short activities. The connection with prior knowledge is promoted as well as the curiosity for new challenges; at this stage, teachers make explicit the required learning outcomes and the scheduling of works.

Explore. Get students involved to build their own understanding. Teachers design educational materials focused on the acquisition of skills and conceptual reconstruction, taking into account misconceptions and processes. This material provides instruction for learners to complete lab-activities and specific questions, designed to stimulate new ideas and lead their integration with prior students' knowledge.

Explain. This phase aims to focusing students' attention. At this stage, concepts have been clarified, teachers may directly introduce concepts or results by means of explanation, and guide learners toward a deeper understanding; students may communicate what they have learned so far and figure out what it means.

Elaborate. This phase allows students to use their new knowledge and continue to explore its implications, train skills, and facilitate conceptual change. In this phase, students have the opportunity to test their conceptual understanding by planning and carrying out additional activities.

Evaluate. In this phase, students have the opportunity to evaluate their understanding and show their learning outcomes. Teachers evaluate students' progress, by comparing these with expected results they may draw useful information to improve learning paths.

1.2.6 Flipped Education

The Flipped-classroom model is emerging worldwide among innovative didactic methods. It is particularly widespread in North America and Northern Europe, but more recently also in Italy.

The methodological innovation strategies adopted in the Italian school are supported and monitored by "Avanguardie Educative", a research project of the National Institute of Documentation, Innovation, and Educational Research (INDIRE) of MIUR. The project is based on innovation promotion starting from the bottom, through experimentation in schools. **Figure 1-5** reports the number of new methodological ideas adopted over time in Italy, it clearly shows the predominance of the flipped classroom strategies [37][37][37][38]

In this model, the traditional relationship between teaching and learning, and between teacher and learner, is being turned inside-out, often exploiting the opportunity given by technologies, see e.g. Maglioni and Biscaro [38]. This model draws its origins from the idea of two chemists, Jonathan Bergmann e Aaron Sams, who in 2006 began to videotape their lectures to allow absent students to see them. They soon realized that even the students attending the lessons used the registration as support for home-study.

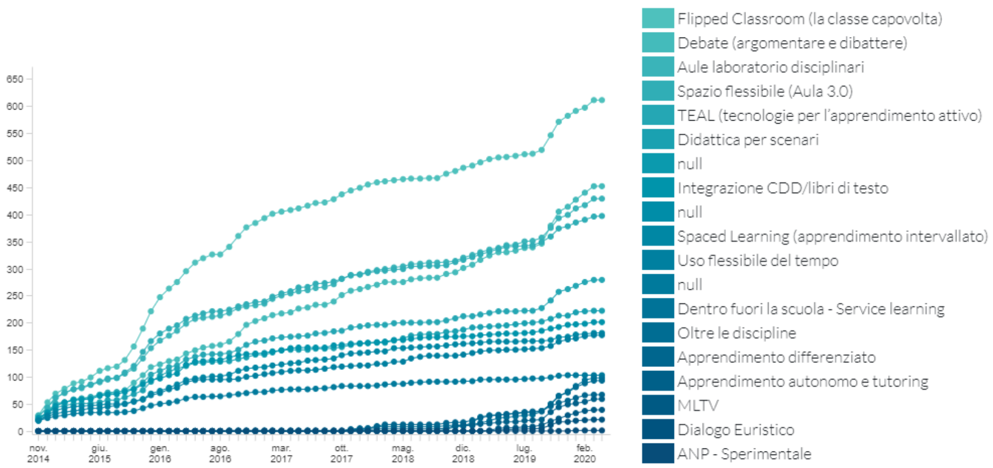


Figure 1-5 Number of new methodological ideas adopted over time in Italy – After [38]

As stated by Carl Reidsema et all [39]· "Flipped Learning is a pedagogical approach in which direct instruction moves from the group learning space to the individual learning space, and the resulting group space is transformed into a dynamic, interactive learning environment where the educator guides students as they apply concepts and engage creatively in the subject matter".

From a methodological point of view, the flipped classroom model is not a radical innovation (see e.g. Ferri [40] and Guarnaccia [41], as it takes inspiration from the work of Dewey [42] and Montessori and Freinet [43], which continually emphasizes experience, experimental learning, freedom, and personal interactions.

In particular, it partially resembles:

- The "peer to peer instruction" by Mazur [44], which suggests moving the notional and routine activities out of the classroom. In this methodology, teachers make the material available to learners to be read before classroom meeting in, while classroom time is used for active working, starting from what they have read at home;
- The "flipped classroom" by Lage, Platt. and Treglia [45], according to which the technology would allow learners to attend lectures at home, while the classroom time is devoted to tasks performed in groups.

The power of this model is that there are many possible ways to flip a class: the model must be customized by each teacher, each topic, and each students' need; educators have to take the principles of flipped learning and apply them in their contexts. This model is particularly interesting when the chosen context is the application of the experimental method. Indeed, in this case, observation, measurement, analysis, and interpretation of phenomena, are often carried out in a collaborative context, and contain all the fundamental elements for effective learning of both hard and soft skills. The quantitative dimension becomes fundamental to train decision-making skills and scientific accuracy. Though flipped classroom is often classified as a Teacher-Centered Methods of Instruction, in the case of Inquiry-based Learning - which is a typical student-centered method of instruction - the teacher becomes a supportive figure, who provides guidance and support for students throughout their learning process.

1.2.7 The Team Based Learning methodology

Team Based Learning (TBL) is a flipped education strategy aimed both to acquire soft skills and to achieve cognitive objectives, especially in basic training. It was proposed by Larry Michaelsen in the early 1990s as part of an American Business School and it can be applied to both small and large classes (> 100 students). It is an educational strategy based on active learning, performed in small teams (see Parmelee [46], p 275) of 5-6 individuals, chosen by the teacher, trying to ensure the greatest possible heterogeneity amongst them.

In the TBL, the teacher specifies what content students have to learn before the classroom activity starts. Students must therefore already know the topics that will be addressed in the classroom. The course must be designed not according to the notions that students should acquire, but rather considering the issues (problems) that students should be able to address and tackle, given those notions. The teacher designs the educational path following seven specific steps:

Step 1. Outside the classroom: assignment of individual learning tasks. Students receive a list of learning activities, accompanied by a series of learning objectives. These activities may include: readings, videos, workshops, tutorials and lessons to be attended.

Step 2. In the classroom: Individual Readiness Assurance Test (I-RAT). Students carry out a test, comprising 10-20 questions, which probe the knowledge required to deal with the case-problem that will be proposed later. The test is graded, and each student receives a mark.

Step 3. In the classroom: Team Readiness Assurance Test (T-RAT). Each group collectively carries out the same test that each individual has previously completed. The answers are given by the group on a form, called Immediate Feedback Assessment Technique (IF-AT), a sort of "scratch card" that immediately shows the correct answers to the team. T-RAT is also graded, each member of each group receiving the same mark.

Step 4. In the classroom: appeal. Students have the opportunity to ask for an appeal, that is, to question the correct answers.

Step 5. In the classroom: clarification session. The teacher might discuss and explain in more details issues which result more difficult to understand, aims to better prepare students for the next stage of applying knowledge.

Step 6. In the classroom: Team – Application (T-APP). Each team is offered a practical case-problem to solve, which requires the application of the previously learned notions. The problem is the same for all teams and its solution requires closed or, in any case, short answers, which must be delivered by all groups simultaneously (also using IT tools). If there are differences in the solutions proposed by the various groups, a discussion between them is promoted and the possibility of modifying the proposed solution is offered. In this step, each group receives a mark.

Step 7. A peer evaluation among the team members is envisaged. The combination of individual and group evaluations, obtained by averaging the individual scores, the group scores, and the peer evaluation, promotes empowerment and activates alliance and cohesion dynamics.

This methodology combines therefore independent study activities with knowledge testing (in practice, concerning the above, notional exercises), discussion, and competition between different groups to achieve higher levels of knowledge [1].

The fundamental characteristic of the TBL is that the students who study more or are more prepared, do not find themselves doing the work for the whole group, perhaps seeing their grades reduced. The "*process requires that everyone is responsible for their individual work and the personal contribution to the team"*. The final grade of the individual student derives from his performance than that of the group, see Parmelee et al. p.276 [46].

[1] On this last point, TBL differs clearly from the Problem Based Learning, which does not provide for any competition and is a methodology aimed at promoting team communication and the ability to accept different opinions.

Chapter 2: Nanoscience as an Educational Opportunity

2.1 Nanoscience

Nanoscience is one of the fastest-growing and most impactful fields in global scientific research, with technological outputs that are already part of everyday life. In HO2020, nanotechnologies are indicated as fundamental key-enabling technologies for the scientific, economic, and social development of EU. Nanoscience and nanotechnologies are a multidisciplinary research field that deals with the study and manipulation of matter at the atomic, molecular, and supramolecular-level. They aim to design and manufacture new materials and systems, with features improved compared to what can be found in nature. The word "Nano" indicates that the study and control of phenomena take place on the nanoscale, i.e., for dimensions typically between 1 and 100 nm.

The ideal birth of these disciplines can be traced back to December 29, 1959, during a meeting of the American Physical Society. On that occasion, the American physicist Richard Feynman (1918-1988) -one of the most extraordinary scientists of the last century- described his studies and intuitions concerning the atomic world in a lecture entitled "There is Plenty of Room at the Bottom". Feynman launched a challenge that at the time appeared as a provocation: *would we ever be able to write the entire Encyclopaedia Brittanica on the tip of a pin? Which kind of instruments and techniques should be envisaged to reach this goal?*

The enormous interest aroused by Feynman's intervention has led to a strong commitment in many research centers and laboratories all around the world.

The Nanotechnology term was coined in 1974 by the Japanese physicist Taniguchi and subsequently taken up by Eric Drexel who, two years later, defined nanotechnology as "... a molecular-level technology that will allow us to position each

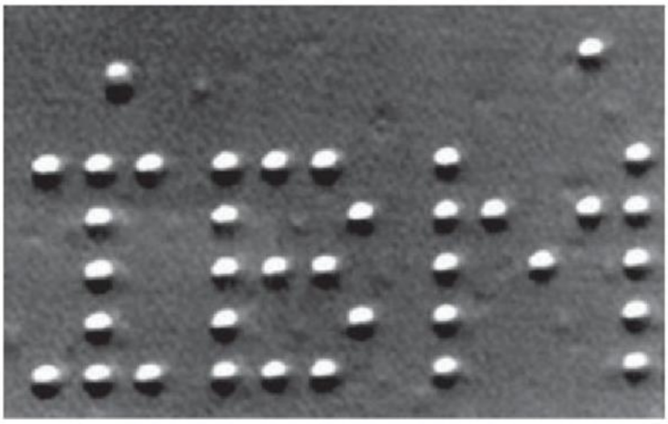


Figure 2-1 First atomic manipulation at IBM by Don Eigler. Maden Research Center, using, a STM to write the IBM logo in xenon atoms at 4 K on the (110) surface of a nickel single crystal. Each letter is 50 Å tall. Image licensed under Fair Use through Wikipedia.

atom where we want".

These studies would have been impossible without the development of powerful investigation tools such as the first Scanning Tunneling Microscope (STM) in 1981 by IBM scientists, and the Atomic Force Microscope AFM, by Calvin Quate, Gerd Binnig and Christoph Gerber in 1986. These powerful instruments immediately proved strategic for studying surfaces at the atomic level: in 1989 Don Eigler and Erhard Schweizer, at IBM's Almaden Research Center, wrote the name of their company with 35 Xenon atoms, thus demonstrating the precision and ability reached by nanotechnology in manipulating matter at the atomic scale.

One of the most relevant goals of nanoscience is to design and realize novel materials with functional properties, the so-called functional materials, by fine-tuning their structure, chemical composition, and morphology at the micro and nanoscale. Indeed, the microscopic characteristics of such materials strongly affect their macroscopic properties, often in highly surprising ways. A nanostructure is typically made up of a small number of atoms, typically from 10 to a few tens of thousands. The physical and chemical properties of nanostructures are often significantly different from those of the same material at the macro scale. Thus, nanostructures can be seen as a specific state of matter, particularly promising for new and extremely useful products. For this reason, nanostructures have become a topic of interdisciplinary research, from electronics to chemistry, from physics of matter to materials science, passing through molecular biology and engineering. The impact of nanotechnologies in all industrial sectors, from energy to biomedical and pharmaceutical applications, from manufacturing to aerospace, is huge. The possibility of integrating organic and inorganic nanostructures represents the basis for a new generation of advanced compounds.

2.1.1 Biomimetics

The new and wide technological possibilities opened by tailoring the properties of materials has promoted the development of biomimetics: a scientific and multidisciplinary research domain in which the study of the models, systems, and elements of Nature is used to solve complex human problems. *The key point for an effective biomimetic exploitation*, said Jeff Karp, a leading biomedical engineer, *is to analyze Nature evolution and what it converges to, trying to learn and to imagine how to do better than Nature* [47]. Drawing inspiration from Nature and from the vast number of solutions that have been tested by evolution for million years, in the last decades, scientists have started exploiting the possibility that manipulation of matter at the nanoscale offers to fabricate novel devices and solutions. This approach has allowed to obtain applications such as Velcro, structural adhesives inspired by geckos, self-cleaning surfaces inspired by Lotus, and so on. It is interesting to note here that a significant fraction of natural systems rely to some extent on micro- and nano-structuration [48]. The possibility to copy from nature to fabricate novel bio-inspired devices and treatments strongly relies on our ability to effectively control shapes and structures at these scales, i.e., on micro- and nano-structuring techniques.

A particularly interesting case study of this kind of research is that of Geckos. It is well known, Geckos are extraordinary climbers: they can run across walls and ceilings, carrying loads as heavy as ten times their weight; in doing so, their toes attach and detach from any surface within few milliseconds. Researchers have demonstrated that Geckoes can climb on whatever surfaces, no matter which material and roughness it presents [49]. Moreover, they ruled out the presence of glue-like secretion to explain this extraordinary effective adhesion. Indeed, as shown in **Figure 2-2**, each of Gecko's toes is formed by thousands of micrometric *lamellaes*, each of them formed by *setaes*, which apexes are furthermore structured down to the nanoscale. This hierarchical structure guarantees a huge contact area between the toe and the surface.

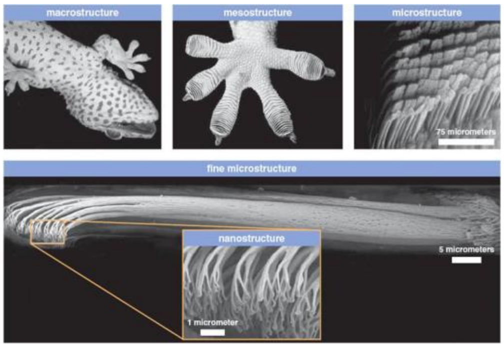


Figure 2-2 Hierarchical structure of Gecko's feet, from the meso-scale, down to the nanoscale (taken from Wikipedia, under creative common permission).

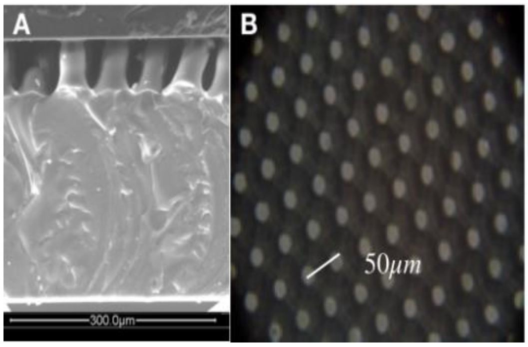


Figure 2-3 SEM image of Gecko micro-structured surface (B) and lateral view of the Gecko®/silicon interface (A). The overall film thickness is 400 μm, and the hexagonal pattern is formed by 50 μm high pillars, with a lattice parameter of 50 μm.

Due to this, the tiny Van der Waals forces acting between each portion of gecko's toe and the wall surface sum up, building an overall adhesive interaction, large enough to overcome Gecko's weight. Moreover, by changing the angle of contact between the toes and the surface, the real contact area can be varied, thus enabling the rapid attaching/detaching from the surface.

Inspired by Gecko, several materials with novel adhesive properties have been designed and manufactured in recent times. Among these, GeckoTape ® film from Nanoplast is easily purchased and reasonably cheap, made with silicon with a thickness of about 0,34 mm and with microscopic elements on one of the sides at a density of ~2.9 10^4 cm^{-2}.

As shown in **Figure 2-3**, the film is characterized by an ordered array of micropillars, cast out from a flexible thin film. The micro-structuration and the flexibility of the material makes it suitable for adhesion on different kinds of surfaces, allowing for interesting application in both medical and aerospace (i.e. at low atmospheric pressure) fields.

Another inspiration for the biomimetic approach is provided by the Salvinia Molesta leaf (**Figure 2-4**), which can separate oil from water by trapping it within the air region under its microstructured tips. By reproducing the structure and working principle of this plant, a bioinspired 3D printed material has been fabricated and successfully used to recover oil dispersed in the sea (see Y Yang [50] [51]).

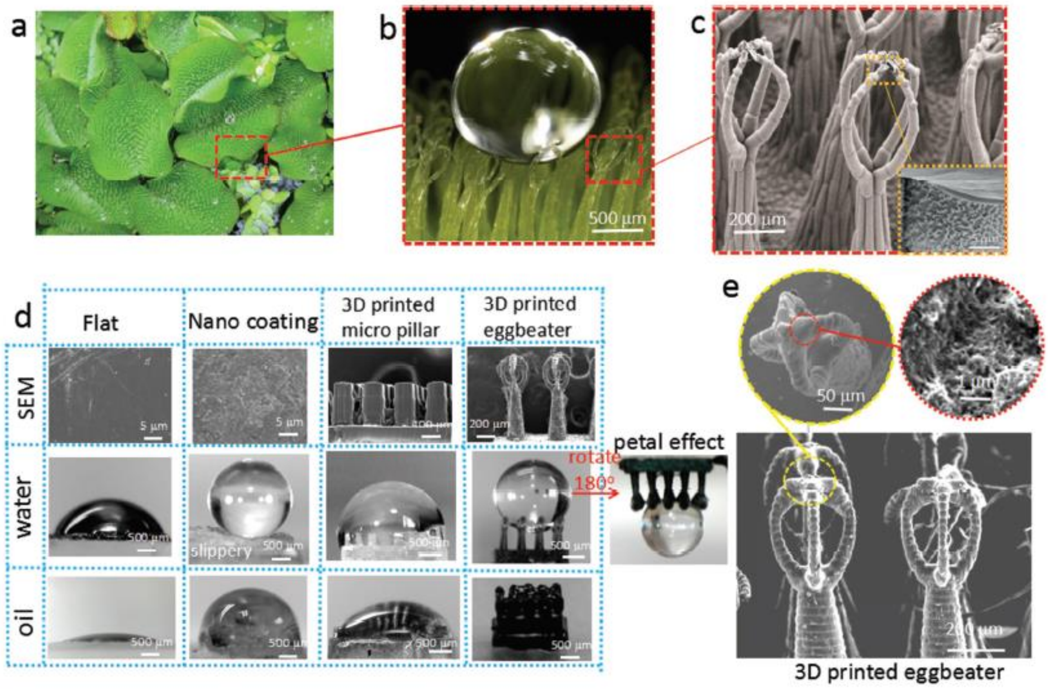


Figure 2-4 Biomimetic super-hydrophobic structure. a) Morphology of S. Molesta leaf, upper side of the leaf surface is densely covered with eggbeater hairs; b) a spherical water droplet on top; c) SEM image of the eggbeater hair structure. d) water and oil on the flat surface, after nanocoating, 3D printed micro pillar surface and 3D printed eggbeater surface; e) SEM images of 3D-printed eggbeater arrays (the insert image shows the magnification of one hair). After [50]. Figure (a–c) reproduced with permission of C. Zeiger et all Bioinspiration Biomimetics 11, 056003 (2016)Copyright 2016, IOP Publishing.

2.2 Nanoscience and modern physics in high school

The future of Nanoscience and Nanotechnology is fundamentally dependent on enhancing a foundation of interest and excitement in pupils already from a very early stage. The ability to understand nanoscience basic concepts and fundamental findings requires a high degree of science literacy. This suggests the opportunity of finding a place for Nanoscience within formal education too. As stated by A. Jackman in "Nanotechnology Education for the Global world" [52], whereas nanoscience and nanotechnology education at higher levels has traditionally focused on scientists and engineers in research positions, the growth of nanotechnology as an economic force calls for inclusion of a wider range of individuals, with different scientific and non-scientific backgrounds and training needs. Indeed, there is a recognized stark urgency for vocational counseling and professional training to gather highly specialized personnel in Nanotech and Nanoscience, to ensure competitiveness and innovation. It can be definitively acknowledged that USA has been pioneer and leader since 2000 in this inclusion process, with a flourishing of initiatives whose intrinsic value is further enhanced by intense networking among different institutions.

The EU has recommended the introduction of nanoscience and nanotechnology in high school curricula since the beginning of the new millennium, due to their highly interdisciplinary character [1] and because they are particularly well-suited for effective hands-on activities [2]. In the Italian school, in particular, the biggest challenges are, on one hand, to improve teachers' awareness and training, on the other, the limited time devoted to experimental and hands-on activities.

2.3 The key ideas of nanoscience

Nanoscience is interdisciplinary by definition. In any discipline, a limited number of fundamental ideas and concepts can be usually identified, which resides at the core of the discipline itself. Due to the intrinsic interdisciplinarity of nanoscience, which intrinsically involves different approaches and perspectives, a clear identification of such key issues is not trivial. To this aim, the United-states National Science Teachers Association produced in 2009 a 'Consensus document', providing an answer to the following question: "What does it mean to be nano-literate?".

In this document, nine big ideas were identified, elaborated, and described, which provide a framework for the long-term development of student understanding throughout the 7–12 curriculum [4]. As schematized in **Figure 2-5**, they can be divided into different groups: the first four ideas (**Size and Scale, Structure of Matter, Forces and Interactions, Quantum Effects**), define the foundational science content, **Size-**

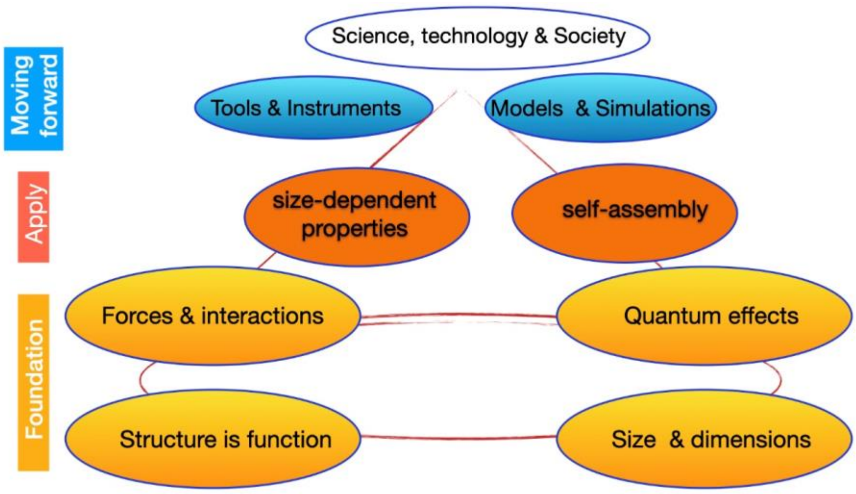


Figure 2-5 The Big Ideas of Nanoscience.

dependent Properties and Self-Assembly are relative to the application of these contents, **Tools and Instrumentations** and **Model and Simulations** define what is considered fundamental for the development of the discipline and, last but not least, a key-issue is **Science, Technology, and Society**.

2.3.1 Foundational science content

1. Size and scale

Size, Scale and geometrical Shape are crucial aspects to describe matter and predict its behavior.

According to their size, natural and artificial objects may belong to different "worlds" (e.g., macro-, micro-, nano-, atomic; see **Figure 2-6**-[53]), each characterized by a scale, i.e, a range of sizes, but also by (1) landmark objects (2) tools that render these objects accessible, and (3) models that describe the behavior of matter at that scale.

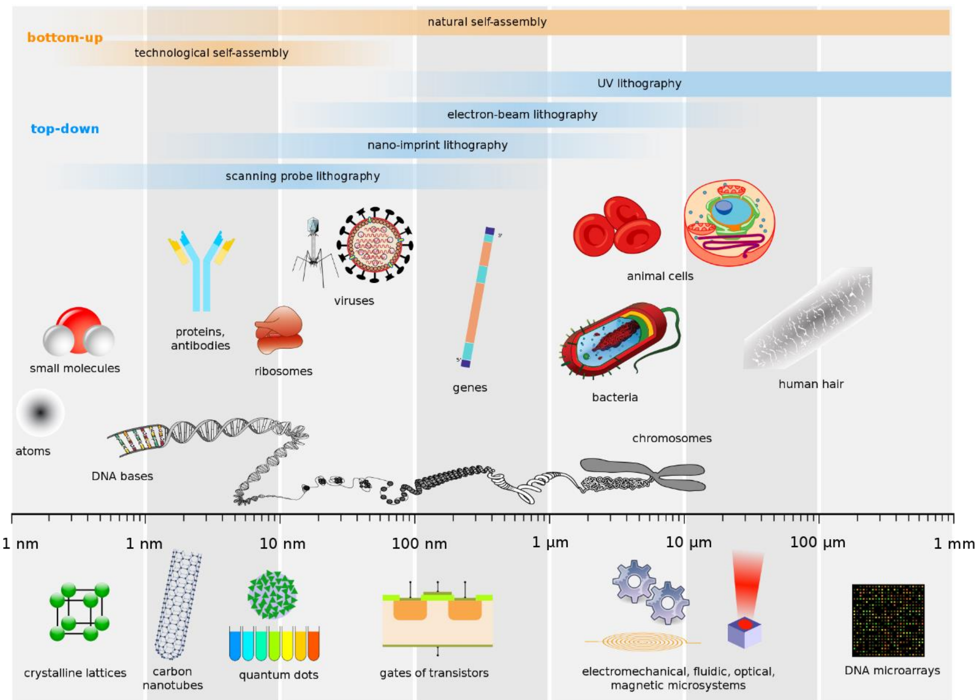


Figure 2-6 Comparison of the scales of various biological and technological. After [53].

As shown in **Figure 2-7**, when the size of materials approaches the nanoscale, the surface/volume ratio increases dramatically. Changes in this ratio often strongly impact the way objects function. Many of the special properties that matter exhibits on the nanoscale result from the effect of size on S/V.

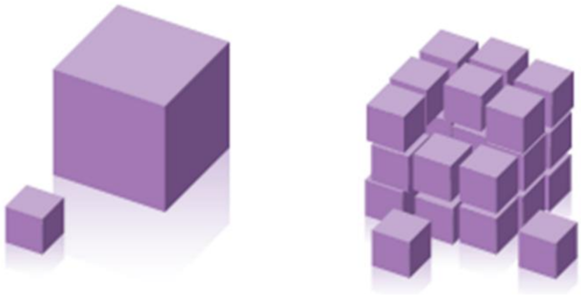


Figure 2-7 Dividing a cube of side L, into N3 smaller cubes of side (L/N), the S/V ratio increases as N (for a sphere as 3N).

2. Structure of matter

Materials consist of building blocks that often had a hierarchy of structure: Atoms interact with each other to form molecules, molecules interact to each other in nanoscale structure. The nanoscopic structure of a material determines its macroscopic properties (mechanical, electrical, optical, etc.).

As well know, the same chemical element, arranged in different structures, may form different materials with completely different properties. This is for instance the case for the allotropic forms of carbon (diamond, graphite, but also graphene, nanotubes, and fullerenes). It is important here to highlight that this key idea is shared by different disciplines, spanning from physiology (the structure of organs determines their

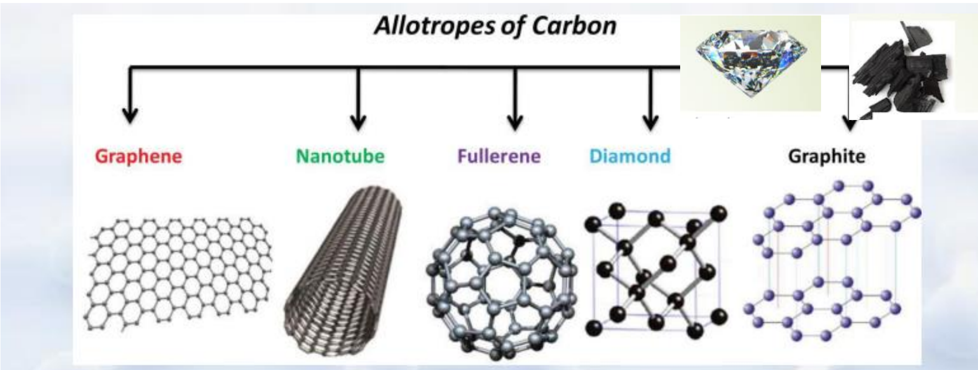


Figure 2-8 The allotropes of Carbon as classical example of “structure is function”.

function), to biochemistry (the structure of proteins) to chemistry and physics, being is some of these cases referred to as *Structure is function*.

3. Force and interaction

All interactions can be described by multiple type of forces, but the relative impact of each type changes with scale.

At the nanoscale we are witnessing a different hierarchy of forces between bodies. A range of electrical forces with varying strengths govern the interaction between structures at the nanoscale, while the role of gravity is often marginal.

4. Quantum Effects

Different models predict the behavior of matter better, depending on the scale and condition of the system; as the size and the mass became smaller, quantum effects became increasingly evident and important.

Classical mechanics, based on Newton's laws of motion, is the appropriate model to describe the dynamics of systems in the macro- and micro-world. Yet, as matter

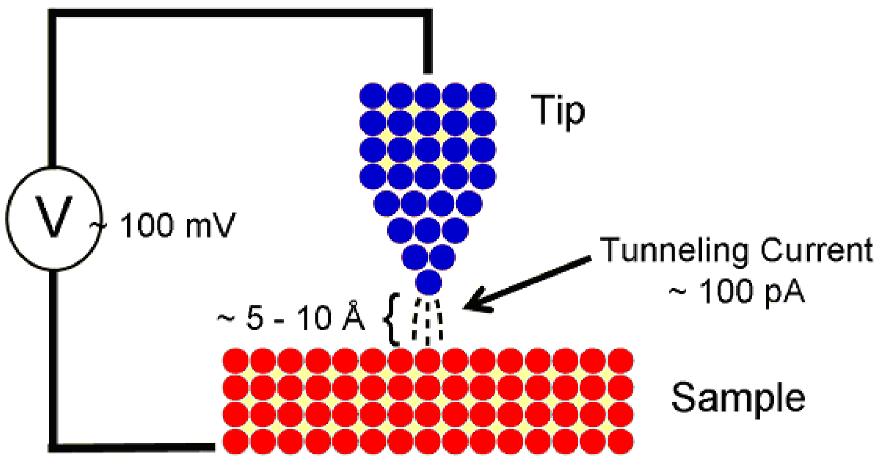


Figure 2-9 The STM tip scanning a surface: tunnelling current depend on surface-tip distance. After [130].

transitions from the bulk (micro- to macroscale) to the atomic scale, classical mechanics fails to describe the behavior of matter, and it becomes necessary to use quantum mechanics. Examples of the importance of quantum effects in nanoscience are for instance provided by the principle of functioning of STM, the optical properties of quantum dots, or the electronic properties of carbon nanotubes.

2.3.2 Applying the Foundational Science Content

5 Size dependent properties

The properties of matter can change by scaling from the bulk material to the individual atoms or molecules and exhibits new properties, often surprising.

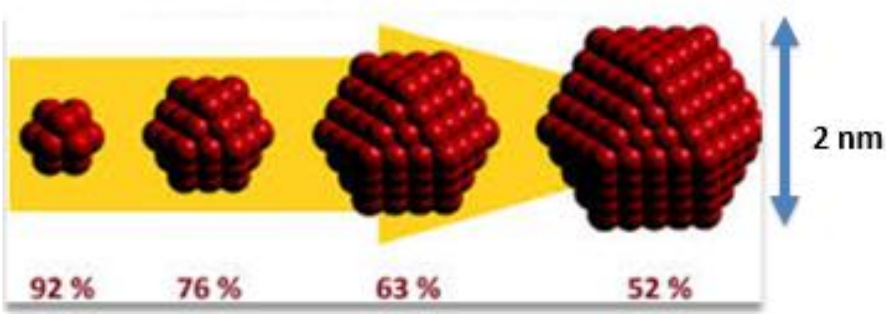


Figure 2-10 Fraction of surface atoms (S/V ratio) in Pt nanoparticles as a function of increasing diameter. After [131].

This key issue is directly linked to all the four big-ideas previously introduced. For instance, several material properties, such as in particular melting point, chemical reactivity, and optical properties, are strongly dependent on the Surface-to-Volume ratio. This is often due partly because surface atoms, due to lower coordination, have peculiar behaviours (for instance they are more reactive) relative to the bulk ones. Moreover, surface boundaries conditions introduce peculiar phenomena at the interfaces.

As far as forces are concerned, the dominance of electric forces over gravity at the nanoscale is nicely exemplified by the case of Gecko toes, where, due to nano-structuration, myriads of tiny Van der Waals forces present at each micrometric/nanometric contact point sum up to a macroscopic force, large enough to counterbalance Gecko weight. Quite obviously, quantum effects play also a crucial role in determining the properties of matter at the nanoscale as, for instance, in the case of quantum dots, for which - due to quantum confinement – the discrete electronic-state energies depend critically on their dimension.

Last but not least, for all the reasons names before, at the nanoscale small variations in the structure of material may determine huge changes in the material properties and functions. For this reason, novel materials with peculiar properties, the so-called functional materials, can be designed and realized, by fine-tuning their structure, chemical composition, and morphology. Examples of Functional materials are semiconductors, polymers, molecular crystals.

A particular type of functional materials are those characterized by a large surface to volume ratio, designed in order to maximize their interaction with the environment, as for instance the bio-inspired GeckoTape ®.

6 Self-Assembly

Under specific conditions, some materials can spontaneously assemble into organized structures. This bottom-up process provides a useful ad highly efficient mean to manipulate matter at the nanoscale and fabricate nanostructures.

7 Tools & Instrumentation

The development of new tools and instruments suitable to investigate, manipulate and fabricate the matter at the nanoscale has played and will also play in the future a crucial role in the development of nanoscience and nanotechnology, leading to new levels of understanding and to novel systems ad material with tailored properties.

The cited STM or AFM microscopes, as well as the electron microscopies, the focused ion beam, and the optical tweezers techniques, are some of the most relevant examples [54], [55].

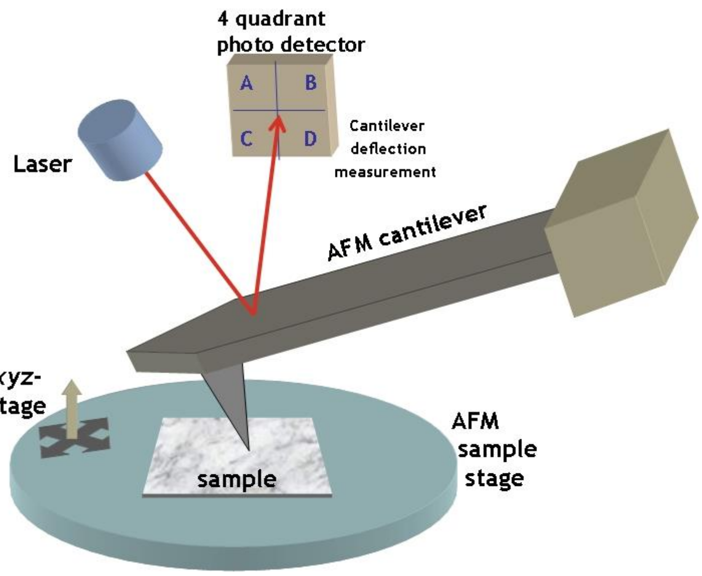


Figure 2-11 AFM - For small tip-surface distances, the Van der Waals force that acts between the tip and the sample causes a deflection of the micro-cantilever, in accordance with Hooke's law. The deflection of the cantilever is measured using a laser beam, impinging on the top of the cantilever, reflected towards a photodiode matrix that acts as an optical lever. After [132].

8 Models & Simulations

Scientists use models and simulations to visualize, explain, and predict the structure, properties and behaviour of physical system, that is very helpful in small size domain.
Theoretical computational physics and chemistry – based on quantum mechanical calculations - are playing a major role in the development in nanoscience. They complement experiment in a comprehensive understanding of the properties of materials; simulations may foresee the properties of novel material, thus allowing their tailoring and designing. Last but not least, computer simulations allow to visualize the structure, as well as the electronic, optical, and magnetic properties of nanostructures.

9 Science, Technology & Society

The advance of science requires awareness on how and why things work, and how to use technology to answer to societal needs. Nanotechnology, as a strategic and interdisciplinary science, provides an opportunity to witness and actively participate in scientific progress and in decision making about how to use new technologies.

2.4 The Nanolab Educational Project

While in the early 2000s nanoscience has been introduced only at high levels of training, the latest recommendations and educational trends prompt to introduce the basic ideas of nanoscience in every level of education [16].
It is clear that the first step to this aim is to recognize that teachers are the key players in this process. Since 2012, the Nanolab project of the University of Modena ad Reggio Emilia, has therefore pursued the objective of providing support to high-school science and physics teachers, helping them in self-training and proposing hands-on activities, designed to demonstrate the big idea of nanoscience.
A large part of the proposed nano-activities designed for young students at national and international level, either in formal and, even more so, in informal education, are actually based on the so-called "wow-effect" (see for instance the list of web-resources of Appendix 2, at the end of this chapter). They consist in high impact, spectacular but strictly qualitative demonstrations, exploiting some of the peculiar properties and behaviour of nanomaterials to fascinate and stimulate discussion. Indeed, the microscopic characteristics of such materials strongly affect their macroscopic properties, often in highly surprising ways. Several functional materials are and can be therefore used in the school labs to trigger pupils' curiosity and interest.

The Nanolab project prompt from this approach, and aims to go beyond: each experiment start from a demonstration of the peculiar properties of a few functional materials, which are nowadays easily purchased, exploiting the wow-effect to engage students' interest and to give them the motivation for pursuing further, more quantitative investigations.

In recent years, collaboration with schools and teachers have made some important needs to emerge:

1. One of the main problems of schools appear to be the limited time available for hands-on activities: TLS of several days/hours can rarely be developed, except in contexts such as on-campus stages, or thanks to highly motivated and experimentally skilful and self- confident teachers.
2. Physics curricula are becoming more and more extensive, and explicitly include the introduction of modern physics [16]. However, many teachers, which graduated in mathematics, have only a superficial knowledge and understanding of modern condensed matter topics.
3. In high school curricula, multidisciplinary is explicitly encouraged, but it is rarely addressed in practice, due to strict time schedule [16]. The multidisciplinary is an intrinsic feature of nanoscience which, for this reason, represents an educational opportunity for STEM education, as well as a communicative challenge between the different disciplinary areas.

Stemming from these reasons, we have been focusing on designing fully quantitative experiments and complete Teaching-Learning-Sequences, which are aimed to introduce the big-ideas of nanoscience, as well as the basic concepts of modern physics, in secondary school.

The chosen context is the application of the experimental method which, through observation, measurement, analysis, and interpretation of phenomena, often carried out in a collaborative context, contains all the fundamental elements for an effective learning, of both hard and soft skills. In Nanolab many activities are therefore designed as much as possible as the didactic counterparts of experiments performed in research laboratories: that is, students play with the real stuff, and explore the physics behind the phenomena in an inquiry-based approach.

The Teaching-Learning-Sequences are structured as modular experiences, which may be also separated and used singularly by teachers. The promotion of Flipped methodology, supported by a wide selection of videos, both for hands-on activities and for lectures, offers further educational instruments to teachers, to be used both for their own self-learning, and as support to lecturing or student's homework. Another useful tool for understanding *the invisible world* [56] is represented by simulations and applets: these tools are increasingly popular on the web. The use of them helps students visualizing the physical system, developing conceptual understanding, and building accurate mental models. Whenever possible, we suggest and provide guides to the use of such web-based tools.

Chapter 3: Friction, wetting, and molecular interactions

3.1 Tribology and energy consumption

The neologism "tribology" was first introduced in 1966 by Peter Jost, chairman of a group of British engineers working on lubrication, in the report "Lubrication (Tribology) - A report on the present position and industry's needs"[57] for the Department of Science and Education. Tribology derives from the Greek word *tribos*, which means rubbing: the literal translation of tribology is therefore *the science of rubbing*. It encompasses the study of friction, but other phenomena as well, such as adhesion, contact formation, wear, fracture, lubrication, indentation. Tribology is by no doubt an interdisciplinary field: no violins, no gym shoes, no bike races would exist without friction. Tribology also involves huge economic issues: as first pointed out in the Joost report and subsequently confirmed by several other studies, almost one-third of the global energy consumption can be traced back to tribological phenomena. For instance, Holmberg *et al.* [58] in 2015 analyses in detail two strategic sectors:

- **the transport sector** (cars, buses and trucks), where almost 30% of the used energy is lost in frictional phenomena
- **the industrial sector,** where energy consumption strongly depends on the level of automation, energy loss ranges from 20% up to 90% (in the extreme case of the mining industry).

The Jost commission identified the main cause of the problem in the incorrect lubrication of the moving mechanical parts: the consequent wear was recognized as the main cause for mechanical system failures. In a later work in 2017, Holmberg *et al.* [59], while discussing possible improvements, highlighted the multidisciplinary dimension of the problem:

- Surface engineering (i.e., the development of ad-hoc coatings and micro/nanostructures surfaces) as well as, anti-wear and anti-friction additives are promising and viable ways to control friction and wear, which requires intelligent design. To this aim, a multidisciplinary approach is required, which involves engineers, as well as chemists, and both experimental and theoretical physicists. In particular, at the micro-and nanoscale, theoretical modelling of interfaces and surface interactions requires sophisticated approaches, based on Quantum Mechanical Theory.

- The biomimetic approach takes inspiration from nature to find novel technological solutions. For example, the role of hierarchical structures that characterize biological organisms endowed of remarkable tribological properties - such as, for instance, the super adhesion of gecko pads or the self-cleaning behaviour of lotus leaves – has been widely studied and mimicked by tribologists [48],[60].

3.2 Nanotribology and Micro Electrical Device development

In recent years, the importance of an in-depth understanding and control of tribological mechanisms at the micro- and nanoscale has hugely increased, due to the miniaturization of magnetic storage systems, and of the so-called Electro-Mechanical devices (MEMS and NEMS - Micro and Nano Electro-Mechanical Systems). The latter integrates on a single microchip electrical and mechanical component to measure different physical quantities, such as vibration, acceleration, etc. [61]. An example of MEMS is given by the accelerometer available in every smartphone or tablet, which allows to realize the automatic image rotation function. In these accelerometers, a mass of micrometric dimensions is connected to a micro-spring: by rotating the cell phone, the mass moves, thus "transferring" the information on the direction of gravity acceleration to the spring. The spring could be realized with piezoelectric materials, allowing conversion of strains in electrical signals; alternatively, as shown in **Figure 3-1 A** the mass could be a silicon capacitor plate, so that its motion induces a measurable capacitance change. To understand the level of miniaturization and the tribological challenges involved in the motion of such small parts, in **Figure 3-1 B-C-D** a typical MEMS is compared with a dust mite (SEM Image by Sandia Laboratories). Although MEMS design and fabrication have now reached unprecedented precision, there are still limits in their real application and durability. Indeed, adhesion between the adjacent components, the relatively low power of the devices, surface contamination and capillary condensation may hinder their operation. The ability to control the tribological properties at this length scales is therefore of paramount importance for future developments of such devices.

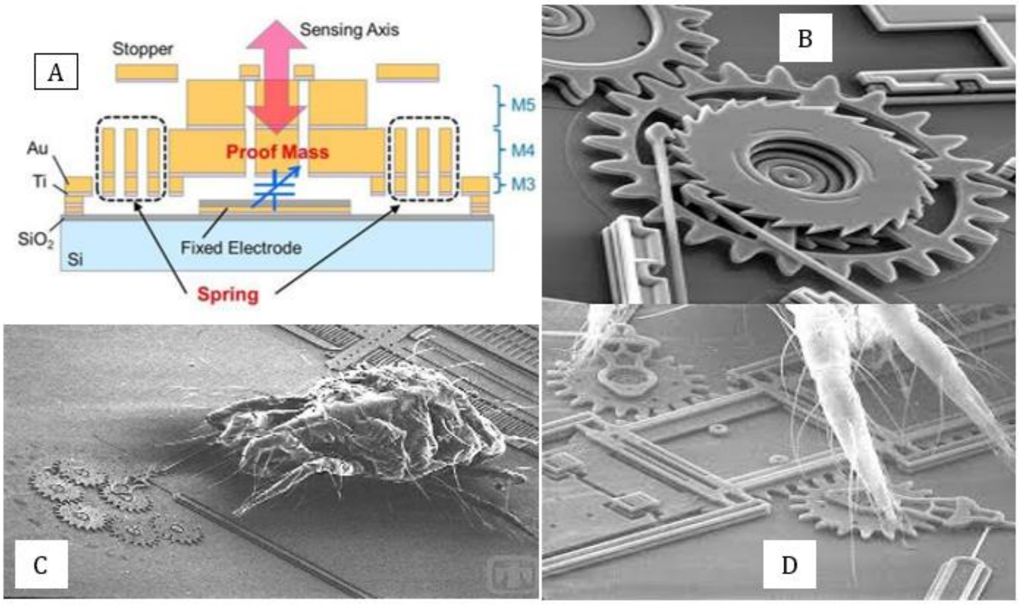


Figure 3-1. A: an example of accelerometers configuration (Keio University. Tokyo) [61]. **B-C-D**: SEM images of a MEMS; to understand the scale dimensions in figures C and D the same MEMS is compared with a dust mite - Photo by Sandia Laboratories.

3.3 Tribology and the microscale challenges

Despite the pervasive importance of the topic, the word "tribology" is unknown to most people, besides specialists, while in schools, friction is considered a marginal topic. What is the reason for such a low visibility of tribology? Popov[62] identifies it in its complexity, which results in simplification and trivialization.

In general, tribological processes are intrinsically complex, as they involve a big number of different phenomena, such as adhesion and reactivity, deformation and abrasion of asperities, presence of absorbed layers, which occur at different length scales and with different modalities, depending on the mechanical and chemical properties of the interface. Indeed, the physical and chemical interactions occurring between two sliding interfaces are yet not fully understood at all length-scale. At the macroscopic level, many technological choices are still partially based on empirical solutions, [63] since the possibility of predicting macroscopic properties still represents a challenge.

In the last decades, the development of few novel experimental techniques, such as atomic force microscopy (AFM), surface force apparatus (SFA) and quartz crystal microbalance (QCM), has allowed investigation on well-characterized materials and physical conditions at the micro- and nanoscale, providing new insight into the basic mechanisms of friction. A comprehensive overview of the subject is far beyond the scope of the present work and can be found in literature, see for example B. Busham *et al.* [64] R.W. Carpick *et al.* [65] and Krim *et al.* [66].

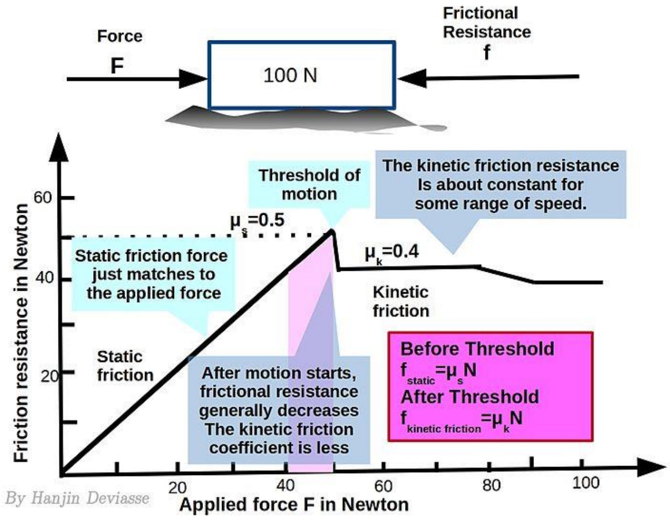


Figure 3-2 Macroscopic friction behaviour: friction force f and coefficient μ vs applied force-F. See the changes in values between static and kinetic.

3.3.1 Friction models

In the following, after a summary of the macroscopic laws of friction and their historical development, I will mainly focus on the main features of the Tabor and Bowden model, which provided the first sound explanation of the microscopic origin of friction.

As it is well known, the first two macroscopic laws of friction were formulated by Leonardo in 1493, and confirmed by Guillaume Amontons in 1699. They state that friction between two (sliding) bodies in contact is:

1. independent of the contact area

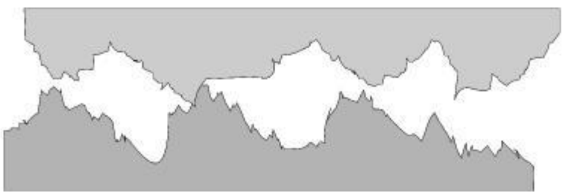


Figure 3-3 Image of the roughness between two surfaces in contact: the lateral view clearly show the very few contact points.

2. proportional to the normal force exerted on the bodies

A third law of macroscopic friction is due to Coulomb (1780) and states that:

3. the coefficient of dynamic friction is independent of the relative sliding speed.

The first explanation of friction is due to Amontons, which identifies surface roughness as the source of friction, and described the interaction between two bodies in contact, though the so-called "mechanical interlock" model, in which microscale asperities hook onto each other as rigid bodies thus hindering the relative motion.

Despite its simplicity and apparent self-evidence, this model is at least partially misleading and completely fails in predicting many phenomena, as, for instance, friction changes at high pressure, rolling friction, and adhesion phenomena. It also fails to explain several experimental observations concerning microscopic friction, as in particular:

i. By adsorbing molecularly thin films on surfaces, friction can be reduced by orders of magnitude while maintaining virtually the same surface roughness;

ii. While it is generally true that friction increases with surface roughness, when the latter is reduced to atomically-smooth surfaces, friction actually increases: highly polished smooth metallic surfaces, sharing a wider microscopic contact area, are more likely to stick together (cold-welding), than to slide frictionless.

Important early contributions in the development of a comprehensive theory of friction are due the studies of Hooke, who first introduced the concepts of deformation and cohesion, and Leonhard Euler, who first defined the friction coefficient, μ, and distinguished between static and dynamic friction.

The birth of modern tribology dates back to the 50ies, thanks to the studies of Tabor and Bowden [67] in 1967. According to their model, when two bodies are approached, only a very small fraction (maybe something like 10^{-4}) of the atoms of the respective surfaces become so near to each other (less than few nm apart) to interact significantly. In usual materials, surfaces are rough on the microscale, and only atoms belonging to matching asperities of both surfaces come into true contact, possibly forming tiny junctions. When the two surfaces are forced to slide over each other, they deform plastically or elastically, depending on the conditions and the materials, and new junctions are continuously formed, while others are severed. On average, the interaction between asperities can be described as a shear force acting parallel to the surface. Moreover, these asperities borne the normal load N – i.e the force exerted by each of the two bodies on the other in the direction perpendicular to the surfaces.

In order to explain the macroscopic laws of friction, Bowden and Tabor assumed that:

- **i.** the real (microscopic) area of contact A is independent on the nominal macroscopic area of contact between the two bodies;
- **ii.** A increases linearly with the load N, mainly due to the deformation of asperities;
- **iii.** the pressure p sustained by each asperity is essentially independent of the normal load N (this was found true in the case of plastic deformation, while it represents a sensible approximation in the elastic case);
- **iv.** a specific shear strength value s is introduced, corresponding to the average value of the shear of contacting junctions.

The total frictional force may than be written as the sum of the parallel force exerted at each junction and is therefore proportional to the actual contact area A:

$$F_f = A \cdot s \qquad (1)$$

Similarly, the total normal force is given by the sum of all perpendicular forces exerted on each junction and can be written as

$$N = A \cdot p \qquad (2)$$

Their ratio μ is therefore independent on both the actual and the geometric areas of contact, thus finding Amontons' law:

$$\mu = \frac{F_f}{N} = \frac{As}{Ap} = \frac{s}{p} \qquad (3)$$

It is interesting here to point out that, in the case of a hard and rough body sliding against a softer body, the latter may deform and adhere to the former. Bowden and Tabor found in this case a non-linear friction-normal force dependence ($F=KN^{2/3}$), which clearly contradicted Amonton's first Law.

Moreover, we here notice that the friction coefficient μ does not only depend on surface roughness, as it may be intuitively expected, but also on other properties of the two surfaces, such as, in particular, their chemical nature and their plasticity/elasticity. In other words, the shear force between asperities does not (only) derive from mechanical interlocking, but should also be ascribed to adhesive forces. This fact also provides some clue to the origin of the lubrication mechanism, in which the so-called 'tribofilm' reduces the friction coefficient, not by reducing surface roughness but by changing the adhesive properties of the interface. Nowadays, a comprehensive description of tribological phenomena must take into consideration the so-called *Third-body* concept.

The third body

The third body may be defined as the region between the two sliding surfaces and should be considered a third material in its own right, characterized by different chemical composition and structural properties with respect to those of the two sliding materials. It is this intermediate space that determines the tribological properties of the materials. The third body properties are influenced by the presence of humidity, lubricants, absorbed layers, debris from wear and scratches, as well as atmospheric composition and temperature.

One of the most interesting phenomena related to the third body is superlubricity, i.e. a regime of motion in which friction vanishes ($\mu < 0.01$) . In the case of diamond sliding on diamond, for instance, $\mu \approx 0.01$ in atmosphere, while in ultrahigh vacuum the friction coefficient hugely increases up to $\mu \approx 10$. The explanation of this difference is that, while in atmospheric conditions diamond surface dangling bonds are passivated by hydrogen and oxygen, in vacuum they are reactive and cause the two surfaces to strongly adhere [68].

Superlubricity may also occur in the absence of a third body, as in the case of dry incommensurate contact. When a graphite flake slides on an atomically flat graphite surface, the coefficient of friction strongly depends on the mutual azimuthal orientation of the two crystalline structures: if the mutual orientation is such that the surface atomic structures are incommensurate, friction vanishes and superlubricity is observed. On the other hand, when the upper flake is in registry (commensurate) with the substrate, a large friction is observed and stick–slip motion occurs. This finding is at the basis of the lubrication properties of graphite [69].

3.3.1 The Stick-slip motion

In some situations, a body dragged over another does not move smoothly. Its motion can be instead described by successive phases of adhesion, which alternate to sliding phases. These different phases are directly connected with a corresponding change in the friction force: during the adhesion phases, friction force increases until it reaches its maximum value, which corresponds to detachment and onset of the sliding phase; during the latter, the two bodies slip one on the other, and a lower dynamic friction force is observed. This behavior is called stick-slip motion, and a wide number of examples of this effect may be found in daily experience: the music of strings instruments, like violin or harp, the noise caused by rubbing a wet finger along the edge of a crystal glass, the sound of basketball shoes squeaking on the court etc. In nature different stick-slip solutions are used to produces specific sounds: locusts and cicadas slides their wings and spiny lobsters rubs their antennae over their heads producing the known typical sounds, see for example S. N. Patek et all [70].

A simple macroscopic model of stick-slip motion is shown in **Figure 3-4** in which a mass is pushed horizontally by a drive system: when the drive system starts to push, the spring R is loaded and the force applied to the mass M increases, until it exceeds the maximum value of the static friction between the mass and the floor. As M starts

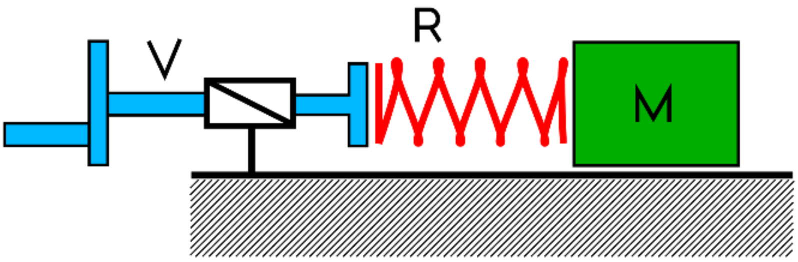


Figure 3-4 stick/slip motion in macroscopic model/situation- After [133].

sliding, the friction coefficient decreases from its static to its dynamic value, so that the force applied by the spring on the mass is larger than kinetic friction and the mass accelerates. This in turn, causes the spring elastic force to decrease, until it becomes smaller than dynamic friction: from this moment M starts to decelerate until it comes to a stop. As the drive continues to push, the spring is loaded again and the cycle restarts. A similar mechanism occurs also at the microscopic scale, as shown in the atomic model described in fig: in this simple model, the atom B_0 belongs to the upper substrate, its bond being represented by the spring. The curve V_{BB} in the lower diagram depicts the corresponding elastic potential energy. The lower substrate is moving right, and the interaction between its surface atoms and B_0 is described by the periodic potential V_{AB}. V_s is the total potential felt by B_0, given by the sum of V_B and V_{AB}: as the lower substrates move the V_s profile changes. In **Figure 3-5** (a) the position of B_0 corresponds to the minimum of the V_{AB} potential. While the lower substrate moves

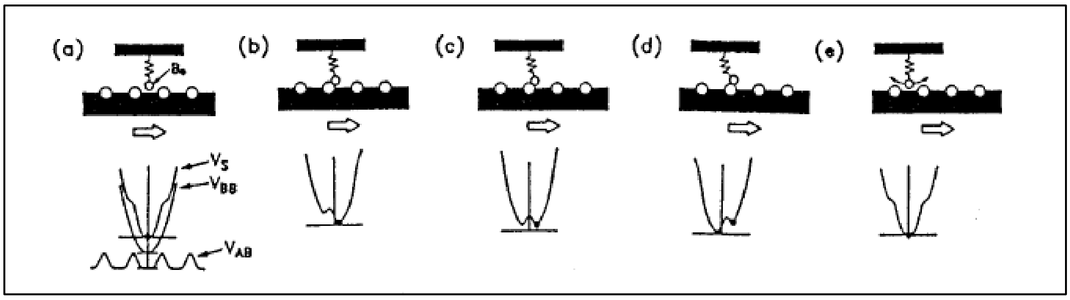


Figure 3-5 Representation of the motion of the atom B_0 in the independent oscillator model: atom-on-spring and atom-in-potential. The left-most diagrams display the relevant potentials subsequent panels illustrate the response of B_0 to progressive sliding of the lower layer of atoms. The location of atom Bo is represented by a black dot in the combined potential VS plotted below each atom-on-spring diagram. After [71].

right, the atom B_0 remains stuck in the right side of the potential well, as in **Figure 3-5** (b)-(d) (stick phase), until it snaps (slip phase) over the potential barrier reaching the new minimum position in Fig.5 (e). During the stick phase, the spring is loaded (this correspond to an increased strain energy): this energy is released in the slip phase and converted into vibrational energy of the surface atoms [71].

Though this model represents an extremely simplified description of any realistic interfaces, it provides an extremely valuable and clear description of the mechanism of energy dissipation during friction. Indeed, it shows how the energy required to strain and eventually cleave the interface atomic bonds may be transferred to atomic vibrations (phonons), i.e., to substrate heating.

3.4 Wetting and microfluidics

A very important property of surfaces is their degree of wetting (wettability), a measure of the degree of adhesion of a drop of liquid deposited on them.

This property strongly depends on intermolecular interactions, both those occurring in the bulk of the liquid and those occurring at the liquid/solid, solid/air and liquid/air interfaces. In the case of solids, it is mainly dependent on the molecular terminal groups present at the surface, which may be hydrophobic (preventing water wetting) or hydrophilic (favoring water wetting).

3.4.1 Wetting properties of surfaces

In general, we call **adhesion forces** those occurring between the solid and the liquid, while we call **cohesion forces** those occurring inside the liquid bulk. Whenever a surface is created from the bulk of a material, for instance cleaving a solid, or creating a liquid droplet, bonds between atoms or molecules within the material have to be

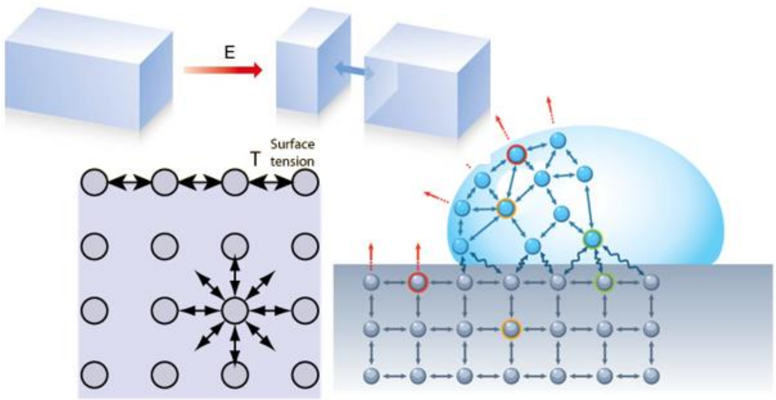


Figure 3-6 Surface Tension: Arrows with straight lines represent cohesion forces that for surface atoms are not isotropic and balanced as they are instead for bulk atoms. Arrows with wavy lines represent adhesion forces. Image from Nanolab [72].

broken (see **Figure 3-6**). The surface free energy is defined as the work done on the system, required to create a unitary surface area. Dimensionally, this quantity is an energy per unit surface [J/m^2], or equivalently a force per unit length [N/m]. Indeed, the surface energy is commonly referred to, in particular in the case of liquids, as surface tension, defined as the force per unit length required to increase the interface frontier.

It is important to notice that, for both solids and liquids, this quantity is not a property of the single material, but rather of the interface, and it is determined by the difference between cohesive energy and adhesion energy. In the case of water, for instance, the cohesive energy, which is due to H-bonds between water molecules, is much greater than adhesive energy (water molecules does not bond to air – i.e., N_2 or O_2 molecules). The water surface tension γWA is therefore quite significant (73 N/m at room temperature) and suspended water droplets tend to assume a spherical shape, which minimizes the surface to volume ratio. In order to provide a quantitative classification of surfaces according to wettability, two important parameters are usually introduced, i.e. static contact angle and roll off (or tilt) angle.

Static contact angle

If we consider a liquid droplet deposited on a solid surface, three different phases -- and correspondingly three different interfaces -- should be taken into account, i.e., water/air, water/solid and solid/air. The equilibrium shape of the droplet is than determined – neglecting the effect of gravity – by the Young equation:

$$\gamma_{SA} = \gamma_{SW} + \gamma_{WA} \cos\theta, \qquad (4)$$

where γ_{SA}, γ_{SW} and γ_{WA} are the surface tension of the solid/air, water/solid and water/air interfaces, respectively, while θ is the so called static contact angle, defined as the angle formed by the tangents to the three interfaces in the point where they met, as shown in **Figure 3-7** contact angles less than 90° are associated with hydrophilic surfaces, i.e. surfaces capable of significant bonding to water molecules, for which adhesive forces dominates on cohesive ones, while hydrophobic, for which cohesive forces dominate, surfaces have contact angles larger than 90°.

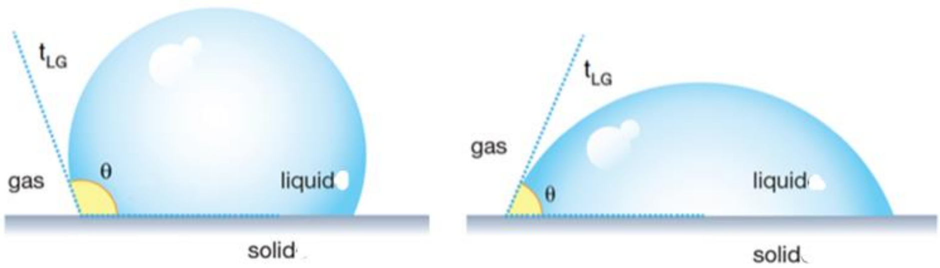
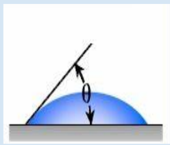
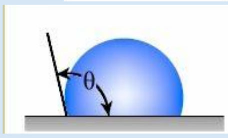


Figure 3-7 Static contact angle for Hydrophobic (left side) and Hydrophilic surface (right side) [72].

Table 3-1 Static contact angle and Hydrophobic/Hydrophilic behaviour-Nanolab [72].

Contact angle	Surface type		
0°	Superhydrophilic		
< 30°	hydrophilic	**Hydrophilic**	
30°-90°	intermediate		
90°-140°	hydrophobic	**Hydrophobic**	
>140°	Superhydrophobic		

In the case of water, surfaces may be classified according to the value of the contact angle as reported in **Table 3-1**. Hydrophobic surfaces naturally minimize the interface between liquid and solid surface. The larger the contact angle, the more spherical is the drop shape and the more hydrophobic the surface. On the other hand, the smaller the contact angle, the flatter is the drop shape and the more hydrophilic the surface

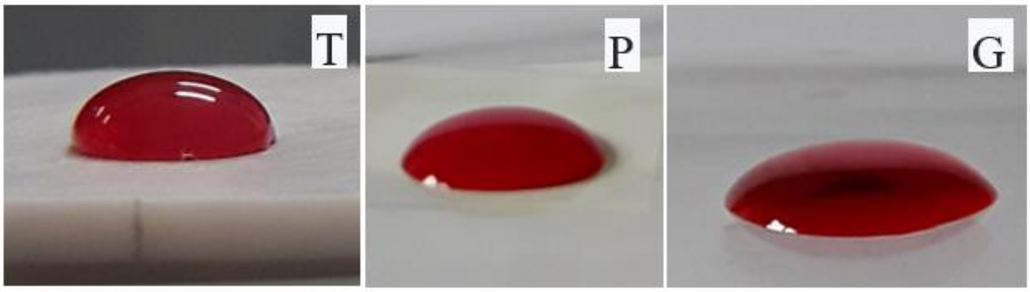


Figure 3-8 The same amount of coloured water (5 drops), deposited on different surfaces; from left to right: Teflon (T), Plastic (P), Glass (G). The differences in the contact angles are evident.

Glass with no special additional treatment for instance is hydrophilic: water drops completely wet the surface, with a contact angle of just a few degrees. On the other hand, Teflon is super hydrophobic and drops exhibit a rounded shape.

Roll off angle or tilt angle

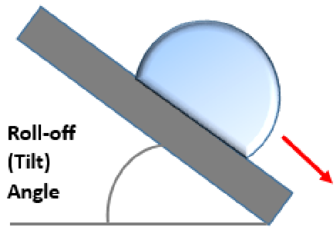


Figure 3-9 Roll off o Tilt angle is the minimum angle you have to tilt the surface to start a drop rolling downhill.

The contact angle provides information on the system static equilibrium. However, in many cases the surface most important feature is whether it allows the liquid to quickly flow away. For this reason, when superhydrophobic surfaces are considered, it is useful to introduce a new parameter. The tilt angle (also called roll off angle) is the minimum angle you have to tilt the surface to start a drop rolling downhill. Surfaces are said to be superhydrophobic when both the static contact angle is around 150° and the tilt angle is <10°.

Contact angle hysteresis

Tilt angles are also related to the so-called contact angle hysteresis, Δϑ. As shown in **Figure 3-10** this is defined as the difference between the rear contact angle (ϑ_r), and the front contact angle (ϑ_f). Typical values of Δϑ in usual solid surfaces may reach 50°. The difference between the two angles is due to substrate inhomogeneity (small heterogeneities, asperities, etc.), which hinders the drop front movement.

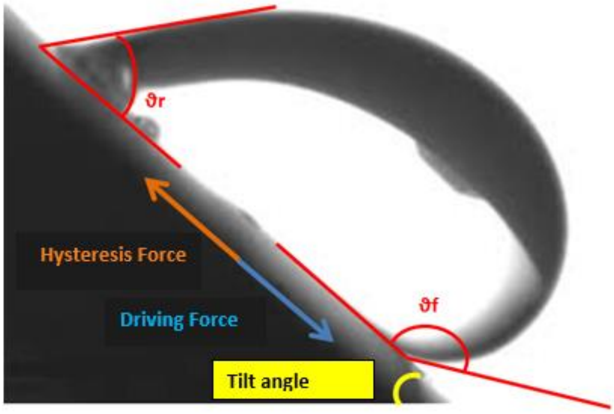


Figure 3-10 Contact angle hystheresis $\Delta\vartheta = \vartheta_r - \vartheta_f$ is a dynamic parameter offering information on drop mobility on the sample surface.

3.4.2 Wettability at the micro- and nanoscale

Surface wettability plays a fundamental role in the research area of microfluidics, an interdisciplinary field devoted to the study both at the basic and applied levels of manipulation of micrometric quantity of fluids (typically µl range) flowing through

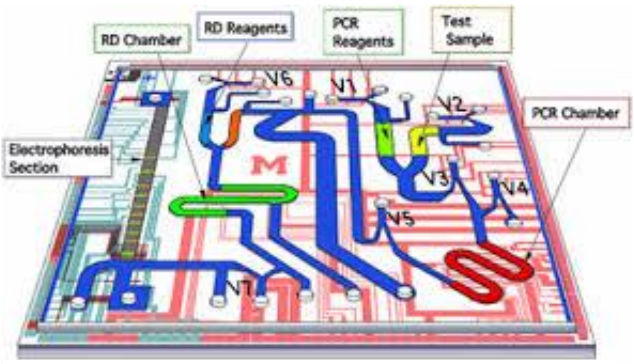


Figure 3-11 Lab on a chip showing various laboratory processes (www.azonano.com- 2013).

sub-millimetric channels. Microfluidic, which has emerged since the beginning of the 1980s in the context of inkjet printheads technology, plays now a central role in lab-on-a-chip technologies, micro-propulsion, and micro-thermal technologies. A lab-on-chip device represents a friendly clinical diagnostic care-point offering optical or electrical information reading, schematically shown in **Figure 3-11**. These types of devices are used for applications in molecular biology, for biomolecular recognition, in medical diagnostics, for analysis of the environmental pollutants of the quality of food, and in the exploration of extraterrestrial environments. They are also the ideal candidates for rapid, simple, and widespread diagnostics on a large scale level, that is required, for example, in the event of pandemics.

In a lab-on-chip, MEMS and NEMS technology are integrated with biological and chemical detection process. The detection is realized by functionalization of a silicon surface with reactive chemical molecules, able to capture the molecular probe with high specificity and efficiency, through electrostatic or covalent bonds [73], [74], [75], [76].

The development of micro- and nano-fluidic devices clearly calls for investigation of the wetting properties of surfaces at the micro and nanoscale. In the following section, the effect of surface roughness and texture is briefly discussed, showing how micro- and nano-structuring represent a valuable route to tailor the wetting properties of surfaces.

Influence of surface roughness on wetting

The wetting properties of a surface are strongly influenced by the presence of impurities. For example, organic contaminants actually reduce wetting and on already hydrophilic surfaces they result in contact angles greater than average.

Surface morphology and roughness also play a fundamental role in determining the wetting properties of a surface. This issue was independently tackled by Wenzel in 1936 [77] and Cassie and Baxter in 1944 [78], who developed two distinct models, describing two possible regimes occurring on rough surface.

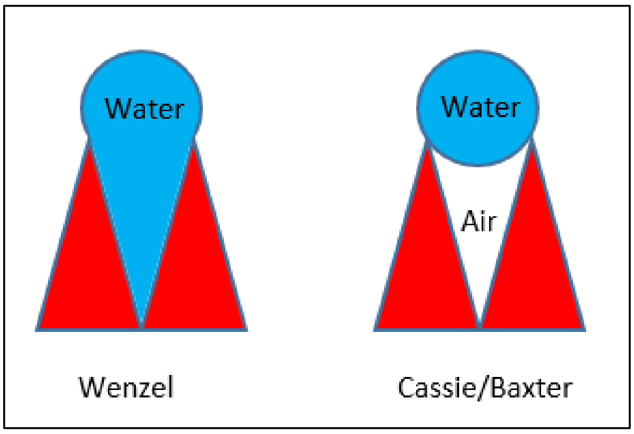


Figure 3-12 Figure 16 different wetting states on a structured substrate: (a) Wenzel and (b) Cassie-Baxter regime. After B. Zhang et all [79].

As shown in **Figure 3-12**, in the homogeneous wetting regime, or Wenzel regime, the liquid fills in the roughness grooves of the surface. In the heterogeneous wetting regime (Cassie-Baxter), on the contrary the surface is composed of patches of both air and solid.

In Wenzel regime therefore, surface roughness increases the available surface area, thus increasing the adhesion phenomena. This implies a decrease in the **measured contact angle** θ^*, according to

$$\cos(\theta^*) = r \cdot \cos(\theta), \qquad (5)$$

where the roughness ratio r is the ratio of *true area* of the solid surface to the *apparent area*.

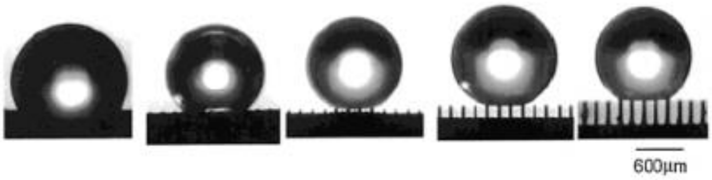
In the case of Cassie-Baxter instead, some air remains trapped inside the groves below the liquid droplet, and the observed increase in the angle of contact can be described by

$$\cos(\theta^*) = r_f \cdot f \cdot \cos(\theta) + (1 - f), \qquad (6)$$

where r_f is the roughness ratio of the wetting patches, and f is their surface fraction. Surfaces which are structured into alternating pillars and voids at different hierarchical levels (micrometric pillars with nanometric asperities manufactured on their top) exhibit a superhydrophobic behavior which can be described within the Cassie-Baxter model.

Such effect, that has been observed on specifically designed surfaces [79], occurs in the case of self-cleaning natural surfaces, such as, for instance, lotus or cabbage leaves. Indeed, the lotus self-cleaning behavior is the reason because this plant is known as a symbol of purity or that because super-hydrophobicity is also known as "lotus effect".

On such structured surfaces a drop appears as almost suspended in air, with an almost perfect spherical shape (contact angles typically between 160° and 175°) - see



Contact angle of water θ' [deg]	114	138	155	151	153
Roughness factor r	1.0	1.1	1.2	2.0	3.1
Pillar height c [µm]	0	10	36	148	282

Figure 3-13 Drops of water on solid microstructured surfaces covered with a Teflon film. Contact angle change as a function of pillar height i.e. of roughness factor *r*. SEM Images. After [80].

Figure 3-13 [80] - and rolls off easily even for very small tilt angles. The reason for this is quite intuitive: the fraction of contact surface between the liquid and the solid is reduced to asperity tips only, so that the adhesion forces, which make the drop stick to the surface, are almost negligible, while cohesive forces prevail.

This is clearly visible in **Figure 3-14**, **right side**, where a scanning electron microscopes image of microscopic water drops on a lotus leaf is reported, showing that water sticks only the top of the leaf pillars.

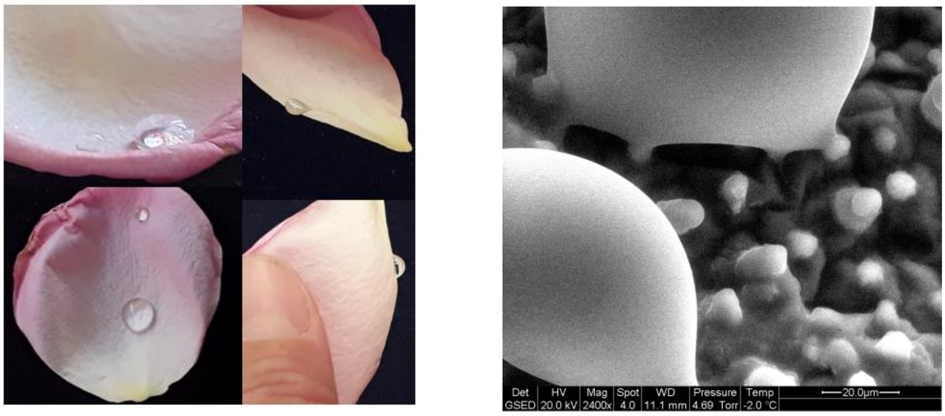


Figure 3-14 Left: Petal Effect- different geometry for a water droplet on a petal of rose, perfectly rounded on the left (upper view side) but extremely high adhesion in vertical geometry or turning upside down the petal (right box of the image). **Right**: lotus Effect - ESEM image of water droplets deposited on a lotus leaf (dried), the drops of water adhere only to the top of the tips of the surface microstructures.

While the lotus effect is widely known, few people have ever heard of petal effect. It may be useful to compare the two of them as examples of the effect of hierarchical structures on the wetting properties of surfaces. In some types of rose petals, water droplets, tough exhibiting high contact angles (see the left side of **Figure 3-14**) stick tightly to the petal surface even when turned upside down (see **Figure 3-14**, top of the right side).

On the rose petals, a hierarchy of micro and nanostructures are observed, apparently similar to those of the lotus leaf: rows and rows of ordered and very close micro-papillas, similar to extremely small pimples, cover the whole surface. Those micro-papillas are covered by nano-grooves, 760nm large. These are too small for water to easily seep in, thus accounting for the surface hydrophobicity (Cassel-Baxter regime). However, as shown in **Figure 3-15**, the spacing between rose petal microstructures is larger than the one of Lotus leaf, allowing water to seep in more easily (Wenzel regime). Water soaking gives rise to rather strong interactions with the petal surface, thus accounting for the droplet strong adhesion [72].

Figure 3-15 Petal effect - Wenzel regime (left) and lotus effect - Cassie/Baxter regime (right).

3.5 Friction and Tribology in educational research

In standard physics curricula, both at high-school and undergraduate levels, the macroscopic laws of friction are usually introduced phenomenologically. Friction, together with normal reaction, tension, and elastic forces, is introduced as an example of macroscopic force, the focus being students' ability to understand and apply Newton's laws and conservation principles rather than to acknowledge the common microscopic origin of these forces, as derived by an atomistic description of matter.

According to Popov [81], the cause of this lack of attention to the topic should be sought in its complexity, which results in simplification and trivialization. An accurate description of friction down to the micro- and nanoscale may at first sight appear far too complex for high-school curricula, as gaining a throughout understanding of the microscopic origin of friction involves complex topics such as the description of non-equilibrium disordered systems, chemical reactions at surfaces and elementary energy dissipation processes, which require the sophisticated experimental and theoretical approaches of modern tribology [66].

Nevertheless, teachers should not be discouraged by this intrinsic complexity, but rather consider it as an opportunity to design a novel and effective way to introduce students to modern physics and chemistry. This is particularly important for those realities, such as the Italian one, in which these disciplines are taught separately. A large study on chemical bonding misconceptions [82] shows that the use of simplified and sometimes inaccurate models may produce misconceptions or clutter ideas in students, negatively influencing their general cognitive development and the ability to understand and explain reality.

In recent years, the marginal role of friction in physics courses, even in the laboratory practices, has been widely discussed, and several attempts have been made to bring tribological phenomena to the attention of STEM teachers. New didactic approaches have been devised, which aim at introducing students to the subject and help them to gain a basic understanding of the complex phenomena underlying friction.

The first extensive educational study of friction at the microscopic level are those of Corpuz and Rebello of 2006 [83], 2011 [84] and 2012 [85]. Their results concerning the progression of students' mental models and the conceptual change dynamics have represented a fundamental basis for many later studies. They have investigated students' mental models on microscopic world, showing how much students' explanation of microscopic phenomena are influenced by their perception of the macroscopic world. Indeed, in most cases, students think that what they know at the macroscopic level should be also true at the microscopic one. To promote students' mental model evolution towards an understanding of the differences between the microscopic and macroscopic domain, they designed and validated a TLS designed to investigate the microscopic origin of frictional phenomena. They aimed to the following educational goals:

1. Friction is due to the "electrical adhesion" of atoms.
2. Friction force depends on the microscopic contact area
3. Friction force varies with roughness in a non-monotonous way, as shown in Figure 3-16
4. When two surfaces become microscopically smooth the friction would be higher if the area of interaction increases.
5. Atomic friction is described by the equation

$$f = \mu \cdot N + c \cdot A, \qquad (7)$$

where A is an adhesive term. During their TLS, without any introductory lesson, students alternate IBSE experimental activities, based on the sliding of different types of materials, and reflection activities, in which they answer questions and try to unfold the observed phenomena (hands-on and minds-on activities), that include cognitive dissonance. At the end of this path, students are asked to create a mathematical model to explain friction at microscopic level (i.e., the formula of item #5). In the 2006 paper (involving two students), both of them were able to correctly represent the graph of **Figure 3-16** by recognizing the different behavior between micro and macro scale; however only one of them wrote the correct mathematical formula and considered the key-role of the true area of contact and the electrical (i.e. intermolecular forces) interactions.

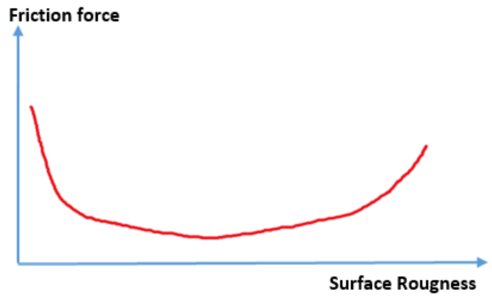


Figure 3-16 Friction Force vs. Roughness of Both surfaces as considered in Corpuz & Rebello [83].

In 2011, Corpuz and Rebello reported the results of their further investigation [84], which regarded two interview sections, conducted with 11 students enrolled in modern physics courses. Questions were designed using multiple representations. The first section focused on establishing students' mental models regarding

- the surface morphology at different length scales;
- the laws of static friction at the atomic level;
- the differences between static and dynamic friction at the atomic level.

The second section of the interview focused on establishing students' explanations of

- the mechanism of lubricants;
- how surface roughness affects friction.

This second phase was realized one or two days after the first one, to test and validate the persistence of previous learned concepts, and to offer students time for reflection.

According to Guba [86], to increase the dependability of data collection, this second interview started by asking students to recall and summarize what they had said during the first session: all students were able to do this accurately. The interview implied both oral answers and multiple representations as, for instance, drawing. Some examples of questions are:

"If we keep zooming in, we will come to the atomic level where we will see individual atoms."

"If we keep zooming in, we will come to the point where we see atoms which look like fuzzy bumps [student draws atom with an electron cloud, of how the electrons are arranged."

Students' sketch of the atomically smooth surface often showed atoms lining up, while in rough surfaces atoms are more scattered apart. The analysis of students' answers showed that the prevailing mental model of friction is the interlocking mechanical model. Only one student considered chemical bonding to explain microscopic friction. Moreover, Corpuz results showed that most students think that what occurs at the macroscopic level is also true at microscopic one, and in particular that atoms can be considered as rigid spheres.

As I will discuss in the next section, the latter misconception has been also largely reported in educational chemistry literature [87] and clearly points out a fundamental challenge that should be faced to effectively introduce nanoscience (or, more in general, modern physics) in schools, i.e., the ability to convey a correct – though simplified - model of atomic structure and intermolecular interactions.

In 2012 the same authors, starting from their previous mental model investigation, redesigned a TLS [85] – which was validated through several iterations and tested with over 30 students - based on a conceptual change strategy, integrating the cognitive conflict and applying the Karplus three-phase learning cycle [88].

The first, exploration phase, aim to activate students' prior knowledge about friction and Amonton's law. During the second, concept-construction phase, students were asked to use multiple representations to explicit their model: for instance, they were asked to sketch how smooth or rough surfaces appear at the atomic scale.

Eventually, in the third application phase, discrepant events created a cognitive conflict which students were asked to solve. For instance, students were asked to consider two different interfaces, one formed by atomically smooth surfaces, and the other by rough surfaces, and predict which of them displayed larger friction: they predicted that friction increases with roughness. They were then asked to perform a dedicated experiment, finding a different result, which generated a cognitive conflict.

Several other research groups, led by Besson [89][7], Montalbano [90], and Onorato [91], designed different TLSs on friction, for both secondary school students and in-service teachers, thus guaranteeing a large statistic. These studies are based on a hands-on approach and realized using poor materials, so that feasibility in schools laboratory is guaranteed. They, therefore, provide a significant contribution to bring educational research closer to school application and reality.

The Educational Physics group in Pavia worked extensively on the didactic of friction, [89] designing a TLS based on the didactic reconstruction model and focused on the investigation of student conceptions. The main points of the sequence may summarize as follows:

- Introduction of simple qualitative experiments to illustrate different types of friction, enhancing the importance of the phenomenon by introducing significant examples taken from daily experience;
- Qualitative experiments, which make students acquainted with the different types of friction, materials, and situations: in particular rubber and other materials which do not behave according to Amounton's laws are also probed;
- Simple qualitative mechanical models aimed at mimicking the energy transfer from sliding motion to the internal parts of the system.

During these investigations, students were asked to provide quantitative relations describing the observed phenomenological laws and stimulated to produce friction models. The educational path was proposed to students and teachers of several secondary school. In 2010 Besson and his group developed a new TLS on friction, adding new experiments involving rolling friction [7]. The analysis of their previous didactic results was also considered, according to the Duit Model [92]. The Pavia's project thus created a bridge between educational research and school, offering an open-source structure, with an essential core of contents, conceptual paths, and methodological choices, suitable to customized re-design by teachers. Secondary school teachers receive a kit (suitcase) containing the material for some experiments and some worksheet, they are asked to test the sequence making personal educational choice, by considering their students' cognitive problems and difficulties, thus contributing, by means of pre-test e post-test, to educational research. This approach is mainly devoted to the study and understanding of macroscopic friction laws.

Instead, the TLS proposed by Montalbano [90] aimed to promote awareness of the microscopic origin of friction phenomena and also to introduce quantitative measurements and uncertainty evaluation. The main points of Montalbano's TLS are the following:

1. A qualitative introduction to friction;
2. Students predict the behaviour of different sliding surfaces by using their previous knowledge and experience;
3. Students perform qualitative experiments on sliding in different situations; they made observations and then made and check new previsions recursively. During this stage, the recorded description changes were similar to those observed by Corpuz, providing a more significant statistics data;
4. Students perform also quantitative experiments to verify Leonardo's laws, which sometimes gave results different from what they expected, that they are called to interpret.

Despite the general interest shown by students, the author pointed out some critical issues that negatively influenced students' understanding, as in particular difficulties in understanding basic concepts, such as direct and inverse proportionality, in merging different observed behaviors in a unique framework and in evaluating experimental uncertainty.

The use of computer simulation and visual models to increase students' ability to build effective models were also suggested, as well as the idea of exploiting IR - thermal imaging to study friction effects. Actually the measurement of energy dissipation due to friction by means of an IR-camera was also designed by J. Haglund, as of a larger study aimed at investigating dissipative processes and heat conduction [93].

3.5.1 Surface and molecular interactions: bridging the gap between physical and chemical sciences

Chemistry and Physics are often taught and learned as totally separated subjects and, sometimes, by teachers that are not actually graduated in these disciplines. Teachers of different disciplines and different background may often have different teaching objectives, that can lead to simplification or even inaccuracy.

In Italy, the atomistic nature of matter is introduced in the first year of the chemistry curriculum (15 years old students) and, in this context, pupils become familiar with the idea that the properties of matter depend on mutual atoms and molecules interactions. Transferring and applying these same concepts to physical phenomena is not trivial, and it is often postponed to the last high-school year, when modern physics is introduced.

Misconceptions at atomic/molecular level

Empirical evidences proved that what students already know plays a key role in their learning process Treagust-Duit [94] - [95].

It is therefore here extremely important to revise the literature examining the main students' misconception and preconceptions in chemistry. I will mainly refer to the work of Griffit and Preston [87], who identified misconceptions related to the fundamental characteristics of atoms and molecules, by interviewing and analyzing the drawings of 30 Canadian 17-year old students, and that of Garnett [96], who realized a comprehensive review on chemical misconceptions concerning the nature of matter, space and forces between particles, bonding and molecules arrangement.

Among all the misconceptions listed and discussed in these works, I summarize in the following those which are more strictly related to our topic:

- Molecules are macro in size, heavy enough to be weighed;
- Atoms may be seen with an optical microscope;
- Pressure may affect the shape of molecules;
- Atoms behave and looks like solid spheres;
- Atoms and molecules share the same properties of the corresponding macroscopic, bulk sample. For example: gold atoms are gold in color, glue molecules are sticky, water molecules are larger and heavier when they are in solid phase than in gas, etc.;
- Matter is continuous and there is no space between particles;
- Matter exists between atoms (i.e., it is difficult for students to imagine the empty space between atoms or molecules).

Many of such misconceptions may be associated with difficulties of students in visualizing matters at atomic scale in terms of particulate model. Several students have the tendency to transfers the macroscopic properties to the microscopic level. These difficulties concerning abstract and unobservable quantities were recognized within the Piagetian epistemological framework and several authors suggest the use of examples taken from real life and well-guided cooperative learning activities to lead students *through the construction of their own knowledge* [96].

Harrison and Treagust [97] showed in 1996 that in teaching designing it is important to take into account student’s difficulties in separating models from reality.

They classified the possible types of models describing a physical phenomenon and observed how they were used by secondary students' completing a chemistry course. Authors found that none of the students recognize that *"the models they were using were only models…. not the depiction of reality"*. Furthermore, many students prefer models that are both discrete and concrete, for example electron clouds are seen as structures in which electrons are embedded, while atoms are drawn as solid marbles. Moreover, words commonly used both in chemistry and biology as, for instance, nucleus and shells, may became a source of misconceptions: so that several students think that atoms can reproduce themselves and grow, like a cell, or that they are alive because they move.

A new didactical point of view to overcome students misunderstanding and, at the same time, to introduce key principles of quantization has been introduced by Taber [98]. He interviewed a small group of U.K. 16-18 years old students, at entry university level, and investigated how students conceptualized topics like atomic orbitals, atomic structure, molecular systems, bond, energy levels. The study showed that students had difficulties conceptualizing quanta and making sense of the orbital idea; they were however very interested in understanding the quantum model of the atom and appreciate basic notions of the structure of molecules in terms of orbitals. They were also helped by a careful choice of terminology, aimed at differentiating microscopic modelling from the everyday experience. In particular, to avoid confusion with the word *particle* - that in everyday language indicates small, but still macroscopic, portions of matter (such as grains of powder) - Taber chose to introduce the collective label *quanticles* to refer to subatomic particles, atoms, ions and molecules. The aim of this neologism is to differentiate macro and micro representation, thus helping students to separate models from reality.

A new educational bottom-up approach

In 2010, Levy-Nahum and Taber proposed an innovative and very challenging approach to the teaching of chemical bond concepts [82]. Starting from the previous Taber's work, they suggested a bottom-up framework - which has been since 2007

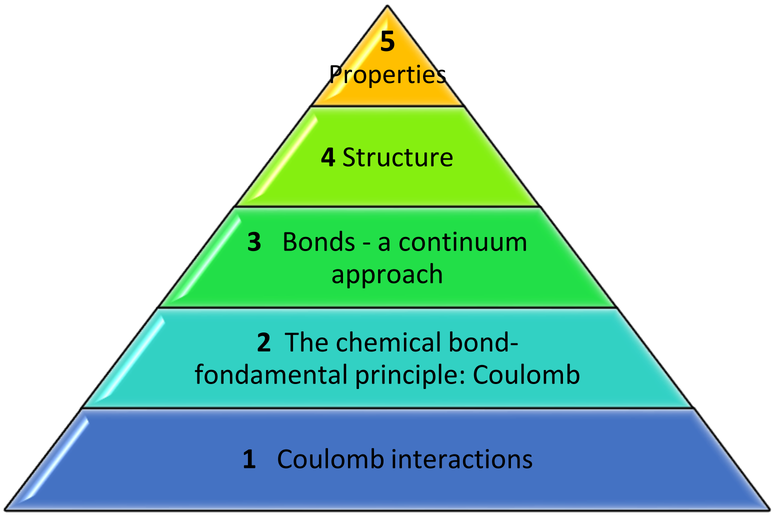


Figure 3-17 Schematic illustration of a new 'bottom-up' framework for teaching chemical adapted from [79]. Teaching arises from a small number of fundamental principles instead of presenting a large number of concepts. It starts to introduce isolated atom principle (stage 1), followed by the discussions of general principles of chemical bonding between two atoms (stage 2), which are used to discuss the different traditional categories of chemical bonding as extreme cases of various continuum scales (stage 3). Equipped with this knowledge, students can then construct a coherent understanding of different molecular structures (stage 4) and properties (stage 5). After [82].

widely applied in Israel high schools - based on the idea that "*to fully understand microscopic concepts students must be familiar with mathematical and physical concepts and with laws that are associated with the key bonding concepts, such as orbital, electro-negativity, electron repulsions, polarity, and Coulomb's law*".

This approach defines chemical bonds starting from the underlying basic principles of single atom electrical interaction, instead of presenting each different bond type as a different entity.

This novel bottom-up framework can be summarized in five stages, as schematized in **Figure 3-17**:

Stage 1: Introduction of the principles that explain the properties and structure of isolated atoms by using the *quanticle* concept;

Stage 2: General discussion on the origin of bonding between two atoms, starting from a qualitative description and general principles, i.e. Coulomb's law and electrical interaction, which is intuitive but also consistent with quantum mechanics. The physical relation between potential energy and force is introduced and used to explain the concept of stability as related to energy minimization. The above principles are best explained by considering the energy curve for any two isolated

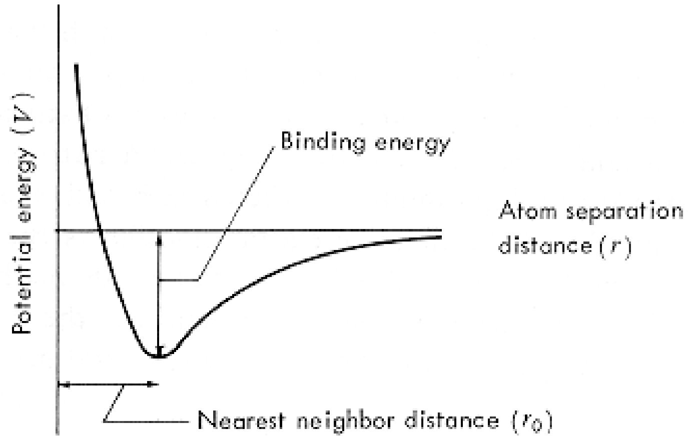


Figure 3-18 Example of a generic interatomic/ intermolecular potential energy as a function of the distance between the two atoms/molecules. After [134].

atoms (**Figure 3-18**) showing the relationship between potential energy and inter-nuclear distance. It is important here to highlight that this description is common and appropriate to all kinds of bonds.

Stage 3: This stage aims to emphasize *"that a continuum scale exists between extreme cases of qualitatively different bonding scenarios*", and favors - removing the artificial division between different types of bonding, which typically ends up in a sort of "zoology" of bonding - a more comprehensive understanding of interatomic and intermolecular interactions [98].

Stage 4 ad 5: Thanks to the previously acquired knowledge, students can then construct a coherent model to understand the different molecular structures (stage 4) and properties (stage 5).

Chapter 4: The Gecko-Tape® Teaching Learning Sequence: design, evolution and testing

The TLS based on Gecko-tape® has been designed, tested, and revised for two years since February 2018. In this chapter, I describe and discuss its evolution during these two years, as inspired by the design-based research (DBR) methodology.

The TLS has been proposed to seven groups of high school students in somewhat heterogeneous conditions: in five cases students were selected considering their particular interest in scientific subjects, while in two other cases whole classes were involved. The first time, the TLS was proposed to a group of fifteen honours students, during a one-week stage, and tested through pre- and post-questionnaires. The one-week format favours students' full engagement and gave them plenty of opportunities for autonomous observation and discussion. While this is surely the best settlement for our type of TLS, it would be actually only rarely feasible in (Italian) schools, where lab sessions are spare; we therefore devoted some efforts to fit the sequence in a narrower time-schedule. In particular, in all subsequent testing sessions were envisaged as one-day stages, the TLS had been squeezed into 3-6 hours. This came to some extent at the expense of the time devoted to testing and of its reliability. The last TLS version was tested in Feb 2020 in a one-day stage (6 hours work) with 27 high-school honours students; it was implemented providing students with some flipped-class material and exploiting on-line questionnaires, which students received and filled-in at home, before and after the stage. As we will discuss in detail in the following, this modality allows us to spare some precious time, and proved to be effective. The TLS validation will be therefore discussed mainly on the basis of tests performed in the first and last TLS versions. Nevertheless, a significant role in the TLS redesigning process was also played by the results of intermediate sessions, which, tough more qualitative, provided important hints for improvements. Moreover, useful hints were also provided by informal interviews with a small group of high-school students.

In the following part of the chapter, I will discuss the TLS design process, taking as a reference and adapting to our case the scheme proposed by Guisasola [9], as summarized in **Figure 4-1**. The first steps of this methodology are discussed in sections from **4.1** to **4.4**. The TLS in its actual - though possibly not final - version is thoroughly presented in section **4.5**, while the testing results are discussed in Sec. **4-6**.

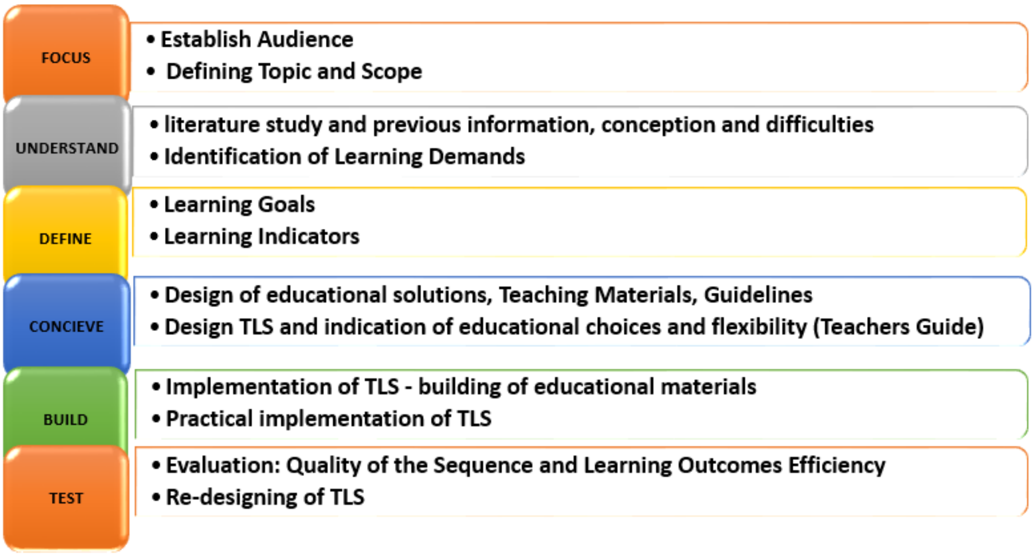


Figure 4-1 Subsequent steps of DBR methodology. After Guisasola [9].

4.1 Focus

While the audience for this TLS has been clearly defined since the very beginning (mainly high- school students, but also their in-service and pre-service teachers), both the topic and scope of the project has shifted from aim to introduce students to some of the key ideas of nanoscience – as in particular the role of surfaces and intermolecular forces in determining the properties and functions of matter at the nanoscale – to explaining and experimentally probing the origin of friction. Our main goal is essentially to shed light on the *microscopic* origin of friction, highlighting the strict relationship between the macroscopic properties of a material and its microscopic structure, as well as the role played by intermolecular forces. Therefore, the focus of our work is to some extent different from that of most TLSs on friction, which aims to provide a better understanding and a rationale for friction macroscopic laws. In this respect, at variance with what suggested by Besson, who considered an explanation of friction at the molecular level too complicate and superfluous for educational purposes [99], we repute essential to provide a direct connection between tribological phenomena and intermolecular forces, down to the atomic scale. In our intentions, this approach may help bridging the gap between physical and chemical wisdom, which is mandatory for an effective STEM education. To this aim, we decided to extend the set of proposed investigations, introducing experiments regarding surface tension and wetting properties of structured surfaces. The latter are considered as instrumental for explaining the crucial role of intermolecular interactions in determining interface properties, rather than a topic on their own.

4.2 Understand

The second step of the DBR process is described by Guiserola in terms of **understanding** the known difficulties and existing solutions.

To this aim, the relevant literature on friction (see Chap. 3.), with particular regard to Besson's and Corpuz's works, was analyzed [89][7][100][85]. Moreover, as the relevance of difficulties and misconceptions regarding the atomic structure of matter and the nature of chemical bonds became apparent during TLS testing, the corresponding literature was also taken into account, with particular regards to the approach of Levi-Nahum, Taber et al [82] and the work of Venkataraman [101].

In **Table 4-1** I summarize the conceptual difficulties and misconceptions which we found most relevant for our approach. It is here interesting to note that the misconception regarding the nature of atoms (indicated with an *), appears twice in this Table, showing its cross-cutting relevance in different contexts (both microscopic friction and chemical bonds).

Table 4-1 Summarize of the conceptual difficulties and misconceptions which we found most relevant for our approach.

Topic	Learning demand	Misconception
Friction at the macroscale	Distinguish between normal force and weight	
	Difference between static and dynamical friction	
	Understand why friction is independent from the nominal area of contact	
Friction at the microscale	Realize the difference between nominal and actual area of contact	
		The origin of friction is mechanical (interlocking mechanism)
		Atoms are visualized as rigid spheres (*)
		The coefficient of friction (COF) monotonously increases with surface roughness
The concept of chemical bonds and intermolecular interactions	Recognize Coulomb forces as the common origin of all different chemical bonds.	Chemical bond has nothing to do with forces and attraction (partially induced by the octet rule)
	Realize that, due to their quantistic nature, atoms are 'fuzzy' and essentially empty entities	Atoms are visualized as rigid, filled spheres (*)
Structure and Size	Correct the overestimated size of molecules and atoms and the idea that solid matter is continuous	Molecules are imagined as macroscopic entities, heavy enough to be weighted; Atoms can be seen using an optical microscope; Pressure affects the shape of molecules

4.3 Define

The specific learning goals of our TLS were defined taking into consideration Besson's and Corpuz's works. While in the first TLS version we had enough time to introduce friction from scratch, and we therefore explicitly devoted some time to revising the basic laws of macroscopic friction, in the following versions we decided to consider the knowledge of the following prerequisites, which students can revise in a flipped-class modality:

(0) laws of macroscopic friction, i.e.,

- *direct proportionality to normal force;*
- *independence from nominal area;*
- *independence from speed;*
- *difference between static and dynamic friction.*

The learning goals of our TLS (in its final version) are as follows:

(i) The microscopic origin of friction is due to intermolecular forces, which are electrostatic in nature and acts at distance;

(ii) Friction between two bodies in mechanical contact depends on the microscopic contact area;

(iii) Friction varies non-monotonously with surface roughness, as shown in **Figure 4-2** *i.e. atomic-flat surfaces may display very high friction (cold welds).*

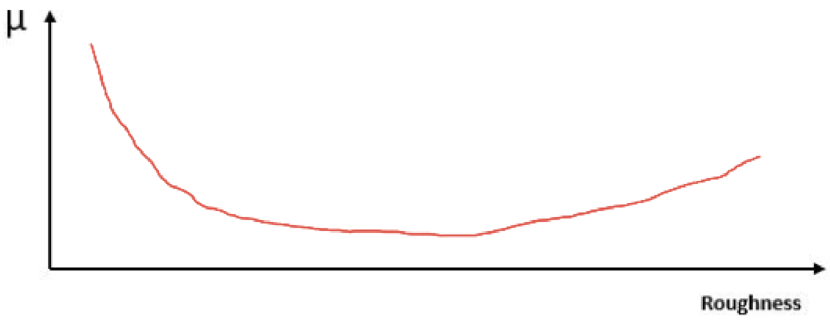


Figure 4-2 Coefficient of Friction COF μ: dependence of surface roughness [85].

4.4 Conceive

The proposed TLS is based on the experimental investigation of the macroscopic and microscopic properties of Gecko-tape®, aiming in particular at

(a) probing the difference between nominal and real area of contact of two mating bodies;

(b) help students building a correct visual representation of the meso- and micro-asperities which characterize real interfaces;

(c) introducing the atomic and molecular interaction model to explain the origin of friction at the microscale level.

To this aim, we decided to broaden the proposed investigation, and introduce the concept of wetting between a liquid (such as water) and a solid surface. Describing wetting as due to intermolecular interaction between the molecules of the solid surface and that of liquid water is indeed quite straightforward. In our intentions, this description may represent a valuable scaffolding: working by analogy, students may be brought to extend this new mental model to the case of solid/solid interfaces, thus substituting the misleading model of mechanical interlock.

4.4.1 Methodology

From the theoretical point of view, our TLS takes inspiration from both the Investigative Science Learning Environment (ISLE) model developed by E. Etkina [33] [5] and the 5E model by W. Bybee [6]. From the former, we took the idea of designing our sequence in a way that mimics as close as possible the modalities of actual scientific research. Students learn through quantitative, highly-guided experiments performed in groups, in a way that essentially resembles the so-called ISLE circle. Partially at variance with this model, rather than leaving students free to design their experiments, we choose a high-guidance modality. This choice was dictated both because of the strict time-schedule and because each proposed different experiment has been designed to provide different pieces of information, which, all together, are meant to scaffold the correct understanding of the phenomena occurring at actual interfaces.

The different phases of the TLS correspond quite strictly to the five Es, i.e., ***Engage, Explore, Explain, Elaborate, Evaluate,*** of the 5E model. Reference to these different phases, as well as details on the modalities of application of the ISLE cycle, are provided in the next section, together with the TLS description.

4.5 Build: description of the TLS sequence

Preliminary work revising some background knowledge and concepts has been assigned to the classroom, in a flipped-classroom modality. In particular, in the case of fourth-grade students (17-18 years-old), the basic laws of macroscopic friction on one hand, and the concept of surface tension and cohesive/ forces, on the other, should in principle be known from previous years (from 14 to16 years-old), through physics and chemistry curricula, respectively. Autonomous revision of the former topic is quite easily implemented[1] and has resulted effective. The latter topic is usually known by students in a quite superficial and bookish way. As it actually involves quite complex concepts, the best way to revised would be within an interdisciplinary project, involving both physics and chemistry teachers. We are currently working on this approach, which exploits flipped-class modalities, but it has not been practically implemented, yet.

[1] students were provided with materials taken from standard textbooks such as, for instance "L'Amaldi verde" vol U Meccanica, Termodinamica, Onde, Elettromagnetismo – Zanichelli Ed (2014).

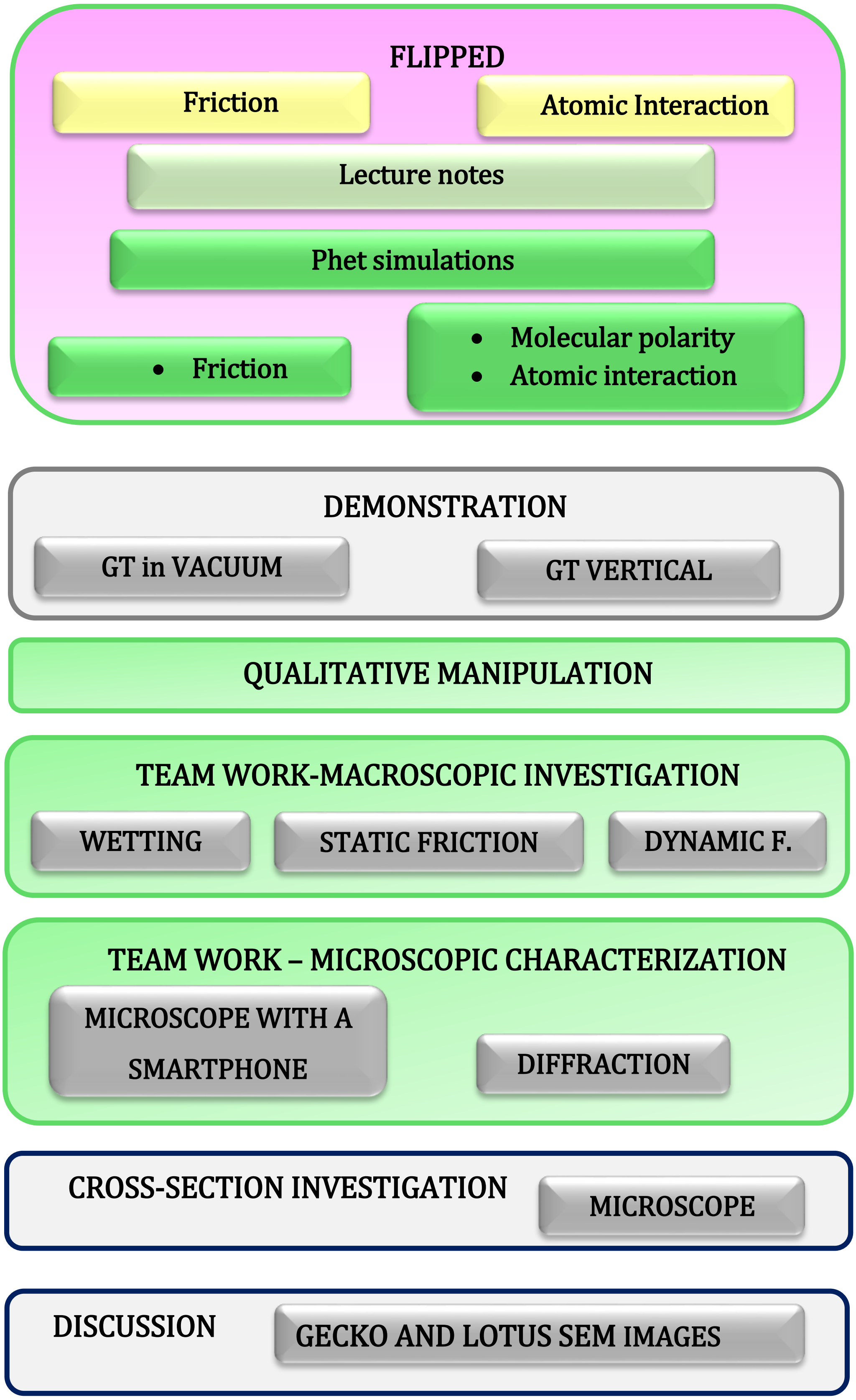


Figure 4-3 The TLS scheme.

The initial activities are designed to *Engage* students' interest, exploiting

i. biomimetics, and in particular the amazing properties of Geckos and lotus leaves, to nail pupils' curiosity;
ii. pupils' interest in technology and energetic issue to boost their interest in friction and tribology.

For this reason, at partial variance with Besson's approach, rather than dealing with the importance of friction in everyday life, the emphasis is put on the role of friction and, more in general, of tribological issues in present and future technology, trying to give a flavour of the ongoing research topics. In this framework, introducing the importance of wetting in nowadays technology is also straightforward.

In particular, the Gecko TLS starts with a brief introduction to friction and wetting, focusing on the importance of controlling friction and wetting for present and future technologies. The concept of contact angle as a mean to measure surface tension is also briefly introduced. Gecko and lotus leaf are used to introduce the experimental investigations, which are mainly focused on the properties of the animal artificial counterpart — i.e. Gecko® tape (GT in the following). At this stage, no preliminary knowledge of GT properties and structure, as well as no explanation for the peculiar properties of Geckos and lotus leaf, are provided.

4.5.1 Preliminary qualitative observations

Initially, GT is provided to students, which can manipulate and test its adhesive properties on different surfaces, comparing its behaviour with that of usual glue-based adhesive. In particular, the absence of any glue can be easily checked, as well as the possibility of restoring its adhesive properties by washing. As we will see in the following, the two sides of GT have the same chemical composition, but are characterized by different morphology and exhibits different properties. The two sides of GT can be easily distinguished by visual inspection, as the smooth one is glossy, while the micro-structured one is opaque, see **Figure 4-4**. We should mention that the different surface roughness may be somewhat perceived by running a fingertip, or a nail, on the tape, but the micro-structuration cannot be distinguished by naked eye.

Figure 4-4 The two sides of GT. Left: the micro-structured surface is opaque. Right: the smooth surface is glossy.

Probing the difference between GT peeling and shearing adhesive properties represents the first essential step to understand the mechanism of adhesion of GT, as well as to strengthen its resemblance to real Geckos properties, introducing the concept of tuneable friction. As shown in **Figure 4-5** a GT strip is carefully positioned on a smooth vertical surface, while a clamp is fixed to it and used to hung increasing weight to it. In this configuration, GT can sustain a shear force up to more than 10 N (it actually breaks before detaching), while the force needed to peel it is almost negligible. This experiment is meant to convey the key-idea that adhesion and friction are strictly related and provides an interesting example in which the normal force is not identified

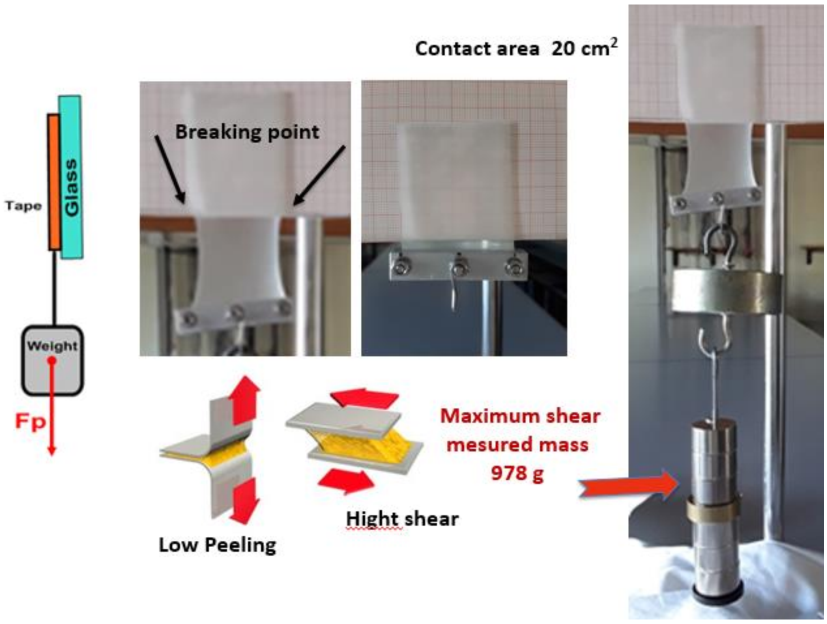


Figure 4-5 Vertical test- to compare peeling and shear adhesion of the GT. To correctly measure the shear adhesion, the applied force must be parallel to the adhesion plane. A contact surface of about 20 cm^2 has supported a mass of almost 1 kg. The main limitation is due to the deformability of the material which, by stretching, tapers and tends to break rather than slip (shear detachment).

with weight[2]. These first experimental evidences easily bring students to rule out glue as a possible explanation for GT adhesion. At this point the suction mechanism usually comes into play as a possible alternative explanation. Following the ISLE circle, we propose to test this hypothesis exploiting a vacuum bell and comparing the adhesive behaviour of a suction-cup with that of GT. Small washers are attached vertically to both the suction cup and the GT. While the suction cup (and the washer) falls from its frame as soon as vacuum is created inside the bell, the washer remains attached to GT, clearly demonstrating that its adhesion does not derive from a suction mechanism.

Following the ISLE circle, we propose to test this hypothesis exploiting a vacuum bell and comparing the adhesive behaviour of a suction-cup with that of GT. Small washers are attached vertically to both the suction cup and the GT. While the suction cup (and the washer) falls from its frame as soon as vacuum is created inside the bell, the washer remains attached to GT, clearly demonstrating that its adhesion does not derive from a suction mechanism. See **Figure 4-6**. At this stage, the adhesive mechanism of GT remains therefore an open question, which engages students in further investigations.

t_1 t_2 t_3

Figure 4-6 Vacuum bell experiment images in increasing times (t_1; t_2; t_3) from left to right. Two small washers (10 g weight) are attached on vertically aluminium plates to both the suction cup and the GT. While the suction cup (and the washer) falls from its frame as soon as the vacuum is created inside the bell, the washer remains attached to GT.

[2] If students have good manual skills semiquantitative measure are also possible: by changing the contact area the dependence of adhesion on the contact area were found and elongation measures allow to estimate Young's modulus and material breaking load.

4.5.2 Experiments

In the *explore* activity, in order to keep the lab activity within a reasonable amount of time, different experiments were assigned to different groups, following the scheme shown in **Figure 4-1**. In particular, each group worked in a cooperative-learning modality and was provided both with a worksheet to guide its specific practical goals and with an open-question worksheet, called “understanding phenomena worksheet” (UPW), aimed to stimulate metacognition and problem-solving skills. For instance, students were invited to detail in the UPW problems faced during the experimental session, envisaged solutions, as well as the source of information they exploited.

Static and dynamic friction

The main goal of this set of measurements is to quantitatively investigate the frictional behaviour of GT, and compare it with that of sandpaper (SP in the following), taken as an example of a material with conventional properties. In particular, we are interested in probing the validity of Amonton's law, i.e., the independence of the frictional coefficients from the nominal area of contact in the two cases.

The standard set-up used in the classroom to measure stating friction consists of a variable-angle sliding plane and a test block. The test block is placed on top of the plane, and its angle gradually increased, till the block starts to slide downwards. The angle θ_S at which sliding starts is measured using a protractor fixed at the vertex of the sliding pane. The friction coefficient is readily determined as:

$$\mu s = \tan(\theta_S), \qquad (8)$$

by applying force balance and the law of static friction. This set-up is typically used to test the validity of Leonardo-Amonton's law varying the nominal contact area between the plane and the block, by changing the face that is in contact with the plane.

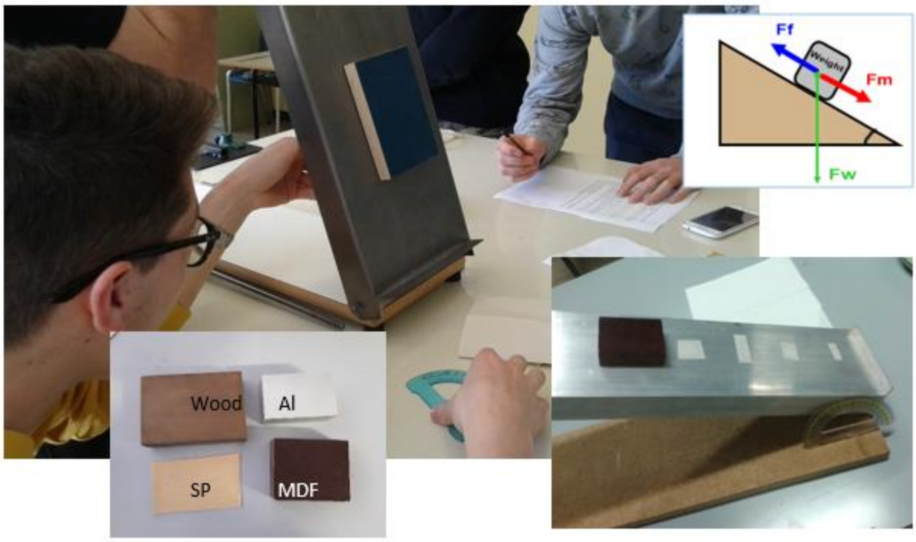


Figure 4-7 inclined plane layout: sandpaper (SP) or GT has attached to the plane and test has been done using different blocks material: wood, Al and a smooth MDF material (a piece of desk plane).

As shown in **Figure 4-7**, we here use a different approach: we glue a few (at least three) pieces of SP with different areas (smaller or equal to that of the test-block) to the sliding plane. The test-block is then carefully placed on top of each piece so that the nominal contact area between the block and the coating piece coincides with that of the latter, and the sliding angle is measured. The same procedure is repeated using GT coating.

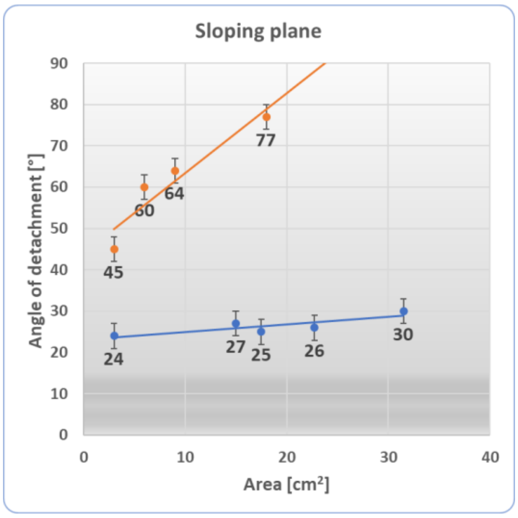


Figure 4-8 Example of measure MDF on GT (orange line) and MDF on SP (blue line).

As shown in **Figure 4-8** in the case of SP, the coefficient of static friction does not depend on the contact area, as expected. On the contrary, in the case of GT (see **Figure 4-8**, orange line), the coefficient of static friction clearly increases with the contact area, in apparent contrast with Amonton's law.

This simple experiment highlights the peculiarities of GT frictional properties in a straightforward and striking way, fostering pupils' interest in unravelling their origin.

The frictional properties of GT can be further tested in dynamic conditions. To this aim, a standard set-up can be considered, as depicted in **Figure 4-9**, in which the

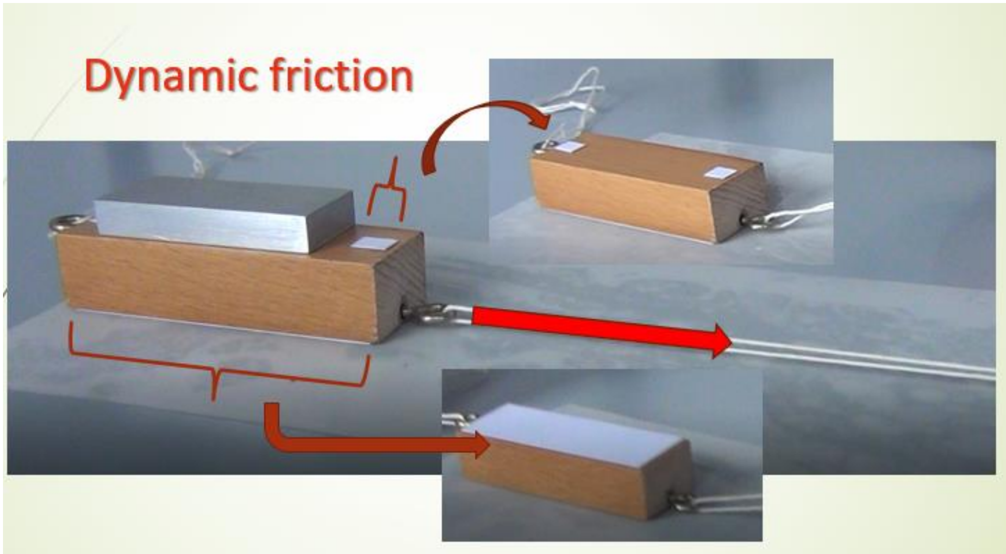


Figure 4-9 Dynamic Friction setup. The two areas realize with white cardboard; the small one in the upper box and the large one in the lower box. The pulling force must be perfectly parallel to the plane (red vector). The metal block is added to increase the friction force.

dynamic frictional force of a wooden block moving on a horizontal plane is measured by a dynamometer. Here, three different types of coatings are considered, i.e., SP and the GT glossy and opaque sides (G-GT and O-GT in the following, respectively). In order to vary the contact area, the two symmetric sides of the test block are covered with different areas of flat cardboard: in one case the whole lateral surface is covered, while in the other only three very small cardboard pieces (few mm^2) are glued to the block. While in the case of SP the measured dynamic friction does not depend on the block side, i.e., on the contact area, in the case of O-GT this dependence is quite remarkable. Interestingly, in the case of G-GT, no dependence on the contact area is observed. The completely different frictional behaviour of the two sides of GT is quite surprising and calls for further investigation on their different properties.

It is interesting here to notice that direct observation of the dependence/independence of the frictional force on the nominal area (in the case of GT/ SP) provokes two different reactions in students:

- For students which are not fully aware of Amontons' law, the behavior of GT is easily accepted, as quite intuitive, while what is surprising is finding that for usual materials friction is not dependent on the area. In this case, pupils often are tempted (and sometimes succeeded) to find a dependence also for usual materials.
- On the other hand, for students which know Amontons' law (having revised it with flipped-class materials), GT results are really surprising and provoke a clear cognitive conflict[3] . We found this latter case more fruitful, as it provides a striking example of the concept of falsification, which is at the basis of the scientific method.

Wetting properties

The concepts of surface tension, hydrophilicity, and hydrophobicity are usually known by students, at least qualitatively, and can be quickly recalled from the chemistry curriculum. Introducing the concept of angle of contact as a measurement of the degree of hydrophobicity of a surface is also quite straightforward. The wetting properties of different surfaces, such as Teflon, glass or different kinds of plastic materials, are easily probed by depositing isovolumetric drops of coloured water on each surface (see **Figure 4-10 A-B**) and measuring contact angle, rolling angle and contact-angle hysteresis using a smartphone camera, as shown in **Figure 4-11**; interesting examples of superhydrophobic surfaces are provided by lotus leaf or treated anti-spots fabrics, see (C).

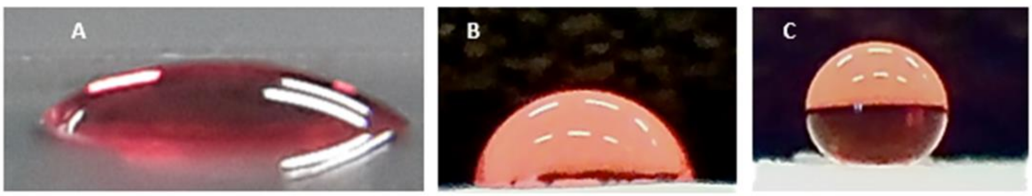


Figure 4-10 Droplet of colored water on Glass (A), Teflon (B), Anti-spots fabric (C).

[3] As an example, we report one student crying out: Damn, this means all what I learned since now was false!

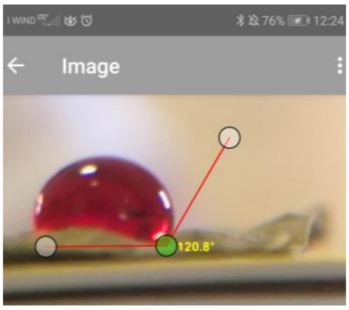


Figure 4-11 Water droplet on lotus leave: measure of the contact angle using a smartphone camera end a common app.

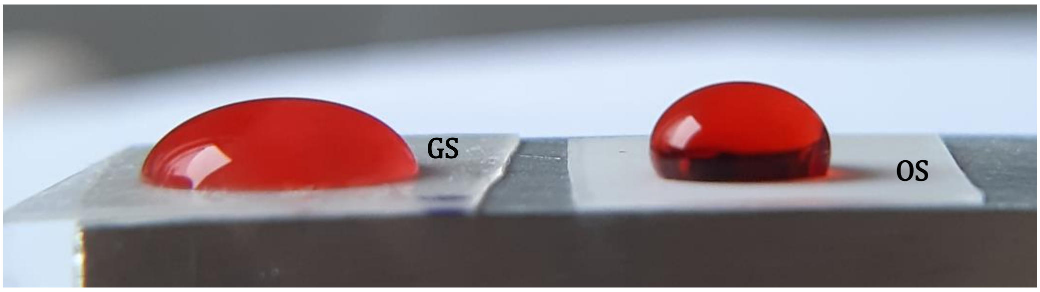


Figure 4-12 Wetting properties of the two side of gecko tape glossy (left) and opaque (right).

The wetting properties of the two sides of GT are then tested, showing striking differences: the opaque side results more hydrophobic than the glossy one, with angles of contact changing about from 62° to 116°. The rolling angles, also differ significantly, as well as the dynamic behaviour of the drops: once the drop starts to roll off the surface, it moves more rapidly on O-GT than on G-GT, and in the latter case it leaves a trail on the surface, as in fig **Figure 4-13**. Using a slow-motion video [102][103], the difference between the two wettability regimes is easily highlighted.

The origin of surface tension and wetting properties of surfaces are commonly associated with the chemical properties of the surfaces, and in particular on their

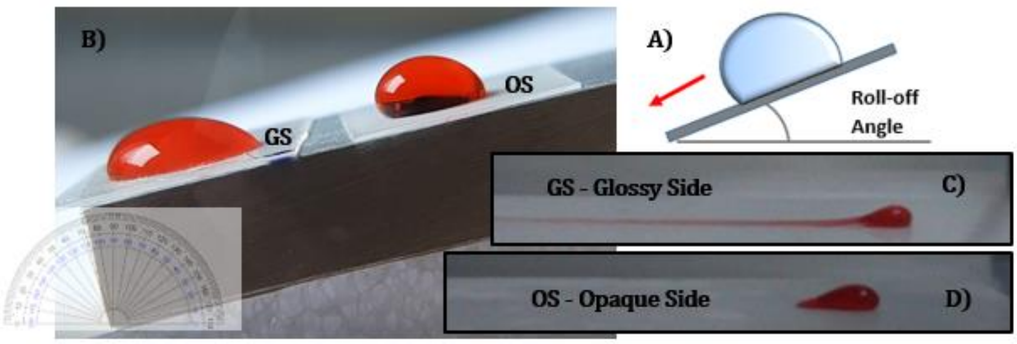


Figure 4-13 Definition of roll-off angle B) Image of two isovolumetric droplets on the two different sides of GT. C) and D) Images of the two sliding droplets taken with a slow motion video-camera (250 fr/sec) fixed to the inclined plane.

capability of forming hydrogen bonds with the surface molecules. In the case of GT, the different behaviour of its two sides cannot be reconducted to their chemical composition, which is the same for both surfaces.

The different wetting properties of the two surfaces, therefore, remain an open question, together with their different dynamic friction behaviour. As we will show in the following, students are led to trace the origin of these differences in their structural and morphological properties.

Structural properties

This part of the TLS aims to investigate the structural properties of GT, i.e., the details of its morphology. We here recall that students are not initially aware of the film micro-structuration.

At this stage, students are led to discover the link between the macroscopic properties of GT (friction and wetting) and its structural properties. The latter can be investigated with two complementary approaches, described in the following sections.

A. Optical Microscope investigation

Due to the dimension and distance of the micropillars (50 μm), the microscopic structure of the GT surface can be easily revealed using a standard optical microscope. Optical microscopes are usually available in school labs, and may also be USB connected to a computer to acquire high-resolution images.

Alternatively, home-made microscopes which exploits the smart-phone optics may

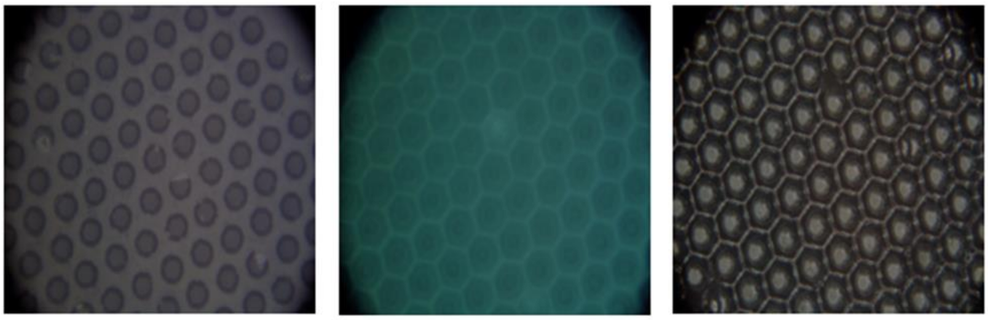


Figure 4-14 GT images under an optical microscope . From left: two on reflection and one on transmission. 32x magnification.

also be used [104][105]. In **Figure 4-15** panels left (A) and right (B), images of the surface, and of the cross-section of GT are reported; in (A) the hexagonal array of micropillars is clearly observed. The GT surface can be observed both in reflection and in transmission, if GT is put on a transparent support. The best cross-section images can be obtained in transmission, by cutting a thin slice of GT (1 mm or less) and holding

Figure 4-15 Optical Microscope images of the surface (A) and of the cross-section (B)of GT.

it vertically on a transparent support. Inspection of the cross-section image (panel B) unravels the morphological difference between the two sides of GT, i.e. the O-GT side micro-structuration and the G-GT flatness.

B. Diffraction investigation

A complementary way to investigate the structural properties of the GT is by means of diffraction. Indeed, the ordered array of Gecko-tape micropillars forms a bi-dimensional hexagonal lattice; furthermore, GT is almost transparent to visible light. As shown in **Figure 4-16**, by shining the light of a laser-pointer through a piece of GT film, a nice hexagonal diffraction pattern can be observed on a screen. By measuring the distance L between the GT and the screen, and the distance d between neighbouring spots (see inset in **Figure 4-17**), a quantitative estimate of the lattice parameter, i.e., the inter-pillar distance a can be easily derived as

$$a = \frac{\lambda}{\sin(\arctan(\frac{d}{L}))} \cong \lambda \frac{L}{d}, \qquad (9)$$

where λ is the wavelength. The value of a determined in the diffraction experiment is in good agreement with that obtained with the optical microscope.

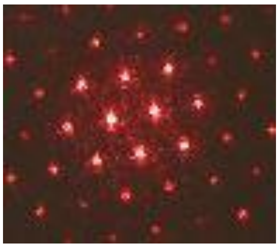


Figure 4-16 GT Diffraction pattern.

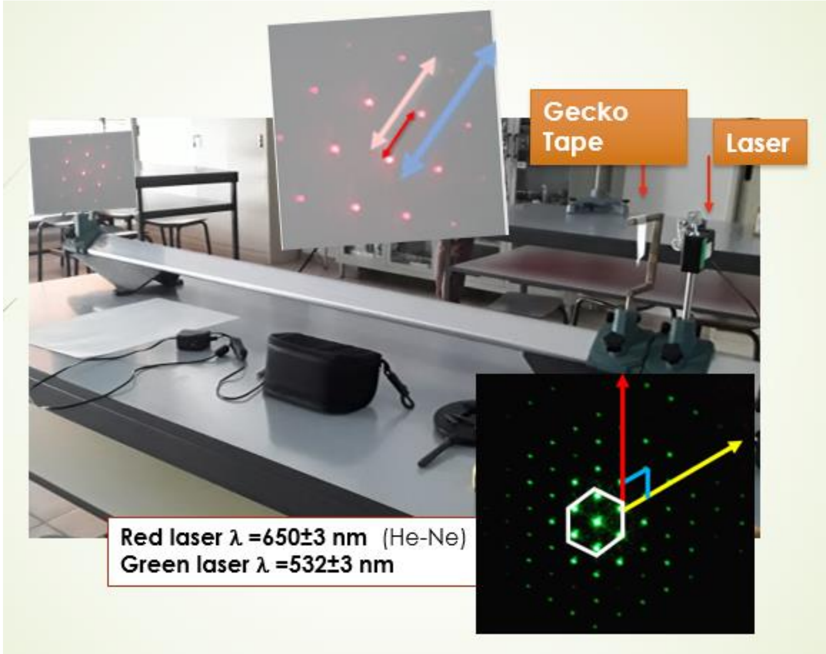


Figure 4-17 GT diffraction measurements: experimental setup and panel of diffraction pattern images taken with red laser (upper insert panel) and green lase (below insert panel).

4.5.3 Guided discussion and cross-section images of solid/solid interfaces

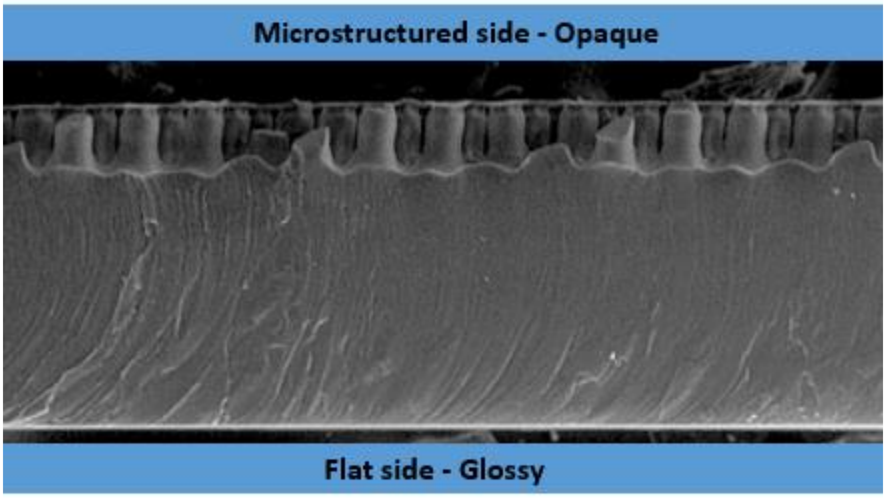


Figure 4-18 SEM Image of cross-section of GT clearly show the differences between flat vs. micro-structured side.

The experimental results obtained in the previously described activities are first discussed within the group and then presented to peers. In this way, each group got to know the results of others' investigation in a way which is meant to resemble a real scientific workshop. The groups could collaborate with each other, share ideas, challenges, and results. The aim of this session is to discuss the direct link between the macroscopic wetting and tribological properties of GT and its morphology, as compared with that of conventional materials, such as SP.

In this ***Explain*** activity, the teacher both acts as a facilitator of the discussion and provides new pieces of information (described in the following) which help building of a comprehensive picture of the investigated phenomena.

At this point, the difference between real and nominal contact area is naturally brought in, together with the concept that friction is related to the real contact area. In this way, the microscopic explanation of Amotons' law and the reason for its deviation, in the case of O-GT interfaces, is also discussed.

Bridging the gap between the mental image of two macroscopic bodies in contact and that of the actual interface at the meso and micro-scale is nothing but trivial. In order to help students building a correct mental image of actual interfaces and of meso/micro-asperities in interaction we exploit the optical microscope to observe the cross-section of different interfaces. This last experimental activity could be directly performed by students, if good-quality microscopes and an appropriate amount of time are available. Otherwise, the teacher can acquire and show the micrographs to students in real-time, exploiting a microscope connected to a computer and a projector.

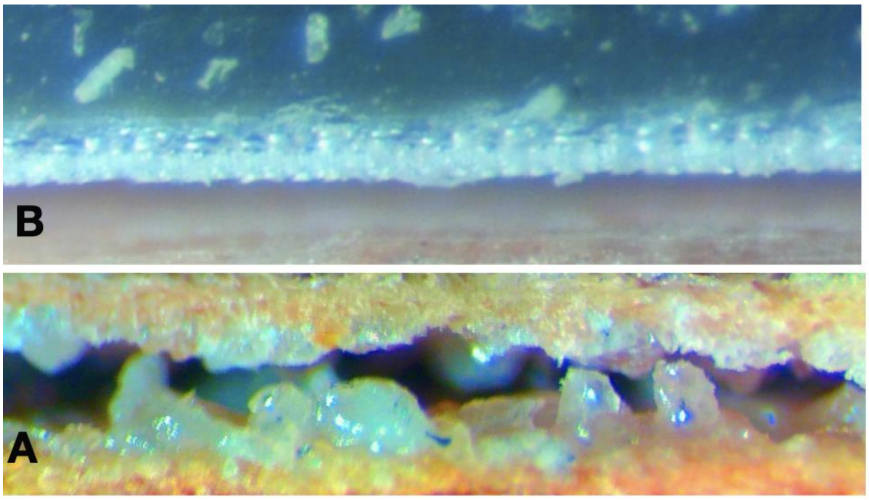


Figure 4-19 Optical micrograph of the SP/SP interface (**A**), and GT/silicon interfaces, lateral views (**B**).

As shown in **Figure 4-19**, panel (**A**), a thin slice of SP is sandwiched between the smooth lateral edges of two 1mm-thin rigid sheet (cut-out from plastic shop cards), and fixed on a microscope-glass. In this way, a cross-section micrographs of the interface between SP and the rigid sheet is readily acquired in transmission. Alternatively, the lateral edge of a microscope slide could also be used.

This image provides a clear picture of the actual area of contact between two conventional surfaces at the meso/microscale, allowing to introduce in a realistic way the key concept of multi-asperity contact.

Indeed, at variance with typical textbook drawing of interfaces, which are two-dimensional, if the optical focus is varied during acquisition, the interface cross section is visualized at different heights, thus providing a depth perception. This helps students to build a realistic 3D mental image of actual interfaces, in which only few asperities get really into contact. When the same procedure is applied to obtain cross-sectional micrograph of GT, a completely different image of the interface is obtained, as shown in **Figure 4-19**, panel(**B**). Indeed, in this case, the contact area between the flexible, micro-structured O-GT and the silicon surface is not limited to few asperities, but it is much more extended.

To help students' understanding, at this stage the teacher can also show the SEM images reported in **Figure 4-20** (and **Figure 4-18**), which provide a more detailed picture of the GT structure. Moreover, the images of Gecko's toe hierarchical structure can also be shown at this stage(see **Figure 2-2**), highlighting the similarities between Gecko and GT.

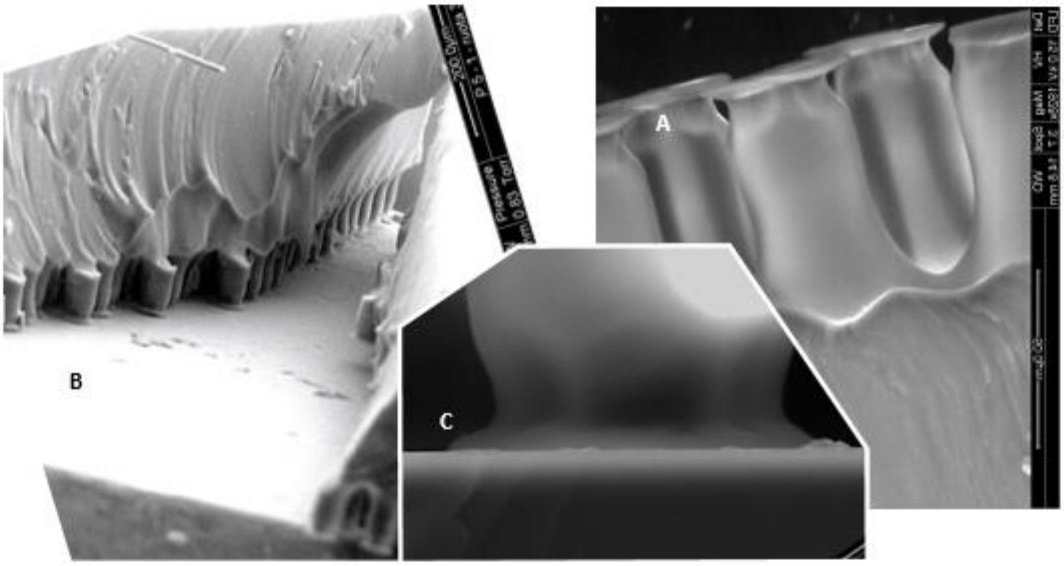


Figure 4-20 ESEM images of the cross section of GT. The mciropillar structure is clearly shown in panel A while real contact area very similar to the geometric one is shown in panel B and C.

Putting together the information obtained by the macroscopic investigation with those obtained by microscopy and Gecko's toe images allows to identify the micro-patterning as the key to explain GT properties. In this phase, an explanation of the different wetting properties of the two sides of GT is also discussed. At this stage, some ***Elaborate*** activities can be envisaged, where students may propose their own experiment. Focus and more insight on the topic of intermolecular forces could also be gained exploiting applet simulation (as in particular Phet Colorado apps).

4.5.4 Peer activities

At the end of the work, taking also into account the suggestion of other groups, each team produces a report, to share their results and their own answer to the initial Inquire learning question "How gecko tape is made, how it works, and how may you physically explain it".

This activity, which corresponds to the ***Evaluation phase***, is quite time-demanding. It has been therefore fully tested only in the first version of the TLS (Feb 2018), that lasted one week. Overall, this stage involved 31 honour high-school students, divided in two groups: 15 “physicists” performed the whole TLS, divided into subgroups, while 16 “mathematicians” were exposed to one-day peer-education activities. Indeed, the physicists, additionally divided in subgroups, realized power-point presentations that were exposed to all classmates, including the “mathematicians”, during the last day of the stage, mimicking a real scientific congress. The groups collaborated with others and with the teacher, sharing ideas and results in a revision session, the last step of which was a dry-run of their presentations.

At the end of the internship week, the students of both groups, “mathematicians” and “physicists”, lectured also their school classmates. This second phase of peer education was appreciated by schools, both by teachers and students, allowing to widen the audience of people involved. Unfortunately, both pre-tests and post-tests have been carried out only by a small fraction of involved students, thus hindering a reliable analysis of the results (see Section 4.7).

4.6 TLS Testing

4.6.1. First test (Feb. 2018)

The performances of both “Physicist” and “Mathematicians” were probed through questionnaires, divided as pre-test and post-tests ones. Furthermore, “Physicists” performed also an intermediate test, after the teacher’s introductory lecture.

In designing the tests, the following conceptual issues have been considered:

- Connections between physical and chemical concepts: Chemical bond/physical interactions;
- Link between electrostatic interactions at interfaces and friction/adhesion;
- Macroscopic laws of friction;
- Geometric vs real contact area.

Examples of pretest/post-test questions are reported below, while the Italian version of the complete test is reported in Appendix C:

1) Consider the atoms of any portion (for example a cube) of a given material: those 'inside' the material are called *volume atoms*, while those found on the external surface are called *surface atoms*. Regarding chemical-physical properties of the material such as cohesion energy, melting temperature, chemical reactivity, etc. do you think that:

a) They depend only on the chemical species by which the material is made (e.g. Silicon, Iron, Carbon).

b) They depend also on environmental parameters (temperature, pressure, humidity).

c) They depend also on the structure of the material (i.e. how the atoms are arranged inside the material).

d) They are the same inside the material (for volume atoms) and on the surface.

2) In particular, do you believe that (underline the correct word):

a) The melting temperature of the surface atoms is greater / lesser / equal than for the volume.

b) The chemical reactivity of the surface atoms is greater / lesser / equal than for the volume.

c) The cohesion energy of the surface atoms is greater / lesser / equal than for the volume.

d) It cannot be said, in general, it depends on the type of material.

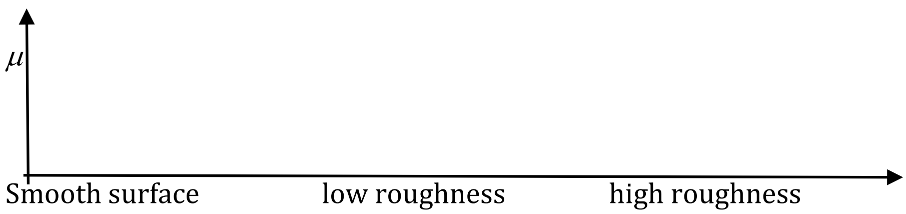
3) Imagine that you have a cube of a given material, with side L. Now imagine that L can vary between 1 meter and 1 nm. The ratio between the number of surface and volume atoms contained into the cube of material:
   a) does not depend on the value of L.
   b) increases as L decreases.
   c) decreases as L decreases.
4) Are you able to derive a mathematical expression to confirm what has been said?
5) The frictional force between two surfaces is
   a) Directed perpendicular to the surface.
   b) Directed parallel to the surface.
   c) It has no precise direction.
   d) Proportional to normal force.
   e) Proportional to the weight force.
6) What do you think are the working mechanisms of a glue?
7) A layer of water on the floor makes it slippery but a thin film of water between two glasses makes them adhere tenaciously, could you find an explanation?
8) What do you think are the causes that produce the adhesion force between the surfaces of two materials at the microscopic level?

4.6.2 Other tests (Feb.-May-Jun 2019)

In the subsequent versions of the sequence, we tried to probe in more details students' mental images of interfaces: as suggested by Corpuz, we asked students to draw solid/solid and solid/liquid interfaces, zooming in from the macro- down to the micro- and atomic scale.

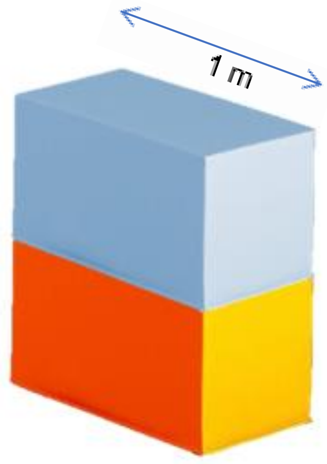
Example of pre-test [1]

1. How the friction coefficient μ changes as a function of the roughness of the two surfaces? Draw a graph in the diagram below.



[1] The integral Italian version in Appendix D.

2. Why do you slip on a wet floor but two wet glass sheets placed in contact adhere strongly to each other?
3. Consider the contact surface between the blue and orange block of the figure. Imagine to use powerful a microscope to zoom in at the interface between the two surfaces and draw what you expect the cross-section profile would look like, with magnification x 100 and magnification x 106, respectively. Consider two cases: smooth surfaces and rough surfaces



	x 100	x 10^6
Smooth surfaces		
Rough surfaces		

4. Now imagine to remove the blue block and depositing a drop of water on the orange block. Draw the profile of the contact surface and the shape of the drop in the two cases (smooth and rough surfaces) and for the two different magnifications.

	x 100	x 10^6
Drop on Smooth surface		
Drop on Rough surface		

4.6.2 Final version (Feb. 2020)

Both pre- and post- tests were completely revised in the last version of the TLS, in Feb 2020.

In order to gain a more detailed information on students' mental models, tests were designed combining both close and open questions. As discussed in more detail in the next section, in this version of the test we decided not to ask students for free drawing, but rather to ask them for an interpretation of provided pictures. [106], [107].

The pre-test was meant to probe students':

(i) Knowledge of macroscopic laws of friction and ability to apply them to solve simple problems

(ii) Understanding of the relation between friction and surface roughness

(iii) Knowledge of the atomic structure and dimension, and of the nature of *intra and intermolecular forces*

In the first part of the test, students were asked to recognize the main characteristics of static and dynamic friction. Moreover, they were asked to explain their origin – in an open question - taking explicitly into account the sentence - taken verbatim from a textbook - and picture displayed in **Figure 4-21**.

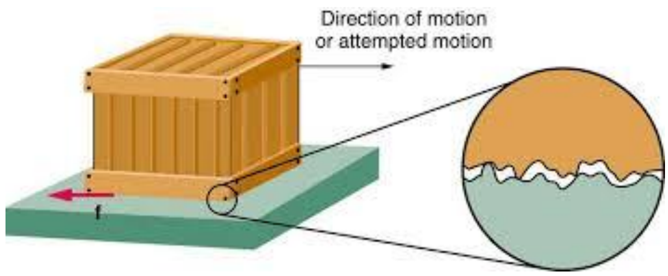


Figure 4-21 Though surfaces may appear perfectly smooth to naked eyes, in fact they are always characterized by microscopic hills and valleys.

Moreover, they were also asked to solve standard problems, involving blocks (a) on sliding planes and (b) pushed by an external force against a vertical wall.

In the second part of the test, we considered what we call 'the interface problem': students were asked to compare between couples of different interfaces choosing the one which displays higher friction. As shown in **Figure 4-22** and **Figure 4-23** in the first case, both upper and lower surfaces of interface (A) are clearly rougher than those of interface (B). In the second case instead, the lower surface in both interfaces is drawn as smooth, while the upper ones have different roughness. The true area of contact - and consequently the COF - results, therefore, larger in case (D) than in case (C).

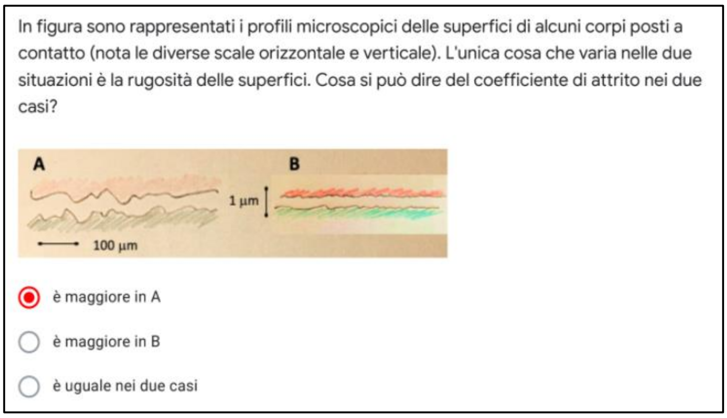


Figure 4-22 Pre-test interface problem question 1.

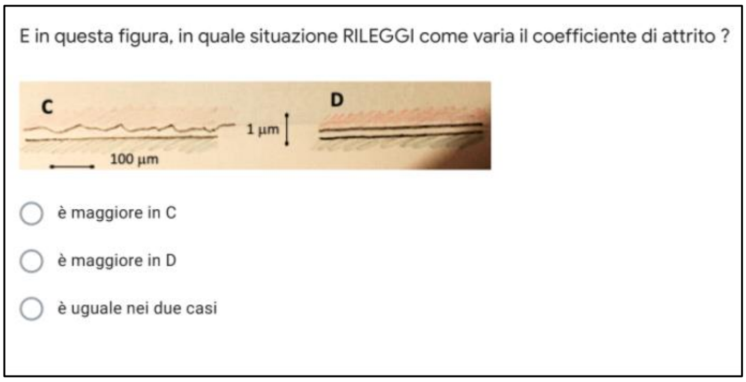


Figure 4-23 Pre-test interface problem question 2.

Eventually, in the third part of the test, few questions probe students' knowledge of the atomic structure and dimensions, the origin of the forces involved in chemical bonds (electric, gravitational, nuclear) and of the meaning of the parameters indicated in the diagram reported in Figure **4-24** representing the potential energy between two apolar molecules as a function of their reciprocal distance.

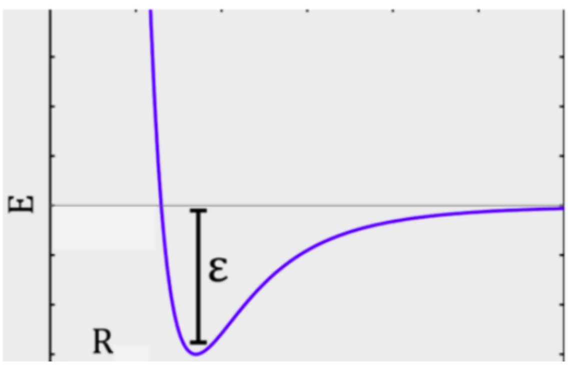
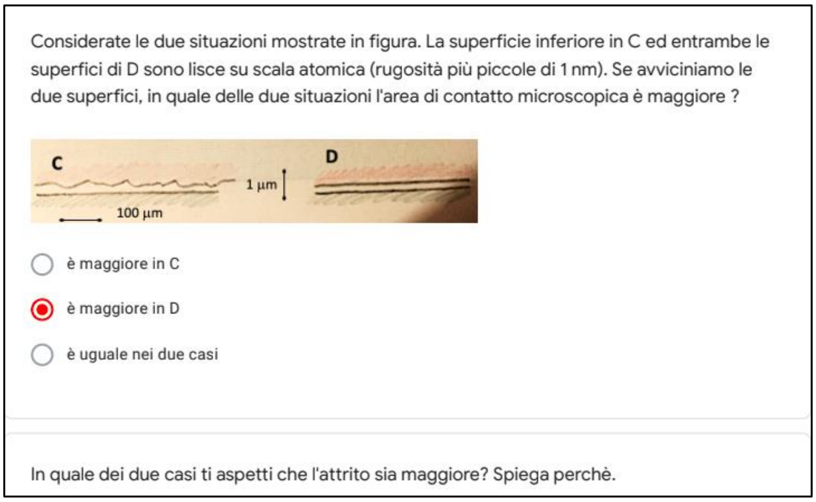


Figure **4-24** Forces involved in chemical bonds investigation question.

In the post-test, the part devoted to macroscopic laws was reduced, though we kept a few questions, aims to check that our TLS did not cloud students' basic understanding of frictional phenomena.


Considerate le due situazioni mostrate in figura. La superficie inferiore in C ed entrambe le superfici di D sono lisce su scala atomica (rugosità più piccole di 1 nm). Se avviciniamo le due superfici, in quale delle due situazioni l'area di contatto microscopica è maggiore ?

- è maggiore in C
- è maggiore in D
- è uguale nei due casi

In quale dei due casi ti aspetti che l'attrito sia maggiore? Spiega perchè.

Figure 4-25 Post-test interface question 1.

In the second part, we propose a different version of the interface problem, as shown in **Figure 4-25** reformulated in such a way to guide students' logical thread, helping them to focus on they have learned during the TLS to find the correct answer. We combine a closed question, that explicitly asks to choose the interface with the higher microscopic area of contact, with an open question, asking which of the two interfaces display the higher COF, and why.

In the third part of the test, we address students' ability to grasp the order of magnitude of lengths at the micro- and meso-scale and their mental images of objects such as atoms, molecules etc. To this aim, we devise small exercises, based on drawings and images, to ascertain their thorough understanding of these issues, as opposed to merely bookish knowledge. For example, as shown in **Figure 4-26** we asked them to compare the thickness of a monolayer of triglyceride molecule adsorbed on a surface to the surface roughness (in the micrometre scale). Moreover, we asked them to discuss the possible influence of such a thin layer on the COF.

Moreover, two questions were also devoted to wetting: students were asked to explain what, the phenomena of surface wetting and of friction, have in common, and what is the role of roughness in determining the wetting properties of a surface.

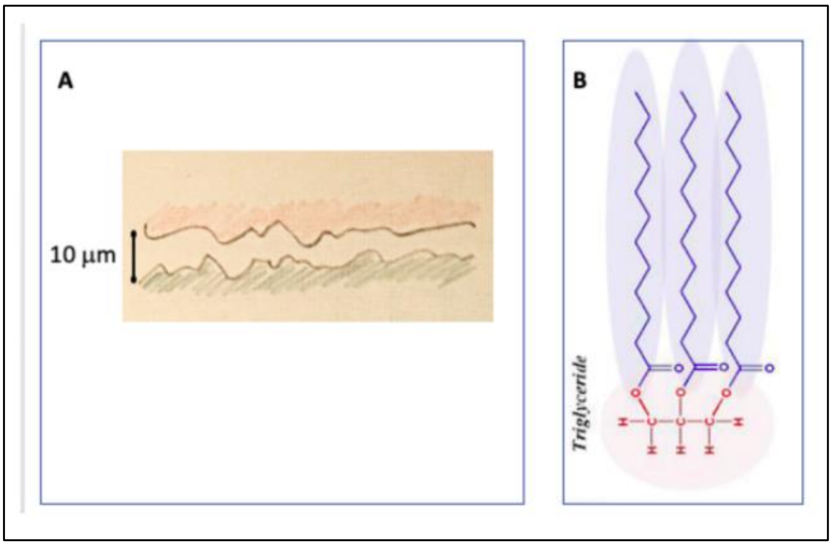


Figure 4-26 Post-test question example .

4.7 Results

4.7.1 Results of Feb 2018 Test - Outcomes of peer education activities

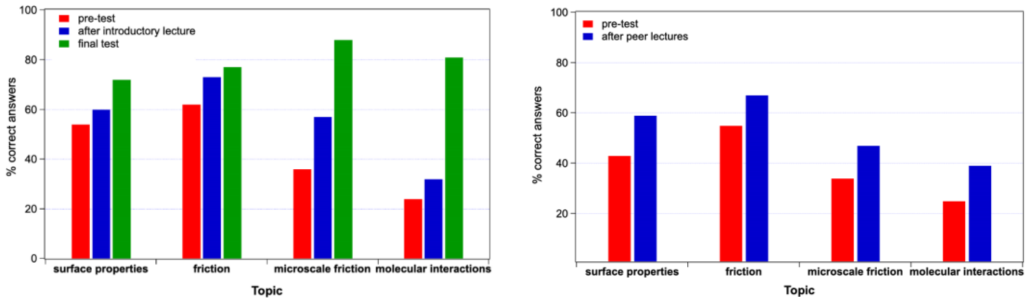


Figure 4-27 Results of validation for two groups of fourth-grade students; the first group (physicists, left) carried out the whole TLS, while the second group (mathematicians, right) attended the peer-education session.

The TLS and the peer education effectiveness were tested for the first time in Feb 2018, (as described in Sections 4.6.1.First test (Feb. 2018) for both groups (physicists and mathematicians), the performances were probed through the same questionnaires given as pre-test and post-tests.

For Physicists, an intermediate test was also performed, after the teacher's introductory lecture. In analysing the results, we divided questions into different groups, according to the topic addressed. As highlighted in **Figure 4-27**, performances increase significantly for all topics, with an average incremental increase in the percentage of correct answers of 10-15% for both physicists and mathematicians: the effectiveness of the peer session results, therefore, are similar to those of teachers' lecturing, supporting the very high competence level acquired by student after the TLS experience.

For physicists, the effectiveness of the experimental sequence is apparent in the final-test results (green bars). Remarkably, the sequence when key issues as nano-friction, surface and atomic interactions are considered, the percentage of correct answers increases from an average of 37% in the pre-test to 74% in the final test.

As explained in Section 4.6.1.First test (Feb. 2018further peer activities were organized in schools. Unfortunately, these testing do not offer accurate results, as only a fraction of students did the post-tests (see **Table 4-2**). Nevertheless, some encouraging results can be highlighted: as shown in **Figure 4-28**, an improvement both in the average of correct answers (from 4 /60 to 10 / 15) and in the best and in the worst performances was obtained.

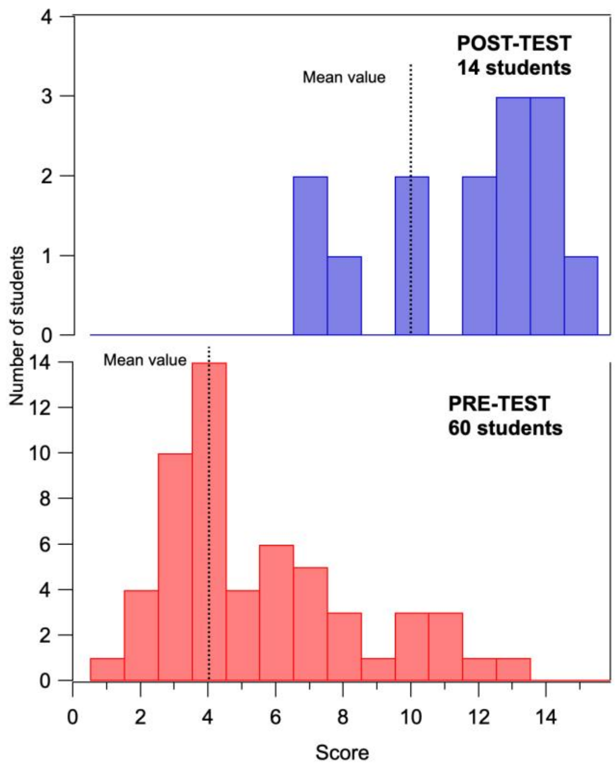


Figure 4-28 Peer-Education effectiveness. The activity involved three classes of the fourth year of secondary school. All classes answered the pre-test but only 14 students, from one class, completed the post-test.

Table 4-2 One day peer education effectiveness after TLS: Pre-test and Post-test results in terms of score i.e. number of correct answers. Total score=15.

PRE -TEST				**POST TEST**			
Number of students	Average score/15	MIN score	Max score	Number of students	Average score	MIN score	MAX score
60	4	1	12	15	10	6	14

4.7.2 Results of the intermediate versions.

I here report the qualitative analysis of drawings and answers produced by students, each student is identified by number and gender (F/M) based on the literature findings reported in Section 3.5.1.

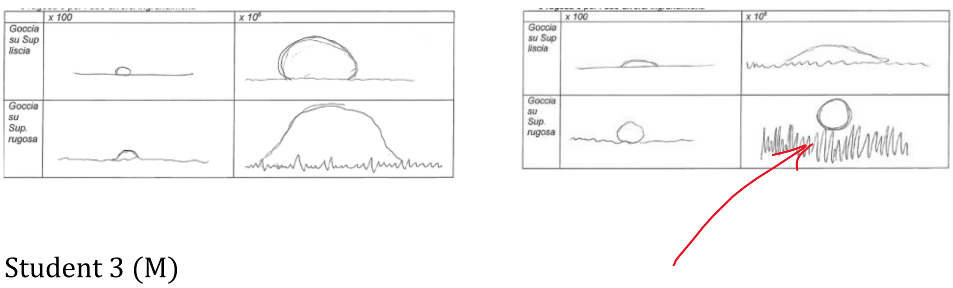
It is important at this stage to point out that the interpretation of these drawings is not trivial. Indeed, while they could be a powerful mean to investigate mental models if accompanied by interviews clarifying students' thought, we found that taken alone, their analysis is somewhat questionable and prone to misinterpretations and/or bias. For this reason, in the last version of the TLS, we changed the test modalities, asking students to discuss and draw conclusions based on drawings provided by the testers.

A. Scales and proportions

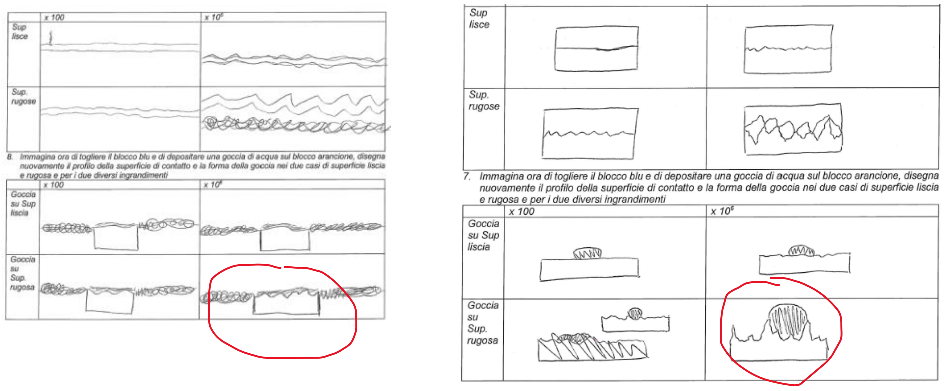
Answers to Questions 2 and 3 provide information on students' ability to recognize scales and proportions. In both questions, the dimension of the block (1 m) is explicitly indicated in the picture, so that magnification x100 corresponds to a macroscopic drawing (1 cm scale), while magnification x10^6 would correspond to the microscopic (1 micron space). In any case, single atoms are not visible. Several students seemed to recognize this point, as exemplified by the following drawings.

Pre-test **Post-test**

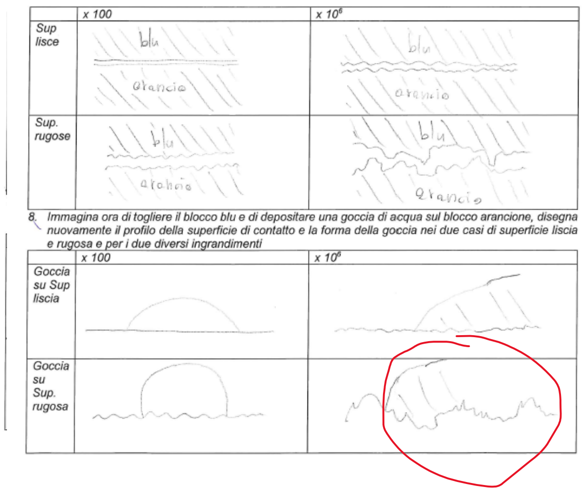
Student 1 (M)



Student 3 (M)



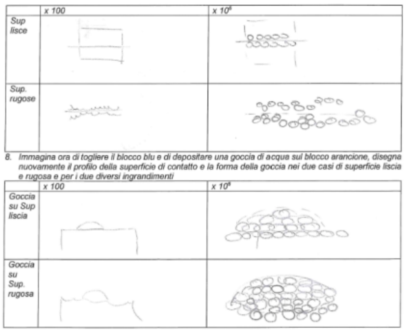
Student 6 (M)

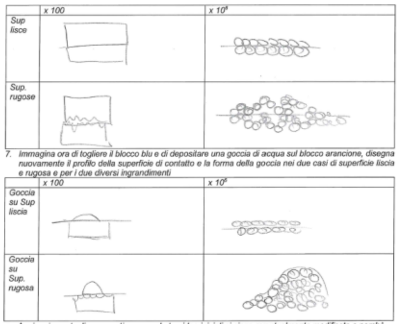


Some students instead, fail to recognize this point, drawing atoms in the case of 10^6 magnifications. In some cases, this mistake persists also in the post-test. Moreover, the description of atoms as touching solids emerges clearly (in particular for student 4).

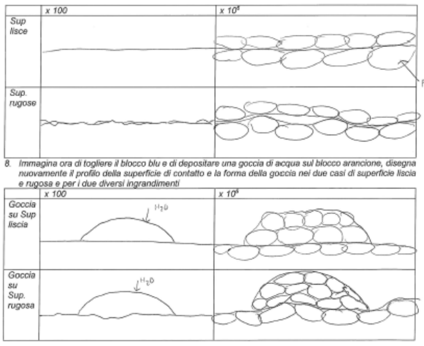
Pre-test **Post-test**

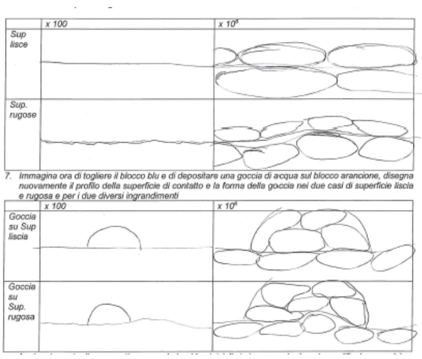
Student 2 (M)



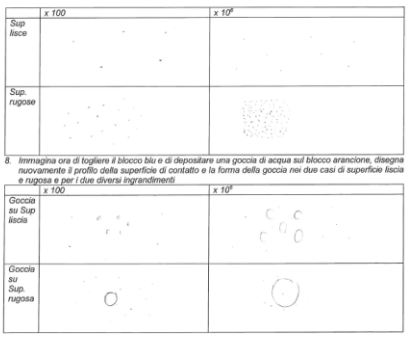


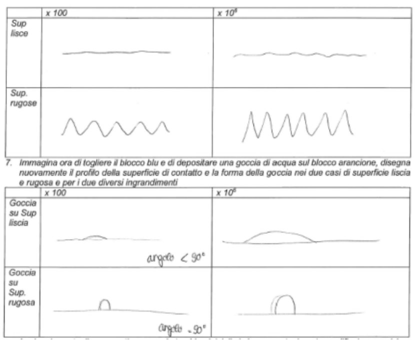
Student 4 (M)





In the case of Student 5 (F), on the contrary, while in the pre-test atoms were drawn for both magnifications, they were not any more visible in the post-test.





B. Mental models concerning friction mechanisms

As inferred from the analysis of the answer to open questions, the dominant model to explain microscopic friction is interlocking; roughness is responsible for friction; the interactions between atoms are mentioned, albeit with many inaccuracies. For almost all students, in both pre and post-tests, the friction coefficient increases with roughness.

Student 7 (M) pre test

2. *Come cambia il coefficiente di attrito μ al variare della rugosità tra due superfici: disegna un grafico di come immagini sia l'andamento di questo coefficiente all'aumentare della rugosità*

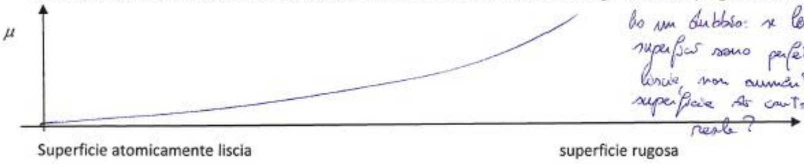
3. *Quali pensi che siano e cause microscopiche dell'attrito?*

Una superficie è più rugosa se le molecole della superficie creano dei "solchi" e dando luogo alla possibilità di incastri con molecole di altre superfici, rendendo difficoltoso così il movimento dell'una rispetto all'altra [Non è piana]

Student 7 (M) post test

No. nel caso di superfici perfettamente lisce allora la forza necessaria è diversa perché cambia la superficie di contatto reale

2. *Alla luce dell'esperienza fatta ridisegna il grafico del coefficiente di attrito μ al variare della rugosità tra due superfici e commenta le variazioni che eventualmente introduci e le ragioni che ti spingono a farlo*



In the case of **Student 8 (M)** instead, the answer to this question changes from pre- to post-tests and in the latter, the non-monotonous behaviour of COF as a function of roughness is envisaged.

5. *Ci sono superfici bagnabili ed altre in cui l'acqua scorre via: che ruolo credi abbia ha la rugosità superficiale nel determinare le caratteristiche di bagnabilità di una superficie?*

La rugosità agisce come l'attrito anche con le molecole d'acqua, riducendone la capacità di movimento e trattenendole quindi.

Pre test

2. *Come cambia il coefficiente di attrito μ al variare della rugosità tra due superfici: disegna un grafico di come immagini sia l'andamento di questo coefficiente all'aumentare della rugosità*

3. *Quali pensi che siano e cause microscopiche dell'attrito?*

L'ATTRITO È CAUSATO DALLE INTERAZIONI TRA GLI ATOMI SUPERFICIALI DI DUE OGGETTI A CONTATTO

Post test

2. *Alla luce dell'esperienza fatta ridisegna il grafico del coefficiente di attrito μ al variare della rugosità tra due superfici e commenta le variazioni che eventualmente introduci e le ragioni che ti spingono a farlo*

In the case of Student 9 (F), the idea of friction (and wetting) as contact between atoms and molecules clearly emerges.

4. *considera i due fenomeni attrito e tensione superficiale: credi che la loro spiegazione a livello microscopico possa essere ricondotta in tutto o in parte ad un'origine in comune? Se si Quale?*

Si sempre al concetto di contatto tra le particelle

5. *Ci sono superfici bagnabili ed altre in cui l'acqua scorre via: che ruolo credi abbia ha la rugosità superficiale nel determinare le caratteristiche di bagnabilità di una superficie?*

Credo dipende sempre dal contatto fra le molecole, e la loro superficie (liscia/ruvida)

C. Wetting and adhesion

It is interesting to note that for several students the adhesion between two wet glasses is due to air that "remains trapped" between the two surfaces o, vice-versa, to "vacuum" (sucker effect).

5. *Ci sono superfici bagnabili ed altre in cui l'acqua scorre via: che ruolo credi abbia ha la rugosità superficiale nel determinare le caratteristiche di bagnabilità di una superficie?*

Più un corpo è ruvido più è "bagnabile": la rugosità fa aderire le gocce d'acqua, quindi un corpo liscio le fa "scivolare" via più facilmente

6. *Perché si scivola su un pavimento bagnato ma due lastre di vetro bagnate poste a contatto aderiscono fortemente fra loro?*

Perché l'acqua sul pavimento diminuisce il μ_s, ma tra due lastre di vetro agisce da "vuoto" aumentando l'attrito.

6. *Perché si scivola su un pavimento bagnato ma due lastre di vetro bagnate poste a contatto aderiscono fortemente fra loro?*

Perché l'acqua sul pavimento diminuisce il μ_s, ma tra due lastre di vetro agisce da "vuoto" aumentando l'attrito.

6. *Perché si scivola su un pavimento bagnato ma due lastre di vetro bagnate poste a contatto aderiscono fortemente fra loro?*

È dovuto alla pressione creata dall'acqua tra le due parti

4.7.3 Results of Feb 2020 test

Analysis of pre-test results

(i) Macroscopic laws of friction.

The results of the first part of the pre-test show that most students answer correctly to both questions and exercises regarding the macroscopic laws of friction, and in particular, correctly state the independence of friction on the nominal area of contact. This shows that the flipped-class modality is effective in providing a common basis for all students engaged in the TLS.

However, it is interesting to note that, in agreement with Besson et al, most students (20/29) state that friction is proportional to weight. Moreover, they found significant difficulties in recasting the known laws in terms of the properties of COF: 6/28 students states that COF is proportional to the normal force, while 11/28 believe it is inversely proportional to it (see **Figure 4-29**).

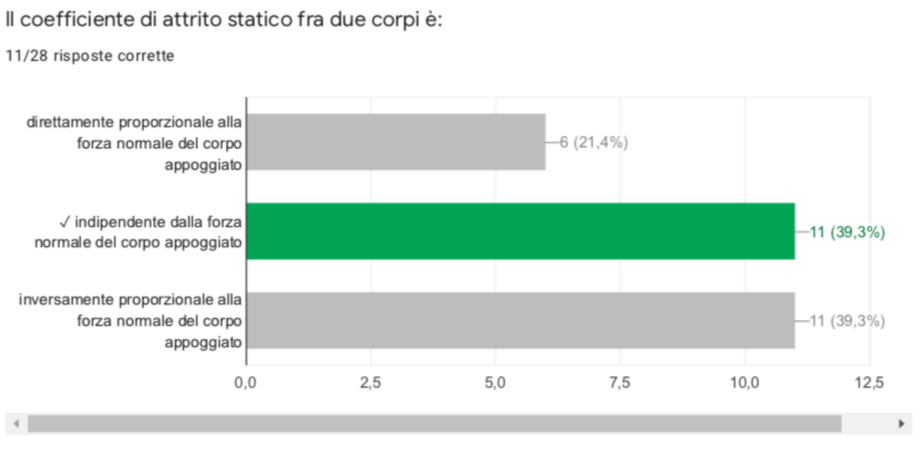


Figure 4-29 Pre-test results on investigating COF model.

(ii) Understanding of the relation between friction and surface roughness

Regarding this aspect, pre-test results clearly show that the interlocking mechanism is the most diffuse mental model and that friction is assumed to be related with roughness, i.e., the rougher the interface, the higher is friction: this is apparent from both the results of the *interface-problem* (see **Figure 4-23**) and from the answer to open questions. Nevertheless, it is important to note that in the *interface-problem* 4/26 students correctly recognize that it is not roughness itself, but rather the true area of contact that influences COF value. These students explain their choice of interface D as the one with higher friction in terms of 'increased complementarity between the two surfaces', *increased area of contact* or *reduced distance between the* *two surfaces, which in turn increases adhesion*. These findings suggest how providing students with drawings of different interfaces, may trigger new insight and perspectives, helping students building a more correct mental image of the physical situation.

(iii) Knowledge of the structure and dimension of atoms and molecules, and of the nature of intra and intermolecular forces

Most students have a basic knowledge of the structure of atoms and of their dimensions (22/26 correct answers) and of the nature of the forces responsible for bonding (23/28), though 2/28 identify it as nuclear, and 3/28 think that it depends on the bond type. On the other hand, only 8/28 students were able to explain the energy potential diagram reported in **Figure 4-24**

Analysis of post-test results

(i) The laws of macroscopic friction

The results of the post-test show that the basic understanding of the macroscopic laws of friction is preserved after the TLS, and that, after the TLS, almost all students correctly discriminate between the behaviour of 'usual' materials (26/27 friction does not depend on nominal area) and that of 'particular' materials like GT (25/27 friction does depend on nominal area).

(ii) The microscopic origin of friction is essentially due to intermolecular forces, which are electrostatic in nature and act at distance;

The electrostatic nature of intra and inter molecular forces was already known by the majority of students, as shown by the pre-test results. The common microscopic origin (i.e., intermolecular forces) of friction and wetting has been correctly grasped by a consistent fraction of students (13/19 – some students did not answer to this question). Moreover, answering the triglyceride question, 10/24 students demonstrate the ability to recognize the fundamental role played by molecular interactions in such a complex tribological context. Moreover 16/27 students were able to identify the correct explanation for the wetting behaviour of water on a micro-structured surface (this issue was not explicitly discussed during the sequence).

These results show that our approach (i.e., exploiting wetting to introduce intermolecular forces) is indeed fruitful. Undoubtedly, it also shows that this connection is not straightforward and that more time should be devoted to the topics of surface tension, wetting and intermolecular forces (see discussion on the flipped-class approach in the following section).

(iii) Friction between two bodies in mechanical contact depends on the microscopic contact area,

As already stated, most students (25/27) achieved a clear understanding of this issue, correctly providing the reason why in some special cases, such as GT, friction does depend on nominal area, while usually it does not. They were also able to relate the proportionality between applied normal force and friction to the variation of the true contact area.

(iv) - Friction varies non-monotonously with surface roughness

Answers to the interface problem give us particularly interesting results: 24/27 students correctly choose interface D as the one with the larger area of contact, and 20/27 correctly deduce form that that COF should also be larger in this case. We should note that, during the TLS, we never explicitly discuss a situation like the one depicted in this problem. Students therefore came to the correct answer by reasoning, and not by merely stating what they have been told. Comparing the results obtained in the pre-test with the one in the post-test, shows the effectiveness of our approach in helping students to grasp the subtleties of tribological phenomena and their connection to the micro- and nano-scale properties of materials.

Chapter 5: Macroscopic Stick-slip effect on GeckoTape® surface

As discussed in Chapter 3, the Stick-slip effect is an oscillatory behavior which takes place in elastic mechanical systems subjected to friction. It can be described as a succession of stick phases, in which elastic potential energy builds up, and slip phases, in which the potential energy transforms in kinetic energy.

In **Figure 5-1** the typical behavior of frictional force observed during stick-slip motion at the microscale is schematically shown. Initially, the block is still and static friction increases, till in reaches its maximum value. Afterwards, the block starts to move and friction reduces to it dynamical value Fk. During motion, friction actually displays an oscillatory behavior, in which the maxima corresponds to the moment in which the block starts to move after a stick phase, and the minima correspond to the moment in which the block stops again.

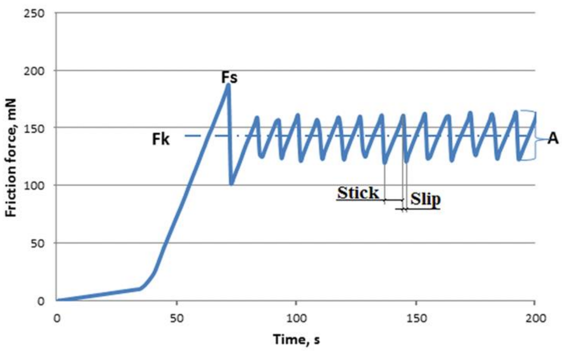


Figure 5-1 Typical behavior of the frictional force in a stick-slip experiment. Fk is the average value of dynamic friction, while A represents the stick-slip oscillation amplitude.

Stick-slip plays a fundamental role in nanotribology, as it represents a simple model which allows to directly introduce a dissipation channel - i.e., the excitation of atomic vibrational motion, which opens when the system switches from the stick to the slip phase. For this reason, this effect and the related model has also a great educational value. In the educational context, the stick-slip effect is often introduced and explained referring to a wide number of examples, such as the sound of chalk on the blackboard, the door squeak, and so on. On the other hand, to the best of our knowledge, no quantitative experiment demonstrating stick-slip is present in the educational literature. The stick-slip behavior of microstructured silicon films similar to Geckotape® has been studied at the microscale using a surface forces apparatus (SFA) [108].

In this chapter, I present and discuss the results of an experiment - based on GT - which highlight and quantitatively investigate the stick-slip effect at the macroscale. These results are then compared with those obtained using sandpaper. By dragging a smooth wooden block on a GT-coated horizontal surface, due to the strong adhesive force exerted by GT on the block, a succession of phases in which the block stands still (stick) and phases during which quick slipping motion occurs, can be clearly observed by eye.

This qualitative observation is turned into quantitative measurements by exploiting a quite simple experimental set-up, based on the use of force sensors and on-line data collection, as well as video recording and Tracker analysis. The experiment is therefore in principle affordable for lab activities at high-school level. On the other hand, as I will briefly explain in the following, careful and skillful control over some critical parameters is in this case mandatory to obtain reliable and reproducible results. For this reason, I suggest this experiment as more appropriate to an undergraduate level. Nevertheless, the experiment may be suitable to be demonstrated to high-school students (using videos) and combined with data analysis and discussion. This experiment has not been yet piloted with students nor teachers.

5.1 Experimental set-up

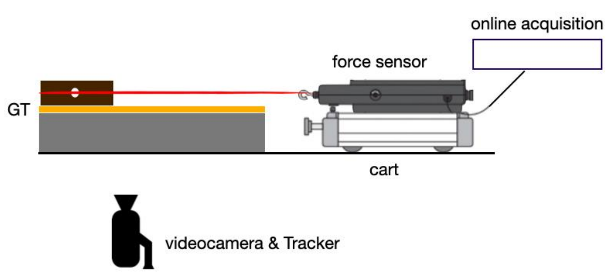


Figure 5-2 Experimental set-up.

As shown in **Figure 5-2** the experimental set-up consists in a smooth wooden block, dragged on a horizontal surface which has been previously coated with a GT film. The block is connected by a string to a dynamic cart (Pasco Scientific), which can be set to move at constant power. A force sensor (Force Sensor CI-6537 - Pasco Scientific) is mounted on top of the dynamic cart, so that the force exerted on the block by the cart can be recorded during motion.

This set-up is usually used – exploiting ordinary materials for the block and the horizontal plane - to demonstrate the independence of friction on speed. In this case,

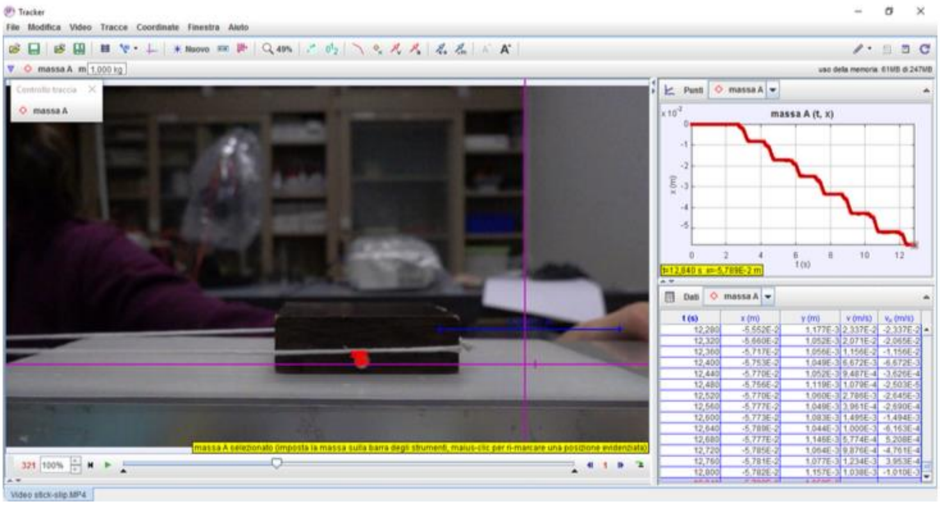


Figure 5-3 Example of a video-frame and of the relative Tracker analysis.

as dynamical friction
is constant, controlling (by turning the proper knob) the power supplied to the cart corresponds to vary its (constant) speed. In fact, in our case the force - and therefore the cart speed - is not constant; what should be considered constant is the power supplied to the cart. In order to collect data on the block dynamics (i.e., its trajectory and speed), the whole motion is video-recorded with a high frame-rate camera (250 fr/s) and subsequently analyzed with tracker. To this aim, an easily trackable white spot is drawn on the lateral edge of the block. An example of Tracker analysis is shown in **Figure 5-3**, where a frame of the recorded video is also displayed.

Measurements are performed on three different coatings: both micro-structured and smooth sides of GT, and SP (fixed to the horizontal surface with double-sided tape). Extreme care should be taken to ensure perfect adhesion between the GT and the horizontal surface, especially trying to avoid air-bubble formation. Another critical issue is the cleanliness of the exposed GT surface, as GT adhesive properties are strongly affected by the presence of dust, small fluff or grease. Moreover, aims at

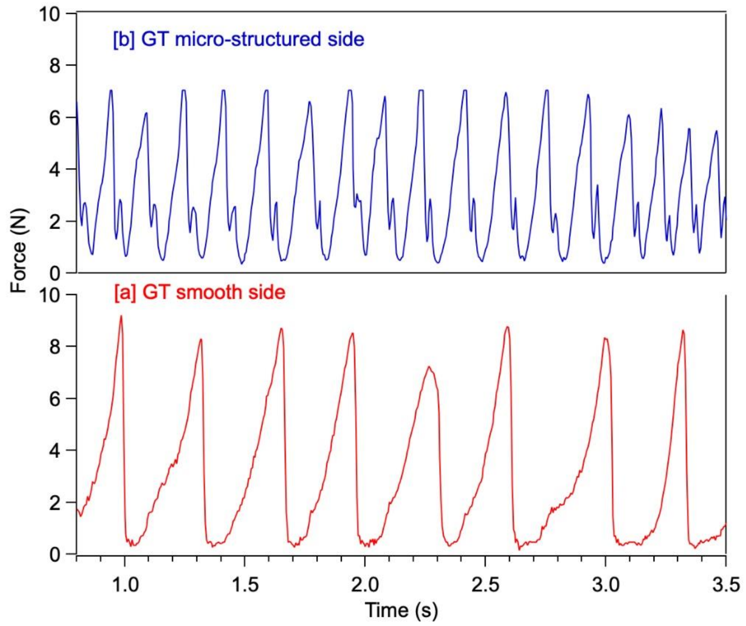


Figure 5-4 Frictional force measurements as a function of time. The red and blue curves refer to the GT smooth and micro-structure sides, respectively.

modifying the mean value of the frictional force exerted on the block, the normal force can be varied by putting a selected number of 50 gr weights on top of the block itself.

5.2 Results and discussion

In **Figure 5-4** examples of measurements taken with our set–up on both the smooth and the micro-structured side of GT are shown. The experimental conditions are the same for both measurements, where a huge oscillatory behavior of the measured frictional force as a function of time is clearly observed. In the case of the smooth side, the observed behavior corresponds exactly to a succession of prolonged stick phases – during which the force increases – and very short slip phases -during which the frictional force goes rapidly to zero. By visual inspection, it can be seen that in the slip phase the block is essentially detached from the horizontal plane, thus explaining the vanishing value of the frictional force. It is interesting to compare the measurements taken on the smooth side of GT with those recorded on the micro-structured side. While the oscillatory behavior is clearly observed in both measurements, a few apparent differences can be highlighted:

i. the force maximum value, occurring at the end of each stick phase and corresponding to maximal static friction, is larger in the case of the smooth side than in that of the micro-structured side;

ii. the period of oscillation is longer in the case of the smooth-side measurements.

The first of these major differences can be rationalized considering that, as the surface of the chosen wooden block is extremely smooth and due to the high deformability of

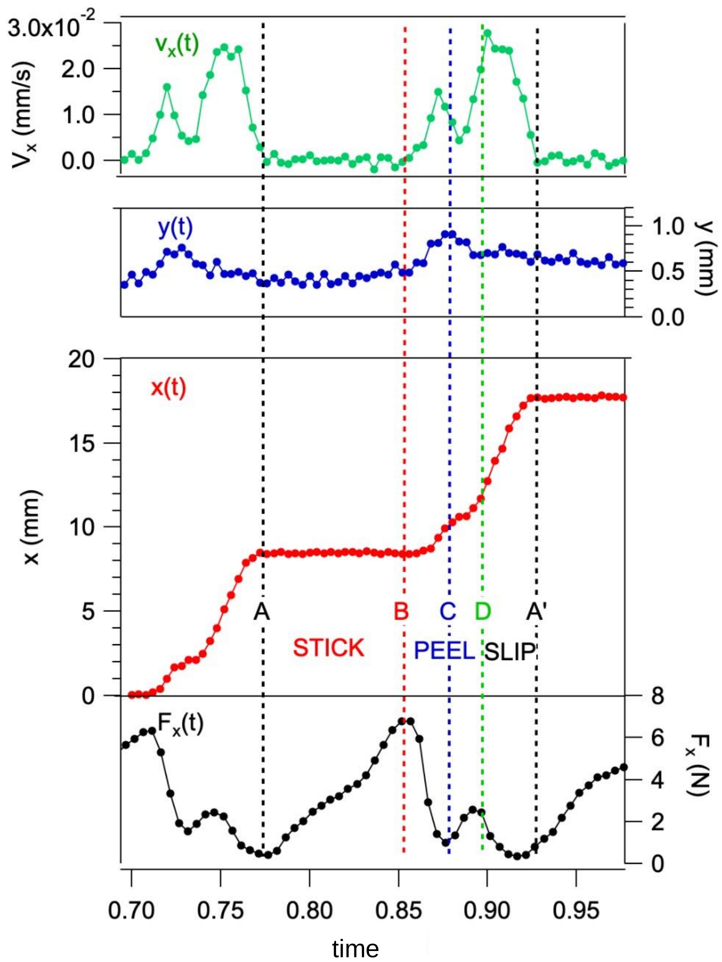


Figure 5-5; Horizontal force F_x (black curve), displacement x (red curve) and speed v_x (green curve) as a function of time, measured for the micro-structure side GT. The blue curve is the block vertical displacement y(t). For $F_x(t)$, a small time offset is introduce relative to the dynamic data, so that the $F_x(t)$ maximum occurs at the same in which the block starts to move horizontally, individuated by the $v_x(t)$ curve.

the GT film, the real contact area is reasonably larger in the case of the smooth-side GT. This implies a larger adhesive force, i.e. a larger value of the observed maximal static friction force. As far as the period is concerned, we note that the duration time of the slip phases is approximately the same in both situations, while the stick phase is much longer in the smooth-side case. This means that, under the same experimental conditions (in particular the same amount of power supplied to the system), in the smooth-side case friction increases more slowly. In turn, this can be reconducted to the higher rigidity of the seamless side, relative to the more deformable pillar structure. In other terms, as more energy is needed to reach the deformation limit of the compact smooth-side GT than to reach that of the pillar structure, if equal power supply conditions are considered, more time will be required in the former case than in the latter.

In **Figure 5-5**, a selection of the datasets relative to the micro-structured side is reported, displaying only two oscillations. The force data displayed in the lower pane, are directly compared with information on the block dynamics provided by Tracker, i.e. the horizontal displacement x(t), the horizontal velocity vx(t) and the vertical displacement y(t). In these graphs, some peculiar features can be highlighted, which are not present in the case of the smooth-side GT. The stick phase can be thus readily identified: it corresponds to the interval(A-B) in which both x(t) and y(t) do not change, v_x is obviously zero and the force F_x increases. The stick phase ends in B, when F_x reaches the maximum value. From B to A' the block moves: in this time interval the force profile shows one minimum (C) and a secondary maximum (D). In the B-D interval, due to the torque applied by the pulling force and friction[1]: the block moves both horizontally and vertically in a movement that can be described as a "bike-stoppie". We refer to this interval as a peel phase, which is favored by the pillar inclination due to deformation. Eventually, during the D-A' interval, the block moves only horizontally, in the usual slip phase.

[1] this movement is emphasized by the fact that the string pulling the block is fixed at its rear see fig. **Figure 5-1** . Slow-motion video available on [127] [128].

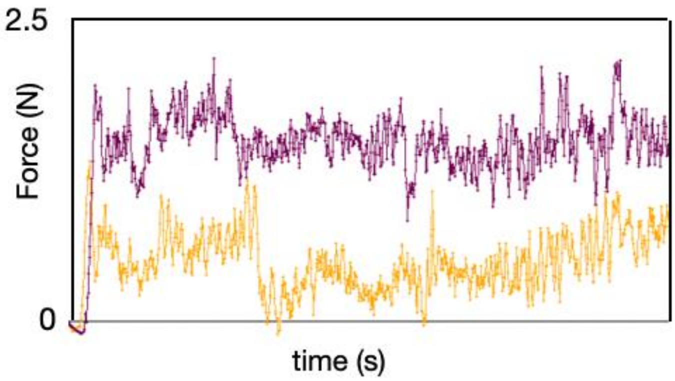


Figure 5-6 Frictional force exerted between the same wooden block (yellow curve)and sandpaper. The purple curve is obtained adding a weight of 100 gr on top of block, in order to increase the normal force (and therefore friction).

In **Figure 5-6**, the results of a similar experiment, carried out on the SP are also shown. In particular, two curves are shown, obtained by varying the applied load (normal force). First of all, it is important to note that the average frictional force in this case is notably weaker than in the GT case (even if the load is increased), clearly showing that friction does not necessarily increase with surface roughness and the fundamental role played by adhesive forces. Moreover, in both cases the curves display a quite noisy and random behavior: while the high frequency variations are simply due to the experimental noise, the lower frequency one are definitely larger the experimental uncertainty and shows the stochastic nature of the frictional force, due to the random distribution of asperities.

Chapter 6: Probing the microscale structure of GT - From Geometrical and Wave Optics to Instruments

A fundamental role in the raise of nanoscience has been played by the development of novel scientific instruments, which allow scientists to detect, measure, manipulate and fabricate matter at the nanoscale, with unprecedented precision and accuracy and, usually, referred to as the "Tools and instrumentation" *Big-Idea* [4].

Any experimental technique which investigates materials is essentially based on some kind of interaction between a probe (light, electrons, neutrons) and matter, which provides direct or indirect information on the properties of matter itself. A possible route to convey this idea to students is to give them the chance to learn how instruments work, through their own experience. Here, we introduce both microscopy and diffraction experiments, to demonstrate how the interaction between light and matter is used to probe the structural properties of matter at the microscopic level.

In this chapter, I describe a TLS which, starting from the basis of geometrical and wave optics, introduces the operating principles of optical microscopy, applying them to the construction of a simple microscope, used to investigate the GT structure. Moreover, starting from the basis of wave optics students are brought to learn how, in a complementary approach, diffraction can also be used to investigate the structural properties of a material. In this way, direct investigation of the GT structure is exploited as a stimulus to engage students in the study of optics; moreover, emphasis can be put on the "Tools and Instrumentation" idea, and the operating principles of optical microscopy and diffraction can be considered as the starting point to introduce the concept of diffraction limit and those tools - such as the transmission electron microscope (TEM), scanning microscopies (AFM, STM, SEM) and electron/neutron/x-ray diffraction techniques - which scientists use to probe the structure of matter at the nanoscale.

6.1 The Educational Framework

In Italian secondary school, the study of optics is often considered marginal, with little connections to other parts of the physics curriculum, and it is the first one to be cut or neglected when lecturing time is not enough.

The school program mainly focuses on the study of the laws of lenses and little time is devoted to learning how these laws are applied in instrumentation; moreover, laboratory activities, especially on wave optics, are seldom proposed. A whole wealth of educational material and online resources - often theoretical worksheets or lecture notes - are currently available, created by several schools, universities, and educators. [109], [110]; Some qualitative experiments, exploiting poor materials, are also available [111], [112][113]. An interesting example can be found in [114], where the instructions to build a simple microscope using a lens recycled from a DVD/CD player and a smartphone camera, can be found. On the other hand, only a few resources [115] propose quantitative experiments.

Though a comprehensive analysis of the vast literature proposing various teaching optics methodology is beyond the scope of this chapter, a few researches which exploit active learning and hands-on activities are worth mentioning here. The ISLE group of E.Ekina [116] designed an ISLE cycle in which ad-hoc videos are used to engage students in quantitative experiments demonstrating the principle of geometrical optics. In 2016 C. Even [117] designed an undergraduate teaching course in geometrical optics based on active-learning approach and on simple, both qualitative and quantitative experiments. Moreover, V. Montalbano proposed a sequence that uses poor materials, such as plexiglass blocks, to study refraction [118].

There is strong evidence in the literature that the laws of optics are far from obvious for students, and that several misconceptions, partially caused also by the misleading use of drawings and concepts, may significantly hinder their understanding [115]. An important example is the concept of light ray, and its use in drawings illustrating Gauss ray diagram for optical lenses: on one hand, students are often brought to consider rays as physical object by themselves rather than a model, on the other, restricted representations of ray tracing, such as for instance the one depicted in Figure 6-1, often induce students to develop incorrect ideas on image formation.

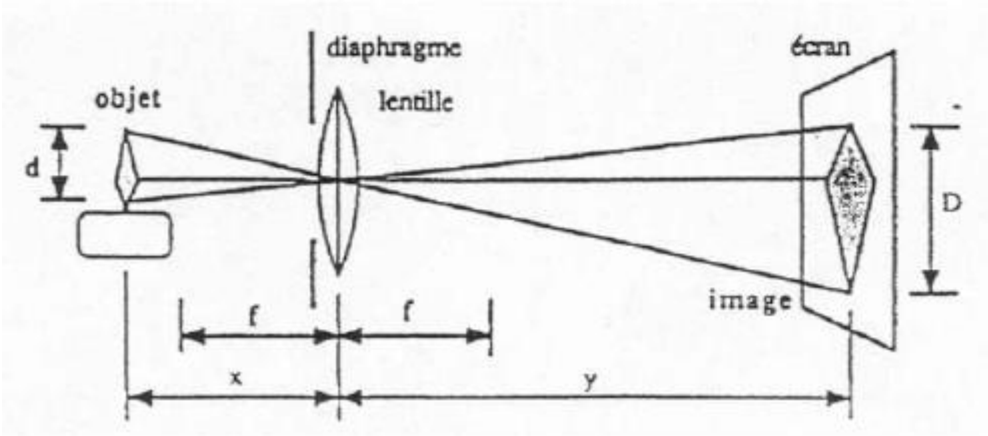


Figure 6-1 Example of a figure depicting an optical device, in which the emphasis on the particular `central' ray may be misleading. After [115].

6.2 The Geckotape® TLS on geometric optics and diffraction

As I mentioned at the beginning of the chapter, the proposed TLS is designed - according to the principles of active learning - around the Gecko Tape® material (GT). This sequence has been preliminary piloted on a group of 16 years old students and on a group of in-service teachers without a throughout and formal testing. It represents therefore a first version, which will be further tested and implemented in the future.
As already shown in Chapter 4, GT film has a thickness of ~ 340 μm, is semi-transparent and its microstructure can be observed under an optical microscope, both in transmission and in reflection. Moreover, its microstructure consists of a hexagonal periodic array of pillars, with an interpillar distance of about 50 μm, which acts as a 2D diffraction grid for monochromatic visible light. The TBL, therefore, starts with an IBSE question, which reads as follows: "How can we possibly investigate the structure of GT at the microscale? Can we build one (or more) instruments to measure it? On what operating principle are they based?"

The complete sequence mimics the scientist daily work and involves, in particular, the construction and calibration of a microscope, which represents an engaging challenge for students and an opportunity to improve their soft and hard skills, such as manual ability, problem-solving, team working, initiative and decision-making skills. The comprehensive scheme of the TLS structure is reported in **Figure 6-2**: it aims at optimizing the time devoted to laboratory activities, it includes some preliminary flipped-class tasks, inspired by the Team-Based Learning (TBL) methodology. It consists of two TBL sequences, devoted to geometrical optics and optical microscopy, and to wave optics and diffraction, respectively.

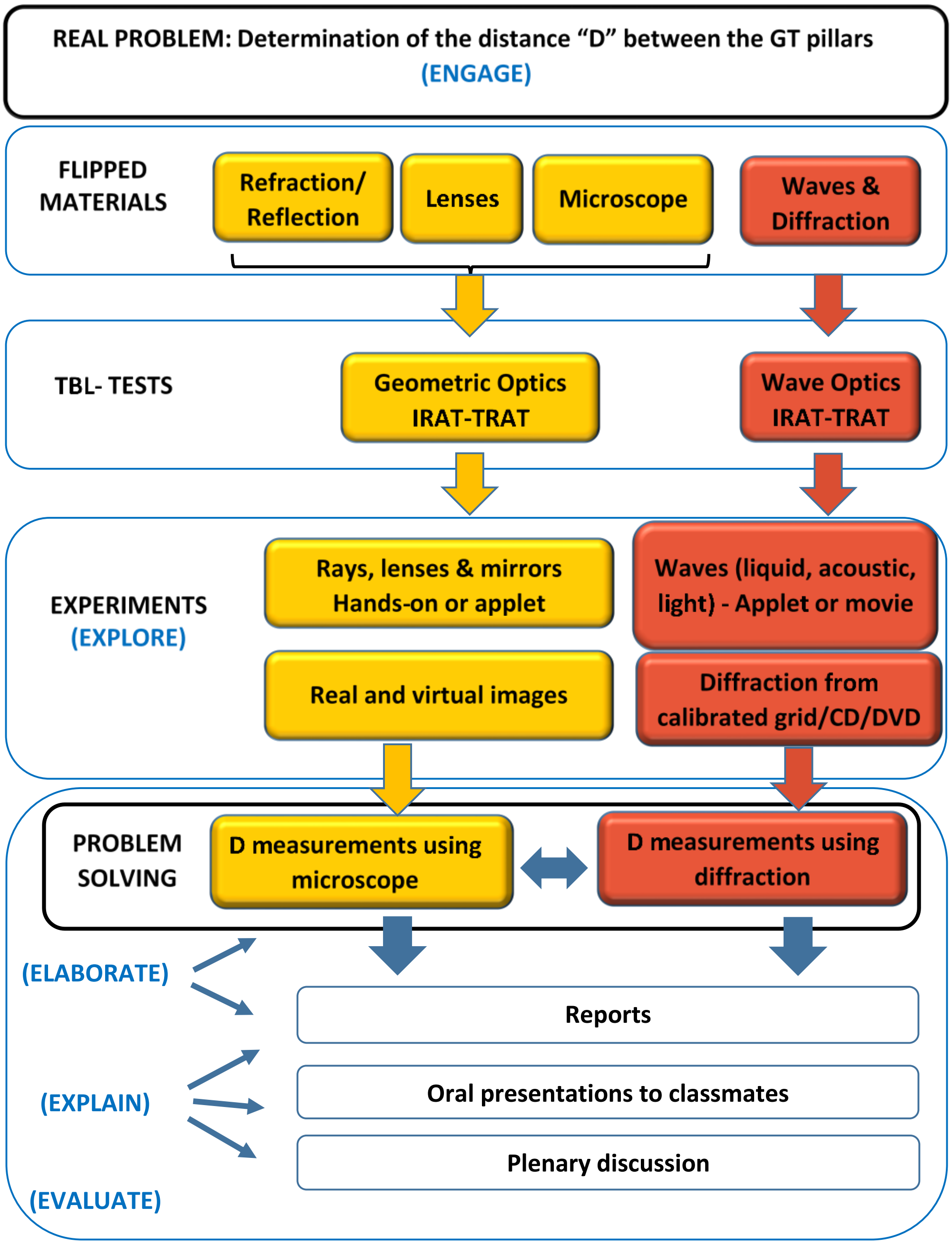


Figure 6-2 Structure of the Gecko - Optics TLS: activities relative to geometric and wave optics are labelled in yellow and red, respectively. The different phases of the 5E methodology are indicated in blue. Experiments are also available as videos at [119]. The use of Colorado University applet [120], [121], [122] is also possible and suggested.

According to the TBL methodology, teachers preliminarily form the students' groups using the criterion of highest heterogeneity and introduce the TBL plan and goals, explaining how the I-RAT and T-RAT[1] tests are aimed at verifying homeworking. In agreement with ISLE methodology, the aim of both sequences, i.e., the determination of the GT structure, is explicitly stated at the beginning of the activity. The determination of GT structure represents also the core of the T-APP problems, which, therefore, at variance with proper TBL methodology, students know from the very beginning.

6.2.1 TBL 1: Geometrical optics and optical microscope

Day one: Introduction and flipped materials

The starting point of this activity is the introduction of refraction/reflection and Snell law. In principle, we believe the best way to do this is through experiments, which can be easily performed in school labs exploiting commercial or home-made didactic kits, as briefly illustrated in **Figure 6-3**; and in **Figure 6-4**.

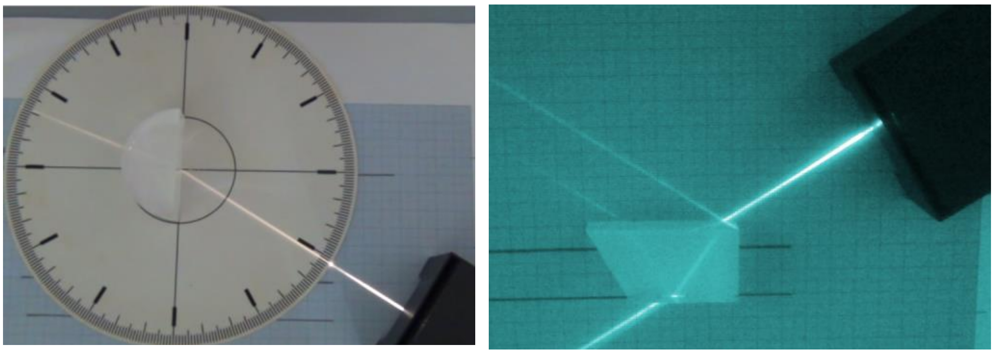


Figure 6-3 Lab kit to illustrate reflection and refraction, and to quantitatively verify Snell law.

Alternatively, teachers might exploit videos demonstrating the laws of reflection and refraction, which are readily available. The main point here is to provide students with the experimental evidence of refraction, which is the physical phenomenon at the basis of the working principle of optical lenses. Then, the basic concepts and terminology regarding lenses (lens type, ray model, definition of focus and center of a lens) are introduced theoretically.

Finally, flipped materials revising this topic and introducing Gauss law are provided (as, for example [123]). At this stage, these concepts are probably perceived as quite artificial, and possibly blindly accepted, without true insight. Nevertheless,

[1] See section 1.2.7 step 2 and 3

the idea here is that providing some basic technical jargon will facilitate, in the subsequent experimental phase, the identification the relevant element, thus fostering a more profound understanding.

Day two: Geometrical optics basics

I-RAT and T-RAT

Individual and team tests are given at the stage, probing the knowledge of the basic concepts and jargon introduced in the flipped material. Result discussion and further explanation are then provided by the teacher.

Experiment - Stage 1: Playing with lenses

In this stage, students are asked to perform simple experiments, designed to provide a clear visualization of the basic concepts previously introduced theoretically, as in particular light ray, center and focus of a lens. Some examples of such experiments are shown in Figure 6-4and Figure 6-6, while the corresponding videos can be found in [119]. These videos may also be used as an alternative to experiments, if time, or lab kits, are lacking.

These experiments make optics basic concepts tangible, thus helping students in the construction of their own mental models. It is important to highlight here that some time should be devoted to discuss and make explicit the nature and limits of the concept of light ray. To this aim, helpful questions may be: What is it exactly that we observe in the experiment and call light-ray? How each ray is produced in the proposed apparatus? Will we see it in the absence of the table? How many rays are produced by each portion of the light source?

At this stage, students are also asked to verify Gauss equation for thin lenses, which

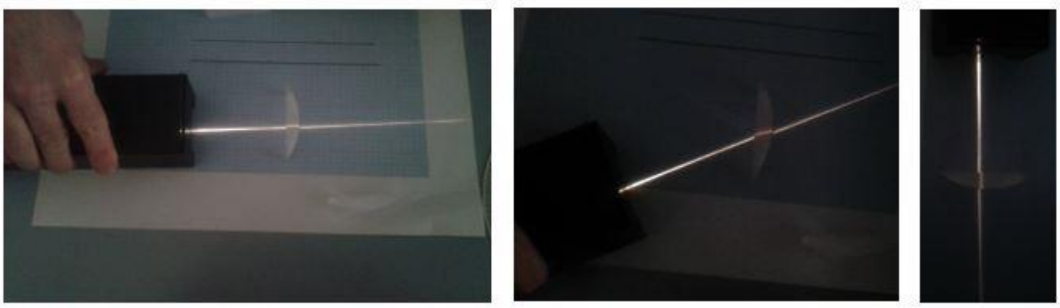


Figure 6-4 Geometric optics experiment to understand the ray model and the concept of lens center.

they has been introduced formally previously. Using a screen and varying its distance from the lens, the concept of image formation can be clarified, showing in practice how the "image" gets blurred and disappears when the distance is different from the one predicted by Gauss law (see for instance the first part of the video on the optical microscope [105]). Students perform experiments following provided worksheets and tests. They are also asked to compare the results of experiments with Gauss diagram simulation made with Geogebra, where the object dimension and distance from the lens can be varied [124].

Experiment - Stage 2: Understanding the difference between virtual and real image

The short demonstration shown in Figure 6-5 aims at illustrating the differences

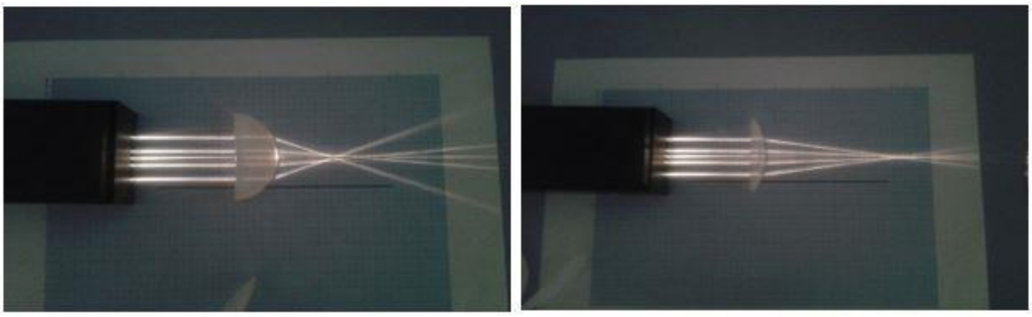


Figure 6-6 geometric optics experiment to understand laws of thin lenses and focal distance concept.

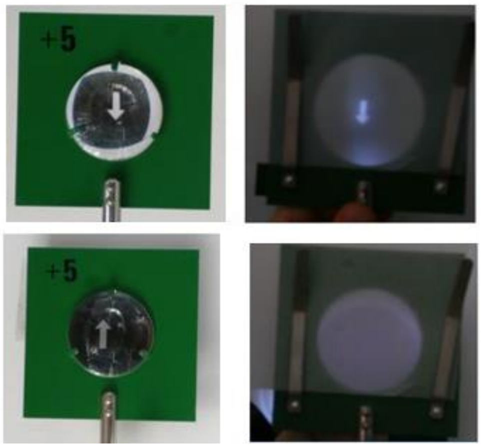


Figure 6-5 Real (top) and Virtual down) images. On the left looking from a small distance to lenses and in only in a specific position for virtual one; On the right using a semi-transparent screen.

between real and virtual images. Two identical converging lenses with focal distance $f = 5$ cm are placed at a distance $f < d_1 < 2f$ (real image) and $d_2 < f$ (virtual image), from an object -represented by an arrow - respectively [125]. In both cases, a sharp image of the arrow can be seen by eye, at the proper distance: it is upside down in case 1 (real image) and upright in case 2 (virtual image). As shown in

Figure 6-5, the image formation is than probed by placing a semitransparent screen at specific positions: while in case 1 the image is formed on the screen at the appropriate distance (real image), in case 2 no image can be observed, at whatever distance the screen is positioned (virtual image).

Experiment - Stage 3: Operating principles of the optical microscope

An optical bench and two lenses are used to make students understand how the image is formed in an optical microscope and the meaning of magnification. We recommend to first do the experiments (or view the videos [105])[2] and then ask students - as a homework - to use the simulation [126].

Experiment - Stage 4: T-app - Build your microscope with a smartphone - @home and in the classroom

In this stage, each group is asked to develop and deploy a self-made microscope. This work can be done in class and/or at home. The final phase of this work is performed in the classroom and involves the calibration of the instrument, performed by measuring a known specimen (such as a diffraction grating, or even a millimetric ruler), the observation of GT images, and measurement of its interpillar distance. The image quality strongly depends on the ability to correctly

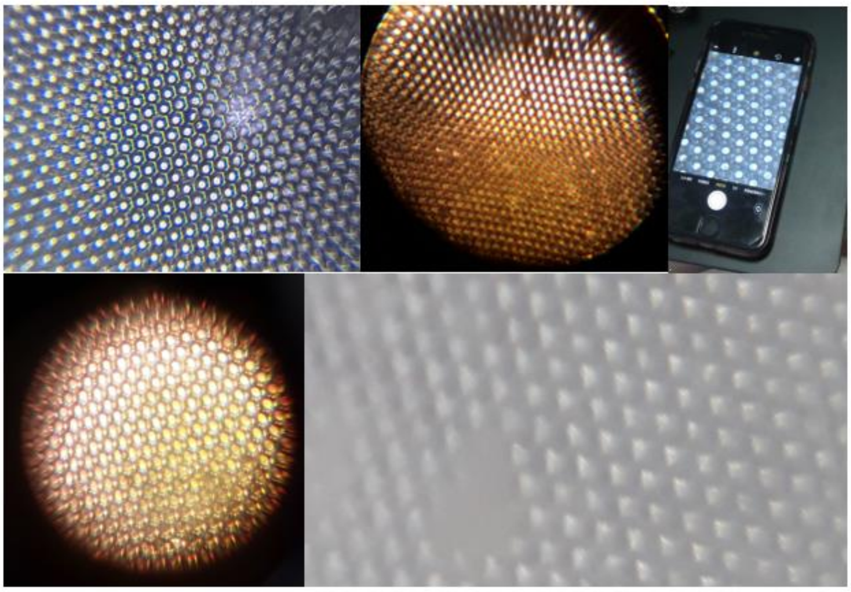


Figure 6-7 Examples of self-made microscope images of GT: different images depending on the quality of the smartphone camera.

position the object relative to the objective lens (the focal distance of DVD-players

[2] For the sake of exactness, we should note that the set-up illustrated in the video is not the standard set-up for the microscope, as the image produced by the second lens (eyepiece) is real, and not virtual: in fact, only in this way, it is possible to visualize in on the screen.

is very small) and the smartphone camera quality. Magnification 20X can be easily achieved (which can be increased using the camera digital zoom). Examples of the obtained images are shown in **Figure 6-7**

Tools and Instrumentation

Optical microscopes are often available in school labs and may also be USB connected to a computer to acquire high-resolution images. In this case, it is therefore possible to

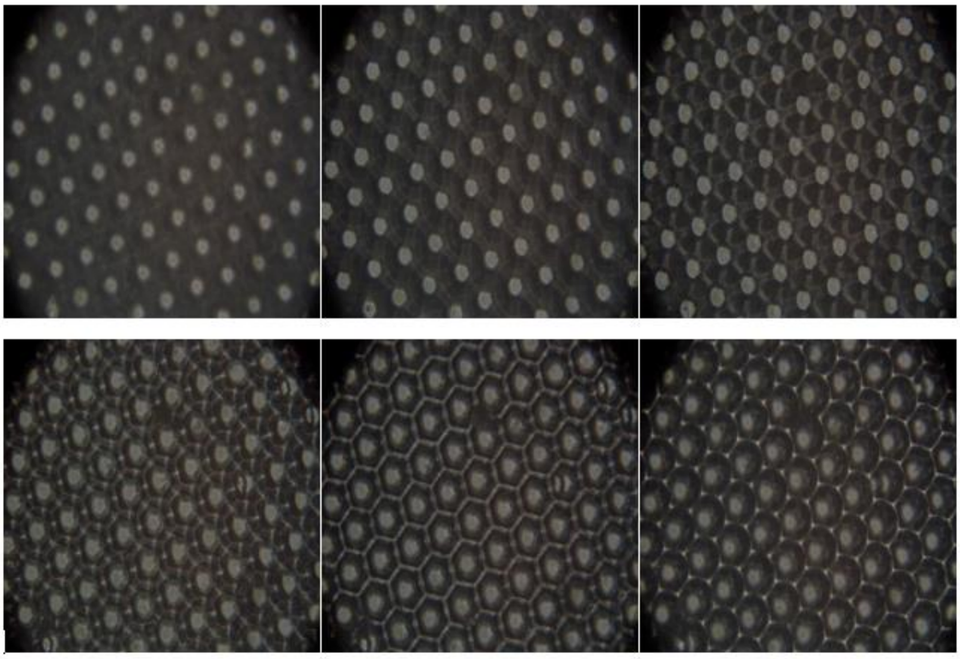


Figure 6-8 GT optical microscope image, taken at different object-objective lens distanced: due to the short the depth of field of the microscope, each image correspond to different heights of the pillar structure. Magnification 20x.

show students GT images of higher quality than that of the self-made microscope. Then, the concept of depth of field may be also illustrated, as a simple turn of the focus control allows to smoothly vary the object-objective lens distance, thus focusing on different heights of pillar structure, as shown in **Figure 6-8**. Optical micrographs can then be compared with images taken with the Scanning Electron Microscope images (see **Figure 6-9**). This provides the opportunity to introduce novel instrumentation, such as SEM and scanning probe microscopies, on one hand, and Transmission Electron Microscopy on the other. In explaining the operating principles of both SEM and TEM, knowledge of the optical microscope represents an important prerequisite.

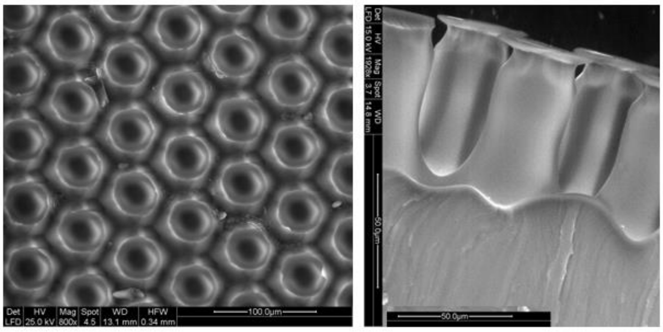


Figure 6-9 SEM image of the GT film surface (left panel, magnification 800x) and cross section (right panel, magnification 1928 x).

6.2.2 TBL 2: Wave Optics

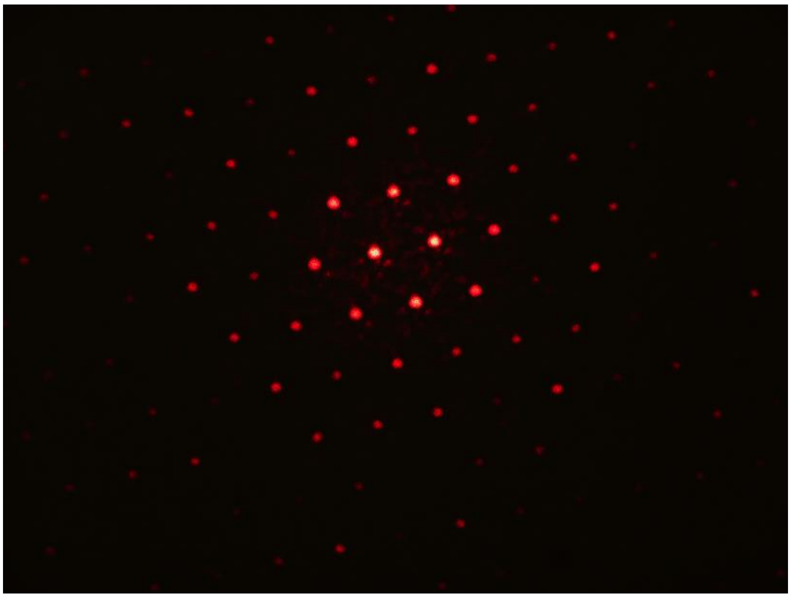


Figure 6-10 GT diffraction pattern-Red He-Ne laser diode; λ= 632,8 nm.

As discussed in Chapter 4 and shown in figure **Figure 6-10**, a light beam from a laser-pointer through a piece of GT produces a nice hexagonal diffraction pattern on a screen. By measuring the distance L between the GT and the screen, and the distance d between neighbouring spots, a quantitative estimate of the lattice parameter, i.e. the inter-pillar distance a , can be easily derived as:

$$a = \frac{\lambda}{\sin(\text{atan}\left(\frac{d}{L}\right))} \cong {}^{\lambda L}/_{d} \quad (10)$$

where λ is the laser wavelength.

The value of *a, as* determined in the diffraction experiment, is in good agreement with that obtained with the optical microscope.

Day one: introduction to TBL plan and flipped materials

Teachers introduce wave optics illustrating only the basic concepts, starting from constructive and destructive interference. Also in this case, the more effective approach would probably be to introduce the phenomenon experimentally, with teacher's demonstrations or students' activities. Afterword flipped material which revises the basic concept is provided.

Day two - Optical diffraction

I-RAT and T-RAT Individual and team tests are given at this stage, probing the knowledge of the basic concepts and jargon introduced in the flipped material. Discussion of the results and further explanations are than provided by the teacher.

Experiment – Stage 1

Students are asked to verify the law of diffraction from a grating, exploiting a simple diffraction grating, which can be purchased for less than few euros, and a laser pointer. If two lasers (green and red) are available, the dependence of the diffraction pattern dimensions on the wavelength can be verified. This experiment is very easy to realize, with a good precision (the laser wavelength can be measured with the precision of tens of nanometres). The aim of this first part of the experiment is twofold: on the one hand it quantitatively verifies the diffraction grating law, on the other it provides a mean to calibrate the instrument (diffractometer) for further measurements. Indeed, the same apparatus can then be used to measure the periodicity of micrometric lattices, such as those of the DVD and CD tracks (in reflection) or - the declared scope of the whole sequence - the GT micro-structuration (in transmission).

6.3 Gecko Tape® and Phase Diffraction studies

As shown in the previous TLS, Gecko Tape® can be considered a peculiar diffraction grating. This makes it a suitable subject for more advanced investigations, at undergraduate level. On one hand, Gecko Tape®, displaying a 2D hexagonal periodicity, may be easily used to illustrate the relation between real and reciprocal lattice. In particular, it is possible to exploit its deformability to prove how a variation in the real lattice periodicity affects the 2D diffraction pattern in the non-trivial case of non-orthogonal lattice vectors. Indeed, by inspecting its diffraction pattern, Gecko Tape®can be easily oriented so that one of its lattice vectors, **a** is parallel to the vertical direction, while the other vector **b** forms an angle of $\frac{\pi}{3}$ with it.

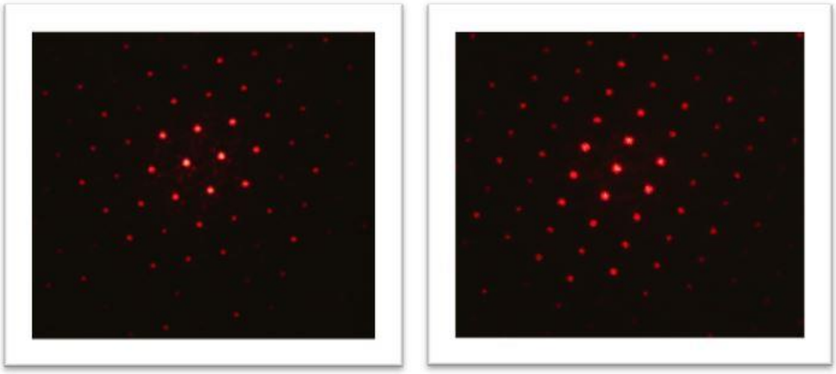


Figure 6-11 Vertical deformation of GT: comparison between diffraction pattern of unstretched (left) and stretched (right) material.

Moreover, it is easy to stretch the Gecko film along the vertical direction, whether manually or by fixing a small weight to the film itself. In doing so, the diffraction pattern deforms, shrinking along a direction which forms an angle of $\frac{\pi}{6}$ with the vertical (see **Figure 6-12**), i.e. perpendicular to vector **b**. This, non-trivial, result nicely illustrates the mathematical definition of the reciprocal vector $\mathbf{G_a}$, i.e.

$$\boldsymbol{G}_a = 2\pi \frac{\boldsymbol{b} \wedge \boldsymbol{k}}{\boldsymbol{a} \cdot (\boldsymbol{b} \wedge \boldsymbol{k})} \qquad (11)$$

where **k** is the unitary vector normal to the Gecko film plane. This simple experiment has been successfully proposed to third-year students of the Physics degree, within the Solid State Physics course.

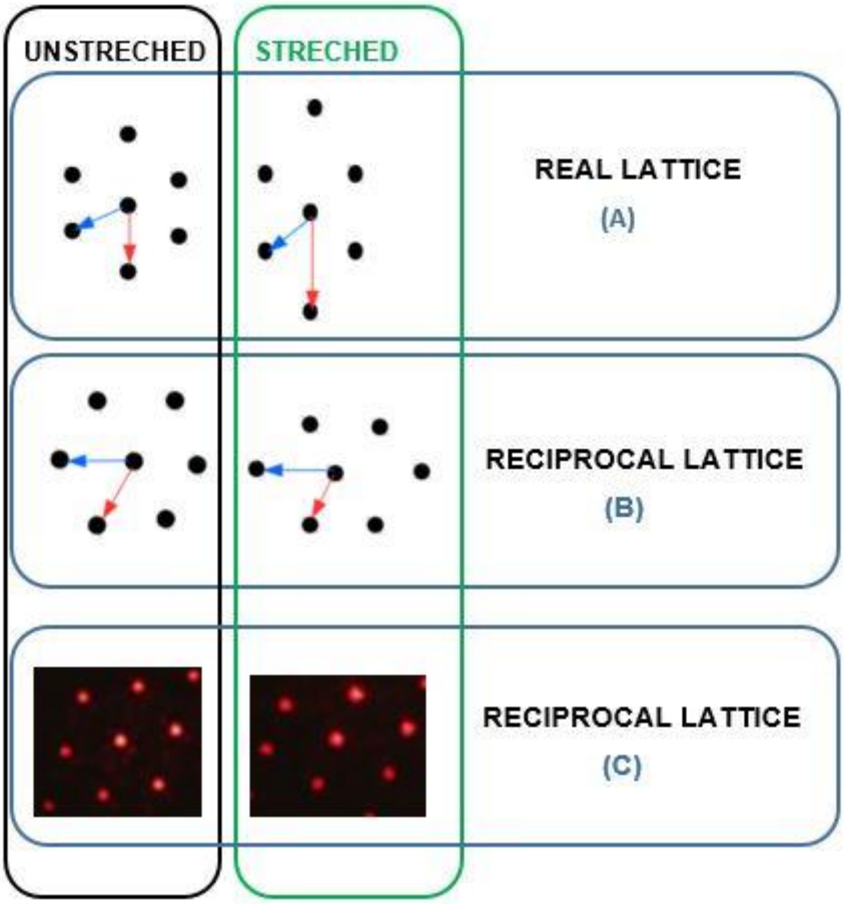


Figure 6-12 Real (upper box A) and reciprocal lattice (central box B) for hexagonal geometry. The left black box encloses the pictures of the unstreched "lattice" condition while the right green box contains the vertical, stretched, corresponding, ones. Red and blue arrows represent two related real/reciprocal vectors. The bottom box (C) shows the acquired diffraction pattern, shown in **Figure 6-11**.

6.3.1 GT as an example of phase diffraction grating.

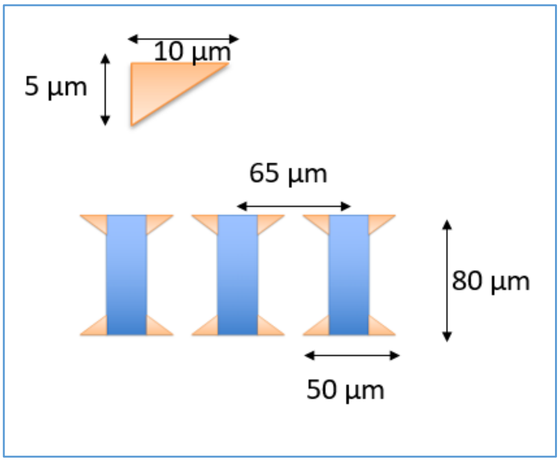


Figure 6-13 Simplified geometric model of the GT pillar structure

As Gecko Tape® is almost transparent, it is therefore expected to behave essentially as a phase diffraction grating, as opposed to more usual intensity gratings. This kind of gratings have interesting properties, which depends on the detailed profile of the grating itself. In the case of GT, the pillar profile is quite complex (see **Figure 6-14**), and can be tentatively modeled as shown in **Figure 6-13**.

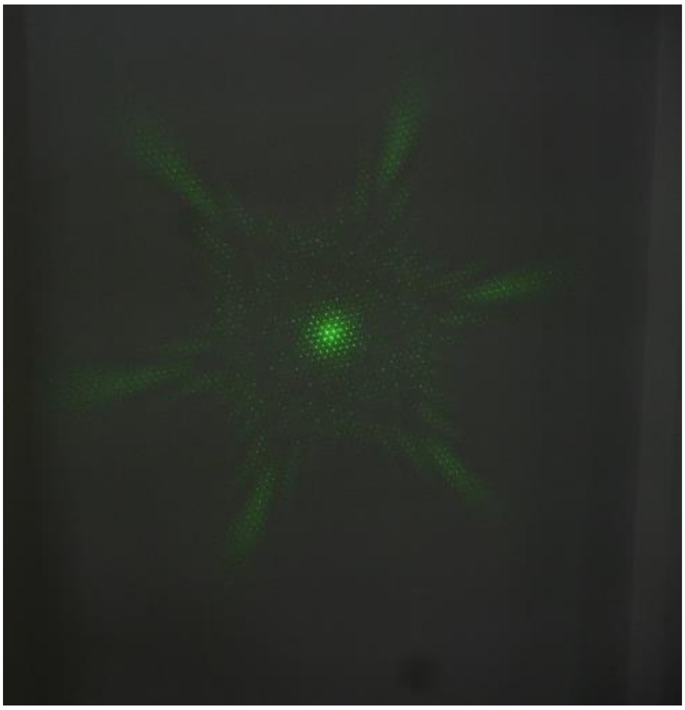


Figure 6-14 Gecko Tape® diffraction pattern obtained using a high intensity green laser.

The complex star-shaped intensity modulation observed in the diffraction pattern reported in **Figure 6-14**, is presumably due to this complex profile. A detailed experimental investigation of this topic has been planned in collaboration with Prof. S. Frabboni (FIM Department, Unimore) but, due to experimental difficulties and the recent stop in all lab activities, has remained in a very preliminary stage. We nevertheless found that, due to the profile complexity, an exact description and experimental determination of the optical properties of this grating is highly not trivial, and possibly not suitable for a TLS at undergraduate level. To overcome these difficulties, we plan to design, in the next future, a TLS suitable for a master-degree course consisting of two fundamental steps:

1. Exploiting soft-lithography, a micro-structured polymeric film is fabricated, with properties similar to GT, but with a much simpler (rectangular-shaped) profile;
2. The fabricated film is used as a phase-grating, allowing to investigate in details its optical properties.

Conclusions

In addition to the huge, technological issue, which naturally appeals to student interest, **nanoscience** offers a novel and effective way to introduce students to modern physics. Indeed, at the heart of nanoscience and its applications lies the idea that material properties, such as resistivity, optical absorption, etc. are essentially determined at the nanoscale: the ability to control the structure of matter at the micro- and nano-scale therefore, makes it possible to design and tune material properties almost at will.

In selected cases, contrary to a common belief which links nanotechnologies with sophisticated, possibly costly procedures available only in advanced research or industrial labs, the properties of nanostructured systems can be investigated and manipulated through simple macroscopic experiments – accessible at the early stages of scientific education – which can be used to highlight some of the key concepts in condensed matter physics and to effectively suggest that, even in the simplest phenomenology of matter, there is more to be understood than usually taught. The **NANOLAB project**, (see Section 2.4) was born following this idea and aims to introduce nanoscience in school curricula. Over time, new educational and practical needs emerged, as for instance the limited school time for lab activities, and the importance of offering resources devoted directly to students and/or to the general public, in particular ready-to-use webpage or videos.

During my PhD work, I designed, deployed, and tested two main Teaching-Learning Sequences (TLS), partially following the Design-Based Research process described by Guiserola [9]. All the TLS designed in this thesis are based on the properties of the **Gecko Tape®**, a commercial structural adhesive bioinspired to the gecko feet, which is readily available off-the-shelves.

The 5E instructional model and the ISLE methodology (see Section 1.2.4 and 1.2.5) inspired our TLS. Students, in small groups, investigate the material properties without receiving any preliminary information, thus mimicking a genuine scientific research investigation; important soft skills such as problem-solving, team working and communication abilities are thus stimulated and trained.

The amazing characteristics of GeckoTape® stimulate students' interest and its versatility allows to study it from different points of view, thus exploring a wide range of basic theoretical concepts, as well as nanoscience big-ideas.

The first TLS aims to investigate the **tribological and wetting properties** of the material, promoting students' basic understanding of the interface behaviour at the micro- and nano-scale, as well as showing the importance of atomic and molecular interaction as basic concepts of chemistry and physics. This TLS represents an original and innovative contribution to tribology educational research. It has been tested with fourth-grade high school students, during several stages which took place at the FIM Department during 2018-2020 (see Sections 4.6 and 4.7). It has been also proposed in a few coaching courses for in-service teachers and presented to several international conferences, as reported in Appendix F (Outcomes).

The second TLS investigates the **optical properties** of GT, which represents the engaging object, based on which the inquire challenge is built: aiming at a quantitative description of GT micro-structure, pupils are brought to learn both geometric and wave optics and to understand the working principles of fundamental research tools, such as optical microscopy and diffraction.

At the moment this TLS has been fully conceived and implemented, but still lacks a full evaluation. **As a future development**, I am planning to complete the DBR methodology process by testing the TLS among secondary school students, exploting the obtained results in the re-designing process.

A related, more advanced experiment – possibly suitable also at the undergraduate-level - is proposed and described in this thesis, which quantitatively looks into the **stick-slip phenomenon** at the micro-scale. A comprehensive evaluation of the possible educational exploitation of this experiment, however, requires testing in different contexts, and it has not being established, yet. This development is currently under way.

Last but not least, as part of my PhD activity the Nanolab web-site has been fully redesigned, substantially extending its goals and targets. In order to support teachers' and students' work, creative common educational materials are shared for each thematic area and laboratory, including educational guides for teachers and students, hands-on worksheets, and video-tutorials, designed both for cooperative learning and for flipped methodologies; the dissemination of active and innovative methodology for supporting online didactics aims at becoming a resource to face today's and tomorrow's educational challenges currently amplified by the ongoing health emergency. A specific section of the website, “thinking like a scientist”, aims at engaging students’ interest in scientific studies by showing them how researchers work and live, and the scientific and technological challenge that very young physicists are called to tackle. The visual communication website choices and a collection of talks aim to involve a popular audience as well.

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Appendix A: QNQ

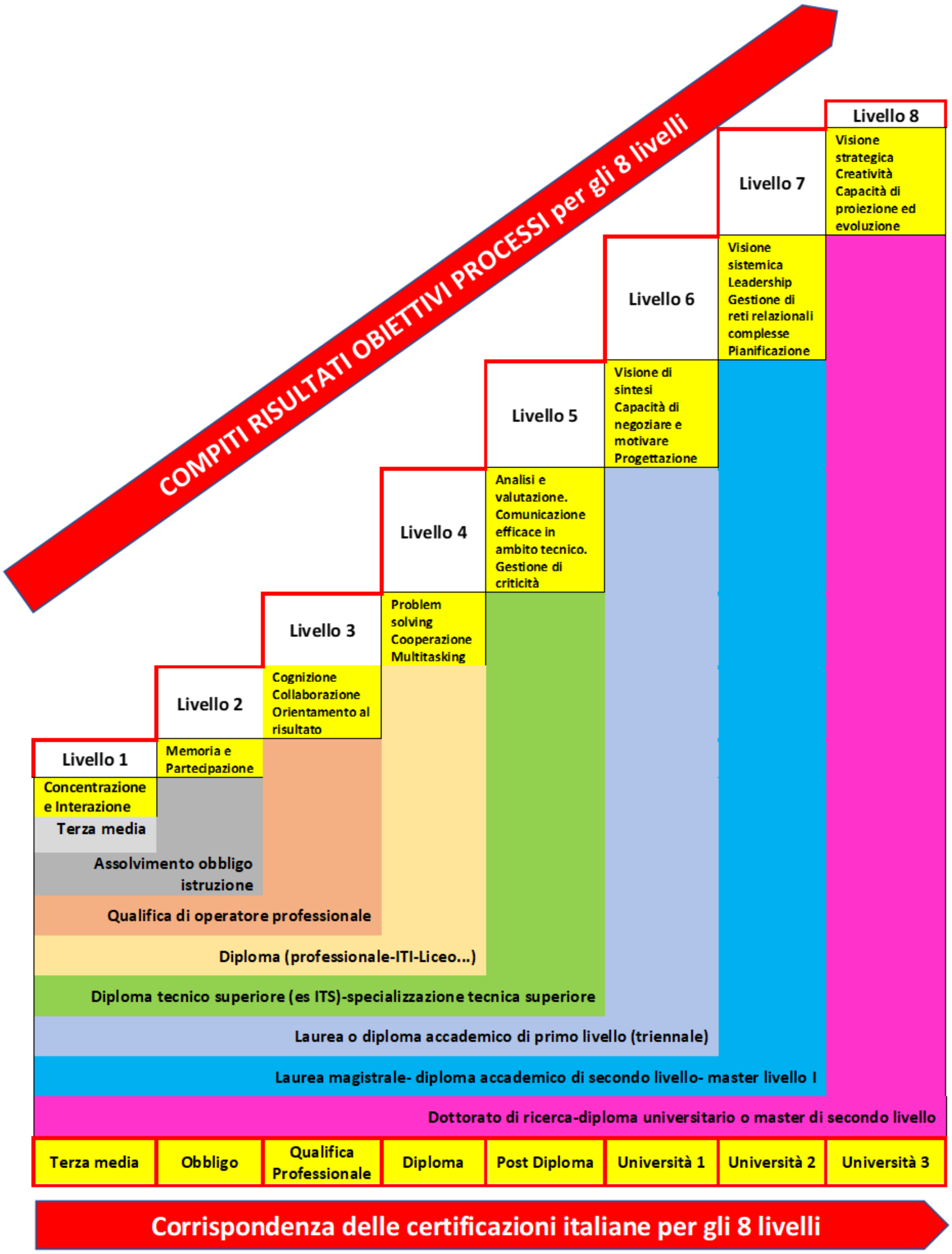


Figure App A: Synthesis of QNQ framework for Italy corresponding to the 8 EQF levels. The eight levels and the corresponding skills described as tasks, objectives, and processes with the correspondence of the Italian certifications. The figure was built in Italian to assure the original language of the qualifications.

Appendix B: Nano education

Non-exhaustive list of web-sites devoted to nanotechnology and nanoscience education.

The Next Generation Science Standards

https://www.nextgenscience.org/get-to-know

Educational

https://www.nano.gov/education-training/teacher-resources

https://www.nsta.org/store/product_detail.aspx?id=10.2505/9781935155072

https://nanoyou.eu/

https://www.nnin.org/education-training/k-12-students

https://www.nanowerk.com/nanotechnology-education.php

http://physicsopenlab.org/category/nanotechnology-smart-materials/

https://cnsi.ucla.edu/education/

Professional movies to explain nanoworld opportunity

https://www.nbclearn.com/nanotechnology

Appendix C: Test FIM 2018

TEST FIM GECKO data _____ Studente______________________

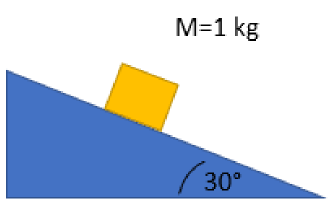
- *I test hanno come unico scopo quello di verificare l'efficacia didattica del percorso proposto vi chiediamo quindi di rispondere con assoluta tranquillità.*
- *Le risposte dovrebbero essere il risultato delle vostre conoscenze o di un ragionamento basato di esse vi chiediamo di non indovinare o "tirare a caso".*

1. Considera gli atomi di una porzione qualsiasi (per esempio un cubo) di un dato materiale: quelli 'interni' al materiale si dicono atomi di volume, mentre quelli che si trovano sulla superficie esterna si dicono 'di superficie". Se pensi ad alcune proprietà chimico-fisiche del materiale (ad esempio: energia di coesione, temperatura di fusione, reattività chimica, etc), ritieni che

a. Esse dipendono solo dalla specie chimica di cui e' costituito il materiale (es. Silicio, Ferro, Carbonio)
b. Esse dipendono anche da parametri ambientali (temperatura, pressione, umidità)
c. Esse dipendono anche dalla struttura del materiale (cioè da come si dispongono gli atomi all'interno del materiale)
d. Sono uguali all'interno del materiale (per gli atomi di volume) e sulla superficie.
e. In particolare, ritieni che (sottolinea la parola corretta):
   I. La temperatura di fusione degli atomi di superficie sia maggiore/minore/uguale che per il volume
   II. La reattività chimica degli atomi di superficie sia maggiore/minore/uguale che per il volume
   III. L'energia di coesione degli atomi di superficie sia maggiore/minore/uguale che per il volume
   IV. Non si può dire in generale, dipende dal tipo di materiale

2. Immagina di avere un cubo di un dato materiale, di lato L. Ora immagina che L possa variare fra 1 metro e 1nm. Il rapporto fra il numero di atomi di superficie e quelli di volume:
   a. Non dipende dal valore di L
   b. Aumenta al diminuire di L
   c. Diminuisce al diminuire di L
   d. Sei in grado di ricavare un'espressione matematica a conferma di quanto affermato:
3. Scegli il completamento più appropriato. La biomimetica studia
   a. le strategie adottate dalla natura per risolvere problemi di similitudine fra piante o animali di specie diverse
   b. come copiare le strategie di successo della natura per ispirare l'innovazione tecnologica dei materiali nanotecnologici
   c. le strategie usate da animali e piante per difendersi dai nemici rendendosi invisibili rispetto al contesto
   d. come copiare e migliorare le strategie di successo della natura per ispirare l'innovazione tecnologica
4. La forza di attrito fra due superfici è
   a. Diretta perpendicolarmente alla superficie
   b. Diretta parallelamente alla superficie
   c. Non ha una direzione precisa
   d. Proporzionale alla forza normale
   e. Proporzionale alla forza peso

5. Calcola la forza d'attrito tra blocco e piano (sin 30°=0,5)
   a.
   b. 9,8 N
   c. 1Kg
   d. 4,9 N
   e. Altro:



6. Confronta la figura con quella del test precedente; il piano ed i materiali sono gli stessi. Cosa cambia rispetto alla forza d'attrito
   a. la forza d'attrito in questo caso è maggiore
   b. la forza d'attrito in questo caso è minore

c. la forza d'attrito non cambia

d. altro:

7. Oltre che dai materiali a contatto l'intensità della forza d'attrito dipende da

   a. massa del corpo

   b. area di contatto

   c. presenza di umidità, colle o la tre sostanze tra le due superfici

   d. angolo del piano inclinato

   e. altro:

8. Com'è fa la forza necessaria per far muovere il blocco confrontare con la forza necessaria per mantenerlo in movimento spiega il fenomeno pensando a cosa accade tra le superfici

9. Spiegare cosa sta succedendo tra
   le due superfici mentre cerchi di spostare il blocco

10. cosa causa l'attrito tra le superfici?

11. Quale credi che sia/siano i meccanismi di funzionamento di una colla?

12. Uno strato di acqua sul pavimento lo rende scivoloso ma un sottile film di acqua tra due vetri li fa aderire tenacemente, sapresti trovare una spiegazione?

13. Quali credi che siano, a livello microscopico, le cause che generano la forza di adesione tra le superfici di due materiali

14. Scegli quali delle seguenti affermazioni sono corrette in riferimento ad un dipolo elettrico

- ***a.*** un dipolo è composto da due cariche elettriche identiche
- ***b.*** la carica elettrica complessiva del dipolo è nulla
- ***c.*** una molecola neutra se avvicinata ad una carica positiva può diventare un dipolo
- ***d.*** le forze di Van der Waals sono interazioni molecolari forti
- ***e.*** le forze di Van der Waals sono interazioni molecolari deboli

Appendix D: Tests FIM 2019

Pre-test

Stage FIM 13-02-2019 test iniziale

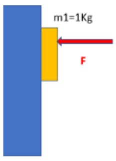
Gocce gecki e nanotecnologie alla ricerca dell'energia perduta

data__________

Scuola______________________________ Studente________

I test hanno come unico scopo quello di verificare l'efficacia didattica del percorso proposto vi chiediamo quindi di rispondere in tranquillità e di non tirare ad indovinare

1. ***In figura il blocco giallo è premuto contro la parete verticale blu: come spieghi il fatto che non cada verso il basso?***

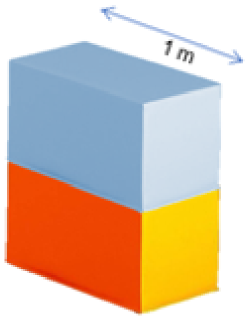


2. ***Come cambia il coefficiente di attrito μ al variare della rugosità tra due superfici: disegna un grafico di come immagini sia l'andamento di questo coefficiente all'aumentare della rugosità***

3. ***Quali pensi che siano e cause microscopiche dell'attrito?***

6. *Perché si scivola su un pavimento bagnato ma due lastre di vetro bagnate poste a contatto aderiscono fortemente fra loro?*

7. *Considera la superficie di contatto tra il blocco blu ed il bocco arancio della figura. Immagina di fare uno zoom della sezione trasversale della zona di contatto tra le due superfici e disegna il profilo, rispettivamente di un ingrandimento x 100 e di un ingrandimento x 10^5 ; così come lo vedresti guardando le superfici a contatto con un potente microscopio.*
Fai questi disegni "zummati" nei due casi in cui i blocchi abbiano entrambi le superfici lisce e nel caso in cui il blocco abbiano invece entrambi le superfici rugose



	x 100	*x 10^5*
Sup. lisce		
Sup. rugose		

8. *Immagina ora di togliere il blocco blu e di depositare una goccia di acqua sul blocco arancione, disegna nuovamente il profilo della superficie di contatto e la forma della goccia nei due casi di superficie liscia e rugosa e per i due diversi ingrandimenti*

	x 100	*x 10^5*
Goccia su Sup. liscia		
Goccia su Sup. rugosa		

Post test

Stage FIM 13-02-2019 test finale

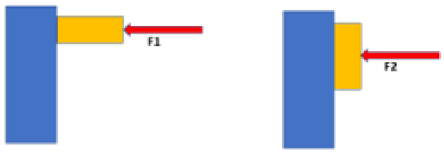
Gocce gecki e nanotecnologie alla ricerca dell'energia perduta

data__________

Scuola____________________________ Studente________

I test hanno come unico scopo quello di verificare l'efficacia didattica del percorso proposto vi chiediamo quindi di rispondere in tranquillità e di non tirare ad indovinare

1. *In figura gli stessi due blocchi giallo e blu vengono posizionati secondo le due geometrie date, si vede quindi che l'area di contatto a destra è maggiore che a sinistra. Le forze F1 ed F2 necessarie per mantenere in equilibrio il blocco giallo sono?*



☐ la stessa forza ☐ forze diverse

Pensi che ci sia una risposta univoca qualsiasi sia il materiale che costituisce il/i corpi?

2. *Alla luce dell'esperienza fatta ridisegna il grafico del coefficiente di attrito μ al variare della rugosità tra due superfici e commenta le variazioni che eventualmente introduci e le ragioni che ti spingono a farlo*

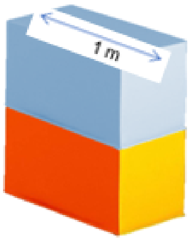
μ

Superficie atomicamente liscia superficie rugosa

3. *Alla luce degli esperimenti svolti hai più chiari i fenomeni attrito e tensione superficiale e la loro spiegazione a livello microscopico?* ☐ *si* ☐ *no*
   Rispetto alla tua risposta precedente sul fatto che possano essere ricondotti in tutto o in parte ad un'origine in comune hai la stessa idea o puoi aggiungere qualche considerazioni e/o rettifiche

4. *Un lubrificante è un liquido che viene utilizzato per ridurre l'attrito fra due superfici: come credi che funzioni?*

5. *Considera un liquido ed immagina una superficie bagnabile ed una non bagnabile da esso: credi che per una delle due quel liquido possa funzionare da lubrificante?* ☐ *si* ☐ *no*
Se hai risposto sì il liquido sarà lubrificante per quella ☐ *bagnabile* ☐ *non bagnabile*
Perché?



6. *Alla luce del percorso laboratoriale svolto ripeti l'esercizio del disegno delle superfici di contatto. Immagina di fare uno zoom della sezione trasversale della zona di contatto tra le due superfici e disegna il profilo, rispettivamente di un ingrandimento x 100 e di un ingrandimento x 10^6 ; così come lo vedresti guardando le superfici a contatto con un potente microscopio.*
Fai questi disegni degli ingrandimenti nei due casi in cui i blocchi abbiano entrambi le superfici lisce e nel caso in cui abbiano invece entrambi le superfici rugose

	x 100	*x 10^6*
Sup lisce		
Sup. rugose		

7. *Immagina ora di togliere il blocco blu e di depositare una goccia di acqua sul blocco arancione, disegna nuovamente il profilo della superficie di contatto e la forma della goccia nei due casi di superficie liscia e rugosa e per i due diversi ingrandimenti*

	x 100	*x 10^6*
Goccia su Sup liscia		
Goccia su Sup. rugosa		

Appendix E: Tests FIM 2020

Pre-Test

FORZA DI ATTRITO

La forza di attrito radente dinamico fra due corpi è: (potete indicare più di una risposta)

- ☐ Diretta parallelamente alla superficie di contatto fra i due corpi
- ☐ proporzionale alla forza-peso del corpo appoggiato
- ☐ dipendente dal tipo di materiale di cui sono costituite le due superfici di contatto

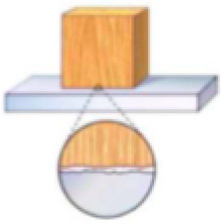
Il coefficiente di attrito statico fra due corpi è:

- ○ direttamente proporzionale all'area della superficie di appoggio fra i due corpi
- ○ indipendente dall'area della superficie di appoggio
- ○ inversamente proporzionale all'area della superficie di appoggio fra i due corpi

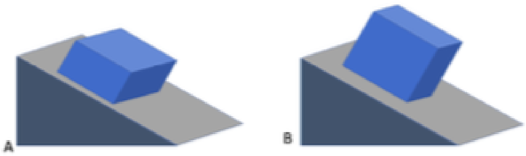
Il coefficiente di attrito statico fra due corpi è:

- ○ direttamente proporzionale alla forza normale del corpo appoggiato
- ○ indipendente dalla forza normale del corpo appoggiato
- ○ inversamente proporzionale alla forza normale del corpo appoggiato

"Anche se ci sembrano perfettamente lisce, le superfici hanno 'valli' e 'colline' microscopiche". Tenendo presente questa affermazione, considera le risposte che hai dato alle due domande precedenti e prova a giustificarle dal punto di vista microscopico.

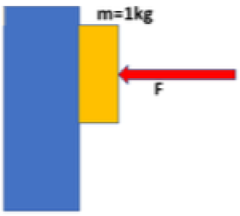


Il blocco blu è posto sul piano inclinato grigio in due modi diversi: in figura A si appoggia sulla faccia di dimensioni maggiori (4cm x 5cm), mentre in figura B la faccia di appoggio ha dimensioni minori (2cmx5cm). La forza di attrito dinamico è:



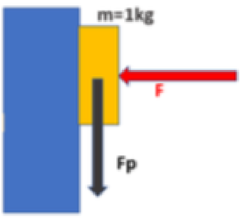
- Doppia in A rispetto a B
- Uguale in A e in B
- Doppia in B rispetto ad A

La massa del blocco arancione è pari a 1 Kg , la forza F vale 15 N, la superficie di contatto fra i due corpi vale 20 cm quadrati. Quale deve essere il valore minimo del coefficiente di attrito statico affinché il corpo non cada? Indica succintamente i passaggi effettuati per giungere alla risposta.



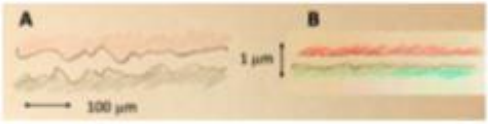
La tua risposta

La massa del blocco arancione è pari a 1 Kg a cui assumiamo corrisponda una forza peso Fp=10 N; la forza F vale 25 N, la superficie di contatto fra i due corpi vale 20 cm quadrati. Quale deve essere il valore minimo del coefficiente di attrito statico affinché il corpo non cada? PROPOSTA IN ALTERNATIVA A QUELLA SOPRA???



- 0,50
- 0,25
- 0,4
- 2,5
- 0,8

In figura sono rappresentati i profili microscopici delle superfici di alcuni corpi posti a contatto (nota le diverse scale orizzontale e verticale). L'unica cosa che varia nelle due situazioni è la rugosità delle superfici. Cosa si può dire del coefficiente di attrito nei due casi?

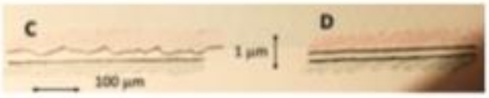


- è maggiore in A
- è maggiore in B
- è uguale nei due casi

Perchè?

La tua risposta

E in questa figura, in quale situazione RILEGGI come varia il coefficiente di attrito ?



- è maggiore in C
- è maggiore in D
- è uguale nei due casi

Perchè?

La tua risposta

ATOMI E MOLECOLE

Questa parte del test ci serve per capire cosa vi ricordate di ciò che avete studiato in chimica a proposito di atomi, molecole, e le forze che agiscono su di esse.

Descrivi brevemente come è fatto un atomo.

La tua risposta

Qual'è la dimensione tipica di una atomo?

- pochi nanometri
- pochi decimi di nanometro
- poche decine di nanometri

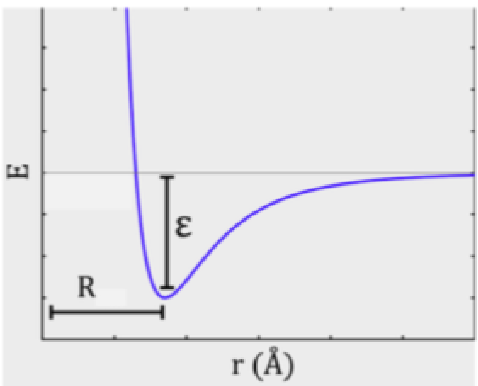
PENSA ALLA GOCCIA DI ACQUA CHE HAI DEPOSITATO SUL GECKO TAPE, TENENDO CONTO DELLE DIMENSIONI DELLA MOLECOLA DI ACQUA E ASSUMENDO CHE LA DISTANZA FRA LE PUNTE DEL GECKO TAPE SIA 50 MICROMETRI CALCOLA QUANTE MOLECOLE DI ACQUA SONO "ALLINEATE" NELLO SPAZIO FRA DUE PUNTE

La tua risposta

Considerate due atomi all'interno di una molecola. Qual è l'origine della forza con cui essi interagiscono fra loro?

- elettrica
- gravitazionale
- nucleare
- non si può dire, dipende dal legame

In figura è mostrato il grafico dell'energia potenziale fra due molecole apolari in funzione della loro distanza. Sapreste spiegare il significato dei parametri R e epsilon, indicati in figura? Per quali distanze la forza fra le due molecole è attrattiva e per quali è repulsiva?



Post-Test

STAGE 'Le interazioni alla nanoscala: il segreto del gecko e della foglia di loto' TEST FINALE

Questo test ha IL SOLO SCOPO di verificare l'efficacia didattica dell'attività di mercoledì 12/2. IL TEST NON VERRA' UTILIZZATO PER VALUTARE VOI e NON AVRA' ALCUNA RILEVANZA ai fini del giudizio finale sull'attività in università. Vi preghiamo perciò di rispondere al meglio delle vostre conoscenze e sulla base di quello che avete capito mercoledì.
POTETE USARE LA CALCOLATRICE (ANCHE SUL CELLULARE), SE NECESSARIO

*Campo obbligatorio

Indirizzo email *

Il tuo indirizzo email

Cognome e Nome *

La tua risposta

FORZA DI ATTRITO

NEI MATERIALI USUALI la forza di attrito dinamico fra due corpi:

- ◯ aumenta con l'area della superficie macroscopica di appoggio fra i due corpi
- ◯ è indipendente dall'area della superficie macroscopica di appoggio
- ◯ diminuisce con l'area della superficie macroscopica di appoggio fra i due corpi

NEI MATERIALI COME il Gecko tape la forza di attrito dinamico fra due corpi:

- ◯ aumenta con l'area della superficie macroscopica di appoggio fra i due corpi
- ◯ è indipendente dall'area della superficie macroscopica di appoggio
- ◯ diminuisce con l'area della superficie macroscopica di appoggio fra i due corpi

Tenendo conto delle risposte che hai dato nei due punti precedenti, spiega l'origine microscopica della dipendenza o indipendenza della forza di attrito dalla superficie macroscopica e l'eventuale differenza fra i due casi.

La tua risposta

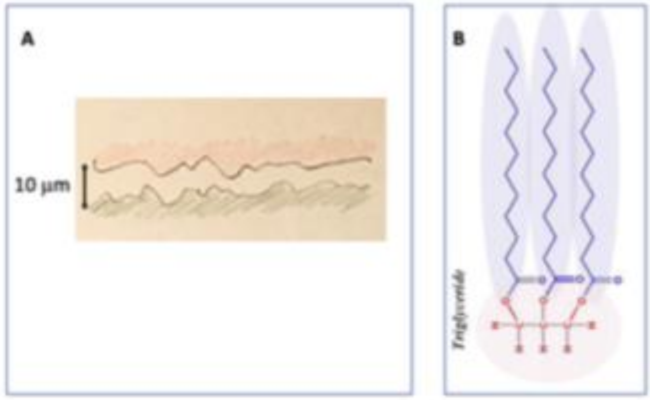
La forza di attrito statico fra due corpi:

- ◯ aumenta all'aumentare della forza normale del corpo appoggiato
- ◯ è indipendente dalla forza normale del corpo appoggiato
- ◯ diminuisce all'aumentare della forza normale del corpo appoggiato

Tenendo conto della risposta che hai dato nel punto precedente, spiega l'origine microscopica dell'eventuale dipendenza della forza di attrito dalla forza normale.

La tua risposta

In figura A è rappresentato il profilo microscopico di due corpi (materiali usuali) posti a contatto (nota la scala verticale delle rugosità). Considera ora la molecola di trigliceride mostrata in figura B (le due figure NON sono in scala!) e immagina di ricoprire una delle due superfici della figura A con un sottilissimo strato monomolecolare (cioè dello spessore di una sola molecola) di trigliceride. Di quanto dovresti aumentare l'ingrandimento del microscopio per potere distinguere lo strato molecolare?

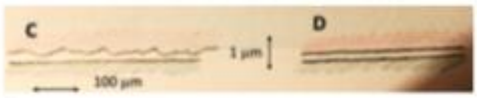


- non occorre aumentare l'ingrandimento
- almeno di un fattore 50
- almeno di un fattore 300
- almeno di un fattore 1000

Pensi che uno strato così sottile possa influenzare l'attrito fra le due superfici? Perché?

La tua risposta

Considerate le due situazioni mostrate in figura. La superficie inferiore in C ed entrambe le superfici di D sono lisce su scala atomica (rugosità più piccole di 1 nm). Se avviciniamo le due superfici, in quale delle due situazioni l'area di contatto microscopica è maggiore?



- è maggiore in C
- è maggiore in D
- è uguale nei due casi

In quale dei due casi ti aspetti che l'attrito sia maggiore? Spiega perché.

Pensa alla goccia di acqua che hai depositato sul gecko tape. Tenendo conto delle dimensioni della molecola di acqua e assumendo che la distanza fra le strutture del gecko tape mostrate in figura sia 30 micrometri, quante molecole di acqua dovresti allineare per creare un 'ponte' fra una torre e l'altra?

- 100
- 1000
- 100 000
- 1 000 000

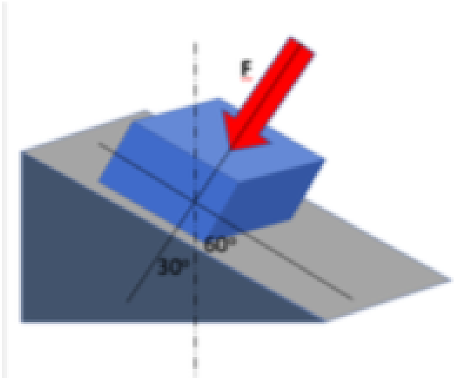
Considera una goccia d'acqua depositata sulla superficie strutturata del gecko-tape mostrata in figura. L'acqua non penetra fra le strutture a torre del gecko-tape perchè:

- le molecole di acqua non passano attraverso gli spazi perchè rimangono incastrate fra essi
- per penetrare le molecole di acqua devono spostare le molecole di aria; queste creano una pressione che si oppone al moto dell'acqua
- per penetrare nello spazio fra le torri e riempirlo, la goccia dovrebbe prima deformarsi aumentando l'area della superficie acqua/aria

Cosa hanno in comune l'adesione di un liquido ad una superficie solida e l'attrito fra due superfici solide ?

La tua risposta

Il blocco blu, di massa M=1Kg, è posto su un piano inclinato con angolo di 30 gradi rispetto all'orizzontale. La forza F è diretta perpendicolarmente al piano inclinato e vale 9.8 N. Quale deve essere il valore minimo del coefficiente di attrito statico affinché il corpo non scivoli? [cos(30)=0.866; sin(30)=0.5]



- 0,58
- 0,27
- 0,29
- 0,25

Appendix F: Outcomes

1 Contributions to international conferences and workshops:

C1 Cinzia Scorzoni, Valentina De Renzi Guido Goldoni “Friction, Surfaces and Atomic Interactions -Hands-on Approach through Comprehensive Investigation of Gecko-Tape Properties” ORAL- International conference of Hands-on science, Barcellona 2018

C2 Valentina De Renzi, Cinzia Scorzoni, Guido Goldoni Teaching Friction through biomimetics: The gecko-tape case study “ ORAL -ATEE WINTER Conference BRAGA 2019

C3 Cinzia Scorzoni, Valentina De Renzi Guido Goldoni t “Structure is Function-Unfolding the relationship between macroscopic properties and microscopic structure of Gecko-Tape® WORKSHOP- GIREP 2019 Budapes1-5 July 2019

C4 Valentina De Renzi, Cinzia Scorzoni, Guido Goldoni “Friction and wetting on bio-inspired surfaces: an inquiry-based teaching approach” ORAL- GIREP 2019 Budapes1-5 July 2019

2. Pubblications

P1 “Friction, Surfaces and Atomic Interactions -Hands-on Approach through Comprehensive Investigation of Gecko-Tape Properties **.** C. Scorzoni, G. Goldoni and V De Renzi, Proceeding of international conference of Hands-on science 2018. ISBN 978-84-8158-779-1

P2. The Gecko-tape approach to Friction: a novel teaching learning sequence
Cinzia Scorzoni, Guido Goldoni and Valentina De Renzi GIREP 2019 Proceedings; in pubblication (2020).

P3. **“**Wetting and Friction of GeckoTape®: an experimental, interdisciplinary investigation of bio-inspired microstructurated surfaces”; Cinzia Scorzoni, Guido Goldoni and Valentina De Renzi (in preparation).

3. Permanent education for secondary school teachers

PE1 Cinzia Scorzoni «NANOLAB - Innovazione didattica fisica della materia/nanoscienze» - on-line course - Master IDIFO6; University of Udine- Research Unit in Physics Education- under MIUR and PLS funding

PE2 Cinzia Scorzoni «Energia per il futuro, il ruolo strategico delle nanotecnologie-nanolab laboratory» University of Modena and Reggio Emilia (patronage of MIUR-SOFIA)

PE3 Cinzia Scorzoni **Nanolab 2019** **25-26-27 Ottobre 2019** (patronage of MIUR-SOFIA)

4. Proactive program to attract students to STEM fields

PP-STEM1 "INTO the Future", feb/march 2018 in collaboration with CNR Nano S3 Modena and CRMO foundation

PP-STEM2«Sperimentare e Comunicare la Scienza» 5 -days stage- Department FIM UniMoRe- February 5-9, 2018

PP-STEM3 «Materiali innovativi superfici ed interazioni molecolari-un viaggio nel nanomondo» conference for teachers and students of «Liceo and Polo Tecnico Lugo" and student-workshop for «Polo Tecnico Lugo» April 7, 2018

PP-STEM 4 "INTO the Future", feb 2019 in collaboration with CNR Nano S3 Modena and CRMO foundation

PP-STEM 5 "SUMMER SCHOOL FIM", JUNE 2018 in collaboration with CNR Nano S3 Modena and CRMO foundation

PP-STEM 6 "Una settimana da scienziato" SCHOOL FIM, Feb 2019 in collaboration with CNR Nano S3 Modena and CRMO foundation

PP-STEM 7 WORKSHOP «NANOLAB» for secondary school "Pascal" Manerbio (Brescia) may 15, 2019

PP-STEM 8 "SUMMER SCHOOL FIM", JUNE 2019 in collaboration with CNR Nano S3 Modena and CRMO foundation

PP-STEM 9 "Una settimana da scienziato" SCHOOL FIM, Feb 2020 in collaboration with CNR Nano S3 Modena and CRMO foundation

5. Teaching activities

T1 Tutoring for lab II course PHYSICS DEGREE (for three years)

T2 Didattica Integrativa LABORATORIO DI FISICA II – Progetto "Competenze Trasversali",

T3 Lecture & demonstrations «Diffraction on flexible lattices - Biomimetics Geckos and Crystals", March 2018 and 2019- Unimore- Solid state physics course

6. Organization of workshops and events

O1 «Physics in society: science, technology and industry "on service and pre-service teachers course; patronage of MIUR -SOFIA n.20674

O2 "Energy for the future- the strategic role of naotechnologies" Conference open to citizens and schools (22 Schools, 3 regions involved) University of Modena &Reggio Emilia 5-11-2018 - financed under Cassini Junior call 2018 –Institut francais d'Italie and embassy of France

O3 "A scuola di Laboratorio " 9-11-13 settembre 2019. In-service and pre-service teachers course; AIF-UniMore patronage of PLS-MIUR -SOFIA ID. 33220

O4 "Nanolab 2019", In-service and pre-service teachers course—Adhesion at national level UniMore patronage PLS- MIUR -SOFIA n. 33947

7.Dissemination activities

D1 WORKSHOP «Friction adhesion and nanotechnology: From research to school and industry» researchers' night September 27, 2017

D2 ORAL «Pensare da scienziato : Biomimetica gechi e nanotecnologie» researchers' night September 28, 2018 – speakers' corner

D3 WORKSHOP «Attrito, gechi e nanotecnologia» researchers' night September 28, 2018 - Hands-on activity stand for the general public

D4 ORAL «Rose Geckos and Biomimetic, learn from nature" feb 27, 2019 -Adipa Association, Castelfranco E. (MO)

D5 ORAL «Geckos roses and molecules - learn from nature" For secondary school B. Pascal (BS) Unimore, may 15,2019

D6-ORAL "ACTIVE LEARNING PHYSICS-Metodologie didattiche di base per un insegnamento efficace" November 12, 2019 Conference for university teachers and student" - UniMore –PLS

8. Works on international facilities

- Soleil synchrotron Paris Jan/Feb 2019 (5 days)

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