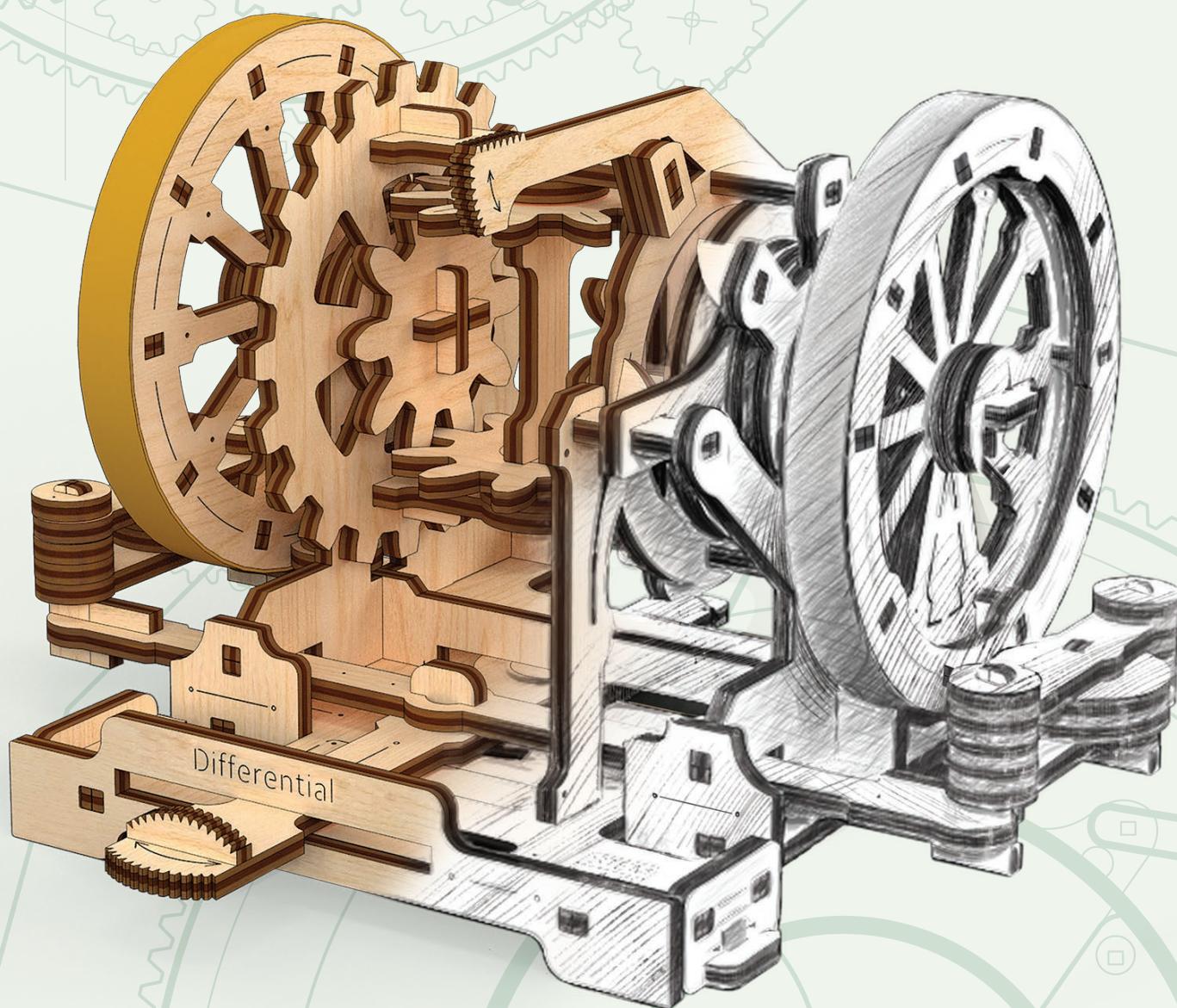


MECHANICAL MODEL

# DIFFERENTIAL

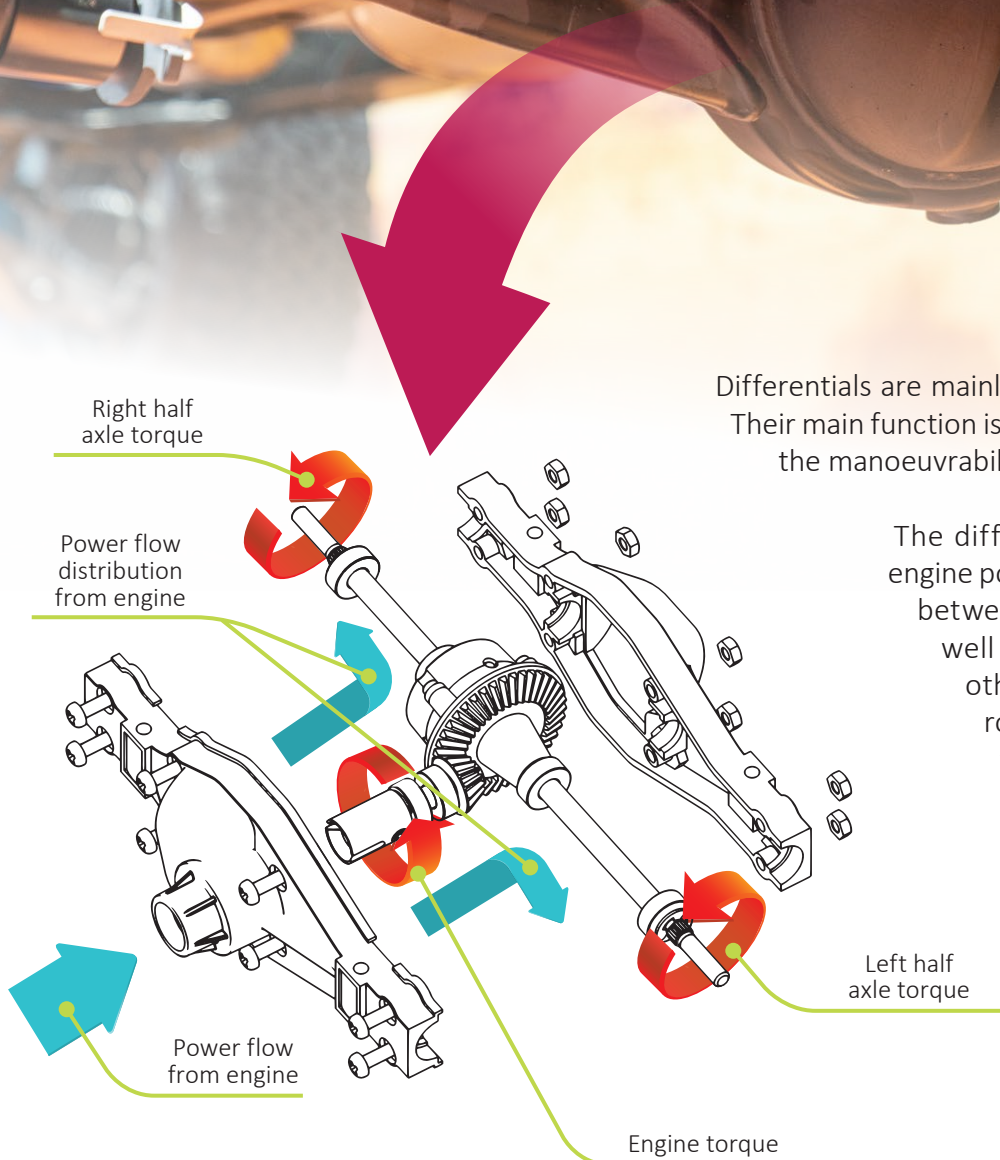


Handbook of A Young Engineer



# §1 Introduction

The modern car has many parts and details. Each of them is very important. Certainly, you wouldn't go far in a car with no engine, or wheels, or, for example, the accelerator pedal. Today we want to look at one of the most essential mechanisms – the differential. The device which plays an important role in maintaining a car's stability and keeps it steady and fast on any track.



Differentials are mainly used in automobile transmission\*. Their main function is to make steering easier and improve the manoeuvrability of a vehicle.

The differential transmits and divides the engine power and the torque\*\* into two flows between the wheels on the same axle (as well as the tracks or propellers used in other vehicles). This allows wheels to rotate at different speeds making the vehicle more stable, without slipping, reducing tyre wear if one of the wheels has poor road adhesion. For example, when turning or driving on slippery surfaces.

Next, you will learn in detail what the differential is used for, who has created it and when, how it works and how and where it is used today.

“Differential” 3D-model will help you to understand in practice the operation of this mechanism. By assembling it with your own hands, you will unravel all the secrets of this important device.

Transmission (lat. transmissio). In vehicles, these are mechanisms connecting engine and driving wheels.

\* In this case, “torque” is the rotational effect of the force on the elements and parts of a mechanism. In the international system (SI) the moment of force (or in our case, the torque) is measured in Newton metre (N · m).



# §2

## Historical reference



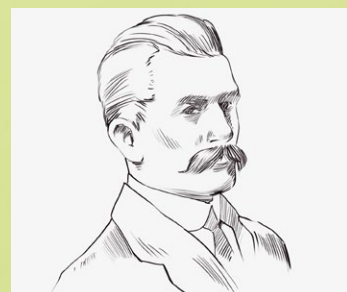
The first cars were way less sophisticated than modern ones. But driving one of those oldies was increasingly more difficult. One of the main problems, the drivers had to face in the beginning of the automobile era was wheel slip on a turn. In the process of turning, the wheels would keep spinning with the same speed while the weight distribution changed significantly. This made driving a hard skill to master and limited the speed. The differential became the perfect solution for this problem that allowed cars to be made faster and safer.



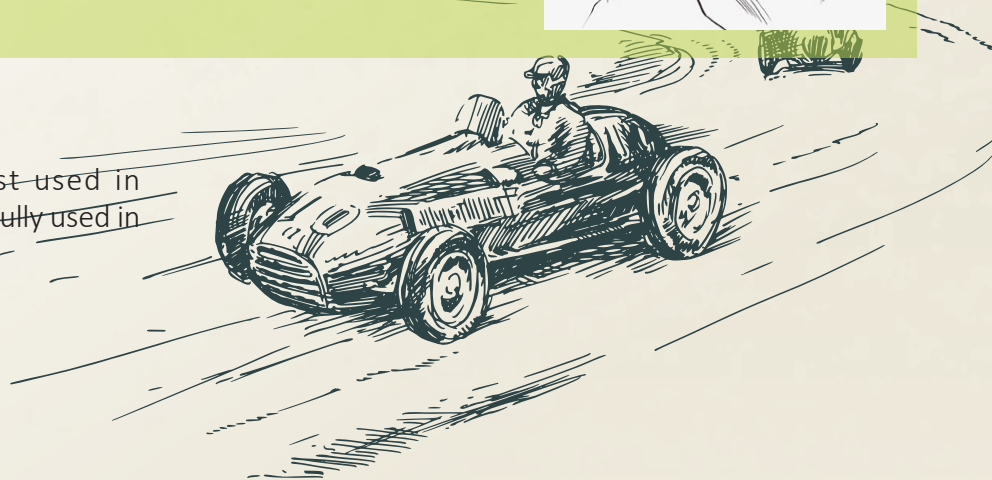
The car differential was invented by a French engineer, Onesiphore Pecqueur in 1825. The mechanism he created worked well with hard dry surfaces, but was ineffective in icy conditions or on a wet road. Obviously, a few improvements were required.



Those were introduced by famous Austrian-German automotive engineer Ferdinand Porsche, which significantly upgraded the mechanism. It took him three years of research, testing and tweaking, eventually producing a gearless differential – the first speed sensitive automatic locking differential. First installed in Volkswagens, this improved version of a differential has been in use in cars ever since.



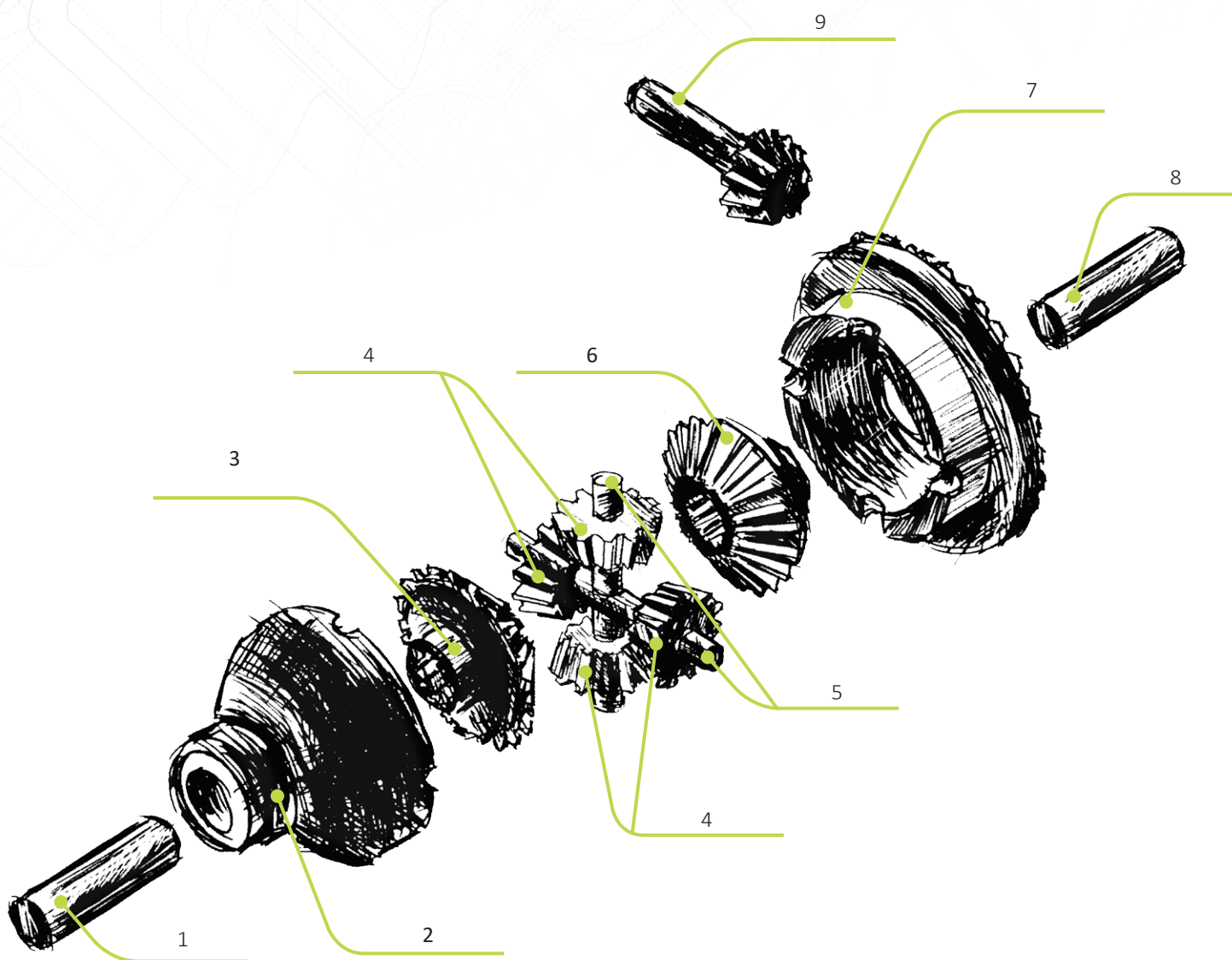
The updated differential was first used in Volkswagen cars and it has been successfully used in the automotive industry so far.



# §3

## About the Mechanism and how it works

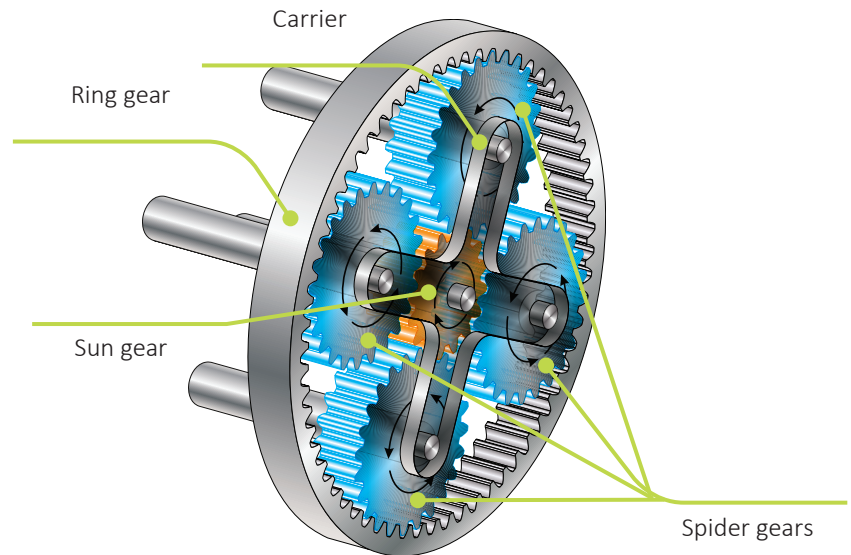
**Differential** (from Latin: Differentia – difference) is a gear arrangement with shafts. Let's look at the composition parts of the symmetrical bevel-gear differential.



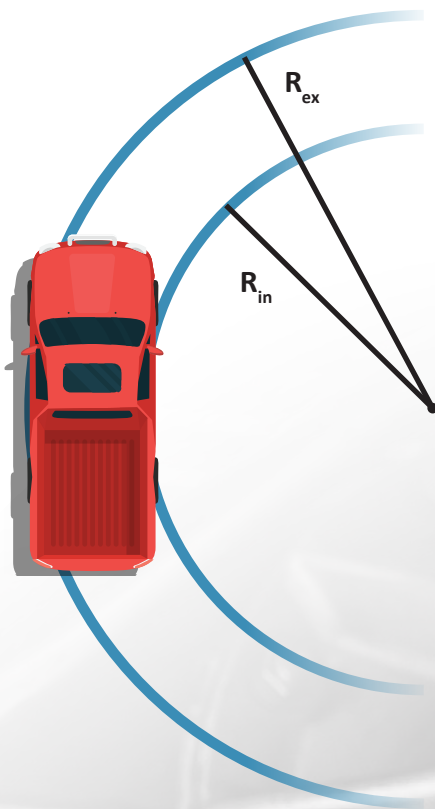
1 — left half axle; 2 — spider gear assembly; 3 — axle side gear; 4 — spider gears; 5 — spider pins; 6 — axle side gear; 7 — spider gear assembly (with ring gear); 8 — right half axle; 9 — axle driven gear;



A planetary gear is the basic element of any differential. This is a mechanical transmission of rotational motion which due to its design is capable of changing, adding and distributing the input angular velocities\* and/or the torque to the spider gears along the same axis of rotation. It also includes the ring gear, the carrier and the central “sun” gear.



Therefore, in a car, the differential has three main functions: torque transfer from the engine to the drive wheels; ensuring the wheels individual angular velocity; and together with the axle drive, serves as gear reduction unit.



When turning or driving on a rough road driving wheels\*\* travel different distances, as shown in the figure (due to the track width of a car).

The radii of the trajectory when turning are different for the left and right wheels ( $R_{ex}$  is the radius of the external trajectory;  $R_{in}$  is the radius of the internal trajectory).

Thus, if both wheels received the same force (torque) from the engine, then their rotation speed would accordingly be the same. Under these conditions, one of the wheels is bound to be slipping. However, if you put a differential between the wheels, you'll be able to distribute the force from the engine and get different wheel speeds. So, the wheels run at a required speed independently of each other.

\* Angular velocity is a vector quantity that characterizes the speed and direction of a solid body rotation (in our case, parts of the mechanism and wheels) relative to the centre of rotation. It is denoted by the Greek letter  $\omega$  (omega) and measured in radians per second (rad/s). Next, we consider this and other quantities in more detail.

\*\* Driving wheels are the wheels to which the torque generated by the engine is transmitted. Both the rear wheels and the front wheels can be driving. In four-wheel drive vehicles, all four wheels are driving. You must have come across such a «4x4» icon.

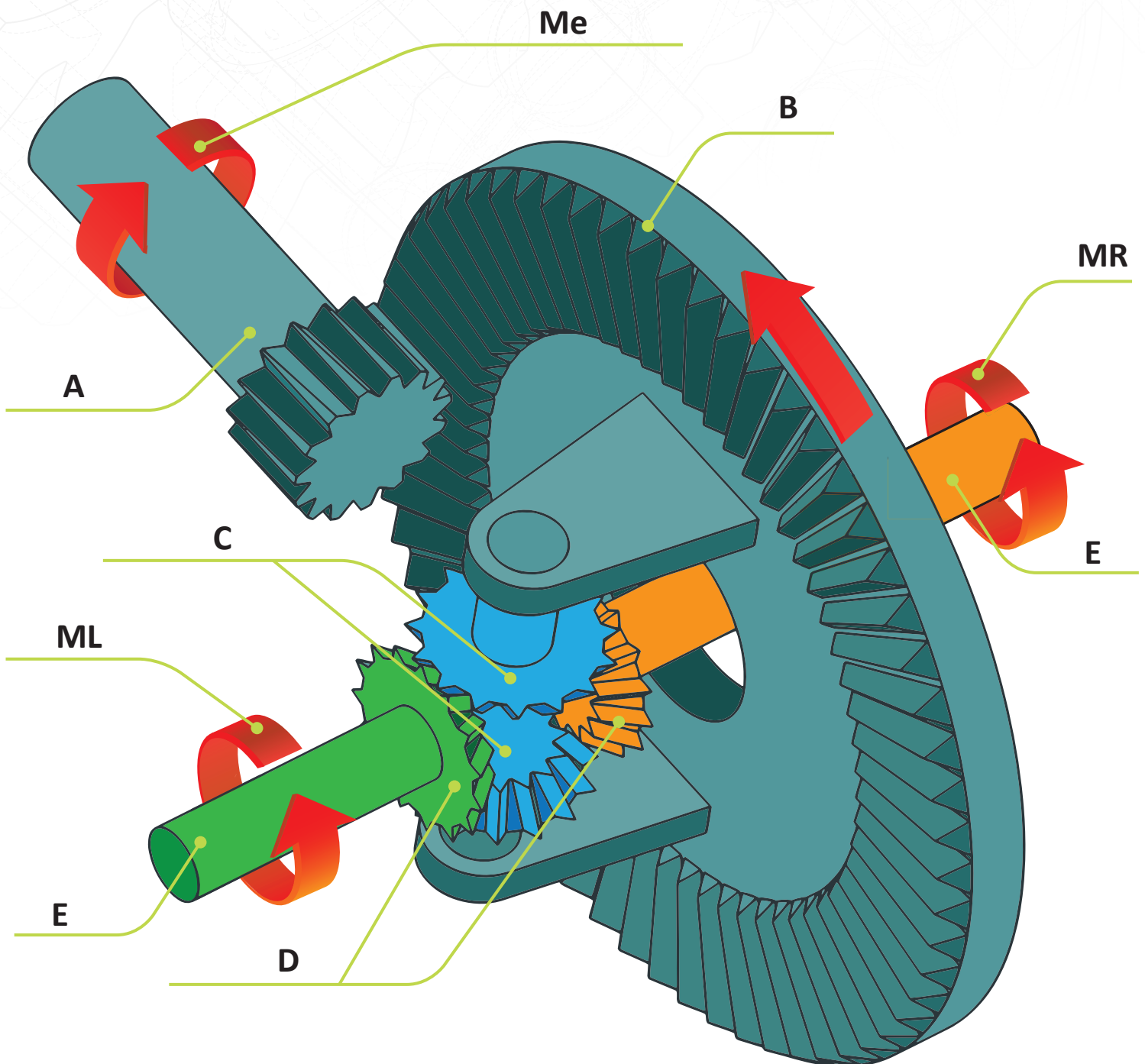
**How does it work?**

Torque ( $M_e$ ) is transmitted to the differential ring gear (B) from the engine through the bevel gear (A).

**The carrier of a planetary gear of such a differential is the wheel gear (ring gear) in the form of a rotating case.**

Torque is distributed to the left and right component of ML and MR through mutually independent spider gears (C). This allows each of the sun gears (D) with the wheel half axles (E) to rotate at different angular velocity.

As a result, as noted earlier, the wheels of a vehicle are free to move along their trajectory without slipping.

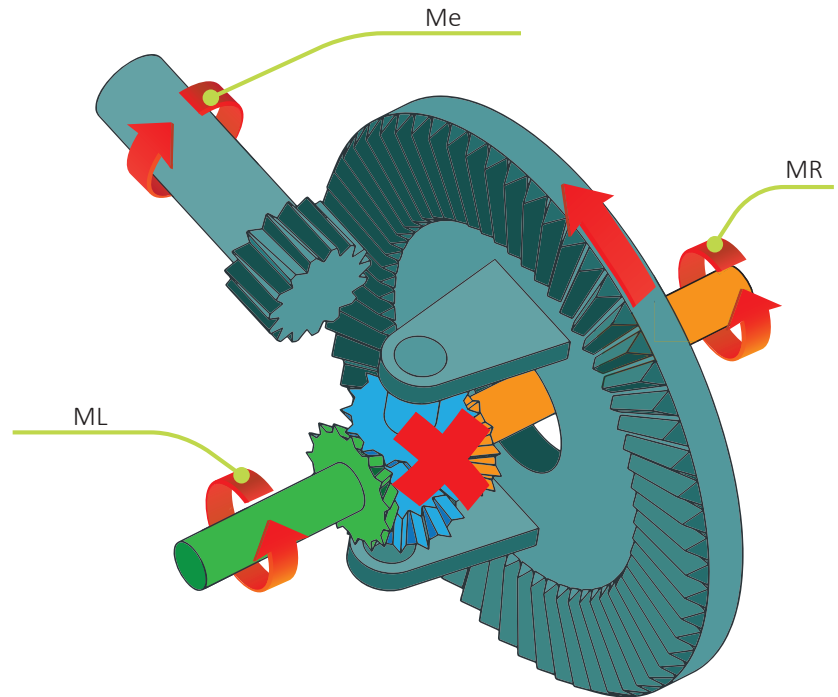




Let's consider how the differential works when a car is moving straight and when it is turning.

When moving straight, the wheels of a car pass the same distance. Accordingly, the left and right wheel torques  $M_L$ ;  $M_R$  and the angular velocities  $\omega_L$ ;  $\omega_R$  are the same:  $M_L = M_R$  and  $\omega_L = \omega_R$ , respectively.

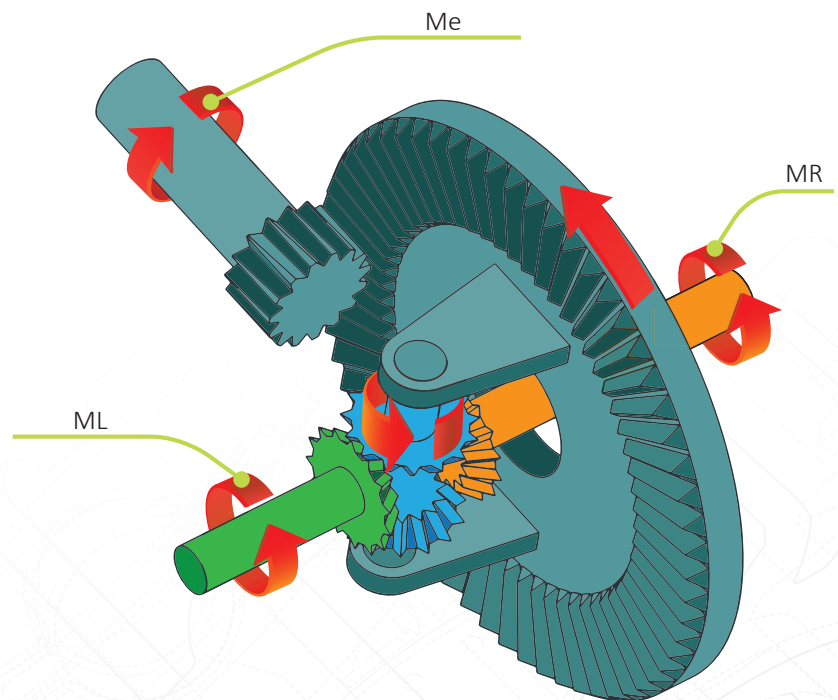
The figure shows that in such a situation the differential body with the ring gear and the spider gears become an integral whole (i.e. the spider gears do not rotate because there is no difference in the rotation of the left and right wheel).



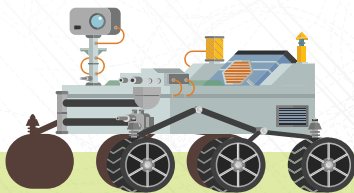
«Differential in operation» when driving a car straight

A completely different situation occurs when turning. The wheels of a car pass different distances (due to the track width). Accordingly, the left and right wheel torques  $M_L$ ;  $M_R$  and the angular velocities  $\omega_L$ ;  $\omega_R$  are not equal:  $M_L \neq M_R$  and  $\omega_L \neq \omega_R$ .

Spider gears allow them to rotate at different speeds, revolving around the sun gears, thus distributing the torque force between the half axes.



«Differential in operation» when turning a car



The space industry uses vehicles (rovers and lunar rovers) with a large number of wheels, with each wheel being driving. This is done for better «flotation» of a vehicle. However it is essential to recall that a differential works greatly as long as the car's driving wheels are tightly adhered to the surface of the road since if one wheel loses road adhesion by being in the air or on the ice, **it will be the only rotating one** – the other wheel remains stationary. To prevent this from happening, the engineers found design solutions to lock the differential.

**So, there are several types of differentials:**

A differential with manual locking – positive locking is required to improve off-road performance. It can be activated by a driver as needed.

**Self-locking:**

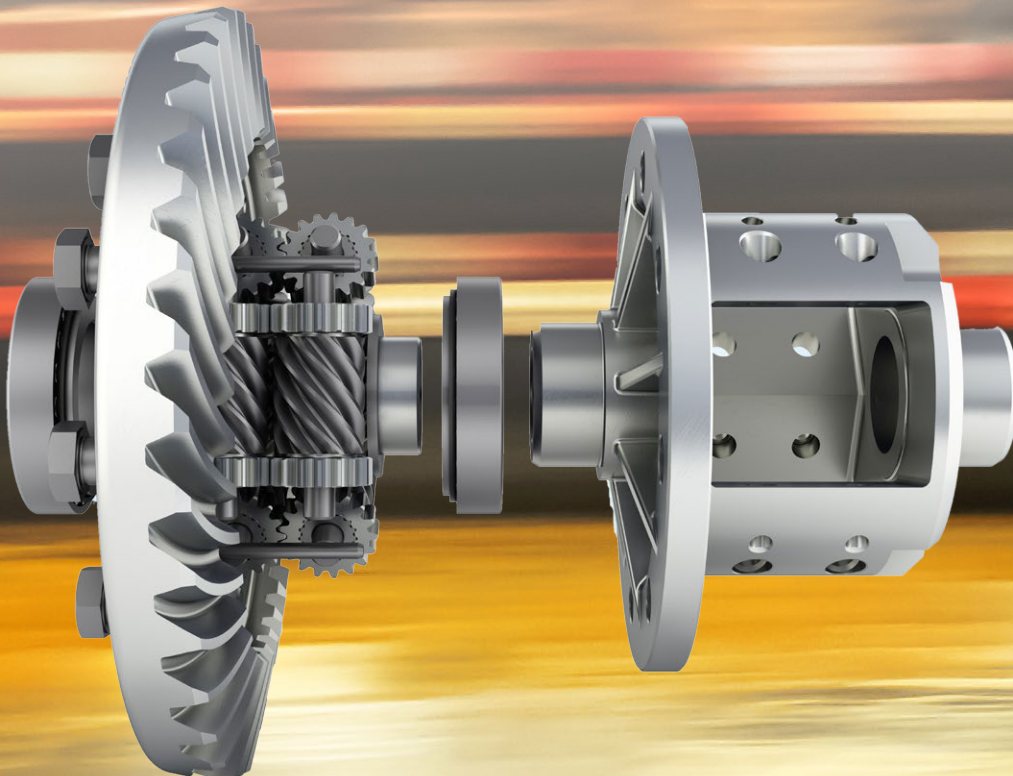
**Visco drive** is a multi-plate coupling in which the torque grows as the speed difference increases between the drive and driven shafts. It is used in full-time all-wheel drive cars and as a differential locking mechanism;

This type of assemblies significantly increase vehicle flotation. The basic principle of self-locking is that certain driving conditions are conducive to the automatic locking of a differential. When there is a significant increase in load difference in the half axles, an oil pressure pump is being actuated. The coupling plates start to converge and the speed of the wheel decreases, as well as the wheel load is distributed correctly when slipping and skidding.

There are a lot of modifications of self-locking differentials for cars.

In some differentials the locking does not result from the difference in the rotation speeds of the shafts, as in the visco drive, but occurs when the balance of torque on the shafts changes. As soon as the moment on one of the shafts increases, the worm pairs “jam” the gears locking the necessary differential gear;

In others, the right and left rows of spider gears get meshed with the right and left gears of the half axle, as well as the spider gears from different rows get inter-meshed with the next but one when one of the wheels is behind. The associated half axle gear starts to rotate slower than the differential body and rotates the spider gear, which rotates the spider gear connected thereto and the latter in turn rotates its half axle gear, thereby ensuring different wheel revolutions when turning.





At the same time, some types of automobiles can go with no differential at all. Having one in your car also means an increased load on the car's transmission and tyre wear.

A four-wheel car with one or two drive wheels can work without it – for example, karts or racing cars with a rear axle designed to race on low traction surfaces.



There are also interaxle differentials that distribute the torque between drive axles as a proportion 50:50, 40:60, etc



Differentials aren't used in railway transport – electric and diesel locomotives, electric and metro trains. Differentials may be absent in two-wheel tractors and other labor saving devices as well as in electric carts in which each wheel is driven by a separate motor.



# §4

## Physics and Mechanics explained in “Differential” STEM-model

A **differential** is a mechanical device that transfers torque from a source to two independent drives in the way that the rotation speed of each of those can be different.

A differential has the following properties: the Rotation power (N), torque (M), and angular velocity ( $\omega$ ).

**Power** is a scalar value that in most cases equals the rate of conversion, transmission or consumption of the system's energy. It is also described as a relation of the work in the period of time to that period of time.

$$N = A/t$$

In the International System of Units (SI) **the base unit of the power** is watt (W), named after James Watt, an 18th-century Scottish inventor.

Power is found by the formula:

$$N = F \cdot v \cdot \cos \alpha$$

In the rotation motion:

$$N = M \cdot \omega,$$

**Where:**

M – is torque,

$\omega$  – angular velocity.

**Torque** can also be called “a rotating power”, N·m in the SI unit. Torque is sometimes called “moment of couple of forces”. This term is initially found in Archimedes' works. If the direction of the force applied to a lever is perpendicular to it, the moment of power is found as a the amount of that power multiplied by the distance to the center of line of rotation of the lever. For an engine it's the rotation force of the crank shaft.

For example, the force of 3 N applied to a lever at a distance of 2 meters from the center of its line of rotation will create the same torque as the force of 1 N applied to the lever at the distance of 3 meters from the center of its line of rotation. The moment on point is describes as a vector multiplication:

$$\vec{M} = [\vec{r} \times \vec{F}]$$

**Where:**

F is a force applied to a point,

r is a vector radius of a point (if the center of rotation is at the at the origin of the coordinates).



**Angular velocity** refers to how fast the angular position ( $\omega$ ) or orientation of an object changes with time. It is represented by the symbol  $\omega$  and the formula:

$$\omega = \frac{\varphi}{t}$$

Per one revolution  $\Delta\phi = 2\pi$ .

Angular velocity is related to the period of rotation and number of revolutions per period of time. It is found as:

$$\omega = \frac{2\pi}{T}$$

и

$$\omega = 2\pi\nu$$

As a SI unit, angular velocity is:  $[\omega] = \text{рад/с}$ .

The real radius of a turn is not a constant number and perfect steady traction is not achievable. If the wheels rotate with the same speed, the turning car will slide and the internal trajectory will be different from external one. This difference is found as:

$$L_{in} = L_{ex} \cdot (1 - L \cdot \omega_z \cdot L_{ex}) \cdot M$$

**Where:**

$S_{in}$  - internal trajectory, m;

$S_{ex}$  – external trajectory, m;

$\omega_z$  – horizon related angular velocity, rad/s;

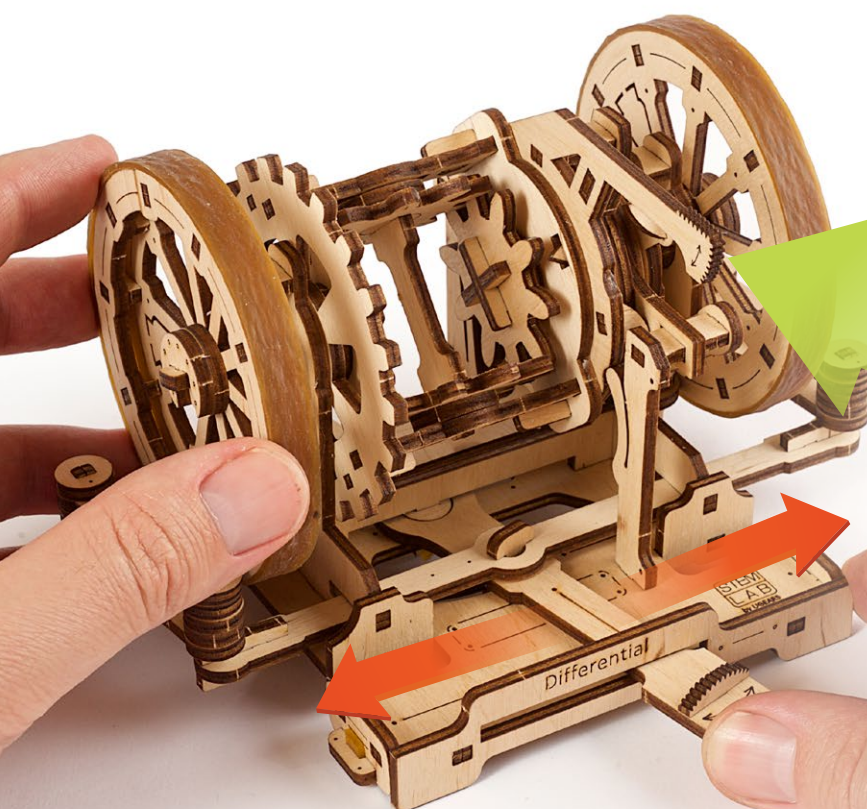
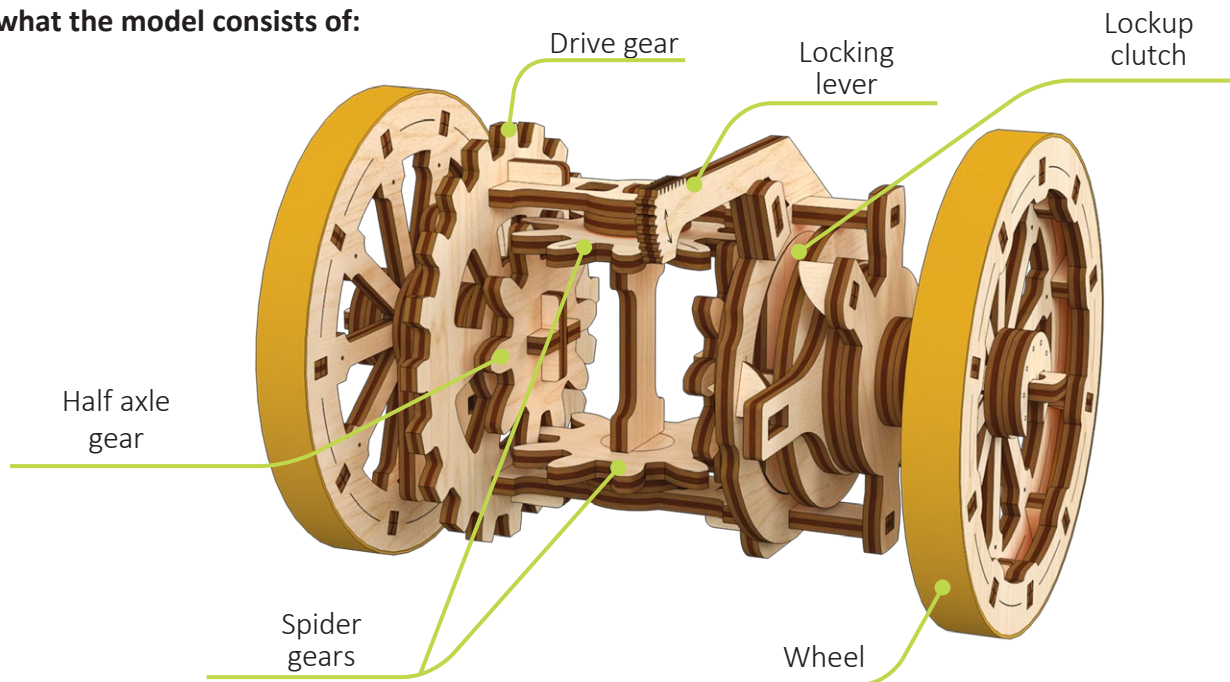
$L$  – distance between wheels, m.

# §5

## Technical design and principles of working

The mechanical model of a differential is an educational aid that explains in an actual example how the device works. It demonstrates the work of planetary gears in the distribution of load from the drive wheel to half-shafts.

**Let's consider  
what the model consists of:**



The impulse can be transferred to one of the wheels or blocked by the lever. The model comprehensively demonstrates how a car turns with increased torque on one wheel and lower on the other.



In the locked position of the lever, the energy of the motor will be equally distributed between wheels.



# §6 Formative hands-on tasks

Measuring rotation speed, angular and linear velocity.

**Differential** - the mechanism that transmits an engine's torque to the wheels and helps to avoid wheel slip and facilitates the work of transmission.

**Objectives:** to study the ways of measuring the rotation speed; to measure the rotation speed of a differential depending on its speed, develop logic, science skills, and spatial thinking

**Equipment:** the Differential, a stop-watch, ruler, notepad and pen.

**Theoretical background of the experiment:**

The task is to measure in several different ways the rotation speed of the disc fixed on a differential's shaft depending on the linear speed with which it is moving. Rotational motion is found through the angular rotation  $\phi$ , rotation speed  $\omega$ , angular velocity  $\beta$ , and time  $t$ . Every point of an object's rotation around an axle has the same rotation speed  $\omega$ . An average rotation speed is found as:

$$\omega = \frac{\phi}{t} (1)$$

Angular velocity  $\beta$  is found through the change of the rotation speed  $\omega$  in time. Therefore, the average angular velocity formula comes as follows:

$$\beta = \frac{\omega}{t} (2)$$

**Preparation for the experiment:**

Assemble the Differential and set it on a flat surface.

## WORK PROGRESS:

**Task 1. Finding the angular rotation.**

1. Choose a point on a rim of a wheel. Mark it with a pencil.
2. Roll the Differential on a flat even surface and check how much time it took your mark to complete a full circle.
3. Use formula (1) to calculate rotation speed. For one full rotation  $\Delta\phi = 2\pi = 2 \cdot 1800 = 3600$ .
4. Repeat the experiment while rolling the Differential with a different speed.
5. Compare the values of the angular rotation and the linear speed.

**Task 2. Finding the rotation speed.**

1. Count the number of rotations that the mark makes in 10 seconds.
2. Calculate the rotation frequency using the formula:

$$\nu = \frac{N}{t}$$

3. Calculate the rotation speed  $\omega = 2\pi\nu$ .
4. Repeat the experiment while rolling the Differential with a different speed.
5. Compare your data.

**Task 3. Finding the angular velocity.**

1. Use data from Task 1 and Task 2 (repeat them if necessary) and formula (2) to calculate the angular velocity.
2. Compare the relationship of the angular velocity and linear speed of the differential.

#### Task 4. Finding the linear speed.

1. Use a ruler to measure a radius of the wheel (the distance between the mark of the rim of the wheel and its center).
2. Use the data from Task 1 and Task 2 (repeat them if necessary) and formula  $v = R \cdot \omega$  to calculate the linear speed.
3. You can also calculate centripetal acceleration using the following formula:  $a = \frac{v^2}{R}$ .



In real-life conditions the radius of the wheel is not a constant number and perfect steady traction is not achievable. This is why if the wheels rotate with equal speed, the turning car will slide and the internal trajectory will be different from external one. Their ratio can be calculated as:

$$L_{in} = L_{ex} \cdot (1 - L \cdot \omega_z \cdot L_{ex}).$$

#### Where:

$L_{in}$  - internal trajectory, m;

$L_{ex}$  - external trajectory, m;

$\omega_z$  - horizon related angular velocity, rad/s;

$L$  - distance between wheels, m.

#### Task 5. Calculate the difference of the rotation speed of the wheels of a truck and the difference between the distance the wheels made.

**Given that:** the turning radius of the internal trajectory of the vehicle is 10 m, the external one is 11.6 m (since this vehicle track width is 1.6 m). The diameter of the wheel is 72 cm.

#### CONCLUSIONS:

In the process of experiments with the Differential, we learned to measure the linear speed, rotation speed and angular velocity.

#### We found out that:

- the rotation speed depends on the linear speed.
- the higher the linear speed, the higher the rotation speed will be.
- the rotation speed and angular velocity are directly proportional.



## ASSESSMENT TASK

**1. Credit for the first experiments with limited slip differential belongs to:**

- ☐ a) Onesiphore Pecqueur
- ☐ b) Ferdinand Porsche
- ☐ c) Volkswagen

**2. A differential provides different rotation speeds of the wheels on the same axle in order to:**

- ☐ a) reduce speed
- ☐ b) reduce slip on the turn
- ☐ c) increase friction.

**3. The improved differential is designed as:**

- ☐ a) a gear train
- ☐ b) a planetary gear
- ☐ c) an automatic transmission

**4. How many differentials do full wheel drive cars have?**

- ☐ a) two
- ☐ b) three
- ☐ c) six.

**5. What is a differential made of?**

- ☐ a) crank shaft
- ☐ b) shafts and gears
- ☐ c) drives

**6. How is rotation speed connected to the linear speed of a differential?**

- ☐ a) it's not connected
- ☐ b) increases when the linear speed increases
- ☐ c) decreases when the linear speed increases

**7. How is angular velocity connected to the linear speed of a differential?**

- ☐ a) via inverse proportion
- ☐ b) via direct proportion
- ☐ c) they have no connection.

**8. A type of a differential in which the torque grows with increasing speed difference between the drive and driven shafts is called:**

- ☐ a) Torsen
- ☐ b) Visco drive
- ☐ c) Quaife

**9. Which physical units characterise a differential?**

- ☐ a) gravity, work, time
- ☐ b) rotation force, torque, angular velocity
- ☐ c) oscillation frequency, friction, linear speed

**10. The unit of measurement of angular velocity is:**

- ☐ a) m/sec
- ☐ b) rad/sec
- ☐ c) m/rad

**Congratulations! You made it!**

Thank you for being with us in this adventure, we hope you had fun and learned a thing or two!