Eliminating friction at the nanoscale

Educator guide

PAPER DETAILS

Original title: Macroscale superlubricity enabled by graphene nanoscroll formation

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Authors: Diana Berman, Sanket A Deshmukh, Subramanian KRS Sankarananrayanan, Ali Erdemir, Anirudha V Sumant

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Annotator(s): Jyothirmayee Aravind S.S.

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DISCUSSION QUESTIONS

	LEARNING STANDARDS
1. What are the differences between contact and non-contact forces? What technique(s) did the authors use to measure friction (a contact force)?	SEP1 PS2.B Scale, Proportion, and Quantity RST.11-12.4 EK3.C.4
2. Why did the authors perform a theoretical simulation instead of replicating a real system? What specific measurements/conclusions did the authors make using simulations?	SEP2 Systems and System Models SP1 VC3
3. How did the authors initially design the superlubricity experiments? What prompted them to redesign and include nanodiamond?	SEP1 ETS1.A RST.11-12.1 NS3
4. What are the essential characteristics of the nanodiamond used in this study? What other materials might offer these same (or similar) characteristics? Do you think an alternative material can still facilitate the formation of nanoscrolls during sliding?	SEP1 PS2.B SP4 EK3.C.2 RST.11-12.9
5. Why might it be advantageous to minimize friction in a mechanical system? What are the potential applications of this superlubric system?	ETS1.A RST.11-12.2 SP4
6. What are the limitations to this superlubric system of graphene, nanodiamond, and diamondlike carbon?	SEP1 ETS1.A RST.11-12.6 SP4 NS3

ACTIVITIES FOR INTERACTIVE ENGAGEMENT

	LEARNING STANDARDS
Writing an abstract Students write a new abstract for the article at a grade-appropriate reading level.	RST.9-10.2 RST.11-12.2
Locating this study in the larger field Students use the annotated list of references to explain how this research builds on the published work of at least one other independent group of scientists. Students will evaluate whether data from this research supports or contradicts previous conclusions and reflect on the statement that scientific knowledge is a "community effort."	RST.9-10.8 RST.11-12.8 NS3
Science in the news Students explore news stories in the Related Resources tab and evaluate the stories for tone, accuracy, missing information, etc. They may then write their own news stories on the article.	RST.9-10.5 RST.11-12.5 RST.9-10.6 RST.11-12.6 RST.9-10.8 RST.11-12.8
Recreating the nanoscale at the macroscale Students use macroscale materials to simulate the nanoscale system using the supplemental resource animation as a guide. What materials are more conducive to the formation of nanoscrolls? What materials produce the least amount of friction? Educators should consider some of the following materials: tennis balls, ball bearings, crepe paper, Kleenex, printer paper, Velcro strips, large textbooks (or other large, heavy objects to replicate the sliding interface)	SEP2 ETS1.A Scale, Proportion, and Quantity SP1 EK3.C.4 VC3
Results and conclusions Students diagram each of the experiments presented in the study (divided up by figure, if appropriate). They then consider the results depicted in each figure, and how these results support the conclusions of the study.	SEP2 Systems and System Models RST.9-10.8 SP1
The next steps Students design a follow-on experiment to this study that either addresses flaws or unanswered questions in the research at hand, or builds on it to explore a new question.	SEP1 ETS1.A RST.11-12.6 NS3

ARTICLE OVERVIEW

Article summary (recommended for educator use only)

Berman *et al.* report the experimental and theoretical studies of superlubricity when sliding diamondlike carbon (DLC) balls against graphene patches and nanodiamonds in a dry nitrogen environment. The formation of graphene nanoscrolls initiated by the attraction between highly reactive graphene patches and the dangling bonds on nanodiamonds is found to be the key factor in reducing the contact area and achieving incommensurate (misaligned) contact, thereby facilitating a substantially reduced coefficient of friction. Though the study reports impressive performance in dry conditions, increased friction is observed in humid test environments. Variable experimental conditions such as load, velocity, and temperature are altered and the criteria for sustainable superlubricity is also presented. Computer simulations were performed by creating point defects on graphene sheets and it was found that in dry environments, superlubricity was unaltered while humidity increased both friction and wear. Furthermore, in order to understand the transition of friction from the nanoscale to observed macroscopic superlubric conditions, the authors simulated a mesoscopic scenario. They analyzed an ensemble of graphene patches and nanodiamonds between DLC and graphene substrate subjected to sliding friction and report a large reduction in the effective contact area, manifesting a superlubric state in the mesoscopic system.

Importance of this research

Better understanding and control of friction, with its direct linkage to energy efficiency and environmental cleanliness of moving mechanical systems, are areas of significant research importance. The authors of this study aim to achieve macroscale superlubricity utilizing a novel nanoscroll mechanism. Diamondlike carbon films, nanodiamonds, and graphene were engineered in a dry atmosphere demonstrating ultralow friction conditions. However, similar experiments in a humid environment failed to show the same improvements regarding reduced friction and/or wear. Hence, further research can be directed towards establishing superlubricity in the presence of water molecules as well, so as to extend the superlubric regime (described here) under variable environmental conditions. The authors suggest that this can be achieved by making the graphene superhydrophobic, either by preparing a hybrid material of graphene by mixing it with polymers or by modifying the preparation technique to incorporate hydrophobic functional groups on graphene sheets. Doping of graphene elements, such as fluorine, has also been found to make graphene water-repellent.

Experimental methods

- Deposition of graphene and nanodiamonds on SiO_2 substrate
  - Graphene solution was prepared and then applied to the SiO_2/Si wafer and ethanol was evaporated under dry N_2 flow. Simultaneously, nanodiamond solution was deposited on the SiO_2 substrate.
- Fabrication of DLC-coated stainless-steel ball
  - DLC film was deposited on a stainless-steel ball by a plasma-enhanced chemical vapor deposition method.
- Tribological tests
  - Performed in both dry and humid environments, with varying loads. Radius of the wear track was varied, as well. All tests were repeated five times to confirm reproducibility of the results.
- Molecular dynamics simulations
  - Simulations carried out with adaptive intermolecular reactive empirical bond-order (AIREBO) potential.

- Effect of humidity
    - To simulate a humid environment, authors have randomly inserted water molecules to achieve 30% humidity between the DLC balls and graphene sheet.
- Defects evaluation
    - The effects of different kinds of defects on graphene sheets in facilitating superlubricity was investigated under dry and humid conditions.
- Experimental stability of the superlubric regime
    - The stability test was performed under different loads, velocities, and temperature conditions.

Conclusions

- Experimental verification of superlubricity: Authors achieved ultralow friction in dry nitrogen using a combination of nanodiamonds, graphene, and DLC materials. Initiation of nanoscrolls as a result of attractive forces between highly reactive graphene patches and dangling bonds on nanodiamonds, as well as additional stabilization by Van der Waals attraction forces, facilitate ultralow friction while sliding. This result may pave new pathways for advanced lubrication technology in reducing wear and friction that could be exploited further for industrial applications involving sliding and rotating contacts.
- Environmental conditions affecting superlubricity: The study also reports environmental impacts in aiding ultralow friction conditions. When water molecules are introduced, greater friction and wear are observed due to the formation of quasi 2D-ordered water layers between DLC and graphene patches, which prevent the formation of nanoscrolls during sliding. This confirms that environmental conditions play a major role in facilitating superlubric regimes at the sliding interface.
- Defects on graphene sheets are found to influence superlubricity: Authors have simulated point defects—such as Stone-Wales and double vacancies on graphene sheets—and investigated their influence on superlubricity under both dry nitrogen and humid conditions. It was observed that in a dry environment, the presence of defects does not influence the process of scroll formation; whereas in a humid atmosphere, water preferentially adsorbs and stabilizes defective sites, thereby inhibiting the formation of scrolls. These results indicate that graphene sheets demonstrate similar performances in dry nitrogen regardless of the presence of defects and hence the method of synthesis of graphene sheets may not be a critical factor. This is important since the large-scale synthesis of defect-free graphene normally involves sophisticated and costly techniques, limiting its practical applications.
- The superlubric regime is found to be stable under different experimental conditions: Friction and wear are strongly affected by kinematic, physical, and chemical parameters such as speed, temperature, and atmospheric conditions. Different loads, velocities, and temperature conditions were tested and the study found that stable, superlubric regimes occur over a wide range of these parameters. These results demonstrate that the combination of nanomaterials used in this study hold great promise as an effective solid lubricant for a variety of kinematic, physical, and chemical conditions.

LEARNING STANDARDS ALIGNMENT

The following tables provide an overview of the learning standards covered by this article, including the A Framework for K-12 Science Education (Framework), Common Core State Standards English Language Arts-Literacy (CCSS ELA), Common Core State Standards Statistics and Probability (CCSS HSS), AP Science Practices, and Vision and Change for Undergraduate Education. Where applicable, activities and information will be marked with specific standards to which they are linked.

A Framework for K-12 Science Education		
Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Asking and Defining Problems (SEP1) Define a design problem that involves the development of a process or system with interacting components and criteria and constraints that may include social, technical, and/or environmental considerations. **Developing and Using Models (SEP2)** Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems.	**PS1.A: Structure and Properties of Matter** The structure and interactions of matter at the bulk scale are determined by electrical forces within and between atoms. **PS2.B: Types of Interactions** Attraction and repulsion between electric charges at the atomic scale explain the structure, properties, and transformations of matter, as well as the contact forces between material objects. **ETS1.A: Defining and Delimiting an Engineering Problem** Design criteria and constraints, which typically reflect the needs of the end-user of a technology or process, address such things as the product or system's function (what job it will perform and how), its durability, and limits on its size and cost.	**Scale, Proportion, and Quantity** In considering phenomena, it is critical to recognize what is relevant at different measures of size, time, and energy and to recognize how changes in scale, proportion, or quantity affect a system's structure or performance. **Systems and System Models** When investigating or describing a system, the boundaries and initial conditions of the system need to be defined and their inputs and outputs analyzed and described using models.

Common Core State Standards English Language Arts-Literacy		
Key Ideas and Details	Craft and Structure	Integration of Knowledge and Ideas
RST.9-10.1 Cite specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions.	**RST.9-10.4** Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics.	**RST.9-10.8** Assess the extent to which the reasoning and evidence in a text support the author's claim or a recommendation for solving a scientific or technical problem.
RST.9-10.2 Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.	**RST.9-10.5** Analyze the structure of the relationships among concepts in a text, including relationships among key terms (e.g., force, friction, reaction force, energy).	**RST.9-10.9** Compare and contrast findings presented in a text to those from other sources (including their own experiments), noting when the findings support or contradict previous explanations or accounts.
RST.11-12.1 Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account.	**RST.9-10.6** Analyze the author's purpose in providing an explanation, describing a procedure, or discussing an experiment in a text, defining the question the author seeks to address.	**RST.11-12.8** Evaluate the hypotheses, data, analyses, and conclusions in a science or technical text, verifying the data when possible and corroborating or challenging conclusions with other sources of information.
RST.11-12.2 Determine the central ideas or conclusions of a text; summarize complex concepts, processes, or information presented in a text by paraphrasing them in simpler but still accurate terms.	**RST.11-12.4** Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 11-12 texts and topics.	**RST.11-12.9** Synthesize information from a range of sources (e.g., texts, experiments, simulations) into a coherent understanding of a process, phenomenon, or concept, resolving conflicting information when possible.
	RST.11-12.5 Analyze how the text structures information or ideas into categories or hierarchies, demonstrating understanding of the information or ideas.	
	RST.11-12.6 Analyze the author's purpose in providing an explanation, describing a procedure, or discussing an experiment in a text, identifying important issues that remain unresolved.	

AP Science Standards	
AP Science Practices	AP Physics 1 Content Standards
Science Practice 1 (SP1) The student can use representations and models to communicate scientific phenomena and solve scientific problems. **Science Practice 4 (SP4)** The student can make claims and predictions about natural phenomena based on scientific theories and models.	**Essential knowledge 3.C.2 (EK3.C.2)** Electric forces dominate the properties of the objects in our everyday experiences. However, the large number of particle interactions that occur make it more convenient to treat everyday forces in terms of nonfundamental forces called contact forces, such as normal force, friction, and tension. **Essential knowledge 3.C.4 (EK3.C.4)** Contact forces result from the interaction of one object touching another object and they arise from interatomic electrical forces. These forces include tension, friction, normal spring, and buoyant.

Connections to the Nature of Science	
Vision and Change for Undergraduate Biology Education Core Competencies and Disciplinary Practices	A Framework for K-12 Science Education Understandings About the Nature of Science
Ability to use modeling and simulation (VC3) As new computational approaches improve our ability to study the dynamics of complex systems, mathematical modeling and statistical approaches are becoming an important part of the scientist's toolkit.	**Scientific knowledge is open to revision in light of new evidence (NS3)** Scientific argumentation is a model of logical discourse used to clarify the strength of relationships between ideas and evidence that may result in revision of an explanation.