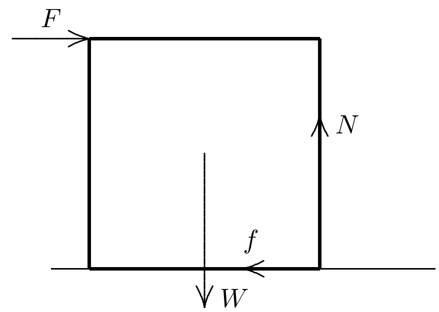
33.

We examine the box when it is about to tip. Since it will rotate about the lower right edge, that is where the normal force of the floor is exerted. This force is labeled N on the diagram to the right. The force of friction is denoted by f, the applied force by F, and the force of gravity by W. Note that the force of gravity is applied at the center of the box. When the minimum force is applied the box does not accelerate, so the sum of the horizontal force components vanishes: $F - f = 0$, the sum of the vertical force components vanishes: $N - W = 0$, and the sum of the torques vanishes: $FL - WL/2 = 0$. Here L is the length of a side of the box and the origin was chosen to be at the lower right edge.



(a) From the torque equation, we find

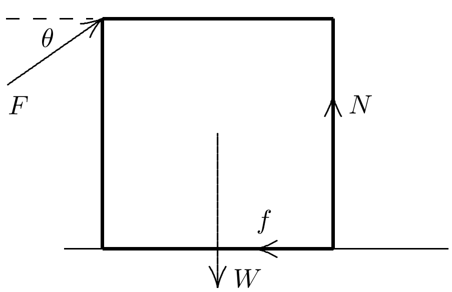
$$F = \frac{W}{2} = \frac{890\,\text{N}}{2} = 445\ \text{N}\ .$$

(b) The coefficient of static friction must be large enough that the box does not slip. The box is on the verge of slipping if $\mu_s = f/N$. According to the equations of equilibrium $N = W = 890\,\text{N}$ and $f = F = 445\,\text{N}$, so

$$\mu_s = \frac{445\,\text{N}}{890\,\text{N}} = 0.50\ .$$

(c) The box can be rolled with a smaller applied force if the force points upward as well as to the right. Let θ be the angle the force makes with the horizontal. The torque equation then becomes $FL\cos\theta + FL\sin\theta - WL/2 = 0$, with the solution

$$F = \frac{W}{2(\cos\theta + \sin\theta)}\ .$$



We want $\cos\theta + \sin\theta$ to have the largest possible value. This occurs if $\theta = 45^\circ$, a result we can prove by setting the derivative of $\cos\theta + \sin\theta$ equal to zero and solving for θ. The minimum force needed is

$$F = \frac{W}{4\cos 45^\circ} = \frac{890\,\text{N}}{4\cos 45^\circ} = 315\,\text{N}\ .$$