If I slowly raise a heavy book one meter up in the air, I do positive work. This work corresponds to an energy transfer. I lose chemical food energy that is consumed by my muscles to lift the book upward. Energy is gained by the book-Earth system in the form of gravitational potential energy that is stored in the gravitational field. But what happens if I slowly lower the book back down by one meter to its original location? The book-Earth system loses all the energy it gained and returns to its starting configuration. I have done negative work this time. But my muscles do not regain their original chemical energy! Where did the lost energy go?

There are losses in my muscles that internally generate thermal energy. If I repeatedly lower sacks of grain slowly from one level to another, I will break into a sweat. As a simple model of this dissipation into thermal energy, consider a box of mass $m$ that is pushed up and then slides back down a rough plane inclined at angle $\theta$ to the horizontal. Let the coefficient of kinetic friction between the box and ramp be $\mu$. A free-body diagram is sketched in Fig. 1 for the case of the box sliding down. Suppose the box slides with a small constant speed $v$. Then the forces must balance perpendicular to the incline so that $N = mg \cos \theta$, and parallel to the incline so that the frictional force $f$ is equal to

$$f = \mu mg \cos \theta = \mu mg \sin \theta, \quad (1)$$

which simplifies to the familiar result

$$\mu = \tan \theta. \quad (2)$$

Next suppose the box slides up the ramp at constant speed $v$ because of an externally applied force $F$, as shown in Fig. 2. Balancing forces again gives $N = mg \cos \theta$ perpendicular to the incline. But now the components parallel to the incline imply

$$F = mg \sin \theta + \mu mg \cos \theta. \quad (3)$$

Substituting the coefficient $\mu$ from Eq. (2) into (3), we find

$$F = 2mg \sin \theta = 2f, \quad (4)$$

where the last equality comes from Eq. (1). Such a factor of 2 is reminiscent of problems that involve what Sciamanda has termed "mandated dissipation." Not all of the work done by the applied force ends up as gravitational potential energy of the box-Earth system. Only half of it does; the other half ends up as thermal energy of the box and ramp. When the box slides down the ramp, an equal amount of thermal energy is again generated.

This model is a mechanical analog of what happens in our bodies. Anytime I use my muscles, I generate thermal energy internally. Even holding a chair stationary in the air is tiring because of the twitching of muscle fibers, as if I were continuously raising and lowering the chair slightly. Considering the human body to be a machine, there are internal mechanisms involving ATP, sweat glands, and the like that will be reconfigured when I lower a heavy weight with my arms.

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**References**

5. In contrast, consider C. Mungan, “The satellite derotator,” *Phys. Teach.* 40, 368–372 (Sept. 2002), in which rotational kinetic energy and angular momentum are simultaneously conserved.

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**Fig. 1.** Free-body diagram for a box sliding down a ramp at constant speed $v$, where $N$ is the normal force, $f = \mu N$ is kinetic friction, and $g = 9.8 \text{ N/kg}$ is Earth’s surface gravitational field.

**Fig. 2.** Free-body diagram when the box is pushed up the same ramp at constant speed by an applied force $F$. 

However if I give my body time to cool back off, the effect is that gravitational potential energy has been converted into thermal energy of the environment (in addition to a loss of a bit of food energy to reset my internal cellular machinery). Similar ideas can explain where the lost mechanical energy goes when a spinning figure skater extends her arms outward or a bug walks radially away from the center of a freely rotating turntable.