

From university laboratory to urban school: teaching cutting edge biomimetic technology to high school students

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ABSTRACT: Biomimetics (mimicking living nature for engineering applications) is a field of science and engineering that became increasingly popular in the past decade. Innovative research leading to publication in the better scientific journals has been undertaken in biomimetic surface science and green tribology involving such areas as *the Lotus Effect*, superhydrophobicity and other biomimetic effects. Teaching urban and minority high school students about this cutting edge research presents both a challenge and an opportunity. This is because many surface science concepts are easy to demonstrate in the classroom. In fact, they involve profound scientific ideas, close to novel technology and multidisciplinary in nature. In this article, prepared by a leading scientist and a teacher from Milwaukee Public School district, the authors report on how this was achieved in the National Science Foundation-sponsored project entitled *Research Experience for Teachers*.

INTRODUCTION

Biomimetics is the study of the structure and function of biological systems as models for the design and engineering of materials and machines [1]. Over the past decade, the biomimetic approach has become very popular in novel areas of materials science and engineering, as it was realised that living nature often achieves efficient solutions exceeding what conventional technology can do. For example, a spider's silk fibre has strength comparable to steel. Humans need high pressures and temperatures, as well as expensive equipment to produce steel, whereas a spider is a tiny creature, which produces its silk at room temperature with the length exceeding its size many times while suspended from it. The key is the sophisticated structure of biological materials and the example demonstrates that there are ways to improve current technologies, and nature can serve as an inspiring source of ideas.

In the area of biomimetic surfaces, several ideas have emerged in the past couple of decades. The most famous is the self-cleaning and superhydrophobic *Lotus Effect* [1-3]. The lotus leaf has the ability to emerge clean even from dirty or muddy water. Studies with Scanning Electron Microscopy in the 1990s showed that this is due to the structure of the leaf's surface, which is built of microscopic bumps (called papillae) covered by hydrophobic wax crystals forming surface roughness with much smaller (sub-micron sized) details.

This phenomenon was related to the effect of the surface roughness-induced superhydrophobicity, which was occasionally discussed in the literature since the 1930s; however, it started to receive more attention since the discovery of the Lotus Effect. Superhydrophobic surfaces repel water and dirt. Significant progress has been made in the past decade in the development of artificial micro/nanostructured superhydrophobic *non-sticky* surfaces for water-, oil-, and ice-repellence, as well as many other applications, making the area of superhydrophobicity one of forefronts of nanoscience and technology [4-6].

The science and engineering of interacting solid surfaces in relative motion is referred to as *tribology*, and it involves the study of friction, wear, lubrication and adhesion. A novel area of *green tribology* or *eco-tribology* has emerged since 2009, and biomimetic surfaces constitute an important component of this area [7-8].

From the educator's viewpoint, wetting and superhydrophobicity constitute unique areas. First, they are very simple to comprehend and many demonstrations are easy and do not require any sophisticated equipment, just a water droplet on a solid surface. Second, despite the apparent simplicity, there are still many unresolved issues related to wetting being investigated by surface scientists and they constitute one of the cutting edges of scientific research [9]. Third, these are related to new nano-, biomimetic and green technology. Fourth, the topic is multidisciplinary in nature, involving biology, mathematics, physics, chemistry and engineering. All this makes it attractive to present these exciting topics to high school students, who could become interested in science and engineering.

During the summer of 2012, one of the authors of the present article, a school teacher of mathematics in the Milwaukee Public School (MPS) system, was the intern at the Biomimetic and Green Tribology laboratory headed by the other author, within the National Science Foundation (NSF) sponsored program *Research Experience for Teachers (RET)*. The purpose was to learn about novel biomimetic surface science technology and to present it to talented MPS students. Some outcomes of this project, unique and original as far as the authors know, are presented in this article.

MAIN SCIENTIFIC CONCEPTS

Water contact angle (CA) and its hysteresis. Water CA is the main parameter that characterises the wetting of a solid surface by water. When water comes in contact with a solid, the water surface usually forms a stable angle referred to as the CA. Surfaces with $0^\circ < CA < 90^\circ$ are called hydrophilic, whereas those with $90^\circ < CA < 180^\circ$ are called hydrophobic. Hydrophobic surfaces with $150^\circ < CA < 180^\circ$ are called superhydrophobic.

In addition, the CA does not always have one single value. When water is added or the water surface advances, the value is usually increased and it is called the advancing CA. When water is removed or recedes, the value of the CA is usually decreased and it is called the receding CA. The difference between the advancing and the receding CA is called CA hysteresis and, together with the CA, it is an important characteristic of wetting.

When a solid surface is rough, the CA, θ , is modified in accordance with the Wenzel equation:

$$\cos\theta = R_f \cos\theta_0 \quad (1)$$

where θ_0 is the CA of droplet with the smooth surface and $R_f \geq 1$ is the roughness factor defined as a ratio of the surface area to its flat projection [10]. It is observed from Equation (1) that surface roughness magnifies hydrophobicity/helicity, i.e. a hydrophilic surface ($\cos\theta_0 > 0$) becomes more hydrophilic (CA decreases), whereas a hydrophobic surface ($\cos\theta_0 < 0$) becomes more hydrophobic and can enter the superhydrophobic region ($\theta > 150^\circ$). For many applications, it is also desirable that air pockets will be trapped between the water droplet and the solid decreasing the contact area (the so called Cassie state).

Mathematical definition of surface roughness. Quantitative characterisation of the surface roughness is of importance in tribology and surface science. The most common parameter is the so called root-mean-square (RMS) defined as:

$$R_a = \sqrt{\frac{1}{L} \int_0^L (z(x) - z_0)^2 dx} \approx \sqrt{\frac{1}{N} \sum_{n=1}^N (z_n - z_0)^2} \quad (2)$$

where L is the sample interval, $z(x)$ for $0 \leq x \leq L$ is the surface profile, z_0 is the average value of z . To substitute the integral with a finite sum (which may be more appropriate for those high school students who are not familiar with the calculus) the interval can be divided into N sections with finite points x_n and $z_n = z(x_n)$ [1].

Note that RMS is a dimensional parameter (usually measured in micrometers). Another parameter that is often used is the non-dimensional Wenzel roughness factor, which can be defined as the length of the profile divided by the length of the sampling interval:

$$R_f = \frac{1}{L} \int_0^L \sqrt{1 + \left(\frac{dz}{dx}\right)^2} dx \approx \sqrt{\sum_{n=2}^N \sqrt{1 + \frac{(z_n - z_{n-1})^2}{(x_n - x_{n-1})^2}}} \quad (3)$$

Minimal surfaces and the shape of menisci, droplets and bubbles. The surface shapes of a bubble, as well as of a droplet or water meniscus are defined by the Laplace equation, which relates the pressure change inside and outside the droplet (or bubble or meniscus) to its curvature. This may be a good introduction to the geometrical concept of minimum surface [1].



Figure 1: A teacher is using combined biomimetics surfaces and nanotechnology (goniometer) knowledge; exploring the Lotus Effect.

TEACHING PLAN

The following detailed teaching plans were developed to implement the concepts in the high school environment, as summarised in Tables 1 and 2.

Table 1: Class lesson *Superhydrophobic Surfaces in Nature*.

Core Idea	Core Idea Question
<p>CORE IDEA ESS2: SUPERHYDROPHOBIC SURFACE IN NATURE</p> <ul style="list-style-type: none"> *Leaves of water-repellent plants (article 2.1) *Insect and birds wings (article 2.2) *Insect legs (article 2.3) 	How and why is nature able to repel water and be self-cleaning?
Component Ideas	Component Idea Questions
ESS2.C: The roles of leaves, insect legs, and insect and bird wings surfaces.	How and why is nature able to repel water and be self-cleaning?
Grade Band Endpoints (Learning Intentions)	
Understand and be able to explain and demonstrate how and why nature is able to repel water and be self-cleaning.	
Lesson Details	Materials Needed and Additional Notes
<p>Day 1</p> <ul style="list-style-type: none"> • Introduce a lesson with a demonstration (by the teacher) on water droplets on ceramic tiles and ask students what will happen to the droplet if the tile is tilted 25°. <ul style="list-style-type: none"> - Students write down what they think is going to happen to the droplet - Students watch and observe the demonstration and write down what they saw - Whole class is sharing <i>Before/After demonstration</i> • Introduce Core Idea: Nature Systems <ul style="list-style-type: none"> - By asking students have a brain storming session about the types of nature that can react in a similar effect to the ceramic tile - Whole class sharing (Make a common list on a poster board) • Assign students to groups of three or four to work on a tri-fold display board project <i>What nature can repel water and self-cleaning? Pick one topic from the poster board</i> <p>❖ Students create a tri-fold display board</p> <ul style="list-style-type: none"> - Students get together in their working area and do brainstorming and start working on their project for the next two days. <p>Day 2</p> <ul style="list-style-type: none"> • Hand out three different articles on nature that can be water repellent. Students continue working on their tri-fold display board <ul style="list-style-type: none"> - Teacher: <ul style="list-style-type: none"> ◆ Observe ◆ Project's process check list ◆ Assist and answer questions <p>Day 3</p> <ul style="list-style-type: none"> • Teacher sets up a classroom for group report presentation • Students present their report to the class • Teacher assesses poster boards and presentations • Students write a short reflection or comments about the lesson. <i>What did you learned from this lesson activities?</i> 	<ul style="list-style-type: none"> • Three minutes' Video of Lotus Effect (Youtube) • Poster board • Markers • Computer and Internet access • Papers and pencils • Scissors and glues • Nature water repellent articles • Tri-fold display board
Formative Assessment	Summative Assessment
<p>Elicitation stage: determines students' preconceptions and should guide modification of the lesson if needed.</p> <p>Engagement: use the discrepant event to motivate student interest.</p> <p>Engagement: ask a question to determine depth of understanding.</p> <p>Explanation stage: includes a pair-share activity around scientific terms.</p>	Assessing student's display board and board presentation

Elaboration stage: includes having students look at a topographic image of lotus leaf to find evidence of and identify Lotus Effect form created by epidermis. Evaluation stages: have students make a display board.		
Approximate time needed: three 45 minute class periods (three days). Day 1: Lesson introduction/start on project; Day 2: Continue working on a project; Day 3: Present a project to the class.		
Mathematics: Concept of contact-angle of water droplet θ_1 and θ_2 , θ_1 – Receding angle, θ_2 -Advancing angle		
ELA: Provide a reading article about the NATURE that is water-repellent.		
Other: Students do research on the Web, what discoveries were made by scientists, the obstacles faced by engineers and what happened to the project.		
Accommodations for Differentiated Instruction (see Curriculum Guides for suggestions)		
Special Needs Assistance with the reading of three articles, Web search, and putting the tri-fold display board together.	English Language Learners Translation for ESL Learners	Gifted and Talented: How does a nature water repellent compare to a non-nature water repellent. Give one or two comparisons.

Table 2: Instructional design for *Superhydrophobic Surfaces in Nature*.

ENGAGE	Notes/reflection
Formative Assessment: Ask the students to ponder this question for about 2-3 minutes and then try to answer it. <i>What nature is considered to be water repellent?</i> Bring out a ceramic tile demo and ask a question <i>What will happen to the water droplet if the ceramic tile is tilted at about 25°?</i>	
EXPLORE	
Formative Assessment: Have students list and describe what nature considers a water repellent. This could be done in their notebooks.	
EXPLAIN	
Formative Assessment: Have students make a tri-fold display board explaining what type of nature can repel water and is self cleaning.	
ELABORATE	
Students may believe that ceramic tile, plastic, glass and other solid objects can be water repellent and self cleaning. Have students research on nature such as leaves of a plant, insect legs and bird wings that can be water repellent and self cleaning.	
EVALUATE	
Summative Assessment: Have students make concept tri-fold display board using new terms from reading articles and Web-search. Remind them to include appropriate connection words and phrases to link the terms on their display board.	

CONCLUSIONS

The area of biomimetic surfaces presents a rare opportunity for educators to involve students into innovative areas of science and engineering. This is due to the unique combination of the simplicity of the concepts of wetting and surface roughness with their relationship to modern science and novel technology, as well as due to the multidisciplinary nature of this area. The authors discussed how this can be implemented for an urban school in the Milwaukee, WI area.

This is especially exciting due to the presence of a large number of minority students, such as African American or Hispanic students. Non-white or Hispanic students constitute 87.6% of the total number of MPS students and are underrepresented in science, technology, engineering and mathematics [11]. These students can be encouraged and inspired by learning about the novel scientific areas.

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