CENTRIFUGE AND CIRCULAR MOTION

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I. THE LAWS OF CIRCULAR MOTION

The laws of circular motion were discovered and formulated by the English mathematician and physicist Isaac Newton (1642 - 1727).

Principle of inertia

'*A moving mass on which no force acts, describes a perfectly rectilinear trajectory*.'

Force concept

'*A force refers at any cause capable of deflecting the trajectory of a mass.*'

Principle of reciprocity

'*Any mass on which a force is acting, responds by a reciprocal action of equal intensity, but of opposite direction.*'

These three laws allow to describe any circular motion:

- Movement of the Earth around the Sun.
- Movement of a centrifuge.
- Movement of a ball that turns around an axis.

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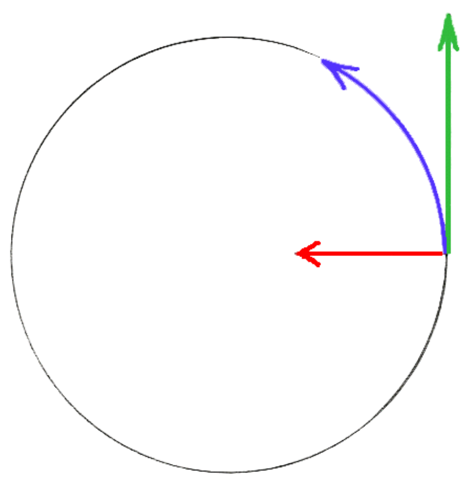
II. EARTH TURNS AROUND THE SUN

The laws of physics are those of the Universe, so these are universal laws: they apply equally to the solar system, to the centrifuge, to the ball that rotates around an axle, to the path of a car or to any circular motion, this has been discovered by the genius of Isaac Newton.

These laws apply to the movement of the Earth which orbits the Sun at a speed of 30 kilometers per second on a circular path radius of 150 million kilometers.

How to explain this trajectory? It is due to the gravitational force created by the mass of the sun. This mysterious force (also called centripetal force) acts at a distance, it is of the same nature as that which, on Earth, attracts objects on the ground.



Schematic representation of the motion of the Earth.

Earth describes a circular path (blue arrow) because of the gravitational force (red arrow) which attracts towards the sun. If this force did not exist, the Earth would take a straight path (green arrow). Be careful not to add force, speed and trajectory!

Change the laws of the Universe ...

Imagine that the laws of the universe are completely changed. What would happen if the Earth had a zero speed or suddenly ceased to obey the attraction of the Sun?

- without speed but driven by gravitation, the Earth immediately would take the direction of the Sun, until to dive into it.

- without gravitation but retaining its speed, Earth immediately would adopt a straight path and move away from the Sun.

Insist on this point: if the Earth was moving away from the Sun, it would be a gravitational force default and not because of any centrifugal force.

The third principle of the third Newton

Newton's principle states that any force acting on a mass causes a reciprocal action of equal intensity but opposite direction.

Does this principle apply in the case of the solar system? Yes of course!

The Sun attracts the Earth, so the Earth also attracts the Sun, with the same intensity but opposite! This force acts at the center of the Sun, it is oriented towards to the center of the Earth.

Why the Earth deflects its trajectory, the Sun remaining perfectly still? It is a question of strength between two unequal masses: the Sun has 333,333 times more mass than the Earth(*).

Conclusion

The concept of centrifugal force is not longer necessary in this description than in any other!

(*) *Mass of the Sun (S): 2 x 10^{30} kg; mass of the Earth (T): 6 x 10^{24} kg; ratio S / T: 0.33 x 10^{6}.*

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III. THE CENTRIFUGE

Everyone knows the principle of the centrifuge which is used in a washing machine or washer dryer.

Centrifuge comes from ‘centrifugal’ that just means 'which moves away from the center.'

Does the centrifuge prove the existence of centrifugal force?

This is what we'll see ...

A fundamental principle ...

A fundamental principle of physics (this is the Newton's first law) provides that the normal trajectory of a moving body is perfectly rectilinear.

This natural path can only be deflected by a transverse force. The concept of force follows from the previous principle: a force is any cause able to deflect a trajectory.

There are two types of forces corresponding to this definition: the gravitational force acting at a distance and the guiding force that acts by contact.

These laws are the foundation of modern physics, they were discovered and formulated by the English physicist Isaac Newton in 1666.

How does a centrifuge?

The essential part of a centrifuge is a drum, a kind of hollow cylinder with holes on surface to let the water out, and an electric motor. The electric motor drives the drum in a circular motion.

The circular motion of the drum forces the wet laundry to describe a circular path.

According to Newton's law, the laundry in motion should take a straight path. If the laundry describes a circular path, it is because it is constantly driven by the force of the drum. This force acts in the direction of the axle, but is no centripetal one (see ADILCA folder '*centripetal force*').

No centrifugal or centripetal force therefore acts on the machine, at any time whatsoever.

The drainage

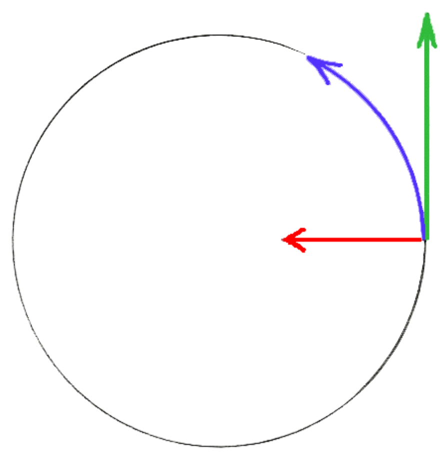
How the water comes out of the drum?

It has been said that the drum is a cylinder with holes. The machine can communicate a guiding force to water molecules only in contact with the drum. When water molecules reach the holes, the guiding force is zero, so they immediately adopt a straight path that leads them to the outside of the drum.

This trajectory is not radial, that is to say in the extension of the radius, but tangential, i.e. perpendicular to the radius of the drum. So, if the water comes out of the drum, it is because of a default guiding force and not because of the centrifugal force.

To be precise, the trajectory of the water molecules is perfectly straight as when they leave the drum, but gradually this path is influenced by the combined action of the force of gravity and the air resistance.

But no centrifugal force affects the water molecules at any time whatsoever, no more inside and outside of the drum.



Principle of the centrifuge

Wet laundry in a circle (blue arrow) through the contact force (red arrow) exerted by the drum. Water leaves the drum on a straight line tangent to the radius (green arrow). Be careful not to add force, speed and trajectory!

Conclusion

The centrifuge exists, but not the centrifugal force!

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IV. A BALL THAT TURNS AROUND AN AXLE

Some 'pseudo-physicists'[1], probably anxious to come to the aid of the concept of centrifugal force, thought they could prove the existence of an imaginary force by describing the circular motion of a ball around a rotation axle! Wasted effort!

Abuse of the concept of centrifugal force comes under the manipulation or incompetence. Indeed, the centrifugal force being an imaginary force, we can and we must do without, whatever the circular motion considered: centrifuge, ball held by a string, car, earth, etc.

If we cannot, it's because there is a 'bug' somewhere! For you to find it!

Description of the device

Imagine a device such as a motor driving a vertical shaft with, at the end of the shaft, a string holding a ball. At rest, a single force acts on the ball, it is its weight. The ball remains motionless because its weight is balanced by the string. The system is in equilibrium.

The rotary system

Let start the engine. Once the system begins to rotate, the equilibrium condition is no longer respected. After the acceleration phase[2], as soon as the rotation speed is stabilized, the ball has moved away from the axle, it describes a circular path in a horizontal plane, the string forms an angle with respect to the vertical.

The Contenders

According to the fundamental principle of physics (Newton's first law), the ball in motion should describe a straight path. If it does not, it is because the ball is constantly driven by a force which imposes this circular path.

This force is directed toward the axle[3], but where does it come from ?

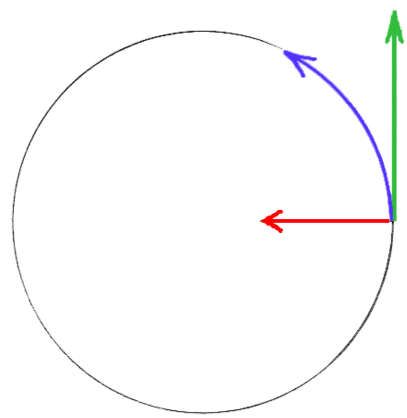
Unlike the situation observed at rest, the equilibrium now is broken because there are two forces involved in the system by the tension of the string:

- a vertical one, of equal intensity but opposite to the weight, that keeps the ball in the air;

- a horizontal one that maintains the ball on a circular path.

The string tension is equal to the resultant (in other words, to the vector sum) of these two forces.

This description is complete like that! There is no need to add anything, especially not centrifugal force. There is no need, and for a good reason: the centrifugal force does not exist!



Device seen from above: the ball describes a circular path (blue arrow) because of the horizontal force (red arrow) transmitted by the string (axle and string do not appear in the drawing). If this force suddenly stops acting, for example in the event of a string breakage, the ball escapes by a rectilinear way (green arrow). Be careful not to add force, speed and trajectory!

Calculation of the horizontal force

What relationship should be used to calculate the intensity of this horizontal force? Only this one:

$$\mathbf{F = M\ V^2 / R}$$

According to the International System of Units (**SI**) and to ensure the validity of the relationship, the mass M of the ball shall be expressed in kilograms (kg symbol), its speed V in meters per second ($m.s^{-1}$ symbol) and the radius R of its trajectory in meters (m symbol).

The result is expressed in newtons (symbol N), the international unit of force.

The consistency of the units:

$$\mathbf{F} = kg\ .\ (m.s^{-1})^2\ .\ m^{-1} = kg\ .\ m^2.s^{-2}\ .\ m^{-1} = kg\ .\ m.s^{-2} = \mathbf{N}$$

The third principle of Newton

The third Newton's principle states that any force acting on a mass causes a reciprocal action of equal intensity but opposite direction.

How this principle, often misunderstood, does apply in the case of the device described above? Of a very simple and very logical way: the ball in motion exerts a pull on the string, and therefore on the axle. The intensity of this traction is equal to the vector sum of the weight of the ball and the horizontal force[(4)].

If the ball goes on the circular path while the axle remains insensitive to this traction, it is either because the motor forms a substantially heavier mass than the ball, either because the device is firmly fixed to the Earth[(5)].

In fact, if it were not the case, the axle and engine would be overthrown by the motion of the ball.

A 'static' description

Imagine now the same device, this time with an observer placed on the axle and turning at the same time as him. The observer then having no longer any perception of rotation, it would require him to reason with statics, that is, to reason as if the ball stopped turning.

Twisted reasoning? Not at all! Humans have reasoned like this for millennia, until the advent of Copernic, Galilei and Newton! Indeed, the truth at that time was to describe the movement of the Sun and the planets of the solar system assuming that the Earth was motionless.

The funny thing is that this way of thinking continues today! With qualifiers that few people understand: they say that they reason in a relative, non-inertial or non-Galilean framework. In short, it is enough to say that we reason in statics, it is strictly the same reasoning!

As for the manual, do not look elsewhere! Our website is almost the only one to carefully distinguish descriptions, and taking great care never to mix them!

This reasoning is called 'static' as opposed to reasoning 'dynamic' explained above. What are the limits of this reasoning?

The ball movement is now frozen, as if watching from a photograph. How then to explain the angle of the string relative to the vertical? This is where the centrifugal force appears. Centrifugal the misnamed!

Indeed, to keep the ball in balance and explain the angle of the string relative to the vertical, imagine a fictive force acting horizontally on the center of mass of the ball, but in a direction opposite to that of the axle! That is the centrifugal force!

The misnamed force because there is neither circular path nor center, the ball motion having disappeared in the eyes of the observer!

Let us add here, the third principle of Newton is strictly inapplicable since there is no interaction, the centrifugal force being an imaginary force.

Calculation of the centrifugal force

What relationship should be used to calculate the intensity of centrifugal force? This one, and the only one:

$$\mathbf{F' = - M\, g \text{ tangent } \alpha}$$

The sign [–] is to specify the spatial orientation of the force. According to the International Units System (SI) and to ensure the validity of the relationship, the mass M of the ball shall be expressed in kilograms (kg symbol), the gravitational acceleration $\mathbf{g}$ in meters per second squared (symbol $m.s^{-2}$) and the angle α of the string with respect to the vertical, in either degrees or radians (trigonometric values have no dimension).

The result is expressed in newtons (N symbol) which is the international unit of force.

The consistency of units and checks:

$$\mathbf{F'} = kg \,.\, m.s^{-2} = \mathbf{N}$$

Equality = danger!

A numerical application of these relations give a surprising result: all other conditions being equal, we find that the horizontal force and the centrifugal force have exactly the same intensity!

However, nothing should be concluded because these two forces do not belong to the same description! The worst mistake is to confuse or mix them:

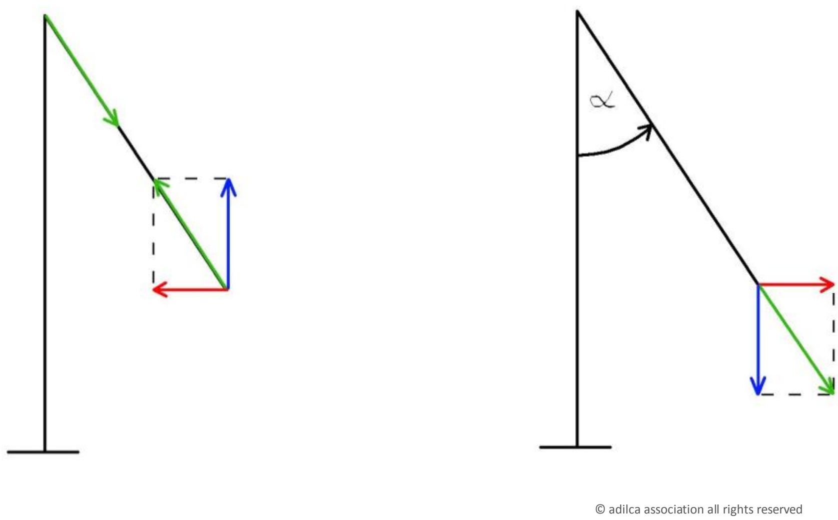
- one of these two forces is acting by contact of the string on a ball in motion, the other is acting miraculously on the center of mass of a ball motionless;

- one of these two forces is the result of an interaction, from the axle on the string and from the string on the ball, the other not;

- one of these two forces is directed towards the axle, the other is in opposite direction. To avoid any confusion, a good precaution is to fit the centrifugal force a negative sign to specify its direction which is contrary to the logic of the movement.

Two drawings to understand ...

The previous two descriptions are not to be confused or mixed, it is imperative to distinguish them by two separate drawings, like these:



First drawing: this is the dynamic description of the rotation of a ball around an axle, in a horizontal view.

- the blue arrow shows the lift force, the one that keeps the ball in vertical balance;

- the red arrow shows the horizontal force, the one that keeps the ball on a circular path;

- two green arrows: one shows the resultant of the two aforementioned forces, it acts on the ball by the string; the other is the reaction to the resultant, it is exerted on the rotation axle by the string.

Second drawing: this is the static description, the axle does not rotate, the ball is stationary in space as by magic but the string shows an angle relative to the vertical.

- the blue arrow shows the weight of the ball;

- the red arrow shows the centrifugal force;

- the green arrow shows the resultant of these two forces.

Conclusion

This is the conclusion: beware of numerous values!

Beware of calculations with identical results, they do not allow for much interchangeable concepts and reasoning!

So follow these tips: always distinguish the nature, the point of application and direction of the different studied forces and associated reactions; never mix descriptions; never associate a real force and an imaginary force!

Also, do not hesitate to question the certainties, demonstrations or drawings of your professors, as friendly, qualified and competent as they are! Research has shown that the best of them could unintentionally mislead generations of pupils and students.

(1) *'Pseudo-physicists': so we called, derisively, the physicists who persist in considering only the fictitious forces or pseudo-forces, ignoring the others.*

(2) *During the acceleration phase, the engine work provides a kinetic energy corresponding to the speed acquired by the ball (disregarding the mass of the string and the air resistance), to which must be added the gravitational energy corresponding to the height difference between the position of the ball at rest and its position after the stabilized speed.*

(3) *This force is not a centripetal one: indeed, the string never approaches the ball from the axle, it simply deviates it from a straight line to give a circular path (see ADILCA folder 'centripetal force').*

(4) *Disregarding the mass of the string. However, in the case of a fairground carousel, it would obviously take into account the mass of the support arm.*

(5) *This means that, in the final analysis, the real forces are all the result of an interaction with the Earth.*

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V. CALCULATION: EARTH TURNS AROUND THE SUN

A. Dynamic description

The earth is moving, she turns around the sun.

1. Calculating the centripetal force:

$$F = M \cdot V^2 / R$$

F: centripetal force, expressed in **N**
M: mass, expressed in **kg**
V: speed, expressed in $\mathbf{m.s^{-1}}$
R: radius of trajectory, expressed en **m**

consistency of the units: **F** = kg . $(m.s^{-1})^2 \cdot m^{-1}$ = kg . $(m^2.s^{-2} \cdot m^{-1})$ = $kg.m.s^{-2}$ = **N**

Let's calculate the centripetal force that drives the Earth around the Sun. Characteristics of the Earth: mass 6×10^{24} kg; orbital speed 30×10^3 $m.s^{-1}$; orbital radius 150×10^9 m.

$$F = 6 \times 10^{24} \times (30 \times 10^3)^2 / (150 \times 10^9)$$

$$F = 6 \times 10^{24} \times 900 \times 10^6 / (150 \times 10^9)$$

$$F = 6 \times 900 \times 150^{-1} \times 10^{+24} \times 10^{+6} \times 10^{-9}$$

$$\mathbf{F} = 36 \times 10^{21}\ \mathbf{N} = 36\ \mathbf{ZN}$$

Note 1: only one force can explain the circular motion of the Earth around the Sun, it is the centripetal force. This force is acting on the center of mass of the Earth and is oriented towards the center of the Sun. No other force exists.

Note 2: according to Isaac Newton's principle of reciprocal action, a reaction of same intensity but opposite direction is acting on the center of mass of the Sun, without effect on its own movement, because of its mass.

2. Calculating transverse accélération:

$$Y = F / M$$

Y: transverse acceleration, expressed in $\mathbf{m.s^{-2}}$
F: centripetal force, expressed in **N**
M: mass, expressed in **kg**

consistency of the units: $\boldsymbol{\Upsilon}$ = kg.m.s^{-2} . kg^{-1} = **m.s^{-2}**

Let's calculate the transverse acceleration experienced by the Earth. Characteristics of the Earth: mass 6 x 10^{24} kg; centripetal force 36 x 10^{21} N.

Υ = 36 x 10^{21} / (6 x 10^{24})

Υ = 36 x 6^{-1} x 10^{+21} x 10^{-24}

$\boldsymbol{\Upsilon}$ = 6 x 10^{-3} = 0.006 **m.s^{-2}**

B. Static description

The Earth stops turning around the Sun, it remains motionless in space.

Calculating centrifugal force:

F' = – M . $\boldsymbol{\Upsilon}$

F': centrifugal force, expressed in **N**
M: mass, expressed in **kg**
$\boldsymbol{\Upsilon}$: transverse acceleration, expressed in **m.s^{-2}**

cohérence des unités : **F'** = kg . m.s^{-2} = **N**

Let us calculate the force that would act on the center of mass of the Earth, if it were motionless (zero orbital velocity), to maintain it in equilibrium in space and prevent it from falling towards the Sun:

F' = – 6 x 10^{24} x 6 x 10^{-3}

F' = – 6 x 6 x 10^{+24} x 10^{-3}

F' = – 36 x 10^{21} **N** = – 36 **ZN**

Note 1: the sign [–] is required, it specifies the spatial orientation of this force conflicts the logic of the solar system.

Note 2: this force is commonly called '*centrifugal force*' which is incorrect since there is no orbital velocity, neither orbital radius nor center (the Earth is motionless and remains in equilibrium). The scientific name of this force is: imaginary force, fictional force, or pseudo-force.

VI. CALCULATION: THE CENTRIFUGE

Let us take as an example a centrifuge with a drum of 0.25 meters in radius which rotates at a speed of 1,200 rpm (20 revolutions per second).

1. Calculation of the circumferential velocity of the drum:

$$\mathbf{V = 2\ \pi.\ R.\ \omega}$$

V: circumferential velocity, expressed in $\mathbf{m.s^{-1}}$
π: constant characteristic of the circle, equal to **3.14** (dimensionless)
R: radius of the drum, expressed in **m**
ω: speed of rotation, expressed in $\mathbf{tr.s^{-1}}$

coherence of units: $\mathbf{V} = \mathrm{m.\ s^{-1}} = \mathbf{m.s^{-1}}$

$\mathbf{V} = 2 \times 3.14 \times 0.25 \times 20 = 31.4\ \mathbf{m.s^{-1}}$ = about 70 mph

This velocity, also called tangential velocity, is the *linear velocity* of drops of water when they leave the drum. Indeed, in the absence of atmosphere, gravitation and obstacle, drops of water would keep this speed on a straight path for eternity, hence the name of linear velocity.

2. Calculation of the transverse acceleration of the laundry:

$$\mathbf{Y = V^2 / R}$$

Y: transverse acceleration, expressed in $\mathbf{m.s^{-2}}$
V: circumferential velocity, expressed in $\mathbf{m.s^{-1}}$
R: radius of trajectory, expressed in **m**

coherence of units: $\mathbf{Y} = (\mathrm{m.s^{-1}})^2\ .\ \mathrm{m^{-1}} = (\mathrm{m^2.s^{-2}},\ \mathrm{m^{-1}}) = \mathbf{m.s^{-2}}$

$\mathbf{Y} = 31.4^2 / 0.25 = 986 / 0.25 = 4{,}000\ \mathbf{m.s^{-2}}$ = about 400 "**g**"

This transverse acceleration is oriented towards the axle of the drum, it keeps the laundry on a circular path, it comes from the *contact force* that the drum exerts on the laundry.

By virtue of the principle of reciprocity, the laundry exerts a reciprocal action on the drum, of equal intensity to this contact force, but of opposite direction. There is no centrifugal force, no centripetal force.

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VII. CALCULATION: A BALL THAT TURNS AROUND AN AXLE

A. Dynamic description

A ball of mass 100 grams (0.1 kg) weighing 1 N (gravitational acceleration "**g**" = 10 $m.s^{-2}$) is hanging from a string and rotates around an axle by describing a circular path of 0.25 radius meter at the speed of 1 turn per second.

1. Calculating the circumferential speed of the ball:

$$\mathbf{V = 2\,\pi\,.\,R\,.\,\omega}$$

V: circumferential speed, expressed in **$m.s^{-1}$**
π: constant characteristic of the circle (3.14), without dimension;
R: radius, expressed in **m**
ω: revolutions per second, expressed in **$r.s^{-1}$**
consistency of the units: **V** = $m\ .\ s^{-1}$ = **$m.s^{-1}$**

V = 2 x 3.14 x 0.25 x 1 = 1.57 **$m.s^{-1}$**

2. Calculating the horizontal force:

$$\mathbf{F = M\,.\,V^2\,/\,R}$$

F: horizontal force, expressed in **N**
M: mass, expressed in **kg**
V: circumferential speed, expressed in **$m.s^{-1}$**
R: radius, expressed in **m**
consistency of the units : **F** = $kg\ .\ (m.s^{-1})^2\ .\ m^{-1} = kg\ .\ (m^2.s^{-2}\ .\ m^{-1}) = kg.m.s^{-2}$ = **N**

F = $0.1 \times 1.57^2 / 0.25 = 0.1 \times 2.465 / 0.25 = 0.986$ **N**

3. Calculating the tension of the string(*):

$$\mathbf{T = [P^2 + F^2]^{1/2}}$$

T: string tension, expressed in **N**
P: ball weight, expressed in **N**
F: horizontal force, expressed in **N**
consistency of the units : **T** = $[(kg.m.s^{-2})^2]^{1/2} = [kg^2.m^2.s^{-4}]^{1/2} = kg.m.s^{-2}$ = **N**

Note: ½ power equals a square root.

T = $[1^2 + 0.986^2]^{1/2} = [1 + 0.972]^{1/2} = 1.972^{1/2} = 1.4$ **N**

B. Static description

Photograph of a 100 gram (0.1 kg) ball rotating around an axle shows that the string holding the ball forms an angle of 44.6 degrees respective to the vertical (gravitational acceleration "**g**" = 10 $m.s^{-2}$).

The movement being frozen, it is necessary to imagine a force acting on the center of mass of the ball to maintain it in equilibrium.

This imaginary force is the centrifugal force, which will be called for want of better (the ball being motionless, it does not move away, moreover, there is no circle or center).

Calculating the centrifugal force:

F' = – M . g . tangent α

F': centrifugal force, expressed in **N**
M: mass, expressed in **kg**
g: gravitational acceleration, expressed in **$m.s^{-2}$**
α: angle to the vertical, dimensionless;
consistency of the units : **F'** = kg . $m.s^{-2}$ = **N**

Note: Trigonometric values are dimensionless.

F' = – 0.1 x 10 x tangent 44.6° = – 1 x 0.986 = – 0.986 **N**

Warning! The sign [–] is required, it means that the spatial orientation of the centrifugal force conflicts the logic of the movement.

At last, it should be noted that, in the context of this description, this calculation is the only one allowed. Indeed, it is impossible to evoke the radius of the trajectory of the ball, let alone its speed!

(*)*The tension of the string is the result of the weight and the horizontal force, it is equal to the vector sum of these two forces (green arrow on the drawing on the left, page 11). The vector sum is calculated from the right triangle formed by the translation of one of the two vectors (without modifying its length or its orientation), according to the properties of the right triangles discovered by Pythagoras, Greek philosopher and mathematician of the 5th century before our era. Pythagoras' theorem states that, in a right triangle, the square of the hypotenuse is equal to the sum of the squares of the other two sides. In other words, in a right triangle, the length of the hypotenuse is equal to the square root of the sum of the squares of the other two sides, this is the relation used here.*

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