How Did Friction Get So "Smart"?

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Imagine a block of plastic on a smooth wooden horizontal plane (Fig. 1a). Is there any frictional force acting on the block? Certainly not in any horizontal direction. If there were such a force, it would cause the block to accelerate in the particular horizontal direction that this frictional force was acting. Since the block remains at rest, there is no frictional force. Now tilt the wooden plane an angle θ_1(Fig. 1b). Suppose the block remains at the same location on the plane; it does not slide. There must be a frictional force acting on the block in the direction along the plane and to the right. Tilt the plane in the other direction an angle θ_2 (Fig. 1c) and again the block remains at rest along the plane. There must be a frictional force acting, this time to the left. If the plane is returned to its original horizontal position, the friction disappears.

How did the friction "know" to change direction when we changed the plane's angle from θ_1 to θ_2? How did it "know" to get larger as θ_1 was made larger? Why did it disappear when the plane was returned to its horizontal position?

Consider a large crate sitting on a horizontal flat surface (Fig. 2). Suppose I attempt to move it by exerting a small horizontal push F. To no one's surprise, the crate doesn't budge! That must mean, if we are to believe Newton's second law, that there exists a frictional force F acting from the surface that is exactly equal to but opposite in direction from my applied force F. If this force weren't present, the crate would certainly have moved (accelerated) when I gave it the push. Since it didn't, the sum of the horizontal forces must be zero. Suppose I push harder, and it still doesn't budge. This friction must be so "smart" that it increases exactly the right amount and in exactly the right direction so that the resultant forces remain zero.

In all these cases friction has acted in the ap-

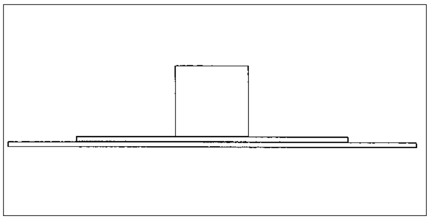

Fig. 1a.

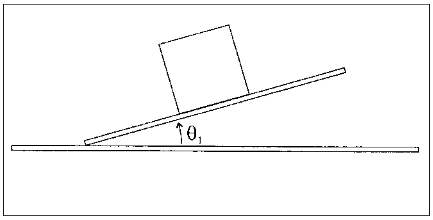

Fig. 1b.

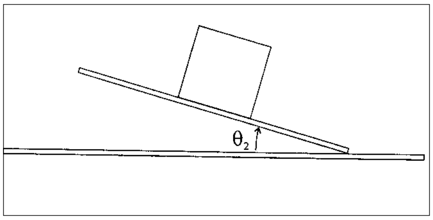

Fig. 1c.

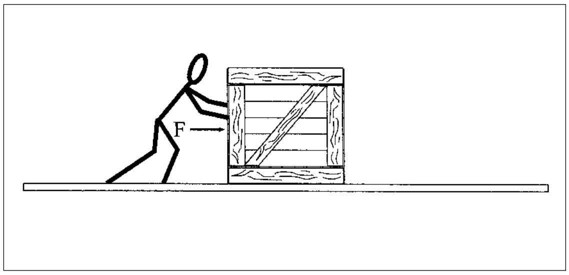

Fig. 2.

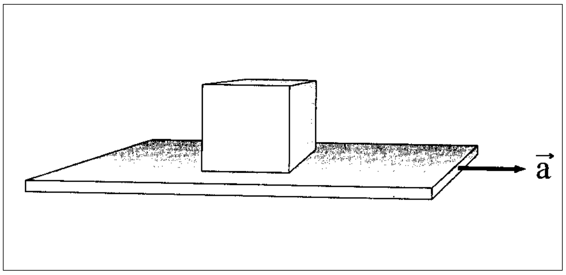

Fig. 3.

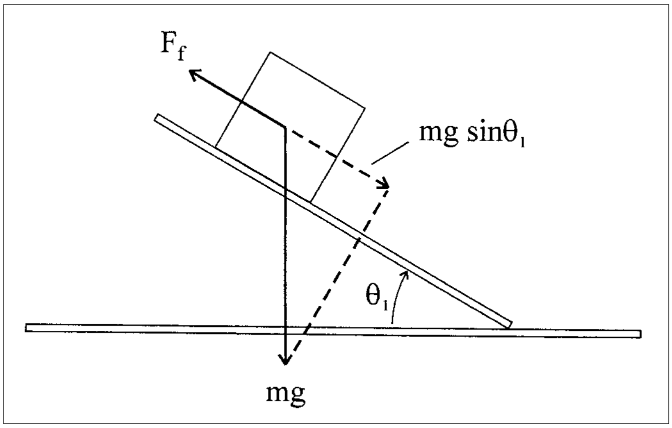

Fig. 4.

propriate direction. Does it always? Imagine that I put our plastic block on the horizontal plane, but now I accelerate *the plane* (Fig. 3). Friction "knows" to act in the same direction as the acceleration and cause the block to accelerate along with the plane. There was no horizontal friction before we accelerated the plane. How did it "know" it was supposed to appear, and how did it "know" in which direction to act?

Try describing these simple demonstrations and asking your students these questions. Have the students think about them for homework, discuss them in small groups, and then in class. As whimsical as an anthropomorphic explanation may be, it certainly does not help us understand these interesting physical phenomena. The explanation, while simple, is usually not discussed in the standard texts or in the teaching literature.

Friction is certainly a complicated phenomenon when examined quantum mechanically at the atomic scale. It depends on the nature and composition of the two surfaces, contamination on the surfaces, humidity, etc., but regardless of these messy details, the fundamental basis of this force is the atomic bonds between the atoms on the two adjacent surfaces. Presumably these bonds could be calculated quite precisely, but for our qualitative purposes, we can use a very simple classical model. This model does correctly represent the nature of the atomic bonds that is essential for this discussion, so we are not begging the question.

A Model

Imagine the bonds between the atoms on the opposing surfaces to be rubber bands—short pieces of elastic material connecting an atom on the plane with an atom on the block. This means there are trillions and trillions of elastic connections between the two planes. Also imagine that these "bands" can be broken with a sufficient force, but that they can also easily and rapidly reconnect as long as the surfaces are in close proximity.

It is the tension in these microscopic elastic "bands" (chemical bonds) that is responsible for the friction. That's all there is to it, nothing more! Consider our first example, the block at rest on a horizontal plane. The bands between the atoms on the plane and those on the block are connected in a totally random way, so the vector sum of all these microscopic forces is zero. After all, if you place one plane of atoms on another flat plane of atoms and connect them with microscopic rubber bands, there is no preferred horizontal direction and therefore no net force from all the microscopic tension.*

Let's examine what happens when the plane is tilted to some angle θ_1 (Fig. 4). Now there **is** a net force along the plane, $mg \sin\theta_1$, and so the block accelerates down the plane. But wait, we observed that the block did *not* accelerate; we said it stayed motionless, at rest on the plane. But that observation was wrong! It did move; *it must move*; we didn't look carefully enough. It moved just enough for the chemical bonds to elongate in one unique direction, stretching like elastic bands. And as they stretch, these bonds create the frictional force on the moving block in the opposite direction to the motion (displacement). This is exactly what happens when we stretch a rubber band. The band exerts a force equal and opposite to the force that produced the "stretch."

The essential point that is usually omitted from the discussion of "static" friction is that *the block moves*, albeit a microscopic distance, before friction comes into play and stops the motion. Without this motion there would be no friction. The displacement creates the unique directions for the frictional force to "operate." It is the "brains" of our "smart" frictional force.

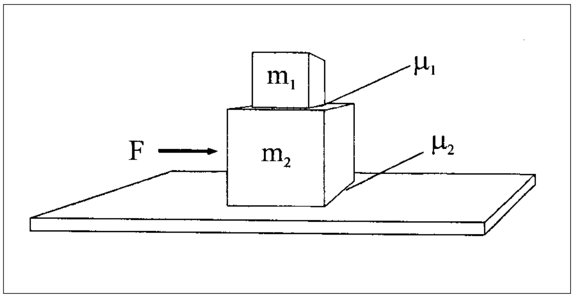

Fig. 5.

Armed with this model we can explain the other experiments. Consider the situation in Fig. 2. The crate *did* move when I pushed it. With a decent optical interferometer, we could even measure its displacement. The more I push, the greater the microscopic displacement, the greater the frictional force. If I succeed in achieving macroscopic acceleration of the crate, I will have broken the atomic bonds. Now we picture the bands being broken and reconnected very rapidly. This creates a frictional force on the crate that opposes its macroscopic motion. Note that it is the *motion* that gives friction its directions, its "orders."

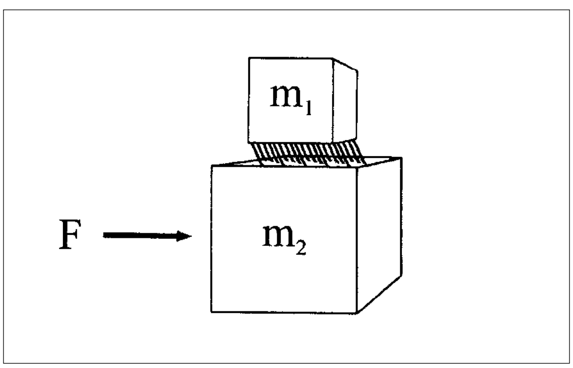

Fig. 6.

The rubber-band model also explains the frictional force on *both* surfaces. One mechanical system difficult for students to analyze is shown in Fig. 5. Usually they understand the frictional force on m_1 due to the contact plane with m_2 but forget that the same force, though acting in the opposite direction, affects m_2. If we redraw the interface between m_1 and m_2 (Fig. 6), it will be more obvious that the bands produce two forces, one on each surface. It also shows the proper directions for each force.

It certainly would help if students could actually see this microscopic displacement, but measuring it requires delicate and expensive optical instruments. Such instruments are clearly beyond the budgets of most high schools. Nevertheless, this model can easily be visualized by the beginning student and even constructed in some oversimplified form.

So friction isn't so "smart" after all! It is nothing more than the manifestation of stretched chemical bonds between adjacent atoms on two surfaces in close proximity, which can be visualized as atomic-sized rubber bands. Simple, but don't forget the stretch—it moves, that's essential.

Footnote

*What about the normal force on the block? Clearly this model cannot explain this force, since one must consider short-range repulsive interactions between the atoms. We are only considering attractive atomic interactions.