

RESOURCE LETTER

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This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course content in specified fields. [The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A indicates rather specialized or advanced material.] No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.

Resource Letter: FMMLS-1: Friction at macroscopic and microscopic length scales

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This Resource Letter provides a guide to the literature on the fundamental origins of friction. Books, reviews, and journal articles are cited for the following topics: History of friction and tribology, the adhesion theory of macroscopic friction, first principles' treatments of frictional energy dissipation at the atomic level, experimental methods for studying friction at the atomic-scale, stick-slip phenomena and lattice commensurability effects. © 2002 American Association of Physics Teachers.
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I. INTRODUCTION

When an object moves along a surface or through a viscous liquid or gas, the forces resisting its motion are referred to as friction. Frictional forces are nonconservative, converting the kinetic energy of materials in sliding contact to internal energy. Thus, if an object is given an initial velocity along a horizontal surface, the temperature of both the object and the surface upon which it slides will increase as the friction resisting its motion brings it to a stop. If an object is initially at rest, a minimum force must be applied to overcome "static friction," giving rise to the familiar phenomenon of an object "jumping ahead" at the instant that sliding is initiated. Static friction, in contrast to kinetic friction, is associated with neither energy "loss" nor sample heating. It is entirely absent for bodies moving through viscous fluids, "viscous friction" being parametrized at low velocities by

$$F = \eta v, \quad (1)$$

where v is the velocity of the object through the fluid. The consequences of friction and wear have enormous economic impact, and are of great concern from both a national-security and quality-of-life point of view. Indeed, by most recent estimates, improved attention to friction and wear would save developed countries up to 1.6% of their gross national product, or over \$100 billion annually in the U.S. alone.²¹

Modern study of friction began at least 500 years ago, when Leonardo da Vinci recorded in unpublished notebooks the laws governing the motion of a rectangular block sliding over a planar surface.⁷ The French physicist Guillaume Am-

ontons is credited with the first published account, in 1699,³² of the familiar friction law for solid surfaces in sliding contact:

$$F = \mu N. \quad (2)$$

The "normal load" N in Eq. (2) is the force that presses the surfaces together, and μ is termed the "coefficient of friction." Amontons also reported that the friction force is independent of the apparent area of contact: A small block experiences as much friction as does a large block of the same material so long as their weights are equal. A third law, attributed to French physicist Charles Augustin Coulomb (better known for his work in electrostatics) is frequently included with those of Amontons: The friction force is independent of velocity for ordinary sliding speeds.

Amontons' and Coulomb's laws have far outlived a variety of attempts to explain them on a fundamental basis, by no means owing to a lack of appreciation for the importance of friction or a lack of scientific interest. That so little is known about how friction originates at microscopic length scales is simply because it occurs at a myriad of buried contacts that not only are extremely difficult to characterize, but are continuously evolving as the microscopic irregularities of the sliding surfaces touch and push into one another.

Many early investigators, including Amontons and Coulomb, envisaged that friction arose from mechanical interlocking between rigid or elastically deforming asperities. The friction force in this scenario is obtained by equating the work done by the frictional force to that done against the normal load as the surfaces separate to allow asperities to slide up and over each other (Fig. 1). This model is deeply

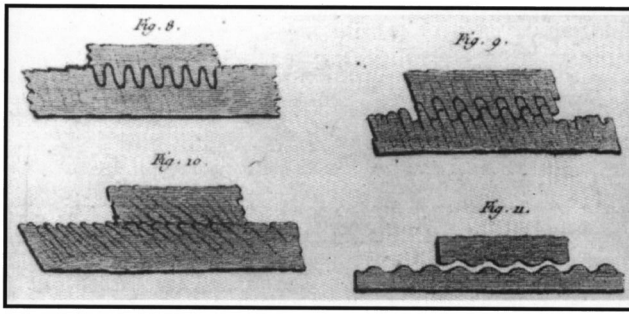


Fig. 1. Schematic of the interlocking theory of friction. From Charles Augustin Coulomb, *Théorie des Machines Simple* (1785) (Ref. 7).

flawed however, since the normal load performs work *on* the system after the asperities have passed over each other and the upper body had settled back into its lowest position: All of the potential energy stored in the “separating” phase of the motion is recovered, so no net energy dissipation, and therefore no friction, can be present. The interlocking view of friction is also deeply flawed in that it contradicts a variety of common macroscopic observations. For example, when two highly polished and smooth metal surfaces are brought into contact, they are far more likely to cold-weld than to exhibit low friction. Finally, advances in surface science³¹ have revealed that molecularly thin adsorbed films on surfaces can change friction by orders of magnitude while maintaining virtually the same roughness that would give rise to the interlocking effect. In light of such overwhelming scientific evidence, the scientific community has abandoned interlocking as a viable explanation for friction.

An alternate, more successful model associated with molecular adhesion at the contacting asperities was advanced in the mid-1950s by Bowden, Tabor, and co-workers at Cambridge University, England (Fig. 2).¹ The basic idea is that when two surfaces touch each other, the actual microscopic area of contact is much less than the apparent macroscopic area, perhaps by a factor of 10^4 . Nonetheless, many asperities do come into contact and exhibit locally very high yield stresses, not unlike tiny cold-welds. When the surfaces are forced to slide over each other, new contact regions are con-

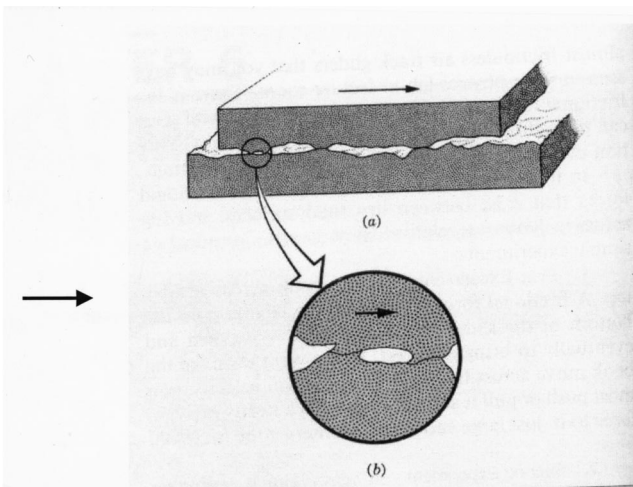


Fig. 2. Schematic of the adhesive model of friction: Increased normal force results in increased contact area.

tinuously formed while others are severed. If the true area of contact A is constant on average, and the contacting junctions all have the same shear strength s , then the friction force is $F = As$. Assuming the normal force to be collectively borne by the contact regions, the average pressure in a contact region is $P = N/A$, so the “adhesive” contribution to the coefficient of friction can be written as:

$$\mu = \frac{F}{N} = \frac{As}{N} = \frac{As}{AP} = \frac{s}{P}. \quad (3)$$

If the contact pressure is independent of normal load, which necessarily implies that $A \propto N$, then Eq. (3) reduces to Amontons’ law, Eq. (2), with $\mu = s/P$. (Note that friction in practice does not fall completely to zero for zero applied load on account of the presence of molecular adhesion.)

To explore the validity of the adhesive theory of friction using Eq. (3), one must establish whether the contact pressure is indeed independent of load, ideally by directly measuring the true contact area as a function of normal load. A great number of methods, ranging from electrical resistance measurements to optical and acoustical methods, have attempted to perform such direct measurements of true contact area,^{5,95,107} but all have shortcomings.

In the absence of precise measurement methods, scientists have inferred the true area of contact by means of contact-mechanics models.^{3,33–40} The most well known of these, treating contact between two spheres, were derived by Johnson, Kendal, and Roberts (JKR), Derjagion, Muller, and Toporov (DMT), and Hertz. For contact between two spheres, $A \propto N^{2/3}$ for perfect elastic deformation and $A \propto N^1$ for plastic deformation. Experimental investigations of contacting spheres have confirmed $A \propto N^n$ to be appropriate for a range of materials, with n closer to $2/3$ for rubber, wood, plastic, and textiles and closer to 1 for more brittle materials such as glass, diamond, and rock salt. And though only a limited number of materials exhibit $A \propto N$ for two spheres in contact, a far wider range of materials displays this dependence when *multi-asperity* contact is considered.⁵

One well-known statistical theory for multi-asperity contact was presented by Greenwood and Williamson in 1966, and is still widely cited.³⁴ Greenwood and Williamson studied the behavior of two different distributions of asperity heights, Gaussian and exponential. They observed that even for elastic contact, where $A \propto N^{2/3}$ for a single contact, a linear relation holds for a *distribution* of contact regions. The linear relation arises because as the load increases, not only the size of each individual contact spot increases, but also the number of contacting asperities. The mean size of a contact thus remains constant, as does the average contact pressure. Greenwood and Williamson found an exact linear relation for an exponential distribution of asperity heights and a nearly linear relation for the more physical case of a Gaussian distribution. Their model also has been extended to self-affine fractal surface geometries (a type of Gaussian distribution that describes a great many physical surfaces), and a nearly linear relation between A and N was again recovered. (It should be noted that friction remains present for zero *external* load, owing to molecular adhesion of the counterface materials.)

The notion that $A \propto N$, which underlies Bowden and Tabor’s molecular adhesion model, is thus well-grounded for a wide range of materials. Assuming this to be the case, the

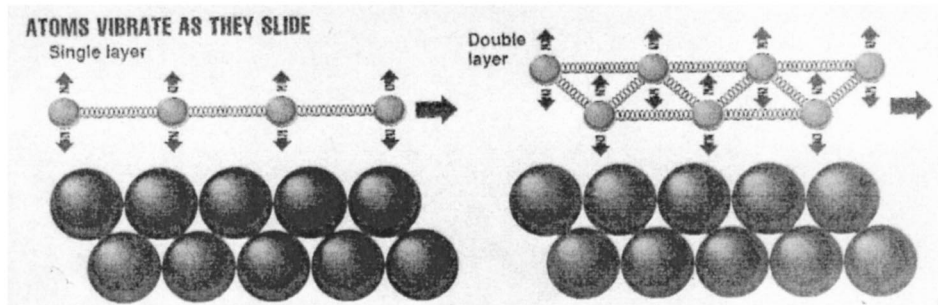


Fig. 3. Schematic of phononic friction. At the atomic level, the excitation of vibrations of atoms due to sliding is eventually dissipated as heat.

model, by Eq. (3), predicts that $\mu = s/P$, where both s and P are properties of materials. Consider, however, the example of ductile metals, where $P \approx 3Y$ for fully developed plastic flow and $s \approx Y/2$, Y being the uniaxial yield stress. Equation (3) predicts values for μ that lie in the range 0.17–0.2, despite the fact that larger values for μ are routinely measured for a range of materials combinations, including ductile metals.

Tabor was hard pressed to explain how friction could rise above 0.2 within the molecular-adhesion model. He explored the possibility that friction might arise from sufficiently strong bonding at the true contact points so as to produce continual tearing away of tiny fragments of material, but this explanation failed to agree with experimental observation. Although high material wear rates and ploughing effects are routinely associated with high friction, friction levels can remain high even in the total absence of wear or plastic deformation.

A first-principles' theory of "wearless" friction had been suggested in fact as early as 1929 by Tomlinson, involving phononic, or lattice vibration mechanisms.⁴¹ Friction arising from phonons occurs when atoms close to one surface are set into motion by the sliding action of atoms in the opposing surface (Fig. 3). The lattice vibrations are produced when mechanical energy needed to slide one surface over the other is converted to sound energy, which is eventually transformed into heat.

Motivated by the Tomlinson model, Tabor attempted, but failed to detect evidence for the phononic contributions to friction. Nonetheless, in a 1991 plenary lecture at a NATO-sponsored conference on Fundamentals of Friction¹¹ (the first meeting to bring together long-established tribologists with surface scientists new to the field), he concluded that friction in the absence of wear must be due to strains building up in the sliding contact that were being released in the form of atomic vibrations. That same year, Krim and coworkers reported Quartz Crystal Microbalance (QCM) measurements of the friction of krypton monolayers sliding on Au(111).⁵⁷ The data were subsequently modeled with molecular-dynamics simulation by Robbins and coworkers assuming that the friction was due to phonons excited in the adsorbed layers.⁵⁸ The combined QCM and numerical results provided the first definitive evidence for the existence of a phononic mechanism for friction.

The discovery of phononic contributions to friction was symptomatic of a renewed interest in fundamental areas of tribology that began in the late 1980s, sparked by a number of new experimental and theoretical techniques capable of studying the force of friction in well-defined contact geometries.²⁴ These techniques benefited directly from ad-

vances in surface science throughout the 1970s, whereby improvements in ultrahigh vacuum technology allowed scientists to prepare unprecedented, well-characterized crystalline surfaces. Surface scientists new to the field of tribology now prepared well-defined interfaces in advance of the measurements rather than trying to characterize innumerable hidden interfaces. Experimental techniques such as the quartz-crystal microbalance,^{56–65,97,98,101,102,124} the surface forces apparatus,^{66–76,102,105,110,114} and the lateral-force microscope,^{77–94,128–130} could now record friction in geometries involving a single contacting interface, a vastly simpler situation than that of contact between macroscopic objects. Faster computers meanwhile allowed large-scale simulations of condensed systems to be increasingly comparable to such experiments in a direct fashion.

The atomic-force microscope (AFM), also referred to as a lateral-force microscope (LFM) is perhaps the most familiar of these techniques, on account of its commercial availability. The AFM was invented in 1986,⁷⁷ and was adapted for lateral-force measurements of atomic-scale friction in 1987.⁷⁸ It consists of a sharp tip mounted at the end of a compliant cantilever. As the tip is scanned over a sample surface, forces that act on the tip deflect the cantilever. Various electrical and optical means (such as capacitance and interference) quantify the horizontal and vertical deflections. In the early 1990s, Mate and co-workers succeeded in setting up a friction-force microscope in ultrahigh vacuum, with a contact area estimated to be less than 20 atoms in extent. They measured a friction force that exhibited no dependence on normal load which, according to Eq. (2), would have implied zero friction. But not only was friction evident in a completely wear-free environment, the shear stress, or force per area required to maintain the sliding, was enormous: one billion Newtons per square meter, a force per unit area large enough to shear high-quality steel! What energy dissipative mechanism could be giving rise to such high friction levels?

Energy dissipation mechanisms and the fundamental origins of friction are in fact at the focus of ongoing efforts by a number of groups worldwide.²³ One interesting aspect of all AFM measurements is that static friction and stick-slip phenomena are ubiquitous.^{105–124} In the vast majority of cases, one stick-slip event is observed per unit cell of the substrate, even in cases where the atomic cell contains more than one species. Accounting for such phenomena in terms of energy dissipation, which is distributed among the tip, substrate, and cantilever, is an ongoing issue in the AFM community. The high-energy dissipation rates associated with AFM geometries in fact may be due to the creation of

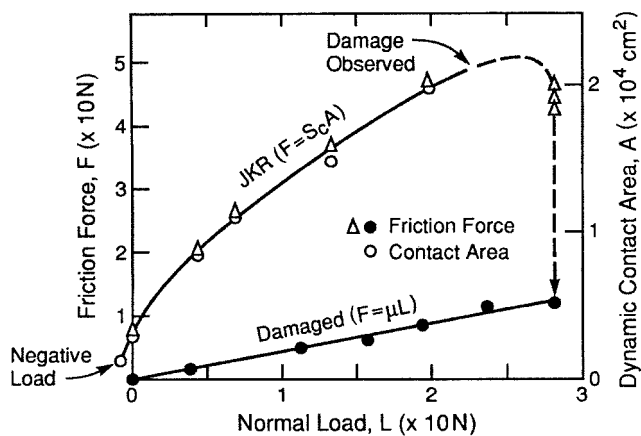


Fig. 4. The surface-forces apparatus has been employed for direct measurements of true contact area, friction, and normal load (Ref. 66).

point defects or atom transfer to and from the tip, or may be due to lattice vibration effects that are as yet unaccounted for.

AFM, as well as numerical simulations, have probed the frictional properties of model lubricant chain molecules attached to atomically uniform substrates. For example, it has been observed that the average frictional force of alkylsilane molecules containing two to eighteen carbon atoms adsorbed on silicon substrates decreases with chain length up to eight carbon atoms, and then remains relatively constant. Salméron and co-workers have proposed that the chain-length dependence arises from the interplay between packing energy of the monolayer film and local deformations in the film, since below eight carbon atom chain lengths, the molecules are relatively disordered. Energy-dissipation mechanisms to be considered in such systems must involve vibrations within individual molecules as well as the creation of kinks and Gauche defects (deformation of extended chains). Numerical simulation efforts by Harrison and co-workers are rapidly converging on a solution to the problem, investigating all of the chain lengths that have been experimentally probed.⁹² These and similar efforts hold great promise for revealing the wide range of energy-dissipative mechanisms in such systems, which are of intermediate complexity.

The surface forces apparatus (SFA) is another experimental probe that is closely identified with microscopic studies of friction.⁶⁶ It was invented nearly 40 years ago, and was adapted for friction measurements by Israelachvili in 1973. The apparatus takes advantage of the fact that the cleavage surface of mica is molecularly smooth, with atomic-step-free areas as great as 1 cm². When two mica surfaces are brought into contact, an asperity-free interface is thus formed. The traditional apparatus consists of two cleaved mica surfaces glued to crossed mica cylinders. The contact area and distance between mica surfaces is determined by means of optical-beam interferometry, with resolution on the order of 0.2 nm or better. The mica surfaces are mounted so they can be moved horizontally or vertically, and the normal and lateral (friction) forces are measured directly from a force-mapping spring. Although the SFA has occasionally been used for direct measurements of friction between two mica surfaces, its more routine use has involved lubricant layers that are squeezed between the contacting surfaces.

The SFA has been employed to study the dependence of friction on contact area (Fig. 4) and the dependence of fric-

tion on the crystalline orientation. As for the case of AFM measurements, static friction and slip-stick phenomena are routinely observed in the SFA geometry. Experimental determination of the structure of films trapped between the SFA's solid surfaces remains one of the most important goals of the nanotribology community. Current efforts to characterize the detailed atomic structure of films confined at an interface include combined synchrotron x-ray/surface-forces' apparatus methods.

The Quartz Crystal Microbalance is an instrument that operates on a time scale short enough to detect phonons, whose lifetimes in the best of cases are no longer than a few tens of nanoseconds. The QCM was employed for decades for microweighing and time standard purposes, and was adapted in the mid 1980s for sliding-friction measurements of adsorbed layers on metal surfaces.⁵⁶ By simultaneously measuring the shift in frequency and the broadening of the resonance (as evidenced by a decrease in the amplitude of vibration of the microbalance), the sliding friction of the layer with respect to the metal substrate can be deduced. The friction can be measured only if it is sufficiently low so as to result in significant sliding, which is accompanied by a measurable broadening of the resonance. For this reason, QCM measurements of sliding friction tend to be carried out on systems exhibiting very low friction, such as rare-gas solids adsorbed on noble metals. For the vast majority of other systems that exhibit higher friction (chemically bonded layers, etc.) the slippage of an adsorbed monolayer on the surface of the QCM is too small to produce a measurable broadening. In this case interfacial slippage or bond breaking can be detected by performing measurements on micron-sized particles, whose larger inertial masses can more readily overcome the stronger frictional forces.

In 1991, Krim and co-workers reported QCM measurements of the friction of krypton monolayers sliding on gold.⁵⁷ The data were successfully modeled though direct molecular dynamics simulation by Robbins and co-workers assuming that the friction was due to phonons excited in the adsorbed layers, and ultimately provided proof for the existence of phononic mechanisms of friction.⁵⁸ A surprising aspect of the excellent agreement between the numerical-simulation data and the experiments is that friction arising from electronic mechanisms was totally neglected. Such friction is related to the resistance felt by mobile electrons in a conducting material as they are dragged along by forces exerted by the opposing surface. Could the simulations have overestimated the friction slightly, masking electronic contributions? The answer is probably yes, since there is just enough uncertainty in the best estimates for corrugation levels of Au(111) substrates to allow for the presence of a moderate level of electronic friction to have been concealed. Indeed, measurements of nitrogen sliding on lead in its normal and superconducting state indicate that electronic contributions are non-negligible for the first adsorbed layer of atoms on conducting metallic substrates.

One of the more remarkable properties of the friction of the adsorbed layers studied so far is the frequent absence of static friction and the fact that both solid-liquid and solid-solid interfaces have been observed to be governed by the viscous-friction law, Eq. (1).⁶¹ The viscous-friction law also has been observed recently in "blow-off" experiments whereby films traveling many orders of magnitude slower than those characteristic of a QCM measurement failed to exhibit static friction.⁹⁹ While such observations are entirely

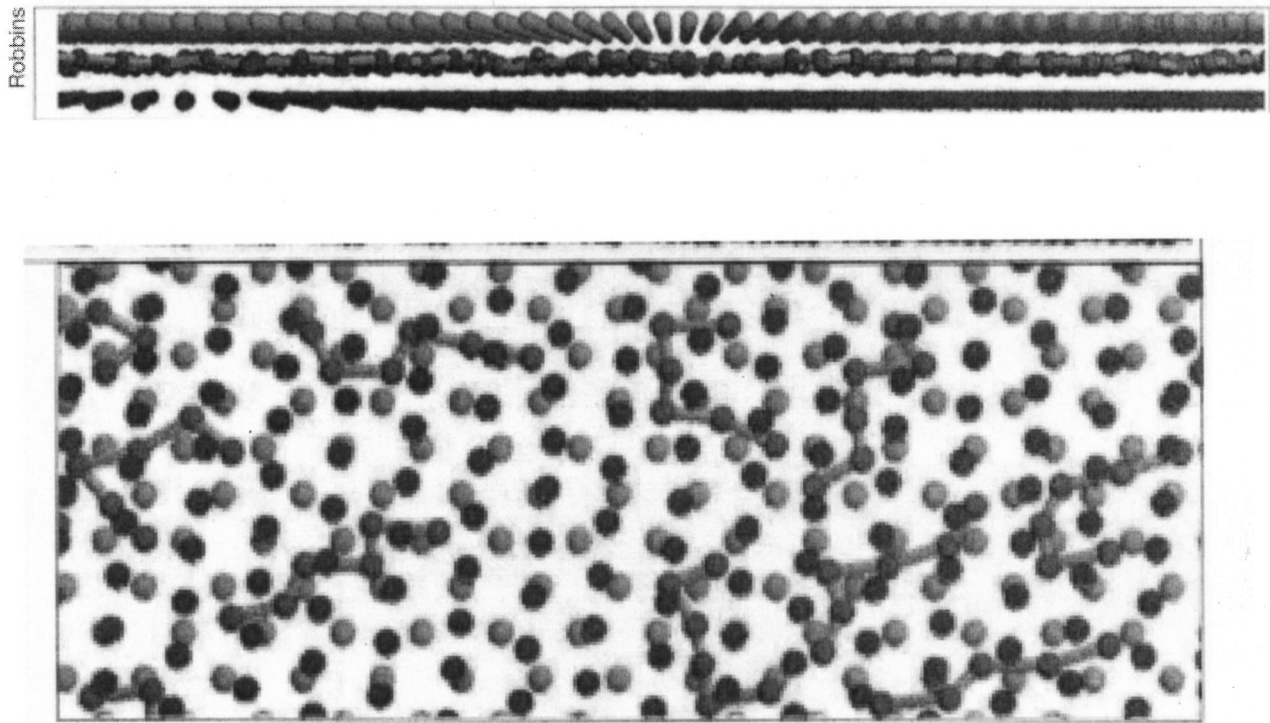


Fig. 5. Top and side view of contaminant molecules, which may lock two macroscopic surfaces together resulting in the occurrence of static friction (Ref. 114).

consistent with atomic-scale theories of friction at clean crystalline interfaces, they are unheard of in the macroscopic world. This gives rise to the obvious question of how fundamental dissipation mechanisms such as phononic and electronic effects are manifested in systems characterized by different length and time scales. Do they play a substantive role in wear-free friction at the macroscopic scale, as Tabor had suspected, or are they simply the primary energy-dissipation mechanisms in molecularly thin films adsorbed on open surfaces owing to the simplicity of the systems under study? These questions have yet to be answered. But a growing body of literature, particularly that focused on the role of commensurability effects in sliding friction, is helping to shed light on this issue.

The relative commensurability of the two surfaces in sliding contact has a profound influence on phononic contributions to friction, at least from a theoretical perspective. (Surfaces are in “commensurate” contact whenever their constituents are equally spaced and rotationally aligned.) For example, a transition from commensurate to incommensurate sliding conditions theoretically can reduce the sliding friction levels by over ten orders of magnitude.⁴² Experimental investigations of the dependence of friction on lattice commensurability routinely show dependence, but the variation is generally less than an order of magnitude.^{125–131} Another manifestation of phononic friction is the theoretical prediction that static friction should vanish for nearly every pair of clean surfaces that deform elastically. But one of the most common everyday experiences with friction at the macroscopic scale is the occurrence of static friction: The force to initiate motion (which itself is quite variable, depending for example on how long the two surfaces have been in contact) is virtually always larger than that required to keep an object in motion. A closely associated phenomenon is that of stick-

slip friction, whereby for certain sliding speeds, the velocity-weakening dependence of the transition from static to sliding friction leads to repetitive sticking and slipping at the interface, producing the all-too-familiar screeching noises associated with brakes.

The key to solving the mystery of static friction and stick-slip phenomena appears to lie buried in the atomic-scale structure of the myriad of contacts formed between the two sliding surfaces, and the nature of the molecules confined between them. The constantly changing nature of the interfacial geometry of the contact areas (even in cases where the contact area is constant) gives rise to friction coefficients and stick-slip event rates that are intrinsically variable. Moreover, the friction force at an individual asperity may or may not increase with applied load, depending on the structure of the contacting solids, and molecules confined within them.

The question remains as to why static friction can be so ubiquitous when theoretically two clean interfaces in sliding contact are not expected to exhibit it. The answer ultimately may prove to lie in “third-body” effects, whereby additional adsorbed molecules act to initially pin the interface (Fig. 5).¹¹⁴ Other issues that remain of particular interest include the following. (1) Understanding the chemical and tribochemical reactions that occur in a sliding contact owing to frictional-heating effects, and the energy-dissipation mechanisms associated with such contacts. (2) Characterization of the microstructural and mechanical properties of the contact regions between the sliding materials. (3) Merging and coordinating information gained on the atomic scale with that observed at the macroscopic scale. Much of the current information is fragmented, with linkages between individual experimental results yet to have been established. (4) Development of realistic interaction potentials for computer simulations of materials of interest to tribological applications. (5)

Development of realistic laboratory test set-ups that are both well-controlled and relevant to operating machinery. Given the recent increase of activity in these and related areas, there is increased optimism that further breakthroughs will be achieved in the coming decades in fundamental aspects of friction.

ACKNOWLEDGMENTS

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II. JOURNALS

Tribology Letters
Tribology Transactions
Wear

III. BOOKS

1. **Friction and Lubrication of Solids**, F.P. Bowden and D. Tabor, 2 Vols. (Oxford U.P., Oxford, 1950, 1964). (A) This is Bowden and Tabor's classic work, which pioneered the adhesive model of friction.
2. **Surface Effects in Adhesion, Friction, Wear and Lubrication**, D.H. Buckley (Elsevier, Amsterdam, 1981). (A) This text, well ahead of its time, marked the beginnings of the surface-science approach to studying friction. While many of the results have been updated, the basic premise that monolayers of adsorbates can alter friction remains intact.
3. **Contact Mechanics**, K.L. Johnson (Cambridge U.P., Cambridge, 1985). (A)
4. **Tribology: Friction and Wear of Engineering Materials**, I.M. Hutchings (CRC Press, Boca Raton, FL, 1992). (I)
5. **Friction, Wear, Lubrication: A Textbook in Tribology**, K.C. Ludema (CRC Press, Boca Raton, FL, 1996). (I) An excellent overview of the current state of macroscopic tribology, written with the student in mind.
6. **Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time**, D. Sobel (Walker and Company, New York, 1995). (E) A popular example of how advances in tribology are closely tied to applications.
7. **History of Tribology**, D. Dowson (Professional Engineering Publishing, London, 1998). (E) An extensive historical review of work in the area of friction and wear, dating back to prehistorical times.
8. **Sliding Friction: Physical Principles and Applications**, 2nd ed., B.N.J. Persson (Springer Verlag, Berlin, 2000). (A)

IV. EDITED COLLECTIONS/CONFERENCE PROCEEDINGS

9. **Friction: Selected Reprints, A project of the AAPT Committee on Resource Letters** (American Institute of Physics, New York, 1964). (A) A collection of reprints that represents the state-of-the-art on fundamentals of friction prior to 1964.
10. **New Materials Approaches to Tribology: Theory and Applications**, edited by L. Pope, L. Fehrenbacher, and W. Winer (MRS, Pittsburgh, 1989). (I)
11. **Fundamentals of Friction: Macroscopic and Microscopic Processes**, edited by I.L. Singer and H.M. Pollack (Kluwer, Dordrecht, 1992). (A) This conference was the first to include tribologists working at both macroscopic and microscopic scales: A landmark event in bringing together the two communities and opening communications between them.
12. **The Handbook of Micro/Nanotribology**, edited by B. Bhushan (CRC Press, Boca Raton, FL, 1999). (A)
13. **Physics of Sliding Friction**, edited by B.N.J. Persson and E. Tosatti (Kluwer, Dordrecht, 1996). (A)
14. **Workshop on Friction, Arching, Contact Dynamics**, edited by D.E. Wolf and P. Grassberger (HLRZ, Forschungszentrum Julich, Germany, 1996). (A) This conference proceedings includes works on granular phenomena, earthquakes, and a broader range of applications than normally treated in the standard tribology literature.
15. "Physical and Chemical Mechanisms of Tribology," edited by W.N. Unertl and M. Grunze, *Langmuir* **12** (19), 4481–4610 (1996). (A)

16. "Fundamentals of Friction," J. Krim, guest editor, *Bull. Mater. Res. Soc.* **23** (6), 20–51 (June 1998). (I) A set of articles spanning the range of micro to macro scale, with a focus on linking theoretical work in the area to current experimental results.
17. **NSF/AFOSR/ASME Workshop on Tribology Issues and Opportunities in MEMS**, edited by B. Bhushan (Kluwer Academic, Dordrecht, 1997). (A)
18. **Tribology on the 300th Anniversary of Amontons' Law**, edited by M.D. Drory and M.O. Robbins (MRS, Warrendale, 1999). (I)
19. **Fundamentals of Tribology and Bridging the Gap between the Macro and Micro/Nanoscales**, edited by B. Bhushan (Kluwer Academic, Dordrecht, 2001). (A)
20. "Progress in the Pursuit of the Fundamentals of Tribology," S.S. Perry, guest editor, *Tribol. Lett.* **10** (1-2), 1–132 (2001). (A) An excellent snapshot in time of the current state-of-the-art in fundamental aspects of tribology.

V. REVIEW ARTICLES

21. "Tribology: Origin and Future," H.P. Jost, *Wear* **136** (1), 1–17 (1990). (I) This work provides useful references on the economic impact of friction and wear.
22. "Progress in Nanotribology: Experimental Probes of Atomic Scale Friction," J. Krim, *Comments Condens. Matter Phys.* **17**, 263 (1995). (I)
23. "Scratching the Surface: Fundamental Investigations of Tribology with Atomic Force Microscopy," R.W. Carpick and M. Salmeron, *Chem. Rev.* **97** (4), 1163–1194 (1997). (I) This work should be considered required reading for those interested in entering the field of scanning-probe studies of friction.
24. "Friction at the Atomic Scale," J. Krim, *Sci. Am.* 74–80 (October 1996). (E) This work, at the popular-literature level, is an excellent introduction to atomic-scale friction, particularly how it differs from that observed at the macroscopic scale.
25. "Tribology—The Last 25 Years—A Personal View," D. Tabor, *Tribol. Int.* **28** (1), 7–10 (1995). (E) A personal commentary by an authority with fifty years of experience in the field.
26. "Nanotribology: Friction, Wear and Lubrication at the Atomic Scale," B. Bhushan, J.N. Israelachvili, and U. Landman, *Nature (London)* **374** (6523), 607–616 (1995). (I)
27. "Atomic-scale Issues in Tribology: Interfacial Junctions and Nano-elastohydrodynamics," U. Landman, W.D. Luedtke, and J.P. Gao, *Langmuir* **12**, 4514–4528 (1996). (A)
28. "Rubbing and Scrubbing," G. Hahner and N. Spencer, *Phys. Today* **51**, 22–27 (1998). (E)
29. "Soft Matter in a Tight Spot," S. Granick, *Phys. Today* **52** (7), 26–31 (July 1999). (E)
30. "Experimental and Theoretical Aspects of Modern Nanotribology," G.V. Dedkov, *Phys. Status Solidi A* **179** (1), 3–75 (2000). (A)
31. "Surface Science and the Atomic-Scale Origins of Friction: What Once Was Old is New Again," J. Krim, *Surface Science Special Millennium Volume 500, Frontiers in Surface and Interface Science*, edited by C.B. Duke (2002), p. 741. (E)

VI. JOURNAL ARTICLES

32. "De la Resistance Causee dans les Machines," G. Amontons, *Mem. de l'Academie Royale* A 275–282 (1699). (A)
- Contact Mechanics*
33. "Über die Berührung fester elastischer Körper," H. Hertz, *J. Agewandte Math.* **92-93**, 156–171 (1882). (A)
 34. "Contact of Nominally Flat Surfaces," J.A. Greenwood and J.B. Williams, *Proc. R. Soc. London, Ser. A* **295** (1442), 300 (1966). (A)
 35. "Microdeformation of Solids," N. Gane and F.P. Bowden, *J. Appl. Phys.* **39** (3), 1432 (1968). (A)
 36. "Surface Energy and the Contact of Elastic Solids," K.L. Johnson, K. Kendall, and A.D. Roberts, *Proc. R. Soc. London, Ser. A* **324** (1558), 301 (1971). (A)
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