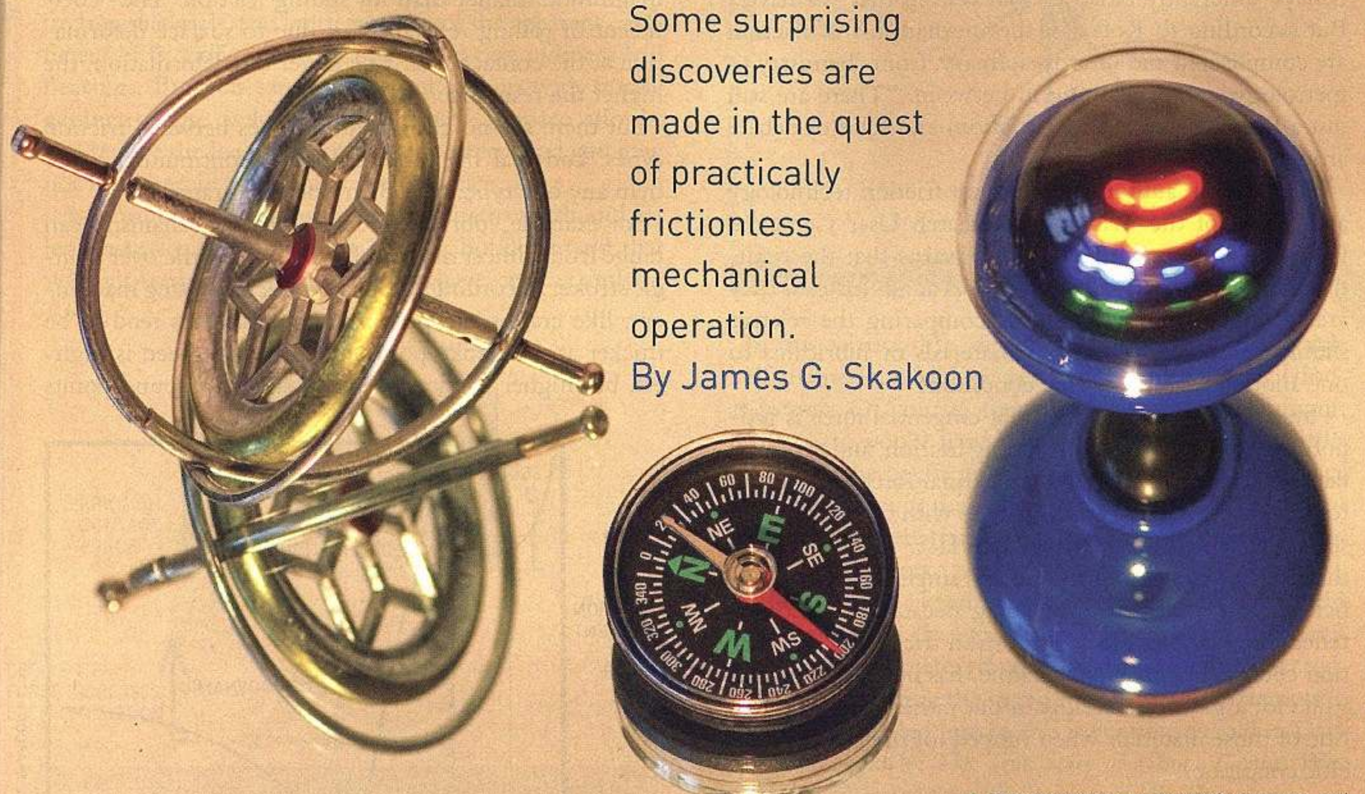
# there's the rub

Some surprising discoveries are made in the quest of practically frictionless mechanical operation.

By James G. Skakoon




▲ This toy gyroscope, magnetic compass, and spinning top have neither lubricants, special materials, nor rolling elements, yet display low friction techniques in their designs.

Michael French, Emeritus Professor of Engineering at Lancaster University in England, has written extensively on mechanical design and advocates a set of practical guidelines for design engineers. He writes in his annotated list of design principles, "Prefer pivots to slides, and flexures to either." This might just embed everything mechanical designers need to know about friction.

I asked French where that phrase came from, and he said, "As far as I know, it is original with me—in that form." He came up with it "mainly by taking thought," he explained in distinctively British words, then added, "Engineers know things like that, but they don't ever bother to say them."

Engineers have plenty of technology for controlling friction and wear, including naturally lubricious materials, high-performance lubricants, and rolling element bearings. But where friction is concerned, good mechanical design starts with guidelines like French's.

Because friction and wear are poorly understood, the best you can do is manage friction so it doesn't affect the performance of your machine. Follow a few simple guidelines, and your designs will be more robust against the unknowns and undesirables of friction. The goal is to reduce frictional forces to be insignificant, regardless of their variation, compared to other forces in a device. Otherwise, expect unpredictable results.

Leading tribologists admit that friction and wear are not fully understood. When asked what we really know about friction, Michael Kotzalas, chair of ASME's Tribology Division and author of a book on bearing analysis, said "Not a lot, actually. We know that materials

James G. Skakoon operates Vertex Technology LLC, an engineering firm in St. Paul, Minn. He is the author of several books, most recently *The Elements of Mechanical Design*, published in 2008 by ASME Press.

behave differently based on the testing that we have." But according to Kotzalas, the mechanisms of friction are complicated and interdisciplinary, from chemistry to metrology, and everything in between. "There are still just a lot of theories (about friction) and a lot of debate around them."

Peter J. Blau, author of a book on friction technology and leader of the Tribology Research User Center at Oak Ridge National Laboratory, warns that the traditional "laws of friction" are not laws at all. Instead, they are "a convenience that allows comparing the relative sliding resistance for various materials or lubricants to one another under the same conditions."

Physics students are taught that tangential force is proportional to normal force in sliding friction, and that contact area does not affect the tangential force. According to Blau, however, "Friction changes with time, reflecting sliding-induced changes to the interface." Blau explained that the traditional single static and single dynamic coefficients of friction are misleading because they do not reflect fluctuations and transitions in friction. "The friction coefficient, static or dynamic, has no single, unique value for a given material pair, but rather is a characteristic of those materials when rubbed together under specific conditions."

## CLASSES OF FRICTION

Friction classifications useful for mechanical design vary, but here's one way to do it:

Dry
Boundary
Hydrostatic
Hydrodynamic
Rolling

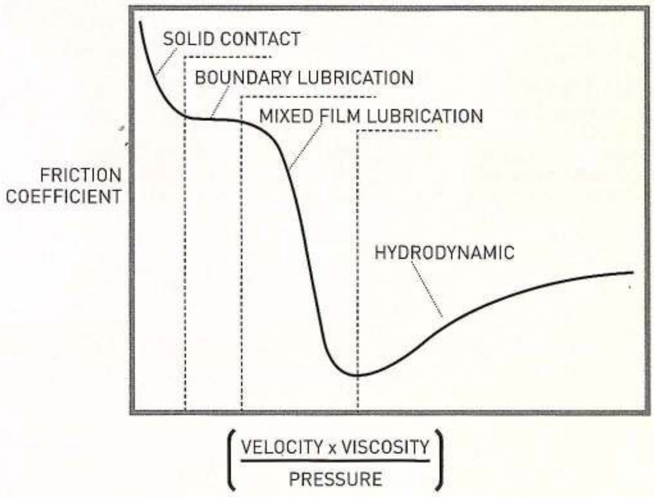
Dry means no lubricant, of course, which, arguably, never exists. Boundary friction is common in lightly lubricated, slow-moving devices, and is often what we think of as everyday lubrication: The base materials still contact each other, but the effects are mitigated by the lubricant's presence. Hydrostatic and hydrodynamic friction both have a fluid film of lubricant that separates the solid surfaces, the first created by externally applied fluid pressure, the second by viscous action.

Tribologists break these classifications further into subsets, and also include elastohydrodynamic friction, which accounts for deformation of the solid surfaces.

In rolling friction, exhibited in rolling element bearings, there is still resistance to motion, albeit orders of magnitude smaller than for sliding friction. The "coefficient of rolling resistance" is due to surface deformation at the contact area: The larger the deformation, the higher the resistance.

But there are no clear dividing lines between friction types, and real machines exhibit a continuum, rather than any one type, over their operating range.

For example, lubricated reciprocating mechanisms can range from almost dry to fully hydrodynamic over a single stroke. According to Blau, "In reciprocating machinery, like cranks and piston assemblies, films tend to be thicker at midstroke positions when the speed is highest, but higher friction occurs at the turnaround points




▲ Stribeck curves relate load, diameter, relative velocity, and fluid viscosity for lubricated journal bearings.

where the film thickness is reduced, letting materials come into intimate contact."

In Blau's view, for lubricated friction, much is embodied in a relationship called the Stribeck curve. "It relates the friction of a bushing to the load, diameter, relative velocity, and fluid viscosity." Blau said that the basics of the Stribeck curve are a good starting point to understand lubricated friction problems.

## THE STARTING LINE

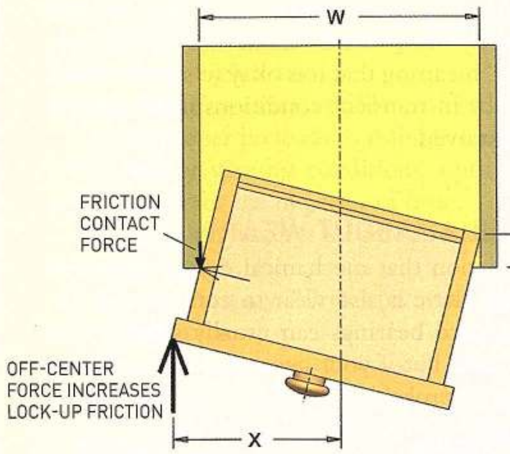
But managing friction starts first with the mechanical design schemes selected for your machine. Least preferred, according to French, are slides. This means, in part, sliding friction, but more accurately, linear motion.

Mechanical engineers often use straight line linkages rather than linearly guided systems, but why? Because linear slides don't work very well. They require lots of space, generate high loads, and often stick or jam.

Consider the all-too-familiar sticky bureau drawer. Whether or not the drawer locks up depends on the length-to-width ratio *(L/W)*, the ratio of length to load position *(L/X)*, and the coefficient of friction, $\mu$.

Anti-friction measures such as linear ball bearings, low-friction materials, and lubricants reduce the apparent coefficient of friction—dramatically, in the case of linear ball bearings. But you can also prevent lockup with simple geometry. Use as long a "wheelbase" as space affords, and reduce the load arm, preferably to zero, and you may not need heroic component performance.

A common rule of thumb for length-to-width and for length-to-load arm is at least 1.5 to 1, but don't trust that without testing it. Also, you must have contact only at




Sticky bureau drawers are too short and too wide. They lock up if pushed off center.

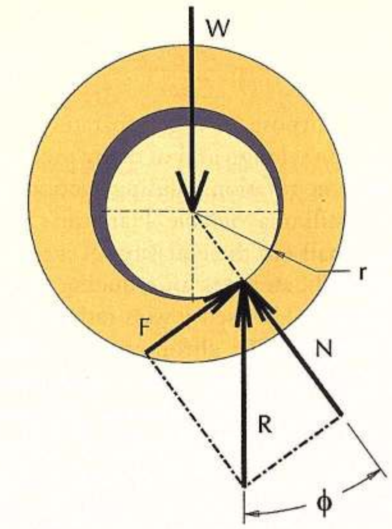
the ends and not in the middle of the moving component, which would only reduce the effective wheelbase. So relieve the middle section in solid parts, or use two end-mounted bearings.

## TURNING RADIUS

The retired president for bearings at the Timken Company, Robert Leibensperger, wrote in a 2003 article for *Mechanical Engineering* magazine that the axle, bearing, and wheel combination, and not the wheel alone, is the most significant invention in human history. The wheel exchanges rolling for sliding friction, but combining it with an axle and journal dramatically reduces frictional torque in man-made machines. Why? Because:

$$M = R \times r \times \sin\phi = F \times r$$

where $M$ is the moment to turn the axle, $r$ the radius of the axle, and $R$ and $F$ the reaction forces due to the bearing load. The accompanying figure shows the relationship among parameters, including load $W$ and normal force $N$.



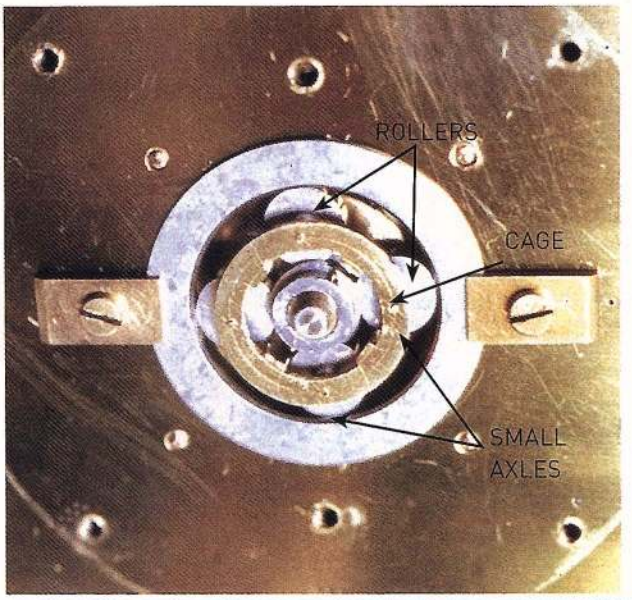

BEER AND JOHNSTON, *VECTOR MECHANICS FOR ENGINEERS, STATICS AND DYNAMICS, 5TH EDITION*, 1988

The forces on a simple journal bearing.

In this relationship, designers should treasure the axle half-diameter, $r$. Make it zero, and you have no frictional torque. Of course, then the bearing would support no load, so you'll have to compromise at least a little. Although the coefficient of friction governs $\phi$, you have little control over that. Tops, toy gyroscopes, and compasses put this relationship to good use, as do many precision instruments.

History offers a keen example. John Harrison, an 18th-century English clockmaker and creator of the first navigational chronometers for determining longitude, is credited with inventing the caged roller bearing. Attempts to reduce friction led him to this invention, as told in Dava Sobel's *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time.*

Bearings like Harrison's have rolling rather than sliding friction—unless the rollers or balls touch each other,




WILLIAM J. H. ANDREWES, *THE QUEST FOR LONGITUDE*, CAMBRIDGE, MA: COLLECTION OF HISTORICAL SCIENTIFIC INSTRUMENTS, 1996.

John Harrison's caged roller bearing, invented to reduce friction in the first successful marine chronometer. The innovation lies in the cage's miniature axles.

which defeats the purpose. A cage separates the rolling elements in Harrison's design and in many modern bearings as well. But some rotational sliding friction between cage and rollers is still unavoidable. Harrison's miniature axles make for a small *r* in the equation.

The power of small diameters for reducing friction was apparent to Harrison. He used jewels rather than roller bearings in his later, smaller chronometers. Even without rolling elements, they were quite sufficient at reducing friction, largely because of their small diameter.

The descriptive equation for a lubricated journal bearing must account for the fluid mechanics of the lubricant. Nonetheless, the proportionality of torque to diameter remains. It's a little more complicated, though, because where the bearing operates on the Stribeck curve also depends on bearing diameter.

## ROLLING RIGHT ALONG

But plain journal bearings often are not up to the task of low friction and low wear with high loads, which is where rolling element bearings enter the picture.

Which rolling element bearing is best for which use always bears repeating. "Ball (bearings) are lower load," said Kotzalas, who is also chief engineer of product design for bearings at the Timken Company. "You don't go up into a roller bearing until you need higher load-carrying ability." But ball bearings endure limited axial thrust, and cylindrical roller bearings endure even less.

"Tapered roller bearings are used when you have high thrust loads with radial loads, Kotzalas said, and added, "Needle bearings are used more where space is a limitation." Needle bearings are common in slow or intermittent motion for smooth, trouble-free function.

Spherical bearings are actually just roller or ball bearings for which one raceway is a spherical surface. "It self-aligns," said Kotzalas, but with some compromises to friction and load performance, and to heat generation. A rotating drum housing for which the bearing locations are not accurately aligned is a typical example.

But there are some surprising watch-outs. According to Kotzalas, "Any rolling bearing that has light loads and very high speeds is not desirable. That has caused lots of burn-up issues in the past." Rolling element bearings, it turns out, like to have some minimum load or preload, which helps the elements to track and roll on the raceways properly.

Most effective for reducing friction are flexures, even if they're often overlooked. French said, "Flexures have the advantages of no friction, no maintenance, no lubrication, but are often excluded by the limited travel available." The lack of friction means that flexure-defined motion is smooth, predictable, and reliable.

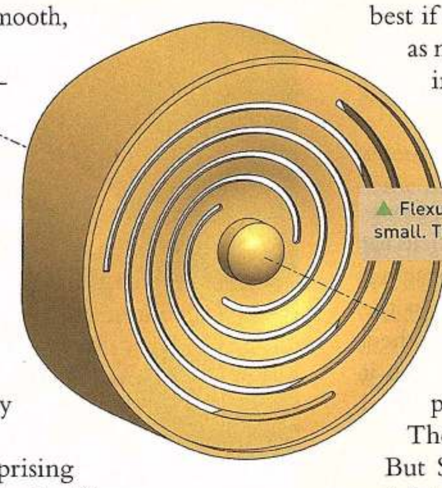
You might also consider more complex geometry for the contacting surfaces to improve performance in sliding, journal, roller, and ball bearings. "That's exactly what we did with our fuel efficient line," Timken's Kotzalas said. "You can design a profile (for a roller) to operate with the least torque under the majority of your conditions," he explained. But outside those conditions, at higher loads for example, the profile "can deform and bring in more contact area to carry the load." On French's list, this is "make the critical case the cruise case," meaning that it is okay to sacrifice friction performance in transient conditions if the general condition is improved.

## WHAT ABOUT WEAR?

It's not just friction that mechanical design engineers need to manage; there is also wear to consider. Manufacturers of standard bearings can usually supply wear and reliability data, but if your geometry or conditions are unusual, you'll probably need your own test results. Nonetheless, there are a few useful guidelines.

"High friction does not always equate to high wear," Blau said, which might be a surprise to design engineers. He also said that, generally, self-mated metals don't fare as well as dissimilar metals for friction and wear.

The same is true for plastics, where, generally, it is also best if at least one material is naturally lubricious, such as nylon, acetal, some polyesters, and PTFE. According to Zan Smith, a retired staff engineer with the plastics resin supplier Ticona, the crystalline materials—of which acetal, nylon, and polyester are examples—offer the best performance for friction and wear, but additives are commonly used for improving performance. "The principle additives are PTFE and silicone oils. These can reduce friction and wear," Smith said.



▲ Flexures are completely frictionless, and are useful when travel is small. This triple spiral configuration has smooth linear motion.

But Smith, whose expertise includes plastic gears, is quick to warn designers about friction and wear in plastics. "Some combinations have real good wear performance, but high friction," meaning again that friction and wear do not equate. "Friction and wear are not material properties; they are system properties. So many test protocols, such as thrust washer tests, will give one result, but actual systems will have different results," Smith said.

So here is what we know about friction in mechanical design:

—Friction force is NOT proportional to load, NOT independent of area, and NOT independent of speed.

—Friction coefficients from tables represent specific conditions. Your results may vary.

—High friction and high wear do not always equate.

And this is what we can do to manage friction:

—Make friction forces insignificant compared to other forces.

—Maximize the length of linearly guided components.

—Reduce the load arm length in linear motion assemblies.

—Always prefer rotary over linear motion.

—Minimize axle diameters for naturally low-friction torques.

—Use rolling element bearings for drastically lower friction with high loads.

—Avoid sliding contact of like materials.

—Apply proper preloads to rolling element bearings.

—In widely varying conditions, optimize frictional performance for the majority of time.

—Design with flexures for zero friction, long life, and low maintenance.

Or you can just say, "Prefer pivots to slides, and flexures to either." ■

## For Further Reading


Andrewes, William J. H. *The Quest for Longitude*, Cambridge, MA: Collection of Historical Scientific Instruments, 1996.

Beer, Ferdinand P. and E. Russell Johnston, Jr. *Vector Mechanics for Engineers, Statics and Dynamics*, McGraw-Hill, 1988: p. 342.

Blau, Peter J. *Friction Science and Technology: From Concepts to Applications, Second Edition*, CRC, 2008.

French, Michael. *Conceptual Design for Engineers, Third Edition*, Springer-Verlag, 1999.

Ganti, Sastry. "Predicting Lock-up in Slide Bearings," *Machine Design*, Penton Media, Jan. 10, 2002: p. 94.

Harris, Tedric A. and Michael N. Kotzalas. *Rolling Bearing Analysis, Fifth Edition*, CRC, 2006.

Leibensperger, Robert. "The Conquest of Friction." *Mechanical Engineering*, New York: American Society of Mechanical Engineers, November 2003: pp. 46-49.

Sobel, Dava. *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*. New York: Penguin Group, 1996: pp. 104-109.