**Lab FV1 - Forces and vectors**

**Online version**

This lab has two goals:

* Check experimentally that forces are vectors and thus add as such.
* Learn to propagate uncertainty through a calculation and understand why this uncertainty is crucial to assess the result of the experiment.

**Equipment**

From the lab kit:

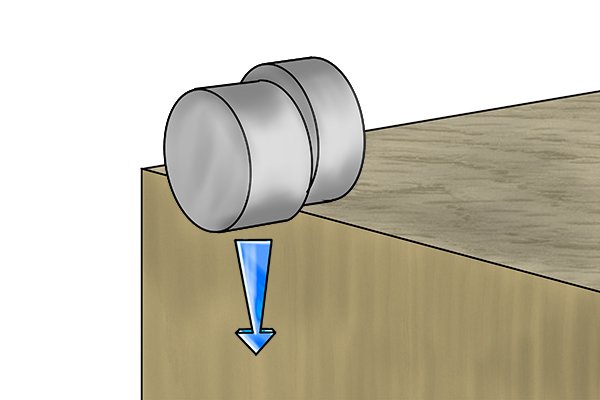
* 2 magnetic hooks
* 2 pulleys
* String
* 3 mini zip bags
* Protractor
* Collection of metals washers with mass labels

Other:

* Flat, vertical metal surface (like a fridge!)
* A portable light source (desk lamp, flashlight…)

**How to separate the magnets in the kit**

These are strong neodymium magnets. If they stick to one another, they are difficult to separate.

1. When you first take the magnets out of the box, try to separate them carefully, using the white plastic ring to keep them from sticking directly to one another.
2. If the magnets stick to one another despite your efforts, **do not attempt to separate them by pulling on the hooks**. Instead, use a non-magnetic table with a sharp edge to fix one magnet, and slide the other one down as shown in the figure.
3. The magnets will also be hard to move once you place them on a metal surface like a fridge. Again, **do not pull the magnet by the hook**. Grab the magnetic base and slide it along the surface.
4. If you are worried about **scratch marks** on the metal surface, place a folded sheet of paper between the magnet and the surface.

**Background**

Three forces with magnitudes *T*1, *T*2 and *T*3 act on an object as shown to the right. If the object is in equilibrium, the sum of the forces must be zero.

*T*1

*T*2

*T*3

*θ*1

*θ*2

*x*

*y*

However, forces are vectors, so this “sum of the forces” must be done separately in the *x* and *y* directions:

 [Eq. 1]

In our experimental setting, we will produce the situation. We will be able to measure the tensions and angles, and then we will be able to check if all the *x* components of the forces add up to zero, and if all the *y* components of the forces add up to zero.

However, chances are that when you add your experimental values, you will not get a perfect zero. You might get, for instance,



Does this mean that Newton’s 2nd law is wrong?

Not so fast. Each of the measurements (tensions, angles) carries an uncertainty. This means that each component of each force carries an uncertainty, and the sum of the components carries an uncertainty.

If the final uncertainty for turns out to be ±3 N, the result of our experiment is that could be anywhere between −1 N and +5 N. This interval contains 0, so our conclusion would be that, within the uncertainty of this experiment, the equilibrium condition in the *x* direction is fulfilled.

If instead the final uncertainty for  was ±0.3 N, the range does not contain zero and the equilibrium condition is not fulfilled.

Our ability to answer our experimental question depends as much on the central values of the measurements (that produced ) as on the uncertainties!

This is why we need to spend time learning how to propagate errors through our calculations. Therefore, we will review that before moving on to the experiment.

**Prelab review – propagation of uncertainty**

Let us assume we have the following experimental values:

*T*2 = (100 ± 2) N

*θ*2 = (25 ± 1) °

Write the minimum and maximum values of *T*2 and *θ*2.

T2min = 98N

T2max = 102N

Θ­2min = 24°

Θ2max = 26°

Find the minimum and maximum values for *T*2*x*, the horizontal component of the tension. Then, write the results as a central value ± error.

89.53 = T2xmincos(θ2min)

91.68 = T2xmaxcos(θ2max)

T2x = 90.56 ± 1.13

Now let’s assume that we did the same thing for *T*1 and *θ*1, and the result for the *x* component is:

*T*1*x* = (−67 ± 3) N

Find the minimum and maximum values for the net force in the *x* direction. Then, write the results as a central value ± error.

Is this experimental result for the net force in the *x* direction compatible with zero (*i.e*., with the equilibrium condition)?

**Experimental setup**

Find a flat, vertical metal surface (like a fridge) and set up the apparatus in the picture, following the steps below.



Before assembling the setup:

* Check that the pulleys spin freely.
* Cut two lengths of string of about 50 cm and one of about 30 cm.
* Hang a mini zip bag to the other end of each string by making a **small** hole in the corner of the bag. Do not tie the other end of the strings yet!

During the assembly:

* Pass the free end of the two long strings through the two pulleys. Then, tie the free ends of the three strings. This knot is point O in the figure.
* Hang the pulleys from the hooks, add some washers until the system is in equilibrium.
* The hooks and pulleys do NOT need to be at the same level, as they appear in the figure.
* Do NOT use the same masses left and right (*i.e*., do not use a symmetrical setting: it’s a boring one!).
* We need the tensions in the strings to be much larger than the (small) frictional forces in the pulleys so these can be considered negligible. Therefore, each bag should contain at least 30 g.
* Make sure that the strings are properly set in the groove of the pulley.
* Make sure that none of the bags touches the ground!
* If the strings are too long/too short, you can fix this with knots as long as the knots are not in contact with the pulley.

Once the apparatus is properly assembled, pull the middle bag a couple of inches down and to one side so as to disrupt the equilibrium, and then release it and allow the system to come back to equilibrium. Make sure that the bags do not hit each other or any other object during this process. Repeat this several times. Point O should always go back to roughly the same location (within a radius of 1 or 2 cm).

Take a picture of your setup and insert it below.

**Data collection**

**Masses**

Record the total mass at the end of each string. The average mass of the bags is 1.1 g.

|  |  |
| --- | --- |
|  | Total mass (g) |
| *m*1 |  |
| *m*2 |  |
| *m*3 |  |

**Angles**

To measure the angles, we will trace the shadows of the strings on a paper.

* Slide a blank paper behind the setup so point O is at the center of the page, and tape in place.
* Place a light source more or less in front of the system, and at least 1 meter away from it. (Ideally, we want parallel rays hitting the system at a 90° angle).
* Using a sharp pencil, draw two marks for the shadow of each string (one near the center, one away from it).
* Remove the paper and use a ruler to connect the marks for each string.
* Label the line for each string 1, 2 and 3 (for masses *m*1, *m*2, *m*3)
* Use the protractor to measure the angles. Note that you will not be able to measure *θ*1 and *θ*2 directly, but rather *θ*1 + 90°and *θ*2 + 90°. Clearly indicate on the paper which angles you are measuring, as well as their values.



In case you need a refresher on **how to use a protractor:**

Draw lines for the sides for the angle you want to measure. The lines should be longer than the radius of the protractor.

Align one of the sides with the 0° line, making sure that the vertex of the angle is at the center of the protractor. Read angle that coincides with the second side, making sure you use the correct scale (the angle in the figure is 40°, not 140°.)

Insert a picture of the paper with all your measurements below.

**Sources of uncertainty**

**Masses**

We will assume that the all the masses are within **3%** of the labeled values.

**Angles**

There are two sources of uncertainty for the angle in our setup:

* The limitations of the protractor (±0.5°)
* The friction in the pulleys. Due to this friction, each time you disturb the system, the center goes back to a slightly different place, and then the angles are slightly different.

We will evaluate the uncertainty due to friction by measuring the angles after several “disturbances” described at the end of the Experimental setup section: pull the middle bag a couple of inches down and to one side so as to disrupt the equilibrium, and then release it and allow the system to come back to equilibrium. Make sure that the bags do not hit each other or any other object during this process.

Place a new sheet of paper behind the system and record the position of the shadows for at least 6 different disturbances (you can number the small marks, or use different colors each time). Remove the sheet, draw all the lines, and measure the angles.

Create a table like the one below on Logger Pro and use it to record your values.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Event | *θ*1 + 90 (°) | *θ*2 + 90 (°) | *θ*1 (°) | *θ*2 (°) |
| 1 |  |  |  |  |
| 2 |  |  |  |  |
| … |  |  |  |  |

Insert your table below.

For each angle, determine the mean value, and use the maximum and minimum values to determine the uncertainty associated with each angle due to friction. (You might have a different uncertainty for each angle.) Enter your results below.

The final uncertainty for each angle is the sum of the uncertainty due to friction and the uncertainty due to the limitations of the protractor (0.5°). Report the final uncertainty for each angle below.

**Propagation of uncertainty**

We now have a measurement of the masses and the angles, and an estimation of the uncertainty of each quantity.

Your goal is to use them to experimentally verify the two equilibrium conditions discussed in section 1. You will first need to find the components of the forces and add them up. However, you also need to propagate the uncertainties throughout the entire calculation, following the steps reviewed in section 2.

Show all your calculations below.

**Conclusions**

Do your results verify the equilibrium conditions within the uncertainty of the experiment? Justify your answer explicitly in terms of the final error for the net force in each direction.