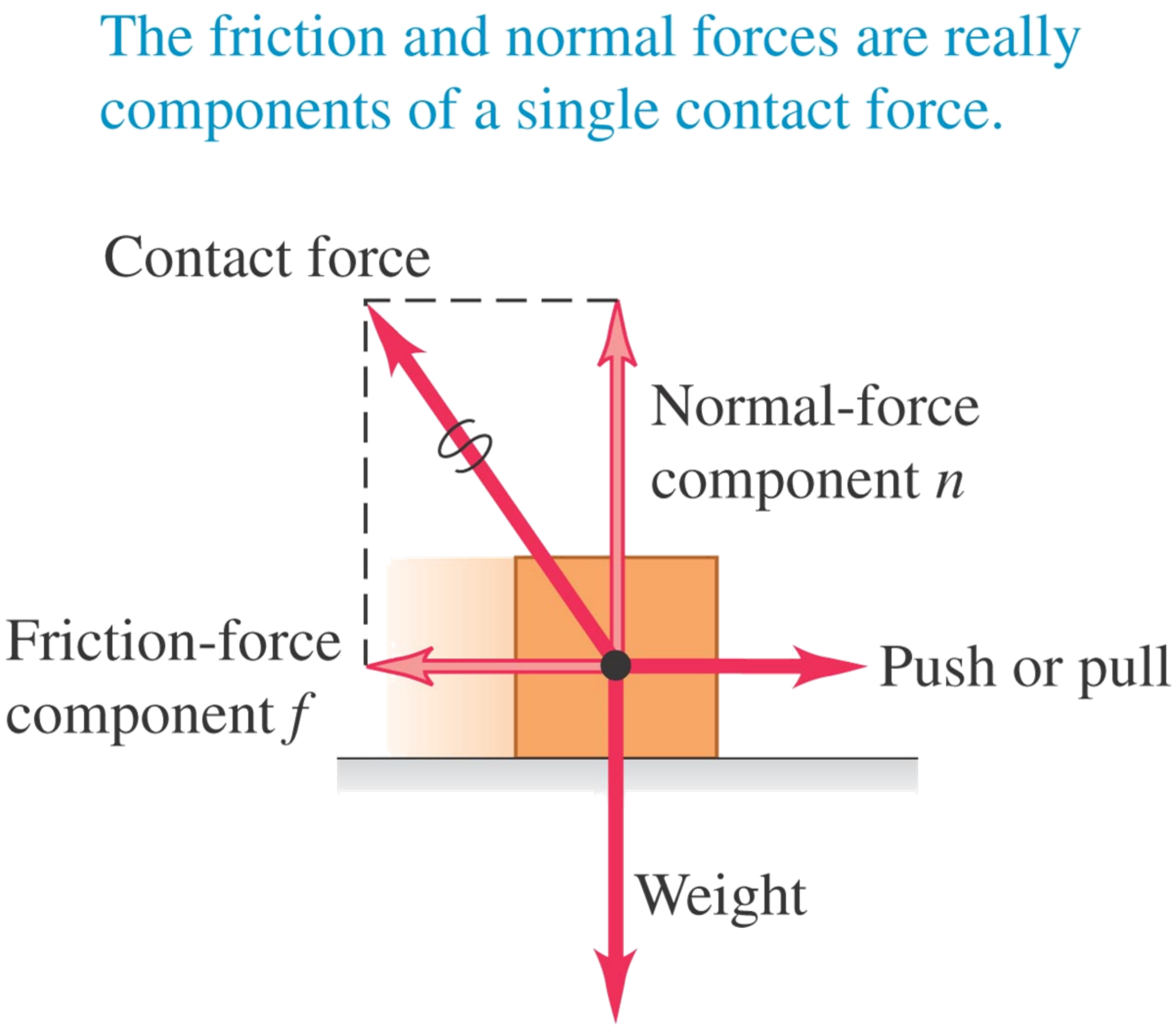
Imagine life without friction.

Frictional Forces



Types of Frictional Forces

kinetic friction

$$f_{\mathrm{k}} = \mu_{\mathrm{k}} n$$

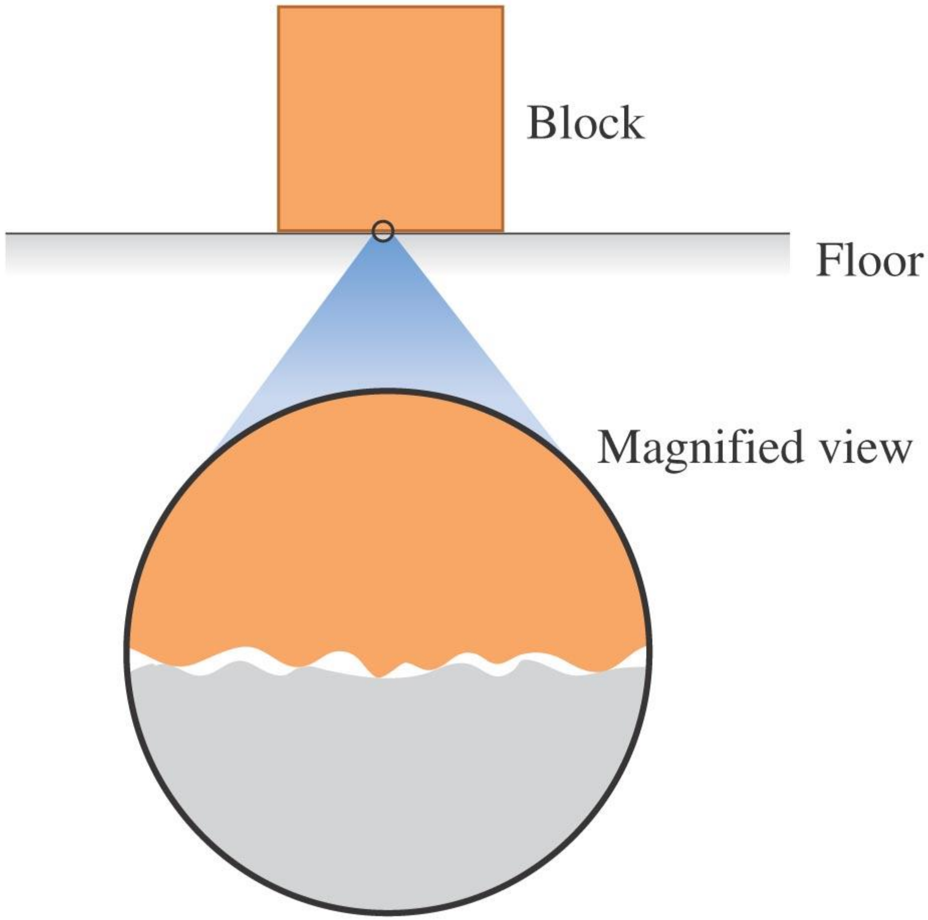
aka “slipping” friction

static friction

$$f_{\mathrm{s}} \leq \mu_{\mathrm{s}} n$$

aka “sticking” friction

Types of Frictional Forces

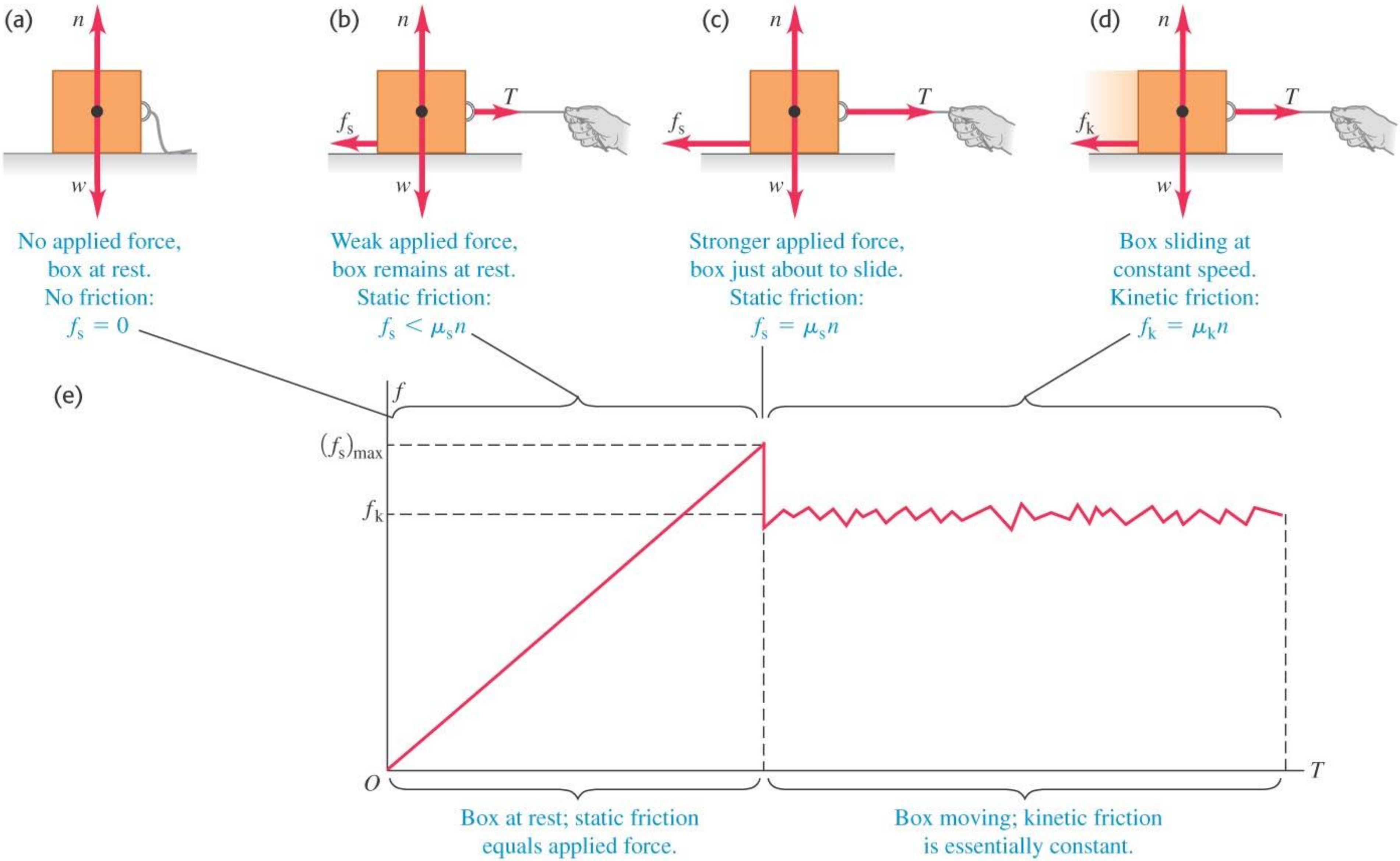


On a microscopic level, even smooth surfaces are rough; they tend to catch and cling.

Coefficient of Friction μ

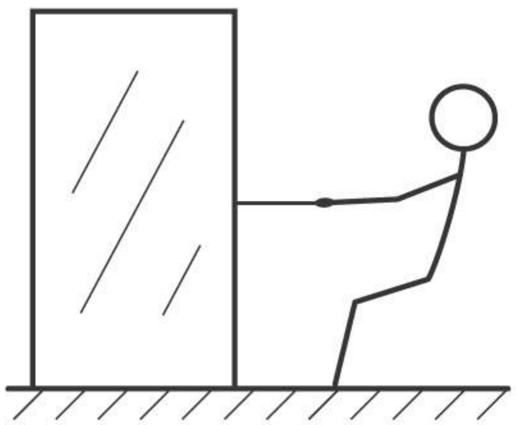
Materials	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Brass on steel	0.51	0.44
Zinc on cast iron	0.85	0.21
Copper on cast iron	1.05	0.29
Glass on glass	0.94	0.40
Copper on glass	0.68	0.53
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Rubber on concrete (dry)	1.0	0.8
Rubber on concrete (wet)	0.30	0.25

Static and Kinetic Friction



Friction in horizontal motion

You are trying to move a 500-N crate across a level floor. To start the crate moving, you have to pull with a 230-N horizontal force. Once the crate "breaks loose" and starts to move, you can keep it moving at constant velocity with only 200 N. What are the coefficients of static and kinetic friction?

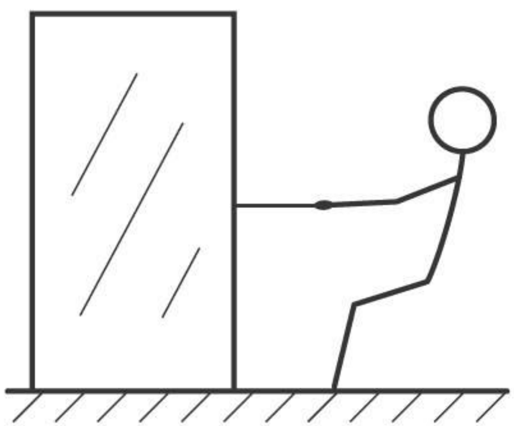


Friction in horizontal motion

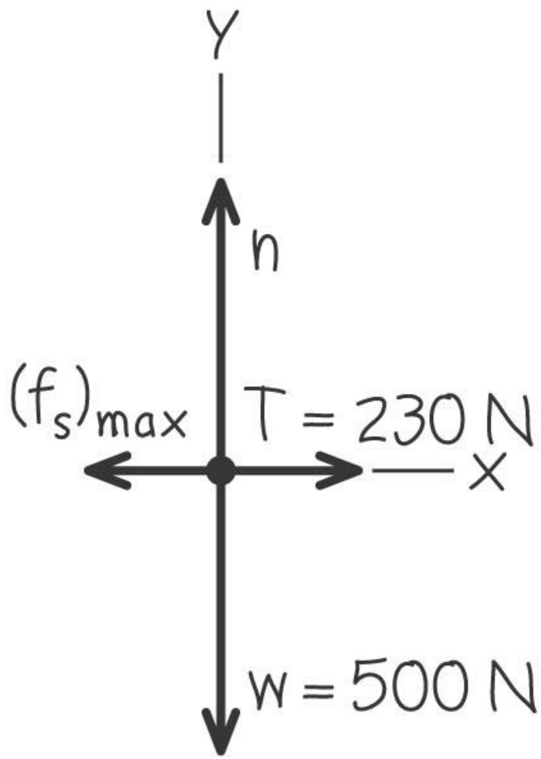
(a) Pulling a crate

answer:

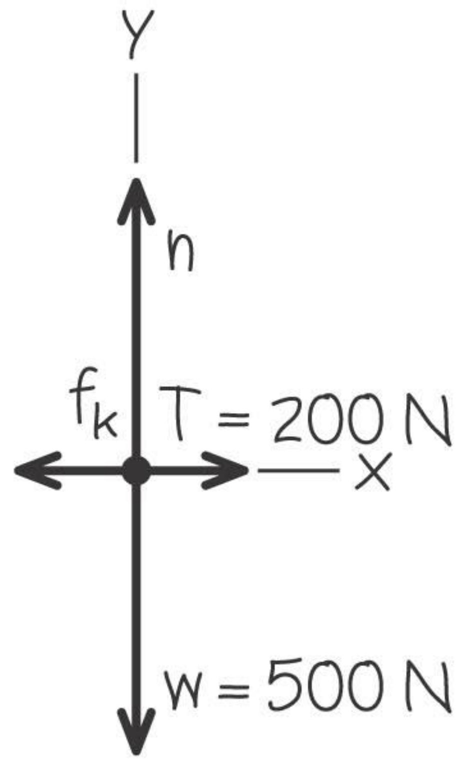
μ_s = 0.46
μ_k = 0.40



(b) Free-body diagram for crate just before it starts to move

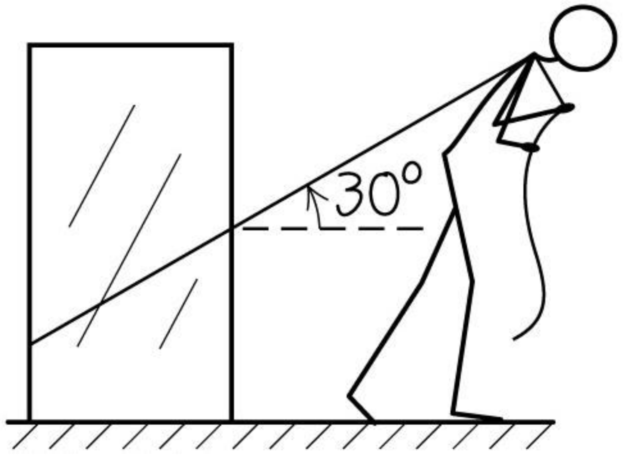


(c) Free-body diagram for crate moving at constant speed



Minimizing Kinetic Friction

In the previous example, suppose you try to move the crate by tying a rope around it and pulling upward on the rope at an angle of 30° above the horizontal. How hard do you have to pull to keep the crate moving with constant velocity? Is this easier or harder than pulling horizontally? Assume w = 500 N and μ_k = 0.40.

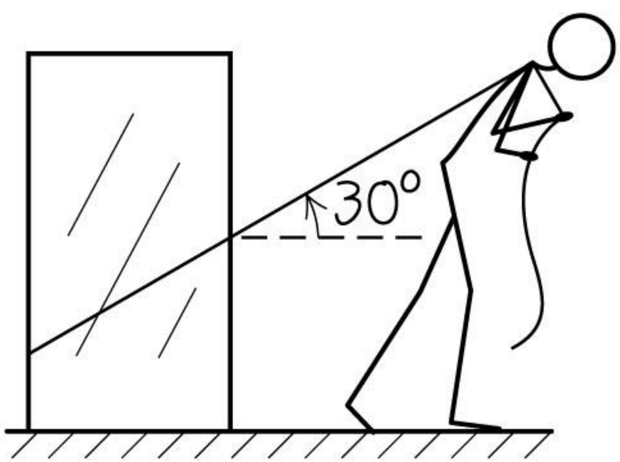


Minimizing Kinetic Friction

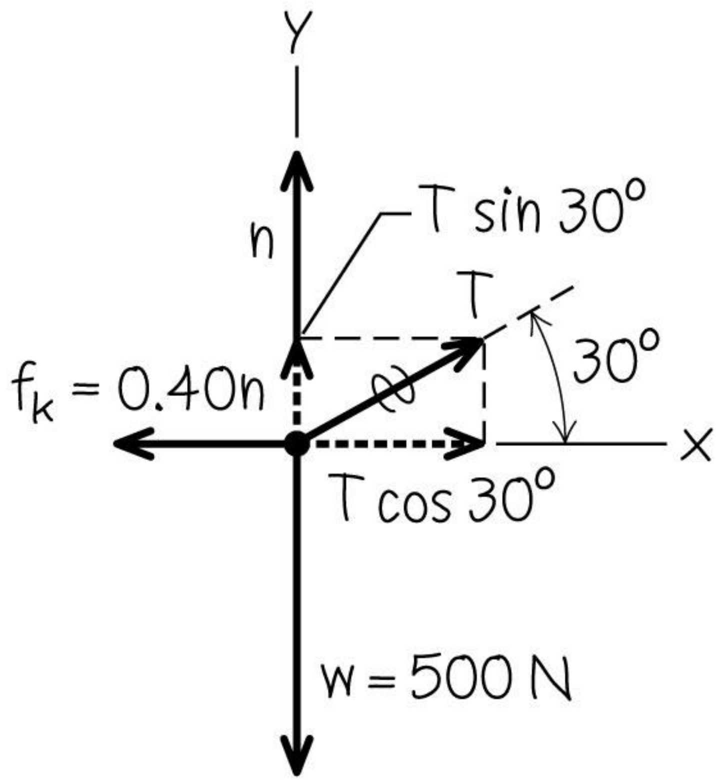
answer:

$\boxed{T = 188\text{ N}}$

(a) Pulling a crate at an angle



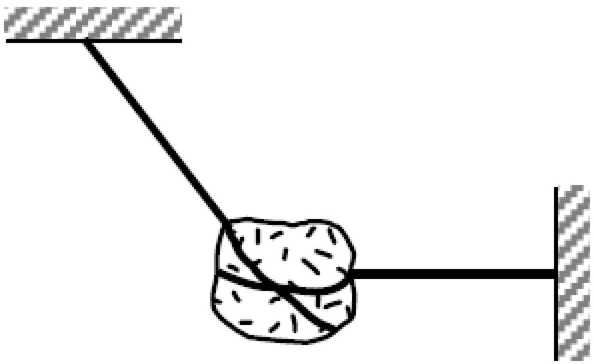
(b) Free-body diagram for moving crate

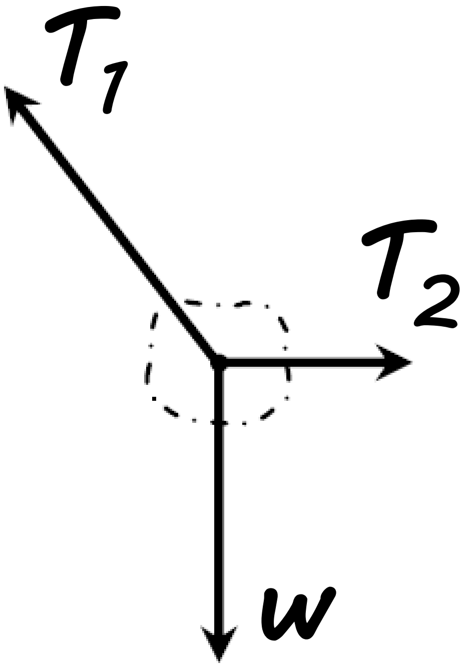


Chapter 5. The Application of Newton’s Laws

Free Body Diagrams for different situations

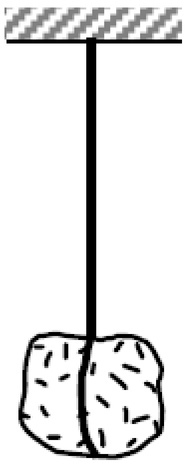
1. Static

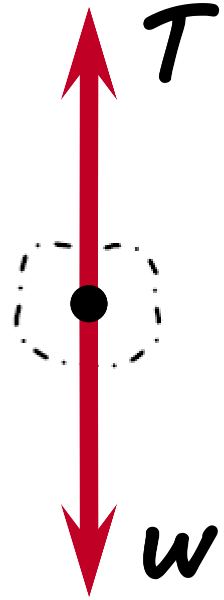




Free Body Diagrams for different situations

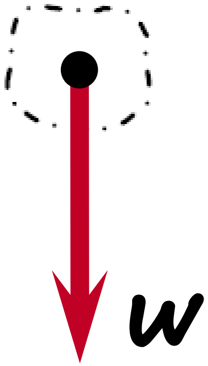
2. Static





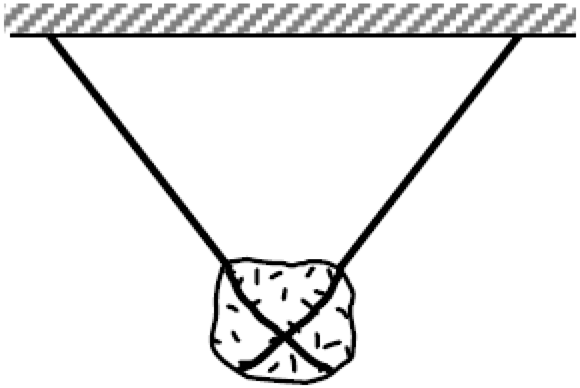
Free Body Diagrams for different situations

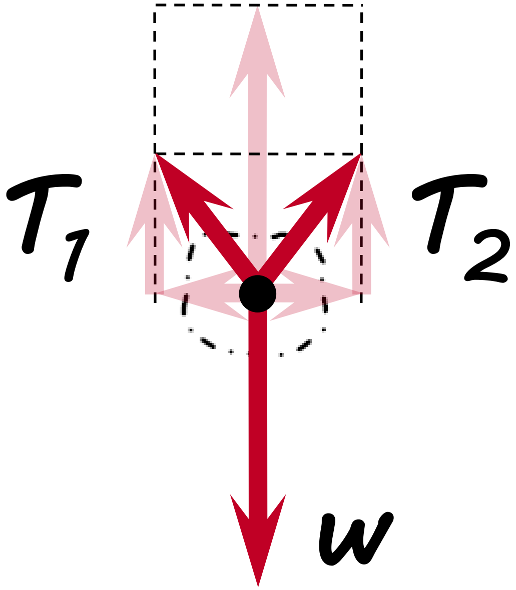
3. Rock is falling. No air friction.



Free Body Diagrams for different situations

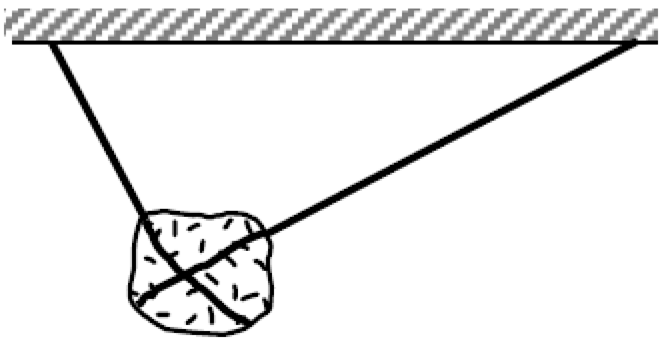
4. Static

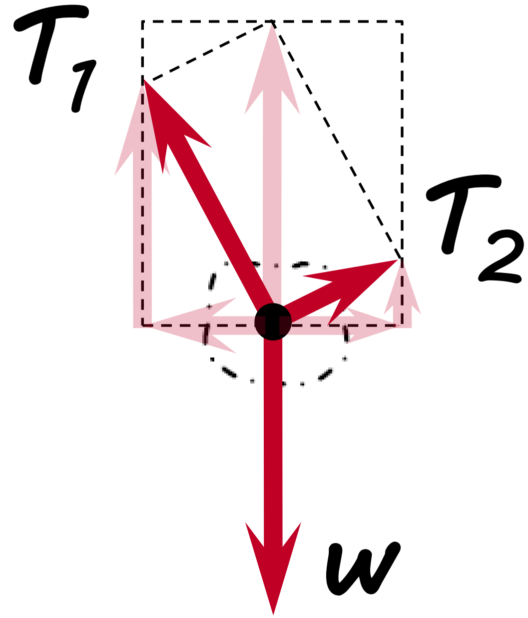




Free Body Diagrams for different situations

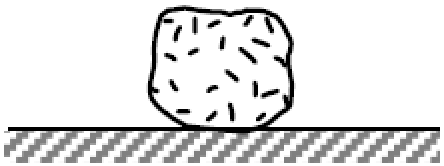
5. Static

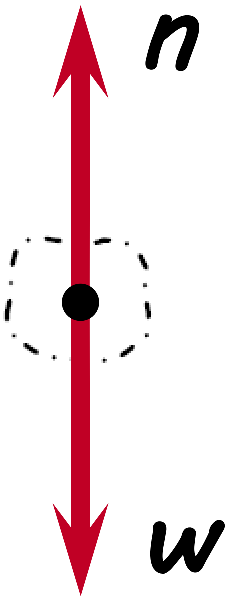




Free Body Diagrams for different situations

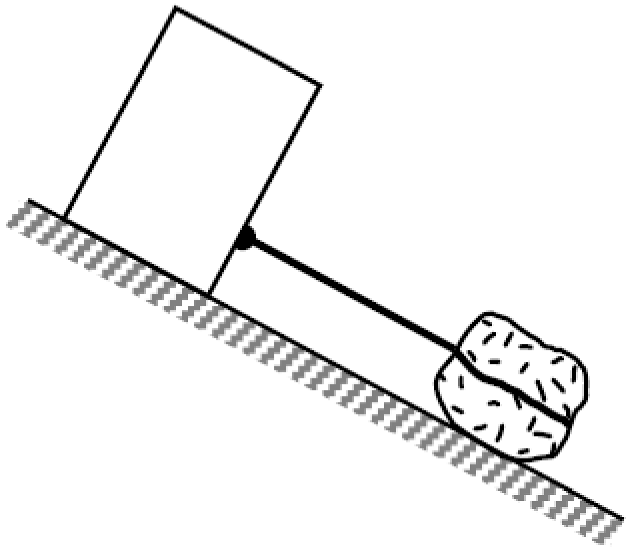
6. Static

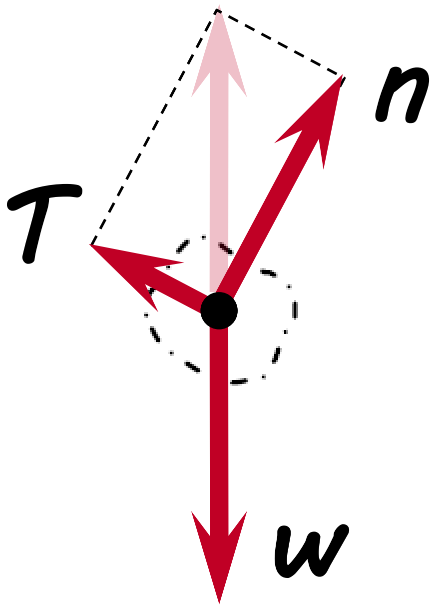




Free Body Diagrams for different situations

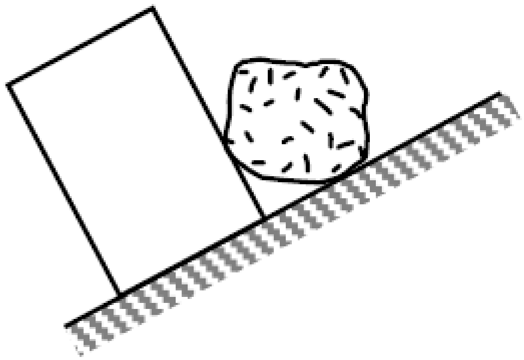
7. Static

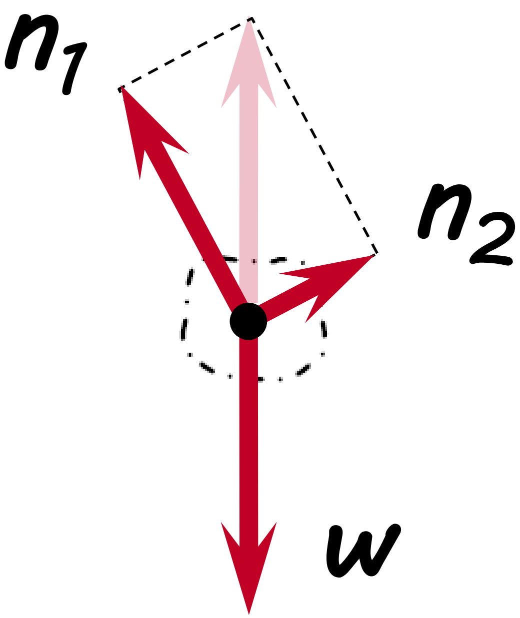




Free Body Diagrams for different situations

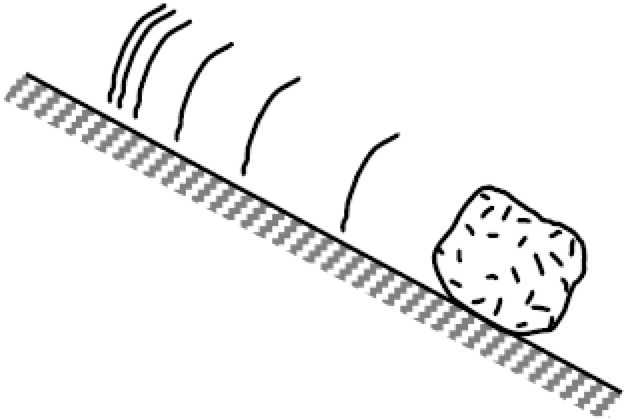
8. Static

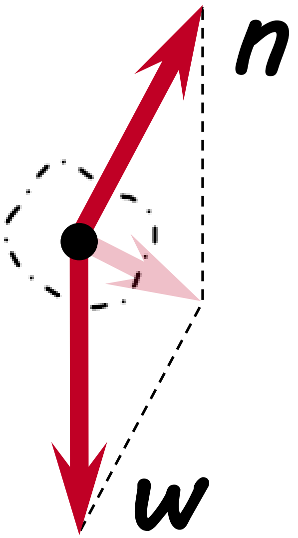




Free Body Diagrams for different situations

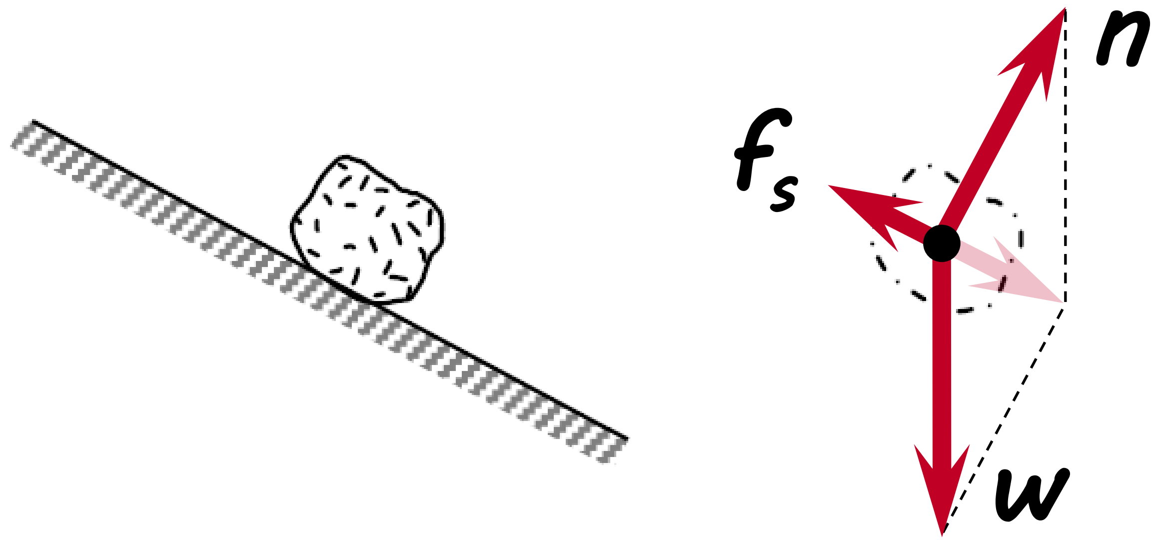
9. Sliding without friction.





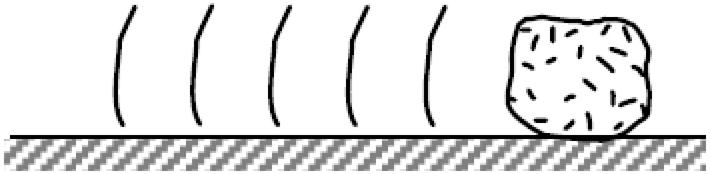
Free Body Diagrams for different situations

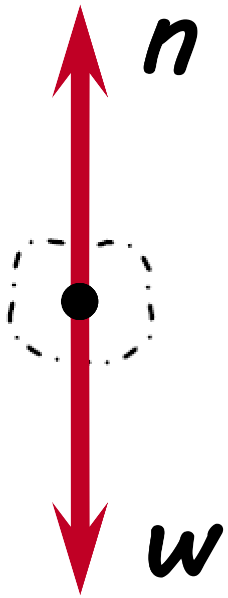
10. Static friction prevents sliding.



Free Body Diagrams for different situations

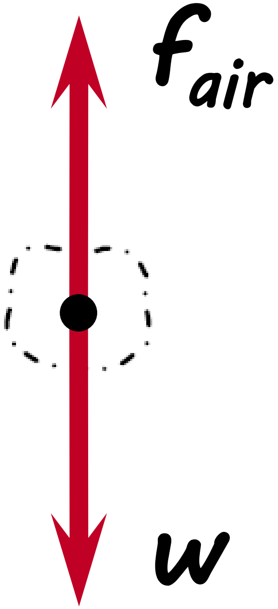
11. Sliding at constant speed without friction.





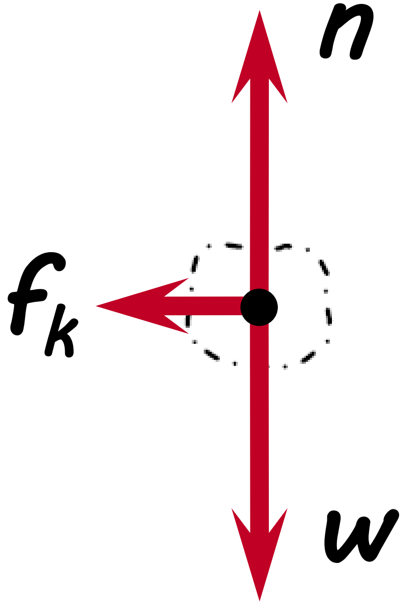
Free Body Diagrams for different situations

12. Falling at constant (terminal) velocity.



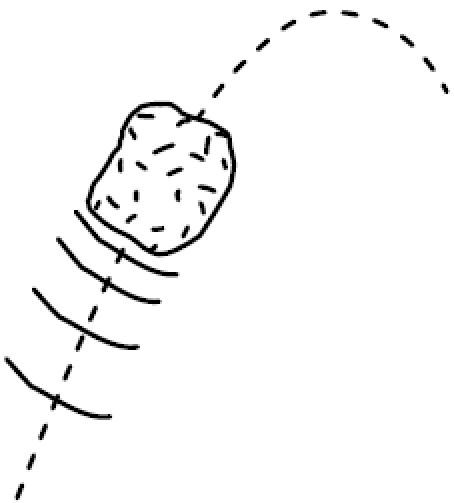
Free Body Diagrams for different situations

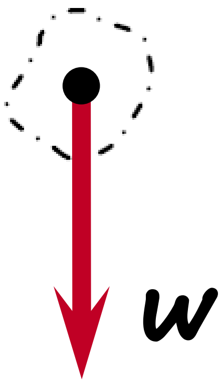
13. Decelerating because of kinetic friction.



Free Body Diagrams for different situations

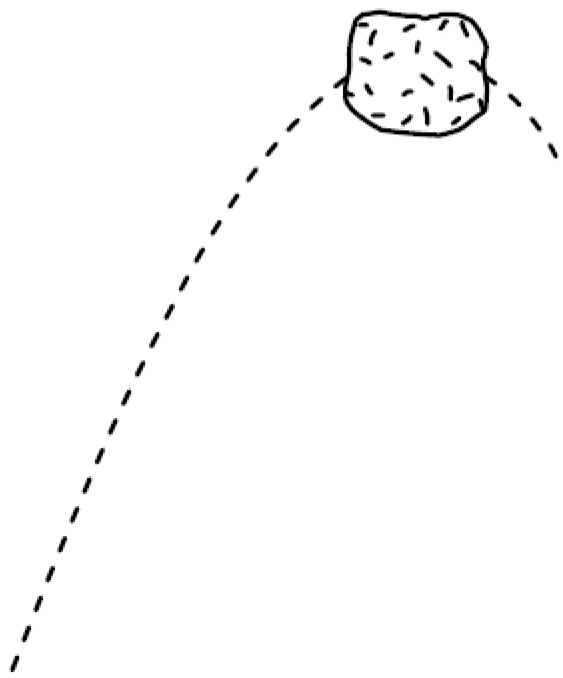
14. Rising in a parabolic trajectory.





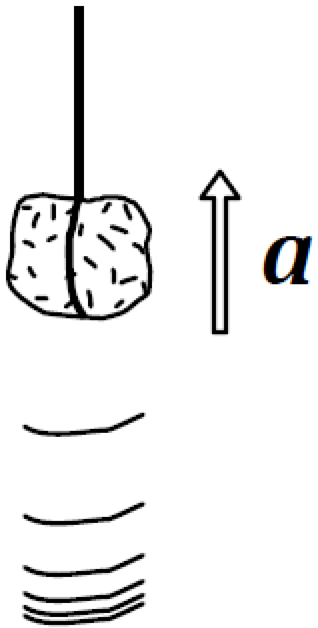
Free Body Diagrams for different situations

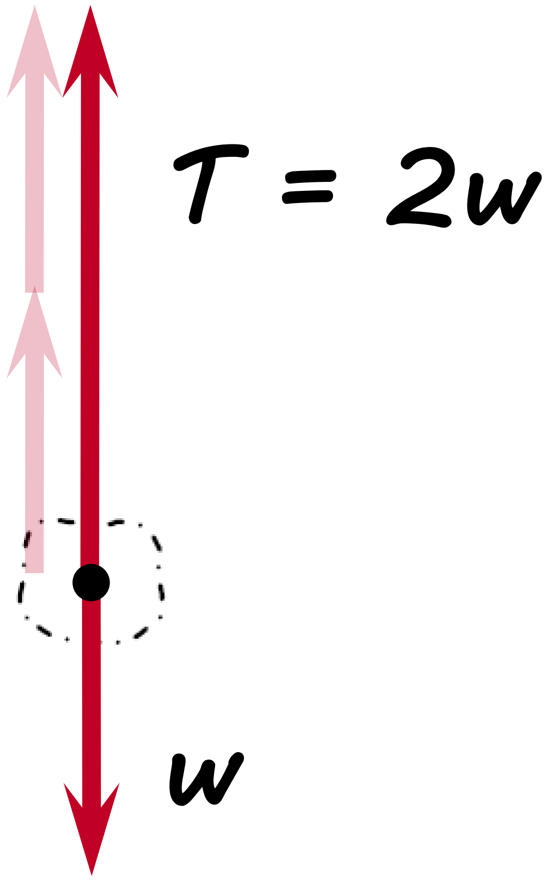
15. At the top of a parabolic trajectory.



Free Body Diagrams for different situations

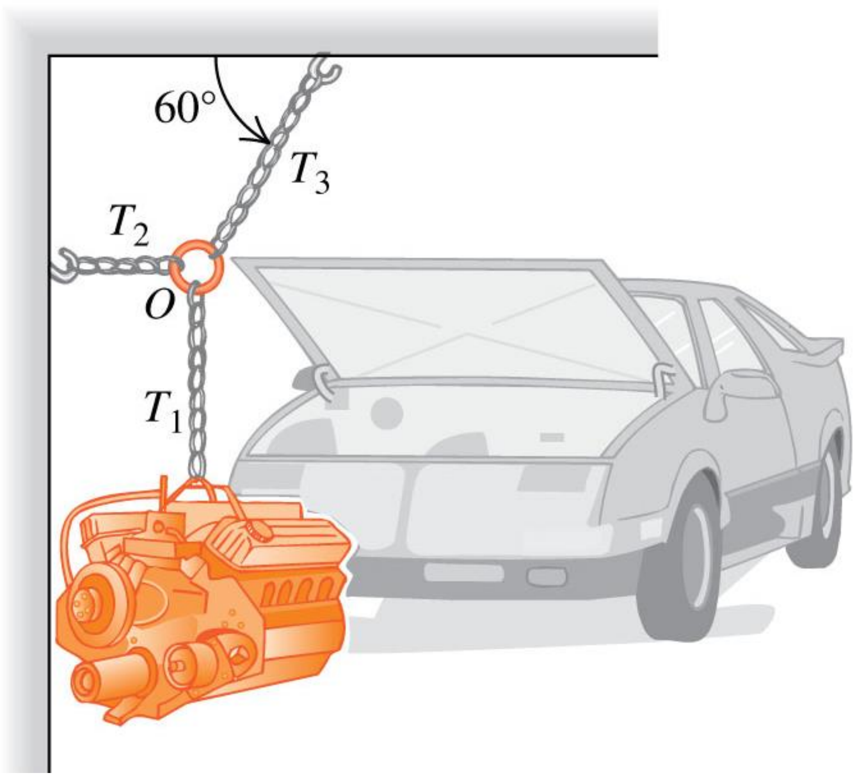
16. Tied to a rope and pulled straight upward. Accelerating upward at 9.8 m/s². No friction.





Applications of the 1st Law:

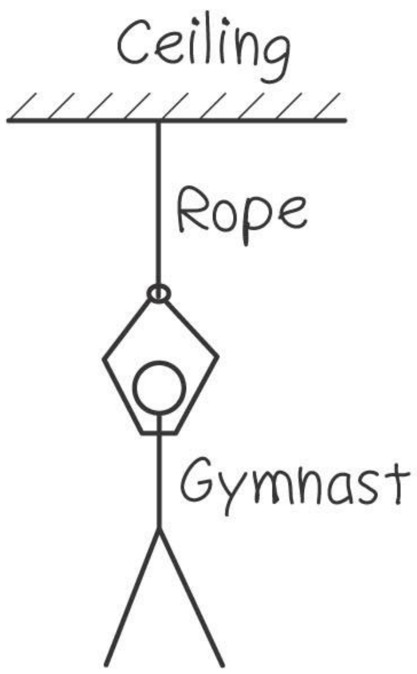
Static Equilibrium



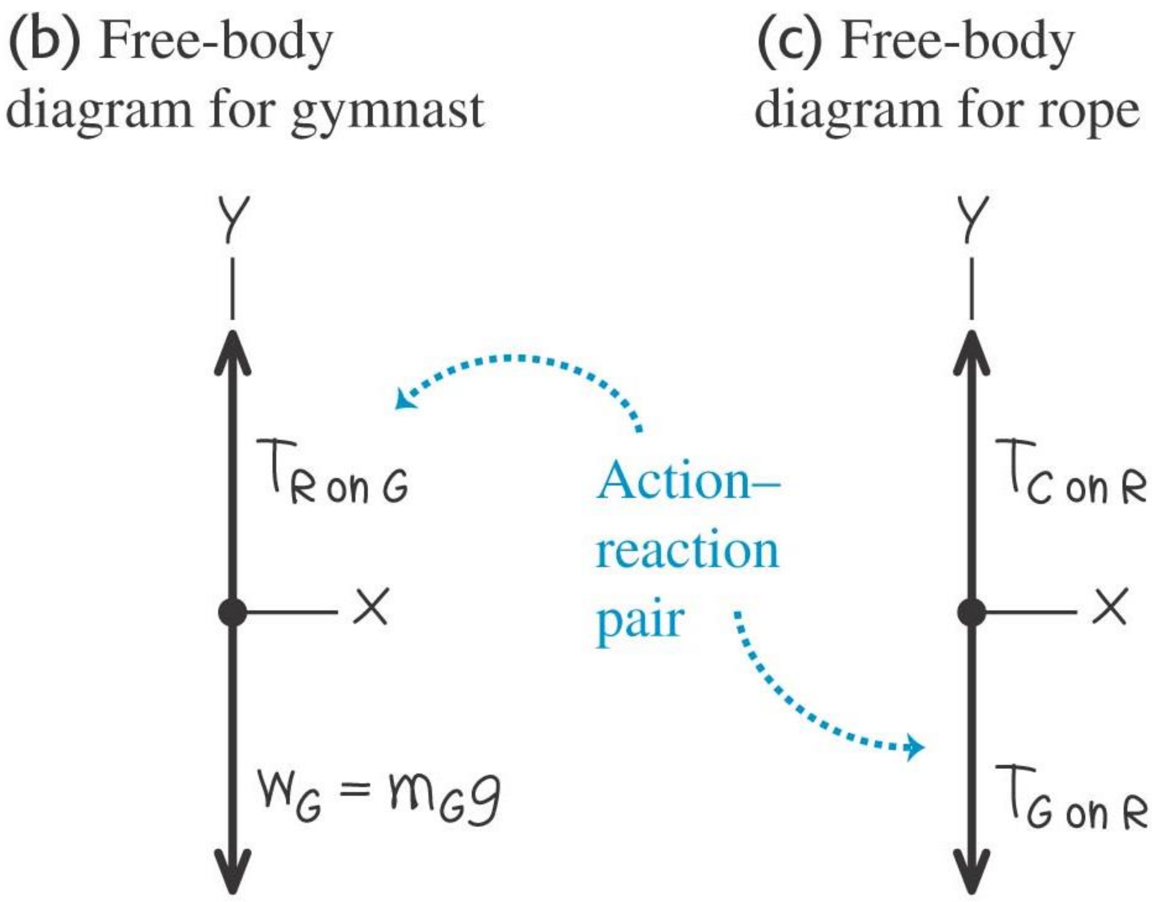
One – Dimensional Equilibrium: Tension in a massless rope

A gymnast with mass m_o = 50.0 kg suspends herself from the lower end of a hanging rope. The upper end of the rope is attached to the gymnasium ceiling. (a) What is the gymnast's weight? (b) What force (magnitude and direction) does the rope exert on her? (c) What is the tension at the top of the rope? Assume that the mass of the rope itself is negligible.

(a) The situation



One – Dimensional Equilibrium: Tension in a massless rope



answer:

(a) mass of gymnast:

m_G = 490 N

(b) tension on rope:

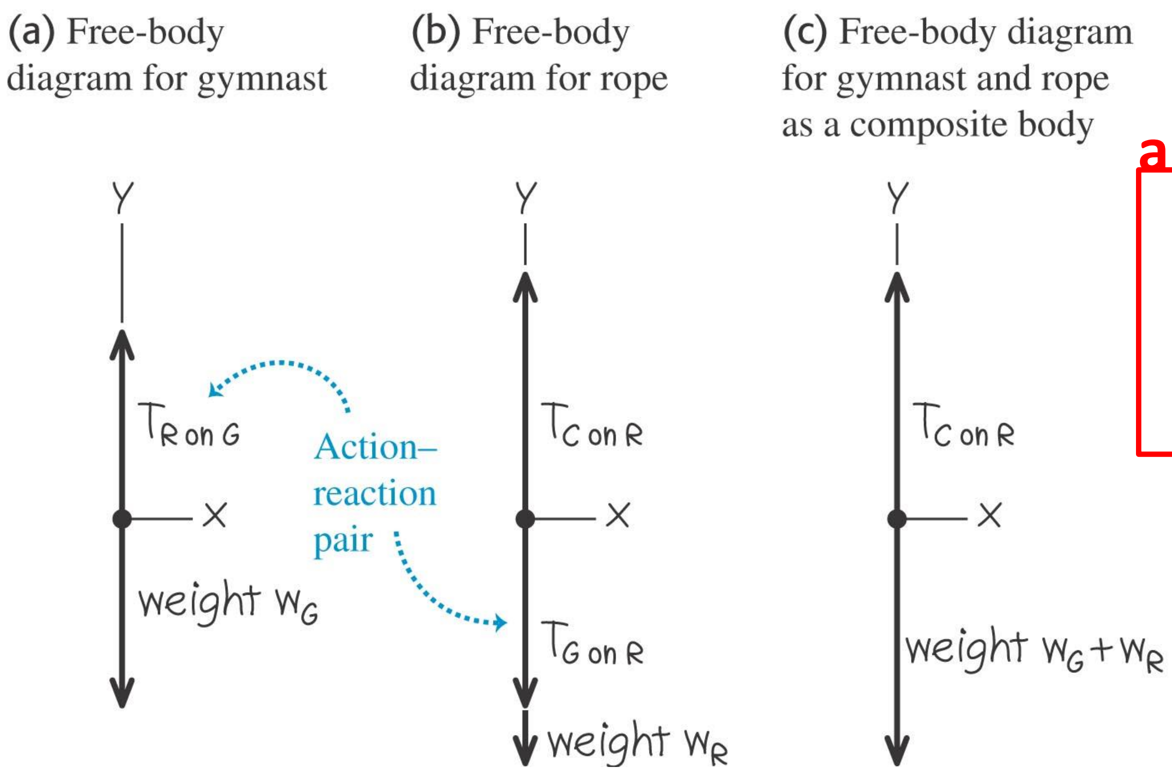
$T_{R\ on\ G}$ = 490 N, up

(c) tension at
top part of rope:

$T_{C\ on\ R}$ = 490 N

One – Dimensional Equilibrium: Tension in a rope with mass

Suppose that the weight of the rope is not negligible but is 120 N. Find the tension at each end of the rope.

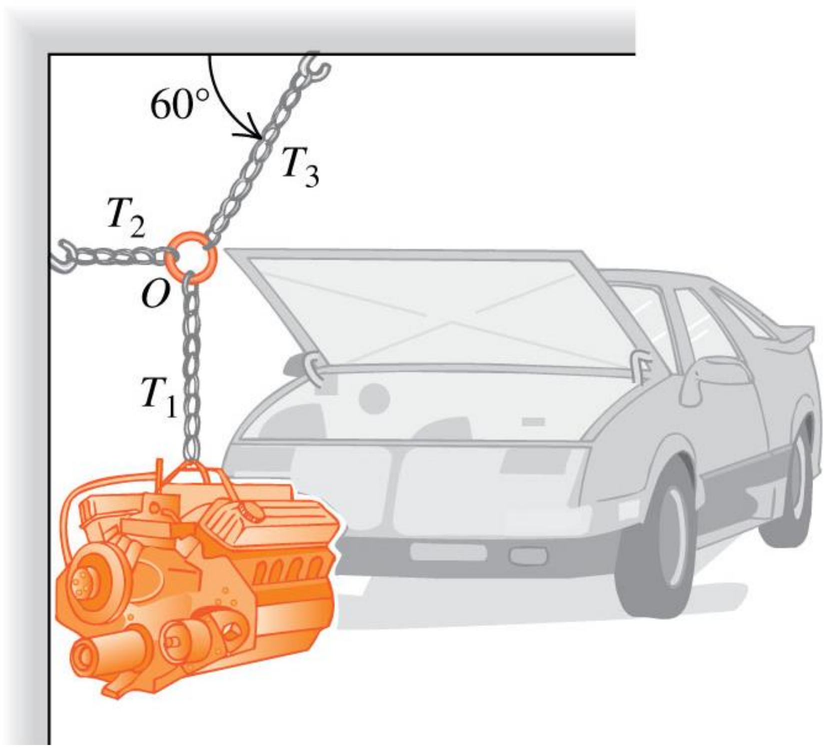


answer:

tension at top part of rope:

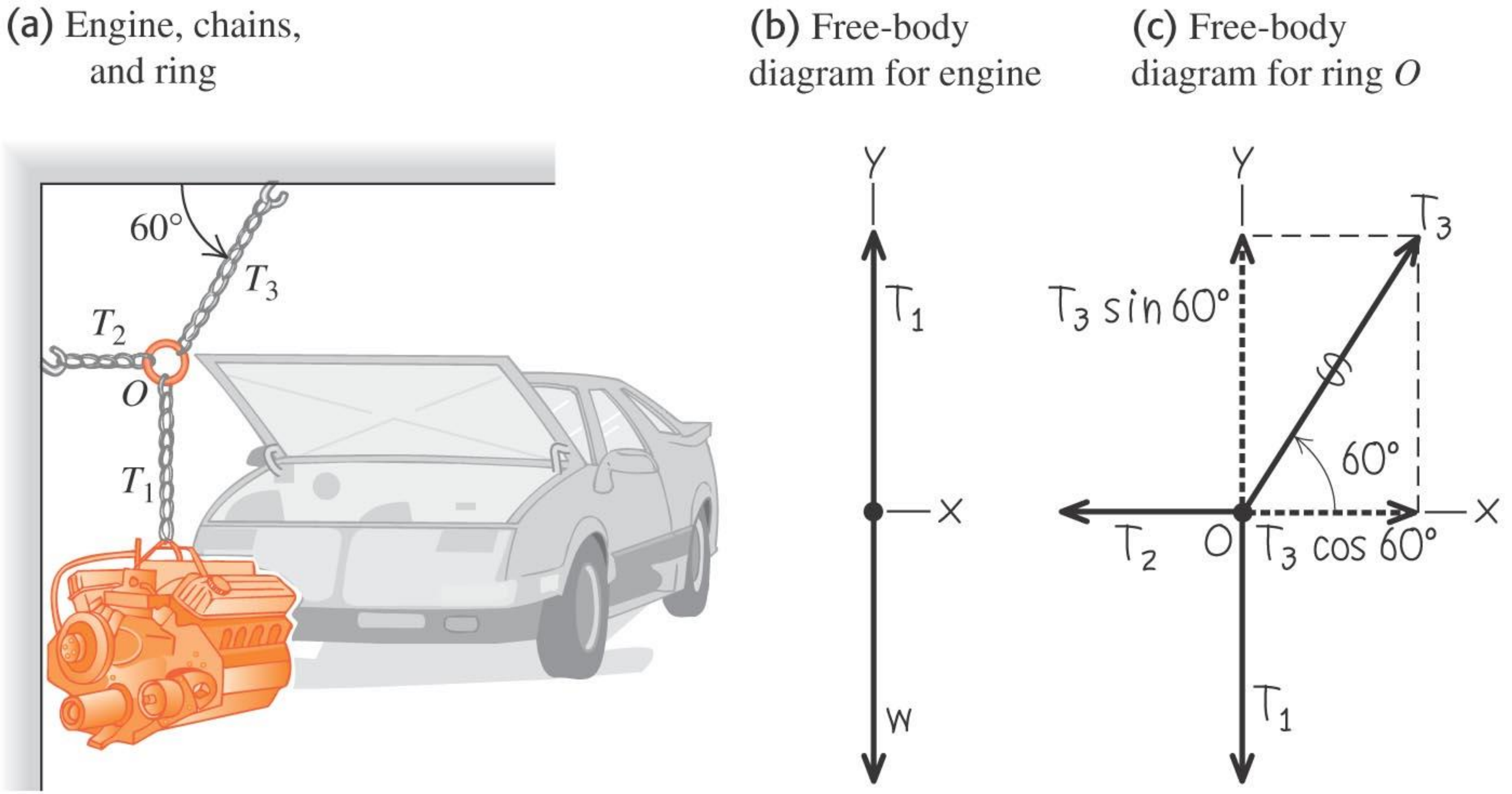
$T_{C\ on\ R}$ = 610 N

Two – Dimensional Equilibrium



A car engine with weight *w* hangs from a chain that is linked at ring *O* to two other chains, one fastened to the ceiling and the other to the wall. Find the tension in each of the three chains in terms of *w*. The weights of the ring and chains are negligible.

Two – Dimensional Equilibrium



Two – Dimensional Equilibrium

answer:

In terms of the engine's weight *w*,

$$T_1 = w \qquad T_2 = \frac{w}{\tan 60°} \qquad T_3 = \frac{w}{\sin 60°}$$

For example, w = 2200 N

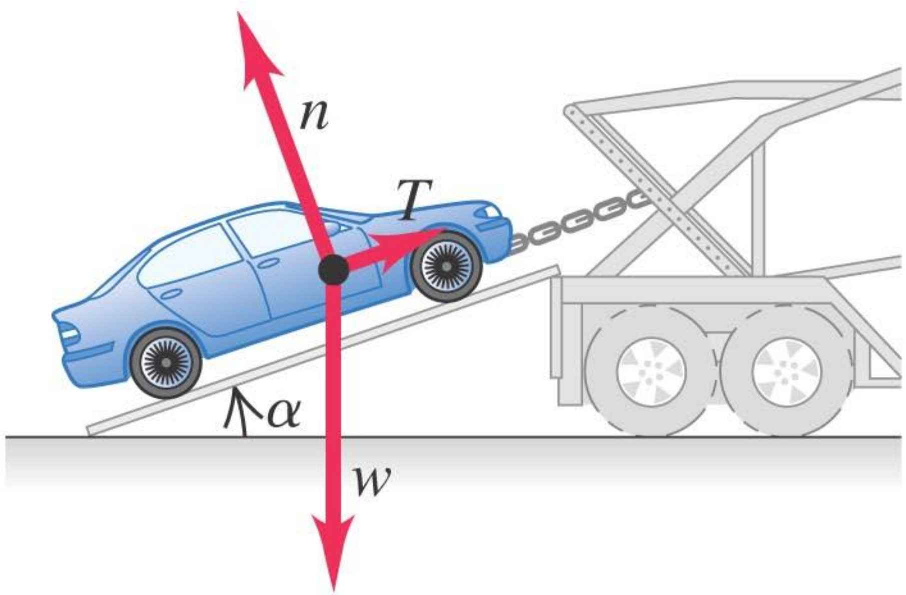
T_1 = 2200 N $\qquad$ T_2 = 1270 N $\qquad$ T_3 = 2540 N

An Inclined Plane

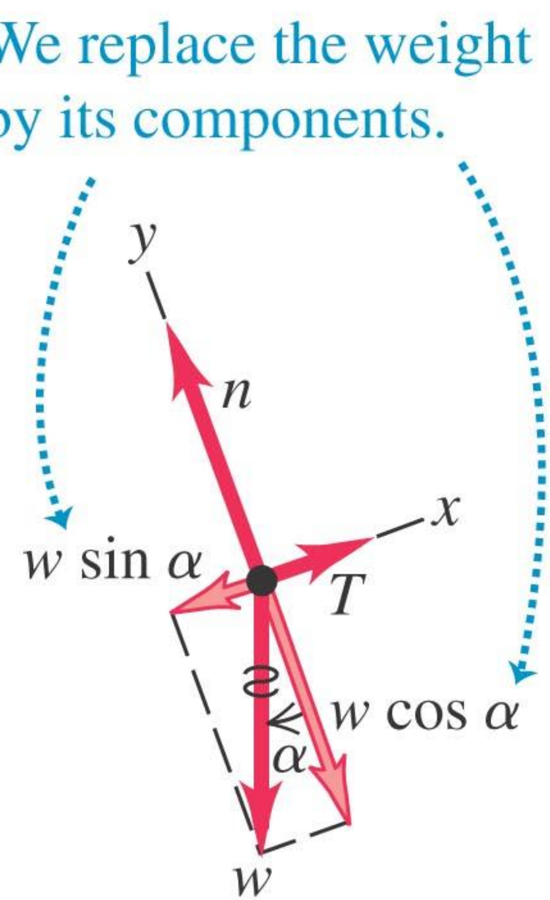
A car of weight *w* rests on a slanted ramp leading to a car-transporter trailer. Only a cable running from the trailer to the car prevents the car from rolling backward off the ramp. (The car's brakes are off and its transmission is in neutral.) Find the tension in the cable and the force that the tracks exert on the car's tires.

An Inclined Plane

(a) Car on ramp



(b) Free-body diagram for car

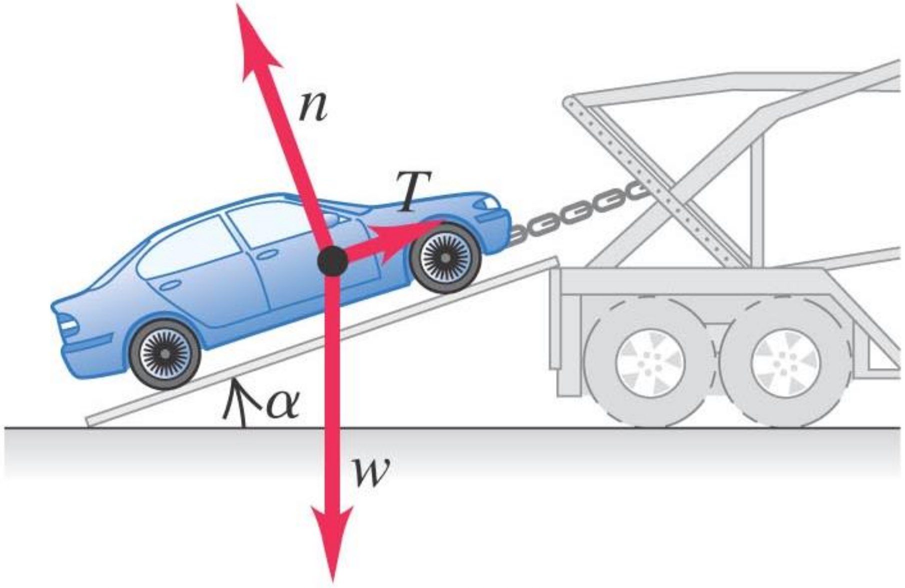


An Inclined Plane

answer:

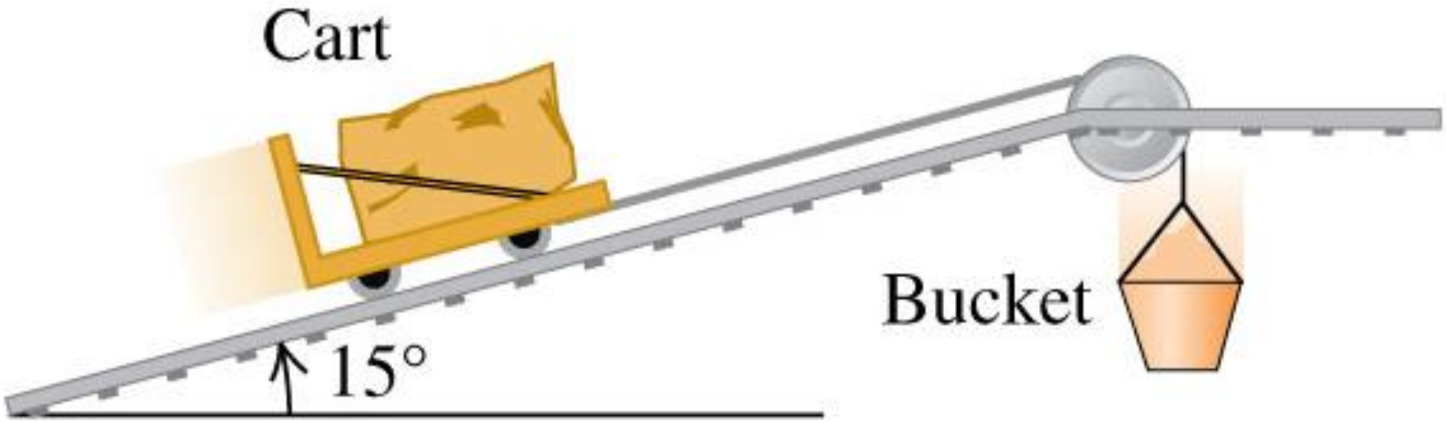
In terms of the car's weight *w*,

$$T = w\sin\alpha \qquad n = w\cos\alpha$$



Applications of the 1st Law:

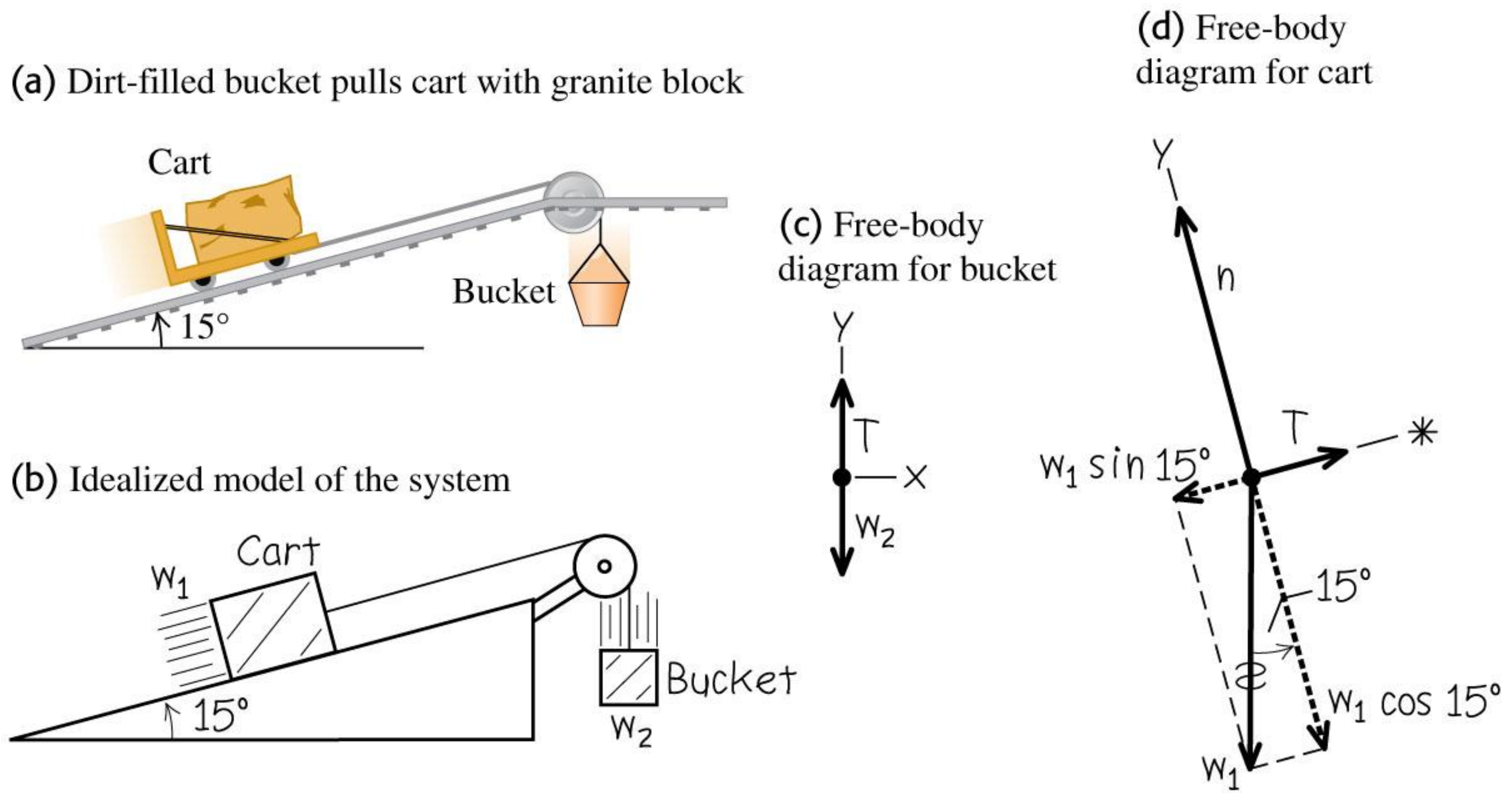
Dynamic Equilibrium



Tension over a frictionless pulley

Blocks of granite are to be hauled up a 15° slope out of a quarry, and dirt is to be dumped into the quarry to fill up old holes. To simplify the process, you design a system in which a granite block on a cart with steel wheels (weight w_1, including both block and cart) is pulled uphill on steel rails by a dirt-filled bucket (weight w_2, including both dirt and bucket) dropping vertically into the quarry. How must the weights w_1 and w_2 be related in order for the system to move with constant speed? Ignore friction in the pulley and wheels and the weight of the cable.

Tension over a frictionless pulley



answer:

$$w_2 = w_1 \sin 15°$$

A Piano on an Inclined Plane

A man pushes on a piano with mass 180 kg so that it slides at constant velocity down a ramp that is inclined at 11.0° above the horizontal floor. Neglect any friction acting on the piano. Calculate the magnitude of the force applied by the man if he pushes (a) parallel to the incline and (b) parallel to the floor.

answer:

(a) $F = 337$ N

(b) $F = 343$ N

Applications of the 2nd Law:

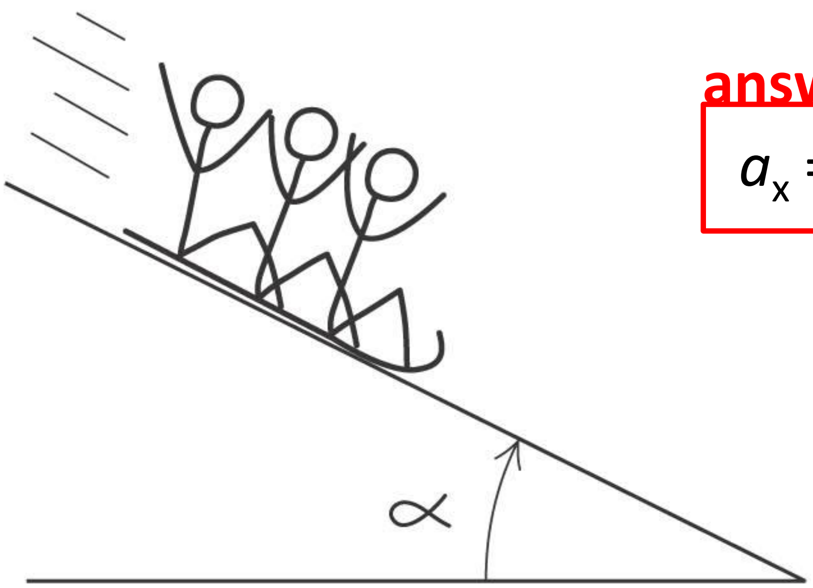
Dynamics of Particles

Acceleration down a hill

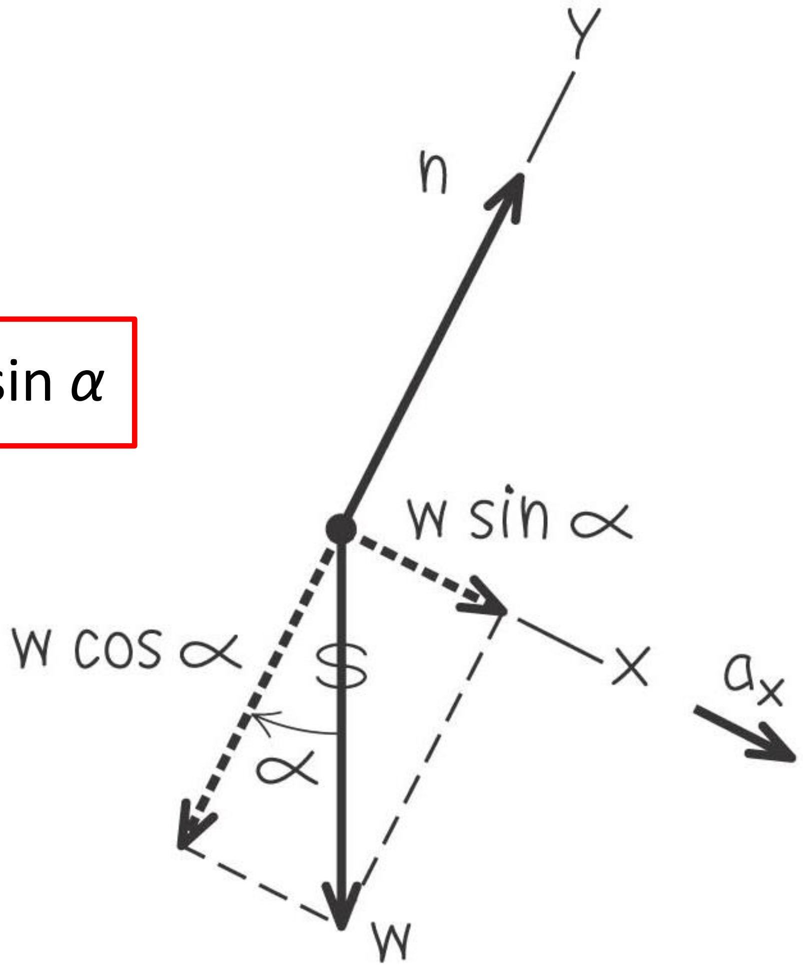
A toboggan loaded with vacationing students (total weight w) slides down a long, snow-covered slope. The hill slopes at a constant angle α, and the toboggan is so well waxed that there is virtually no friction. What is its acceleration?

Acceleration down a hill

(a) The situation



(b) Free-body diagram for toboggan

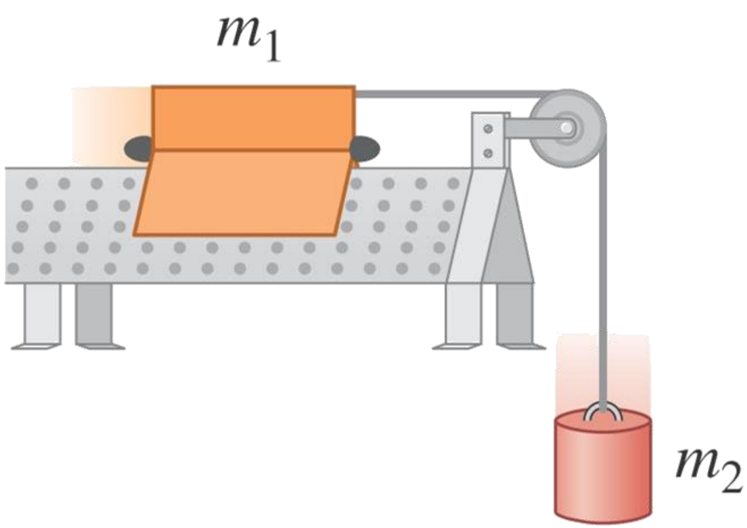


answer:

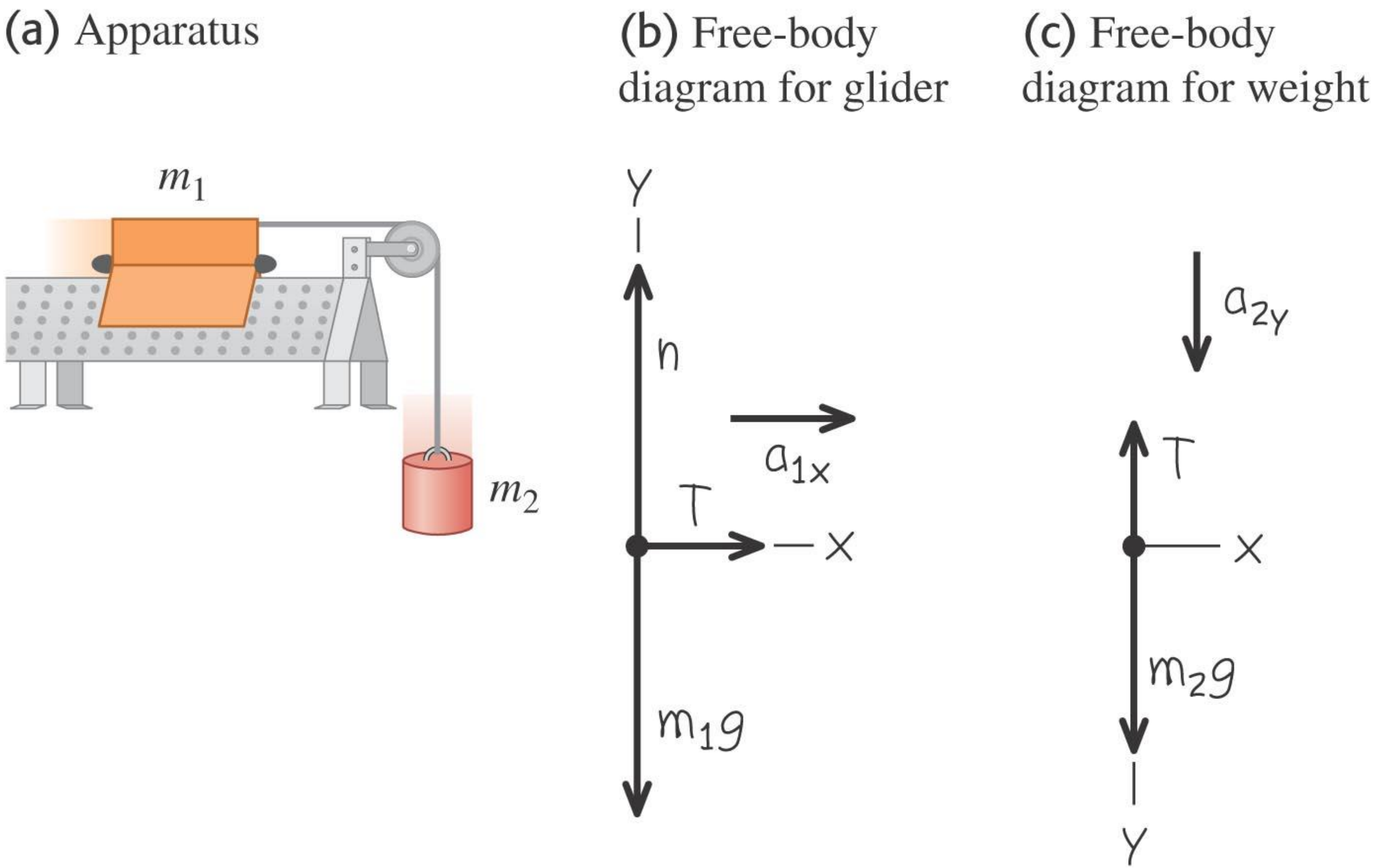
$$\boxed{a_x = g \sin \alpha}$$

Two bodies with the same magnitude of acceleration

The figure below shows an air-track glider with mass m_1, moving on a level, frictionless air track in the physics lab. The glider is connected to a lab weight with mass m_2 by a light, flexible, non-stretching string that passes over a small frictionless pulley. Find the acceleration of each body and the tension in the string.



Two bodies with the same magnitude of acceleration



Two bodies with the same magnitude of acceleration

answer:

The accelerations of the glider and the lab weight are the same.

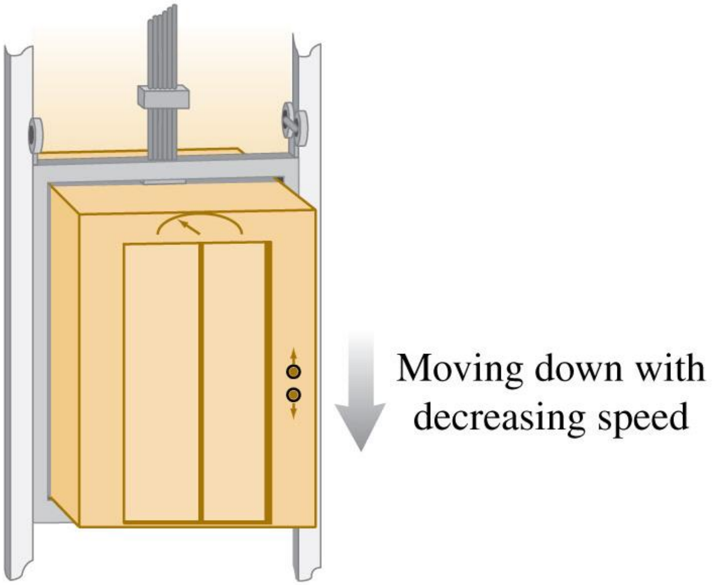
$$a_{1x} = a_{2y} = \left(\frac{m_2}{m_1 + m_2}\right)g$$

The tension in the string is

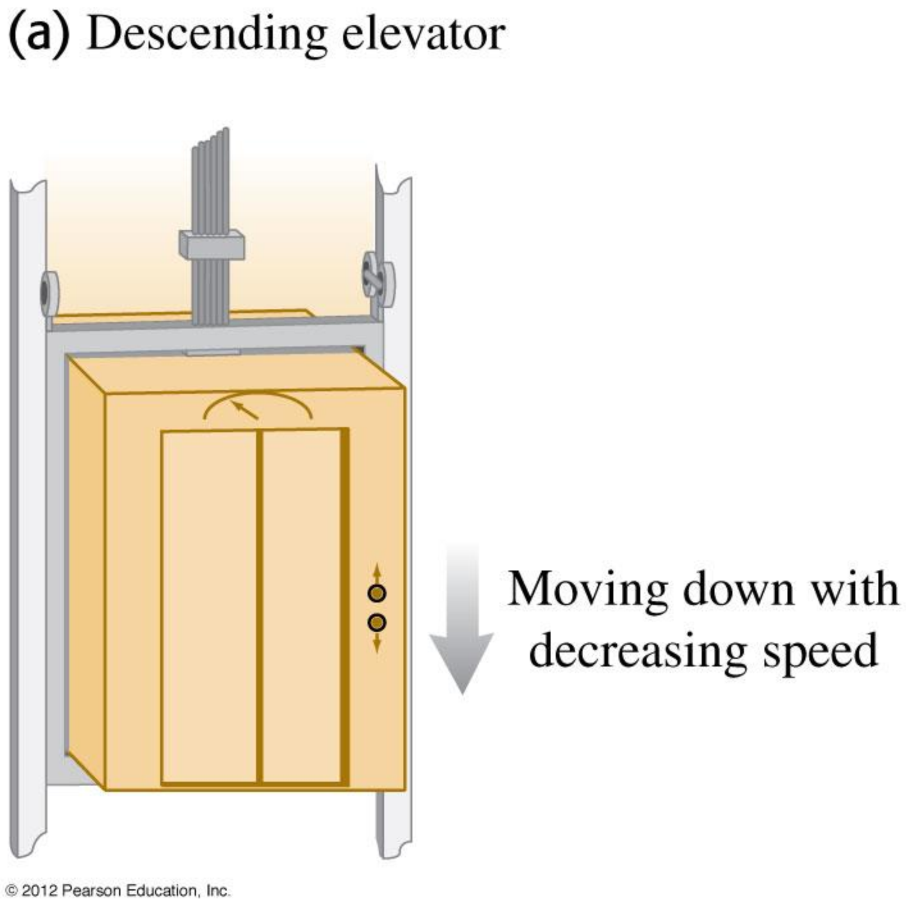
$$T = \left(\frac{m_1 m_2}{m_1 + m_2}\right)g$$

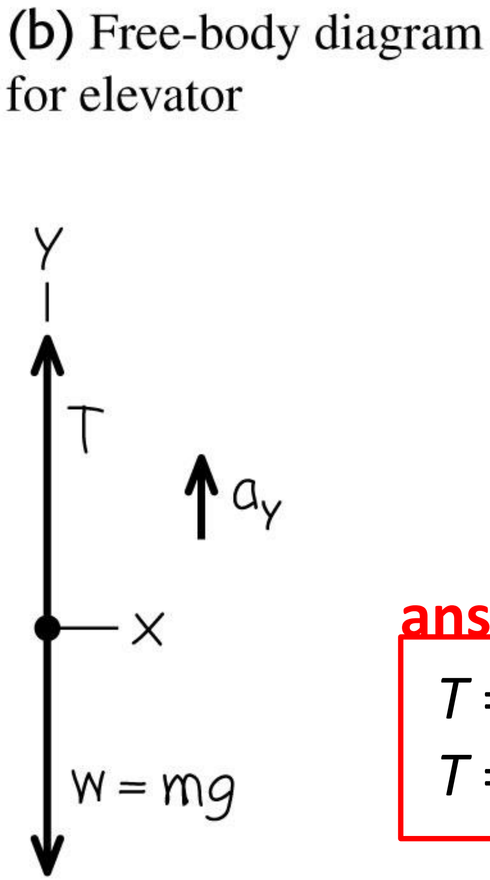
Tension in an elevator cable

An elevator and its load have a total mass of 800 kg. The elevator is originally moving downward at 10.0 m/s; it slows to a stop with constant acceleration in a distance of 25.0 m. Find the tension *T* in the supporting cable while the elevator is being brought to rest.



Tension in an elevator cable





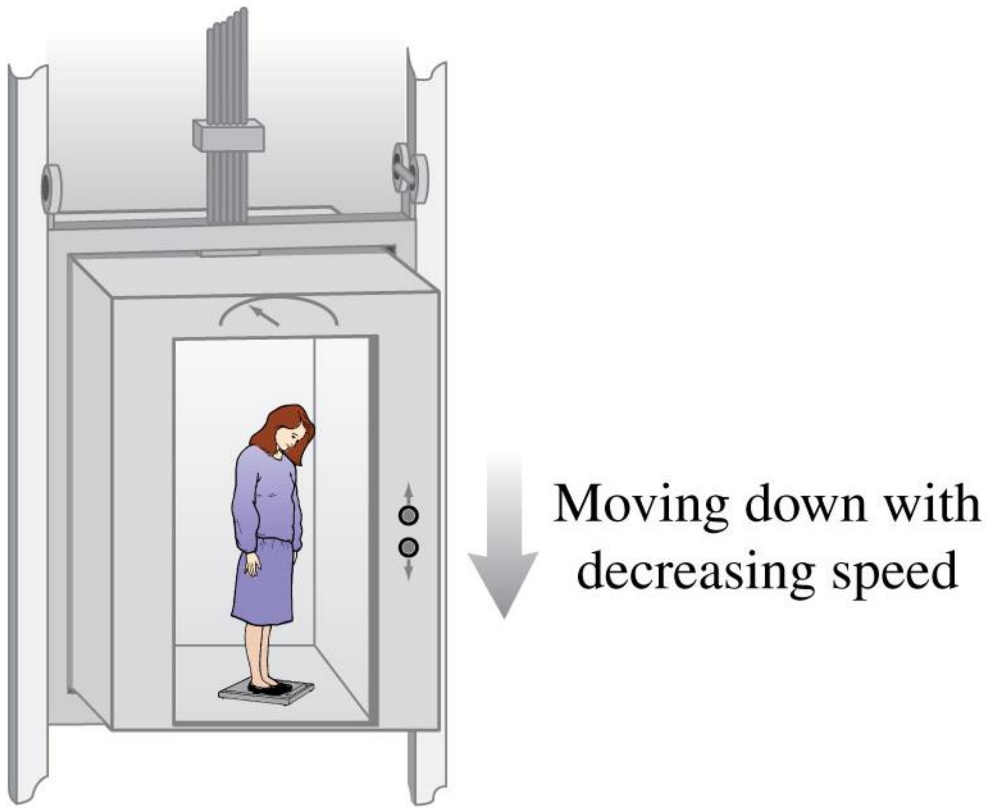
answer:

$T = m(g + a_y)$

$T = 9440\text{ N}$

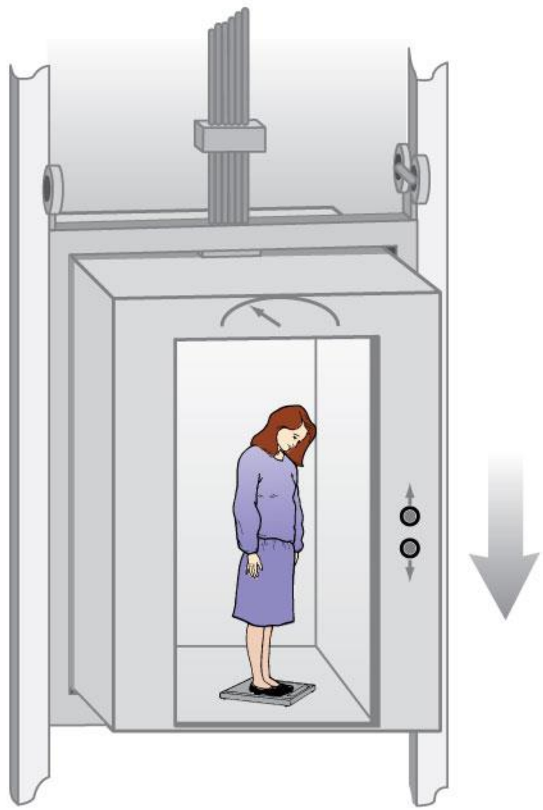
Apparent weight in an ascending elevator

A 50.0-kg woman stands on a bathroom scale while riding in the elevator in the previous example. What is the reading on the scale?



Apparent weight in an ascending elevator

(a) Woman in a descending elevator



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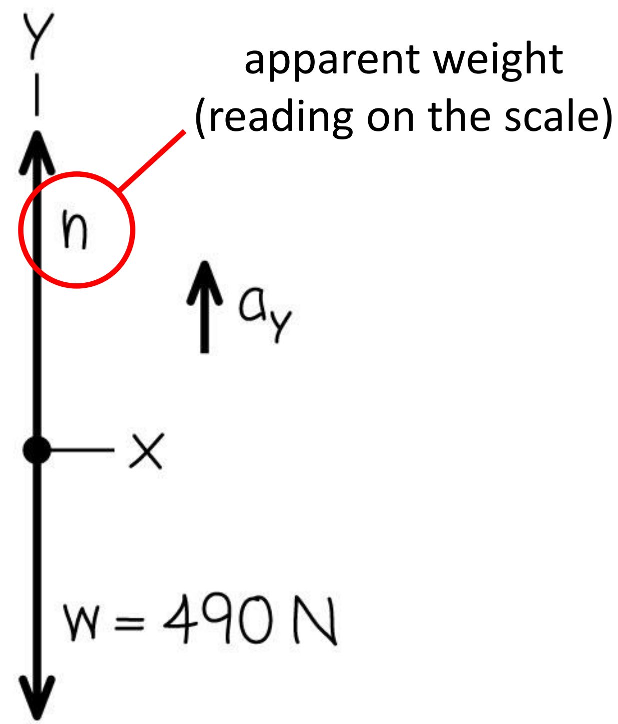
Moving down with decreasing speed

answer:

$$n = m(g + a_y)$$
$$n = 590\ \text{N}$$

(b) Free-body diagram for woman

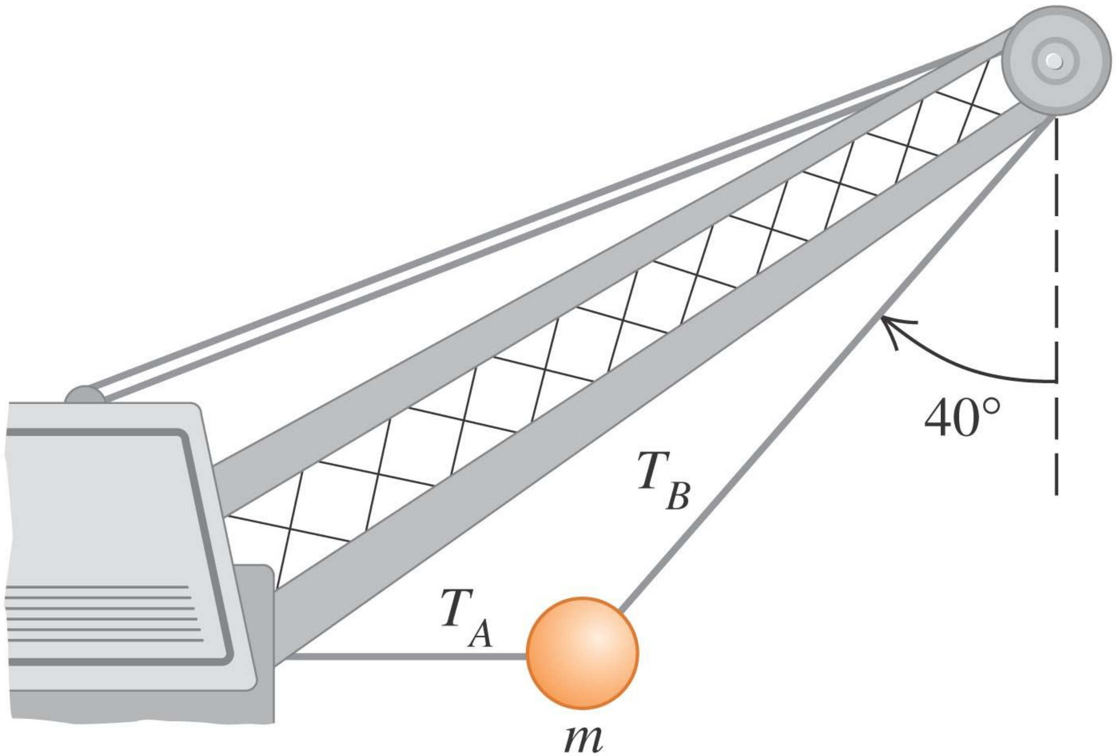


Weightless.
(apparently)

Priceless. Timeless. Weightless.

Review

A large wrecking ball is held in place by two light steel cables. If the mass *m* of the wrecking ball is 4090 kg, what are (a) the tension T_B in the cable that makes an angle of 40° with the vertical and (b) the tension T_A in the horizontal cable?



answer:

$T_B = 5.23 \times 10^4$ N

$T_A = 3.36 \times 10^4$ N

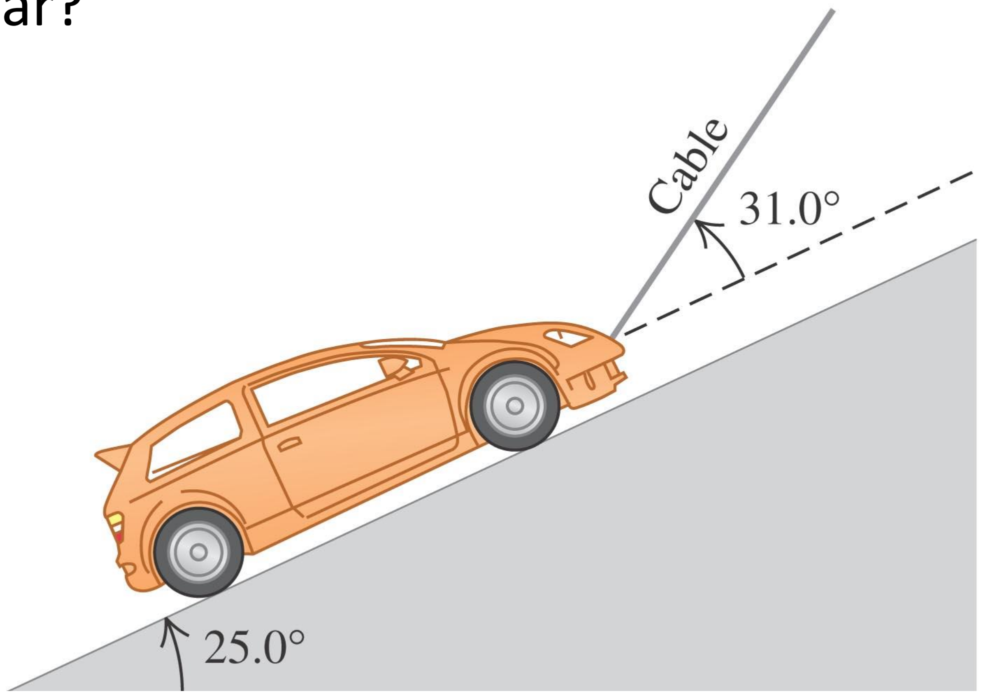
Review

A 1130-kg car is held in place by a light cable on a very smooth (frictionless) ramp. The cable makes an angle of 31.0° above the surface of the ramp, and the ramp itself rises at 25.0° above the horizontal. (a) Draw a free-body diagram for the car. (b) Find the tension in the cable. (c) How hard does the surface of the ramp push on the car?

answer:

T = 5460 N

n = 7220 N



Review

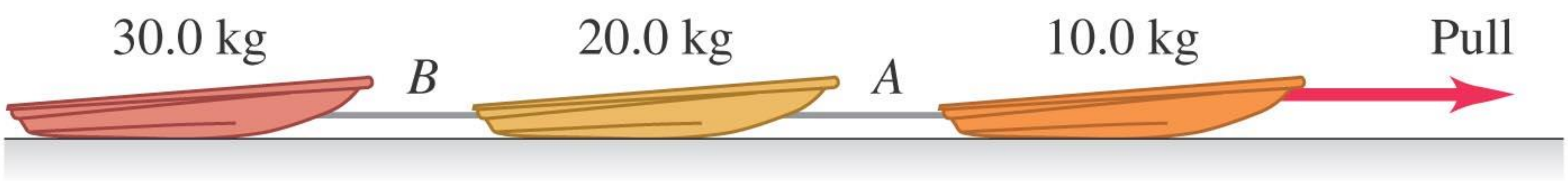
Three sleds are being pulled horizontally on frictionless horizontal ice using horizontal ropes. The pull is horizontal and of magnitude 125 N. Find (a) the acceleration of the system and (b) the tension in ropes A and B.

answer:

$a = 2.08\ \text{m/s}^2$

$T_A = 104\ \text{N}$

$T_B = 62.4\ \text{N}$



Review

Consider the system shown. Block A weighs 45.0 N and block B weighs 25.0 N. Once block B is set into downward motion, it descends at a constant speed (a) Calculate the coefficient of kinetic friction between block A and the tabletop. (b) A cat, also of weight 45.0 N, falls asleep on top of block A. If block B is now set into downward motion, what is its acceleration (magnitude and direction)?

answer:

$$\mu_k = 0.56$$

$$a = 2.8\ \text{m/s}^2$$

Opposite to the motion of block A