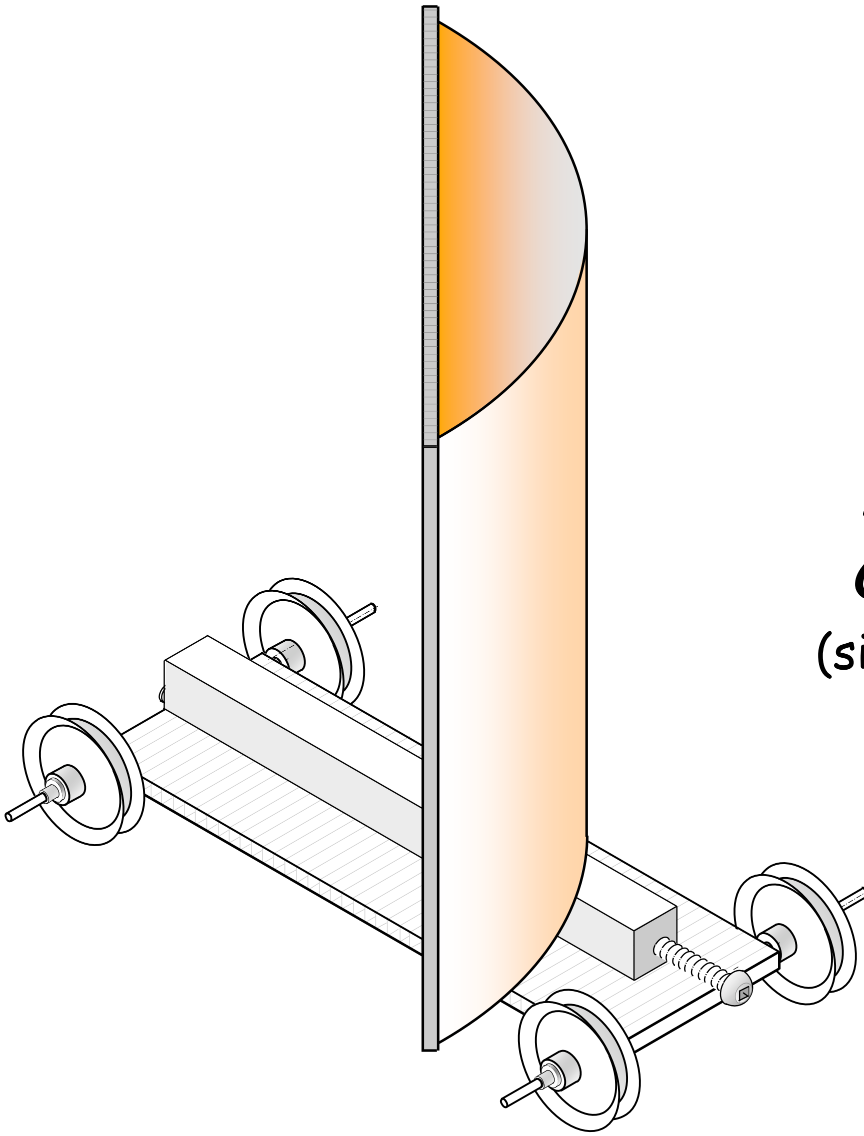
centre de développement pédagogique
pour la formation générale en science et technologie

Working document



AEOLUS' CHARIOT
(simplified LES)

STUDENT BOOKLET

December 2011

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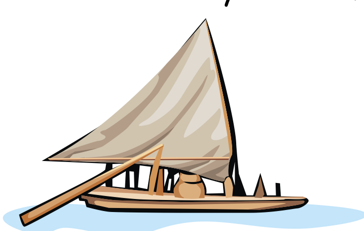
The force of Aeolus tamed for centuries!

NOTE: **This LES was designed within the framework of training sessions. It may require adaptation before being used with students.**

Does the name Aeolus mean anything to you? According to Greek mythology, he is the god of wind. The power of this god is intimately linked to the power of storm winds. It is not surprising then, that the ancient Greeks gave him an important role in their mythology.

In any case, humans have long since tamed the force of wind. Wind power today occupies an ever greater place in electric power generation. Long ago, windmills were not a negligible source of energy. Among all its uses, however, it is particularly the use of wind power for transportation over water that was of greatest importance. For the longest time, sailing was the only way to navigate long distances over water. Sailboats drove commerce, exploration and the conquest of new territories.

Humans have been using wind power for propulsion over water for centuries. As long ago as 1500 B.C., the Egyptians went up the Nile using the north wind. Later the Vikings on their longships sailed the seven seas. Even though their longships had square sails and could not sail against the wind, they reached the Americas 500 years before Christopher Columbus.



Later, boats were perfected to be able to sail into the wind by tacking (zigzagging into the wind). Arab feluccas, equipped with triangular sails, could already sail into the wind.

It is aboard three much bigger ships, the Pinta, the Nina and the Santa Maria, that Christopher Columbus discovered America in 1492. Here you see two caravels, the Pinta on the left and the Nina, to the right. The much more manageable galleons came later in the 16th century and were equipped with port holes for canons.

Today, sailboats no longer hold this strategic advantage, but sport sailing is still alive and well. Sailing is exhilarating as well as being respectful of the environment, so many describe this activity as the new "in" thing.
Here are six video clips that illustrate today's current enthusiasm for sailing. The first two show a very popular sport in the north of France, land sailing. The third sequence shows a sailboarder in action. In the fourth, a catamaran is outwitted by Aeolus. The fifth shows a sailboat that practically flies. Finally, a giant with a rigid sail in the midst of winning the America's Cup.

Initiation to land sailing (3:15): http://www.youtube.com/watch?v=_fQ3aJGRyIM

Land sailing championship (2 :10): http://www.youtube.com/watch?v=F85tIPCaGMo&NR=1

Sail boarding (0:37): http://www.youtube.com/watch?v=TLtCC_D8sL0&feature=related

Catamaran (1:05): http://www.youtube.com/watch?v=do7nWUgijZs&feature=related

Sailing hydrofoil at 95 km/h (1:45):
http://www.youtube.com/watch?v=9eJgsiS3xH8&feature=fvsr

Trimaran with a rigid sail (1 :27): http://www.youtube.com/watch?v=0lK-eICWZY0

In the light of this introduction, several questions may come to mind:

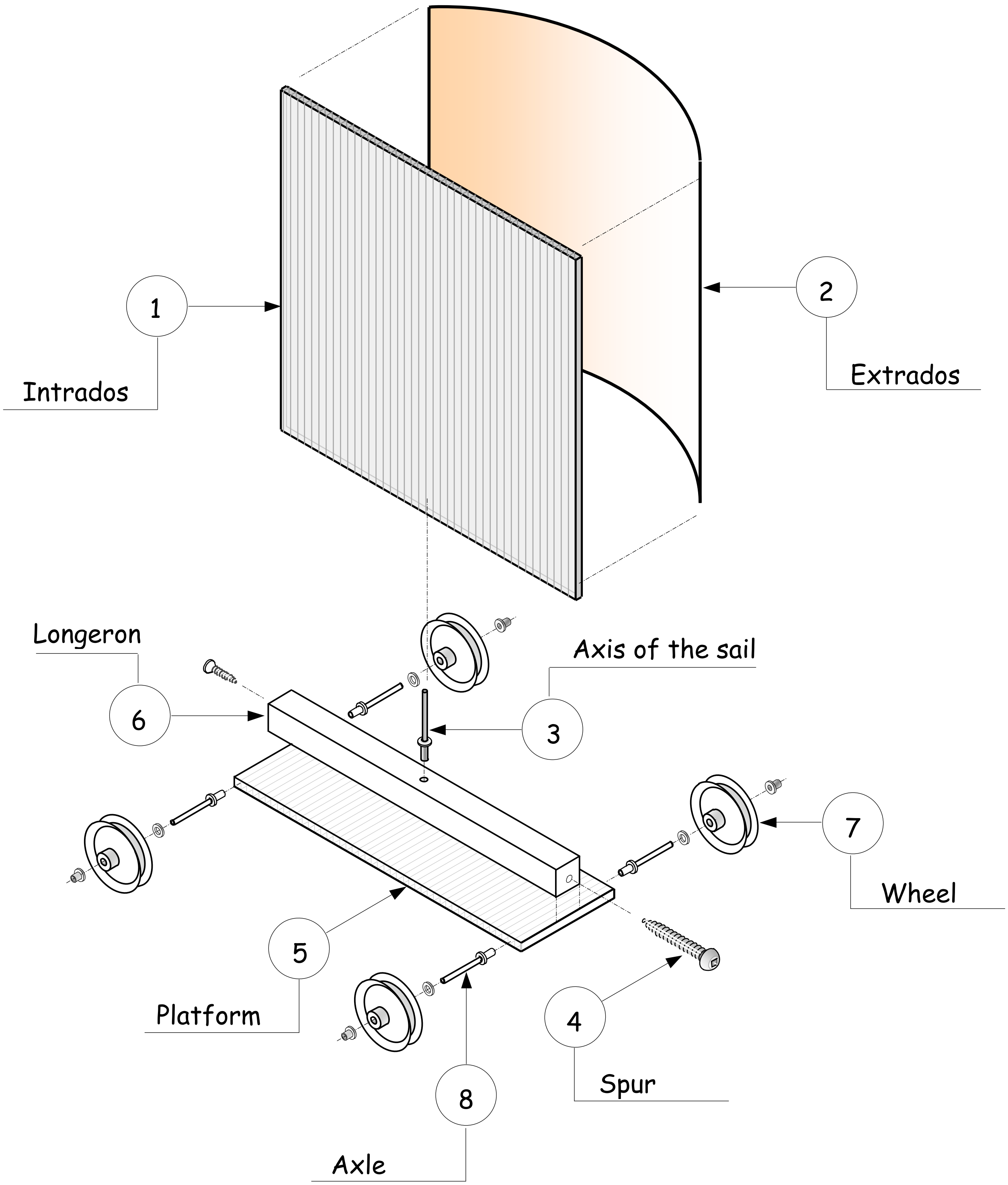
1. How does the force of wind act on the sails to make the mobile (boat, board or chariot) move?
2. How can a mobile, propelled by wind, sail into it?
3. How can it attain the greatest possible speed?
4. How can this mobile be made more efficient?

To answer these questions, we have designed a very special vehicle, as well as a various other devices. You will have to analyse the operation of this mobile equipped with a rigid, pivoting sail. We have named it Aeolus' chariot.
Before carrying out the scientific analysis of the chariot, you need to remember some mechanical notions you have studied previously. You must also become familiar with some new concepts and gain some know-how.

By the end of this LES, sailing should no longer be a mystery to you.

O.K. now, get to work!

Nomenclature of Aeolus' chariot

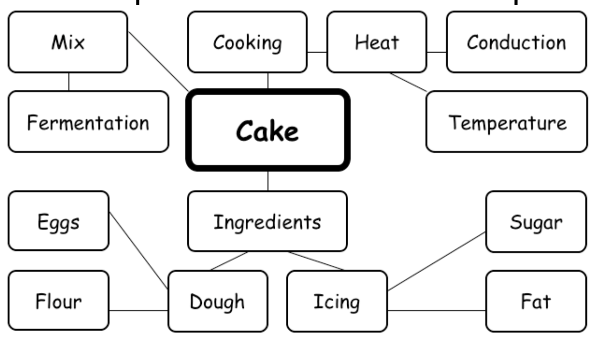


Let's warm up a bit!

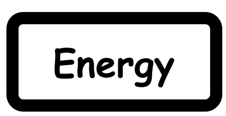
Now you will build a network of concepts seen in fourth year. This will give you good ideas for strategies that will allow you to better understand Aeolus' chariot. Build the network in the form of a visual card.

Word bank: labour, force, displacement, equilibrium between two forces, potential gravitational energy, mass, weight, kinematic energy, speed, acceleration.

Example of a network of concepts



Network of concepts

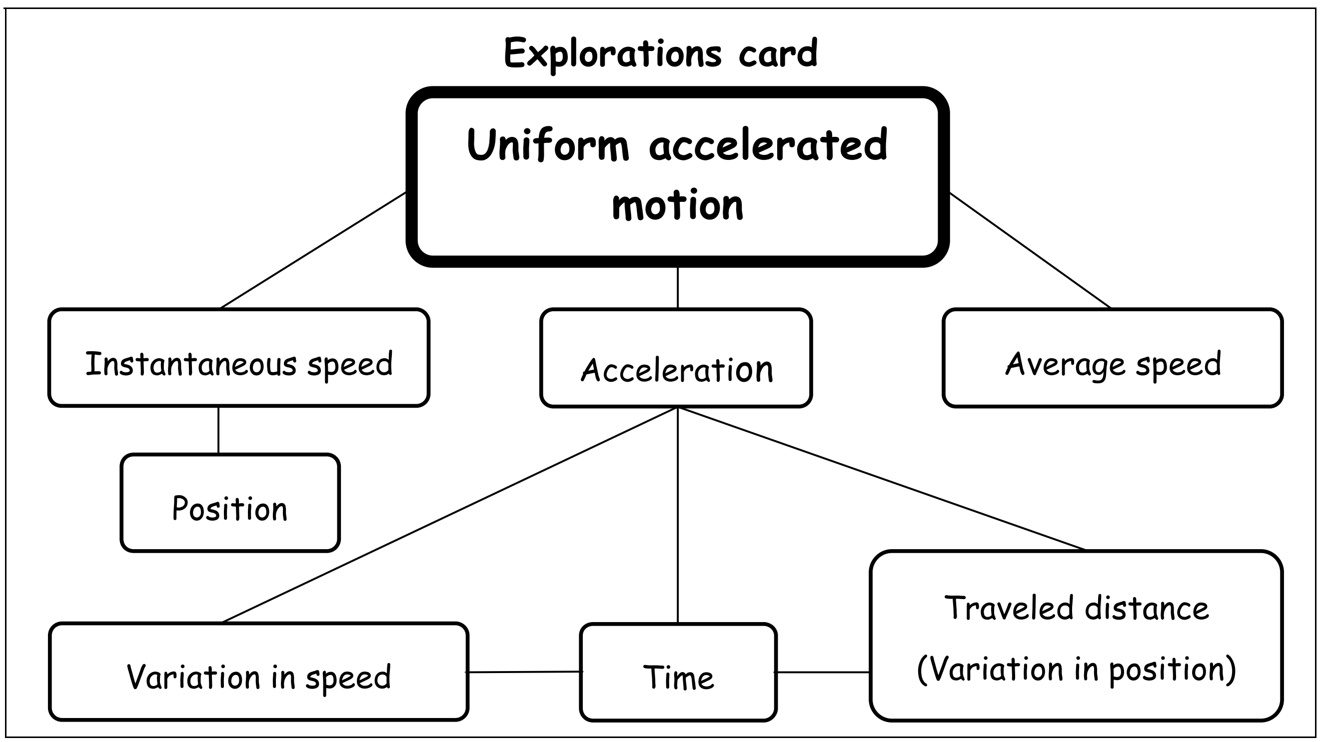


Uniformly accelerated motion

Now it's time to acquire some new knowledge. The study of rectilinear uniform motion gives us the opportunity to be well prepared for the study of sailing. The following questions, among others, will be broached:

- **What is the relation between position, speed and acceleration of the mobile and the elapsed time?**
- **What is the relation between acceleration, the variation in speed and the elapsed time?**
- **What is the relation between acceleration, the distance traveled and the elapsed time?**

What graphs can we draw in each case?

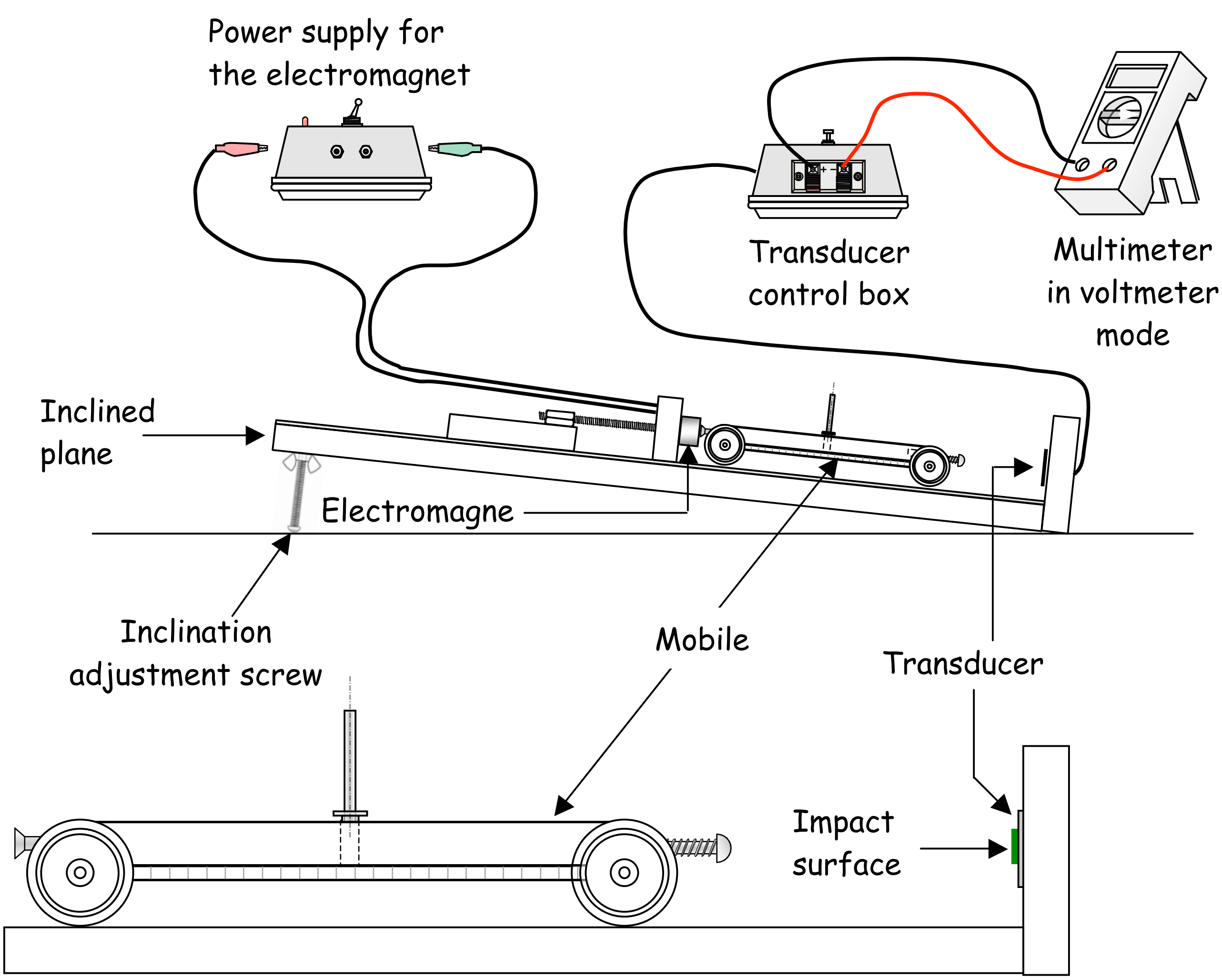


Directed laboratory (uniformly accelerated mobile)

Materials

- 1 mobile (Aeolus' chariot without its rigid sail)
- 1 inclined plane (ramp) with transducer and control box
- 1 electromagnet
- 1 - 9 volt power supply for the electromagnet
- 1 multimeter
- 1 ruler
- 1 scale

Assembly diagram



Manipulations

1. Weigh the mobile and enter the mass in data table 1.
2. Connect the power supply onto the electromagnet (in "off" position).
3. Connect the multimeter onto the transducer control box.
4. Turn the multimeter on, in CC voltage mode (approximately 2 volt scale).
5. Incline the plane by lifting the end opposite to the transducer using the adjustment screw. The distance between the bottom of the inclined plane and the surface of the table should be 6.5 cm.
6. Affix the electromagnet, face down, by inserting its dowel in the lowest position (once the mobile is placed, the distance between the spur and the transducer should be as small as possible).
7. Turn the electromagnet power supply on.
8. Position the mobile on the inclined plane in such a way that it is held back by the electromagnet and aligned with the guiding line.
9. Measure the distance between the spur on the mobile and the impact surface on the transducer. Note it in the data table.
10. Press the reset button on the transducer control box (the multimeter should now read zero).
11. Immediately after having pressed the reset button, turn off the power to the electromagnet and read the highest voltage that momentarily appears on the multimeter. **(the spur of the mobile must hit the center of the transducer).**
12. Note this voltage in the data table.
13. Repeat steps 7 to 12 twice more, calculate the average and note it.
14. Repeat steps 7 to 12 five more times, gradually increasing the distance between the spur and the transducer.

Data Table 1				**Mass (g) =**	
n°	**Distance spur — transducer (cm)**	**Voltage (V) trial n° 1**	**Voltage (V) trial n° 2**	**Voltage (V) trial n° 3**	**Average voltage (V)**
1					
2					
3					
4					
5					
6					

Analyse the results

Analyse your data

Question 1
Is the voltage read on the multimeter increasing or decreasing in relation to the distance between the spur and the transducer?

Question 2
Why does the voltage vary that way?

Question 3
Would we have obtained the same results if we had kept the electromagnet in place and gradually moved the transducer up?

Draw your conclusions

Question 4
In your opinion, is it possible to determine the speed of the mobile right before it hits the transducer?

It is indeed possible to determine these speeds after calibrating the transducer. The next section will summarily describe the operation of the transducer. Then we will guide you through the fabrication of a calibration graph.

Theory about the piezoelectric crystal

Before going any further, it will be useful to know a little more about the transducer used in the previous experiment.

A transducer is an instrument that transforms energy from one form to another. In our case, a miniature piezoelectric crystal takes care of this work. We took the crystal from a singing birthday card. In the case of the card, the crystal converts electrical energy from a small battery to the mechanical energy of vibration, namely the sounds.

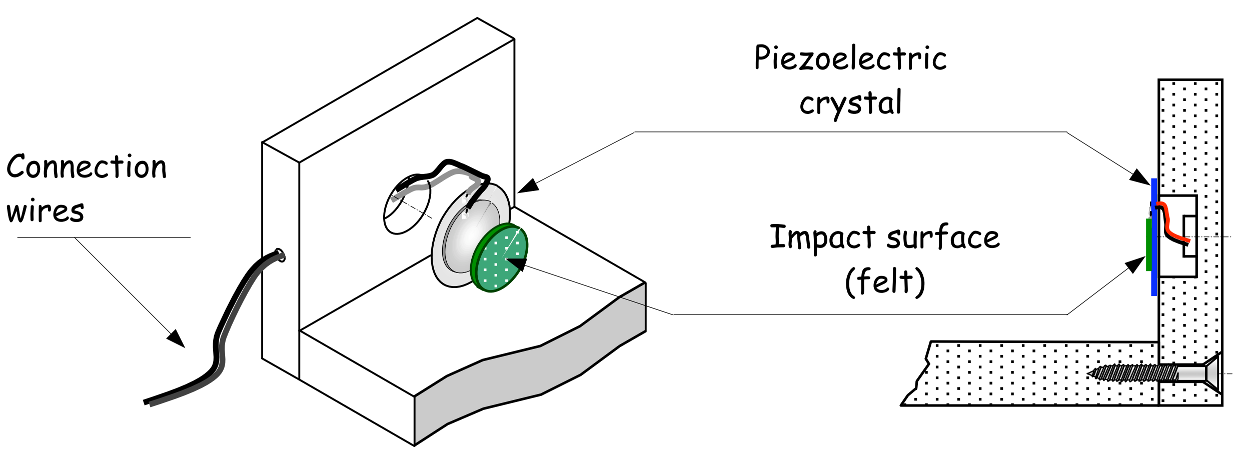
Here, we will use the crystal in the opposite direction. We will supply it with mechanical energy by hitting it and it will convert this energy to the electrical energy that we measure with the multimeter.

The red button found on some BBQs uses the same principle. Inside it, a small mechanism hits a crystal. The crystal is distorted and thus generates a large enough voltage to produce a spark, which in turn lights the gas.

To be able to study the descent of the mobile in more depth, we have to calibrate the transducer. This means relating the electrical voltages measured before, to the different quantities of potential gravitational energy. This energy corresponds to the labour carried out on the crystal to distort it or to the kinematic energy of the mobile at the moment of the collision.

Here then is a process that will allow you to easily calibrate the transducer.

Piezoelectric transducer



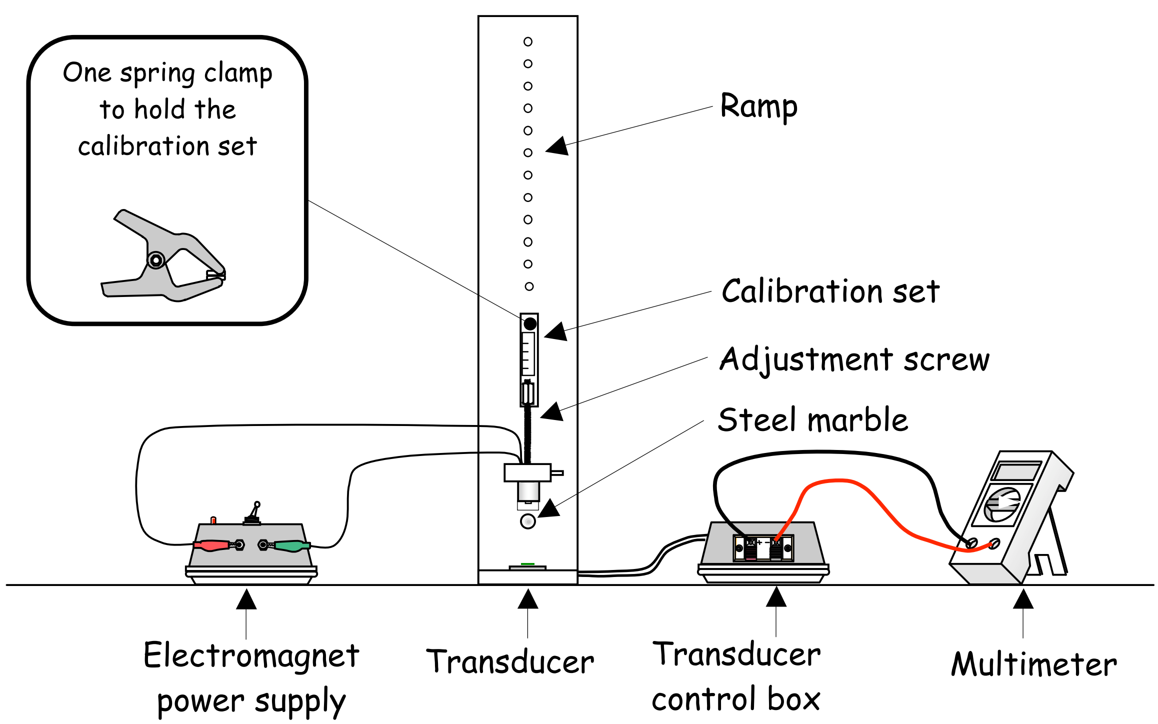
Calibrating the transducer

Questions: What mathematical ratio relates the mechanical energy (labour) to the electrical voltage generated by the transducer? What type of curve can we draw from our experimental results?

Materials

- 1 "calibration set" including:
  - 1 electromagnet
  - 1 ruler
  - 1 height adjustment screw for the electromagnet
- 1 ramp (inclined plane) with transducer and control box
- 1 steel marble
- 1 multimeter
- 1 - 9 volt power supply for the electromagnet
- 1 scale

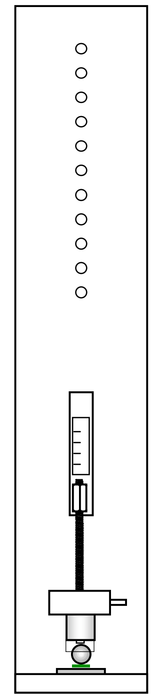
Assembly diagram



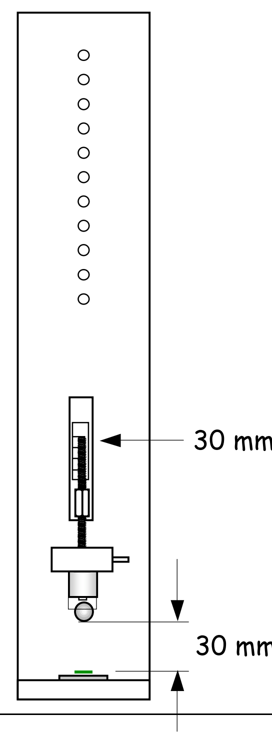
Manipulations

1. Turn the ramp (inclined plane) vertically (see the drawing on the previous page)
2. Affix the calibration set using a spring clamp.
3. Connect the electromagnet onto its power supply without turning it on (switch open).
4. Connect the multimeter onto the transducer control box and set it to CC voltage mode (approximate 2V scale).
5. Weigh the steel marble and note its value in the data table.
6. Place the marble onto the impact surface (felt).
7. Set the height of the electromagnet at zero using the adjustment screw.
8. Lean the electromagnet on the marble by sliding the calibration set (remove a bit of pressure on the spring). Ensure that the whole assembly is perfectly vertical (see drawing 1).
9. Turn the power supply to on, to supply the electromagnet.
10. Move the electromagnet up to a height of 30 mm (3.0 cm) using the adjustment screw. The steel marble should be held back by the electromagnet (see drawing 2).
11. Press the reset button on the transducer control box. (The multimeter should now read zero).
12. Immediately after having pressed the reset button, turn off the power to the electromagnet and read the highest voltage that momentarily appears on the multimeter. **(The marble must hit the center of the transducer).**
13. Note this voltage in the data table.
14. Turn the power to on, to supply the electromagnet.
15. Manually move the marble back up so that it is again held by the electromagnet.

Drawing 1



Drawing 2



Manipulations (continued)

16. Press the reset button on the transducer control box. (The multimeter should now read zero).
17. Immediately after having pressed the reset button, turn off the power to the electromagnet and read the highest voltage that momentarily appears on the multimeter. **(The marble must hit the center of the transducer).**
18. Note this voltage in the data table.
19. Repeat steps 14 to 18 one last time (to make an average).
20. Repeat steps 14 to 18 three times for each of the following heights: 2.5 cm, 2.0 cm, 1.5 cm, 1.0 cm and 0.5 cm.
21. Calculate the average voltages.

Data table 2					
Mass of the marble (g):					
n°	**Height of the marble (cm)**	**Voltage (V) trial n° 1**	**Voltage (V) trial n° 2**	**Voltage (V) trial n° 3**	**Average voltage (V)**
1	**3.0**				
2	**2.5**				
3	**2.0**				
4	**1.5**				
5	**1.0**				
6	**0.5**				

Analyse the results

Analyse your data

Question 1

During this experiment, there are several transformations of energy. The energy changes form several times, in fact. **At the beginning of the experiment when the marble is held by the electromagnet, what form of energy is it in?**

Question 2

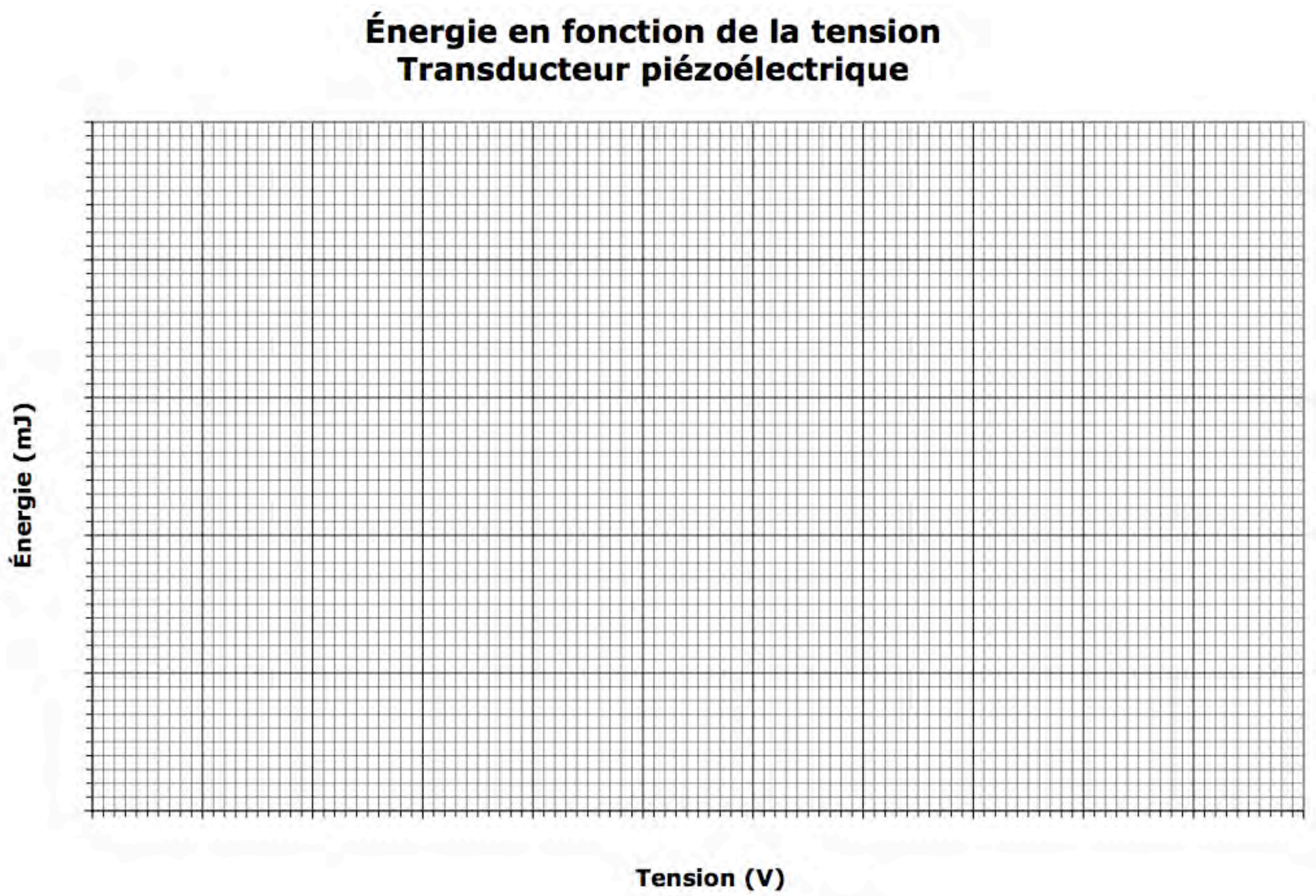
Calculate the potential energy of the marble (in milli Joules) for each height and use your results in the table below.

$E_P = m \cdot g \cdot h$ where $E_p \Rightarrow$ potential energy in J , m $\Rightarrow$ mass in kg, g $\approx 9.8\ m/s^2$, h $\Rightarrow$ height in m

Data table 3

n°	Height of the marble (cm)	Potential energy (mJ)	Average voltage (V)
1	3.0		
2	2.5		
3	2.0		
4	1.5		
5	1.0		
6	0.5		

Question 3
Draw the calibration graph (energy in relation to voltage).



Highlight the trends

Question 4
What algebraic function (linear or quadratic) best models the cloud of points obtained by the calibration data? Explain your choice.

Question 5

Determine the equation for the model you chose[1].

- In the case of a first degree algebraic equation (linear function), determine the rate of variation using two distant points. The equation found will be in the form of $Y = ax$.
- In the case of a second degree algebraic function (quadratic function), take two distant points from the curve and form two second degree equations in the form of $Y = ax^2 + bx$. Then determine the values of parameters a and b by resolving the equation system. The equation found will also be in the form of $Y = ax^2 + bx$.

[1] The use of the appropriate technological tool (calculator or spreadsheet) will ease the estimation of the correlation coefficient.

Question 6
Indicate all the forms of energy present during this experiment by completing the following table:

Summary table	
Type of energy (or labour)	At a given time
	When the marble is held by the electromagnet
	Just before the marble hits the crystal
	When the crystal is distorted
	When an electrical current is generated

Draw your conclusions

Question 7
How can the calibration graph from question 3 help you?

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Kinematic study of the uniformly accelerated mobile

Question 1

Complete columns 2 and 3 of Results table 4 below. Simply recopy the data from Data table 1.

Question 2

Complete column 4 of Results table 4 below. Use the calibration graph (or the equation model chosen) to evaluate the kinematic energy of the mobile just before it hits the transducer for each collision.

Question 3

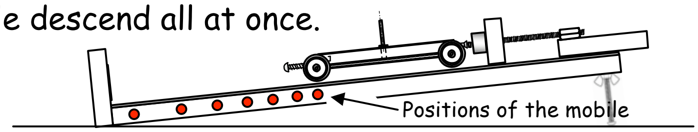
Now calculate the speed of the mobile just before if hits the transducer for each collision trial. To do so, isolate the speed in the equation below. (Watch the units of measure!) The mass of the mobile is written in Data table 1. Complete column 5 in Results table 4 below.

$E_{kinematic} = \frac{1}{2} m \bullet v^2$ where $E_{kinematic}$ ⇒ energy in J, m ⇒ mass in kg, v ⇒ speed in m/s

Calculations

Question 4

During this experiment, we measured the energy liberated during several impacts and for different heights of the inclined plane. What we did is the same as if we had cut a longer timed experiment into smaller segments. Had we performed that experiment, we would have let the mobile descend all at once.



That is why columns 2 and 6 in Results table 4 are identical. Column 6 represents the position of the mobile measured from the moment it leaves the electromagnet. **So, recopy column 2 into column 6.** The speeds in column 5 are those of the mobile at the different positions.

Question 5

Finally, it is necessary to calculate the time that corresponds to each position and speed. To do so, we will use the following equation.

$$x - x_0 = \frac{1}{2} (v + v_0) t$$

Where
- x is the position of the mobile at a given time
- x_0 is the initial position of the mobile (in our case, at the beginning of the experiment)
- v is the speed of the mobile at a given time
- v_0 is the initial speed of the mobile (in our case, at the beginning of the experiment)
- t is the elapsed time throughout the experiment

In our case, the experiment begins when we cut the power on the electromagnet. At that precise instant, the position of the vehicle is at 0 cm and its speed is nil. The values x_0 and v_0 from the previous equation can simply be omitted. **Write the simplified equation below.**

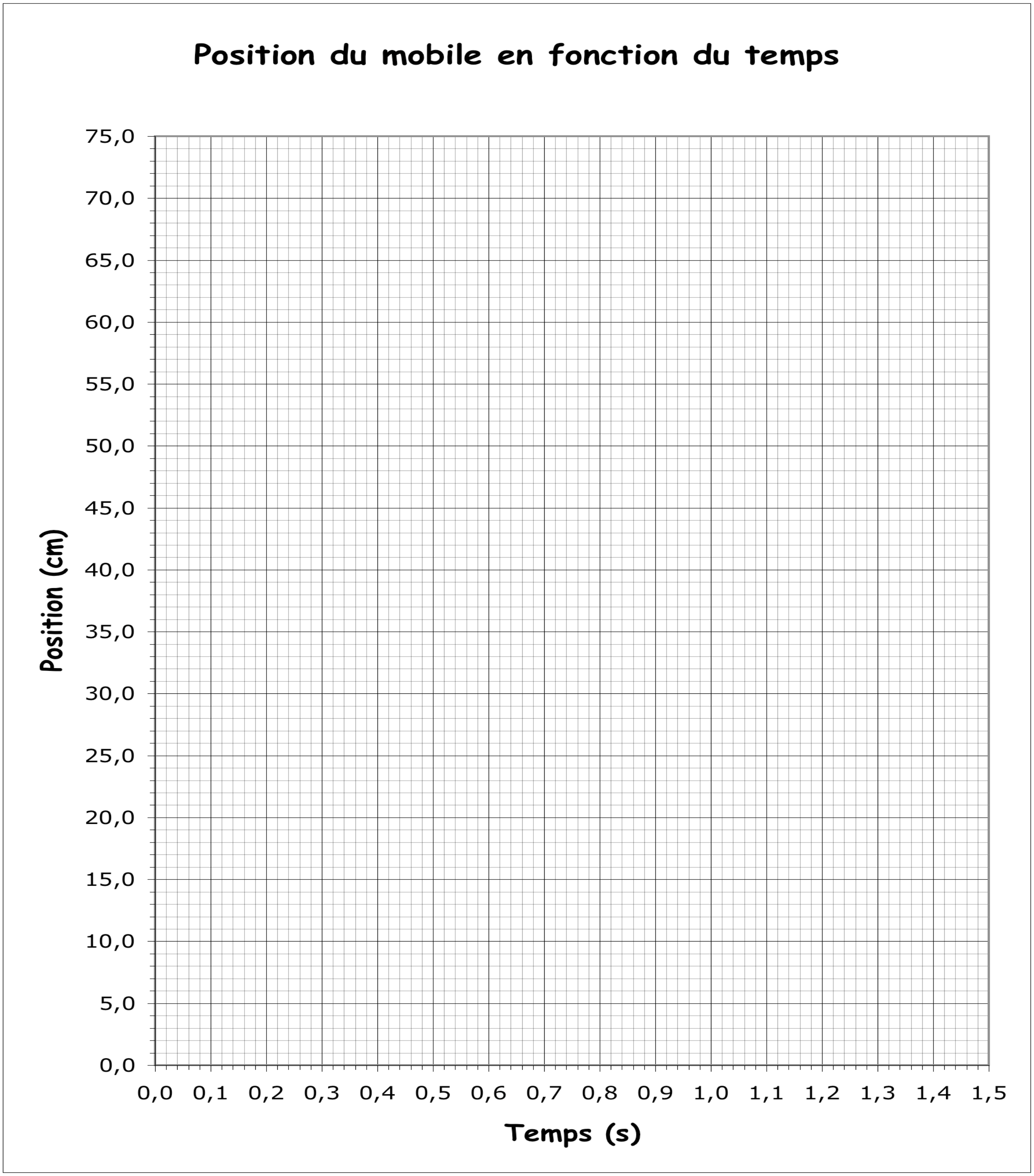
Question 6

Now calculate the time corresponding to each position and speed. To do so, isolate time in the above simplified equation. Complete column 7 of Results table 4 below.

Results table 4 (uniformly accelerated mobile - kinematic)						
This section is drawn from the six small collisions carried out				If we had simulated a single descent for the mobile		
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
Collision number	**Distance spur — transducer (cm)**	**Average voltage (V)**	**Kinematic energy (mJ)**	**Speed v (cm/s)**	**Position x (cm)**	**Time t (s)**
1						
2						
3						
4						
5						
6						

Question 7

So finally, results table 4 is completed. Now let's try to make the results "talk". Nothing is better than a graph to get the big picture and highlight the trends. So below, **draw a graph showing position vs. time.** Note that at time 0 seconds, the mobile was at position 0. The curve therefore goes through the point of origin.



Question 8

What type of curve do you see on your graph?

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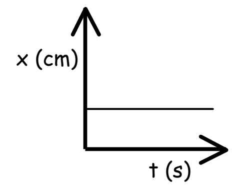
Question 9

How do you interpret the graph at right? Does the position change? Does the speed change?



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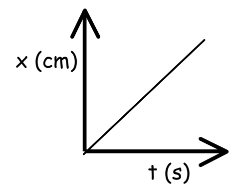
Question 10

How do you interpret the graph at right? Does the position change? Does the speed change?



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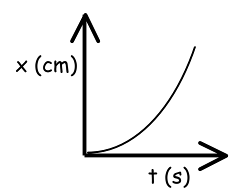
Question 11

How do you interpret the graph at right? Does the position change? Does the speed change?



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Question 12

Now, interpret the graph of the position of the mobile in relation to time. Does its position change? Does its speed change? Does it accelerate?

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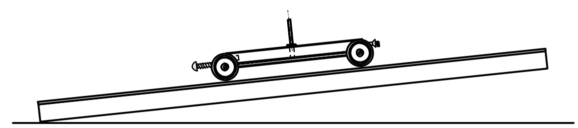
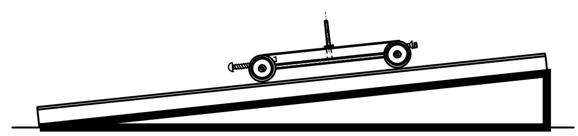
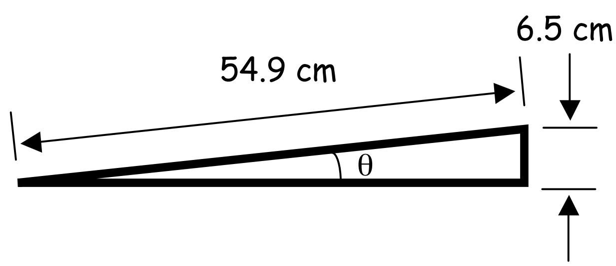
Dynamic study of the uniformly accelerated mobile

Now let's study the phenomenon from another angle. Let's pay more attention to the forces that act on the mobile. To complete this exercise, you will need certain mathematical concepts that you have studied before. It will therefore be useful to review the following notions:

- Adding vectors to find the result (resulting vectors)
- Trigonometry

The primary objective of this study is to determine the resulting force that draws the mobile towards the bottom. With this information, we will be able to calculate acceleration, speed and the position of the mobile at all times. Finally, we will be able to broaden our graphical analysis of the phenomenon.

Here is our mobile on the same inclined plane as in the previous experiment. The image has been simplified, keeping only the essential elements.	
The angle between the table and the plane forms a right triangle. It is therefore easy to find the angle (with a bit of trigonometry).	
Find angle θ.	

NOTE: To simplify the graphical representation at right, we exaggerated the inclination of the inclined plane. In addition, the vector lengths are not to scale.

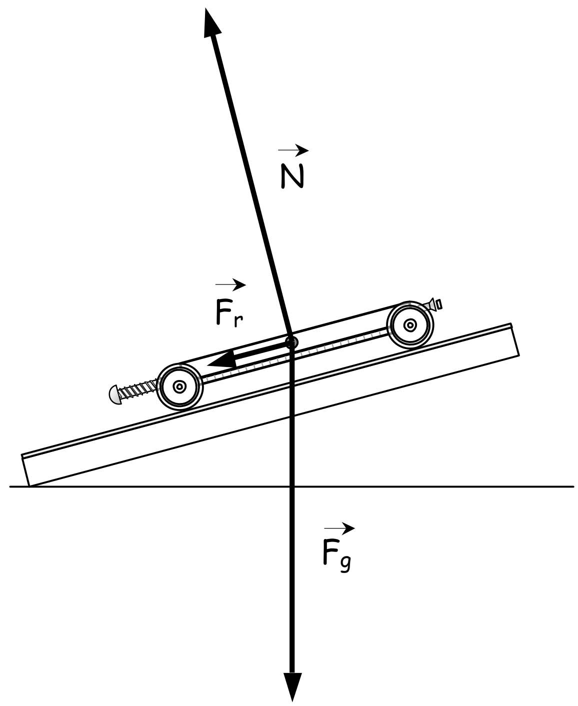
Here is the description of the three vector forces present.

- $\vec{F_g}$ is the force of gravity, calculated with Newton's second law.

$$\vec{F_g} = m \bullet \vec{g}$$

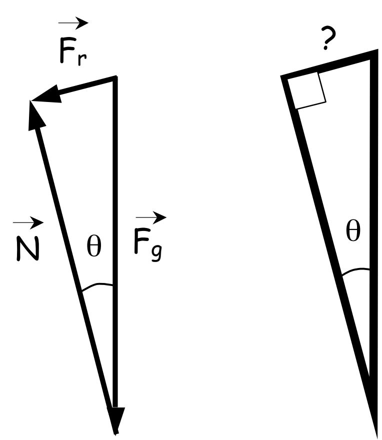
- $\vec{N}$ is the normal reaction force of the inclined plane. This vector force is perpendicular to the inclined plane. It all conforms to Newton's third law of action and reaction.

- $\vec{F_r}$ is the resulting force that we want to find. This vector force is parallel to the inclined plane.



Calculate $\vec{F_g}$ the gravitational force.

To simplify things, the three vectors can be moved around and placed end to end. We must, however, keep their orientation and size. Here, we can see that gravitational force pulls downwards and that the reaction force of the plane pushes upwards with an angle θ. The sum (the resulting vector) of these two forces is $\vec{F_r}$. **Calculate $\vec{F_r}$, considering the right triangle.**



Question 1

Now that we have the force that pushes the mobile downwards, calculate the theoretical acceleration of the mobile using Newton's second law.

Question 2

Recopy column 7 (time) from Results table 4 into Results table 5 below.

Results table 5 (uniformly accelerated mobile - dynamic)							
n°	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Time, t (s)	**0**						
Speed, v (cm/s)	**0**						
Position, x (cm)	**0**						

Question 3

Now let's determine the speed of the mobile from the acceleration found in question 1 above. To do so, we will use the kinematic equation that follows.

$\mathbf{v = v_0 + at}$

Where
- v is the speed of the mobile at a given time (instantaneous speed)
- v_0 is the initial speed of the mobile (in our case, at the start of its descent)
- a is the mobile's acceleration
- t is the elapsed time throughout the experiment

In our case, the initial speed of the vehicle is nil. The value v_0 from the preceding equation can therefore be omitted. Now calculate the speed for each time and complete the corresponding line in Table 5.

Calculations

Question 4

Finally, let's determine the position that the mobile holds at each time. To do so, we will use the following kinematic equation.

$$x - x_0 = \frac{1}{2} (v + v_0) t$$

Where
- x is the position of the mobile at a given time
- x_0 is the initial position of the mobile (in our case, the beginning of the experiment)
- v is the speed of the mobile at a given time.
- v_0 is the initial speed of the mobile (in our case, the beginning of the experiment
- t is the time elapsed throughout the experiment

Again here, values x_0 and v_0 can be omitted. Now calculate the position for each time and complete the corresponding time in Table 5.

Calculations

Question 5

So finally, results table 5 is completed. Now let's try to make these new results "talk". To make the talking easier, draw a new curve on the same graph we drew before. **Draw a new curve on the graph called *position of the mobile in relation to time* from the previous section.** Since the new curve is created from dynamic calculations, identify it as such: dynamic. the other curve can be identified by the term kinematic.

Question 6

Which curve (dynamic or kinematic) moves upwards more quickly?

____

Question 7

In which case (dynamic or kinematic) has the mobile traveled the greatest distance for a given time?

____

Question 8
In which case (dynamic or kinematic) has the mobile attained the greatest final speed? To help you, look at the rate of variation of the last straight section of the curve.

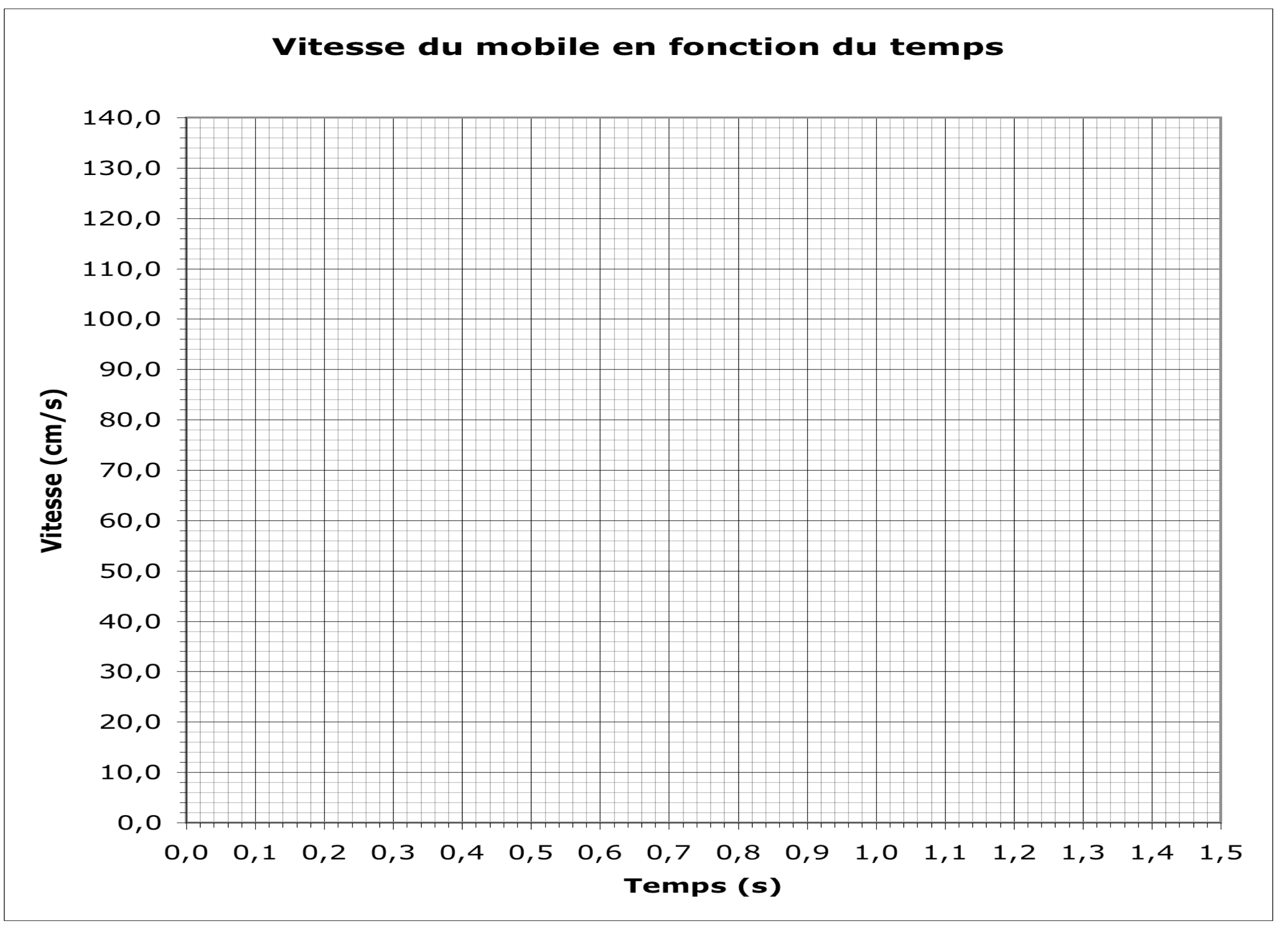
Question 9

In which case (dynamic or kinematic) does the mobile accelerate the most quickly? To help you, look at the curvature of the parabola.

Question 10
In your opinion, what is the reason for the differences between the two curves?

Question 11

Let's take the time now to look at the evolution of the speed of the mobile in relation to time. From Results table 5, draw the graph of the speed of the mobile in relation to time.



Question 12

Describe the evolution of speed on the graph called *"Speed of the mobile in relation to time".*

Question 13

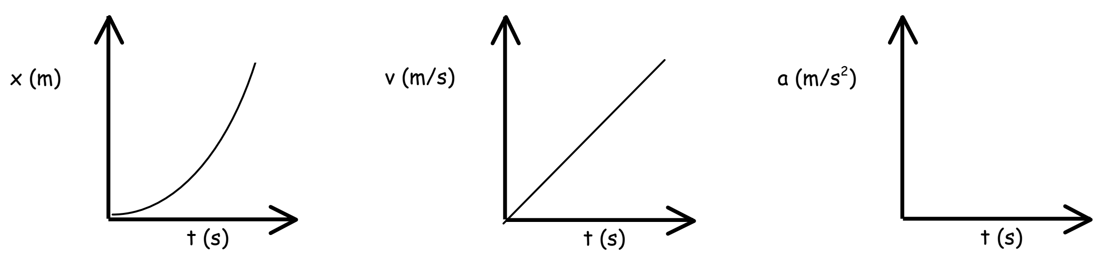
What can you say about acceleration?

Question 14

To what does the rate of variation of the straight section of this graph correspond?

Question 15

Here are three graphs that describe a movement similar to our mobile's: uniformly accelerated rectilinear motion. The first two graphs describe the position and the speed in relation to time. **Complete the third graph with an appropriate curve.**



Basic notions about sailing

Now it's time to learn a little more about sailing. This section gives you what you need to make your Aeolus' chariot move so you can study its motion. We will deal with the following subjects:

- The notions of true wind, relative wind and apparent wind.
- Bernoulli's principle as applied to a sail.
- The direction and orientation of the sail.
- A directed laboratory on the dynamics of Aeolus' chariot.

Winds

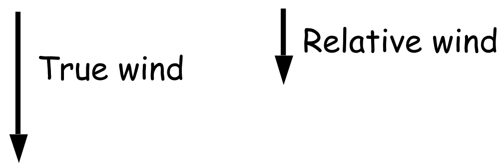
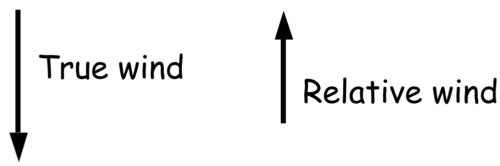
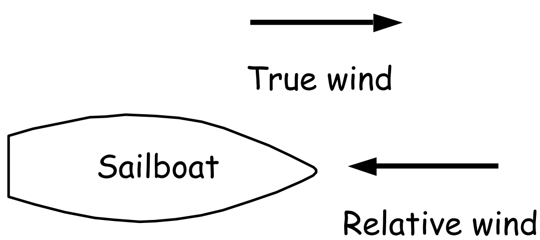
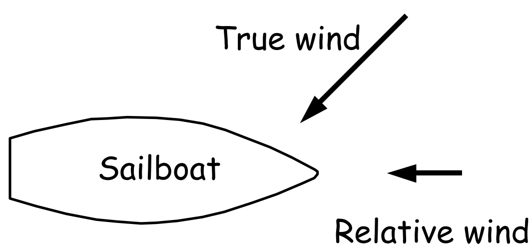
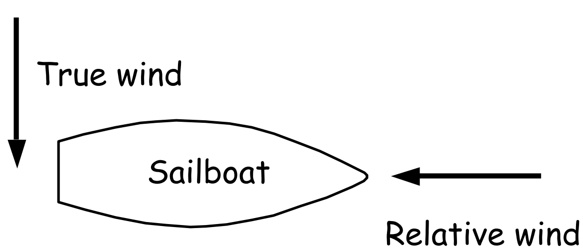
In sailing, feeling the wind is critical. It is by feeling the wind on his face that the windsurfer can tell the direction and strength of the wind and adapt his movements in relation to what he perceives. Even the intensity of the wind's whistling in his ears can give him an indication as to the direction from which the wind is blowing. With the wind in your face, you should hear the wind with equal intensity in each ear. This wind is called **true wind.**

If there were only true wind, things would be simpler. But our motion adds another type of wind: **relative wind.** It is all a question of reference. On a nice, calm day, there is no wind. We can then say that there is no true wind. If we climb on our bike and ride at a good clip however, we perceive wind on our cheeks. This wind is not really wind, it is simply due to the fact that we are displacing immobile air.

Things become even more complicated when we travel on a windy day. The wind that we will then perceive will be the **apparent wind.** This is the vector sum of the true wind and the relative wind. You can easily imagine this concept using the bicycle example. Imagine that you are on a bike, standing still at the top of a hill. Imagine too, that you have wind in your face coming exactly from the bottom of the hill. When you start rolling, the wind will seem stronger and stronger as you accelerate.

On a moving sailboat, the only wind we feel is the apparent wind. It is also this wind that generates the force when you move. Here are some exercises that will allow you to better understand of what apparent wind consists.

Exercises about winds

From these two wind vectors,	find the resulting vector, the apparent wind.
	
	
	
	
	

Bernoulli's principle, applied to a sail

According to Wikipedia – September 2009

(translated from http://fr.wikipedia.org/wiki/Théorème_de_Bernoulli)

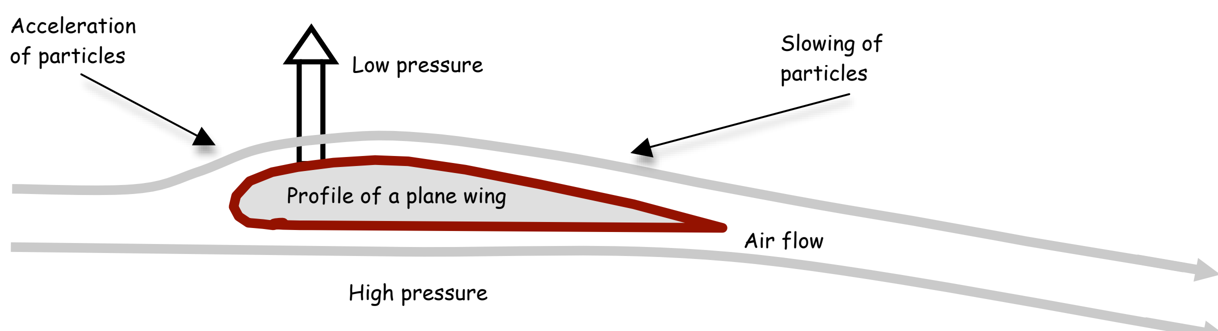
***Bernoulli's theorem**, established in 1738 by Daniel Bernoulli, expresses the simplified hydraulic balance of a fluid in a conduit. He established the basis for hydrodynamics and more generally, of fluid mechanics.*

Daniel Bernoulli (1700 – 1782)
Swiss mathematician and physicist

Essentially, Bernoulli showed that the speed and pressure of a fluid vary in inverse proportions. Thus, great speed in the fluid creates low pressure in it. Conversely, slow speed will engender strong pressure.

A simplistic way to understand this phenomenon is to imagine that when the particles accelerate, they get further away from one another. In an area where the fluid has great speed, there are therefore fewer particles present. As we know, pressure is generated by the collision of particles with objects. We can thus conclude that the fact that there are fewer particles implies lower pressure.

Increase in the speed of the particles → Increase in the distance between the particles → Decrease in the number of particles in a given volume → Decrease in the number of collisions made by the particles → Decrease in the pressure exerted by the particles



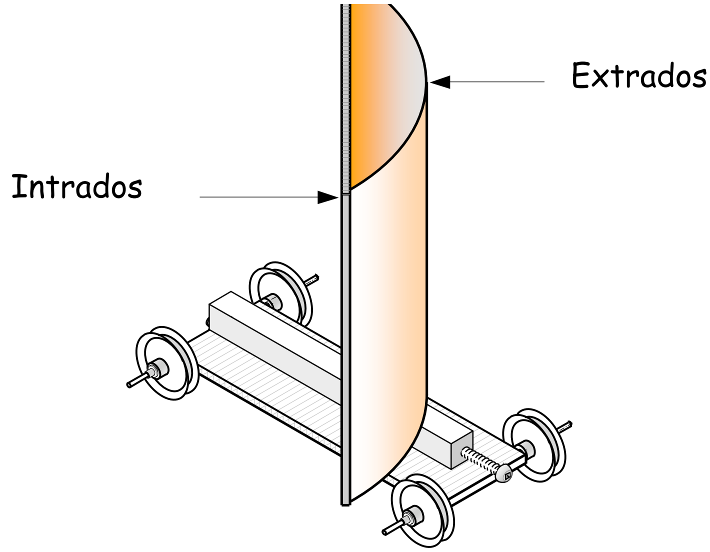
To resume:

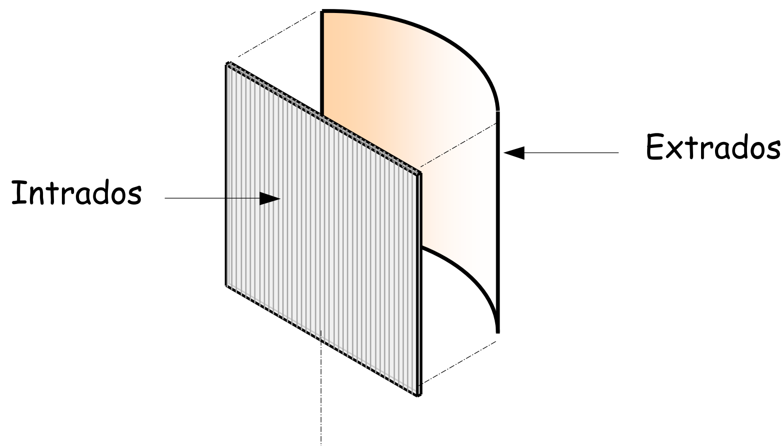
The airflow around the wing generates these high and low pressure zones. Objects always tend to move from a high pressure to a low pressure zone. We need only think of a bullet in the canon of a revolver, a sneezing person or the simple presence of wind. An ascending force thus appears and this force supports the plane in flight.

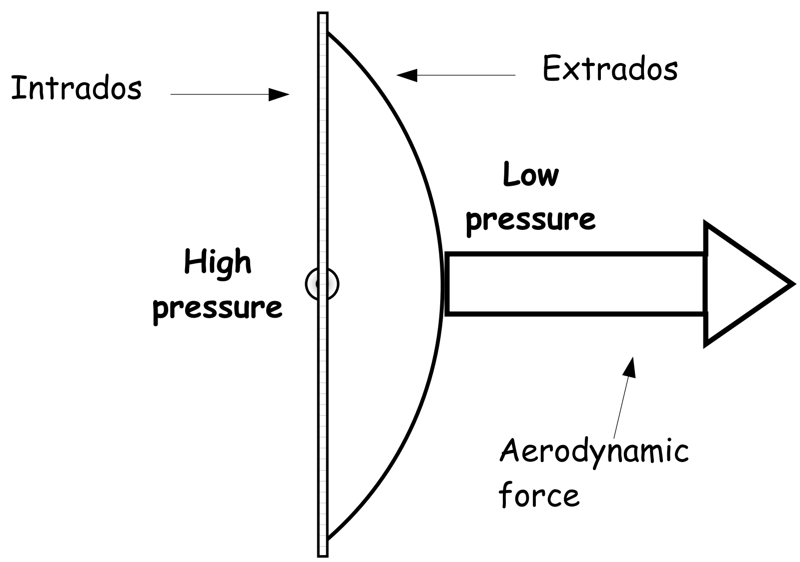
In the case of our Aeolus' chariot, the rigid sail behaves like the airplane wing. We preferred a rigid sail to a flexible sail to simplify its shape. It becomes easier to place the aerodynamic force vector that the sail creates. When the wind goes around the sail, it must split in half. One part of the wind goes on the intrados side, the other, on the extrados side. The path traveled by the air going on the extrados side is longer. In accordance with Bernoulli's principle, a low pressure zone is create on this side. A high pressure zone appears on the intrados side. The sail tries to move from a high pressure zone to a low pressure zone and creates the aerodynamic force.

To make things easier, we will consider that the aerodynamic force is always perpendicular to the sail.

Now let's put it all into practise. Let's study the behaviour of Aeolus' chariot when it is subjected to winds from different directions.

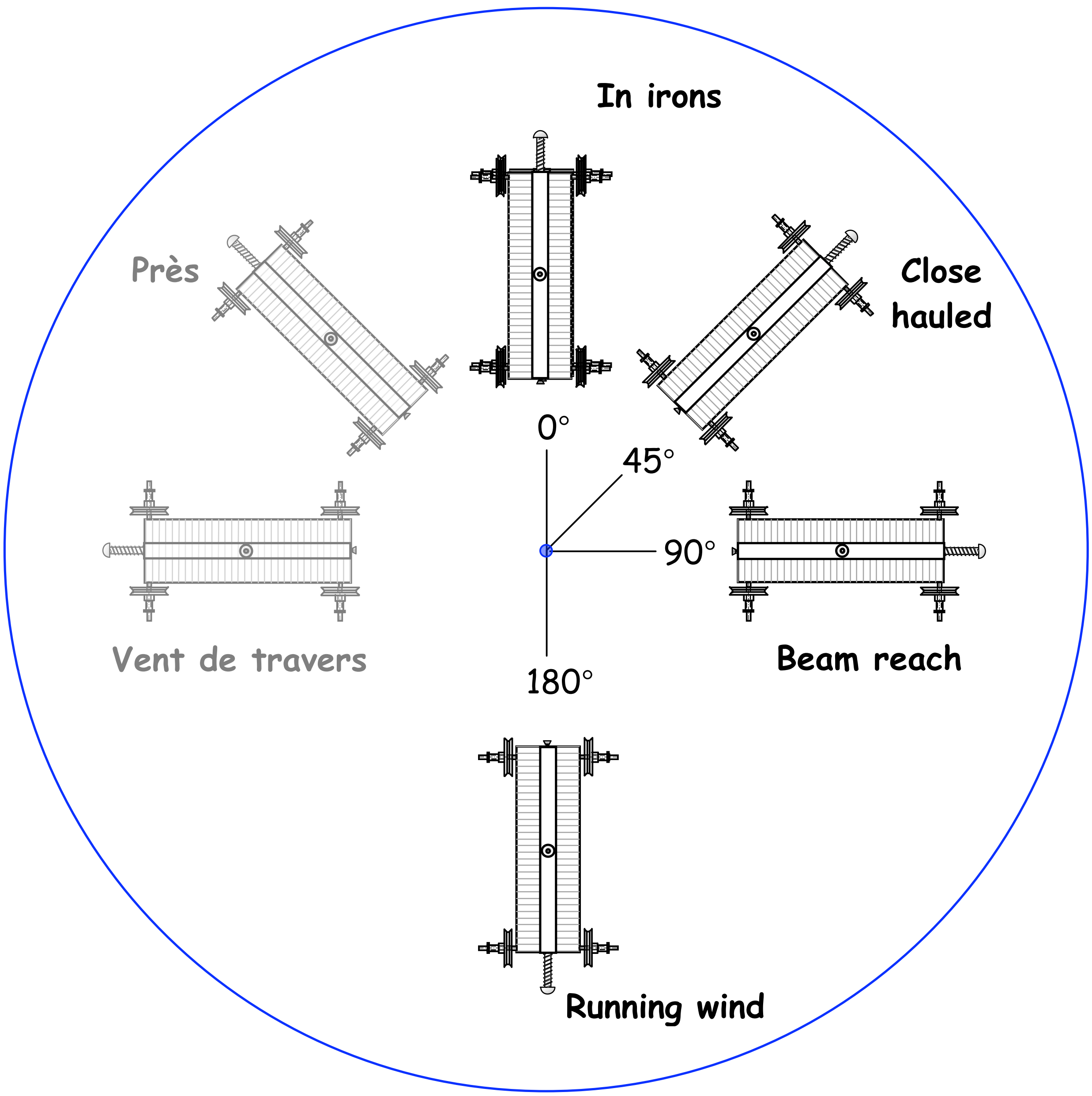






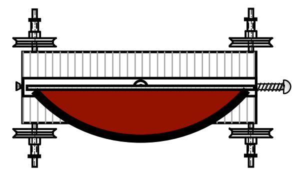
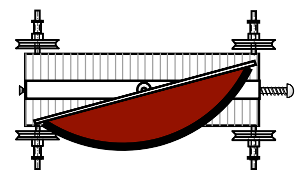
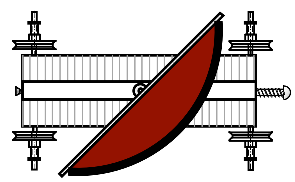
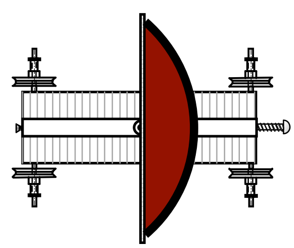
Points of sail (orientation of the chariot in relation to the wind)

A point of sail is the direction towards which a sailed vehicle moves in relation to the direction of the wind. Though there are at least 6 points of sail, we will make it simpler by only remembering three: close hauled (close to the wind), beam reach and running. In close hauled, Aeolus' chariot moves upwind at a 45 degree angle to the wind. (In the illustration below, we show Aeolus' chariot from above.) Note that when the chariot is in irons (facing the wind) it can't move forward. Moving into the wind is an easy way to immobilise yourself when sailing. In our case the aerodynamic force would be parallel to the wheel axle (inefficient).

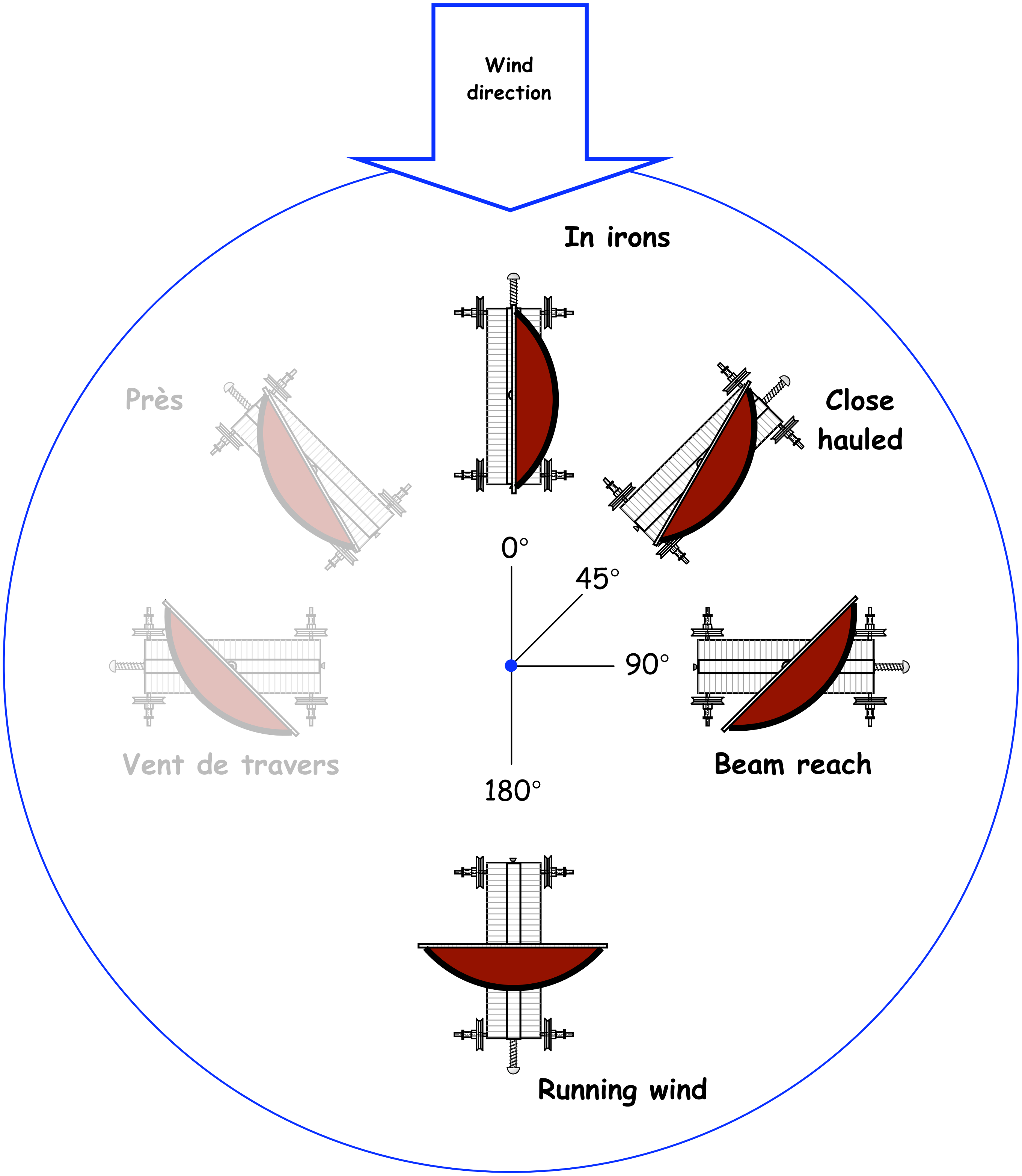


Position of the sail in relation to the chariot

Note the angle of the sail in relation to the chariot axle for each sail point.

In irons The chariot doesn't move. In the case of our rigid sail, there is aerodynamic force, but it is parallel to the wheel axle, so it is inefficient. If we had a cloth sail, it would luff (flap).	 0°
Close hauled Here is how you must set the sail when you are sailing close hauled.	 15°
Beam reach Here is how you must set the sail when you are sailing perpendicular to the wind.	 45°
Running wind Here is how you must set the sail when you are sailing with the wind.	 90°

Summary (orientation of the sail and the chariot)



Directed laboratory (dynamics of Aeolus' chariot)

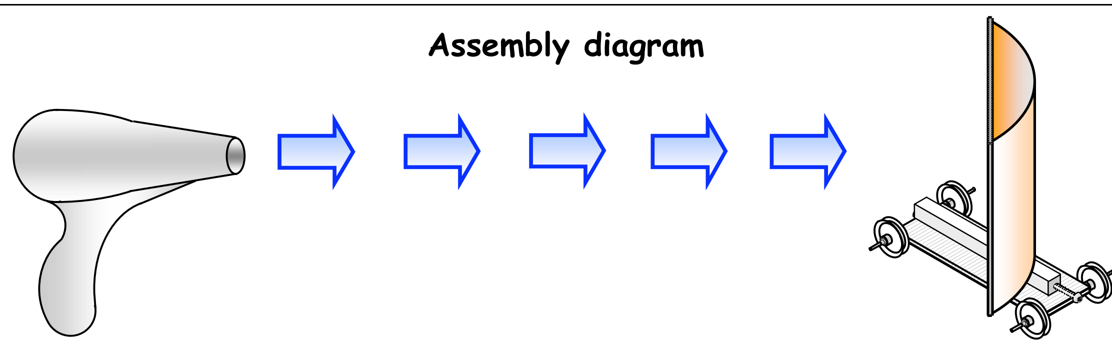
This lab will give you the opportunity to better understand the forces in play when Aeolus' chariot moves. There is the aerodynamic force of the sail, the counter-drift force of the wheels and the force of propulsion. To begin with, you make Aeolus' chariot move using different points of sail intuitively. Then you will study the forces that will initiate a movement for each point of sail.

First part (making Aeolus' chariot move)

Materials

- 1 Aeolus chariot with its sail
- 1 hair dryer
- 1 very smooth surface

Assembly diagram



Manipulations

1. Adjust the angle of Aeolus' chariot sail for a running wind point of sail.
2. Place the chariot on the smooth surface, locating it so that it can move freely.
3. Connect the hair dryer and hold it at a distance of about 1 meter, so as to simulate wind from behind.
4. Turn the hair dryer on and observe the motion of the chariot.
5. Repeat steps 1 to 5 for close hauled and beam reach points of sail.

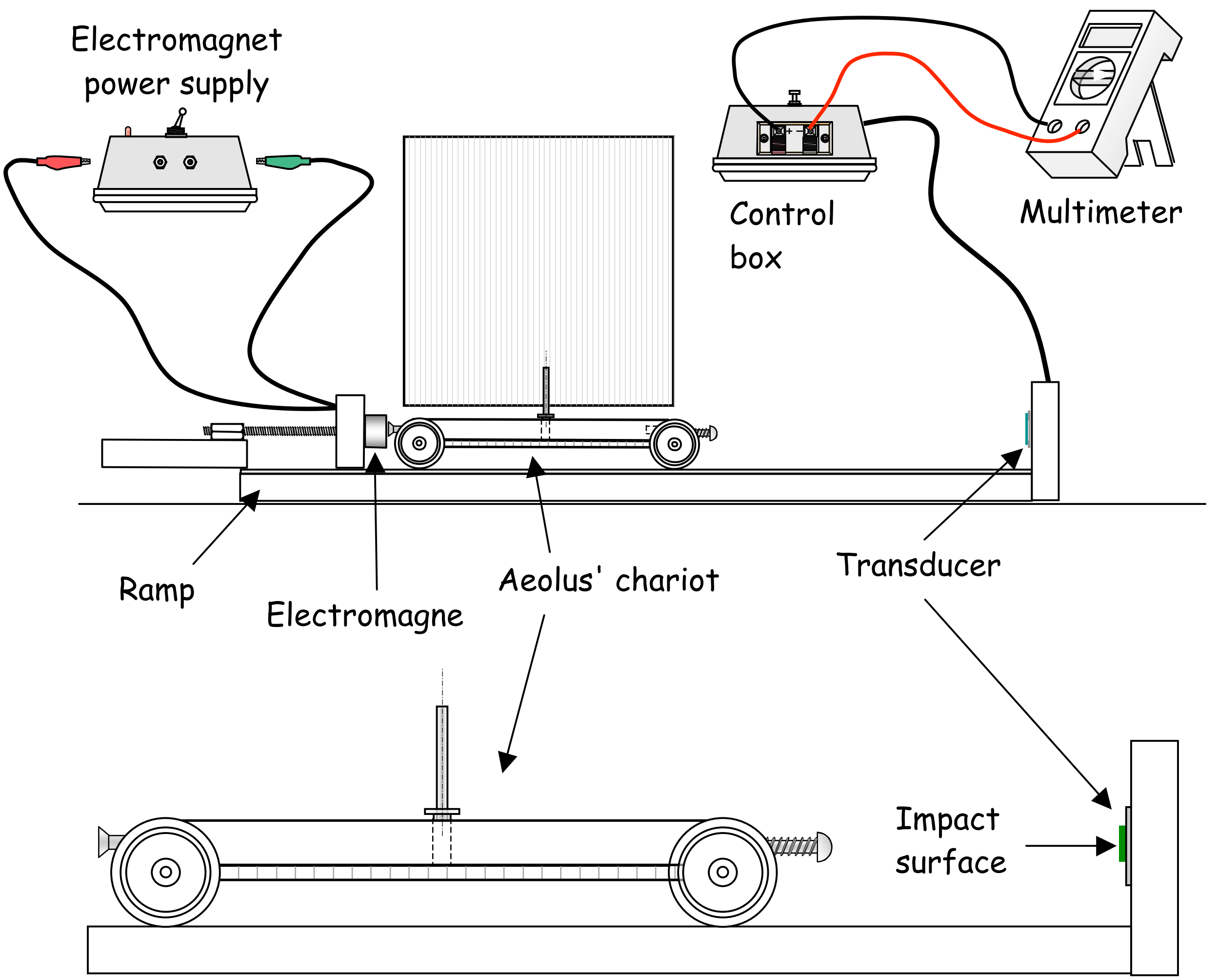
Note: For the close haul, you may need to put the chariot at an angle greater than 45° to the wind (possibly 60°). Placing the chariot as close to perpendicular to the wind will make your task easier. (The chariot must nonetheless move upwind).

Second part (Initial forces for each point of sail)

Materials

- 1 Aeolus' chariot equipped with its rigid sail
- 1 ramp (identical to the inclined plane) with transducer and control box
- 1 hair dryer
- 1 electromagnet
- 1 - 9 volt power supply
- 1 multimeter
- 1 ruler
- 1 scale
- 1 strip of paper

Assembly diagram



Manipulations

1. Weigh the chariot and note the mass in Data table 6.
2. Adjust the angle of Aeolus' chariot sail for a running wind point of sail.
3. Place the ramp, equipped with its transducer, on a flat surface.
4. Affix the electromagnet on the ramp so as to allow the **smallest possible displacement of the chariot** (close to the transducer).
5. Place the chariot on the ramp between the electromagnet and the transducer as shown on the assembly diagram.
6. Affix the hair dryer to a universal support with a universal clamp.
7. Place the dryer at a distance of about one meter in order to simulate wind from behind (the dryer must be far enough from the transducer so it does not cause interference).
8. Turn the hair dryer on and adjust the trajectory of the air flow so it reaches the center of the sail. (You can detect this "wind" using the strip of paper).
9. Turn the hair dryer off.
10. Connect the power supply, in the "off" position, to the electromagnet.
11. Connect the multimeter onto the control box of the transducer.
12. Turn the multimeter on in CC voltage mode (approximate 2V scale).
13. Turn the electromagnet power supply on.
14. Lean the chariot against the electromagnet so it is held by it.
15. Align the chariot on the guiding line.
16. Measure the distance between the spur of the mobile and the impact surface of the transducer and note this measurement in the data table.
17. Turn the hair dryer on again, being careful not to change its direction.
18. Press the reset button on the transducer control box. (The multimeter should now read zero).

22. Immediately after having pressed the reset button, turn off the power to the electromagnet and read the highest voltage that momentarily appears on the multimeter. (The chariot must hit the center of the transducer).
19. Note this voltage in the data table.
20. Repeat steps 13 to 20 twice more and calculate the average.
21. Repeat steps 2 to 21 with two other points of sail: beam reach and close hauled. For the close haul, you may need to put the chariot at an angle greater than 45° to the wind (possibly 60°).

Data table 6 (dynamic Aeolus' chariot)				
Point of sail	**U (V)** **Trial n° 1**	**U (V)** **Trial n° 2**	**U (V)** **Trial n° 3**	**Average voltage (V)**
Running wind				
Beam reach				
Close hauled				
Distance spur — transducer Δs (cm)				
Mass of Aeolus' chariot (g)				

Analyse the results

Analyse your data

Question 1

Complete column 2 of Results table 7 that follows. Use the same calibration graph (or equation model) as for the uniformly accelerated mobile. This will allow you to evaluate the kinematic energy of the chariot right before it hits the transducer for each point of sail. Note these energies in column 3.

Question 2

This quantity of energy corresponds to the labour performed by the wind to accelerate the chariot over this short distance. Recopy column 3 into column 4.

Question 3

Now calculate the effective force, in Newton, (in the same direction as the displacement of the chariot) for each point of sail. So, isolate the force in the following equation. Use the spur - transducer distance from Table 6 as displacement. Complete column 5.

$W = F \cdot \Delta s$ where $W \Rightarrow$ labour in J (Joule), $F \Rightarrow$ force in N, $\Delta s \Rightarrow$ displacement in m (in the same direction as the force)

Question 4

Finally, calculate the acceleration of the chariot for each point of sail. Isolate the acceleration in the following equation. Use the mass of the chariot from Table 6. Complete column 6.

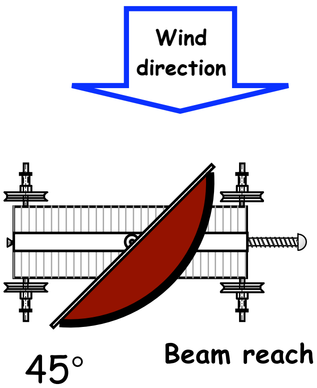
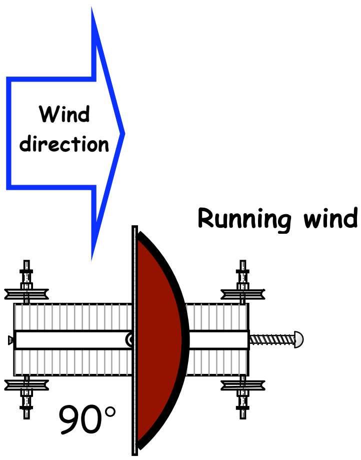
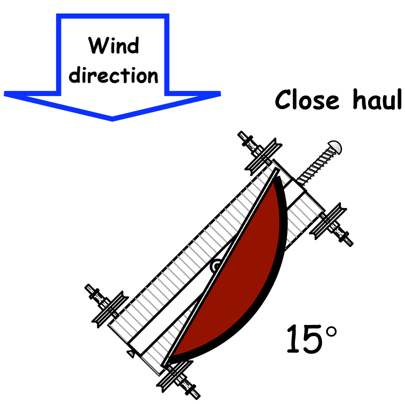
$F = m \cdot a$ where F ⇒ force in N (Newton), m ⇒ mass in kg, a ⇒ acceleration of the chariot in m/s^2 or N/kg

Results table 7 (dynamic Aeolus' chariot)					
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
Point of sail	**Average voltage (V)**	**Energy (mJ)**	**Labour (mJ)**	**Effective force (N) (propulsive)**	**Acceleration (m/s^2)**
Running wind					
Beam reach					
Close hauled					

Analyse your data (continued)

Question 5

The **propulsive force** that you have just found is essentially the sum of the two other forces. The first force is the **aerodynamic force** of the sail, which acts perpendicular to the sail. The second force is the **anti-drift force** which acts parallel to the wheel axle. The anti-drift force prevents the chariot from moving sideways from the effect of the wind's pressure.

Since you know the direction of these three forces and the size of the propulsive force (the size of the resulting vector) graphically determine the size of the two other forces.	
Illustration of the situation	Vector addition (graphically)
	
	
	

Draw your conclusions

Question 6

Describe the evolution of each force, from running to close haul winds.

Question 7

In your opinion, at which point of sail can you attain the greatest speed? Why?

Question 8

What forces act on our chariot when it is facing the wind and its rigid sail is in the boat's axis?

Kinematic analysis of Aeolus' chariot

In the preceding experiment, we studied the forces that act on the chariot when it was practically at rest. Indeed, the distance between the electromagnet and the transducer was very small. In the rest of this document, we will refer to those forces as static forces.

Now it is time to deepen our study by looking at what happens when Aeolus' chariot attains greater speed. To do so, we perfected a fan with which we made our chariot move. To simplify it, we limited our experiment to the fastest points of sail (running wind and beam reach). Since it is difficult to study such a rapid phenomenon, we filmed it. Your work will consist of doing the kinematic analysis of this video clip.

An Aeolus' chariot that attains greater speed may behave differently than one at low speed. Several points may be raised:

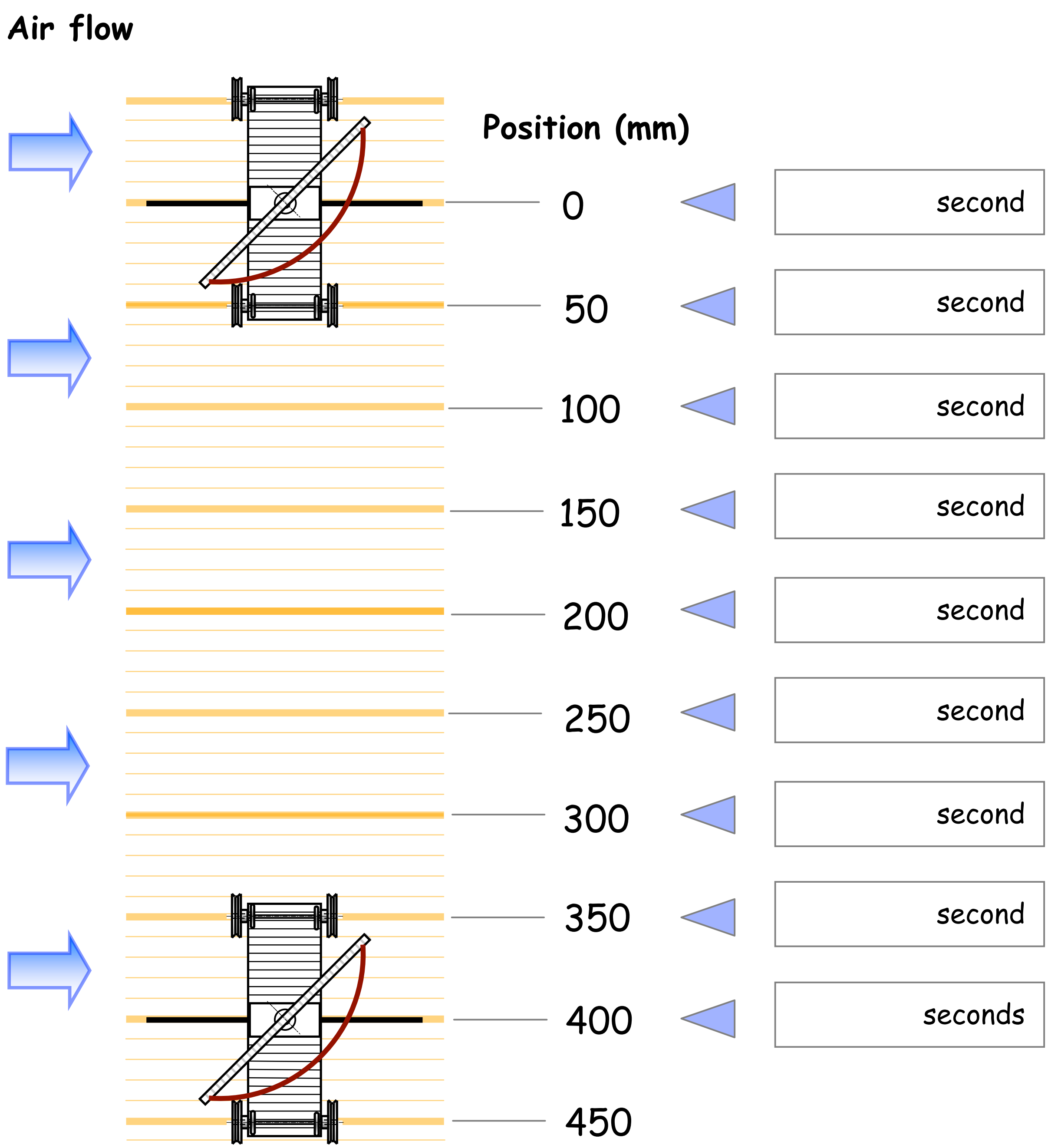
- **Are the initial forces previously found for each point of sail still valid at a greater speed?**
- **To how much acceleration will the chariot be subjected for each point of sail?**
- **Which point of sail (running or beam reach) will allow the greatest speed?**

Watch the following video clip carefully, taking note of the "split" times for the chariot for each point of sail. You will then have to represent the data graphically.

Since the size of the fan was limited, an extrapolation to 3 seconds will be necessary to complete your kinematic analysis.

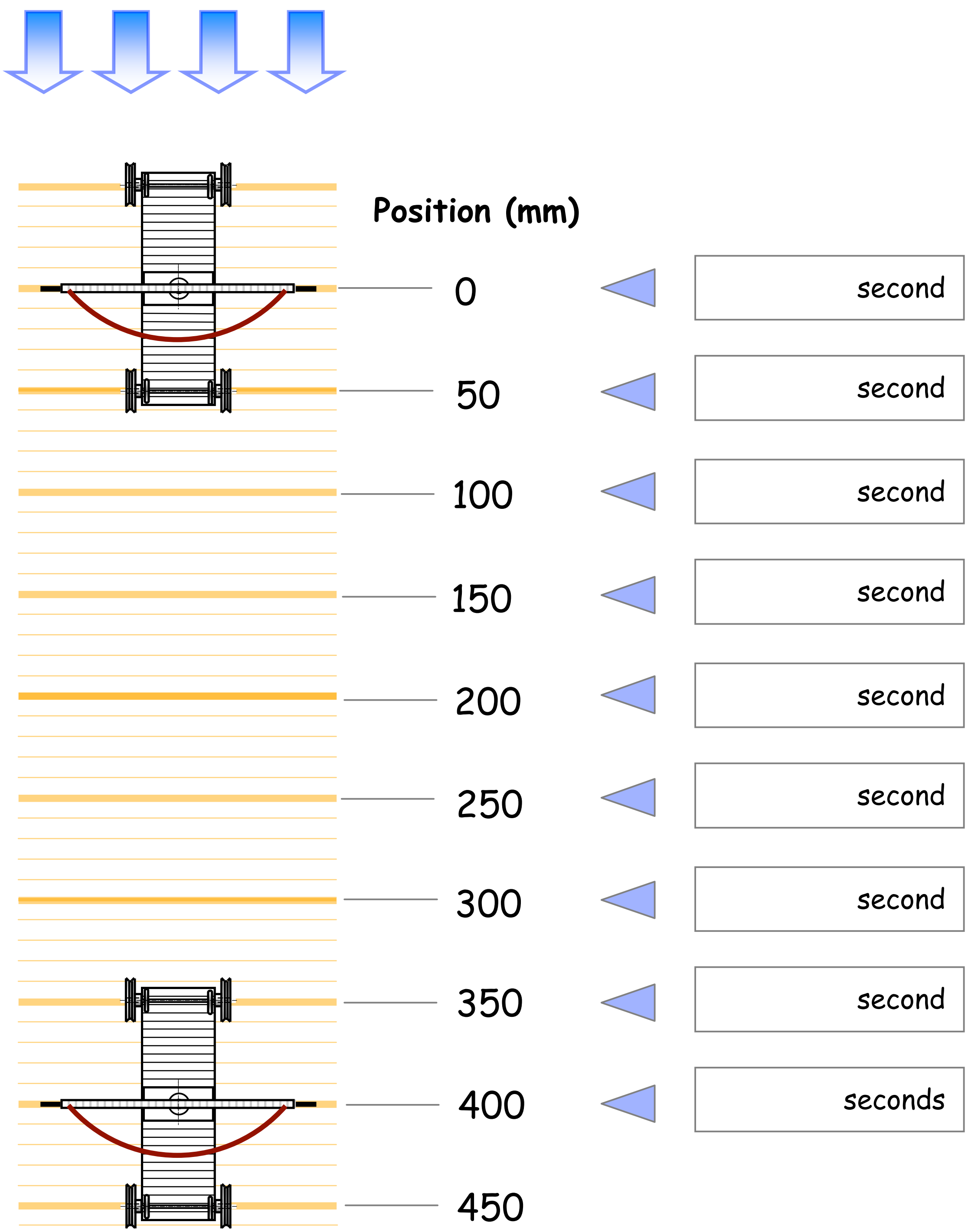
Had the fan had been larger, we would, in fact, have noticed that the chariot attains constant speed. At that moment, the propulsive force is equal to the force of friction so that the resulting force on the chariot is nil. It therefore stops accelerating and maintains constant speed. **The extrapolation must therefore be linear.**

Time recording in relation to position for beam reach point of sail



Time recording in relation to position for running wind

Air flow



Outlining the mandate after the video

What do you have to do to respond to this mandate?
(Kinematic analysis of Aeolus' chariot)

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Your kinematic analysis must be handed in as a distinct document. It must answer the following questions:

- **Which point of sail allows the greatest acceleration?**
- **Which point of sail allows the greatest speed to be reached?**

All your observations or deductions must be justified by scientific explanations or calculations.

Integration and reinvestment

<table>
<tr><td>In light of your study of Aeolus' chariot, build a network of concepts related to kinematics. This exercise will allow you to appreciate how far you have come by studying the wonderful world of sailing.</td><td>Word bank: instantaneous speed, meter, position, meters per second, variation in speed, time, acceleration, average speed, meters per seconds squared, variation of position, distance traveled, second, etc.</td></tr>
<tr><td colspan="2">Network of concepts

Kinematics</td></tr>
</table>

In light of your study of Aeolus' chariot, build a network of concepts related to dynamics. This exercise will allow you to appreciate how far you have come since the beginning of the LES.	**Word bank:** force, trigonometry, component, angle, sine, normal, Newton, vector, resultant, tangent, acceleration, cosine, speed, position, etc.
Network of concepts	

Reflection

We now invite you to use your acquired skills and knowledge to push your thinking a little further. To do so, you must produce a document that may take the form of a PowerPoint presentation, a poster or simply a written document.

This document must include a kinematic and dynamic description of an everyday situation.

Work plan