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Disclosing the Microscopic Picture: An Interdisciplinary Investigation of Friction and Wetting Using a Gecko-Inspired Tape

Cinzia Scorzoni, Guido Goldoni, Alberto Rota, and Valentina De Renzi*

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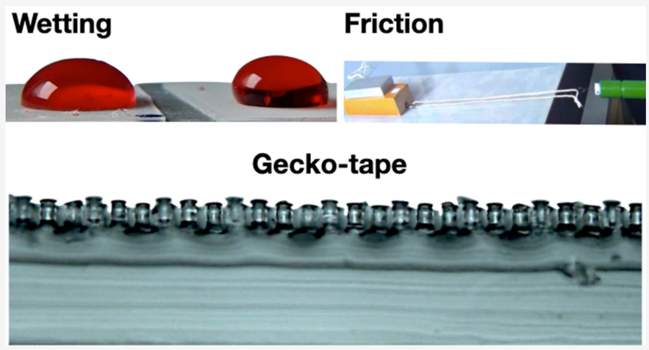

ABSTRACT: We propose an innovative approach to teaching friction. Our approach aims to educate students on its microscopic nature by highlighting its origin in intermolecular interactions. We have designed a teaching sequence (TS) based on a set of experimental investigations of the properties of a gecko-inspired tape at different length scales. The TS has been conceived to unravel the peculiar behavior of this man-made, commercially available biomimetic material and to train students to identify the connection between the micrometer-scale patterning and the peculiar tribological properties. Specifically, our approach compares friction (and adhesion) to wetting, occurring at solid/solid and solid/liquid interfaces, respectively. The aim is to scaffold a correct mental model of real interfaces and disclose the common origin of both phenomena in intermolecular interactions. The TS has been devised according to the design-based research scheme and it was inspired by the Investigative Science Learning Environment (ISLE) and the 5E paradigms. It has been tested and tuned with students at level 3 in the International Standard Classification of Education (ISCED), during several on-campus stages. We report here the details and results of pre- and post-tests, which demonstrate the effectiveness of our method. Specifically, we measure success in terms of the students' comprehension of the link between contact area and friction and of the role of intermolecular forces. We are confident that the learning experience with our TS will lead students to recognize the enormous potential impact of surface patterning in technological applications, in a curiosity-driven manner that will likely result in students' interest in quantitative studies of science and technology.

KEYWORDS: *High School/Introductory Chemistry, Interdisciplinary/Multidisciplinary, Noncovalent Interactions, Material Science, Inquiry-Based/Discovery Learning, Hands-On Learning/Manipulatives, Misconceptions/Discrepant Events, Testing/Assessment, Collaborative/Cooperative Learning*

■ INTRODUCTION

Friction and wetting are complex physicochemical phenomena occurring whenever different phases (solid, liquid, and/or vapor) come into intimate contact and/or slide on top of each other. At the microscopic level, both phenomena stem from intermolecular forces and strongly depend on the morphology of the interfaces. From the technological point of view, tuning frictional and wetting properties of materials represents an extremely active research area at the crossroad between chemistry, physics, and engineering. The potential impact in present and future applications is huge. It is estimated that half of the 20% of the world's total energy consumption originating from friction and wear could be saved by smart dealing with tribological phenomena.[1] Furthermore, adhesive forces dominate in miniaturized technologies; the ability to control friction and wetting is mandatory, for example, in the design of micro electromechanical systems (MEMS),[2] as well as in lab-on-a-chip technologies for cheap transportable medical diagnosis.[3]

From the educational point of view, friction and wetting are typically—at least in the Italian secondary school context—taught as separate subjects and with different perspectives. Surface tension and capillary forces are usually addressed in chemistry courses, where their connection with wetting and intermolecular forces is quite straightforward. On the contrary, friction—together with normal reactions, elastic forces, and tension—is usually introduced in a phenomenological way within physics curricula, aiming to understanding and applying Newton's laws rather than to acknowledge the microscopic and statistical origin of this force. This approach is unlikely to engage students' interest, while it completely neglects the

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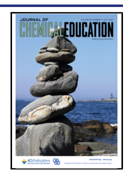

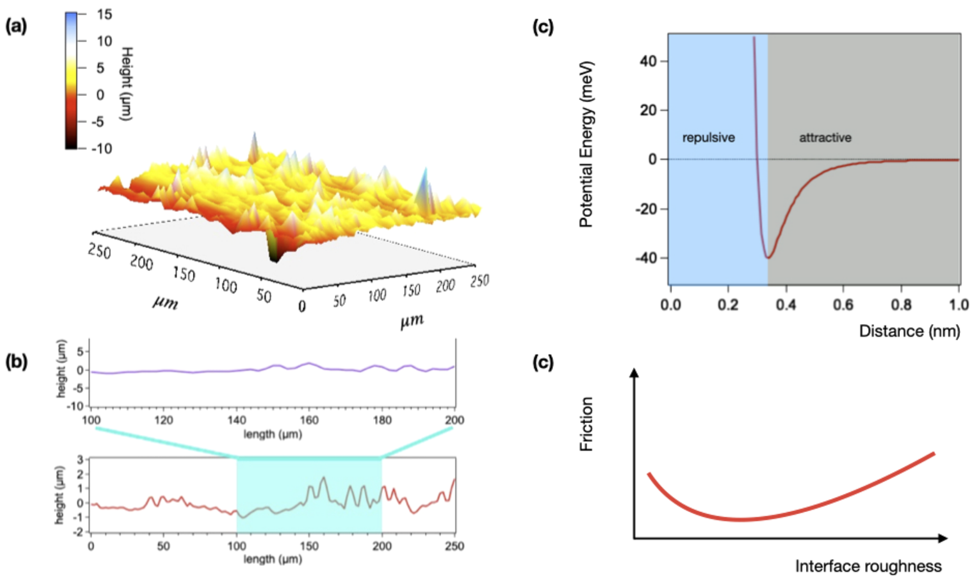

Figure 1. (a) Typical 3D height profile of a real surface, as measured with a profilometer (scanning speed = 1000 μm/s; tip curvature radius = 2 μm). (b) 2D profile of the same surface. Note that, in the lower graph, the vertical scale unit is 10 times smaller than the horizontal one. The upper graph reproduces the light-blue region with a 1:1 height-to-width ratio, highlighting how the actual slope of asperities is rarely more than a few degrees. (c) Lennard–Jones potential describing the interaction between two Argon atoms as a function of distance. (d) Qualitative dependence of friction on the interface roughness.

chemical aspects inherent to tribological phenomena. We believe that highlighting the common features of the two topics represents an educational opportunity to convey key-concepts belonging to both chemistry and condensed matter physics, exposing how macroscopic properties of matter arise at the micro- and nanolength scales and can be manipulated at one's advantage—the essence of any nanotechnology. In doing so, the chance also arises to correct some common misconceptions related to the atomic and molecular scales, which negatively influence the students' general cognitive development and the ability to understand and explain reality, as we will discuss below.

The role of surface interactions at the nanoscale is often popularized by the ability of geckos (Family: Gekkonidae) to climb walls without any biochemical secretion or hooks. This ability is purely based on the intimate contact established between the hierarchical micro- and nanostructures of its toes and the wall asperities. Analogously, the self-cleaning properties of lotus (*Nelumbo nucifera*) leaves exemplify the role of micro- and nanostructuring in determining the wetting properties of materials. These two examples are paradigmatic of the biomimetic approach, i.e., to engineer artificial materials inspired by natural systems.[4] A few of such bioinspired materials have since long reached the shelves: Velcro fastener—patented by George de Mestral in 1955—was for instance inspired by the hooking devices of Goosegrass (*Galium aparine*) fruits, while textured swimsuits mimic shark skin.

In this work, we propose to teach friction and wetting in a comprehensive way, exploiting their subtle connection to disclose the fundamental role of intermolecular forces common to both phenomena, crossing the bridge between the chemical and the physical approach. To this aim, we have designed an innovative, hands-on teaching sequence (TS) based on the experimental investigation of the macroscopic and microscopic properties of Gecko-tape(GT), a commercially available, cheap, bioinspired synthetic material with extraordinary adhesive properties. Our TS focuses on (a) probing the difference between nominal and real area of contact of two mating bodies, (b) helping students to build a correct visual representation of the meso- and microasperities of real interfaces, and (c) introducing the intermolecular interaction model to explain the origin of friction and wetting. The TS is designed following a design-based research (DBR) scheme[5] and inspired by the ISLE[6] and 5E[7] paradigms. The TS effectiveness has been probed through pre- and post-testing sessions with fourth-year high school students (within ISCED level 3). We show that our approach helps students to grasp the subtleties of tribological phenomena and their connection to the micro- and nanoscale properties of materials, highlighting the potentialities of associating friction and wetting in a cross-disciplinary approach.

■ PHYSICOCHEMICAL BACKGROUND

Friction at the Microscale

A comprehensive understanding of tribological processes still represents a major challenge in current research. However, in the past decades, novel experimental techniques and theoretical tools have provided new insights into the basic mechanisms of friction at the micro- and nanoscale. An ample overview of the subject,[8−10] as well as an historical perspective,[11] can be found in the literature. Here, we briefly review the Bowden and Tabor model,[12] a solid, easy-to-grasp groundwork for understanding the microscopic origin of friction.

Bowden and Tabor Model. As shown in Figure 1a,b, surfaces are usually rough at the microscale, exposing a 3D structure that is quite different from the naive mental image of a flat surface at the macroscale. Only a small fraction of atoms of two mating surfaces are close enough (few nanometers) to allow for significant intermolecular interactions. Hence, the real (microscopic) area of contact A between two surfaces is much smaller than the geometric one, and it is fairly

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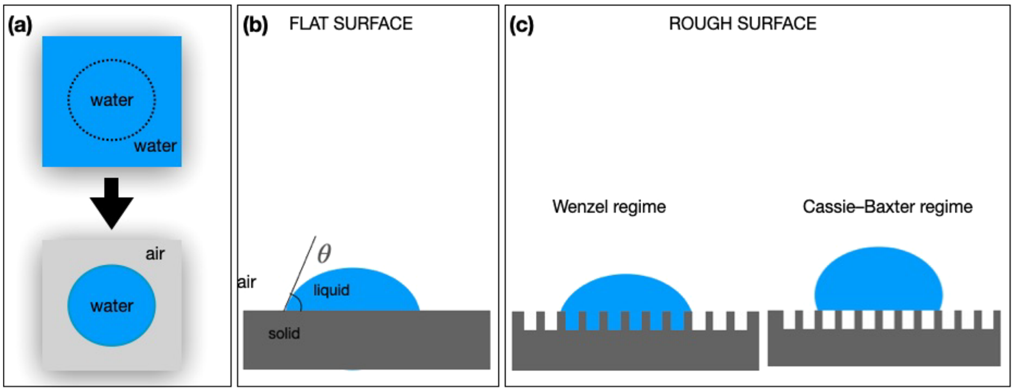

Figure 2. (a) Droplet formation obtained by replacing water molecules outside the boundaries (dashed line) with air molecules. (b) Definition of the contact angle of a droplet on top of a smooth surface. (c) Wenzel and Cassie–Baxter regimes occurring on rough surfaces.

independent of the latter. This small surface fraction—represented by matching asperities—is the one that actually bore the normal load N exerted in the direction perpendicular to the geometric surfaces.

By increasing the load, the contact asperities deform (either in an elastic or in a plastic regime). The real area of contact A increases proportionally, according to

$$A = \frac{N}{p} \tag{1}$$

where p is the average pressure that each asperity may sustain. p depends on the mechanical properties of the material, in particular its Young modulus and Poisson ratio.

When two surfaces are forced to slide over each other, asperities deform (again plastically and/or elastically). New junctions continuously form, while others break. The interaction between asperities can be described as a shear force acting parallel to the surface. By introducing an average value of the shear s, considering a Gaussian distribution of asperity heights and neglecting wear, according to Tabor and Bowden the total frictional force F_f reads

$$F_f = As \tag{2}$$

By substituting eq 1 in eq 2, we recover Amontons' proportionality $F_f = \mu N$. The friction coefficient $\mu = s/p$ is independent both from the microscopic and the geometric areas of contact. Therefore, within this model, friction is related to the elastic and plastic properties of the mating surfaces and to the shear interactions between asperities, i.e., to intermolecular forces.

Role of Intermolecular Forces in Friction and Adhesion. It is important to underline the nature of the intermolecular forces.[13] Depending on the surface chemical composition, they span from weak London dispersion forces to hydrogen bonds and to covalent or ionic bonding, as it occurs in the cold-weld case described below. Despite these differences, all intermolecular forces share a common origin, namely, the Coulomb interaction between the charge distributions (both electron and nuclei) of the interacting molecules.

As shown in Figure 1c for the case of Lennard–Jones potential, intermolecular forces are repulsive at short distances (typically below one nanometer) and become attractive in the few nanometer range. The short-distance repulsion accounts for a mechanical interlocking mechanism, whereby microscale impenetrable asperities bump onto each other. The long-range attractive term, instead, explains why two bodies experience an adhesive force whose intensity is related to the number of atoms of the two surface facing each other, i.e., to the real area of contact. Indeed, it is precisely the attractive London dispersion forces at the origin of gecko's ability to exert an adhesive force, which in a few milliseconds varies from zero to a value exceeding their weight by tens of times.[14] For the same reason, highly polished smooth metallic surfaces sharing an extended microscopic contact area tend to stick together (cold-welding) rather than to slide frictionless. Therefore, as sketched in Figure 1c and contrary to common experience, friction increases for vanishing roughness, i.e., for atomically flat surfaces.

The role of intermolecular forces is also well-exemplified by the fact that friction may be reduced by orders of magnitude, introducing a molecular-thin lubricant film, which is able to quench adhesive forces at the interface. All in all, the friction coefficient μ not only is proportional to surface roughness but it also depends on the chemical nature of the two surfaces.

Wetting of Microstructured Surfaces

Whenever an interface is created between two different phases i and j (being they air, liquid, or solid phases), for instance cleaving a solid or creating a liquid droplet, bonds between molecules belonging to the same phase are severed, which requires energy. The surface free energy $\gamma_{i/j}$ is the work done to create a unitary surface area at the interface (in units, e.g., of J/m^2). In the particular case of liquids, $\gamma_{i/j}$ is equivalently referred to as surface tension, i.e,. the force per unit length (in units, e.g., of newton per meter) required to increase the length of the interface boundaries.

The surface free energy is a property of the interface, not of the single material. Indeed, $\gamma_{i,j}$ is the difference between the cohesive energy between molecules within each phase and the adhesion energy between molecules across the interface.[15] For example, a water droplet (Figure 2a) forms by replacing water with air. This significantly reduces the cohesive energy, which is large between water molecules due to H-bonding but almost negligible between water and N_2 or O_2 molecules. This justifies the large value of water/air surface tension, $\gamma_{W/A}$ = 73 N/m at room temperature and the strong tendency to assume a spherical shape to minimize the surface-to-volume ratio.

For a water droplet on a solid surface (Figure 2b) the surface tensions $\gamma_{S/A}$, $\gamma_{S/W}$, $\gamma_{W/A}$ come into play (S, solid; W, water; A, air). The equilibrium shape of the droplet is determined—neglecting the effect of gravity—by Young's equation $\gamma_{S/A} = \gamma_{S/W} + \gamma_{W/A}\cos(\theta)$, where θ is the so-called contact angle

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	Misconceptions	Learning Demands
Atomic properties	Atoms as rigid spheres	Atoms are 'fuzzy' and essentially empty entities
	Atoms can be seen using an optical microscope	Correct the overestimated size of atoms and the idea that solid matter is continuous
Chemical bonds	Chemical bond has nothing to do with forces and attraction	Recognise Coulomb forces as the common origin of all different chemical bonds
Friction	The origin of friction is mechanical (interlocking mechanism)	Realise the difference between nominal and actual area of contact
	Friction monotonously increases with surface roughness	Realise the role of molecular interactions in friction

Figure 3. Survey of the main misconceptions and learning demands relevant to the present TS. "Chemical" items (gray background) are taken from refs 21 and 22, while "friction" items are taken from refs 19 and 20.

between the tangents of S/L and L/A interfaces. θ is a measure of the wettability: surfaces with $\theta < 90°$ are termed hydrophilic surfaces, while for hydrophobic surfaces $\theta > 90°$.

Young's equation applies to ideal flat surfaces. If surface roughness is taken into account, we distinguish different regimes, as illustrated in Figure 2c.[16] In the so-called Wenzel regime, the liquid completely wets (adheres to) the rough solid surface. The observed θ_W is given by the Wenzel equation $\cos(\theta_W) = r \cos(\theta)$, where the roughness factor r is the ratio between the real surface area and its planar projection. For rough surfaces $r > 1$. Therefore, θ decreases for hydrophilic surfaces and increases for hydrophobic surface. In other words, both hydrophilic or hydrophobic behaviors are enhanced by roughness.

On the contrary, if air pockets prevent the liquid to entirely wet the surface, only a fraction $f < 1$ of the droplet surface is actually in contact with the solid surface, a regime named Cassie–Baxter. In this case, θ is determined by the Cassie–Baxter equation

$$\cos(\theta_{CB}) = r_f \cdot f \cdot \cos(\theta) + (1 - f) \quad (3)$$

where r_f is the roughness ratio of the wetting patches. When incomplete wetting occurs, therefore, it is possible to have hydrophobic contact angles even from intrinsically hydrophilic surfaces. In the case of superhydrophobic surfaces, with alternating pillars and voids at different hierarchical levels (micrometric pillars with nanometric asperities manufactured on their top), $\theta > 150°$ may be obtained. Lotus leaves owe their superhydrophobicity to nanostructuring of their surface. Water droplets roll over their surface without sticking, removing dirt.

■ DESIGNING THE TEACHING SEQUENCE

We propose an approach to teaching friction and wetting on the basis of experimental activities, which focus on the comparison between the behavior of conventional and nonconventional, man-made materials: here, a sample of GT. The TS has been planned and reviewed in an iterative way, according to the principles and following the five sequential phases of DBR,[5,17] as discussed below.

Focus: Establish Topic, Scope and Audience

We address fourth-grade students (ISCED level 3, ages 17–18). In most Italian high-schools, the laws of macroscopic friction and the concepts of surface tension and cohesive forces are part of the first-years (ISCED level 2, ages 14–16) physics and chemistry curricula, respectively. Building on this previous knowledge, we aim to highlight the strict relationship between the macroscopic properties of a material and its microscopic structure. This is a key-idea in chemistry and physics (as well as biology and physiology). In more details, our TS aims at:

(a) probing the difference between nominal and real area of contact of two mating bodies
(b) helping students to build a correct visual representation of the meso- and micro- asperities of real interfaces
(c) introducing the atomic and molecular interaction model to explain the microscopic origin of friction

We believe that jointly discussing friction and wetting may represent a valuable scaffolding toward these goals. Indeed, it is quite straightforward to explain wetting as due to interactions between molecules of the solid surface and of water. Working by analogy, we than bring students to extend this mental model to the case of solid/solid interfaces, namely, friction, thus substituting the partially misleading model of mechanical interlocking.

Understand: Identify Misconceptions and Learning Demands

A survey of the literature allows us to pinpoint the major learning difficulties and the possible educational solutions. As far as friction is concerned, we specifically took into account Besson et al.[18] and Corpuz and Rebello.[19,20] From the chemical point of view, we took into account the work of Venkataraman et al.[21] on the atomic structure of matter and the nature of chemical bonding, as well as the novel approach to teaching chemical bonds and molecular interactions developed by Levi Nahum and Taber et al.[22] This approach has been extensively tested in Israeli schools and introduces a unified conceptual framework for all types of chemical bonds and molecular interactions, which emphasizes their common features (i.e., the role played by the Coulomb interaction and by the atomic structure) and relies on fundamental physics concepts, such as the link between potential energy and forces.

The result of the literature survey is summarized in Figure 3, where we report the most relevant misconceptions and learning demands on atomic properties, chemical bond, and friction. The comparison between "chemical" and "friction" misconception is particularly significant, as it clearly shows (as indicated by arrows) the "chemical" origin of the interlocking misconception and highlights the importance to provide students with a correct, even though simplified, description of atomic and molecular interactions. For our scopes, the Levi

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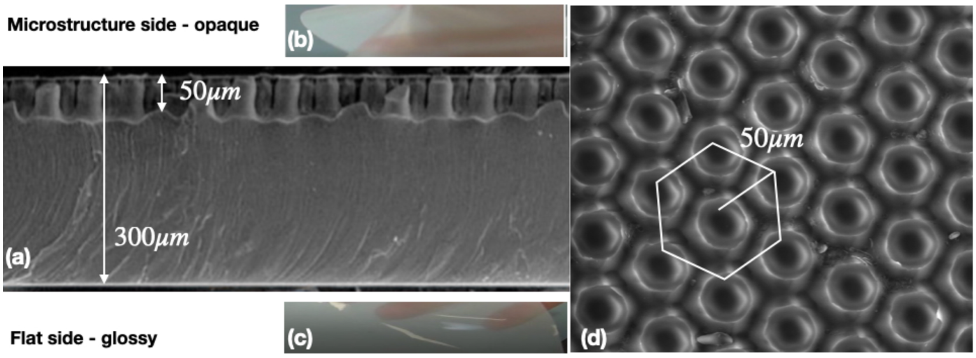

Figure 4. (a) SEM image of the GT film cross section, showing the microstructuring of (b) the opaque side and (c) the flat surface of the glossy side. The different surface roughness may be somewhat perceived by running a fingertip on the tape, but the microstructuring cannot be distinguished by naked eyes. (d) SEM image of the microstructuring. The film thickness, the height of the micropillars, and the hexagonal lattice parameter are also indicated.

Nahum approach is particularly well-suited, allowing us to promote a mental model in which molecules and atoms may attract each other at a distance, without the need to enter in the details of the different types of molecular interactions.

Defining the Learning Goals and Indicators and Designing the Sequence

Starting from the general goals defined in the Focus phase, the following TS learning goals were progressively refined during the recursive DBR process:

1. Demonstrate, through the use of words and sketches, an understanding that friction between two bodies in mechanical contact depends on the microscopic contact area
2. Demonstrate, through the use of words and sketches, an understanding that the microscopic origin of friction rests in intermolecular forces, which are electrostatic in nature and act at distance
3. Demonstrate, through the use of words and sketches, an understanding that friction varies nonmonotonously with surface roughness, as shown in Figure 1d, i.e., that atomic-flat surfaces may display very high friction

We inspired ourselves by the Investigative Science Learning Environment (ISLE) model developed by Etkina:[6] here, students learn through quantitative experiments performed in groups, mimicking the modalities of actual scientific research. We also closely followed the phases of the 5E model by Bybee et al.,[7] engage, explore, explain, elaborate, and evaluate, as detailed in the next section.

In a first version, the TS lasted 1 week. A few hours were devoted to review the macroscopic laws of friction and the concepts of surface tension and intermolecular forces. The experimental phase lasted 2 days, allowing for a truly inquiry-based, open approach, in which students were able to design their own procedures. While this approach was quite successful[23] and may be a valuable choice when time is not a demanding issue, say a summer camp, it can hardly fit into the school time-schedule and, in particular, into the limited amount of time usually devoted to laboratories.

Therefore, in the later—much shorter—versions of the TS, we decided to partially rely on students' previous school knowledge. We asked students—who came from different school types—to review the concepts of friction, surface tension, and intermolecular forces on their textbooks in a flipped-class modality, hence establishing a well-defined, common knowledge, which is crucial for the success of subsequent scaffolding. Moreover, in the experimental phase, rather than leaving students free to design their experiments as in the ISLE model, we choose a high-guidance modality. In addition to reducing the time demand, this approach allows for performing precisely designed experiments and minds-on activities, aimed to provide complementary pieces of information. These, all together, are meant to scaffold the correct understanding of the phenomena.

Building the Teaching Sequence

The TS is based on the experimental investigation of the macroscopic and microscopic properties of GT, a bioinspired adhesive with applications in areas as diverse as the medical and the aerospace (i.e., at low atmospheric pressure) fields. As shown in Figure 4a, GT is a 300 μm thick silicon film, patterned on one side with an hexagonal lattice of micropillars, which mimics to some extent the gecko foot-pads. The TS is build with close resemblance to the 5E model, as described in the following.

Engage. To engage students' interest, we first emphasize the role of tribological issues in present and future technologies. In this context, introducing wetting and its relevance in nowadays technology is also straightforward. The amazing properties of gecko toes and of lotus leaves—the latter can be easily demonstrated in classroom in addition to GT experiments—are then introduced. At this initial stage, no explanation for the peculiar properties of gecko toes and lotus leaves or preliminary knowledge of the properties and structure of GT are provided. Exploiting a hands-on approach, students are next allowed to explore the adhesive properties of a sample of GT on different surfaces. A simple vertical arrangement (see Figure S1 in the Supporting Information (SI)) shows the striking difference between the adhesive behavior of the sample when subject to peeling or shearing. In this way, the resemblance to gecko's abilities is strengthened and the concept of tunable friction introduced. While these first hands-on experiences easily bring students to rule out glue as a possible explanation for GT adhesion, students usually suggest the suction mechanism as an alternative. Following the ISLE circle, we then propose a vacuum-bell experiment that compares the adhesive behavior of the sample and a suction-cup (see Figure S1b in the SI); the GT retaining its adhesive properties at low pressure clearly rules out the suction mechanism, engaging students in further investigations.

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Explore. We then assign several quantitative experiments to run in parallel by different groups of students. Three experiments focus on the macroscopic investigation of friction and wetting properties of GT (see Figure S2 in the SI for experimental details), as compared to conventional materials, which are exemplified by a piece of sandpaper (SP).

I. Static and Dynamic Friction. The frictional behaviors of GT and SP are quantitatively compared. Using a standard setup consisting of a variable-angle sliding plane and a test block, students probe the validity of Amonton's law—the independence of the friction coefficients from the nominal area of contact—for the two materials. The friction coefficient of GT strongly increases with the contact area (see Figure S2 in the SI), in striking contrast with Amonton's law, which instead is followed by SP. Analogously, Amonton's law is tested in dynamic conditions by pulling a test block on a horizontal plane and measuring the force by a dynamometer. Here, both the glossy and the opaque surfaces of GT (G-GT and O-GT, respectively) are probed and compared to SP. Interestingly, while no dependence on the contact area for G-GT (i.e., the smooth side) is observed, as with SP, for O-GT (the microstructured side), the dependence is apparent. In both experiments, the violation of Amonton's law learnt in textbooks is a striking example of falsification, which provokes a fruitful cognitive conflict.[24] The different frictional behavior of O-GT and G-GT is also particularly surprising and calls for further investigation of their surface properties.

II. Wetting. The concept of contact angle and its relation to surface tension is introduced to students in an operative way. Students are asked to probe the wetting properties of different surfaces—glass, aluminum, Teflon, lotus leaves, and treated antispots fabrics—measuring the contact-angles of deposited water droplets on close-up photos and classify surfaces from hydrophilic to superhydrophobic. GT wetting properties are then investigated, and the different wetting properties of O-GT and G-GT highlighted (see Figure 5); the contact angle in O-GT is indeed significantly larger than that in G-GT, a nice example of Cassie−Baxter wetting behavior. Since the observed differences in the friction coefficient and wetting properties of O-GT and G-GT cannot be traced to a different chemical composition, an open question remains about their origin. Students are thus led to investigate the microscopic structure of the two surfaces, which is pursued by the next two experiments.

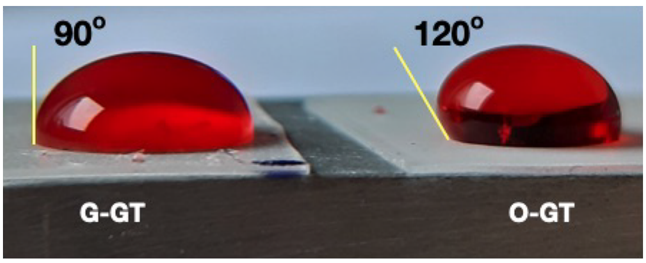

Figure 5. Isovolumetric water droplets deposited on the G-GT and the O-GT surface; photos are taken with a smartphone camera, framing the droplet through a magnifying lens for further magnification. The tangents to the droplet boundaries and the corresponding contact angles are also shown.

III. Optical Microscope. Due to the dimension and distance of the micropillars (50 μm), the microscopic structure of the GT surface can be observed with standard optical microscopes usually available in school laboratories. Images of the surface and of the cross-section of a GT sample are reported in Figure 6a,b, respectively, uncovering the hexagon array of micropillars. This surface microstructuring is only present on one side of the film (the O-GT side), accounting for both the different naked-eye aspect and frictional/wetting behaviors observed in the macroscopic experiments I and II.

IV. Diffraction Pattern. Diffraction is a complementary, instructive way to investigate the structural properties of the GT. Due to the partial transparency of the material, the micropillar array composes a 2D diffraction grating for visible light. The light of a laser-pointer passing through the sample produces a clear hexagonal diffraction pattern on a distant screen (see Figure 6c). A quantitative estimate of the interpillar distance a can be derived from $a = \lambda L/d$, where L is the distance between the sample and the screen, λ the laser wavelength, and d is the distance between neighboring spots, and compared with that obtained with the optical microscope.

Explain. The experimental results obtained in the explore activities are first discussed within the groups and then presented to peers. In this way, each group gets to know the results of other groups' investigation, in a way that resembles a scientific workshop. The groups are allowed to collaborate with each other, share ideas, challenges, and results. The aim of this session is to focus on the link between the macroscopic properties, wetting and adhesion, and the morphology of GT. In this phase, the teacher's task is to ease the discussion and to provide new pieces of information (described below), which help to build a comprehensive picture of the investigated phenomena. The difference between real and nominal contact area is thus naturally brought in, as well as the relationship between friction and real contact area. In this way, the microscopic explanation of Amotons' law and the reasons for its violation by O-GT interfaces are discussed.

Bridging the gap between the mental image of macroscopic bodies in contact and the actual interface at the meso and microscale is nothing but trivial. In order to help students building a correct mental image of real interfaces and interacting meso/microasperities one can again exploit the optical microscope to observe the cross-section of different interfaces.[25]

Figure 7a shows a cross-section of the interface between two thin slices of SP pressed together, acquired in transmission. This image provides a clear picture of the actual area of contact between conventional surfaces at the meso/microscale and allows us to introduce the key-concept of multiasperity contact. Indeed, at variance with a physics-textbook drawing of interfaces—which are typically 2D—the image perspective and its in-focus/out-of-focus portions provide a 3D depth perception. This helps students to build a realistic 3D mental image of actual interfaces, in which only few asperities get really into contact at a time.

When the same procedure is applied to obtain a cross-section micrograph of GT a completely different image of the interface is obtained, as shown in Figure 7b. In this case, the contact area between the flexible, microstructured 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 SEM images of the GT structure, as reported in Figure 4 and Figure 7c, as well as those of gecko's toe hierarchical structure,[14] highlighting the similarities between the two. Gathering information from the macroscopic investigation, microscopy, and gecko toes images allows us to

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Figure 6. Micrographs taken by a standard optical microscope in transmission (a) with 20× magnification of the surface and (b) the cross-section of GT. (c) Transmission diffraction pattern produced on a screen by a red laser pointer shone through the sample.

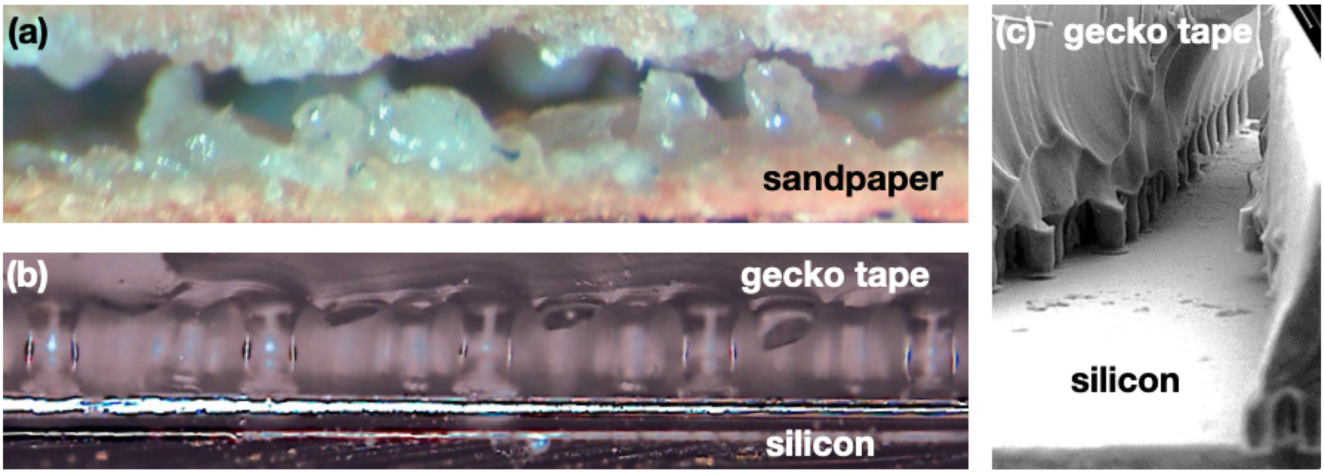

Figure 7. Optical micrographs of (a) the cross sections of a SP/SP interface and (b) a GT/silicon interface. (c) SEM image of the GT/silicon interface. The depth of field in SEM is much larger than in optical microscopy, allowing to better appreciate the 3D nature of the interface.

identify the micropatterning as the key to explain GT properties. In this phase, an explanation of the different wetting properties of the two sides of GT (i.e., flat-surface wetting vs Baxter−Cassie regime) is also discussed. SEM images of the micro- and nanostructures of lotus leaves are also shown at this point, to disclose the morphological origin of lotus superhydrophobicity.

■ TEST DESIGN AND TS RESULTS

The effectiveness of the TS has been probed through pre- and post-tests, with a combination of both closed and open questions. Throughout the DBR process, tests were progressively improved and focused. For instance, in a first version—inspired by Corpuz' work—students were asked to draw their own sketches of interfaces at different scales.[19,20] However, in the absence of direct interviews, the interpretation of these drawings leaves room for some ambiguity, and we eventually chose a different, more fruitful strategy, providing students with sketches of different interfaces (see Figure 8), which they were asked to discuss. In the following, we summarize the results of the final TS, which was proposed to 29 students during a one-day stage. Students were asked to take the pre-test a few days before the stage, after their flipped-class revision, while post-tests were answered few days after the stage itself.

Pre-test

The first part of the pre-test aims to probe the knowledge of macroscopic laws of friction and the ability to apply them to solve simple problems. It consists of standard open questions and exercises, which most students answered correctly, showing that the flipped-class modality was effective in reviewing previously acquired knowledge and providing a common background for all students engaged in the stage.

In the second part of the pre-test, we probe students' understanding of structure and dimensions of atoms and of the nature of intra- and intermolecular forces. Most students show a fair knowledge of these topics: 82% correctly attribute molecular forces to Coulomb interactions, while 7% identify it as nuclear and 11% believe that it depends on the bond type. The potential energy diagram describing intermolecular interactions, as shown, e.g., in Figure 1c— as quite expected—was known by only 28% of the students.

In the last part of the pre-test, we investigate students' understanding of the microscopic origin of friction and its relationship with surface roughness. In agreement with the literature, we found that the interlocking mechanism is the most diffuse mental model and that friction is assumed to be directly proportional to roughness. This is apparent from both answers to open questions and the results of what we call the interface-problem. Students were asked to compare couples of different interfaces, shown as drawings P.1 and P.2 in Figure 8, and choose the one that, in their opinion, displays higher friction. While most students correctly indicate the rougher interface A in P.1 as the one displaying higher friction, 85% of the students failed to recognize that it is not roughness itself but rather the true area of contact that influences friction and choose interface C in P.2. It is nevertheless interesting to note

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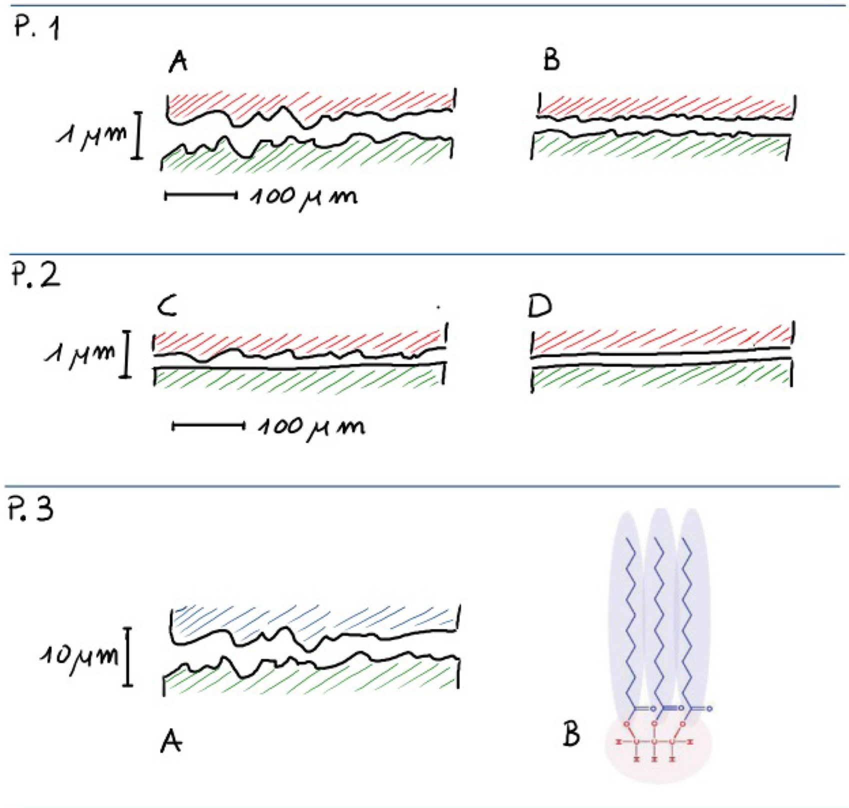

Figure 8. P.1 and P.2: Sketches of mating interfaces used in pre-test and post-test questions. In P.1, both the upper and lower surfaces of interface A are rougher than those of interface B, so that friction is higher in A than in B. In P.2, the lower surfaces are drawn as smooth, while the upper ones have different roughnesses. Hence, the true area of contact—and therefore the friction coefficient—is larger in D than in C. P.3: (A) sketch of rough mating surfaces and (B) chemical structure of a triglycerides. Its dimension can be estimated knowing the (approximate) length of a C—C bond.

that the 15% of the students that correctly chose interface D in P.2 explained their choice in terms of 'increased complementarity between the two surfaces', 'increased area of contact', and 'reduced distance between the two surfaces'. These answers suggest how providing students with drawings of different interfaces may trigger new insight and perspectives, helping to gain a more correct mental image of the physical situation.

Post-test

The post-tests were specifically designed to probe the learning goals identified during the design phase and reported in the Designing the Teaching Sequence section. The relationship between friction and the microscopic contact area was grasped by the vast majority of students (95%), who provided the correct explanation for the different behavior of GT and usual materials. Students were also able to relate the proportionality between applied normal force and friction to the variation of the true contact area.

In order to test the second learning goal—understanding that friction varies nonmonotonously with surface roughness—we reformulated the interface problem to guide students' logical thread, helping them to focus on what they have learned during the TS to find the correct answer. Specifically, referring again to the drawing set P.2 in Figure 8, we explicitly ask to choose the interface with the higher microscopic area of contact. Afterward, we ask which interface displays a higher friction and why (open question). Answers to this problem are particularly interesting: 89% of the students correctly choose interface D as the one with the larger area of contact and 74% correctly deduce that friction should also be larger in this case. A comparison of the results in the pre-test and post-test demonstrates the effectiveness of our approach in helping students to grasp the subtleties of tribological phenomena and their connection to the micro- and nanoscale properties of materials. It is important to emphasize that we never explicitly discuss a situation like the one depicted in P.2 during the TS; students therefore came to the correct answer by reasoning and not by merely stating what they have been told.

In the last part of the post-test, students' understanding of the microscopic origin of friction in terms of intermolecular forces is addressed. While the electrostatic nature of intra- and intermolecular forces was already known by the majority of students, as shown by the pre-test results, we have been particularly interested in probing their mental images and understanding beyond merely bookish knowledge. We first devised a problem meant to address students' ability to grasp the order of magnitude of distances at the micro- and mesoscale and their mental images of surfaces and molecules. In the drawing set P.3 in Figure 8, we sketched the lateral optical micrograph of a rough interface (A) covered by a monolayer of the triglyceride molecule (B). Students were asked to (i) estimate the increase in magnification which would be needed to observe the monolayer and (ii) discuss the possible influence of such a thin layer on friction. This first question—81% of correct answers—brought students to compare the surface roughness (in the micrometer scale) to the (nanometric) molecular dimensions (which they should be able to estimate). Moreover, 42% of the students answered correctly also to the second question and demonstrate the ability to recognize the fundamental role played by molecular interactions in such a complex tribological context.

Eventually, the common microscopic origin of friction and wetting—which was not elicited during the sequence—was correctly grasped by 46% of students,[26] while 60% of the students were able to correctly identify in the hydrophobicity of air (rather than pressure exerted by air or mechanical interlock of water molecules) the reason a water droplet does not easily penetrate the grooves of a microstructured surface.

■ CONCLUSIONS

We propose a novel, interdisciplinary teaching sequence associating friction and wetting in a hands-on, cross-disciplinary approach based on a commercially available, biomimetic, microstructured adhesive film. Contrary to a common belief that links nanotechnologies with sophisticated, possibly costly procedures limited to research or industrial laboratories, in selected cases, nano- and micromaterials—like Gecko-tape—are available off-the-shelves, safe, and cheap, and they can be investigated and manipulated through simple macroscopic experiments accessible at the early stages of scientific education. This allows us to highlight key concepts common to different disciplines and to effectively suggest that, even in the simplest phenomenology of matter, there is more to be understood than usually taught. This is one of the leading concepts behind our *NANOLAB – Hands-on educational nanoscience* project,[27] aiming to introduce topics related to nanoscience, condensed matter physics, and chemistry in school curricula and to expose students to the challenges of current research in material science. Following these ideas, our TS, designed according to the DBR process and suited for ICSE level 3 students, promotes the understanding of the common microscopic origin of friction and wetting. It highlights the strict correlation between the Gecko-tape microstructure and its macroscopic friction and wetting properties. Indeed, we believe that discussing these two phenomena—usually separately addressed in physics and chemistry curricula—in a unified perspective helps to scaffold a correct mental model of interacting surfaces, going beyond the mechanistic interlocking-asperities picture of friction that prevails among students.

Results of post-test analysis show this approach to be extremely fruitful, though they also suggest that more time should be devoted to revising the concepts of chemical bond and intermolecular forces. In this contest, this can be best done following the approach proposed by Levi Nahum et al.,[22] leaving plenty of room for novel didactic activities across STEM disciplines. More generally, successfully connecting the phenomenology of friction and wetting to a correct mental model of intermolecular forces promotes a knowledge construction with positive consequences on the understanding of other physical−chemical phenomena—say, liquid internal dynamics or phase transitions in fluids.

Last but not least, we showed that the use of carefully devised tests, based on sketches representing surfaces and interfaces at the meso- and microscale and balancing close and open questions, allows for unambiguous post-evaluation and are also effective in fostering further reasoning and understanding, as shown for instance in the case of the interface-problems.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c01175.

Figures of the set-ups for the initial engagement experiments and results of the static and dynamic friction experiments (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Valentina De Renzi − *Department of Physics, Informatics and Mathematics, University of Modena and Reggio Emilia, 42125 Modena, Italy; CNR-NANO S3, Istitute of Nanoscience, 41125 Modena, Italy;* orcid.org/0000-0001-6458-9246; Email: valentina.derenzi@unimore.it

Authors

Cinzia Scorzoni − *Department of Physics, Informatics and Mathematics, University of Modena and Reggio Emilia, 42125 Modena, Italy; Istituto di Istruzione Superiore Paradisi, 41058 Vignola, Modena*

Guido Goldoni − *Department of Physics, Informatics and Mathematics, University of Modena and Reggio Emilia, 42125 Modena, Italy; CNR-NANO S3, Istitute of Nanoscience, 41125 Modena, Italy*

Alberto Rota − *Department of Physics, Informatics and Mathematics, University of Modena and Reggio Emilia, 42125 Modena, Italy; CNR-NANO S3, Istitute of Nanoscience, 41125 Modena, Italy*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.1c01175

Notes

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