3. Newton's Laws of Motion

Grade 11 Physics

Olympiads School

Four Fundamental Forces

Strong Nuclear Force

- Strongest out of all four
- Overcome the repulsion of positively charge protons by keeping them together.

Electromagnetic Force

- Most of "everyday" force other than gravity
- Contact forces
  - Electrons interacting with each other

Four Fundamental Forces (Cont.)

Weak Nuclear Force

- Very weak, short range
- 10,000 time weaker than strong nuclear force
- Cause a neutron transforms into a proton

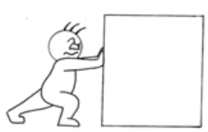
Gravitational Force

An exchanged force with a mass-less mediating particle called graviton

- Gravitational waves were detected in Feb. 2016 for the first time (LIGO)
- Weakest of all forces

Force, $\vec{F}$

- Force is the mechanical interaction between two objects.
  - Force can be a push or a pull



- The unit of force is a newton, in honour of sir Isaac Newton:

$$1\text{ N} = 1\text{ kg m/s}^2$$

Force can act through a contact….

- ……or over a distance

Forces

- Some common forces:
- *At-a-distance*
  - Gravity ,F_g, between any two objects
- *Contact*
  - Normal force, F_N, on objects supported by a surface
  - Static and kinetic friction, F_s, and F_k
  - Air resistance (drag), F_D, on objects moving in air
  - Tension force, F_T, from ropes and cables
  - Applied force, F_A

Gravity, $\vec{F}_g$

Newton's law of universal gravitation:

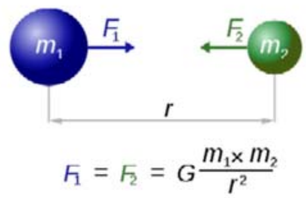
$$F_g = \frac{G m_1 m_2}{r^2}$$

Quantity	Symbol	SI Unit
Masses of objects 1 and 2	m_1, m_2	kg (kilograms)
Distance between the centres of masses	r	m (metres)
Universal gravitational constant	G	N m^2/kg^2

The universal gravitational constant has a value of G = 6.67x10^{-11} N m^2/kg^2

Force of Gravity

- Force of gravity is a force of attraction



Gravity

- The force due to gravity F_g is also called *weight*
- We can use this equation to determine the weight of an object::

$$\vec{F}_g = m\vec{g}$$

  where g is the acceleration due to gravity. On the surface of Earth we use the average value of 9.81 m/s^2 [down]
- *g* is slightly different depending on where you are on Earth

Gravity

Location	Acceleration due to gravity (m/s^2)	Altitude (m)	Distance from Earth's centre (km)
North Pole	9.8322	0 (sea level)	6357
equator	9.7805	0 (sea level)	6378
Mt. Everest (peak)	9.7647	8850	6387
Mariana Ocean Trench* (bottom)	9.8331	11 034 (below sea level)	6367
International Space Station*	9.0795	250 000	6628

Wait! Aren't astronauts in the space station "weightless"?

Gravity

We can get the acceleration due to gravity on other planets by applying the law of universal gravity:

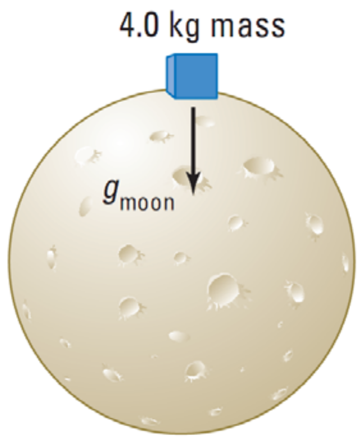
$$mg = G\frac{Mm}{R^2}$$

$$g = G\frac{M}{R^2}$$

Location	Acceleration due to gravity (m/s^2)
Earth	9.81
Moon	1.64
Mars	3.72
Jupiter	25.9

Sample Problem

Example 3: Calculate the weight of a 4.0-kg mass on the surface of the Moon.

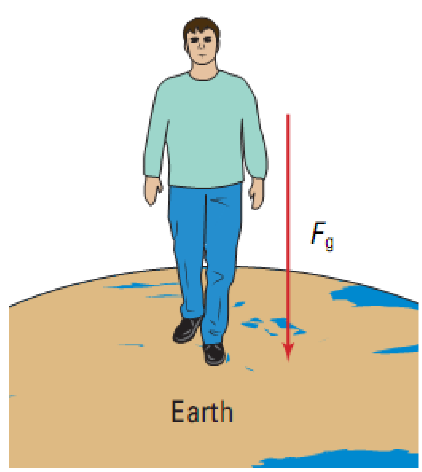


Solution:

$\vec{F}_g = m\vec{g}_M$
$\vec{F}_g = 4.0\ kg\ x 1.64\ m/s^2$ *[to the centre of the Moon]*
$\vec{F}_g = 6.6\ N$*[to the centre of the Moon]*

Sample Problem

Example 4: A student standing on a scientific spring scale on Earth finds that he weighs 825 N. Find his mass.



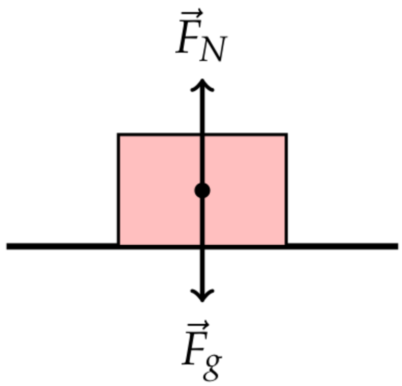
Solution:

$\vec{F}_g = m\vec{g};\ m = \frac{F_g}{g}$

$m = 825\ N/\ (9.81\ m/s^2)$

$m = 84.1\ kg$

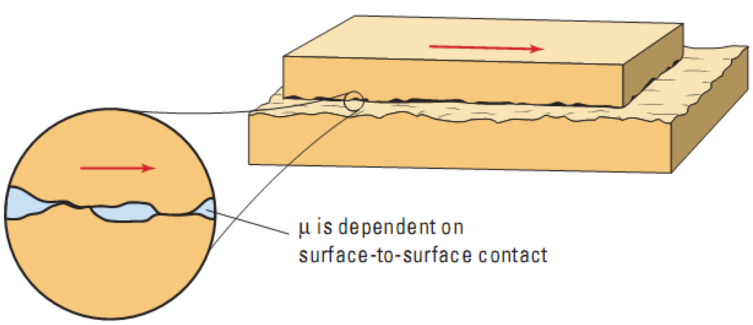
Normal Force, $\vec{F}_N$



- This stationary object has a weight F_g acting on it, therefore the surface must be pushing back, otherwise it will accelerate right through it!
- The push back is called the normal force
- "Normal" means perpendicular, because F_N is always perpendicular to the surfaces in contact
- In this case, F_N equals to gravity in magnitude, but it is opposite in direction (this isn't always true!)

Friction, $\vec{F}_F$

Friction is a force between two surfaces that is responsible for opposing sliding motion.



Static Friction, $\vec{F}_S$

- The friction between the two surfaces that are *not* moving relative to each other
- Static friction depends on applied force; it is at maximum when the object is just about to move.

$$\max F_s = \mu_s F_N$$

Quantity	Symbol	SI Unit
Magnitude of static friction	F_s	N (newtons)
Coefficient of static friction	μ_s	No units
Normal force	F_N	N (newtons)

Kinetic Friction, $\vec{F}_K$

- The friction between the two surfaces that are moving relative to each other
- The kinetic friction is constant along the path of movement

$$F_k = \mu_k F_N$$

Quantity	Symbol	SI Unit
Magnitude of kinetic friction	F_k	N (newtons)
Coefficient of kinetic friction	μ_k	No units
Normal force	F_N	N (newtons)

Typical Friction Coefficients

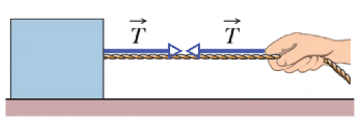
In general,

$$\mu_k \leq \mu_s$$

Surfaces	Coefficient of Static Friction μ_s	Coefficient of Kinetic Friction μ_k
rubber on dry solid surfaces	1 – 4	1
rubber on dry concrete	1.00	0.80
rubber on wet concrete	0.70	0.50
glass on glass	0.94	0.40
steel on steel (unlubricated)	0.74	0.57
steel on steel (lubricated)	0.15	0.06
wood on wood	0.40	0.20
ice on ice	0.10	0.03
Teflon™ on steel in air	0.04	0.04
lubricated ball bearings	< 0.01	< 0.01
synovial joint in humans	0.01	0.003

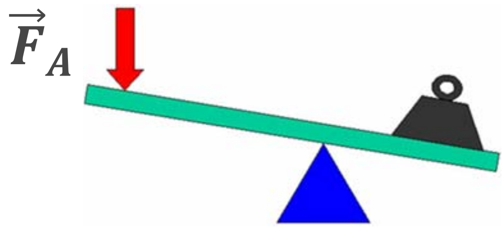
Tension, $\vec{\boldsymbol{F}}_{\boldsymbol{T}}$ or $\vec{\boldsymbol{T}}$

- Forces exerted by objects that can be stretched, e.g. the force in a rope that is being pulled
- Tension is a "pull"
- Direction: towards the centre of the rope, spring, cable etc.



Applied Force, $\vec{F}_A$

A general term for any contact force



Drag (Air Resistance) , $\vec{F}_D$ or $\vec{F}_{Air}$

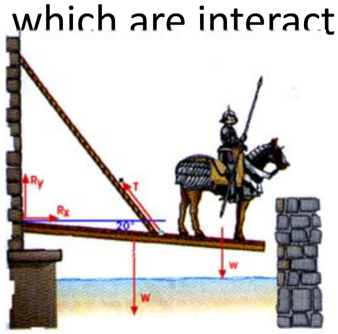
- The force opposing the motion of an object in air
- Unlike friction, drag depend on velocity

Drawing Forces

- System Diagram
- Free Body Diagram (FBD)

System Diagram

- Shows all objects, which are interacting



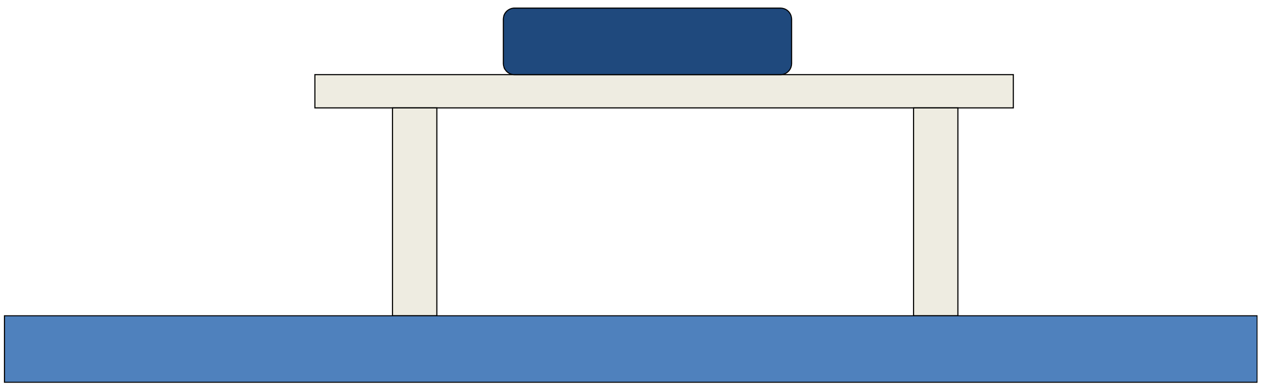
FBD

- Shows all forces acting on a single object

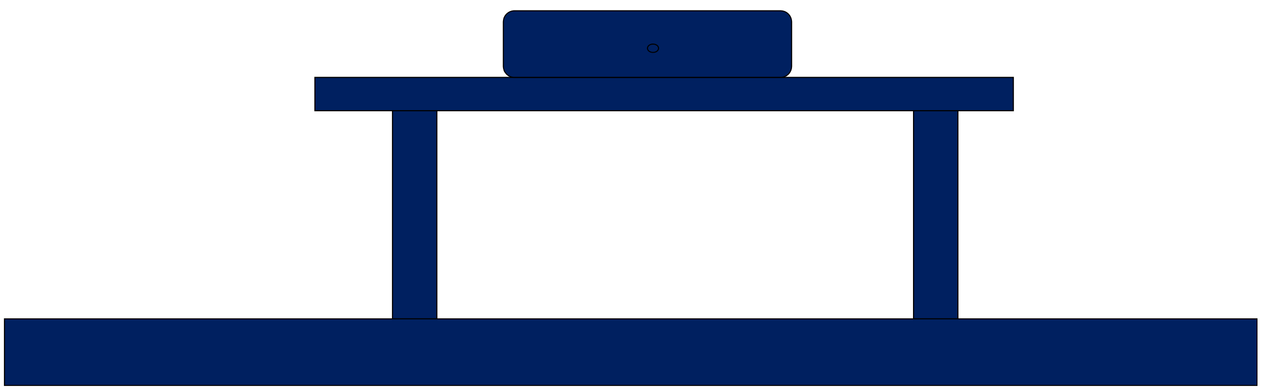
RULES FOR FBD

1. Draw a system diagram (all objects)
2. Select a single object
3. Draw forces at-a-distance (gravity)
4. Count objects, which are in contact with the selected one
5. If the count = *n*, draw *n* contact forces (an label them: applied, tension, normal)
6. Is there any friction present? If yes, indicate it.
7. Add x, y frame of reference.
8. You have drawn a perfect FBD!

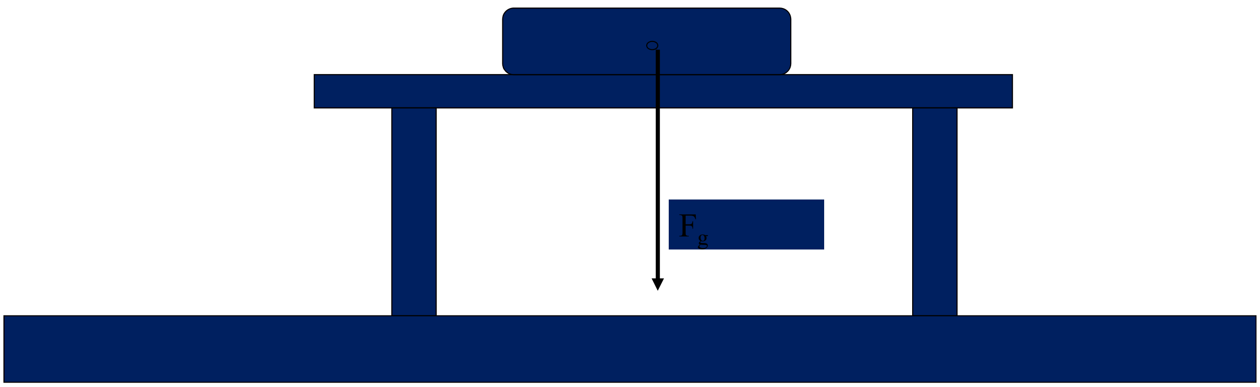
System Diagram



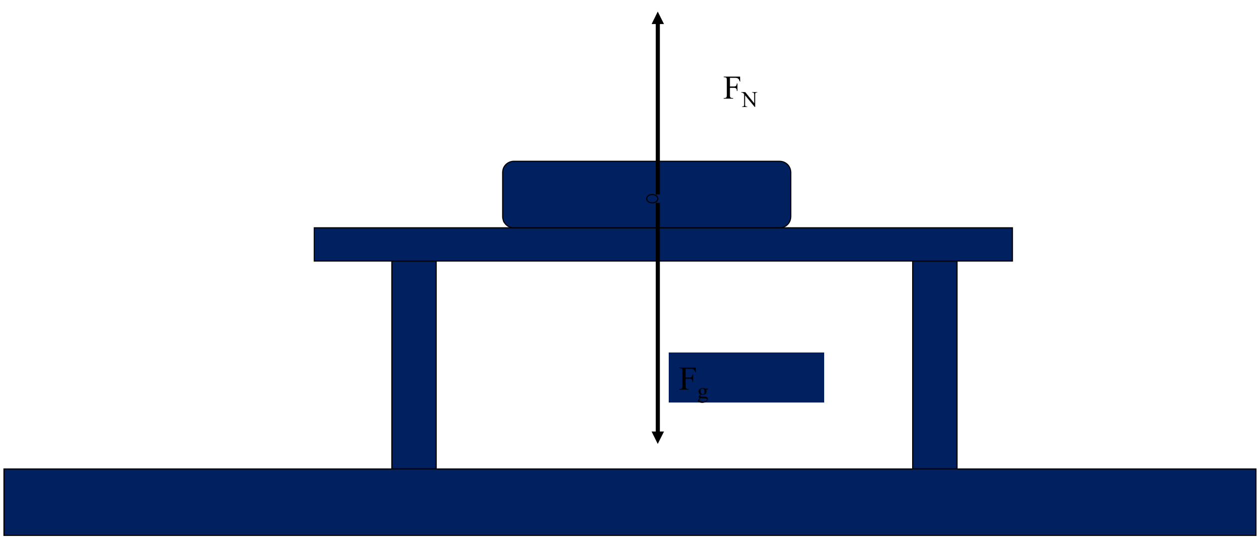
Select Object



Gravity? - Yes

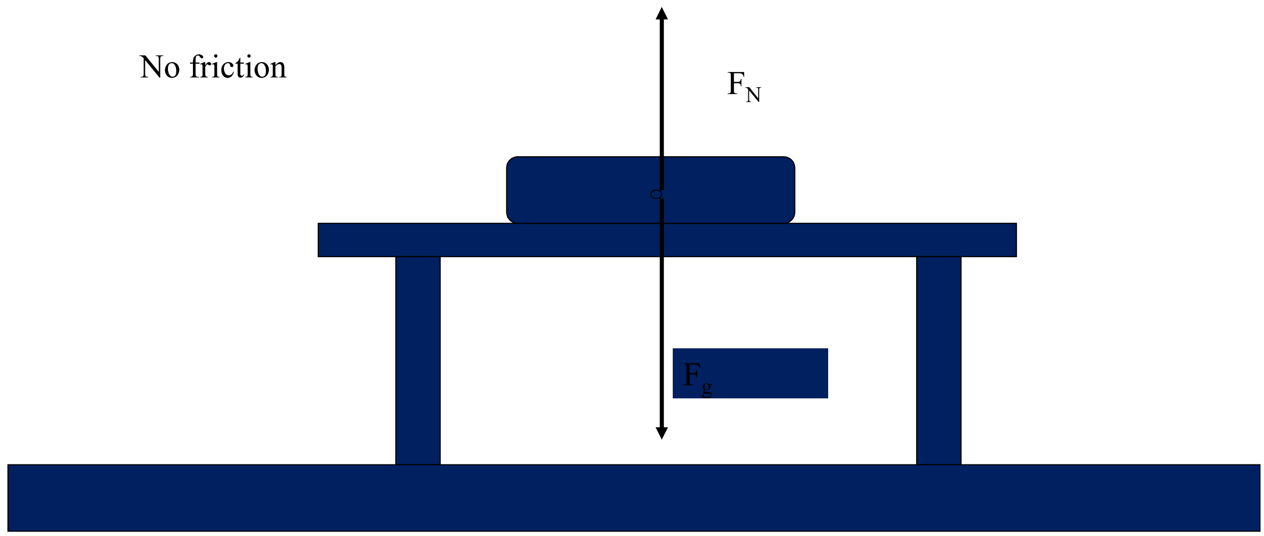


Contact Forces ? - Yes (1)

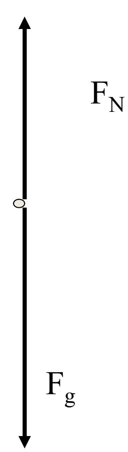


Friction ?

No friction



FBD (Free Body Diagram)

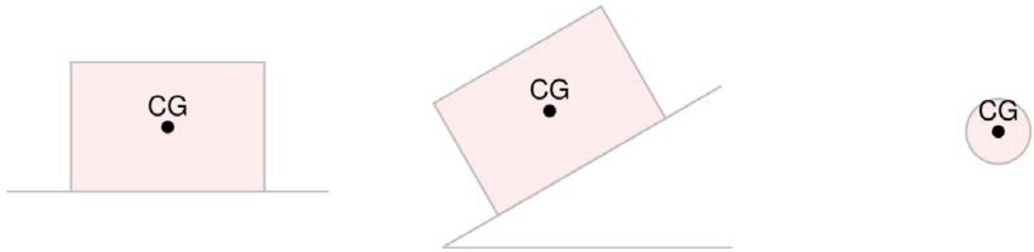


[Up] is "+"

Free-Body Diagrams

Step 1: Draw a “big dot” to represent the centre of mass (aka centre of gravity) of the object

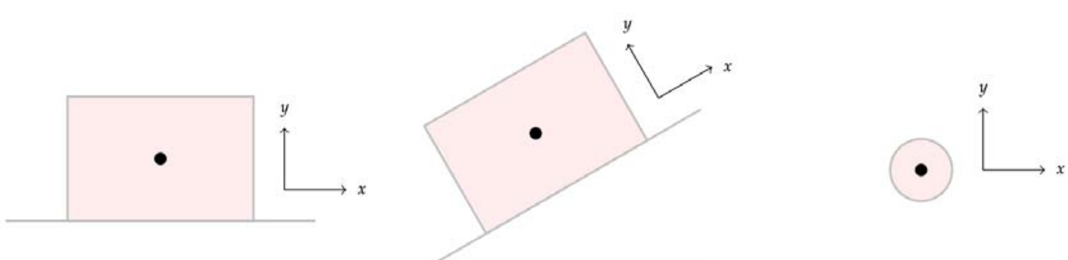
- This makes sense, because we assume that all masses are point masses anyway



Free-Body Diagrams

Step 2: Define a coordinate system (x and y axes)

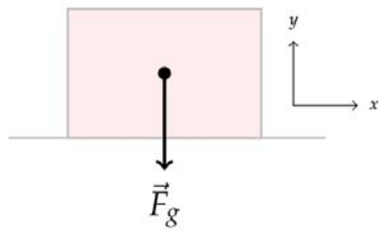
- We can define the axes in any arbitrary direction, but we want to simplify our problem.

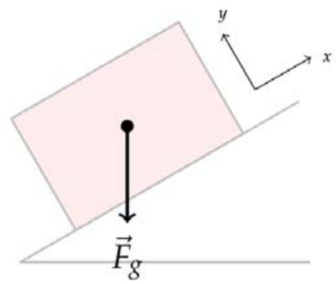


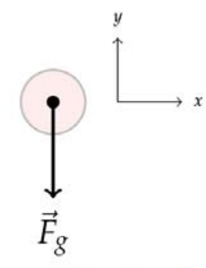
Free-Body Diagrams

Step 3a: Add weight (force due to gravity) F_g

- The force is represented by an arrow that originated at the CG
- F_g always points down by definition
- Generally we want to make the length of the arrow proportional to the other forces on the object



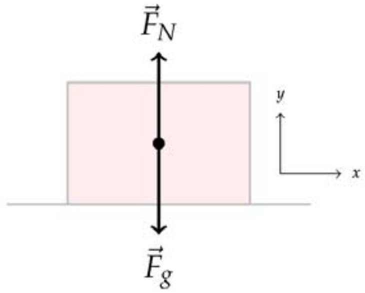


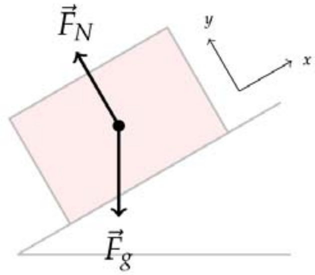


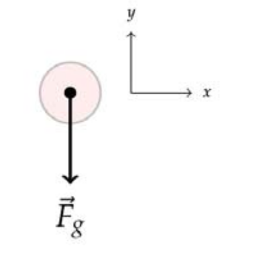
Free-Body Diagrams

Step 3b: If the object is on a surface, then there is a normal force F_N

- Not every problem has a normal force, only the ones where the object is on a surface!
- F_N is always *perpendicular* to the contact surface



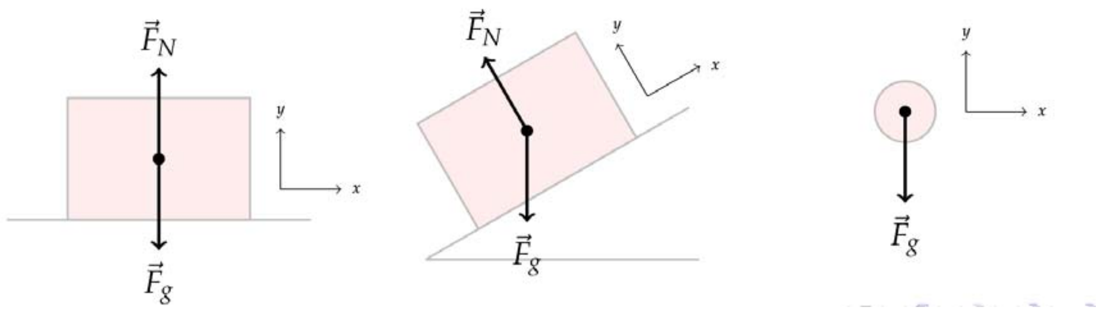




Free-Body Diagrams

Step 3c: Is the object being pulled/pushed? If so, then there is an applied force F_a

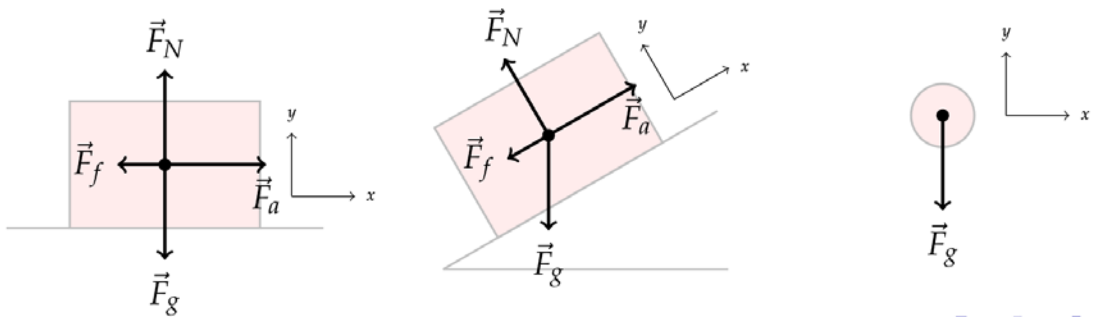
- Not every problem has an applied force, **so read the questions carefully!**
- The direction of F_a is usually given in the problem



Free-Body Diagrams

Step 3d: Is the object moving against a surface? Is there any friction?

- The direction of the friction force is opposite the direction of
-



Free-Body Diagrams

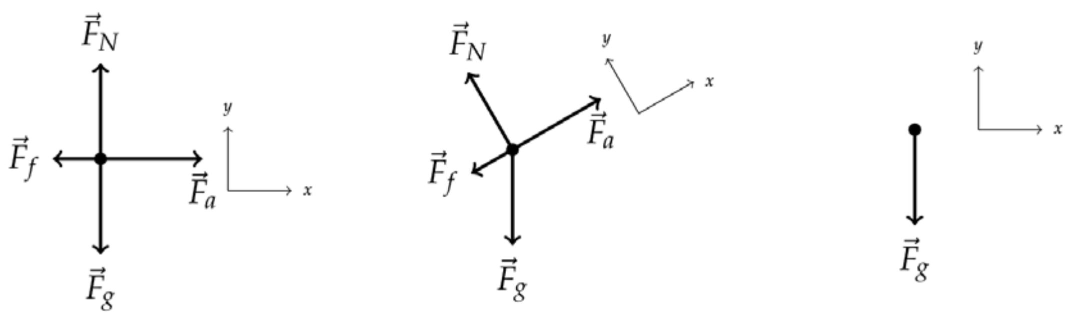
Step 3e: Are there any other forces?

- Is it being pulled by a cable? Draw **Tension**
- Is it moving in air or another fluid? Draw **Drag** (Most problems in Grade 11 Physics ignore drag)

Free-Body Diagrams

Step 4: The final free-body diagram does not require drawing the object itself.

- Make sure the arrows representing the forces originate at the CG
- It is generally a good practice to approximately scale the lengths of the arrows to the magnitude of the forces



Why FBDs?

- To find a net force

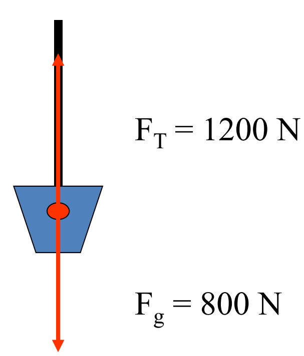
The net force is the vector sum of all forces acting on an object

Symbol : $\vec{F}_{NET}$, or $\sum \vec{F}$

FBD and NET FORCE

Example 1.

Pulling up a bucket on a rope

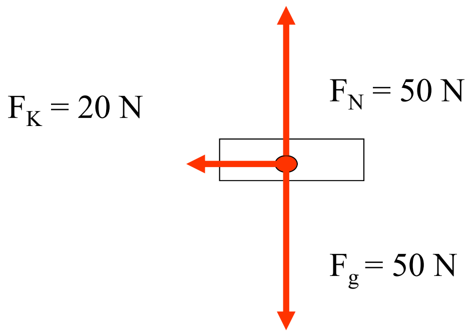


$\boxed{F_{NET} = 400 \text{ N [up]}}$

FBD and NET FORCE

Example 2.

Cart coasting along a horizontal track

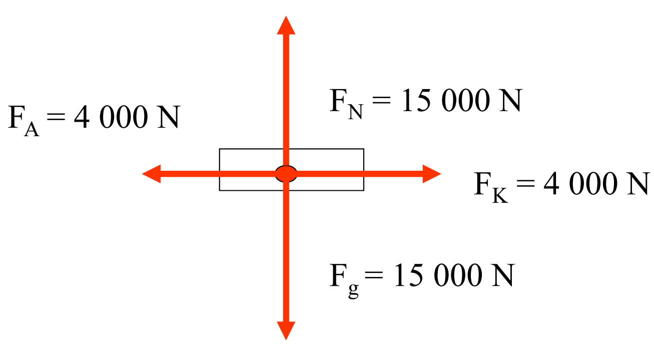


$\boxed{F_{NET} = 20 \text{ N [left]}}$

FBD and NET FORCE

Example 3.

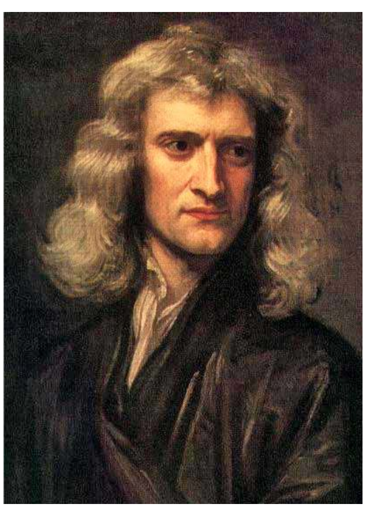
Car on a road



$\boxed{F_{NET} = 0 \text{ N}}$

The effect of the net force on object’s motion was formulated by: ……………….

The Beginning of Physics



- 1687: *Philosophiæ Naturalis Principia Mathematica* (“Mathematical Principles of Natural Philosophy”)
- One of the most important publications in science
- Laid down the foundation of what we now call
  - Classical (or “Newtonian”) mechanics
  - Calculus
- Based on works by Galileo and Johannes Kepler
- The physics (and all the equations) based on Newton’s Laws are very successful in describing and predicting most physical phenomena

Newton's First Law of Motion (N1LM):

If the net force acting on the object is zero, the object will remain its state of rest or constant velocity (has no acceleration)

WHEN FORCES ARE BALANCED

OBJECTS AT REST, STAY AT REST

OBJECTS IN MOTION, STAY IN MOTION

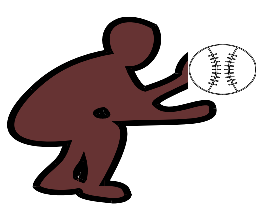
[SAME SPEED & DIRECTION]

First Law (The Law of Inertia)

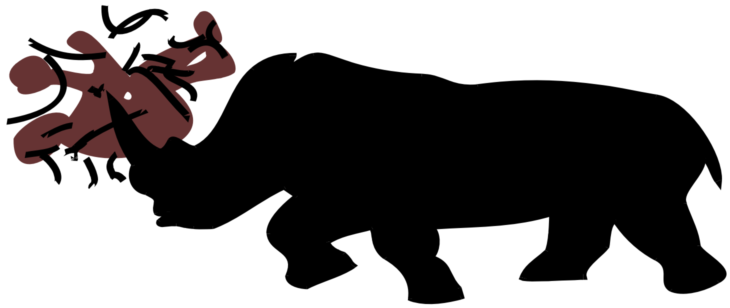
DEFINITION OF INERTIA

Inertia is the natural tendency of an object to remain in its current state of motion. The amount of an object's inertia is directly related to its mass.

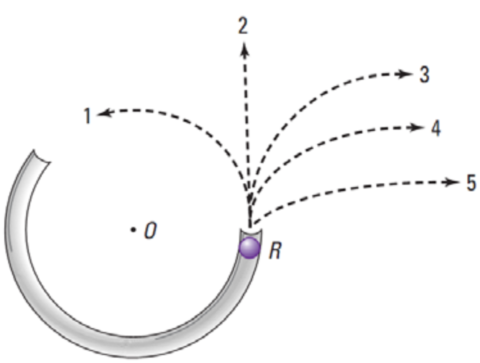
Can you catch a baseball?



Can you catch this object…….?



Sample Problem



Top View

Example 1: A marble is fired from a circular tube that is anchored onto a frictionless tabletop. Which of the five paths will the ball take as it exits the tube and moves across the tabletop? Justify your answer.

Second Law (F = ma)

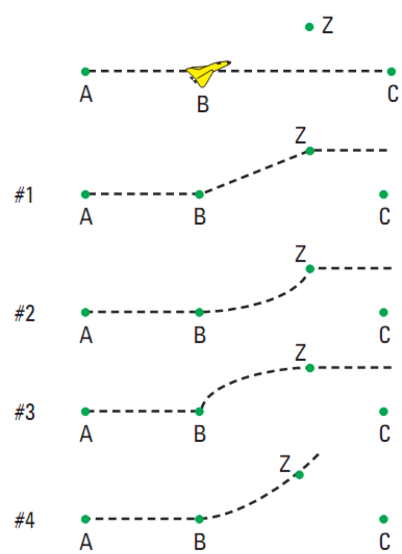
Second Law The force acting on an object is equal to the mass of that object times its acceleration.

$$\vec{F}_{\text{net}} = \sum \vec{F} = m\vec{a}$$

- This equation is correct only when mass is constant

Example Problem

Example 2: A spacecraft is lost in deep space, far from any objects, and is drifting along from point A toward point C. The crew fires the on-board rockets that exert a constant force exactly perpendicular to the direction of drift. If the constant thrust from the rockets is maintained from point B until point Z is reached, which diagram best illustrates the path of the spacecraft?



Newton's Third Law (Action-Reaction Law)

Third Law For every action there is an equal and opposite reaction.

- **Important note:** The action/reaction forces act on different objects!
- F_{AB} and F_{BA} DO NOT cancel each other!

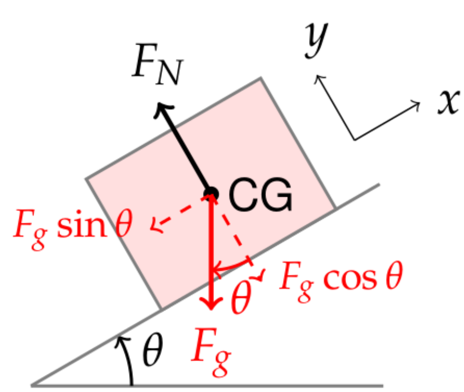
$$\vec{F}_{\text{A on B}} = -\vec{F}_{\text{B on A}}$$

Normal Force on an Inclined Surface

There is a relationship between gravity an normal force for an object on a slope:

$$\begin{aligned} F_N &= F_g \cos\theta \\ &= mg \cos\theta \end{aligned}$$

Normal force decreases as θ increases (at θ = 90°, then there is no long any normal force.) At the same, time, the component of gravity along the ramp (F_g $\sin\theta$) increases from zero at ϑ = 0° to mg at ϑ = 90°.



Sample Problem

Example 5: During the winter, owners of pickup trucks often place sandbags in the rear of their vehicles. Calculate the increased static force of friction between the rubber tires and wet concrete resulting from the addition of 200 kg of sandbags in the back of the truck.

Solution:
μ_s =0.70
$F_s = \mu_s F_N$;
F_N = mg (on leveled road)

$\Delta F_s = \mu_s \Delta F_N$;
$\Delta F_N = (\Delta m)g$

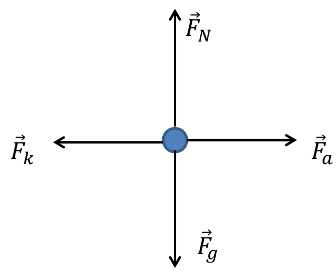
$\Delta F_s = (0.70)(200)(9.81)$N;
$\Delta F_N = 1.4\text{x}10^3$ N

Sample Problem

Example 6: A horizontal force of 85 N is required to pull a child in a sled at constant speed over dry snow to overcome the force of friction. The child and sled have a combined mass of 52 kg. Calculate the coefficient of kinetic friction between the sled and the snow.

Solution

- FBD



$\vec{v}$ is constant, the forces are balanced:

$F_N = F_g$
$F_a = F_k$

$F_N = mg$
$F_N = (52\ \text{kg})(9.81)\ \text{N}$
$F_N = 510\ \text{N}$

$F_k = 85\ \text{N}$
$\mu_k = \frac{F_k}{F_N}$ *(definition)*

$\mu_k = \frac{85\ N}{510\ N}$

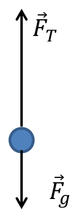
$\mu_k = 0.17$

Sample Problem

Example 7: A man is riding in an elevator. The combined mass of the man and the elevator is $7.00\text{x}10^2$ kg. Calculate the magnitude and direction of the elevator's acceleration if the tension (F_T) in the supporting cable is $7.50\text{x}10^3$ N.

Solution

- FBD



The forces are not balanced

Let Up be positive
Net Force : $\sum \vec{F} = \vec{F}_T + \vec{F}_g$

$$\sum \vec{F} = +F_T - F_g$$

$$\sum \vec{F} = 7.50x103\ N - (7.00x102\ kg)(9.81\frac{m}{s^2})$$

$$\sum \vec{F} = 6.33x102\ N$$

$\vec{a} = \frac{\sum \vec{F}}{m}$; $\quad \vec{a} = \frac{6.33x102\ N}{7.00x102\ kg}$; $\vec{a} = \frac{6.33x102\ N}{7.00x102\ kg}$;

$\vec{a}$ =9.04x10^{-1} m/s^2

Sample Problem

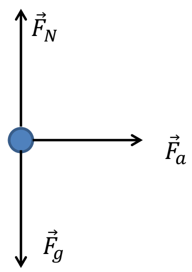
Example 8: A curler exerts an average force of 9.50 N [S] on a 20.0 kg stone. (Assume that ice is frictionless.) The stone started from rest and was in contact with her hand for 1.86 s.

- Determine the average acceleration of the stone.
- Determine the velocity of the stone when the curler releases it.

Solution

The forces are not balanced

- FBD



Net Force : $\sum \vec{F} = \vec{F}_g + \vec{F}_N + \vec{F}_A$

$$\sum \vec{F} = \vec{F}_A$$

$\vec{a} = \frac{\sum \vec{F}}{m}$; $\vec{a} = \frac{9.5N[S]}{20\,kg}$;

$\vec{a}$ =4.75x10^{-1} m/s^2 [S]

$\vec{v}_2 = \vec{v}_1 + \vec{a}\Delta t$; $\vec{v}_1$=0

$\vec{v}_2$ = (4.75x10^{-1} m/s^2 [S])(1.86 s)

$\vec{v}_2$ = 8.84x10^{-1} m/s[S]

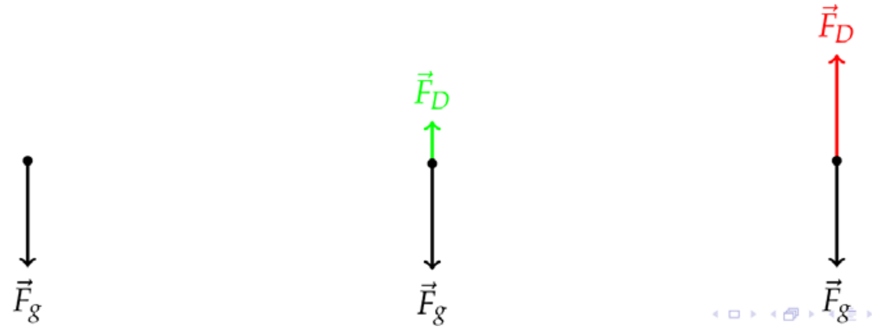
Terminal Velocity

So far, we have ignored effects of air resistance, but if it is present, a falling object will not accelerate infinitely. Instead it reaches a terminal velocity.

There is no air resistance just as the object begins to fall. Acceleration is due to gravity alone.

Drag increases as v increases. Magnitude of acceleration decreases, but the object continues to gather speed

Terminal velocity is reached when the drag force equals the object's weight. Not net force; no acceleration.



Unit 3 Homework Answers

4. b) 1.1×10^2 N; c) 2.9 m/s^2
5. a) 66.5 kg; b) 654 N; c) 604 N
6. b) 20.6 N; c) 3.50 N; 0.170
7. 40 N [N30^0E]
8. a) 5.49×10^6 N; b) 6.1×10^6 N
9. NOTE: Change the last sentence to: The box starts from the rest and slides for 2.0 s.
9. b) 11 N; c) 3.8 m/s^2; 7.6 m
10. 17^0
11. D
12. D
13. A
14. A
15. D
16. D
17. C
18. B
19. D
20. A
21. C
22. D
23. B
24. C
25. A
26. D
27. D
28. B
29. A
30. A
31. B
32. D
33. D