Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

Student names

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Date

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PHY 103 Discovery Lab
Ecole polytechnique
Taking on the Paris 2024 Olympics

Technical note 1: for you report: you can fill up this .docx file, and eventually add extra image files to it.

Technical note 2: please save any data you need to save on your computer in the folder C:\BACHELOR\ (you can create a subfolder with your name in this folder).

Technical note 3: You might want to be ready to copy and bring some data home, make sure you know how to use any data transfer option (WEtransfer, Gdrive etc.) or bring a USB key (a few Go will be enough).

0- Introduction

You set yourself a challenge: winning a medal in hammer throw at the next Olympics. Having watched the Tokyo games (Figure 1) you noticed that only the escape velocity and the throwing angle of the hammer are given after each athlete's throw. As a scientist, you might wonder if those two parameters are the only one that need to be optimized in order to get the best throw possible. If so, you might also want to know how these parameters affect the distance of the throw, and ask for instance if there is an optimal throwing angle?

To answer those questions, we will reproduce in the lab the conditions and study the impact of the launch parameters.

Figure 1. Hammer throw during the Tokyo olympic games (by Quentin Bigot, in 2020). l'Equipe.fr.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

These experiments will allow you to observe the trajectories of objects and learn about kinematics, without — at first — being concerned about the forces that cause the motion. Then, we will try to understand the forces at play that lead to the observed trajectories.

There are two experimental setups on your table. In the first one, you will analyze the motion of a bead falling freely in the air. In the second one, you will look at what happens to the motion of a bead on a rotating disk, when the bead is filmed with a camera rotating with the disk.

Before beginning any experiment, please read carefully the technical Appendix.

1. Object in free fall

The first step towards understanding what influences the hammer throw is to study the trajectories of an object in free fall. You have in front of you a simple bead launcher with two adjustable arms, shown in Figure 2. The height of the launcher h is h = 32.5 cm, and the radii of the circles are R = 7 cm.

To launch the bead, place it in the bead holder (Figure 3), and pull the launching pin. If need be, you can unscrew the red screw on the bead holder to adjust the position of the holder.

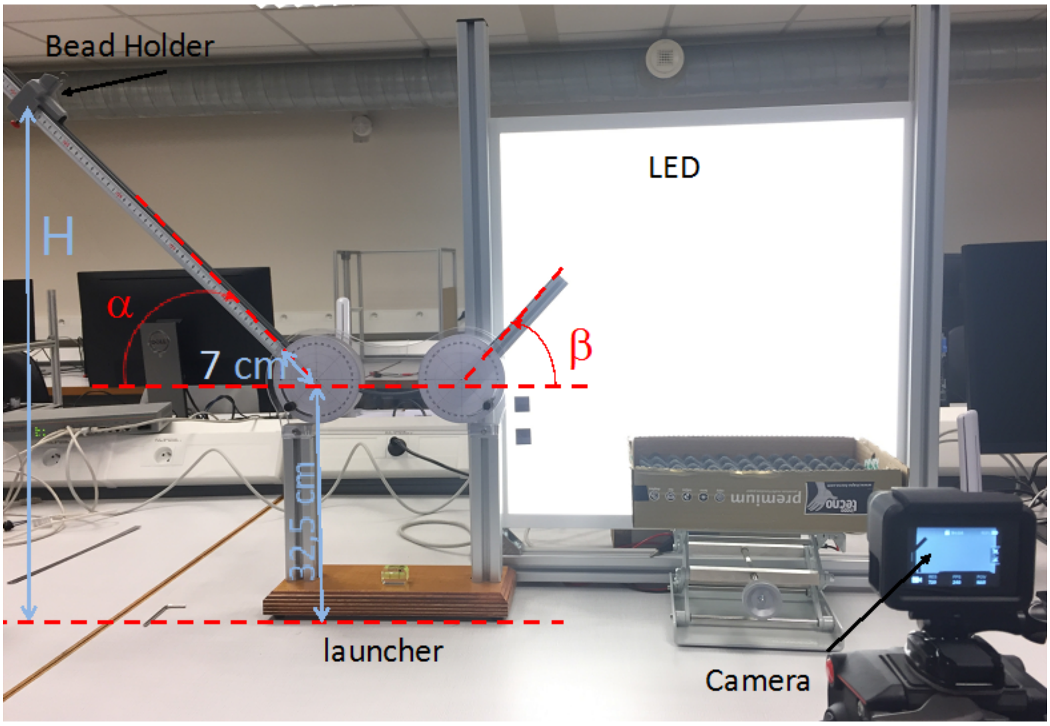


Figure 2. Bead launcher.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

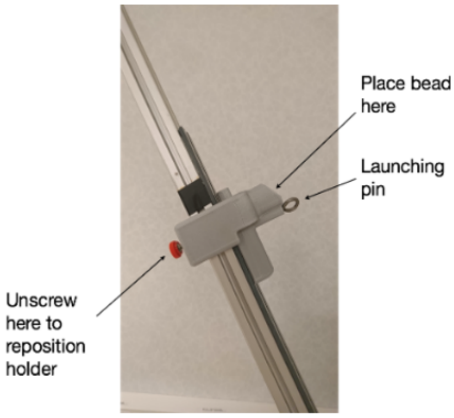


Figure 3. Bead holder.

1.1 First experiments

Question 1. Choose two angles for the arms, put the bead holder at a height *H* above the table, and write down the values you've chosen:

$\alpha = \pi/4$	$\beta = \pi/4$	$H = 58.66\ cm$

- Turn on the LED panel.
- Align the GoPro as parallel as possible to the launcher, and at a distance such that the bead trajectory in the air can be entirely seen on the movie (You do not need to capture the bead motion when the bead is still on the launcher).
- Choose the 240 fps video setting and start recording.
- Let the bead go freely from the bead holder.
- Stop your recording before picking up the bead.

1.2 – Reproducibility

We want to check to what extent keeping both parameters (the angle and the initial speed) constant leads to the same results.

1.2.a Experiments

Question 2. Choose how many times you want to repeat the experiment to test for reproducibility and write it down below.

Number of times the experiment is repeated: 4

- Record as many movies of the bead's trajectories. Do not change any parameter when you're repeating the experiment, and make sure the camera does not move between takes.

1.2.b Superimposition of trajectories

Now we're going to look at the trajectories you've recorded.

- Connect the GoPro to your computer with a USB cable and transfer your movies to your personal folder on the computer.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

- Follow the instruction in in section 05 to convert your mp4 movies in avi, and then to show the trajectories from each movie using image j.
- Then, again using image j as explained in section 05 in the technical appendix, superimpose all your trajectories using and save the result as a jpg file with all superimposed trajectories named *"freefall_reproducibility.jpg"*.

Question 3. By eye, what do you think of the reproducibility of your experiments?

By our reservation, the experiments is really reproducible until the ball hits the foam. Where the trajectories start to derivate but in air the trajectories look highly similar.

Question 4. If you think your experiments are not reproducible, what do you think the cause of the irreproducibility is?

The window was open during the experiments and hence the air resistance was varying (since the density of the air was changing). And experimental error due to human mistakes during the experiment could be a cause to be consider. For example, it was observed that when the pin was pulled more quickly the ball would have a higher velocity and since the pin was pulled by a human on each trial the velocity at which the ball travelled could have varied which might have caused an experimental error.

1.2.c Data analysis

Let us analyze the trajectories you've recorded.

- Open the software **Tracker**, and for each experimental movie, plot the bead's horizontal position x as a function of time t.
- Then plot the bead's vertical position y as a function of time t.
- Save the graphs in your directory as png files, and give them an incremental name (e.g.*freeFall_x_1, freeFall_y_1, freeFall_x_2, freeFall_y_2,* etc..). To save a graph in **Tracker**: right-click on the graph, select "Snapshot" and then go to File -> Save As

File name for $x(t)$: freefall 1_x, freefall 2_x, freefall 3_x, freefall 4_x

File name for $y(t)$: freefall 1_y, freefall 2_y, freefall 3_y, freefall 4_y

Question 5. Do $x(t)$and $y(t)$have the same shape? If not, where does the difference come from?

No, the graph of $x(t)$ is linear which implies that the magnitude of the velocity in the horizontal direction is constant (no acceleration).

However, the graph of $y(t)$ is more like the image of a quadratic function, since on the vertical direction the ball starts to fall faster and faster so there is a downward acceleration (which we know is caused by the gravitational force applied by the earth).

Question 6. We are going to fit a parabola to the bead's height as a function of time:$y(t) = At^2 + Bt + C$.What are the units of A, B and C?

$[A]$ = cm/s^2	$[B]$ = cm/s	$[C]$ = cm

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

Question 7. What do you think these fit parameters physically correspond to?

A= half of the gravitational acceleration on earth

B= vertical velocity

C= initial vertical position

Question 8. For each experiment you've recorded, give the values of A, B and C. Write down their units between the parentheses in the first row of the table.

Experiment #	A (cm/s^2)	B (cm/s)	C (cm)
1	-5.864E2	1.741E1	-9.855E-2
2	-7.132E2	6.473E0	1.760E-1
3	-5.791E2	1.290E-1	2.146E-1
4	-5.169E2	9.633E0	-5.317E-2

Question 9. Can you change your experiment to vary only A? Only B? Only C? If yes, say how. Understanding how to play on these coefficients is very important to find an optimal pitching strategy.

Only A: change the altitude at which the experiment is conducted

(since $F_g = \frac{G*(mass\ of\ the\ ball)*(mass\ of\ the\ earth)}{(distance\ between\ the\ center\ of\ masses\ of\ the\ objects)^2}$) ; however at the scale at which this experiment was conducted the effect would be too small.

Only A: Conducting the experiment in a vacuum chamber to minimize/eliminate the effect of air friction.

Only A: Go to a different region of the universe where the net force of gravity is different.

Only B: change the angle between the arms of the launcher and the launcher or change the height of the launcher or change the material of the ball and the path it follows on the launcher to minimize or increase friction or conduct the experiment in a vacuum chamber to minimize air friction.

Only C: change the angle between the arms of the launcher and the launcher to make its initial vertical position or using a different inertial reference frame.

Question 10. Now, fit a straight line to $x(t)$:$x(t) = Dt + E$. What are the units of D and E?

$[D]$ = cm/s $[E]$ = cm

Question 11. What do you think these fit parameters physically correspond to?

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

D= initial horizontal velocity

C= initial horizontal position of the ball

Question 12. For each experiment you've recorded, give the values of D and E. Write down their units between the parentheses in the first row of the table

Experiment #	D (cm/s)	E (cm)
1	7.030E-1	2.794E-1
2	8.226E-1	1.599E-1
3	6.599E1	1.643E-1
4	6.170E1	7.608E-2

Question 13. Can you modify only D? Only E? If yes, say how.

D= change the angle between the arms of the launcher and the launcher or change the height of the launcher or change the material of the ball and the path it follows on the launcher to minimize or increase friction or conduct the experiment in a vacuum chamber to minimize air friction.

E= change the angle between the arms of the launcher and the launcher to make its initial horizontal position or using a different inertial reference frame.

Question 14. Can you modify independently the 5 fitting parameters A, B, C, D and E?

Only A can be modified independently since B and D, and D and E are dependent on each other (they are the components of the velocity and position vectors respectively).

Question 15. Which fitting parameters are relevant if we want to know whether the experiment is reproducible or not?

A, B, C, D, and E since the trajectory of the ball is dependent on all of them.

Question 16. Calculate the mean and standard deviation of these relevant parameters

A: mean=-5.990E2 cm/s^2, standard deviation=8.233E1 cm/s^2

B: mean= 8.410 cm/s, standard deviation= 7.183 cm/s

C: mean= 5.970E-2 cm, standard deviation= 1.584E-1cm

D: mean= 3.230E1 cm/s, standard deviation= 3.646E1 cm/s

E: mean= 1.700E-1cm, standard deviation= 8.351E-2cm

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

Question 17. Conclude on the reproducibility of your experiment.

Overall, the standard deviations for the parameters are bigger than the means and hence the uncertainty in the values are high. This might be caused by the possible errors in the experiment mentioned before or possible errors made in the analysis of the data. Although the latter seems less likely since the analysis was made thoroughly and in an organized fashion. Regardless, despite the simplicity of the experiment the data seem to suggest that the experiment is not highly reproducible given the experimental and analytical procedure. However, this experiment is known to be reproducible since there is a definite literature value for the gravitational acceleration of the Earth. This again seems to suggest that some errors in the experiment came into play.

1.3 Effect of initial speed of the bead

We now want to change the initial speed of the bead $\overrightarrow{V_0}$ as it leaves the rail of the launcher.

Question 18. What is one way of doing it?

Change the height

Change the angle between the arms of launcher and the launcher or change the point on the launcher's arm at which the ball is released.

- Perform 3 experiments, changing $\overrightarrow{V_0}$ each time.
- Using **<u>Tracker</u>**, fit parabolas to $y(t)$ and straight lines to $x(t)$, and report your results in the table below.
- Determine the initial horizontal speed V_{0x} and the vertical speed V_{0y} at which the bead leaves the launcher using **<u>Tracker</u>**: simply *right-click* on the y label of your graphs; and selectV_x or V_y to see the evolution of the corresponding velocities with time.

Question 19. Write down your results in the table below.

α (°)	*H* (cm)	β (°)	*A* (cm/s^2)	*B* (cm/s)	*C* (cm)	*D* (cm/s)	*E* cm)	V_{0x} (m/s)	V_{0y} (m/s)
45	72.81	45	-5.963E2	6.879E1	1.553E-1	1.035E2	3.691E-1	1.035E2	6.879E1
45	69.27	45	-6.249E2	8.130E1	-1.097E-1	1.222E2	3.067E-1	1.222E2	8.130E1
45	65.73	45	-5.012E2	8.070E1	4.785E-2	1.066E2	2.349E-1	1.066E2	8.070E1

Question 20. Which fitting parameter(s) change when you change the launching speed?

B and E so V_{0x} and V_{0y} have a noticeable change.

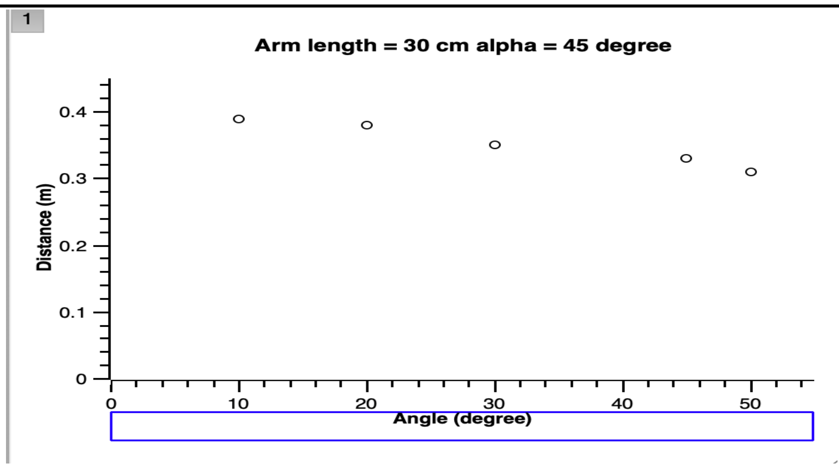
Question 21. Can you think of another way of varying the speed $\overrightarrow{V_0}$?

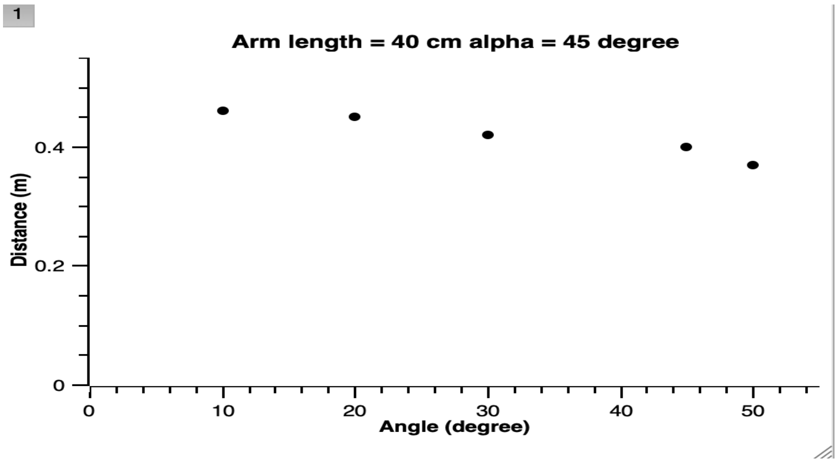
Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

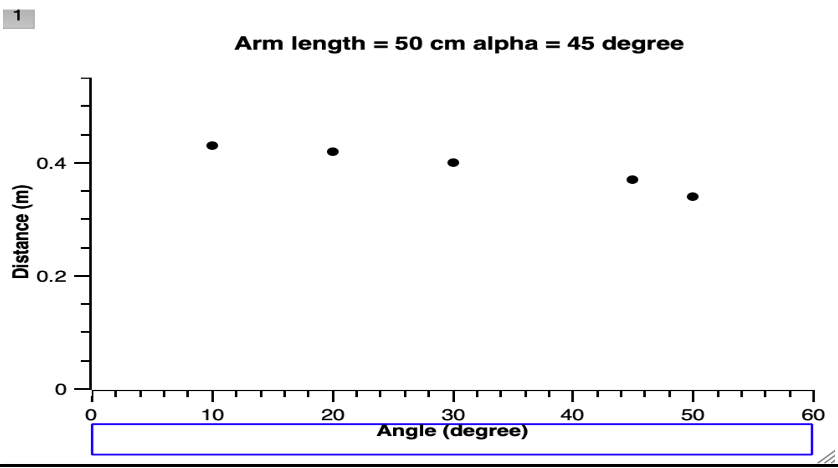
Changing the materials used to minimize or increase friction.

1.4 Effect of the angle β on the distance travelled by the object

Question 22. Keep a constant norm of the initial velocity $|\overrightarrow{V_0}|$ and perform 5 experiments with different values of β. Do the same thing for 3 different $|\overrightarrow{V_0}|$. On a single graph and for each $|\overrightarrow{V_0}|$ plot the distance travelled by the object as a function of the angle β.







Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

Question 23. What do you think is the best strategy when it comes to choosing a pitching angle β? What about the best initial speed?

We were not able to accurately determine at what angle the object goes the farthest, since the measurement software Tracker can only measure the distance under light conditions, and many of our experiments have objects that fly beyond the measurement range, which means we can't really measure it that accurately but from the graph that shows that when the β increase the distance decreased

1.5 Analytical trajectories

Newton's second law states that, for any body of mass m and of acceleration $\vec{a}$, the product of m and $\vec{a}$ is equal to the sum of the forces acting on the body. By definition, acceleration is the second derivative of position with respect to time: accelerations in the horizontal and vertical directions are written:

$$a_x = \frac{d^2x}{dt^2} \qquad \text{and} \qquad a_y = \frac{d^2y}{dt^2}.$$

A body in free fall is subjected to a single force: its weight. The weight of a body is equal to the product of its mass m, and the acceleration of gravity, which we write $\vec{g}$. The value of$|\vec{g}|$ is 9.81 $m.s^{-2}$.

Question 24. Is there a force acting on the bead in the horizontal direction? In the vertical direction?

Ignoring air friction there is no external force acting on the ball in the horizontal direction but in the vertical direction the gravitational force is acting on the ball.

Question 25. Write down the differential equations satisfied by $x(t)$ and $y(t)$, and solve them.

Since $F_x = 0$, a_x=0 so $\frac{d^2x}{dt^2}$=o

Then, x(t)= c_1*t+c_2, where c_1=$\frac{dx}{dt}$=v_{0x} and $c_2 = x(0) = x_0$

Since F_y = m*g, a_y=g so $\frac{d^2x}{dt^2}$=g

Then, y(t)= $c_1\frac{t^2}{2}$+c_2*t+c_3, where c_1=$\frac{d^2x}{dt^2}$=g, $c_2 = v_{0y}$ and $c_3 = y(0) = y_0$

Question 26. Do experiments and theory agree for the overall shape of $x(t)$ and $y(t)$?

Yes they agree the shape x(t) is linear in both and the shape of y(t) is parabolic in both.

Question 27. Calculate the mean value and the standard deviation of the fit parameter A over all your experiments. Write these values down below, as well as the number of experiments you fitted.

Number of experiments:15

α	β	Height	A
45	45	72.81	-5.963E+02
45	45	69.27	-6.249E+02

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

45	45	65.73	-5.012E+02
45	20	58.66	-5.754E+02
45	20	65.73	-5.624E+02
45	20	72.81	-5.354E+02
45	30	58.66	-4.506E+02
45	30	65.73	-4.736E+02
45	30	72.81	-5.754E+02
45	50	58.66	-5.803E+02
45	50	65.73	-5.129E+02
45	50	72.81	-5.244E+02
45	10	58.66	-5.182E+02
45	10	65.73	-5.960E+02
45	10	72.81	-5.897E+02
Mean Value (cm/s^2)	-5.478E+02		
Standard Deviation	50.063		

A = -5.478E2 ± 50.063 cm/s^2

Question 28. Comment on the value of A you find: does it fit with the theoretical prediction? Why or why not?

2*A=g (should be)

It doesn't fit with the theoretical prediction; in fact, it is higher than the prediction likely because of experimental errors in the experiment.

Question 29. One implicit constant parameter was that all experiment were done on Earth. Big news, you learn that participants will be allowed to perform at the Olympics from the surface of the moon. Is it at your advantage to throw hammers from there? Why?

It is at our advantage to throw hammers from there since the gravity on the moon is around 1/6th the gravity on the Earth and hence the time the hammer is in the air and thus the distance it travels is higher than on earth with the same initial conditions except gravity.

Question 30. You are now familiar with the impact of the launch parameters on the distance travelled by hammers. can you predict the travelled distance from those parameters ?

Yes, the distance travelled is $\frac{{v_0}^2}{g} * sin(2\theta)$.

Question 31. Here is a chart summarizing the results of athletes during the 2019 world championships. Write down the predicted distance and compare it to the actual distance the hammer travelled back then.

β (°)	37.1	40	35.2	42.2	39	38.3	44.3
V_0 (km/h)	100.5	100.5	96.2	96.5	101.6	97.1	95.7
D (m)	75.31	74.52	75.45	73.25	78.18	77.38	73.6
Predicted D(m)	76.44	78.23	68.57	72.90	79.41	72.14	72.01

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

Difference	1.13	3.71	6.88	0.35	1.23	5.24	1.59
Gravity	9.957	10.29	8.915	9.762	9.965	9.145	9.598

Question 32. From those data try to compute an estimation of the acceleration of gravity on Earth.

$$g = \frac{{v_0}^2}{d} * sin(2\theta)$$

We take the mean value of all the actual data that we have gravity= 9.663 ± 0.486 m/s^2

1.6 Other trajectories

With your new knowledge you have a fresh look on the sports practiced by your peers. You notice a surprising detail. Depending on the sport you are watching, sometimes the knowledge you have previously acquired seems to apply perfectly, while at other times it seems incomplete. A great example of that is shown in Figure 4 where you can compare the trajectory of a basketball (Fig. 4a) and of a shuttlecock (Fig. 4b, a shuttlecock is the projectile used when you play badminton).

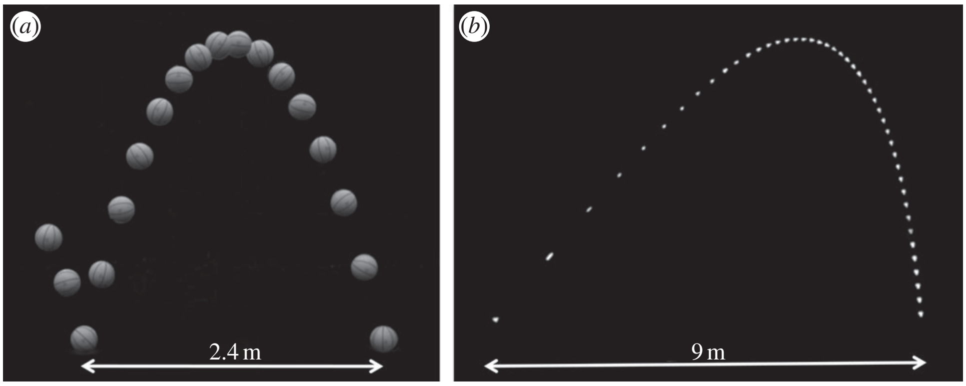


Figure 4: (a) Trajectory of a basketball. Time between two pictures: 40 ms.(b) Trajectory of a shuttlecock. Time between two pictures: 40 ms. Pictures taken from Cohen et al., *Proc. R. Soc. A* (2013).

Question 33. Does the trajectory of the basketball after its first rebound on the ground look like it can be fitted to a parabola? What about the trajectory of the shuttlecock?

Yes the trajectory of the basketball does look parabolic but for the shuttlecock it is not the case due to air friction. When the same force is applied to both objects the shuttlecock accelerates more since it has less mass and since the drag is dependent on velocity it also experiences more drag which makes it slow down and deviate from a parabolic path.

Question 34. Where do you think the difference between the two trajectories comes from? Does Newton's second law still apply in both cases?

As mentioned above the shuttlecock slows down due to drag. Newton's law still applies in both cases when drag is also taken into account.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

2 Trajectories in a rotating reference frame

You now wonder what would happen if the Olympics took place on a very small planet were the rotation could no longer be neglected. In such a world, a simple tennis game would challenge your intuition as the ball would have a very strange behaviour.

A great example of how surprising such a world would be is shown in the **following video** (link_VF [jammy] link_English [MIT video]).

In this part of the lab work, you're going to launch a bead on the top of a rotating turntable, shown in Figure 5. There are two cameras filming the trajectories of the bead. One camera is rotating at the same rate as the turntable. The other is immobile. We will study the trajectories of the bead as filmed by both cameras. Note that the diameter of the turntable is 50 cm.

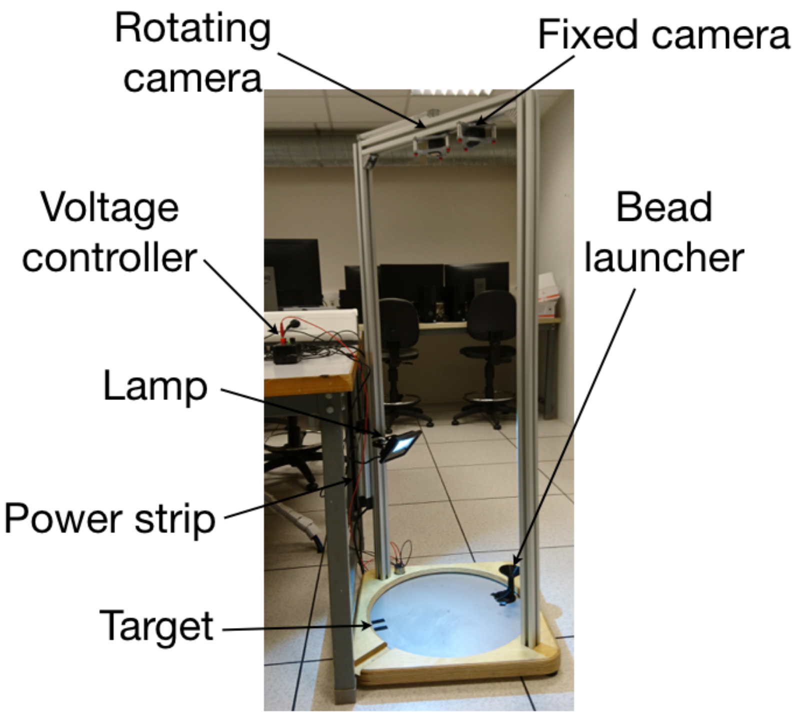


Figure 5: Rotating turntable.

2.1 Experimental protocol

- **Be very careful not to hurt yourself with the turntable, the rotating cameras or the transmission belt! Before turning on the turntable, make sure that the cameras are not connected to any USB cable and that nothing stands in the way of the rotation. If in doubt, call the person in charge of the lab session. While the turntable is running, you should not try to touch any part of the turntable, except for the launcher.**
- To turn on both the lamp and the turntable, switch the power stripon (Figure 6a).
- If you need to stop the turntable while still having the light on, disconnect one of the wires on the voltage controller (Figure 6b).

Notes : In the first setup we didn’t have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

- The rotation rate of the turntable can be adjusted by varying its input voltage: turn the knob on the right of the voltage controller, as shown in Figure 6b. Leave the knob on the left of the voltage controller (I/mA) at its minimal value. The higher the voltage, the faster the rotation rate. The direction of rotation can be switched by switching the black and red wires on the voltage controller (see Figure 6b).
- To launch a bead, you will use the bead launcher shown in Figure 7a: simply let the bead go in the funnel.

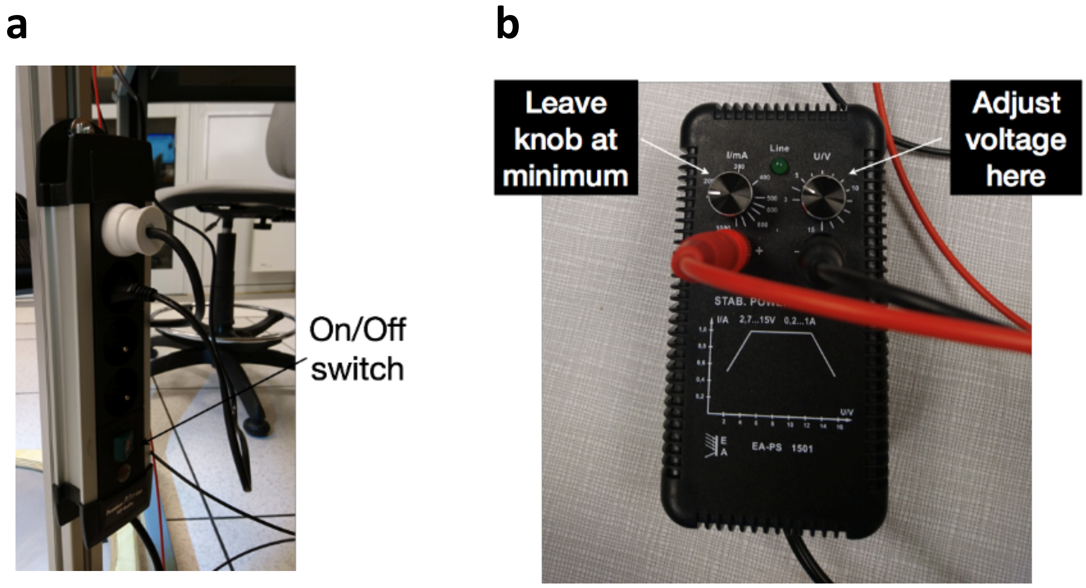


Figure 6: (a) Power strip controlling the lamp and the voltage controller. (b)Voltage controller. Turn the U/V knob to adjust the rotation rate. Switch the red and black wires to change the direction of rotation. Disconnect any wire to stop the rotation.

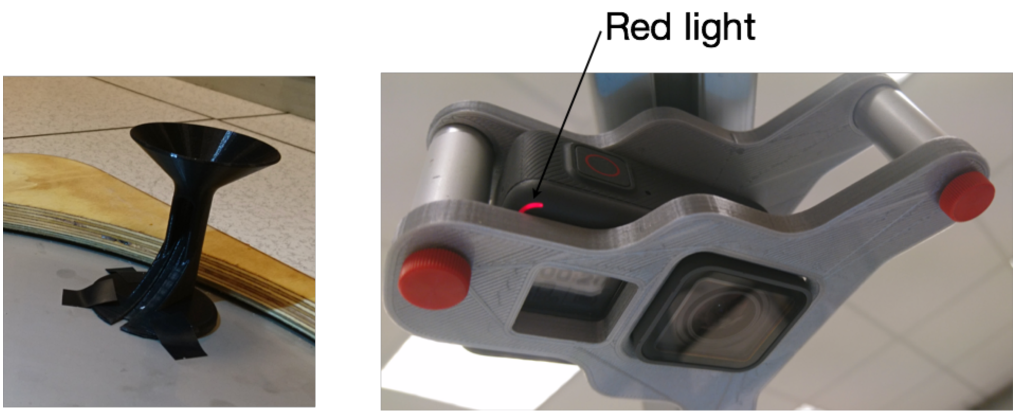


Figure 7: (a) Bead launcher. (b) Camera. When filming, the red light turns on.

2.2 Trajectory without rotation

- Adjust the position of the bead launcher so that the bead reaches the target: the two black strips positioned on the turntable (see Figure 5).
- Use the black scotch tape to stick the launcher to the turntable.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

2.3 Trajectory with rotation of the turntable

- **Make sure no USB cable or other cable is attached to the cameras or in the way of rotation.**
- Start recording with the two cameras. A red light should start blinking on the camera, see Fig. 7b.
- Turn on the turntable by plugging both wires in and use the highest possible rotation rate (voltage = 15V).
- Launch the bead.
- Turn off the turntable when the bead has reached the other end of the turntable.
- Stop recording your movies.

Again, be very careful not to hurt yourself with the turntable! Ask for help if unsure on how to proceed.

Question 35. Does the bead arrive between the two black strips?

No, the bead doesn't arrive between the two black strips when the turntable is on instead it follows a curved path towards the ends of the turntable.

2.4 Comparison of trajectories in fixed and rotating frames

- Transfer your movies to the computer
- Show the trajectories in each movie by converting them to avi and then using Imagej <u>as explained in section XXX</u>.
- Write down the names of the individual jpg files below:

Trajectory captured by the immobile camera: Immobile trajectory 15V.png

Trajectory captured by the rotating camera: Mobile trajectory 15V.png

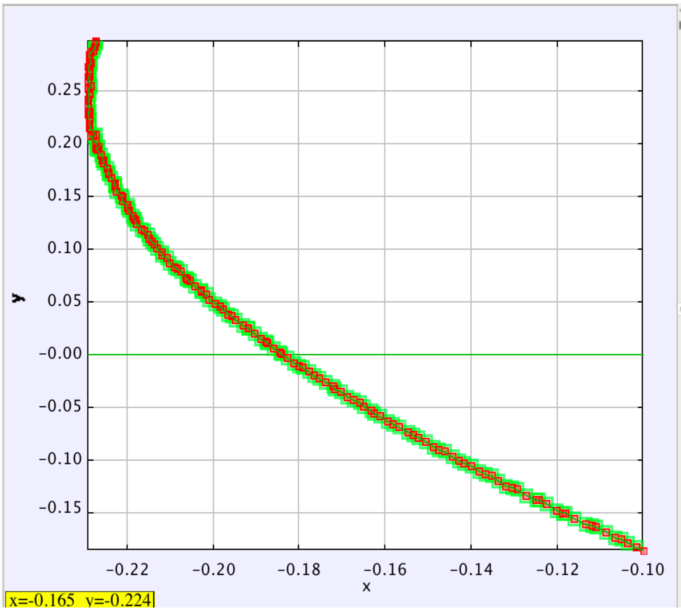
Question 36. Describe the trajectories recorded by the immobile camera, and by the rotating camera. Are they the same? *(you can insert or draw pictures)*

NOTE: Since the ImageJ is unable to open the avi. format document so we try to use Tracker and our own visual evaluation of the videos to describe the trajectories.

The trajectory recorded by the immobile camera was mostly linear, while the trajectory recorded by the rotating camera was more curved since the reference frame in the two cameras are different (with the immobile one being inertial). The rotating camera's recording also hinted towards a force acting towards the outside of the turntable while this force didn't exist in the immobile one (since the immobile one was inertial)

The trajectory recorded by immobile camera:

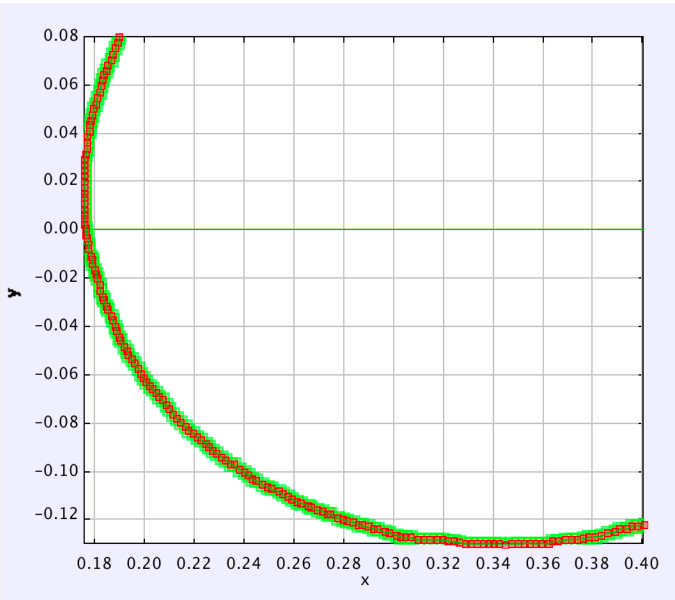
Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle



markers		✓
lines		☑
style		
axis	horiz	vert

row	x	y
0	-9.999E-2	-0.186
1	-0.102	-0.183
2	-0.104	-0.178
3	-0.105	-0.175
4	-0.107	-0.174
5	-0.109	-0.168
6	-0.111	-0.163
7	-0.112	-0.162
8	-0.114	-0.161
9	-0.116	-0.155
10	-0.118	-0.150
11	-0.119	-0.150
12	-0.120	-0.148
13	-0.123	-0.141
14	-0.124	-0.138
15	-0.125	-0.138
16	-0.127	-0.134
17	-0.129	-0.128
18	-0.131	-0.126
19	-0.132	-0.124
20	-0.134	-0.120
21	-0.135	-0.115

The trajectory recorded by mobile camera:



markers		✓
lines		☑
style		
axis	horiz	vert

row	x	y
0	0.190	8.026E-2
1	0.189	7.752E-2
2	0.188	7.556E-2
3	0.187	7.271E-2
4	0.186	7.075E-2
5	0.185	6.799E-2
6	0.184	6.612E-2
7	0.183	6.421E-2
8	0.183	6.191E-2
9	0.182	5.976E-2
10	0.182	5.698E-2
11	0.181	5.507E-2
12	0.180	5.205E-2
13	0.179	5.023E-2
14	0.179	4.751E-2
15	0.178	4.522E-2
16	0.178	4.372E-2
17	0.178	4.096E-2
18	0.177	3.887E-2
19	0.177	3.633E-2
20	0.177	3.355E-2
21	0.176	3.155E-2

Question 37. How can you explain qualitatively the trajectory recorded by the rotating camera?

The trajectory recorded by the rotating camera was is the effect of bead's approximately linear motion and camera's rotational motion, which is the combination of two types of motion

2.5–Effect of rotation rate

Question 38. How do you expect the effect will change if you slow down the rotation rate ω_0, while keeping the initial velocity of the bead $\overrightarrow{V_0}$constant?

The rotation rate and linearity of the trajectory of the bead will be inversely proportional. In other words, decreasing the rotation rate will result in a less curved path and the bead will reach a point closer to the strips.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

- Test your hypothesis by taking at least 3 movies with the rotating camera, at three different rotation rates, while keeping $\overrightarrow{V_0}$ approximately constant. Do not move the position of the bead launcher between movies!
- For each experiment, measure ω_0 (in rpm: round per minute) and give its value in rad/s.
- **You only need to take movies with the rotating camera, not with the fixed camera.**
- Trim your movies to the minimal length with **Avidemux**, and determine the initial speed of the bead $|\overrightarrow{V_0}|$(in m/s) using **Tracker**.

Question 39. Save individual trajectories using Imagej as explained previously. Write down below the names of the files with the trajectories, as well as the corresponding $|\overrightarrow{V_0}|$and ω_0.

NOTE: Since the ImageJ is unable to open the avi. format document so we try to use Tracker to first find Vx(t) and Vy(t) by checking the slope of the graph and use the formula $|\overrightarrow{V_0}| = \sqrt[2]{(Vx(t))^2 + (Vy(t))^2}$

$|\overrightarrow{V_0}|$ (m/s)	ω_0 (rpm)	ω_0 (rad/s)	Trajectory file name
0.678	18.5(15V)	1.94	18.5RPM_trajectory X(t), 18.5RPM_trajectory Y(t)
0.364	10.1(10V)	1.06	10.1RPM_trajectory X(t) Y(t)
0.285	3.0(5V)	0.31	3.0RPM_trajectory X(t) Y(t)
0.383	5.0(7V)	0.52	5.0RPM_trajectory X(t) Y(t)

Question 40. Calculate the mean value for $|\overrightarrow{V_0}|$

$<|\overrightarrow{V_0}|>$(m/s) = 0.428 m/s

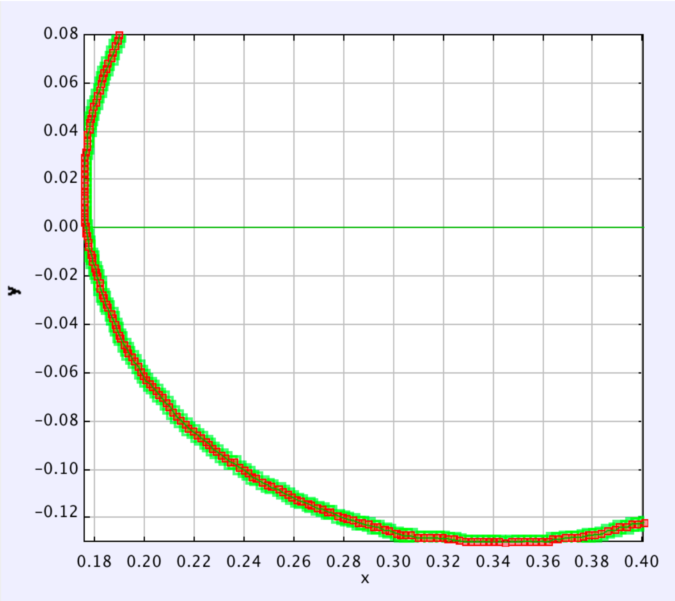
- Superimpose the individual trajectories using Image j (see section 05 in technical appendix). Rename the resulting file with superimposed trajectories as "*TrajectoriesVaryingOmega.jpg*".

Question 41. Describe how the trajectories change as the rotation rate is slowed down. *(you can insert or draw pictures)*

As the rotation rate is slowed down the bead follows a straighter path and comes closer to the strips.

The graph of mobile with 18.5 RPM:

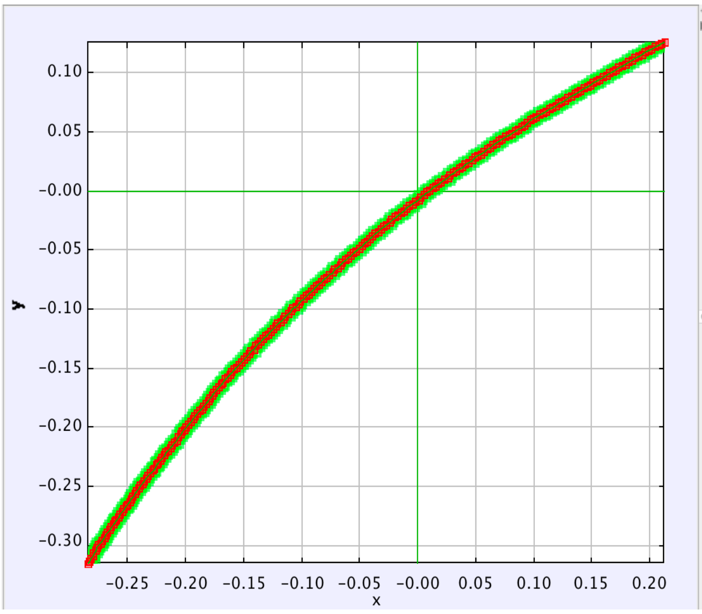
Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle



markers	✓
lines	✓
style	
axis	horiz / vert

row	x	y
0	0.190	8.026E-2
1	0.189	7.752E-2
2	0.188	7.556E-2
3	0.187	7.271E-2
4	0.186	7.075E-2
5	0.185	6.799E-2
6	0.184	6.612E-2
7	0.183	6.421E-2
8	0.183	6.191E-2
9	0.182	5.976E-2
10	0.182	5.698E-2
11	0.181	5.507E-2
12	0.180	5.205E-2
13	0.179	5.023E-2
14	0.179	4.751E-2
15	0.178	4.522E-2
16	0.178	4.372E-2
17	0.178	4.096E-2
18	0.177	3.887E-2
19	0.177	3.633E-2
20	0.177	3.355E-2
21	0.176	3.155E-2

The graph of mobile with 3.0 RPM:



markers	✓
lines	✓
style	
axis	horiz / vert

row	x	y
0	0.212	0.127
1	0.210	0.125
2	0.207	0.124
3	0.204	0.122
4	0.201	0.121
5	0.199	0.120
6	0.195	0.118
7	0.193	0.116
8	0.190	0.114
9	0.187	0.113
10	0.185	0.111
11	0.182	0.110
12	0.179	0.108
13	0.176	0.106
14	0.173	0.105
15	0.171	0.103
16	0.168	0.102
17	0.165	0.100
18	0.163	9.859E-2
19	0.159	9.695E-2
20	0.156	9.509E-2
21	0.154	9.374E-2

Therefore we can tell from the graph if the rotation rate is slowed down the bead follows a straighter path and comes closer to the strips.

2.6 Effect of variation of direction of rotation.

Question 42. What happens if you change the direction of rotation, while keeping $\overrightarrow{V_0}$constant?

IF the direction of rotation is changed the direction the bead's path is curved is reversed, ie. While the rotation is clockwise the bead's path curves towards the left and to the right when the rotation is counter-clockwise.

- Test your hypothesis by taking 2 movies with 2 equal and opposite rotation rates, while keeping $\overrightarrow{V_0}$ constant.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

- Measure for each experiment the rotation rate ω_0. Again, you only need to take movies with the rotating camera. Trim your movies to the minimal length with **Avidemux**, and determine the initial speed of the bead $|\overrightarrow{V_0}|$ (in m/s) using **Tracker**.

Question 43. Save individual trajectories using Image j. Write down below the names of the files with the trajectories, as well as the corresponding V_0 and ω_0.

NOTE: Since the ImageJ is unable to open the avi. format document so we try to use Tracker to first find Vx(t) and Vy(t) by checking the slope of the graph and use the formula $|\overrightarrow{V_0}| = \sqrt[2]{(Vx(t))^2 + (Vy(t))^2}$

$|\overrightarrow{V_0}|$ (m/s)	ω_0 (rpm)	ω_0 (rad/s)	Trajectory file name
0.678	18.5(15V)	1.94	18.5RPM_trajectory X(t), 18.5RPM_trajectory Y(t)
0.718	-18.5(15V)	-1.94	18.1RPM_trajectory X(t) Y(t) OP
Superimposed directions			We don't have the file since our Image I have some program problems

Question 44. Describe how the trajectories *y=f(x)*change as the rotation rate is reversed. *(you can insert or draw pictures)*

If the rotation rate is reversed its magnitude stays the same and only its direction changes and hence the paths look similar except their direction with their curvature being the same. So the trajectory gets reflected about the bead's normal trajectory it would follow with if there were no rotation.

2.7 Effect of variation of $\overrightarrow{V_0}$

Question 45. How do you expect the effect would change if you could slow down or speed up the launch speed of the bead V_0, while keeping the same rotation rate ω_0?

If the speed of the bead is increased while keeping the rotation rate constant, then the bead's path curves less when its velocity is higher.

- Test your hypothesis by taking 2 movies with the rotating camera for2 different $\overrightarrow{V_0}$, while keeping ω_0 constant (Change the bead launcher for varying $\overrightarrow{V_0}$, keeping the same position). Again, you only need to take movies with the rotating camera.
- Trim your movies to the minimal length with **Avidemux**, and determine the initial speed of the bead $|\overrightarrow{V_0}|$ (in m/s) using **Tracker**.

Question 46. Save individual trajectories using Imagej. Write down below the names of the files with the trajectories, as well as the corresponding $|\overrightarrow{V_0}|$and ω_0.

NOTE: Since the ImageJ is unable to open the avi. format document so we try to use Tracker to first find Vx(t) and Vy(t) by checking the slope of the graph and use the formula $|\overrightarrow{V_0}| = \sqrt[2]{(Vx(t))^2 + (Vy(t))^2}$

$|\overrightarrow{V_0}|$ (m/s)	ω_0 (rpm)	ω_0 (rad/s)	Trajectory file name
0.678	18.5(15V)	1.94	18.5RPM_trajectory X(t), 18.5RPM_trajectory Y(t)

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

0.735	18.5(15V)	1.94	18.1RPM_trajectory X(t) Y(t) HI
Superimposed trajectories			We don't have the file since our Image I have some program problems

Question 47. Describe how the trajectories $y=f(x)$change as the initial velocity of the bead changes. *(you can insert or draw pictures)*

As the initial velocity of the bead increases the path it follows gets less curved. This is due to the fact that the camera rotates at the same rate regardless of the bead's speed and with higher velocity the bead travels further in the time it takes for the camera to rotate and hence the path looks less curved.

2.8Comparison of times

Question 48. Compare the time t_{bead} to cross the turntable versus the time t_{table} to make one halfturn.

t_{bead} $1/\alpha$ ball's initial velocity

t_{table} $1/\alpha$ the rotation rate of the turntable

and hence they are independent on each other and are inversely proportional with the ball's initial velocity and the rotation rate of the turntable respectively. Generally the latter is bigger.

Question 49. If $\frac{2\omega_0}{|V_0|} \ll 1$, would you expect to observer different trajectories when filming with the rotating camera and the fixed camera?

In this case the bead would be travelling faster than the rotation of the turntable which would result in a less curved or in some cases even almost perfectly (to the human eye) linear path however it would still be curved even if a little.

2.9 Subsidiary questions (TO GO DEEPER)

Imagine you are with a friend at two opposite ends of a merry-go-round which rotates clockwise (as seen from above). You want to throw a ball to your friend, who should be able to catch it without having to run all over the place.

Question 50. Should you aim directly at your friend? If not, should you aim to her right? To her left?

You should aim to our right (so her left) since the path the ball follows will be curved towards our left.

Challenge: try to the reach the target, while the turntable is rotating!

- Choose a rotation rate $\omega_0$of the turntable and measure it.

Question 51. Determine the orientation of the bead launcher that allows the bead to end its course between the two black strips. Explain below you're calculations (a drawing can help).

Rotation rate ω_0 (rpm) =	ω_0 (rad/s) =

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

Angle of the bead launcher ϕ with respect to the vertical (°) =

- Once you succeed experimentally, record the trajectory using the rotating camera, using Imagej.

Trajectory captured by the rotating camera:

2.10 Coriolis effect(科里奥利效应)

What you are visualizing is called the Coriolis effect: in a rotating frame of reference, trajectories of an object are deviated as if a force were acting on the object. This force is called the Coriolis force, and is what is termed an "inertial" (or "fictitious", or "pseudo") force: it results purely from the change of coordinate system between an inertial frame of reference, where Newton's laws can be directly applied, and a rotating coordinate system.

Gustave Gaspard de Coriolis was, incidentally, a student (class of 1808) and then a professor at EcolePolytechnique. In 1835, he rigorously derived the equations describing the effect that now bears his name. The first intuitive mention of the Coriolis effect can however be found as early as in manuscripts from the 17th century, by Italian astronomers Riccioli and Grimaldi. The Coriolis force is written:

$$\overrightarrow{\boldsymbol{F_C}} = -2m\vec{\omega} \times \vec{V}$$

where $\vec{\omega}$ is the angular velocity vector of the frame of reference, with respect to an inertial frame; $\vec{V}$ is the speed of the object with respect to the rotating frame of reference; and m is the mass of the object.

Question 52. Is this formula consistent with your observations?

The formula is consistent with our observations. The angular velocity of the frame of reference, ie. the rotation rate of the turntable was observed to be proportional to the curvature of the path of the ball (which is proprotional to the force acting on the ball). Since we didn't use balls of different mass the effect of the mass on the force can't be deduced from this experiment; however, knowing that mass is proportional with an object's moment of inertia we can predict that a heavier ball would resist the motion more and hence would require a higher force to curve its path. The velocity of the ball was observed to be inversely proportional with the curvature of the path of the ball but the path was still curved which meant there was still a net force acting on it and hence the force had increased whicha agrees with the theory. Finally, the direction of rotation and force were observed to be in different directions in the experiment, ie. while we would expect the ball to be pulled to the right since the ground was moving towards the right it was being pulled towards the left which agreees with the minus sign at the start of the formula.

2.11 Coriolis effect on Earth.

The earth rotates on itself in one day.

Question 53. If you take a movie of yourself throwing a ball, with a camera which is fixed in the room, do you expect to see an effect on the trajectory such as the one seen with the bead on the turntable? Why or why not?

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

"No I wouldn't since I am not in a rotating fram of reference" would be my observation but in fact the earth is rotating around itself. The reason I wouldn't be able to tell is the ratio of the velocities. As mentioned before when the ball is considerably faster than the rotation rate the path observed by the human eye looks linear. So on this scale even if the effect still technically exists it would be negligible and unnoticable.

Question 54. What if you were to shoot a cannonball across the country?

As mentioned above the effect observed is dependent on the velocities and scale. In this case since the both the spacial and temporal scale is higher so a bigger portion of the earth over a longer period of time the coriolis effect wouldn't be negligible anymore and the cannonball's path would either curve towards the left or right depending on the direction it was thrown.

Notes : In the first setup we didn’t have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

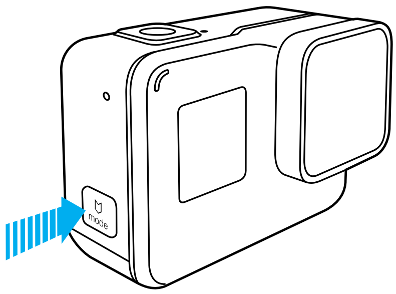
Technical Appendix

Filming, transferring data and trimming movies.

All trajectories will be filmed with one or two GoPro cameras. You will transfer the movies from the GoPro to your computer, and analyze your data with the software Tracker.

01. Filming with a GoPro

Turn your GoPro on by pressing the Mode button.



Mode button

To Power On:

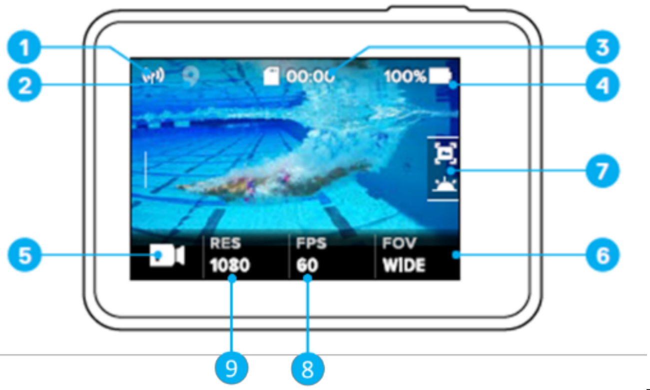
Press the **Mode** button [ ]. The camera beeps several times while the camera status lights flash. When information appears on the touch display or the camera status screen, your camera is on.

To Power Off:

Press and hold the **Mode** button for two seconds. The camera beeps several times while the camera status lights flash.

Make sure that your GoPro is set up to take movies at a rate of 240 frames per second (fps). The screen on the back of your GoPro should look like the one below.

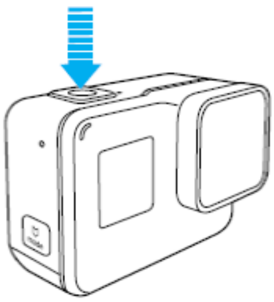
Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle



1. Wireless Status
2. GPS status
3. Time remaining/ Photo taken
4. Battery Status
5. Camera Mode
6. Settings
7. Advanced Settings (icons)
8. **FPS icon**
9. **Video Resolution**

If your camera is not set in Movie mode, tape the icon (5), and set the camera to Movie mode by tapping "Movie". Similarly, if the camera is not set to record at 240 fps, tape on the FPS icon (8), and select 240 by tapping it. Choose a resolution of 720p (1280*720) by tapping on icon (9).

To take a movie, first make sure the camera is on, and that you're in movie mode. Press the shutter button to start recording, and press the same button to stop recording.



Press the **Shutter** button

The camera beeps and the camera status light flash while the camera is capturing.

To stop capturing video or time lapse, press again the **Shutter** button. The camera beeps and the camera status lights flash quickly.

We strongly advise you to take movies as short as possible, and to record a single trajectory per movie. This procedure should greatly facilitate the data transfer to the computer, and increase the speed of the following data analysis.

Notes : In the first setup we didn’t have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

02. Positioning the camera

Attach the GoPro to the tripod. **Place the GoPro as parallel as possible to the launcher** – a spirit level is at your disposal – and at a distance such that the trajectory can entirely be seen on the movie. If necessary, mark the tripod footprints on the floor, to make sure that the tripod won’t move during your experiments.

03. Transferring the data

The fastest option to transfer your movies from the camera to the computer is to connect the camera to your computer using the USB cable. The cable should be long enough for the camera to remain on the tripod during the data transfer.

Open the directory "Computer/HERO 5 Black/GoPro MTP Client Disk Volume/DICM/", which contains all your movies. Drag and drop the movie files you want to analyze to your directory on the computer.

After having transferred the data, disconnect the USB cable to be able to record other movies.

04. Trimming your movies

The shorter your movies, the quicker they will be processed by the analysis softwares. To trim your movies:

- Open the software **Avidemux**.
- Open your movie by clicking on the folder icon in the upper left part of the screen, see Figure 1 below.
- Select the part of interest of your movie: drag the slider to the point that will be the beginning of your trimmed movie, and press the “A” button. Then drag the slider to what will be the end point of your movie, and click on “B”. Make sure that the time frames for “A” and “B” have changed in the lower right part of your screen (see Figure 1)
- Make sure that the output format is MP4 Muxer (see Figure 1).

Click on the floppy disk icon to save your movie.

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

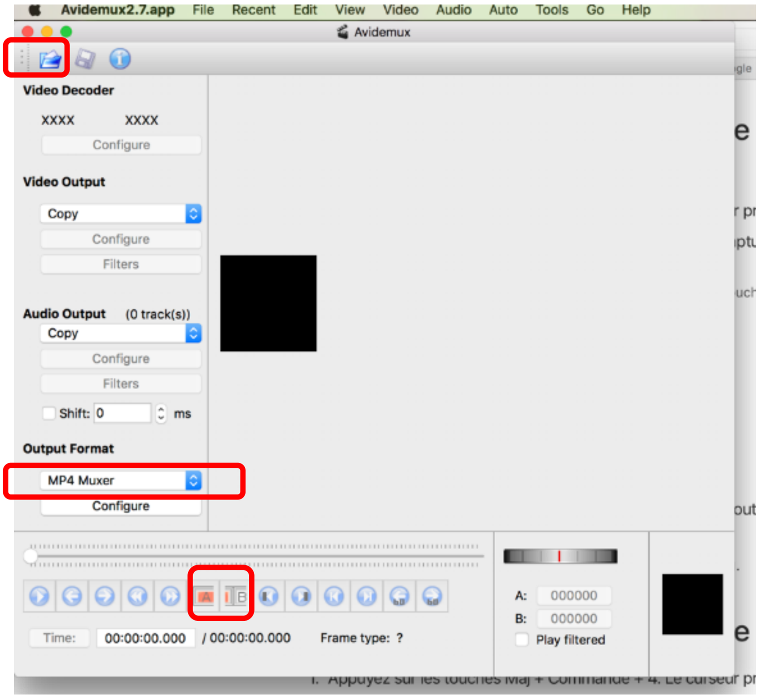


Figure 1: View of Avidemux

05. Showing and superimposing trajectories extracted from movies recorded with a gopro camera

There are several steps detailed to:

Convert Gopro movies from mp4 to avi (**05a**)

Open these avi movies with the software Image j (**05b**)

Show trajectories after selecting a limited region in space and time in your movie (**05c**),

Superimpose several trajectories using again Image j (**05d**).

- **05a. Convert Gopro movies from mp4 to avi (05a)**

We will use the software ffmpeg to convert the movie:

- press the **Windows key + R** to open the “Execute” window,
- type **cmd** then enter to open the command prompt,
- type on a single line the ffmpeg instruction below, first obviously adapting the path (C:\BACHELOR\yourgroupname\) and filenames (gopromovie.mp4 and convertedmovie.avi):

ffmpeg -i C:\BACHELOR\yourgroupname\gopromovie.mp4 -an -c:v mjpeg -q:v 3 -y C:\BACHELOR\yourgroupname\convertedmovie.avi

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

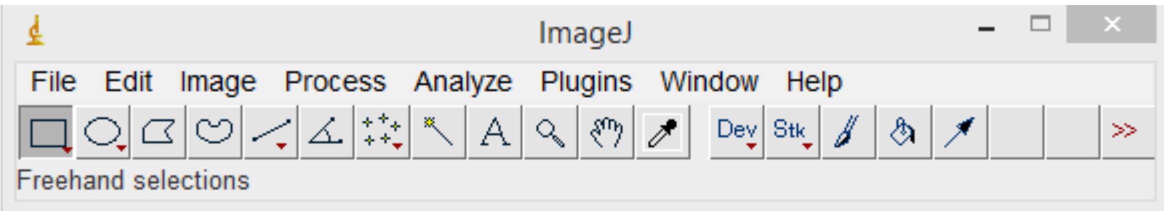
Tip: you can copy this line above (after adapting the name, then select and Ctrl-C), and paste it (right click and paste) to the cmd prompt to avoid any painful typing (but double check the spelling of you files).

Your conversion is over well-done! Now, a very strong suggestion: create a folder for your group on the computer, in the C:\BACHELOR\ folder, for instance: C:\BACHELOR\yourgroupname\

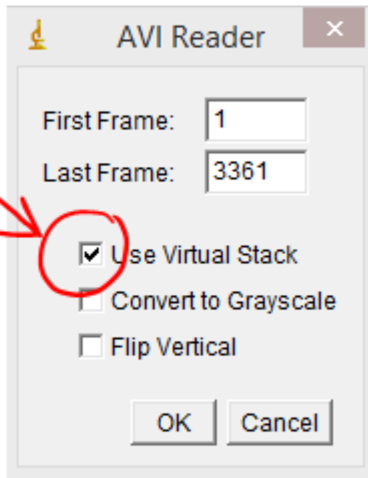
- **05b. Open these avi movies with the software Image j**

Image j is a light and free yet powerful image-processing software that you will use to: import the convertedmovie.avi movie, select a region of interest of a range of frames (to spare computer memory), superimpose video images in this range to show the trajectory, superimpose several trajectories if needed. Follow the instructions and everything show work out smoothly!

Open Image j (icon in the bar menu or on the desktop, or look for "imagej"), see image below.



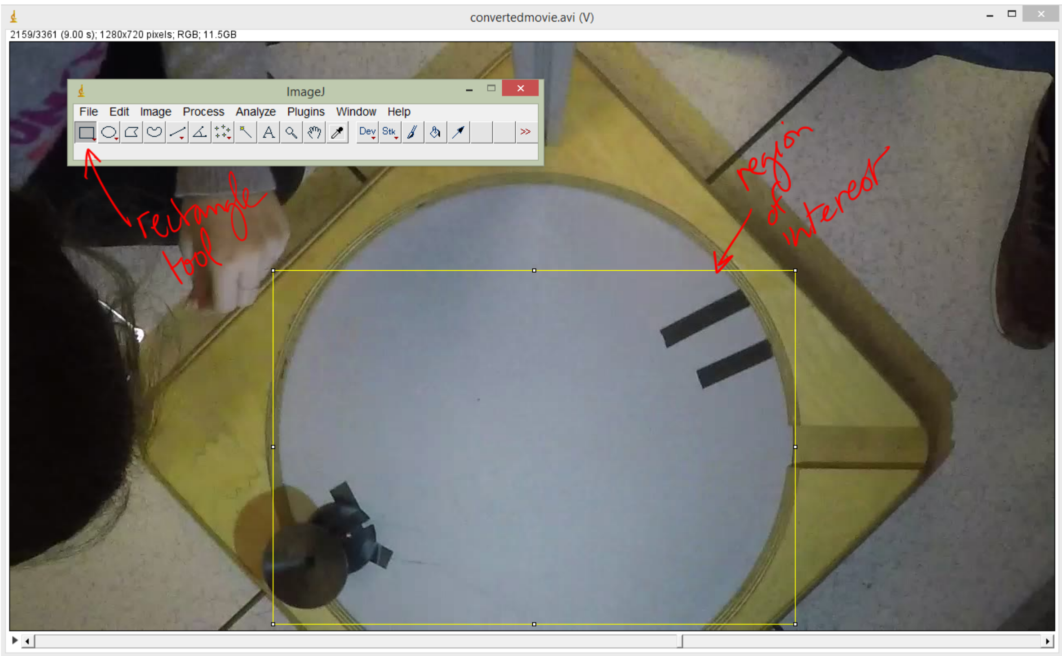
Import the converted avi movie by dragging the file on the Imagej window, which will open an AVI Reader window, **important: let the "Use Virtual Stack option" checked** (see image on the right).



Now you can choose on the open movie a start and end frame using the cursor (see image below).The starting frame should show the bead leaving the launcher, and the last frame should show the bead hitting the ground or target.

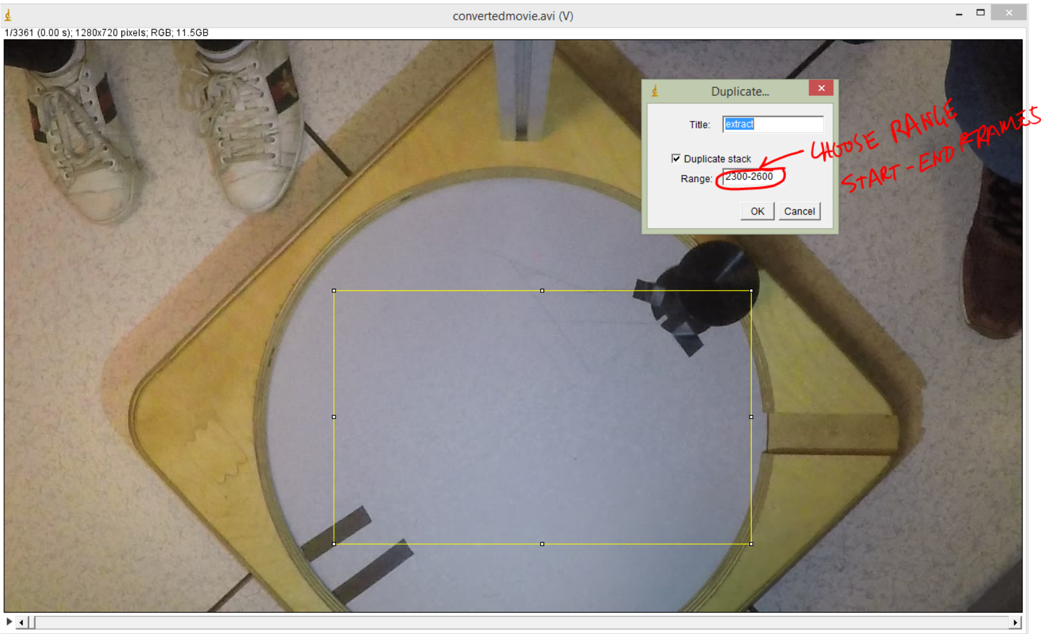
Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle

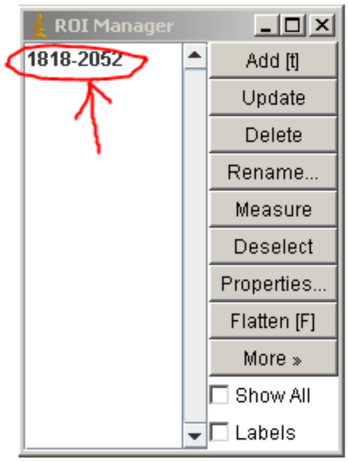
Chose a limited rectangle in your movie that will contain the trajectory, only it, to avoid processing useless part of the images. Choose the **rectangle selection tool** in the Image j window and select a region of interest in your movie (see image below).



Now **duplicate** this limited submovie typing **Ctrl+Shift+D,** then write the range of frames you want, Image j will duplicate only the rectangular region of interest over this range of frames (see image below).

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle





IMPORTANT TIP: you might want to use exactly the same rectangular region for all your movies, to precisely superimpose several trajectories. It is simple to do so in image j : once you set a rectangular section, type "t", which opens the ROI manager (see image on the right). Now when opening any other movie as explained before (as a virtual stack etc.), all you need to do is click on the (only) line in the ROI Manager (red arrow on the right) to plot exactly the same rectangle in the movie you just opened.

You now only have to do a projection of the whole movie on a single image using the command: **Image/Stacks/Z project**, use option **Min Intensity** (see image below), and voilà! You can save this projected image as a jpg with the instruction **File/Save As/Jpeg.**

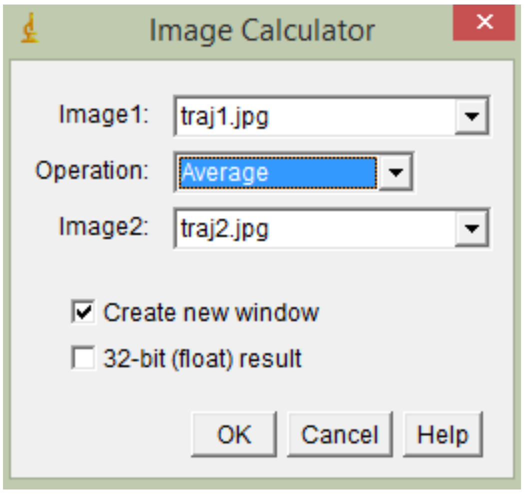
- **05c. Superimpose several trajectories on a single image.**

Let's say you want to superpose 3 trajectories, named traj1.jpg, traj2.jpg, and traj3.jpg.

Open the three files in Image j (drag and drop, or menu **File/Open**).

Run Imagej instruction **Process/Image Calculator**, then select two trajectories to superimpose, Operation "Average" should give a good aspect (see image below).

Notes : In the first setup we didn't have the squares to measure the distance and one of the protractor of the right arm was not fixed which caused problems with the measurement of the angle



You will get the averaged image with a name that might look like "Result of traj1.jpg".

Now **repeat the same operation** with files "Result of traj1.jpg" and "traj3.jpg" **to combine with the third trajectory.**

Iterate this process to combine as many trajectories as you want.

All set, don't forget to save your final superimposed image.