Free-Body Diagrams

Unit: Forces in One Dimension

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS2-10(MA)

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): 2.2.A, 2.2.A.1, 2.2.A.1.i, 2.2.A.1.ii, 2.2.A.2, 2.2.B, 2.2.B.1, 2.2.B.2, 2.2.B.3, 2.2.B.4

Mastery Objective(s): (Students will be able to…)

- Draw a free-body diagram that represents all of the forces on an object and their directions.

Success Criteria:

- Each force starts from the dot representing the object.
- Each force is represented as a separate arrow pointing in the direction that the force acts.

Language Objectives:

- Explain how a dot with arrows can be used to represent an object with forces.

Tier 2 Vocabulary: force, free, body

Labs, Activities & Demonstrations:

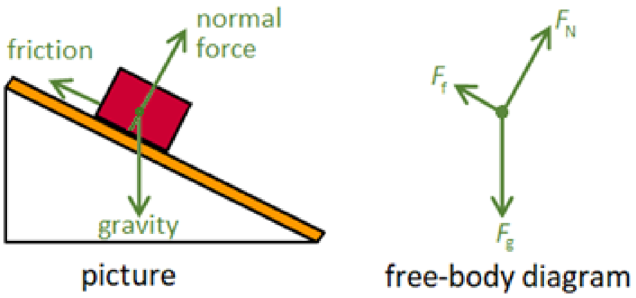
- Human free-body diagram activity.

Notes:

free-body diagram (force diagram): a diagram representing all of the forces acting on an object.

In a free-body diagram, we represent the object as a dot, and each force as an arrow. The direction of the arrow represents the direction of the force, and the relative lengths of the arrows represent the relative magnitudes of the forces.

Consider the following situation:



In the picture, a block is sitting on a ramp. The forces on the block are gravity (straight down), the normal force (perpendicular to and away from the ramp), and friction (parallel to the ramp).

In the free-body diagram, the block is represented by a dot. The forces, represented by arrows, are gravity (F_g), the normal force (F_N), and friction (F_f).

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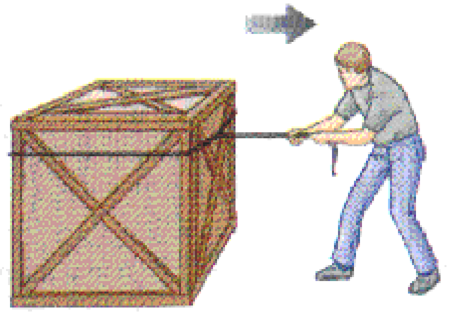
Now consider the following situation of a box that *accelerates* to the right as it is pulled across the floor by a rope:

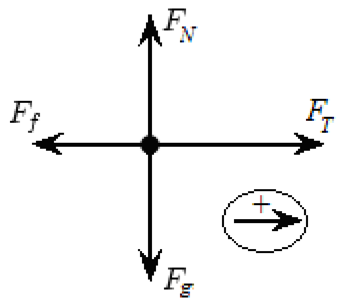


From the picture and description, we can assume that:

- The box has weight, which means gravity is pulling down on it.
- The floor is holding up the box.
- The rope is pulling on the box.
- Friction between the box and the floor is resisting the force from the rope.
- Because the box is accelerating to the right, the force applied by the rope must be stronger than the force from friction.

In the free-body diagram for the accelerating box, we again represent the object (the box) as a dot, and the forces (vectors) as arrows. Because there is a net force, we should also include a legend that shows which direction is positive.

The forces are:



- $\vec{F}_g$ = the force of gravity pulling down on the box
- $\vec{F}_N$ = the normal force (the floor holding the box up)
- $\vec{F}_T$ = the force of tension from the rope. (This might also be designated $\vec{F}_a$ because it is the force *applied* to the object.)
- $\vec{F}_f$ = the force of friction resisting the motion of the box.

Notice that the arrows for the normal force and gravity are equal in length, because in this problem, these two forces are equal in magnitude.

Notice that the arrow for friction is shorter than the arrow for tension, because in this problem the tension is stronger than the force of friction. The difference between the lengths of these two vectors would be the net force, which is what causes the box to accelerate to the right.

In general, if the object is moving, it is easiest to choose the positive direction to be the direction of motion. In our free-body diagram, the legend in the bottom right corner of the diagram shows an arrow with a "+" sign, meaning that we have chosen to make the positive direction to the right.

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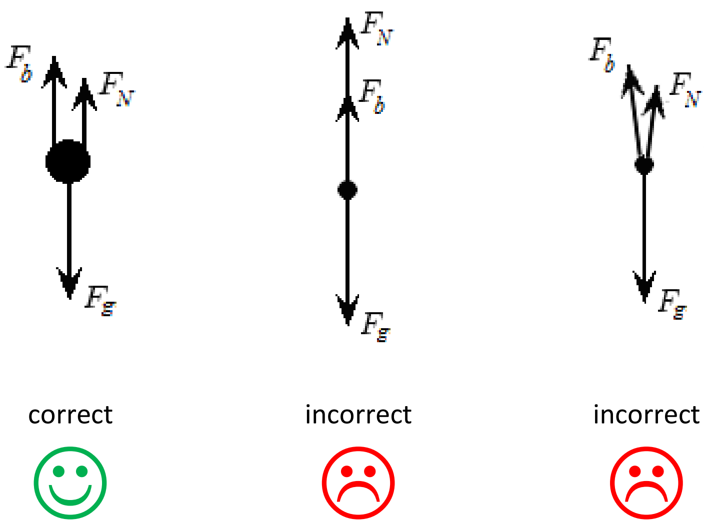
If you have multiple forces in the same direction, each force vector must originate from the point that represents the object, and must be as close as is practical to the *exact* direction of the force.

For example, consider a rock sitting at the bottom of a pond. The rock has three forces on it: the buoyant force ($\vec{F}_b$) and the normal force ($\vec{F}_N$), both acting upwards, and gravity ($\vec{F}_g$) acting downwards.



The first representation is correct because all forces originate from the dot that represents the object, the directions represent the exact directions of the forces, and the length of each is proportional to its strength.

The second representation is incorrect because it is unclear whether $\vec{F}_N$ starts from the object (the dot), or from the tip of the $\vec{F}_b$ arrow.

The third representation is incorrect because it implies that $\vec{F}_b$ and $\vec{F}_N$ each have a slight horizontal component, which is not true.

Because there is no net force (the rock is just sitting on the bottom of the pond), the forces must all cancel. This means that the lengths of the arrows for $\vec{F}_b$ and $\vec{F}_N$ need to add up to the length of the arrow for $\vec{F}_g$.

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Steps for Drawing Free-Body Diagrams

In general, the following are the steps for drawing most free-body diagrams.

1. Is gravity involved? (In most physics problems that take place on Earth near the planet's surface, the answer is yes.)
   - Represent gravity as $\vec{F}_g$ pointing straight down.
2. Is something holding the object up?
   - If it is a flat surface, it is the normal force ($\vec{F}_N$), perpendicular to the surface.
   - If it is a rope, chain, *etc.,* it is the force of tension ($\vec{F}_T$) acting along the rope, chain, *etc.*
3. Is there a force pulling or pushing on the object?
   - If the pulling force involves a rope, chain, *etc.*, the force is tension ($\vec{F}_T$) and the direction is along the rope, chain, *etc*.
   - A pushing force is called thrust ($\vec{F}_t$).
   - Only include forces that are acting currently. (Do not include forces that acted in the past but are no longer present.)
4. Is there friction?
   - If there are two surfaces in contact, there is almost always friction ($\vec{F}_f$), unless the problem specifically states that the surfaces are frictionless. (In physics problems, ice is almost always assumed to be frictionless.)
   - At low velocities, air resistance is very small and can usually be ignored unless the problem explicitly states otherwise.
   - Usually, all sources of friction are shown as one combined force. *E.g.,* if there is sliding friction along the ground and also air resistance, the $\vec{F}_f$ vector includes both.
5. Do we need to choose positive & negative directions?
   - If the problem requires calculations involving opposing forces, you need to indicate which direction is positive. If the problem does not require calculations or if there is no net force, you do not need to do so.

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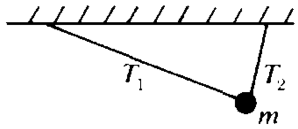
AP®

What AP® Free-Body Diagram Problems Look Like

AP® force problems almost always involve free-body diagrams of a stationary object with multiple forces on it. Here are a couple of examples:



Q: A ball of mass m is suspended from two strings of unequal length as shown above. The magnitudes of the tensions T_1 and T_2 in the strings must satisfy which of the following relations?

(A) $T_1 = T_2$ (B) $T_1 > T_2$ (C) $T_1 < T_2$ (D) $T_1 + T_2 = mg$

A: Remember that forces are vectors, which have direction as well as magnitude. This means that T_1 and T_2 must each have a vertical and horizontal component. The ball is not moving, which means there is no acceleration and therefore $F_{net} = 0$. For F_{net} to be zero, the components of all forces must cancel overall, *and separately in every dimension*. This means, the vertical components of T_1 and T_2 must add up to mg, and the horizontal components of T_1 and T_2 must cancel (add up to zero). Therefore, answer choice (D) $T_1 + T_2 = mg$ is correct.

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Homework Problems

For each picture, draw a free-body diagram that shows all of the forces acting upon the object (represented by the underlined word) in the picture.

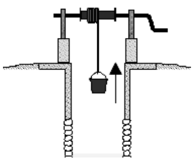
1. **(M)** A bird sits motionless on a perch.

2. **(M)** A hockey player glides at ***constant velocity*** across the ice. (*Ignore friction.*)

3. **(M)** A baseball player slides into a base.

4. **(M)** A chandelier hangs from the ceiling, suspended by a chain.

5. **(M)** A bucket of water is raised out of a well at ***constant velocity***.



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6. **(M)** A skydiver has just jumped out of an airplane and begins ***accelerating*** toward the ground.

7. **(M)** A skydiver falls through the air at ***terminal velocity***. (*Terminal velocity* means the velocity has stopped changing and is constant.)

8. **(M)** A hurdler is moving horizontally as she clears a hurdle. (*Ignore air resistance.*)

9. **(M)** An airplane moves through the air in ***level flight*** at ***constant velocity***.

10. **(M)** A sled is pulled through the snow at ***constant velocity***. (*Note that the rope is at an angle.*)

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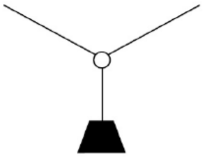
11. **(M)** A stationary metal ring is held by three ropes, one of which has a mass hanging from it. (*Draw the free-body diagram for the metal ring.*)



12. **(M)** A child swings on a swing.
(*Ignore all sources of friction, including air resistance.*)

13. **(M)** A squirrel sits motionless on a sloped roof.

14. **(M)** A skier moves down a slope at ***constant velocity***.

15. **(M)** A skier ***accelerates*** down a slope.

Use this space for summary and/or additional notes: