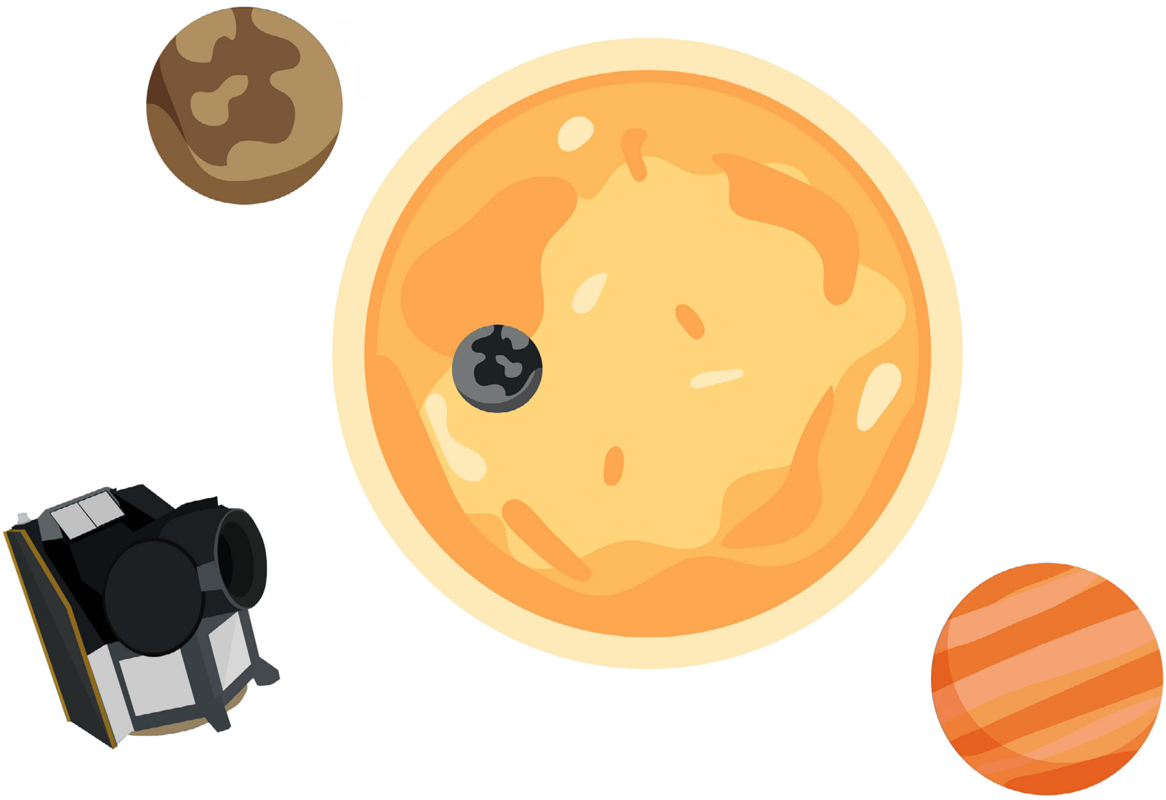
esa

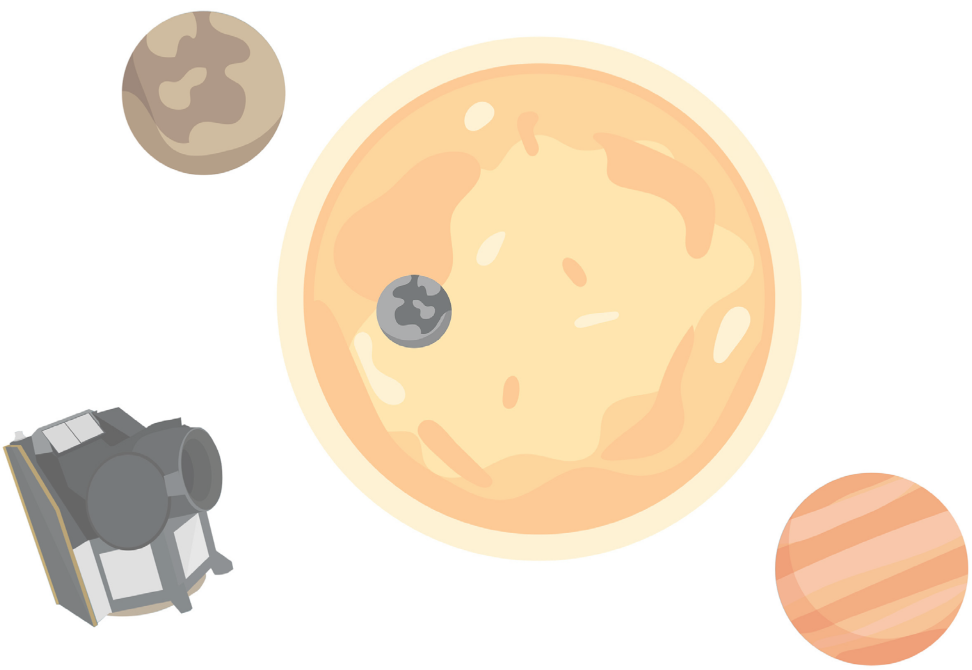
teach with space

→ EXOPLANETS IN MOTION

Building your own exoplanetary system



teacher guide & student worksheets



Teacher guide

teach with space – exoplanets in motion | P32
www.esa.int/education

The ESA Education Office welcomes feedback and comments
teachers@esa.int

An ESA Education production

Last update November 2024

→ EXOPLANETS IN MOTION

Modelling exoplanet transits

FAST FACTS

Subject: Mathematics, Physics, Astronomy

Age range: 14-19 years old

Type: Teacher's guide and student worksheets

Complexity: Medium

Lesson time: 60 minutes

Cost: Low (0-10 euros) - medium (10-30 euros)

Location: Classroom

Includes use of: Light meter app or data logger, 3D printed components (optional), rover (optional)

Keywords: Physics, Mathematics, Astronomy, Exoplanets, Light Curves, Transits, Orbits, Scaling, Graphs, Period, Robotics, 3D printing

Brief description

In this set of activities students will learn how scientists study exoplanets with satellites like Cheops (CHaracterising ExOPlanet Satellite), using the transit method. Students will build their own model exoplanetary system, then observe and interpret model light curves.

Assembly instructions for three different transit models are provided: turntable (simple), rover (intermediate) and 3D printed (advanced).

This activity is part of a series that includes "**Exoplanets in Transit**" where students analyse real data from ESA's Cheops satellite and "**Exoplanets in a Box**" where students build a transit model inside a shoebox and calculate the size of an exoplanet

Learning objectives

- Understanding what exoplanets are and how satellites investigate them.
- Understanding how the transit method is used for the detection and characterisation of exoplanets.
- Enhancing experimental skills by observing and interpreting measured light curves.
- Developing team working skills through collaborative problem solving.
- Communicating scientific and mathematical findings to peers.

→ Summary of activities

Summary of activities					
	Title	Description	Outcome	Requirements	Time
1	Introduction to Exoplanets	Introductory activity exploring the basics of exoplanets and the transit method.	Learn what exoplanets are and how the transit method can be used to both find and learn more about them.	None	20 minutes
2	Transiting Exoplanet Model	Students will create their own model exoplanetary system and use it to explore the transit method by taking measurements with a light meter app/data logger.	Follow instructions to create a model exoplanetary system. Sketch and interpret graphs and understand how the size of the model exoplanets will affect the light measured by the detector.	Knowledge from activity 1	40 minutes, depending on the transit model used it can take longer

→ Introduction

Exoplanets, or extrasolar planets, are planets outside our own Solar System, orbiting a star other than our Sun. Exoplanets are detected and studied using both telescopes on Earth and in space.

Exoplanets are difficult to detect, as the signal that we receive from them is small in comparison to the much larger signal coming from their bigger, brighter host stars. Typically, much less than 1%.

There are several main methods that are used to search for and find exoplanets, these are the main ones:

- **Direct imaging** – as the name suggests, the exoplanet is directly imaged. This is the only method that detects the exoplanet and measures its light directly.

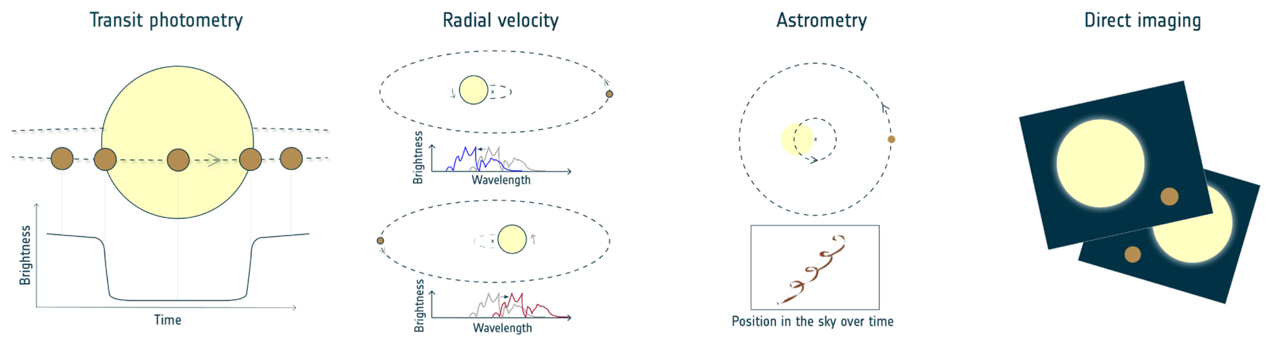
- **Transit photometry** – the exoplanet is detected by measuring a dimming in the light coming from the star.

When a star is orbited by an exoplanet, the star and the exoplanet will orbit around the centre of mass of the whole system. The small orbital motion from the star is used by the next two methods to characterize the exoplanets orbiting it.

- **Radial velocity** – the exoplanet is detected by measuring shifts in the spectral profile of the star.

- **Astrometry** – the exoplanet is detected by measuring the wobble in the star's position.

Figure 1



↑ Exoplanets detecting methods.

In this set of activities, students will build a transit model exoplanetary system. The depth of the dip depends directly on what percentage of the light from the star is blocked by the passing exoplanet, which depends on the size of the exoplanet relative to the star. The bigger the planet is relative to the star, the more of the light it will block. If we know the size of the star, we can determine the size of the planet.

→ Activity 1: Introduction to Exoplanets

To introduce the students to the topic of exoplanets you can use the video material available in the links below or use the background information as a complementary resource.

- **Meet the Experts series – Other Worlds:**
  esa.int/ESA_Multimedia/Videos/2020/07/Meet_the_Experts_Other_worlds

- **Meet Cheops, the Characterising Exoplanet Satellite:**
  esa.int/ESA_Multimedia/Videos/2019/12/Meet_Cheops_the_Characterising_Exoplanet_Satellite

- **Paxi explores exoplanets!**
  esa.int/ESA_Multimedia/Videos/2019/12/Paxi_explores_exoplanets

Once the students have been introduced to exoplanets, the transit method and Cheops, they can work through Activity 1 in the student worksheet.

Exercise 1 – Exoplanet Basics

Please find indicated below possible answers to questions 1 and 2 on the student worksheet.

1.1 Exoplanets are planets outside of the Solar System. In the same way that planets, including the Earth, orbit the Sun, other stars may have planets orbiting them.
1.2 Light

Extra information: Cheops has a single science instrument onboard: a specialised camera called a photometer. The light from stars reaches the photometer via a 32-centimetre-diameter telescope. Cheops is sensitive to optical light (that we can also detect with our eyes) as well as light that is bluer and redder, specifically light wavelengths in the region of 350 nm to around 1100 nm.

Exercise 2 – The Transit Method

Displayed below is a possible answer to question 2.1.

2.1 *With this method we directly measure the amount of light the planet blocks when it passes in front of the star, indirectly we can calculate the planet's size.*
If the telescope observes two consecutive dips in the light curve, then we can also infer the orbital period of the planet, which is the time it takes for the planet to complete one full orbit around its host star.

Extra information: When combined with other measurements we can also calculate the planet's density and derive information about its atmosphere. Cheops will also be able to determine the phase curve and albedo of some exoplanets, which provide insight into their temperature, reflectivity, and climate.

Discussion

After completing the activities, the students should be encouraged to discuss their answers. You may wish to split the class first into pairs or groups, before discussing the answers with the whole class.

Before starting Activity 2, where students will build a transit model, you can discuss with them proposals of how they would create an exoplanetary model system.

→ Activity 2: Transiting Exoplanet Model

In this activity, students will build and test their own model of an exoplanetary system orbiting a star, represented by a light bulb. Assembly instructions for three different exoplanet transit models are available in the annexes: turntable (simple), rover (intermediate) and 3D printed (advanced). Choose the exoplanet transit model that best fits your students.

- **Turntable Edition (simple):** a turntable is used to create the circular motion of the model exoplanet and simulate an orbit. The turntable version of the exoplanetary system model is the simplest of the three possible models for this resource.
Assembly instructions link: https://youtu.be/oTibvYu3vyA

- **Rover Edition (intermediate):** a rover is used to create the circular motion of the model exoplanet and simulate an orbit. The rover version can be combined with programming, robotics, and movement analysis.
Assembly instructions link: https://youtu.be/VIrTvsamQrg

- **3D Printed Edition (advanced):** a custom open-source 3D printed mechanism is used to create the circular motion of the model exoplanet and simulate an orbit. The 3D printed version of the exoplanetary system model requires access to a 3D printer to print the model. The mechanism is customisable and can be edited to fit your own requirements.
Assembly instructions link: https://youtu.be/GyEK6WNOhFA

  Pre-prepared 3D files: esamultimedia.esa.int/docs/edu/3Dprint_files_ExoplanetsInMotion.zip

  After setting up the model, the students will measure the light from the light bulb as the model exoplanets orbit and observe the effect that the size and speed of the model exoplanets have on the measured light curve.

This activity can be run either as a demonstration to the class, or as a group activity to be done in groups of 3 to 5 students.

Extra: Although not explored in this set of activities, the exoplanetary system model can be used to introduce Kepler's laws of planetary motion. A planet in a circular orbit will travel at constant speed (Kepler's Second Law). This speed is determined by the mass of the star, and the distance between the planet and the star (Kepler's Third Law).

Equipment

List of material:

- light bulb fitting and support
- high luminosity light bulb
- plasticine/modelling clay
- ruler
- wooden skewers
- light meter (e.g. phone with light meter app, or data logger)
- Additional material for the exoplanet transit model per group:
    - **Turntable Edition:** turntable (e.g. record player, rotating serving tray, bicycle wheel)
    - **3D Printed Edition:** motor, 3D printed parts of the model
    - **Rover Edition:** Rover (e.g. WeDo 2.0)
    - **Suggested apps:** Android and IOS: Physics Toolbox Sensor Suite and Phyphox

Please note that the LEGO WeDo 2.0 rover mentioned in this classroom resource has been discontinued. While some sections of this resource was originally designed with the use of the LEGO WeDo 2.0 rover, it can be adapted with alternative rovers offering comparable functionalities. The resource also offers variation of the activity without the use of the kit (see Annexes).

Exercise 1: Make your Exoplanets

In this exercise the students will use plasticine or modelling clay to create 2 or 3 different model exoplanets. The parameter that will create a bigger impact in the transit is the size of the exoplanet, but make sure the planets are not too big or too heavy so that they will still work with the mechanisms. The students are also asked to creatively name their planets.

You may wish to set your own time limit on this activity to ensure there is enough time to complete the other exercises.

Exercise 2: Build your exoplanet transit model

In this exercise the students will set up the model exoplanetary system, test it and analyse the light curve measured with the light meter. Choose the exoplanet transit model that best fits your students. Assembly instructions for three different exoplanet transit models are available in separate documents: turntable (simple), rover and 3D printed (advanced).

The student worksheet is valid for the three models.

Exercise 3: Analyse a transit with your exoplanet transit model

As the students are asked to describe their observations in their own words, the following answers are just examples. It is possible that some students will describe their results referring to the model, and others to the real exoplanet system, so it is important to distinguish between observation and model here.

It is important that the model exoplanet is rotated at a steady pace, regardless of the speed. Depending on the rotation speed of the model, the dip in the light curve can appear as a sharper "v-shape" or a wider "u-shape".

3.1 Star - **Light bulb**
Telescope - **Smartphone / detector**
Exoplanet – **Plasticine ball**

3.2 *For each scenario, the students have to make a sketch of the light curve they observed and describe it in their own words.*

a) The light intensity displayed on the graph will be approximately constant except when the model exoplanet passes between the sensor and the light source. At this point we can observe a drop in the measured light intensity.

Sketch:

b) The light intensity will drop every time the model exoplanet passes between the detector and the light source. The depth and width of each of the three dips is the same, and the distance between consecutive dips does not change.

Sketch:

c) A larger model exoplanet produces a deeper dip in the light intensity, a smaller model exoplanet results in a smaller or shallower dip on the graph.

Sketch:

smaller/shallower larger/deeper

d) Each model exoplanet passing in front of the light bulb will produce its own dip in the light intensity. The larger model exoplanet creates a deeper dip than the smaller model exoplanet, whilst the width of the dip is similar.

Sketch:

Discussion

After completing this activity, each group should present their results to the class. The students should be able to describe the components of the transit model and understand the importance of the size of the exoplanet on this experiment. Students should also have an idea about the limitations of the model.

As a conclusion to the activity and to foster discussion you may ask your students the following question to introduce the connections between the model and the real exoplanetary system:

Question: *After observing the light detected from your model exoplanetary system, what do you expect to see in the light curve when the satellite observes an exoplanet transit?*
Expected answer: a dip in the light curve.

As a bonus activity you could ask the students to analyse the data collected from the light detector quantitatively and, for example, complete Activity 3 of the **Exoplanets in a Box** classroom resource.

If you want to continue analysing light curves with your students you can complete the activity **Exoplanets in Transit**, where students can compare model and a real satellite data from ESA's Cheops mission.

→ EXOPLANETS IN MOTION

Building your own exoplanetary system

→ Introduction

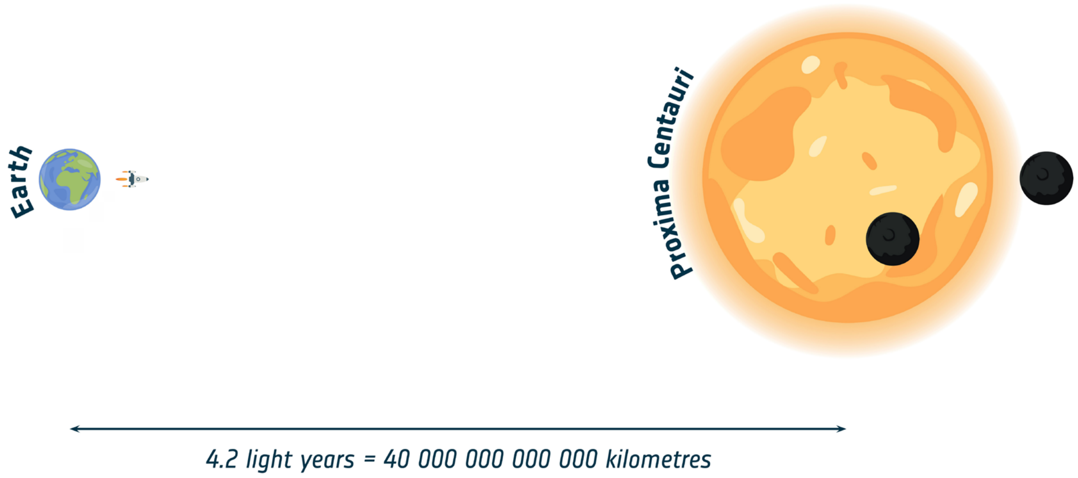
Just as the planets in our Solar System orbit our star, the Sun, there are other planets in the universe orbiting other stars too! Exoplanets, or extrasolar planets, are planets outside our own Solar System.

Since the first discovery of an exoplanet orbiting a star similar to our Sun in 1995, more than 4000 exoplanets have been discovered, and we are still finding more. Each exoplanet is unique. Some are large and gassy, like Jupiter, some are small and rocky like Earth and Mars, and some are unlike anything we have seen in our Solar System

In this activity you will build your own exoplanet system and learn how scientists find these unknown worlds far away from us in space.

Did you know?

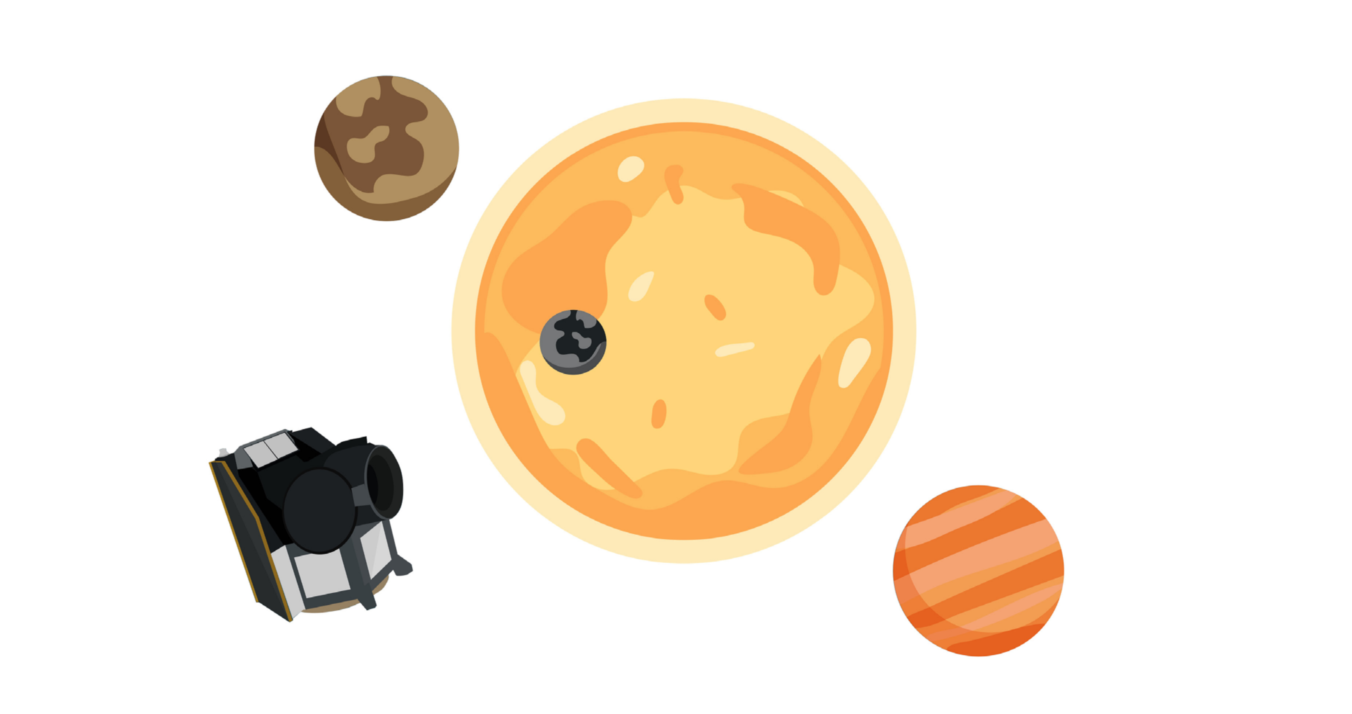
The nearest exoplanet to us is a planet orbiting the star Proxima Centauri. Light takes only 4.2 years to travel from Proxima Centauri to Earth, but it would take over seven thousand years for the fastest spacecraft that currently exists to reach this exoplanet!



→ Activity 1: Introduction to Exoplanets

In this activity you will learn more about exoplanets.

Figure 1



↑ Artistic impression of ESA's satellite Cheops (CHaracterising ExOPlanet Satellite)

Exercise 1: Exoplanet basics

1.1. In your own words, explain what an exoplanet is.

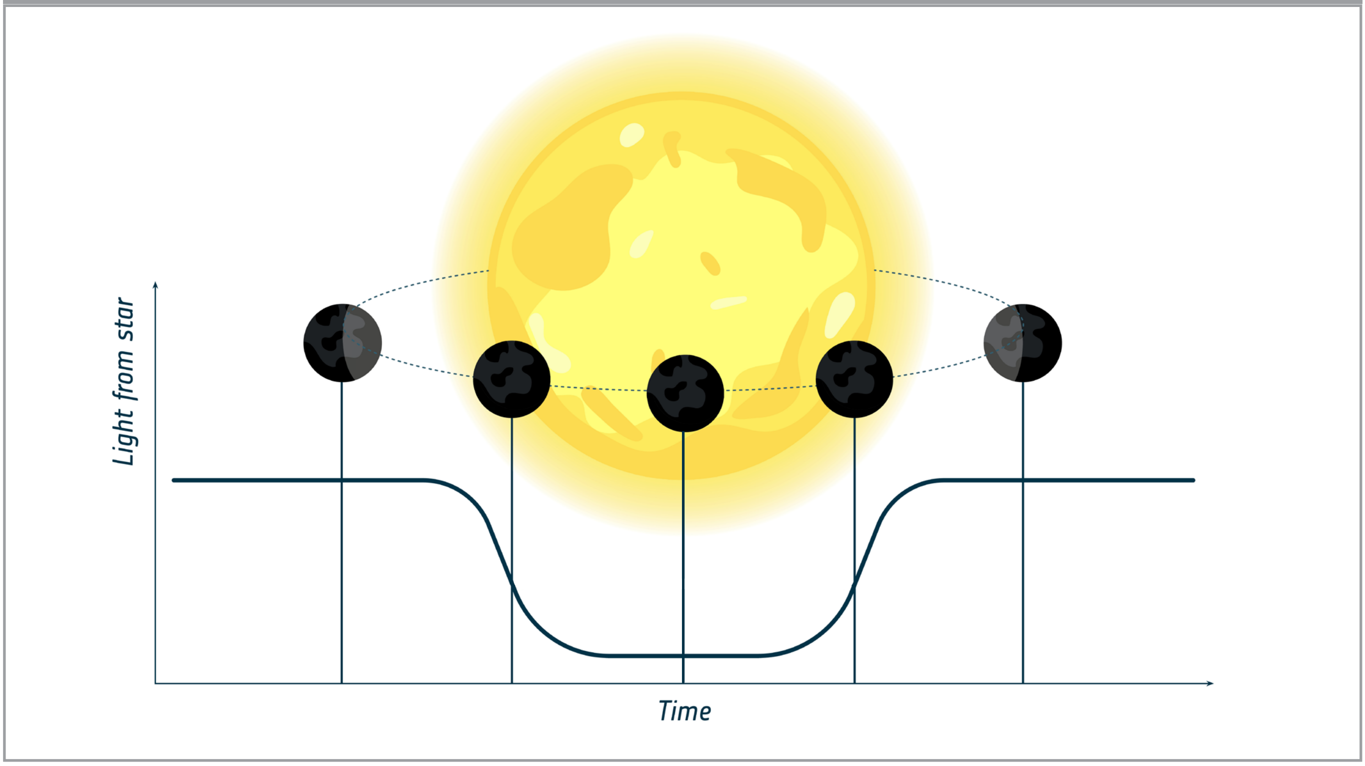
1.2 Cheops is a satellite that studies exoplanets. What does Cheops measure?
Circle the correct option:

Temperature **Colour** **Distance** **Light** **Sound**

Exercise 2: The Transit Method

The **transit method** can be used to both find new exoplanets and to learn more about them. To be able to use this method the exoplanet needs to pass directly between us and the star that it is orbiting. As an exoplanet passes in front of the star it will block some of the light that we can see from the star. We can monitor the light coming from a star over time using a telescope. The graph that represents the star light as a function of time is called a **light curve** (see Figure 2).

Figure 2



↑ Representation of a light curve measured during an exoplanet transit

2.1. Cheops uses the transit method to study exoplanets. What can we learn about exoplanets using this method?

→ Activity 2: Transiting Exoplanet Model

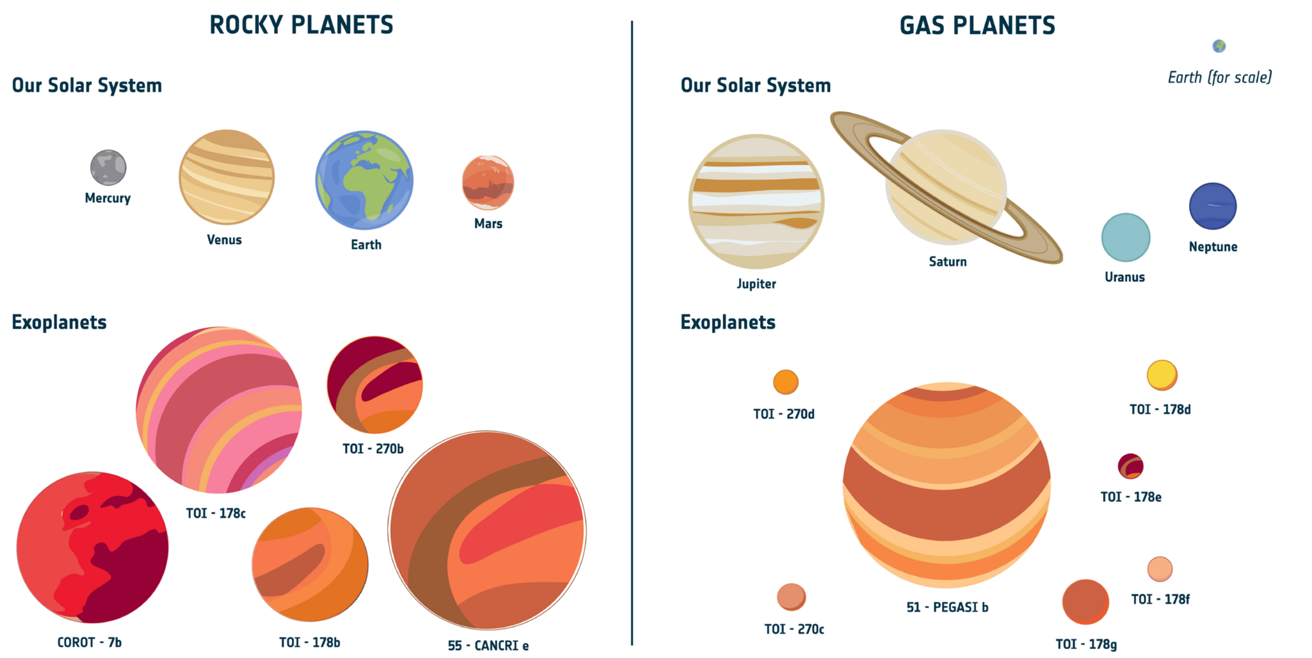
In this activity, you will build your own model exoplanetary system, with plasticine exoplanets moving around a light source that represents the star. You will measure the intensity of the light detected from the light source as the model exoplanets move around it and observe the effect that the size of the model exoplanets have on the amount of light that you measure.

Exercise 1: Make your exoplanets

Using the materials provided, in your group create two or three model exoplanets that will be used in your model.

The plasticine balls need to be between approximately 1 cm and 3 cm in diameter, and of different sizes.

Figure 2



↑ Examples of artists' impressions of real exoplanets that have already been discovered orbiting nearby stars!

1. Give your exoplanets names, feel free to get creative

____

____

____

Did you know?

By convention, exoplanets are named after the star that they orbit followed by a lower case letter starting from b (then c, then d, etc.), to indicate the order in which they were discovered. For example, the first planet discovered orbiting the star 51 Pegasi is called 51 Pegasi b (or 51 Peg b for short).

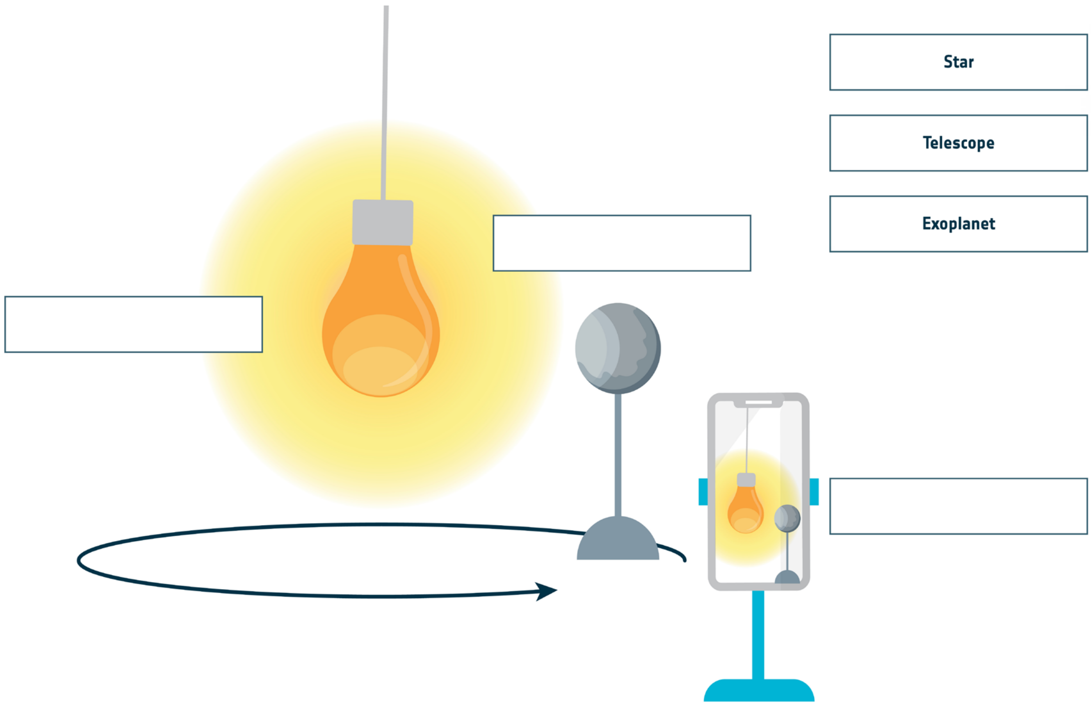
Exercise 2: Build your exoplanet transit model

Following the instructions given to you by your teacher, assemble your model exoplanetary system using one of the model exoplanets made in the previous exercise.

Ensure that the detector, model exoplanets and light source are aligned. Test your exoplanet transit model.

Exercise 3: Analyse a transit with your exoplanet transit model

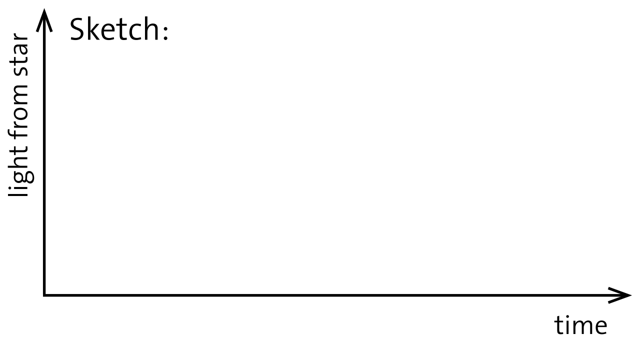
3.1. Fill in the labels on the diagram using the words provided



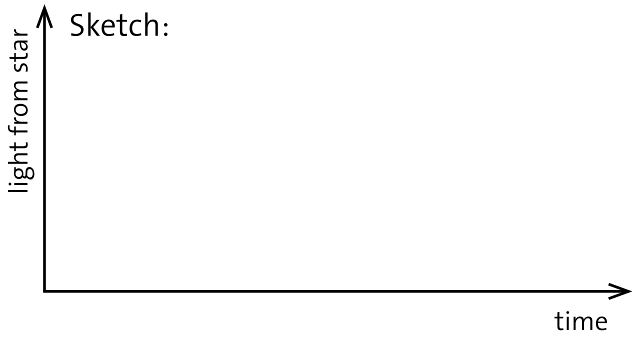
3.2. The graph you see plotted on your detector screen shows you the intensity of the light source in your model exoplanetary system.

Follow the instructions given in each of the questions below. Make a sketch of the light curve you observe and describe it also in words.

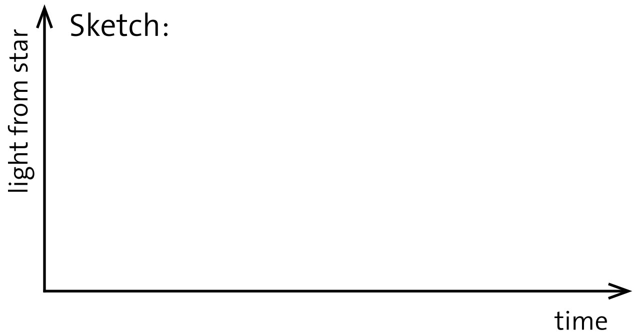
a. Stick one plasticine exoplanet to the model and begin the rotation. Stop the rotation when the plasticine exoplanet has completed one full orbit around the bulb:

Description:	Sketch:
	

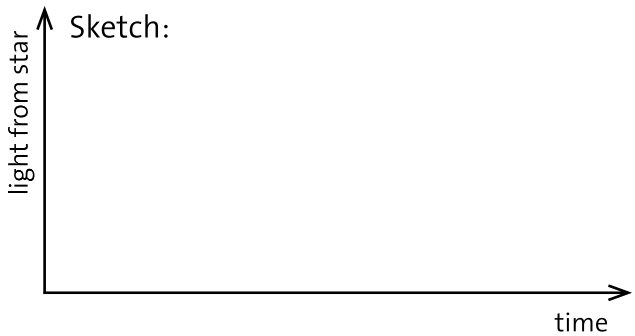
b. Begin the rotation again and stop it when the plasticine exoplanet has completed 3 full orbits around the bulb:

Description:	Sketch:
	

c. Change the size of the plasticine exoplanet. Let the new plasticine exoplanet complete 3 full orbits around the bulb:

Description:	Sketch:
	

d. Add a second plasticine exoplanet of a different size to the model. Begin the rotation and stop when both plasticine exoplanets have completed 3 full orbits around the bulb:

Description:	Sketch:
	

→ Links

Assembly instructions for the transit exoplanet models:

The 3D Printed Edition: *youtu.be/GyEK6WNOhFA*

The Rover Edition: *youtu.be/VIrTvsamQrg*

Turntable Edition: *youtu.be/oTibvYu3vyA*

Pre-prepared 3D files: *esamultimedia.esa.int/docs/edu/3Dprint_files_ExoplanetsInMotion.zip*

ESA resources

ESA classroom resources: *esa.int/Education/Classroom_resources*

Teach with exoplanets: *esa.int/Education/Teach_with_Exoplanets*

Meet Cheops: the Characterising Exoplanet Satellite:
esa.int/ESA_Multimedia/Videos/2019/12/Meet_Cheops_the_Characterising_Exoplanet_Satellite

Meet the Experts series – Other Worlds:
esa.int/ESA_Multimedia/Videos/2020/07/Meet_the_Experts_Other_worlds

Paxi explores exoplanets! *esa.int/ESA_Multimedia/Videos/2019/12/Paxi_explores_exoplanets*

Hack an Exoplanet *hackanexoplanet.esa.int*

ESA space projects

ESA's exoplanet missions: *esa.int/Science_Exploration/Space_Science/Exoplanets*

Cheops - CHaracterising ExOPlanet Satellite: *esa.int/Science_Exploration/Space_Science/Cheops*

Webb - James Webb Space Telescope: *esa.int/Science_Exploration/Space_Science/Webb*

Detecting exoplanets with Gaia: *esa.int/Science_Exploration/Space_Science/Gaia*

PLATO - PLAnetary Transits and Oscillations of stars: *esa.int/Science_Exploration/Space_Science/Plato*

ARIEL - the Atmospheric Remote-sensing Infrared Exoplanet Large-survey:
esa.int/Science_Exploration/Space_Science/Ariel

➔ Turntable Edition

Assembly instructions for the transit exoplanet model

The exoplanet transit model **turntable edition** uses a turntable to create the circular motion of the model exoplanet and simulate an orbit. The star is represented by a light bulb.
To set up the turntable model, follow this assembly guide.

Additional supporting video material can be found here: *youtu.be/oTibvYu3vyA*

Equipment

- Model exoplanets
- High luminosity light bulb
- Fixture and support for the light bulb
- Light meter (e.g. smartphone with light meter app, or data logger)
- Wooden skewers
- Turntable (e.g. record player, rotating serving tray, bicycle wheel)

Assembling your model:

Step 1:

Stick a model exoplanet onto a wooden skewer and fix the skewer onto the turntable with plasticine.

Step 2:

Hang the light bulb over the centre of the turntable, so that it is at the same height as the model exoplanet.

Step 3:

Align your light detector with the light bulb and the model exoplanet.

Step 4:

You are now ready to start collecting data. Check the setup of your model:

- Confirm that the light detector is aligned and receiving light from the correct light source.
- Rotate the turntable at a slow and steady speed. Ensure that there is a dip detected in the light curve when the model exoplanet passes between the detector and the light bulb.

Step 5:

(Optional) You can add multiple exoplanets to your model.

→ The Rover Edition

Assembly instructions for the transit exoplanet model

Please note that the LEGO WeDo 2.0 rover mentioned in this classroom resource has been discontinued. While this section of the resource was originally designed with the use of the LEGO WeDo 2.0 rover, it can be adapted with alternative rovers offering comparable functionalities. The resource also offers variation of the activity without the use of the kit (see other Annexes).

The exoplanet transit model **rover edition** uses a rover to create the circular motion of the model exoplanet and simulate an orbit. The star is represented by a light bulb.

The LEGO WeDo 2.0 rover is used as an example in these instructions, but different rovers can be used in this transit model. To set up the rover model, follow this assembly guide.

Additional supporting video material can be found here: *https://youtu.be/VIrTvsamQrg*

Equipment

- Rover
- Model exoplanets
- High luminosity light bulb
- Fixture and support for the light bulb
- Light meter (e.g. smartphone with light meter app, or data logger)
- Dry erase pen (optional)

Getting your model ready:

1. Assemble your rover, making sure it moves in a circle. If using the WeDo 2.0 rover, you can follow the step-by-step instructions found in Setting up the WeDo 2.0 “Exoplanet Rover”. You can attach a pen to the rover, to confirm that circular motion has been achieved. Don’t forget to attach your model exoplanet to the rover.
2. Find the centre of the circle that your rover is travelling on.
3. Hang your light bulb so that it is at the same height as the exoplanet on the rover, and directly over the centre of the rover’s orbit.
4. Set up the light meter so that it is aligned with the light bulb.
5. You are now ready to start collecting data. Check the setup of your model:
    - Confirm that the light detector is aligned and receiving light from the correct light source.
    - Ensure that there is a dip detected in the light curve when the model exoplanet passes between the detector and the light bulb.

Setting up the WeDo 2.0 “Exoplanet Rover”

Follow the assembly instructions shown in the pictures step by step to set up the rover transporting the model exoplanet.

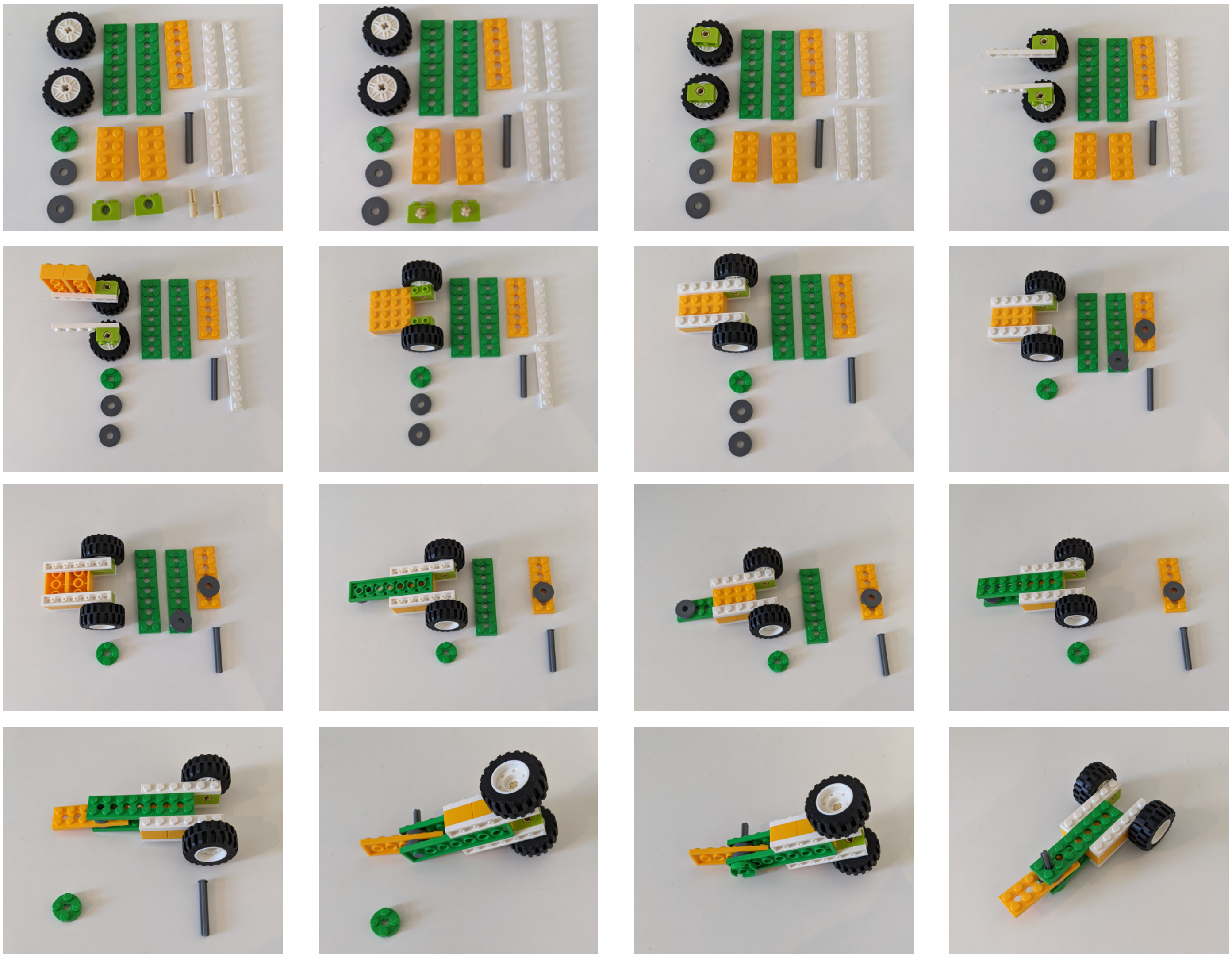
A timelapse video of the assembly can be found at
https://youtu.be/VIrTvsamQrg?t=15

Step 1:

Find the material needed. The necessary parts are displayed on the image to the right.

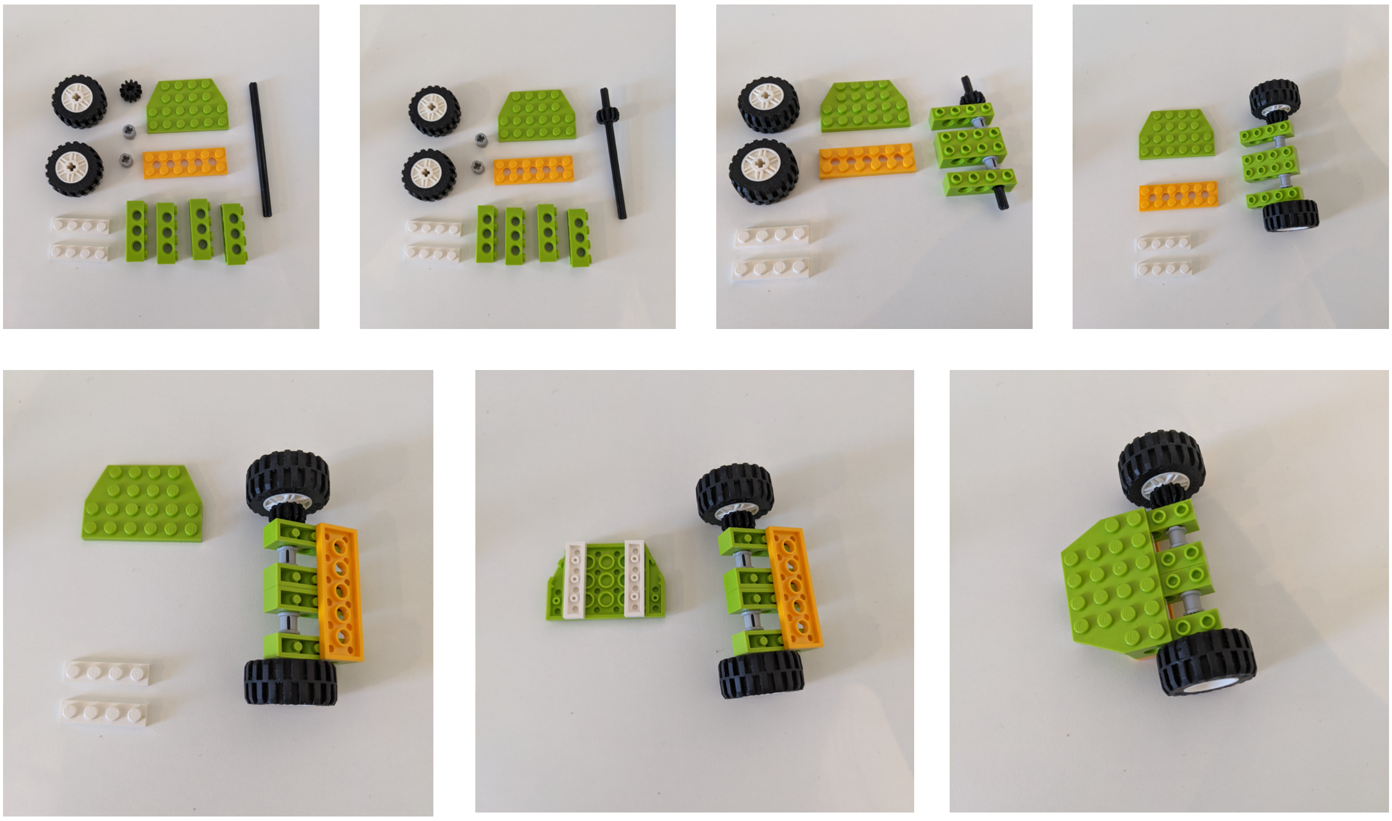
Step 2:

Build the front of the WeDo rover:



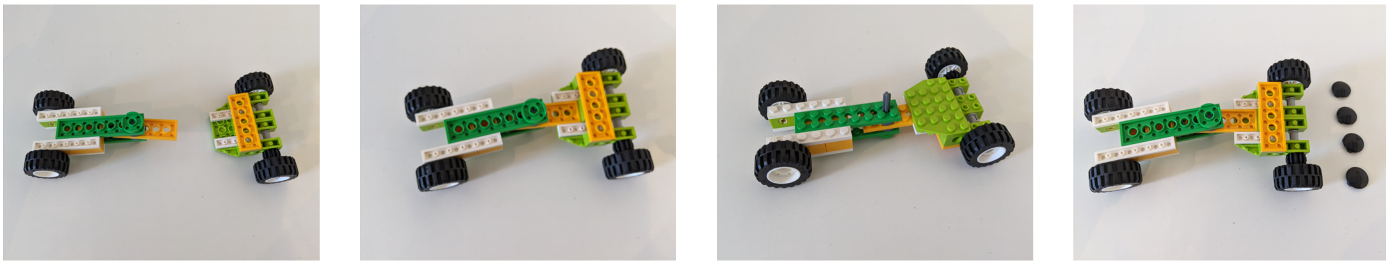
Step 3:

Build the back of the WeDo rover:



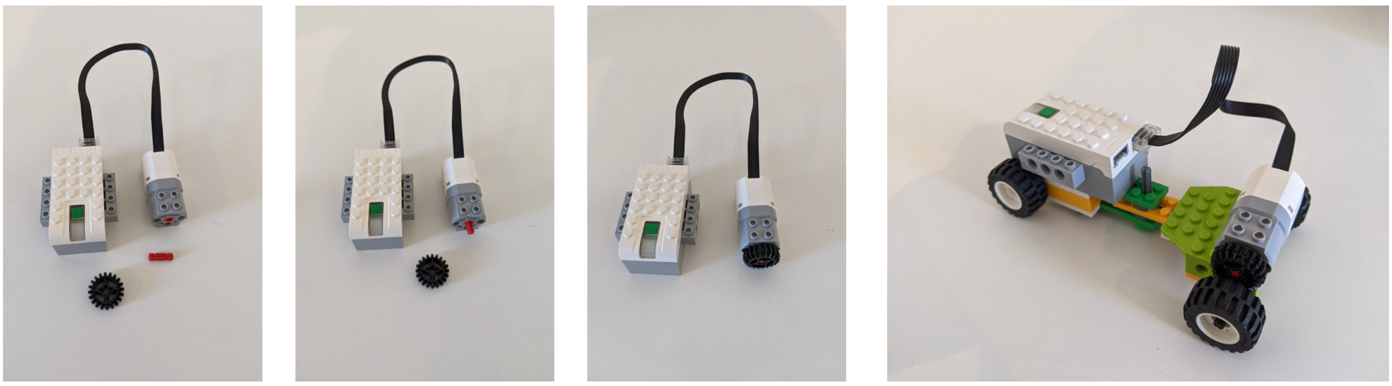
Step 4:

Join the front and back of the WeDo rover:



Step 5:

Assemble and mount the motor:

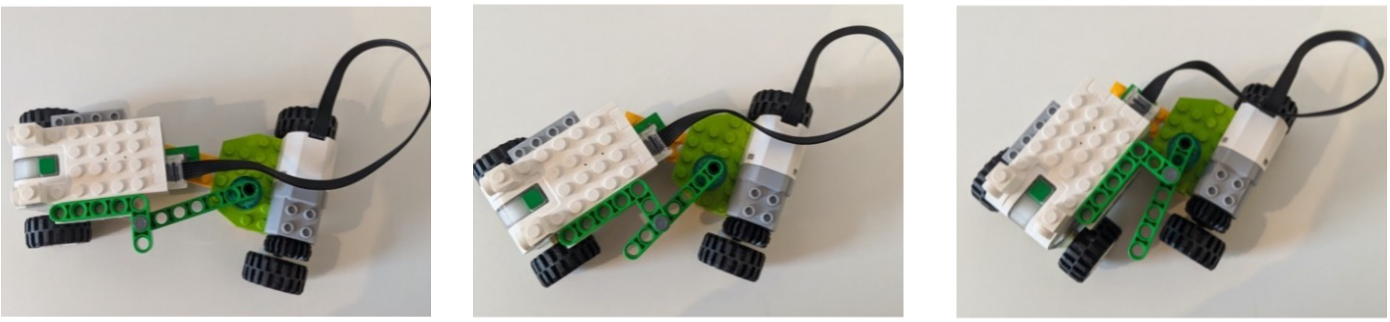


Step 6:

Attach the angle-setting system to your WeDo rover:

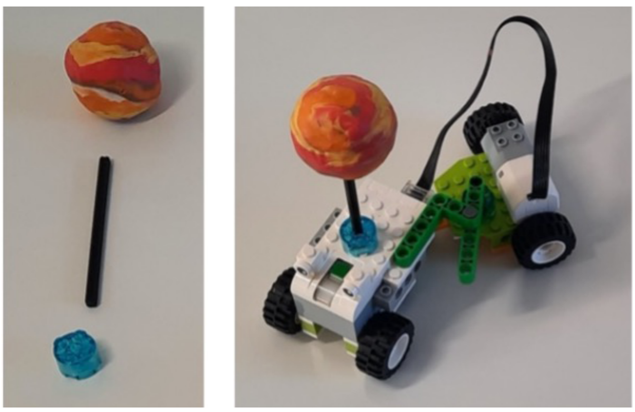
Step 7:

Choose an angle for your rover to determine the diameter of its orbit:
To change the angle of the rover, remove the pin from the green supports, adjust the rover and place the pin between a different set of holes.



Step 8:

Attach the exoplanet to finalize the rover:



Step 9:

Connect the rover to the WeDo software and get ready to experiment!

➔ The 3D Printed Edition

Assembly instructions for the transit exoplanet model

The exoplanet transit model **3D printed edition**, uses a custom open-source 3D printed mechanism to create the circular motion of the model exoplanet and simulate an orbit. The star is represented by a light bulb.

The model represents a stellar system with two exoplanets orbiting a star. The orbiting of the model planets around the central light source is achieved through two arms that rotate in different periods around the light bulb.

The mechanism is customisable and can be edited to fit your own requirements. To print and set up the 3D printed model, follow this assembly guide.

Additional supporting video material can be found here:

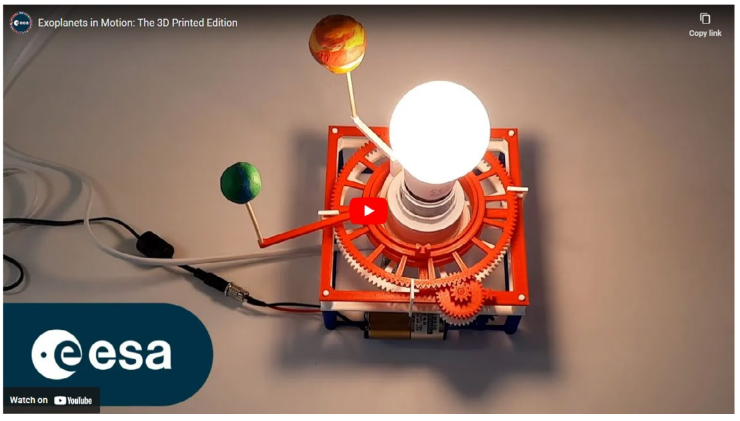
https://youtu.be/GyEK6WNOhFA

You can find the pre-prepared 3D files and instructions for printing here:

esamultimedia.esa.int/docs/edu/3Dprint_files_ExoplanetsInMotion.zip

Equipment

- Model exoplanets
- High luminosity light bulb
- Light meter (e.g. smartphone with light meter app, or data logger)
- 2mm diameter wooden skewers
- 3D printer
- PLA material
- Motor (~100rpm) and power supply
- Fixture and support for a high luminosity light bulb (E27 fixture)



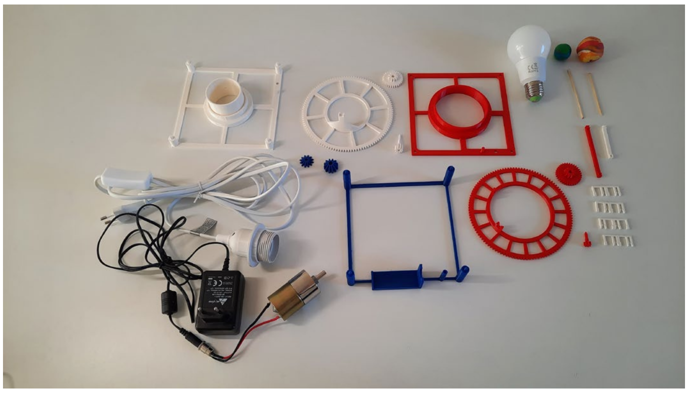
Getting your model ready:

1. Download the *3D printing .stl files* and print your model. Further instructions are available in the 3D printing guide. No modifications of the 3D model are needed if you use the following parts:
    - lamp fitting: E27 with cable switch and mount ring (Ø 40 mm)
    - DC motor: 12V 100RPM 166 oz-in brushed with a 6 mm D-shaped shaft
2. Assemble your model, following these step-by-step instructions.

Setting up the 3D printed mechanism

Follow the assembly instructions shown in the pictures step by step to set up the 3D printed mechanism transporting the model exoplanet.

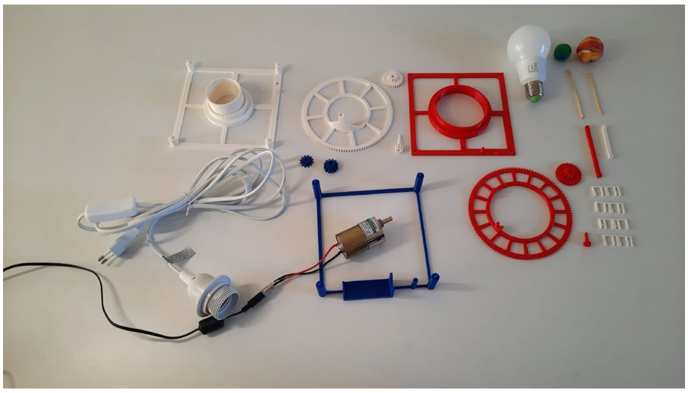
A timelapse video of the assembly can be found at
https://youtu.be/GyEK6WNOhFA?t=28



Step 1:

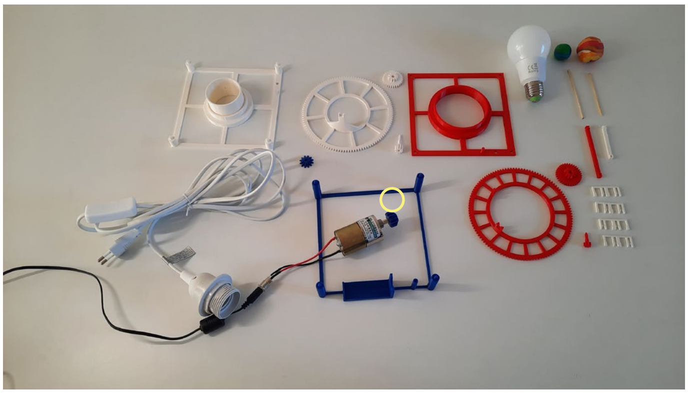
Get all equipment needed, ready for setting up the exoplanetary system model.

Note: Make sure your model exoplanets are not too heavy.



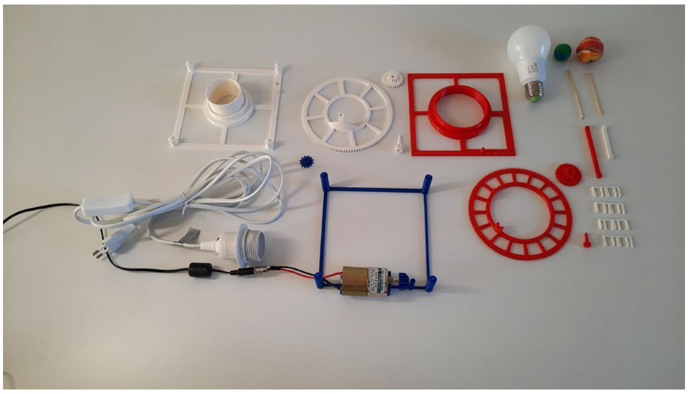
Step 2:

Take the **motor base** and the **motor** to start the assembly.



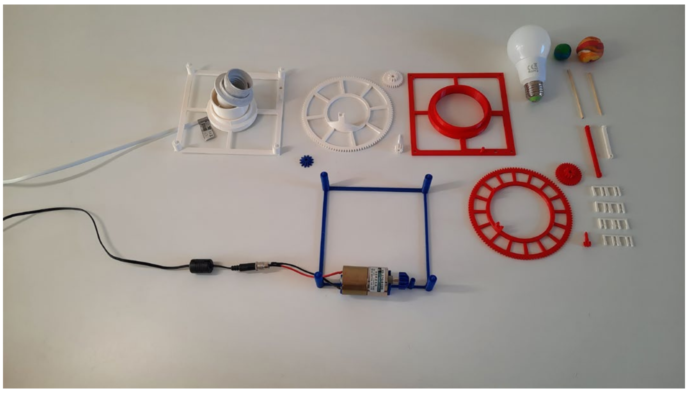
Step 3:

Place the **motor gear** to the shaft of the motor.



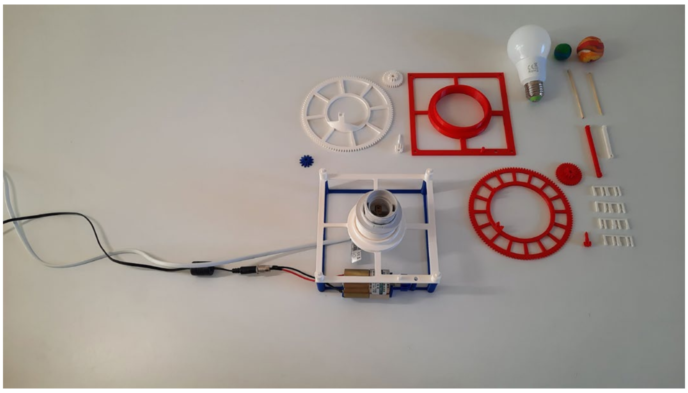
Step 4:

Attach the motor to the **motor base**.



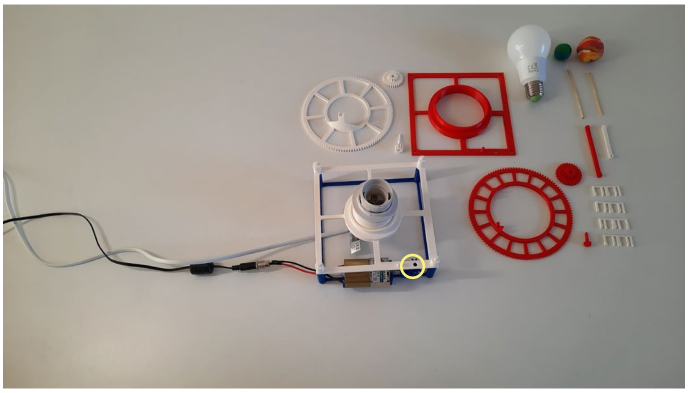
Step 5:

Pull the cable of the lamp fitting through the **lower level base** to prepare it for mounting.



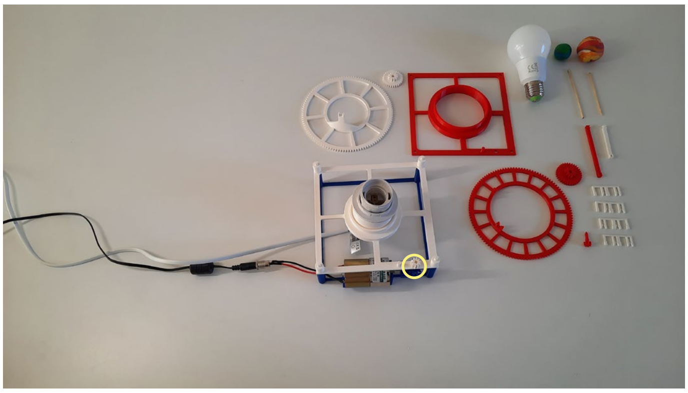
Step 6:

Place the **lower level base**, including the lamp fitting, onto the **motor base**.



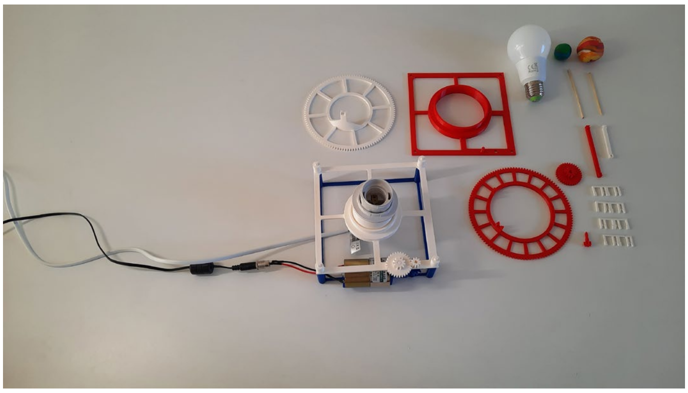
Step 7:

Insert the **drive gear** between the **motor base** and the **lower level base**.



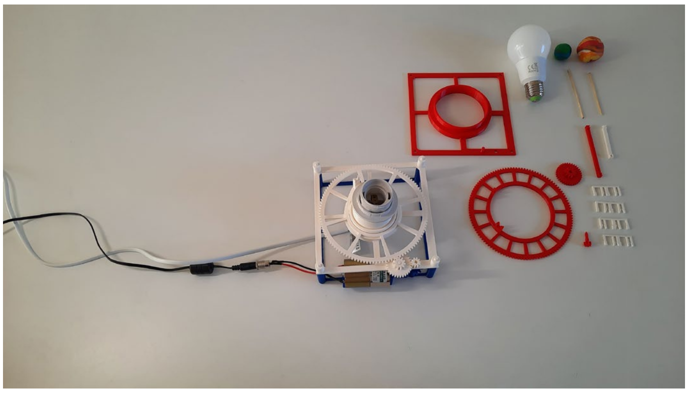
Step 8:

Stick the **hold gear** through the hole in the **lower level base** to attach the **drive gear**.



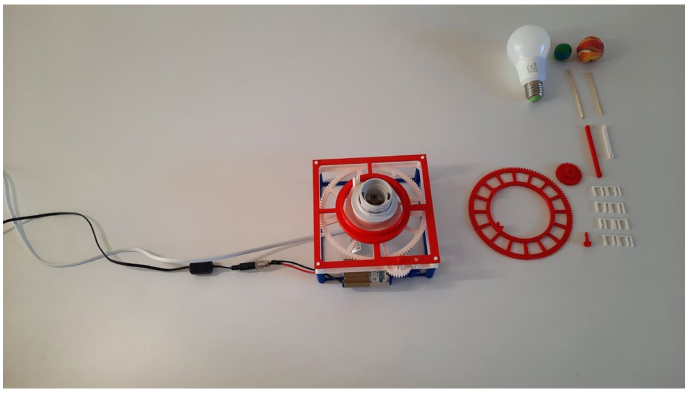
Step 9:

Add the **connect gear 1** to the pin on the **lower level base**.



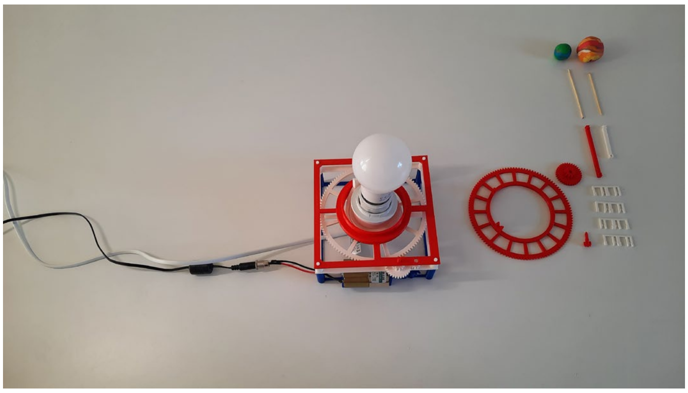
Step 10:

Put the **exoplanet gear 1** over the lamp fitting and check that the gears engage/mesh correctly



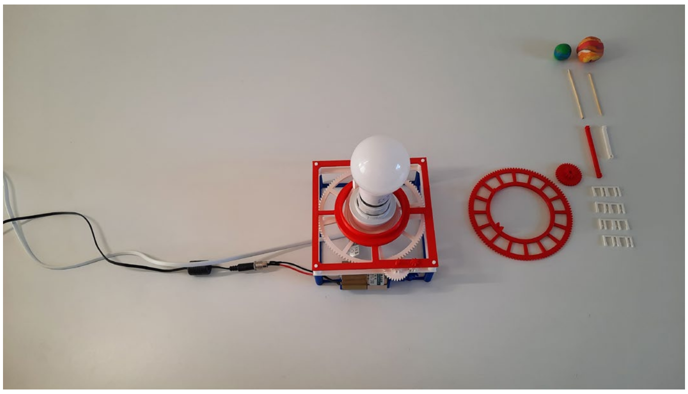
Step 11:

Place the **upper level base** on top of the **lower level base**.



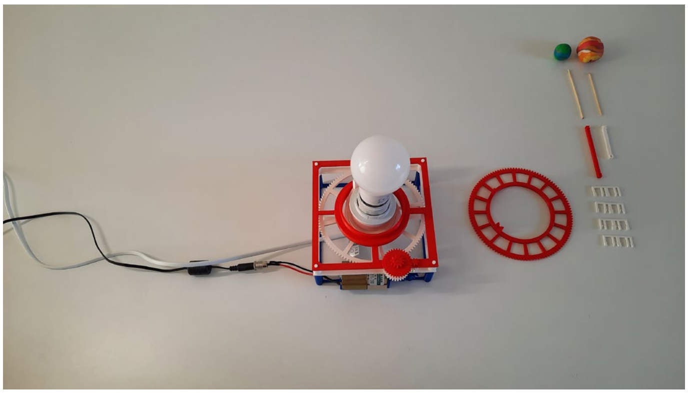
Step 12:

Screw the light bulb into the lamp fitting.



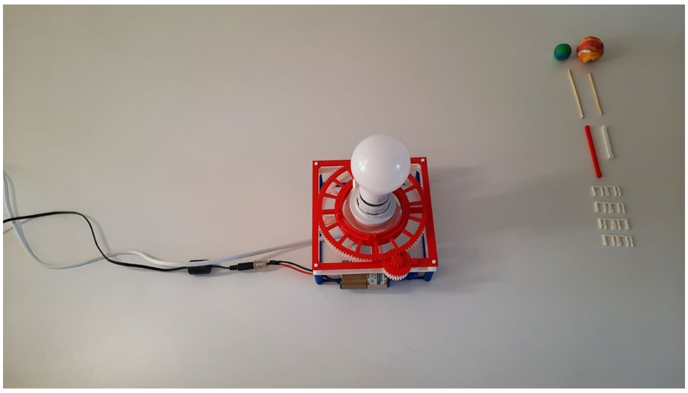
Step 13:

Stick the **upper motor gear** through the hole in the **upper level base**.



Step 14:

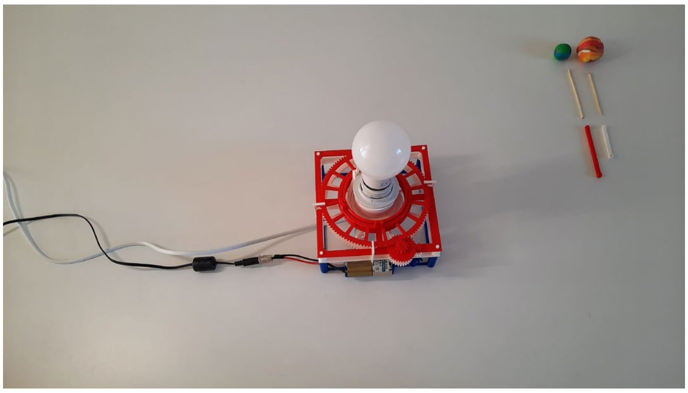
Thread the **connect gear 2** onto the pin on the **upper level base**.



Step 15:

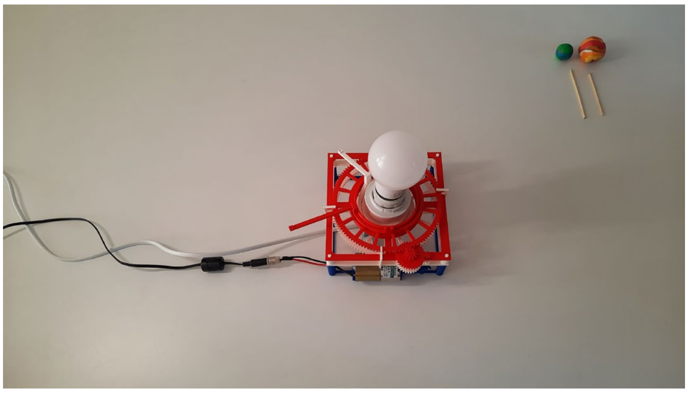
Place the exoplanet gear 2 over the light bulb and rest on the upper level base.

The gear system is now fully assembled. Check that the gear wheels engage correctly.



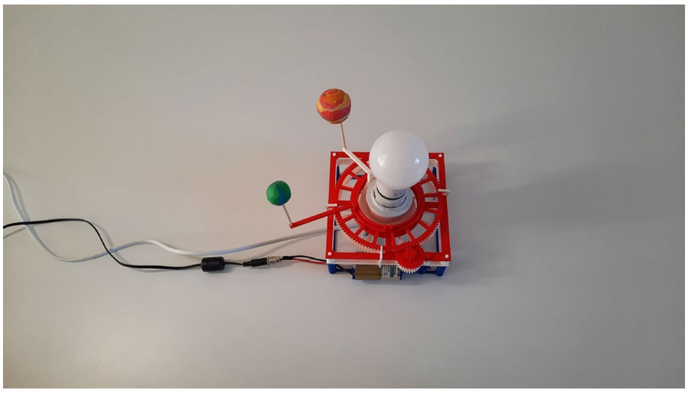
Step 16:

Add one of the four fixation **clips** to the middle of each of the four sides of the 3D model. These clips keep the different layers in place.



Step 17:

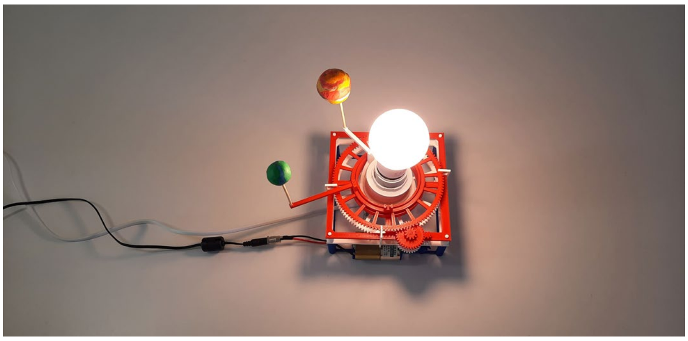
Attach the **exoplanet arm 1** and **exoplanet arm 2** to **exoplanet gear 1** and **exoplanet gear 2** respectively.



Step 18:

Stick one end of the wooden skewers into the holes at the ends of **exoplanet arms 1 & 2**. Attach the model exoplanets at the other ends of the skewers.

The skewers need to be of an appropriate length such that the centre of the model exoplanets and the centre of the light bulb are aligned.



Step 19:

Switch on the light bulb and start the motor to test your 3D printed exoplanetary model.

3. Align your light detector with the light bulb and the model exoplanet.
4. You are now ready to start collecting data. Check the setup of your model:
    - Confirm that the light detector is aligned and receiving light from the correct light source.
    - Ensure that there is a dip detected in the light curve when the model exoplanet passes between the detector and the light bulb.

Modifying the 3D printing files

The files provided have been designed assuming the specifications of a particular motor. If you use a different motor, you may need to modify the 3D designed **motor base** and **motor gear**.

Instructions are given below on how to change the files using **Fusion 360**:

Step-by-step instructions:

1. Open EXTRA-adjustable motor gear.f3d and EXTRA-adjustable motor base.f3d in Fusion 360
2. Go to MODIFY > change parameters
3. Adjust the parameters to fit your motor

You can use this overview to find the measurements you will need to take: