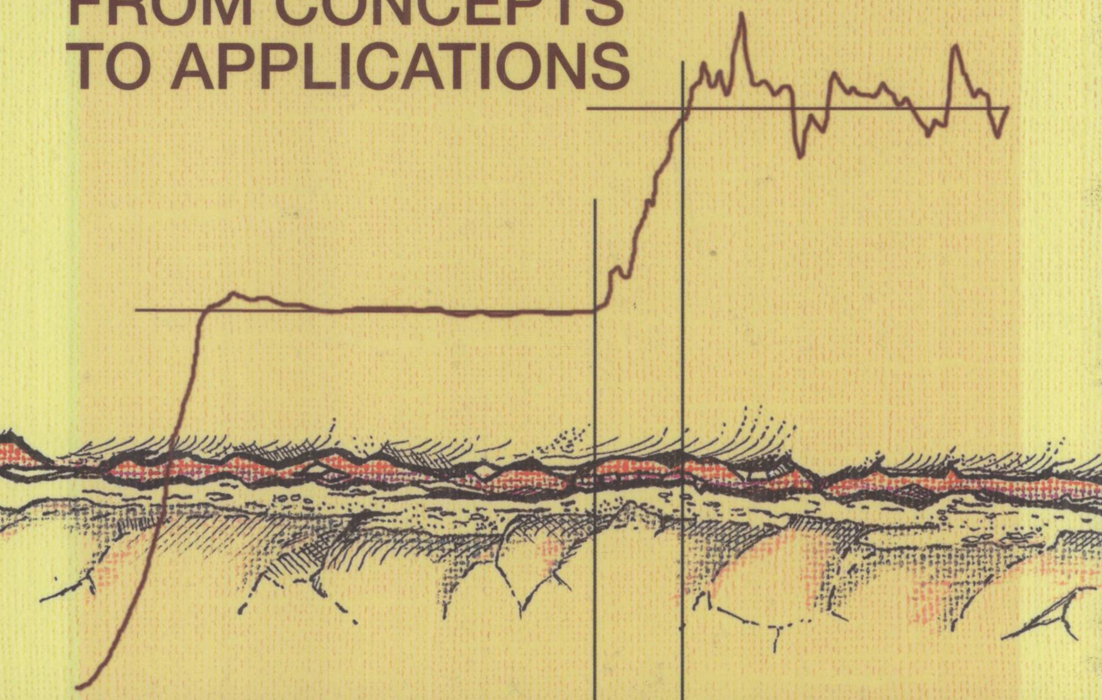
# Friction Science and Technology

## FROM CONCEPTS TO APPLICATIONS



SECOND EDITION

Peter J. Blau

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# Dedication

*This book is dedicated to the memory of my parents: to my father, a principled, hardworking man who valued ethics and personal responsibility, and had a wonderful sense of humor; and to my mother, a small woman with a big heart, who opened my eyes to the richness of music and art.*

*One researcher had an addiction*
*To seeking the causes of friction;*
*He'd often confide,*
*Whilst watching things slide,*
*That he suffered that mental affliction.*

# Foreword

The first edition appeared in late 1995. Since that time, there have been many new developments in our understanding of friction. Examples of these are new ASTM standards for friction measurement, laser dimpled surfaces for friction control, friction of nanocomposites and alloys for light-weight bearings, and most importantly, leading edge research on friction at the molecular scale—perhaps the fastest growing aspect of the field.

This book begins with a thorough development of the history of thought on the subject of friction, which puts the book in context. This history provides grounding for the main goal of this book, which is to address the mechanics, materials, and applications-oriented aspects of friction and friction technology. As a result, this book does a fine job of comprehensively covering the subject. Key topic areas are mechanics-based treatments of friction, including typical problems and equations for estimating the effects of friction in simple machines; the wide range of devices that have been crafted to measure the magnitude of friction, some designed to simulate the behavior of engineering tribosystems; modeling of static and kinetic friction; the effects of tribosystem variables such as load, speed, temperature, surface texture, and vibration on frictional behavior, the result of which demonstrates how the same materials can exhibit much different frictional behavior when the contact conditions are changed; and the response of different types of material combinations to frictional contact.

I think the discussion on the same materials exhibiting different frictional behavior under differing contact conditions is particularly beneficial as so often in the past engineers would look up a material's inherent coefficient of friction in some handbook, apply that to a design, with the result of total mystification that the resultant friction is much different.

Subsequent chapters deal with run-in processes, which I found interesting as the importance of this is particularly acute in the bearings used in laser targeting and high-resolution photoimaging devices. There is also a useful chapter on lubrication by gases, liquids, and solids.

There is also an interesting chapter on the solid friction of materials. It covers a wide variety of combinations such as leather, wood, stone, metals, a variety of alloys, metallic glasses, ceramics, polymers, carbon-/diamondlike materials, ice structures, just to name a few.

A unique feature is the inclusion in various chapters of numerous interesting and unusual examples of the application of friction science, proving that tribologists and tribological problems are truly indispensable and multidisciplinary. A few examples covered in the book that highlight the breath of these applications are friction problems in Olympic and other sports, coatings for icebreakers, interparticle friction (toners, pills, powders, etc.), cosmetics, starting a fire caveman style, joint replacement, reducing heat in dental root canal tools, the touch of piano keys, human skin friction, the drag of ships through the water, earthquakes, and the "bounce" in shampoo. This aspect of the book alone makes it an interesting read for both highly technical people as well as those with more than the usual curiosity for how things work.

**Dr. Robert M. Gresham**
*Director of Professional Development*
*Society of Tribologists and Lubrication Engineers*

# Preface

It is amazing that friction, a phenomenon that influences so many aspects of our daily lives, is so widely misunderstood. Even after centuries of study by bright and inquiring minds, friction continues to conceal its subtle origins, especially in practical engineering situations where surfaces are exposed to complex and changing environments. With the possible exception of rolling element bearings under thick-film lubrication, the prediction of the friction between materials in machinery is often based more on experience and experiments than on first-principles theory. The richness of friction science is revealed to those with the patience to dig deeper, and requires a willingness to surrender preconceived notions that may oversimplify physical reality.

Although there is a lot of new material in this second edition—particularly as regards engines and brakes—my essential writing philosophy has not changed. I wanted to take the reader on an intellectual journey that begins with common introductions to friction, in which friction coefficients are simply numbers to look up in a table, and travel to a new place, in which we question where those numbers came from, whether they actually apply to specific problems, and why things are not as simple as those watered-down explanations of friction we are taught in high school and introductory college physics might lead us to believe.

When I began to write the first edition more than 10 years ago, the word "tribology" was foreign to many people, even to some in science and engineering. And although the term remains obtuse to the general public, the advent of computer disk drives, microdevices, and nanotechnology has thrust friction science and tribology to the forefront. Designers must now confront the challenges of controlling interacting surfaces in relative motion at sizes far too small for the naked eye to see. Despite the current focus of popular science on nano things (think little and propose big ...), many macroscale challenges remain. These larger-scale challenges should not be ignored, and so they populate the pages of this second edition. I hope that the next generation of tribologists will be motivated to study friction problems across a broad spectrum of sizes, and not lose sight of the forest for the trees.

Almost every day I become aware of new and interesting studies and applications of friction science, and it was difficult to call an end to this project for fear of leaving something out. Yet, any treatise on science or engineering is at best a snapshot of the author's thinking at the time. I have learned a lot since completing the first edition of *Friction Science and Technology* and wish I could change a few things even before this second edition appears in print.

I am indebted to a number of individuals for encouraging and educating me in tribology. First, I would like to thank Dave Rigney, professor emeritus of the Ohio State University, for introducing me to the subject. Next, I want to thank many kind individuals who have expanded my perspective of the subject over the years: Bill Glaeser, Ken Ludema, David Tabor, Olof Vingsbo, Ward Winer, Ernie Rabinowicz, Marshal Peterson, Lew Ives, Bill Ruff, Vern Wedeven, Ray Bayer, Ken Budinski,

Doris Kuhlmann-Wilsdorf, Mike Ashby, Brian Briscoe, Koji Kato, Maurice Godet, Ali Erdemir, and many others.

Finally, many thanks to my wife, Evelyn, for tolerating my long hours of isolation on the iMac, and to Allison Shatkin of Taylor & Francis/CRC Press whose encouragement motivated me to set aside other writing projects and focus on this second edition.

**Peter J. Blau**
*Knoxville, Tennessee*

# Contents

# 1 Introduction

We, as a group of specialists, are familiar with the fact that the friction coefficient is just a convenience, describing a friction *system* and *not* a materials property.

**Dr. Ing. Geert Salomon,**
in the Introduction to *Mechanisms of Solid Friction* (1964), p. 4

Friction is a remarkable phenomenon. As pervasive as friction is in daily experience, there is still much to learn about its nature, how it changes under different circumstances, and how it can be predicted and controlled. Its effects on the behavior of machines and materials have been the source of study and contemplation for hundreds and even thousands of years, reaching back at least as far as Aristotle (384–322 BC).[1] In fact, it could be argued that the undocumented first use of a log or rounded rock to move a heavy object was an engineering solution to a prehistoric friction problem.

Great thinkers like Hero, da Vinci, Hooke, Newton, Euler, and Coulomb, all considered friction; however, a complete description of its fundamental causes and a single quantitative model—which is generally applicable to any frictional situation—remains elusive. The fact that so much learned effort has failed to uniquely discern the fundamental nature of friction might seem surprising at first, but as the reader will grow to appreciate, the complexities and interactive variables that influence frictional systems sometimes defy easy definition. A great deal is now known about friction in specific circumstances but not in the elusive *general case*, if indeed there is such a thing.

In recent years, there have been attempts to "bridge the gap" between friction studies at nanometer scales and the behavior of contacting bodies that operate at macroscales, millions of times larger. Partly as a consequence of those efforts, the definition of a "friction coefficient" has been extended far beyond classical approaches that concern macroscopic bodies rubbing together into realms that can only be investigated with electron microscopes or probes that are far too small for an unaided human eye to see. This book reviews, at various levels of detail, conceptual approaches to understanding, modeling, testing, and applying concepts of solid friction to engineering systems, both lubricated and nonlubricated. It will be shown that the appropriate size scale and investigative tools must be selected on a case-by-case basis.

According to *The Oxford English Dictionary* (1989 edition), the word *friction* derives from the Latin verb *fricare*, which means to rub. Interestingly, the word *tribology*, which encompasses not only friction but also lubrication and wear, derives from the Greek word τριβοσ (tribos), which also means rubbing, but the use of this term is much more recent. It can be traced back to a suggestion of C. G. Hardie of Magdalen College, and it emerged around 1965 when H. P. Jost, chairman of a group of British lubrication engineers, attempted to promulgate its use more widely.

In fact, four national tribology centers were established in England a few years after the Jost report revealed the major impact that friction, lubrication, and wear had on the industry and economy of the United Kingdom. The word friction has a number of less-used relatives including the following:

1. Fricase, *v.*—to subject to friction
2. Fricate, *v.*—to rub (one body on another)
3. Frication, *n.*—the action of chafing or rubbing (the body) with the hands; the action of rubbing the surface on one body against that of another; friction
4. Fricative, *adj.*—sounded by friction, as certain musical instruments (also relates to the sounds produced by the breath as it passes between two of the mouth organs)
5. Fricatory, *adj.*—that rubs or "rubs down" (Latin *fricator*, one who rubs down)
6. Frictile, *adj.*—obtained by friction

Interestingly, the word *fricatrice*, which was used in the 1600s and derives from the same Latin origin, is defined as *a lewd woman*.

Frictional phenomena exact a high cost on society. It has lifesaving positive benefits, such as braking moving vehicles to avoid property damage, injury, or death. But it also has powerful negative effects, such as robbing machines of energy that could otherwise produce useful work. Studies[2,3] have estimated that millions of barrels of oil or their equivalent could be saved by lowering the friction in engines. The precise cost is very difficult to determine, but in 1985, Rabinowicz[4] estimated the annual cost of resources wasted at interfaces in the United States. Table 1.1 indicates that tens of billions of dollars are expended each year due to both friction and wear. Considering the vast number of additional situations not listed in Table 1.1, it is clear that the understanding and control of friction has great economic consequences. Although frictional losses have been estimated to account for about 6% of the U.S. gross national product, there have unfortunately been no comprehensive updates of the decades-old studies concerning the costs of friction.

**TABLE 1.1**
**Resources Wasted at Interfaces (ca. 1985)**

| Interface | Dollars Dissipated/Year |
|---|---|
| Piston ring/cylinder—internal combustion engines | $20 billion |
| Human body—seat in clothing | $20 billion |
| Tires on road surfaces | $10 billion |
| Tool/workpiece in metal cutting | $10 billion |
| Drill/hole in oil drilling | $10 billion |
| Head/medium in magnetic recording | $10 billion |

*Source*: Adapted from Rabinowicz, E. in *Tribology and Mechanics of Magnetic Storage Systems*, ASME, New York, 1986, 1–23.

## 1.1 WORLD OF FRICTIONAL PHENOMENA: GREAT AND SMALL

There are many manifestations of friction. Gemant's book[5] describes a host of phenomena, all related to friction. He stated, with remarkable foresight, more than 50 years ago:

> Indeed, it is hard to imagine any process, whether in nature or in industry, that is entirely free of friction. It appears that only processes of the largest and the smallest dimensions, namely astronomical and interatomic motions, can be described without the involvement of friction. However, even this situation might change with a better understanding of the universe on the one hand and of the elementary particles in the atom on the other.

Gemant's book discusses sound waves, viscosity of solutions, viscosity of structures, flow of fluids, lubrication, plastic flow in solids, internal friction in solids, material damping capacity, friction between solids, and other phenomena. Internal friction in metals and alloys has been used to deduce the fundamental processes of diffusion, time-dependent viscoelastic behavior, creep, and vibration damping capacity. The friction of tiny whiskers within a surrounding matrix has been strongly linked to establishing the mechanical properties of advanced ceramic composite materials[6] (see Figure 1.1). Friction occurs in other forms as well: rolling friction, frictional fluid drag in pipes, friction within powder and soil layers, friction in geological formations and glaciers, and aerodynamic friction. Astrophysicists have even used the term *tidal friction* to describe the torque generated between the convective core and the radiative envelope in early stars.[7]

Introductions to friction come early in life; for example, children are taught the frictional benefits of rubbing one's hands together to stay warm. Primitive tribesmen and wilderness campers learned how to create a fire by rubbing wood together. According to Dudley Winn Smith,[8] who claims to hold the world record for starting a fire with a "fire bow," with the proper technique and sufficient practice it is possible to start a fire by this method in under a minute. In Smith's own words, when describing his winning performance in a fire starting competition in Kansas City:

> ... When the starter said "Go" I drew my bow back and forth with long complete strokes. In about three seconds a little pile of smoking black charcoal issued from the pit. Then I stopped rubbing, picked up both the board and the tinder and blew directly onto the smoking pile, which immediately turned into a red ember. In 7-1/5 seconds after I drew the first stroke the tinder burst into flame. Lucky for me, the three timers all agreed ...

Smith recommended using a 29 in. long bow with an octagonally shaped fire drill, approximately 9 in. long and $\frac{9}{16}$ in. in major diameter. His upper pivot, hard but not prone to produce excessive friction, was made from the glass knob of a coffee percolator embedded in a wood block. The $\frac{3}{8}$ in. thick fireboard contains a "fire pit," a hole where the tip of the drill rests, and that is crossed by a U-shaped notch surrounded by tinder. Supposedly, the best woods for the drill and fireboard were said to be yucca and American elm, and red cedar shavings are best for tinder.

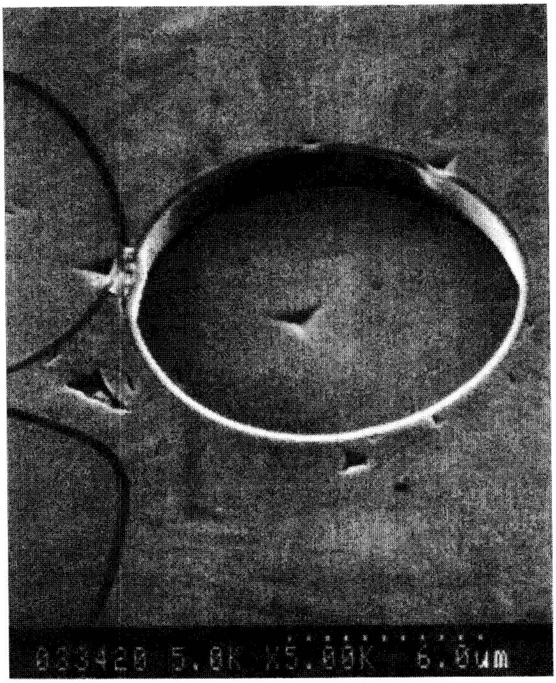


**FIGURE 1.1** The friction forces between a fiber and the matrix material in a ceramic composite are estimated from experiments that push the fiber into the matrix with a nanoindentation device. In the center of the ceramic fiber is the impression left by the tip of the three-sided pyramidal indenter used for pushing. (Scanning electron micrograph, courtesy of L. Riester, Oak Ridge National Laboratory.)

As subsequent chapters will discuss, frictional phenomena occur on and within the human body. For example, unpublished studies funded by shampoo and conditioner manufacturers have addressed the friction of hair on hair. The bamboo-type structure of human hair results in directional sliding properties. Friction of hair sliding over hair "against the grain" is much higher than "with the grain." The kinetic friction of hair under various humidity levels affects the "bounce" in styled hair. As will be further discussed in Chapter 9, the friction of skin lubricated by soaps, colorants, and lotions has significant economic implications for cosmetics manufacturers who are expanding their product lines to target specific ethnic groups.

The development of acceptable replacement materials for ivory piano keys is partly affected by the friction of skin on the key material. Studies by Dinc et al.,[9] partly funded by Steinway, Inc., used an apparatus that simulated a piano keyboard to study the friction of skin on polymethylmethacrylate, nylon 66, polytetrafluoroethylene, polycarbonate, and phenolic. It was not only friction, but also the feel of the material that determined its desirability for the application. Sometimes the friction was relatively low, but the tactile sensation was unpleasant to the subject. Increasing humidity and increasing perspiration tended to raise the friction coefficient and