How do you solve a problem like friction?

I wish I could say I worked out a rough answer from first principles, as Feynman might have done.

I learned to respect friction, as a phenomenon with many nuances, when I was a graduate student. One day, while teaching a problem session in elementary mechanics, I unwisely invented a new problem to illustrate some principles. Suppose you roll a bowling ball on a smooth, rigid floor, giving it an initial velocity V and no initial spin. Given the coefficients of static and sliding friction between the ball and floor, work out, first, how far the ball goes before it is rolling and no longer sliding, and, second, how far it will go before it comes to rest. Neglect wind resistance.

The first part, I quickly demonstrated, is easy. Assuming the force of sliding friction is independent of velocity, then this friction causes the ball's speed to decrease linearly with time. Meanwhile, that same friction makes it begin rolling with an angular speed that increases linearly with time. Matching the two expressions gives the moment when the ball stops sliding; it happens quickly for a tiny ball, and very slowly for a large ball (close to the moment when it comes to rest).

But on moving confidently to the second part of the problem, I suddenly realized that I was in big trouble and that the problem I'd posed has no sensible solution. Once the sliding has stopped, friction — at least as described by the familiar empirical friction laws — no longer figures in the problem and cannot do any work to slow the ball, which should therefore keep rolling forever. I wish I could say I reported this to the class, and then worked out a rough answer from first principles, as someone like Richard Feynman might have done. Instead, I mumbled incoherently for two or three minutes, flummoxed, until the class ended — and then promised to work it all out for the next class.

Sadly, I couldn't do that either. But by then I could at least explain why — because the problem was in reality far harder than I'd anticipated and the phenomenon of friction far more subtle than I'd imagined. The ball would slow down only through processes such as the dissipation of energy through the deformation of both the floor and the ball, and lots of other happenings (which I could only dimly imagine) at the molecular scale in the contact between those surfaces.

Today there's still no 'first principles' solution to my simple problem. But the science of the micro-physics behind friction is happily making great strides, especially through advanced experiments, so that it is possible to talk sensibly about the micro-processes that really underpin what we so loosely call 'friction'. An impressive example is a recent series of experiments exploring the micro-details of static and sliding friction, performed by Oded Ben-David, Shmuel Rubinstein and Jay Fineberg (*Nature* **463,** 76–79; 2010).

Their idea was to use a sheet of laser light to make very accurate measurements of the interface between two small polymer blocks as they made one block slide over the other. Each block was about 200 mm long and 6 mm wide. Cleverly, they aimed the laser so that it hit the interface between the blocks at an angle greater than that for total internal reflection for detached portions of the interface. Hence, the transmitted light at any point along the interface, which they could measure using a fast camera, gives a measure of the total interface detachment at that point.

The experiments show, not surprisingly, that what appears at the macro-level to be an abrupt shift from sticking to sliding, involves something vastly more complex at the molecular scale. In the experiments, they initiated sliding by pushing on one block with a gradually increasing force. The laser measurements reveal the intermittent creation and movement of 'detachment fronts', well before the final onset of macroscopic sliding, which travel along the interface at speeds up to the Rayleigh-wave speed of 1,280 $m\ s^{-1}$. Each front starts at the block's trailing edge and travels forward into the interface before eventually terminating. These fronts act effectively to compress the block and increase the average shear stress along the interface. An awful lot of interesting dynamics and structural change take place before sliding ever begins.

The actual transition to macro-motion takes place in only a few microseconds as a crack-like front passes along the entire interface, greatly reducing the contact between the surfaces. This starts what the researchers call 'phase II' of the process. Immediately after the rupture, the experiments show that the surfaces slide very freely and at high speed. The duration of this phase seems always to be about 60 ms — possibly, the authors suggest, because this is the time required for the dissipation of the considerable heat generated in the initial transition to sliding, which probably involves widespread plastic deformation of irregularities on the polymer surfaces (capable of producing temperatures as high as 1,000 °C).

After this 60 ms of free sliding, the surfaces cool sufficiently and regain shear strength, in a kind of phase transition, at which point the block slides (in phase III of the motion) at a speed ten times slower. In these particular experiments, this phase lasts about 350 ms, before the block stops. An equally fascinating process then commences, as the two blocks begin 're-healing' their physical contacts, and an 'ageing' process begins. This point marks the gradual strengthening of contacts, with the contact area growing according to a power law for short times and then logarithmically later.

That, in crude terms, is what seems to lie behind just one short stick–slip cycle, and it's certainly much more interesting and dynamically complex than one might naively expect.

I wish I'd known some of this back when I was a graduate student. Presumably, for a ball rolling on a wooden floor, the floor must deform locally around a zone of contact between the ball and floor surfaces. Irregularities in both surfaces must drive an erratic interaction between the surfaces that is surely more complex than that studied by Ben-David *et al.*

In any event, these experiments make me feel a little less stupid when I recall standing, confused, in front of my class. The experiment taught me to think twice before inventing problems off the cuff, in the belief they should be trivial. But I also learned that it's good not to be too cautious, because in your mistakes you may learn a lot — including how to deal more gracefully with your own ignorance. ❐

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