

THE CENTRIFUGAL FORCE

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I. WHAT YOU NEED TO KNOW ABOUT CENTRIFUGAL FORCE

The concept of centrifugal force rarely comes with an instruction manual: like the Coriolis force and the inertial force, centrifugal force belongs to the category of fictitious forces, also called apparent forces or pseudo-forces.

Why are they called this way? The reason is that these forces can only exist in the context of imaginary descriptions. In effect, these forces do not really exist.

Here is a selection of various observations, experiments or demonstrations supposedly proving the existence of centrifugal force, followed by the correct interpretations.

A few definitions...

A *reference frame* refers to a set of points from which the characteristics of the motion of a mass can be measured.

A *force* is any cause capable of changing the speed or trajectory of a mass.

Centrifugal means '*which takes away from the center*'.

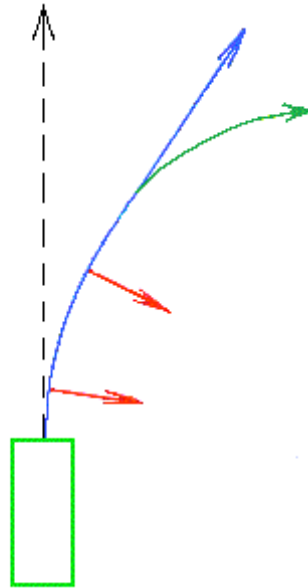
Thus, according to these definitions, a force qualified as centrifugal should be able to push away a mass from any center or axis of rotation along a radial trajectory, i.e. in the direction indicated by the extension of a radius.

The circular motion ...

If we observe a car that crosses a curve, we can see that the possible trajectories are three in number, and only three, but we note that the car never moves away on a radial trajectory:

1. The driver ignores the turn, the car keeps a rectilinear trajectory and goes straight (dashed black arrow), it is the normal trajectory of a mass on which no force acts.
2. The driver places the car on a circular path and normally crosses the curve (green arrow), which is the case most of the time.
3. The driver goes out of the way (blue arrow). However, the car was deviated from its rectilinear trajectory. Incompletely deviated, but deviated anyway. That brings us back to case number 2.

Note that centrifugal force does not appear in any of these three possibilities.



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The three possible trajectories:

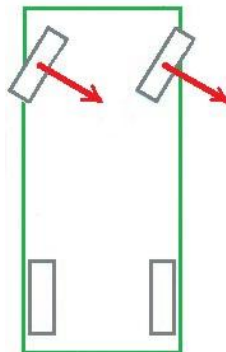
1. The driver ignores the turn and goes straight (black dotted arrow).
2. The driver normally crosses the curve (green arrow).
3. The driver goes off the road (blue arrow).

The cause that can deflect the rectilinear trajectory is shown in red.
(Be careful not to mix forces and trajectories!).

... and its cause

What is the cause of the circular motion? Where, why and how was the car deviated from its initially straight trajectory?

The rotation of the steering makes pivot the steering wheels, so a transverse force is exerted on the tires in contact with the ground, it is the guiding force (see ADILCA file 'guiding force'). This force is the sole cause of circular motion.



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Note: the guiding force is a centripetal-oriented contact force (this means that it is oriented towards the center of the trajectory) but not centripetal in nature (the centripetal term characterizes a force 'which approaches the center', it is not the case here, see ADILCA file 'centripetal force').

The object on the hood....

What is centrifugal force? To understand it, an experiment is necessary.

Let us put an object on the hood of a car (e.g. a traffic cone). The experiment consists in setting the car in motion, first in a straight line then a turn.



The so-called 'traffic cone' experiment

Now observe this experiment from a window or a balcony: as soon as the driver steers the steering wheels, the guiding force deflects the car from its original trajectory.

As the hood is a smooth area, this force cannot be transmitted to the object, which keeps its rectilinear trajectory and falls to the ground. The object in question is not subject to any force, it is simply left to itself.

Seen from the inside of the car, the object effectively falls to the ground at the beginning of the bend, as if pulled away from the trajectory by an apparent force.

This apparent force is called centrifugal force, but this force does not exist since the traffic cone is simply delivered to itself.

Two reference frames

These two observations are contradictory and incompatible because it is important to distinguish between two reference frames:

1. The Earth is the reference frame to describe the trajectory of the traffic cone, observed from a window or a balcony, so the description takes place in an absolute reference frame.

1. The car is the reference frame to describe the trajectory of the traffic cone, observed from the driver or passenger seat, so the description takes place in a relative reference frame.

Why is the car reference frame qualified as relative?

The motion of a land vehicle only exists in relation to the Earth, it does not exist in the reference frame of the car. This means that, in this reference frame, the vehicle must be considered as motionless. Of course, it is forbidden to mix the two descriptions.

Now we can analyze all the other experiments supposed to prove the existence of the centrifugal force.

The mascot hanging from the mirror...

Let's get in a car with a mascot hanging from the mirror and observe it.

In a straight line at constant speed, the mascot shows the vertical. When the car makes a turn, the mascot tilts to the side, as if driven by an apparent force. This apparent force is centrifugal force.



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Mascot hanging from the mirror

But in the reference frame of Earth, the mascot is only deflected from an initially straight line: the guiding force is exerted first on the tires of the steering wheels and is then transmitted to the chassis, to the bodywork and all the car accessories; it finally reaches the mascot through the mirror after which it hangs. Hence its inclination.

The apparent force which, from the passenger's point of view, seems to move the mascot, is therefore only an optical illusion. In fact, this force does not exist.

The passenger's sensations...

When the car makes a turn at top speed, the passenger of a car feels pressed against the edge of the seat or against the door, as if driven by an apparent force...

Where does this sensation come from? Is it the centrifugal force?

When the driver turns the wheel, the car is subject to the guiding force exerted on the tires of the steering wheels; this force is then transmitted to the chassis, the bodywork and all the accessories of the car.

The objects that are firmly attached to the body undergo this force fully and without delay, stowage consisting precisely in enabling the body to communicate this force.

But this is not the case for the passengers who, though seated on their seats, still retain some freedom of movement. When the car starts to turn, the passengers maintain a straight path, just like the mascot in the previous experiment, and they do so until the edge of the seat, the door or the body transmits the guiding force to them.

It is not therefore the centrifugal force that the passenger's experience, but simply the guiding force exerted on the car and transmitted by the seat, seatbelt or part of the body of the car.

The movement of luggage...

Let's take a look at luggage placed in the trunk or objects on the rear shelf.

The explanation is the same as for passengers: when the car turns, the movement of luggage placed in the trunk or objects on the rear shelf is only apparent in relation to the car.

In fact, objects that are not perfectly secured maintain a straight path as long as no part of the body can transmit a guiding force to them.

Conclusion: the centrifugal force does not exist, neither in the cockpit, nor on the rear shelf, nor in the trunk!

Centrifugal force: the true definition

All these observations, all this reasoning, all these deductions lead us to two original and unpublished definitions of centrifugal force:

'In the reference frame of the car, centrifugal force is the imaginary force that would have to be exerted on the center of mass of the passengers and luggage of a stationary car to see them driven by a motion identical to that observed in reality when the car is subject to the guiding force.'

There are three fundamental requirements to these definitions:

1. The car must be stationary.

2. This force is hypothetical, as clearly stated by the conditional: *'the force that would have to be exerted'...*

3. It is technically impossible to exert any force directly on the center of mass of any mass... This requirement alone would suffice to prove the unreality of centrifugal force.

These are sufficient reasons to assert that centrifugal force does not exist!

This definition makes it clear that the reference here is the car reference system. Which brings another question: could centrifugal force appear in the Earth reference system?

The rolling motion...

Observe a Citroën 2CV full turn. Because of the soft suspension, the outside wheels are compressed while the weight on the inner wheels is released. This phenomenon is called the 'roll'.

Why does the car behave this way? To deflect the car from its initially straight path, the driver had to apply a transverse force called guiding force. This force is exerted on the steering wheels in contact with the ground, but not on the center of mass.

It is therefore the height of the center of mass that explains the rolling motion: the car turns in on itself in a transverse plane.

Under the effect of the guiding force, the car simply acts like a person unbalanced by the carpet being pulled under her feet.

If the guiding force was exerted directly on the center of mass, there would be no roll and the car would take 'flat' corners.

So, the rolling motion has nothing to do with the centrifugal force.

Both descriptions

However, the observation of the rolling motion allows two possible descriptions of the same phenomenon:

1. A real description, called 'dynamic', which describes all the movements of the car and their cause.

2. An imaginary description, called 'static' which considers that the car is immobile. In which case it would be necessary to imagine a force capable of creating a movement of artificial roll.

Now the concept of centrifugal force comes in:

'In the reference frame of Earth, centrifugal force is the imaginary force that would have to be exerted on the center of mass of a stationary car to create on the tires and suspensions an effect identical to that observed in reality when the car is subject to the guiding force.'

The three previously stated requirements remain valid:

1. The car must be stationary.

2. This force is hypothetical, as clearly stated by the conditional: *'the force that would have to be exerted'*...

3. It is technically impossible to exert any force directly on the center of mass of any mass... This requirement alone would suffice to prove the unreality of centrifugal force.

Conclusion: the centrifugal force does not exist, neither inside the car, nor outside!

In any case, the description of imaginary forces that could be exerted on stationary cars is of absolutely no interest, cars being machines designed for movement and intended to satisfy the needs of displacement.

Reciprocity: the Newton's third law

Could centrifugal force be regarded as the reciprocal action to guiding force?

Consider Newton's law:

'When one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction to that of the first body.'

The previous experiments clearly demonstrate that the circular motion of the car is due to the action of a single force, the guiding force.

We observed that the guiding force is exerted on the tires in contact with the ground. Logically, the reciprocal action can only occur at ground level, too.

In fact, when a driver activates the guiding force, the car performs a horizontal thrust at ground level, and this thrust should logically affect the Earth's rotational movement.

Fortunately, the effect is purely theoretical because the mass of the car is considerably lower than that of Earth ^(⁶), so that the car has no choice but to slide or register obediently on a circular path!

In addition, should the effect be noticeable, it would be negated by the divergent trajectories of the large number of vehicles on the road.

This famous reciprocal action therefore exists, but it has nothing to do with the concept of centrifugal force!

The feelings of the passengers

The misuse of the concept of centrifugal force led motorists to believe that they could feel the effects of an imaginary force, thus proving its existence.

Let us detail the mechanism of the circular motion: the guiding force is exerted on the tires in contact with the ground, it is then transmitted to the passengers via the wheels, the frame, the bodywork and the seats.

The principle of reciprocity then applies: the passengers are subject to the guiding force transmitted by the bodywork and the seats, they thus exert a reciprocal action on the seats and the bodywork, of equal intensity but of opposite direction.

Therefore, what the passengers feel is this interaction and not the centrifugal force.

All this is very logical because it is obviously impossible to observe or feel the effects of an imaginary force.

What is the correct formula?

Does the famous formula $F = MV^2/R$ prove the existence of centrifugal force?

Let us first make sure it truly is a force.

According to the *International System of Units* (symbol: **SI**) – compulsory in most countries around the world, for instance in United States since 1964, in United Kingdom since 2004 – force is measured and expressed in kilograms-meters per second squared (symbol: **kg.m.s⁻²**). That is a derived quantity obtained by combining three fundamental quantities: mass and length and time.

The measurement obtained is the very definition of a *newton* (symbol: **N**), the international unit of force.

To check the consistency of this formula, consider how the different quantities introduced in this equation are combined: mass is expressed in kilograms (symbol: **kg**), speed is expressed in meters per second (symbol: **m.s⁻¹**) and the radius of the path is expressed in meters (symbol: **m**).

Let us combine these different quantities:

$$F = MV^2/R$$

$$F = \text{kg} \cdot (\text{m} \cdot \text{s}^{-1})^2 \cdot \text{m}^{-1}$$

$$F = \text{kg} \cdot \text{m}^{+2} \cdot \text{s}^{-2} \cdot \text{m}^{-1}$$

$$F = \text{kg} \cdot \text{m}^{+2-1} \cdot \text{s}^{-2}$$

$$F = \text{kg} \cdot \text{m} \cdot \text{s}^{-2} = \text{N}$$

There is no possible doubt, this formula is perfectly consistent, and therefore it expresses the measurement of a force.

A force indeed, but which one? Centrifugal or guiding? That is the question!

FORMULE DE LA FORCE CENTRIFUGE

Force centrifuge = $\frac{\text{Masse du véhicule} \times \text{Vitesse au carré}}{\text{Rayon de virage}}$

FC = $\frac{MV^2}{R}$

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Correct formula, but not correct force!
(French Ministry of Transport official document)

What force is it?

What force are we dealing with?

We have already shown elsewhere that there were only two possibilities and two only:

- from the reference frame of the car, the centrifugal force is an apparent force and, obviously, can only be exercised on passengers and luggage but certainly not on the car;

- from the reference frame of Earth, the guiding force is a real force which is exerted on both the car and everything it contains.

How can we tell? How to distinguish the two? How to settle the debate?

The answer comes naturally by examining the various quantities introduced in the equation of the mass of the car, its speed and the radius of its trajectory.

Isn't it obvious?! These variables exist in the reference frame of Earth but they have no existence in the reference frame of the car!

To understand this significant nuance, try to imagine for a moment what the speed of the car or the radius of its path could be by reasoning exclusively in the reference frame of the car...

Evidently, this formula does not express the centrifugal force, but only the guiding force. The latter and the latter only is what it is all about.

How to measure centrifugal force...

Can the intensity of centrifugal force be measured?

Yes! It is indeed quite possible to measure the intensity of an imaginary force, i.e. the intensity of a force that does not exist, but that would have to be resorted to if... Physicists love this kind of exercise!

However, with regard to centrifugal force, the usual approach is not correct, and here's why.

First things first: in science, as a rule, one should always check the origin of the quantity one is faced with, what it represents, and how it was obtained. This is what you may call a principle of traceability.

Before any calculation is carried out, a physicist must perform experiments, define benchmarks and make measurements. The process is what matters most.

Calculations only come next, but they are necessarily based on concrete measures, numerical values whose origin and meaning are certified – in short, quantities that really exist.

It is only later, thanks to a purely theoretical reasoning, that the physicist can transpose his reasoning to the study of an imaginary phenomenon.

In other words, to get to centrifugal force, which is an imaginary force, it is necessary to start from the guiding force, which is a real force. Indeed, there is no imaginary force without a real force. But the reverse is not true: the guiding force alone is enough to explain everything while the centrifugal force is always necessarily dependent on the guiding force.

It is therefore strictly forbidden to mention the centrifugal force without explaining where it comes from, what it represents and how it was obtained.

These details of what is in fact a very logical approach are often ignored or overlooked. To illustrate this, here is a concrete example.

A concrete example...

Take the example of a car with a mass of 3,300 lb (1,500 kg) which describes a circular path of radius 330 ft (100 m) at a speed of 45 mph (20 m.s⁻¹).

The famous formula, which is often used indiscriminately and of which we have detailed the applications, calculates the intensity of the guiding force **F** that is exerted on the tires of the car in contact with the ground:

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

$$\mathbf{F} = 1,500 \times 20^2 / 100 = 6,000 \mathbf{N}$$

The corresponding transverse acceleration is:

$$Y = V^2 / R$$

$$Y = 20^2 / 100 = 4 \text{ m.s}^{-2}$$

It is only from this result that we can deduce the intensity of the centrifugal force F' , the famous force that would have to be exerted on the center of mass of the car, if it was stationary, in order to produce an effect comparable to that observed when the car is subjected to the guiding force.

But what formula should be used? The following one, and no other:

$$F' = - M Y = - F$$

The calculation is easy: to produce an effect comparable to what is observed in reality, a force of **- 6,000 N** would be required!

In other words, to a guiding force of **6,000 N** in a real description, there is a centrifugal force of **- 6,000 N** in an imaginary description!

In effect, the 'guiding force' and the 'centrifugal force' have the same modulus but yet, everything divides them:

- the formula used to calculate the intensity;
- the point of application (one of these two vectors has its origin at the periphery of the tire and the other at the center of mass);
- the direction (here, the often forgotten [-] sign is crucial, it shows that the spatial orientation of the centrifugal force, if such force existed, should be strictly opposite to that of the guiding force);
- last but not least: one of these two vectors is applied to a moving car and the other to a stationary car!

In short, these two vectors do not belong to the same description at all! Thus: the intensity of the centrifugal force is deduced from that of the guiding force, and it is never the other way round!

And the quantity supposed to prove the existence of centrifugal force results in fact in confusion with the guiding force!

The inertial sensor...

Can a simple inertial sensor (also called lateral accelerometer) directly measure the intensity of centrifugal force?

Let us detail the principle of operation of this device: a block capable of sliding in a tube, is maintained at rest by two springs, but can nevertheless move along a slider in case of lateral acceleration of the car. The device is securely attached to the car body

Let us get back to the example of a car in a circle of radius 330 ft (100 m) at a speed of 45 mph (20 m.s⁻¹).

If the mass of the block is 10⁻² kg, if the device is accurately calibrated, the cursor indicates a force of 4 x 10⁻² N, this is the force necessary to curve the trajectory of the block.

The fundamental relation of dynamics enables one to calculate the intensity of the transverse acceleration communicated to the block by the car:

$$Y = F / M$$

$$Y = 4 \times 10^{-2} / 10^{-2} = 4 \text{ m.s}^{-2}$$

Note that this transverse acceleration is strictly identical to that of the car, since the sensor is a part of the car body and describes a circular path of the same radius.

As there is no motion without cause, it is deduced that the transverse acceleration of the block comes from the guiding force exerted on the car.

In other words, the inertia sensor measures the intensity of the guiding force, and its operating principle has nothing to do with the concept of centrifugal force.

The true meaning of the word 'exist'...

The centrifugal force does not exist, as we have just been demonstrating at length. However, you can still come across contrary opinions here and there, especially on the web. A true dialogue of the deaf! Who is to be believed?

For some, the only trace of the concept of centrifugal force in a physics book would suffice to prove its existence: since it is written in the book, it really exists!

Let us first remember that '*physics*' refers to the science of natural things, it is focused on the observation and knowledge of real things, and this is precisely what makes it a concrete and rigorous hard science.

The misunderstanding about centrifugal force rests on the true meaning of the verb 'exist'. According to the dictionary, the word applies to everything that is part of reality, as opposed to what is only fiction.

However, the fact that some physics books make mention of centrifugal force does not prove its *existence*, in the physical and literal sense of the word...

Indeed, many abstractions may be conceived on paper, but in science, only reality matters... Is not fact stranger than fiction, as the saying goes!

The example of literature...

To understand this significant nuance, let us look at literature and ask ourselves this question: do the characters found in novels really exist?

Let us take one universal example: Father Christmas!

Of course, there are many children's stories dealing with Father Christmas and in this case, Father Christmas exists for good, both in the tale and on paper... But it does not prove his *existence* in the physical and literal sense of the word.

And there is a good reason for this: Father Christmas is not a historical figure, he has never been and will never be part of reality, nobody has ever met him. Father Christmas does not *exist*, therefore, in the physical and literal sense of the word!

In short, there definitely are two meanings to the word 'exist', and these meanings are by no means equivalent.

Father Christmas does not exist, nor does centrifugal force.

Conclusion

Just like the inertial force and the Coriolis force, centrifugal force is a fictitious force that has no real existence: it appears only in the context of imaginary descriptions.

Let us make it clear, it is obviously impossible to observe or feel the effects of an imaginary strength. This concept was consequently used wrongly to describe the phenomena observed when driving a car.

The truth is much simpler: the normal trajectory of a moving car is straight. To deflect the trajectory, a transverse force called 'guiding force' must be activated.

The guiding force is a contact force exerted on the outskirts of the tires of the steering wheels when the driver operates the steering control.

The clear, logical and rational explanations to all the other phenomena that may be observed in a car result from this truth.

(*) *If one compares a car that weighs 2 metric tons and Earth (6×10^{24} kg), the mass ratio is 1 to 3×10^{21} , that is 1 to 3,000 trillion!*

II. CENTRIFUGAL FORCE: THE CALCULATION MODE

1. Guiding force

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

F: guiding force, expressed in **N**

M: mass, expressed in **kg**

V: speed, expressed in **m.s⁻¹**

R: trajectory radius, expressed in **m**

Consistency of the des units: $F = \text{kg} \cdot (\text{m} \cdot \text{s}^{-1})^2 \cdot \text{m}^{-1} = \text{kg} \cdot (\text{m}^2 \cdot \text{s}^{-2} \cdot \text{m}^{-1}) = \text{kg} \cdot \text{m} \cdot \text{s}^{-2} = \text{N}$

Example: calculate the guiding force acting in contact with the ground and which maintains a car with a mass of 1,500 kilograms (3,300 lb) on a circular trajectory of 100 meters radius (330 ft) at a speed of 20 meters per second (45 mph):

$$F = 1,500 \times 20^2 / 100 = 1,500 \times 400 / 100 = 6,000 \text{ N}$$

2. Transverse acceleration

$$Y = F / M$$

Y: transverse acceleration, expressed in **m.s⁻²**

F: guiding force, expressed in **N**

M: mass, expressed in **kg**

Consistency of the units: $Y = \text{kg} \cdot \text{m} \cdot \text{s}^{-2} \cdot \text{kg}^{-1} = \text{m} \cdot \text{s}^{-2}$

Example: calculate the transverse acceleration of a car with a mass of 1,500 kilograms (3,300 lb) describing a circular trajectory of 100 meters radius (330 ft) at a speed of 20 meters per second (45 mph):

$$Y = 6,000 / 1,500 = 4 \text{ m} \cdot \text{s}^{-2}$$

3. Centrifugal force

$$F' = - M \cdot Y$$

F': centrifugal force, expressed in **N**

M: mass, expressed in **kg**

Y: transverse acceleration, expressed in **m.s⁻²**

Consistency of the units: $F' = \text{kg} \cdot \text{m} \cdot \text{s}^{-2} = \text{N}$

Example: calculate the force that should be exerted on the center of mass of a stationary car to create, on the suspensions and the tires, an effect comparable to that observed in reality when this car describes a circular trajectory of 100 meters of radius (330 ft) at the speed of 20 meters per second (45 mph):

$$F' = - 1,500 \times 4 = - 6,000 \text{ N}$$

Note 1: this force is commonly referred to as "*centrifugal force*" which is an incorrect name since there is neither trajectory nor center (the bicycle + cyclist set remains motionless all the time). The scientific name of this force is: imaginary force, fictional force, or pseudo-force.

Note 2: the sign [-] is required, it specifies that the spatial orientation of the centrifugal force conflicts the logic of the movement.

Note 3: beware to misinterpretation, the numerical equality of results does not allow the interchangeability of descriptions, concepts or reasoning.

Note 4: the different calculations must be done in the order indicated. It is indeed impossible to directly calculate the centrifugal force without performing the intermediate calculations detailed above.

Note 5: Every scientific approach goes through four steps:

- from observation to *experiment* (here: a car which describes a circular path);
- from experiment to *measurements* (here: measuring the mass of the car, its speed and the radius of its trajectory);
- from measurements to *calculations* (here: calculation a guiding force and a transverse acceleration);
- from calculations to *reasoning* (here: the concept of centrifugal force).

This transition from concrete to abstract reasoning, from the real to the imaginary, has often been short-circuited, hence the confusion or misunderstanding about centrifugal force.

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III. HOW TO DRAW THE CENTRIFUGAL FORCE

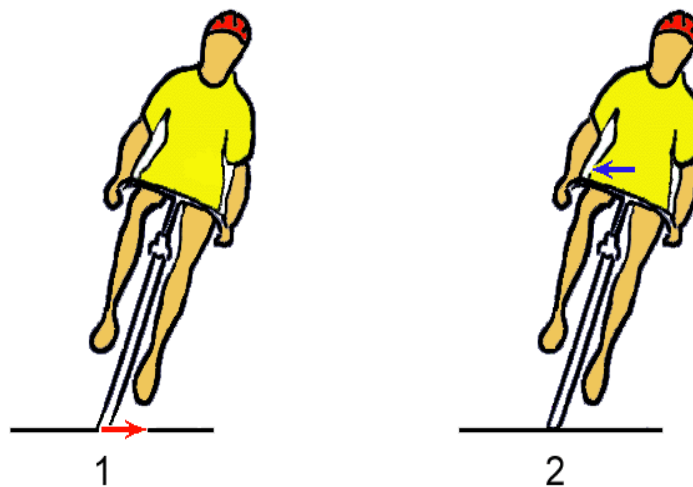
How to correctly draw an imaginary force? Let us take again the definition of the centrifugal force and apply it to the movement of a cyclist who describes a circular trajectory:

'Centrifugal force is the imaginary force that should be exerted on the center of gravity of a stationary cyclist (we neglect the mass of the bicycle) to maintain it in equilibrium despite its inclination with respect to the vertical.'

Let us recall the requirements of this definition:

1. the cyclist is motionless;
2. this force is imaginary, confirmed by the use of conditional: *'the force that should be exerted...'*;
3. the impossibility of exerting a force directly on the center of gravity of any mass.

That's why two drawings are needed:



Why two drawings? Only one would be enough to explain the movement of the cyclist, but if you want to draw the centrifugal force, you need a second one. Naturally, to clear up a misunderstanding, each drawing requires its own caption:

Drawing 1: this is the real description (said as *'dynamic'*): the cyclist is in motion, he describes a circular trajectory, he has been deviated from a rectilinear trajectory by the *guiding force* exerted on the tires in contact with the ground (red arrow).

Drawing 2: it is an imaginary description (said as *'static'*): the cyclist is motionless, he leans but does not fall, thanks to an imaginary force which is exerted on his center of gravity (blue arrow). That is the *centrifugal force*.