Newton's laws of motion

1. *The law of inertia.* An object in motion remains in motion with constant velocity if the net force on the object is 0.

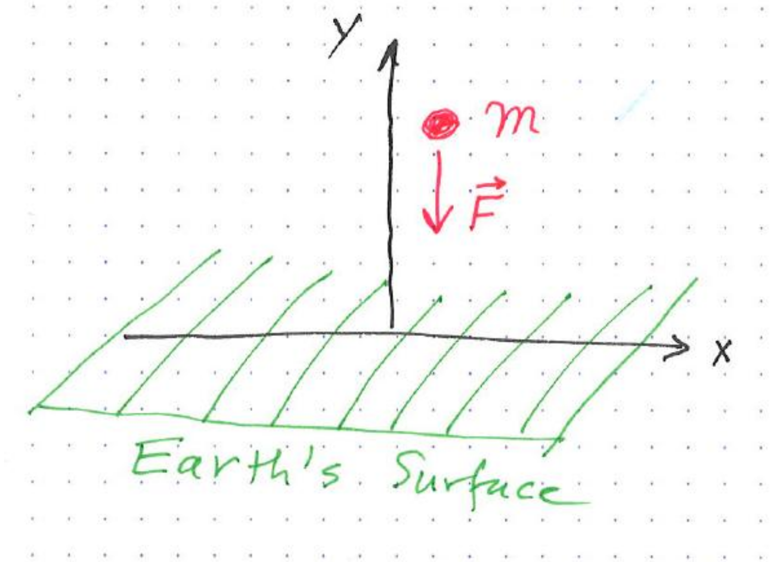
2. *Force and acceleration.* If the net force acting on an object of mass m is $\mathbf{F}$, then the acceleration of the object is $\mathbf{a} = \mathbf{F}/m$. Or, $\mathbf{F} = m\mathbf{a}$.

3. *Action and reaction.* For every action there is an equal but opposite reaction.

Action means *force.*

Example

What is the force of gravity on the mass *m*?



If released, its acceleration would be $\mathbf{a} = -g\hat{\mathbf{j}}$

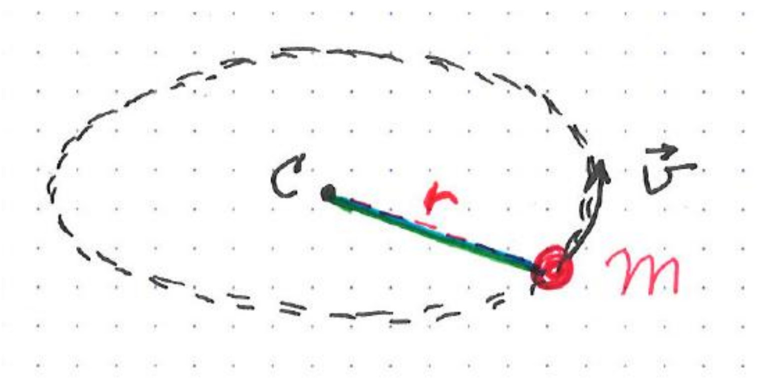
By Newton's second law the force on *m* must be

$$\mathbf{F} = -mg\hat{\mathbf{j}}$$

(By the way, what is the reaction force?)

Example

What is the tension in the string?



The "string tension" is the strength of the force exerted by the string at either end.

Uniform circular motion implies centripetal acceleration, and

$$\mathbf{a} = -(v^2/r)\,\hat{\mathbf{r}}$$ (Christian Huygens, 1673)

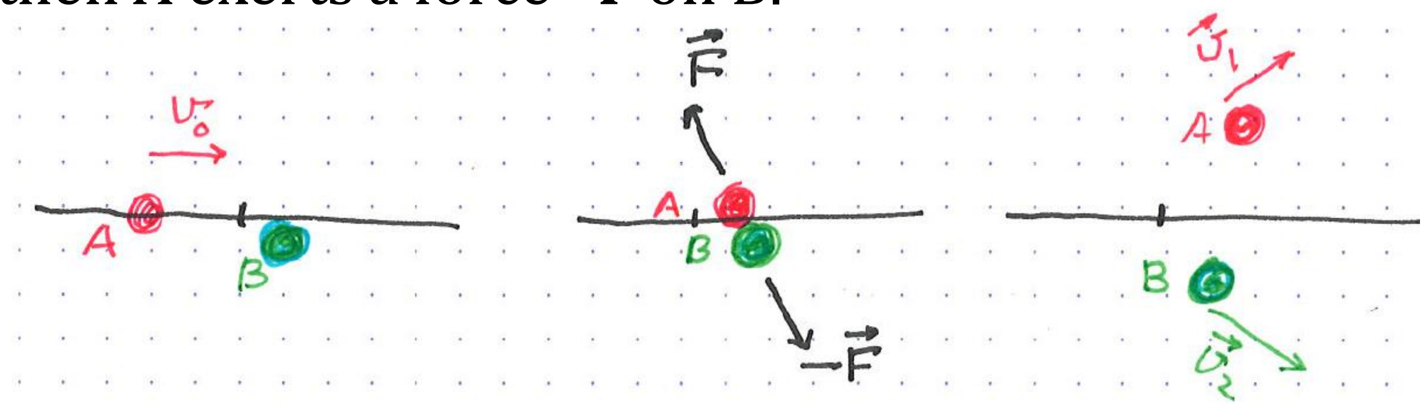
Therefore, $\mathbf{F} = -(mv^2/r)\,\hat{\mathbf{r}}$ the force on *m*

$$T = \frac{mv^2}{r}$$

Newton’s third law

For every action there is an equal but opposite reaction.

If an object B exerts a force **F** on another object A, then A exerts a force **–F** on B.



Forces always occur like this, in equal but opposite pairs.

Sometimes confusing!

Example

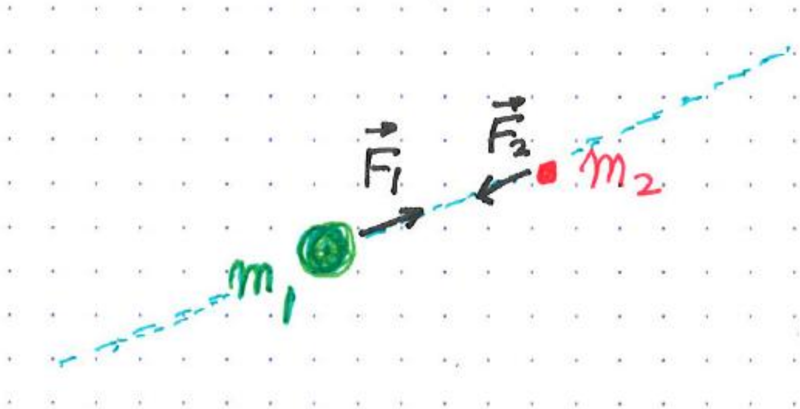
How much force does the block exert on the table?

Careful analysis…

- **The force of gravity on the block is −mg.**
- **The net force *on the block* is 0, because it does not accelerate.**
- **The force exerted by the table *on the block* must be *+mg* so that the net force is 0.**
- **By Newton's third law, the force exerted by the block *on the table* must be *−mg*.**

Answer : $-mg$

An example of Newton's third law – Universal gravitation



$$\mathbf{F_1} = \frac{Gm_1m_2}{r^2}\mathbf{n_1}$$

$$\mathbf{F_2} = \frac{Gm_1m_2}{r^2}\mathbf{n_2} = -\mathbf{F_1}$$

$$G = 6.67 \times 10^{-11}\ \mathrm{m^3\ s^{-2}\ kg^{-1}}$$

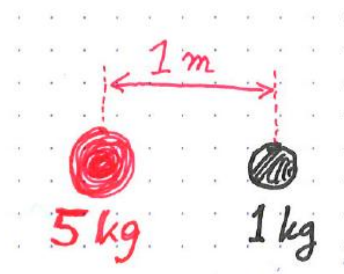
<u>Example</u> Suppose the Earth attracts a man with a force of 180 pounds (= his weight, by definition).

The man attracts the Earth with a force of 180 pounds.

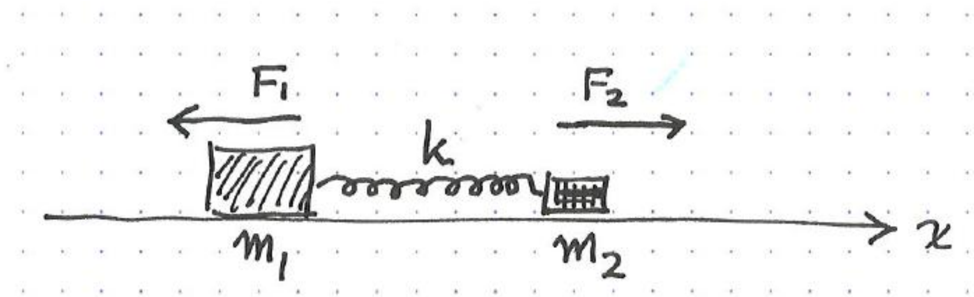
<u>Example</u>

The force on the 1 kg mass is -33×10^{-11} N.

The force on the 5 kg mass is $+33 \times 10^{-11}$ N.



Example of Newton's third law – a spring



Let L = the equilibrium length of the spring.

Compression: $x_2 - x_1 < L$

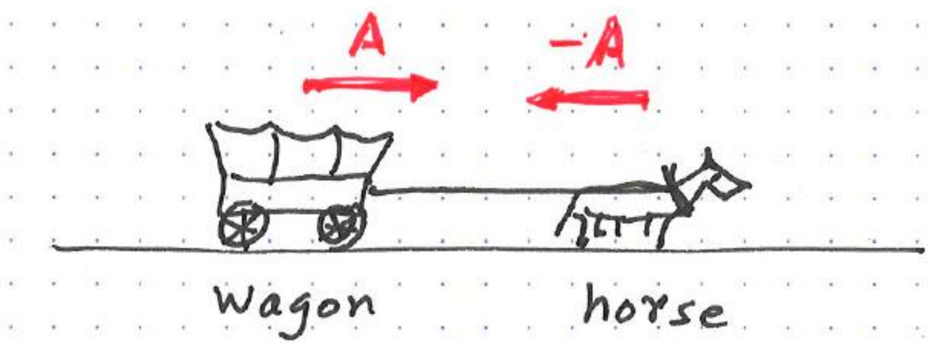
The force on the mass m_2 is $F_2 = -k(x_2 - x_1 - L)$ in the x direction

(k = Hooke's constant)

The force on the mass m_1 is $F_1 = +k(x_2 - x_1 - L)$ in the x direction,

. . . which agrees with Newton's third law.

Example: horse and wagon



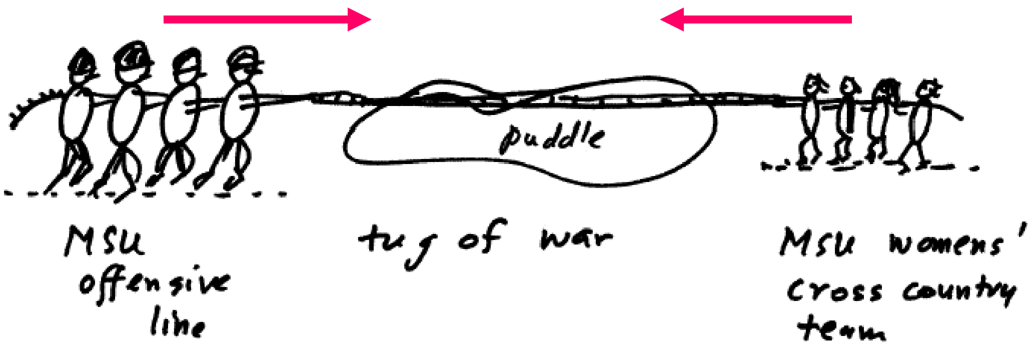
The horse pulls the wagon with a force *A* (to the right).

According to Newton, the cart pulls the horse with a force −*A* (to the left).

So how can they move, or accelerate if starting from rest?

A puzzle …

Tug of War



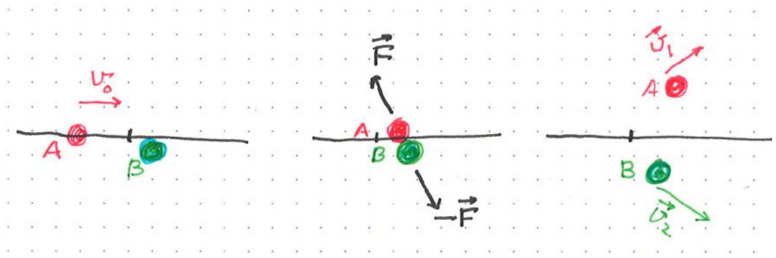
Which team will end up in the puddle?

But aren't the forces equal but opposite !?

Resolution: Don't forget that *there are other forces acting.*

Momentum

As vectors, $\mathbf{p} = m\,\mathbf{v}$



Define $p = mv$.

When two objects interact,

$$\Delta p_1 = m_1 \Delta v_1 = m_1 a_1 \Delta t = F_1 \Delta t,$$

and $\Delta p_2 = m_2 \Delta v_2 = m_2 a_2 \Delta t = F_2 \Delta t$.

By Newton's third law, $F_2 = -F_1$, so

$$\Delta p_1 + \Delta p_2 = 0;$$

i.e., $p_1 + p_2$ is constant.

Conservation of momentum

A puzzle …

A small car collides with a big truck. Which is greater – the force exerted by the truck or the force exerted by the car?

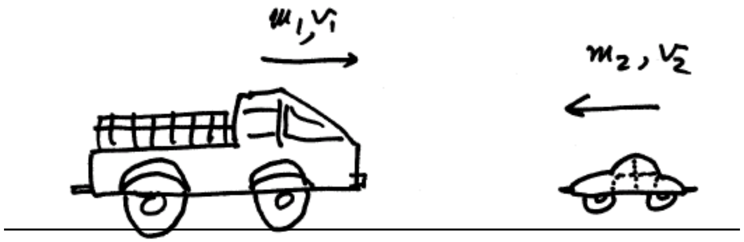
Conservation of momentum:

initial = final

$m_1 v_1 + m_2 v_2 = (m_1 + m_2) V$

Thus,

$m_1 (v_1 - V) = m_2 (V - v_2) \quad (*)$



According to Newton's third law, the two forces are equal. Let's calculate them, assuming the collision time is a small Δt.

$$F_1 = m_1 a_1 = m_1 \frac{\Delta v_1}{\Delta t} = m_1 \frac{(V - v_1)}{\Delta t}$$

$$F_2 = m_2 a_2 = m_2 \frac{\Delta v_2}{\Delta t} = m_2 \frac{(V - v_2)}{\Delta t}$$

$$F_2 = -F_1 \qquad \text{by} \quad (*)$$

The four fundamental forces

- Gravity
- Electromagnetic
- Strong nuclear force
- Weak nuclear force

unified by Maxwell's theory

comes from QCD, the interaction of quarks and gluons

not really a force, but an interaction that causes certain radioactive decays

All these interactions obey conservation of momentum, i.e., Newton's third law.