The Demonstration Laboratory

Freek Pols & Ron Haaksman

Contents

1. TU Delft DemoLab

1.1 About this book

This book started off as a collection of pdf's from the '90s. We realised this was a valuable but static and outdated archive. We envisioned an updated online and dynamic repository of physics demonstrations which is accessible to all. By utilizing GitHub we would enable others to contribute, allow them to offer suggestions, fix bugs, while maintaining version control and ensuring quality. Our ultimate goal was to create a 'living', 'ever-growing' repository where the quality of the demonstrations can be continuously enhanced through active contributions from fellow educators, see Figure 1.

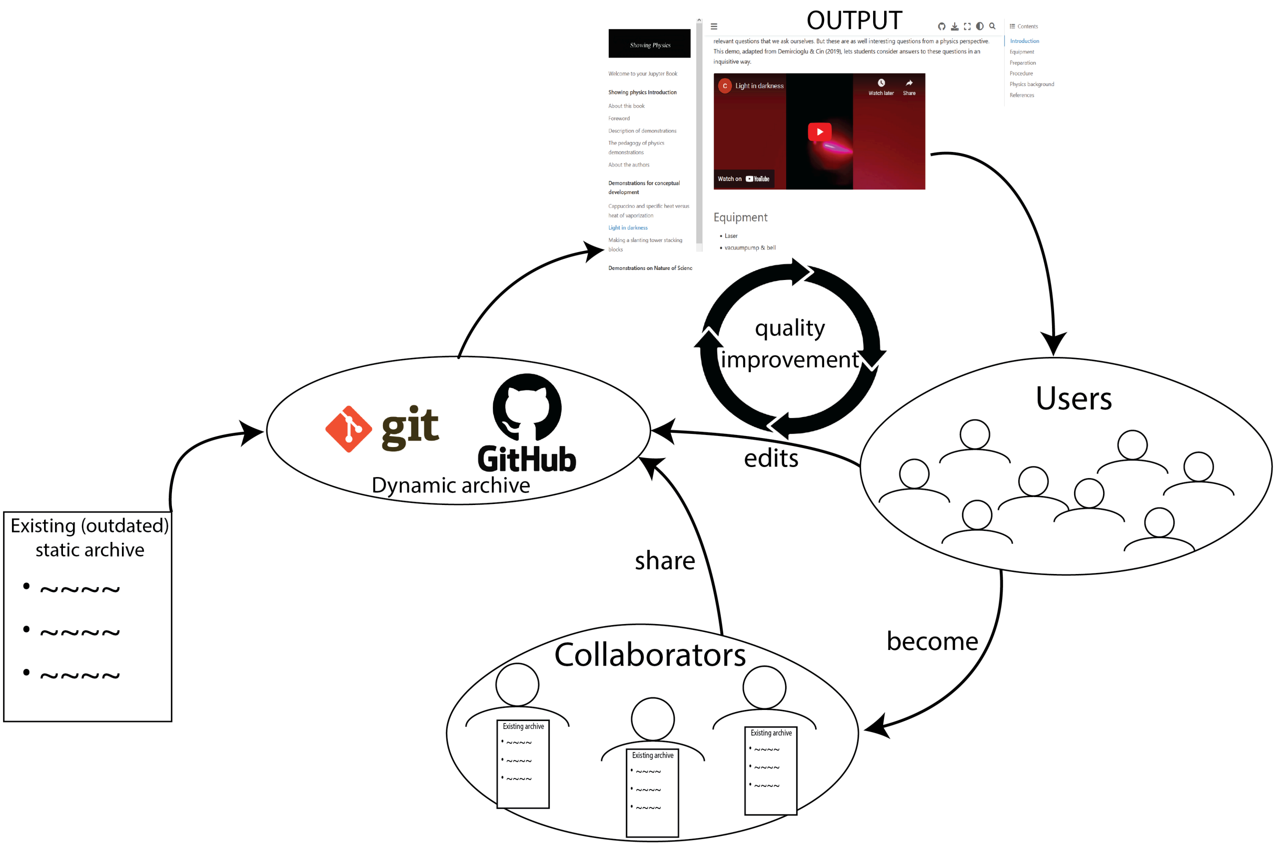

Figure 1.1: Our approach to creating a living, ever-growing repository.

Hence we set to work, converting the pdf's to markdown files (the work of Luuk Fröling) and creating a first Jupyter Book. All drawings were remade, resulting in high-quality vector drawings (the work of Hanna den Hertog). New pictures and video's were made (with the help of Tom Haanstra). Where possible, python codes where added, allowing for simulations and data analysis. This resulted in this book 'The Demonstration Laboratory'.

We consider the book not finished, as it is intended as an ever expanding repository. The book is an output of a dynamic repository. We can add and change demonstrations, improve the quality of descriptions, add code, and so on. You may contribute to this, and you will be recognized for it!

1.1.1 Your contribution

You can contribute to this book in various ways:

1. Enhance the quality by adding comments and/or suggestions using the feedback button button.
2. Add content

If you spot a typo, if something is not clear, or anything needs to be adjusted, click either the feedback button or the edit this page button at the top of the screen and open an issue. (You need to have a github account though). We then receive a notification of your query, and we will address the issue as soon as possible.

If you want to add your material, you can do so by contacting us. You can become a team member of the github repository and are allowed to add materials. If you are interested in how this works, see the teachbooks manual on the matter.

1.1.2 Editors

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1.1.3 Authors

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1.1.4 Contributors

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1.1.5 Licences

All drawings have been made by Hanna den Hartog. The videos were mainly recorded for the various courses at the Applied Physics and Nanobiology program at Delft University of Technology.

1.1.6 Contact

1.2 The Demonstration Laboratory

This source contains a collection of physics demonstrations tailored for university classroom lectures. The book is structured in accord with the so-called Physics Instructional Resource Association (PIRA).

Important

Please note that this resource is still work in progress. However, all documented demos have been copied from the previous website de-monstrare.nl into this resource. They are accessible in the form of a hyperlink to the previous website de-monstrare.nl. Our new demos will also include media content such as video recordings of the individual demos.

1.2.1 How we Work

We consider our ***Demonstration Room*** as a “shop” and we “sell” our demonstrations for free. We encourage professors to use our facilities and expertise. We need to encourage them because professors are not familiar with all the ideas available and they certainly have no time to investigate all the possibilities that exist.

1. we have many demos in stock
2. we know the physics
3. we know about didactics
4. we have theatrical experience
5. we have experience in designing demonstrations and conducting them
6. we know the literature and the ideas that are proposed worldwide and we keep up to date
7. we know what is commercially available

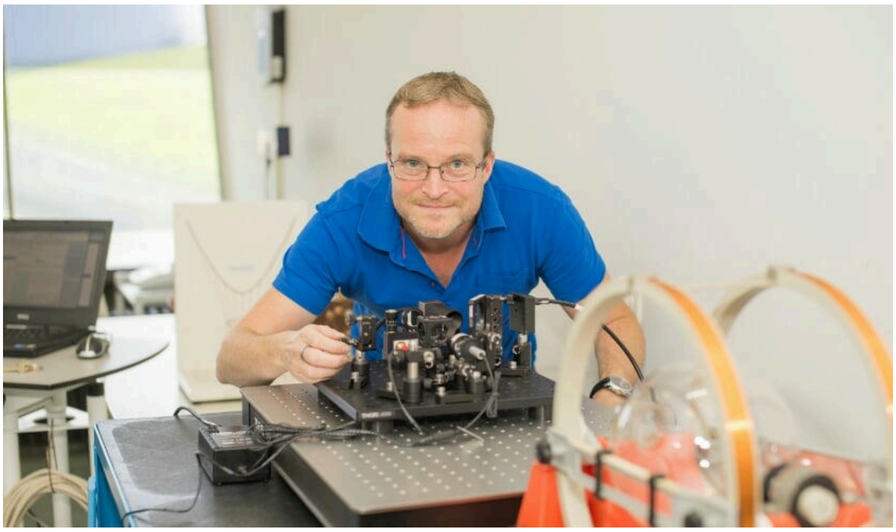


Figure 1.2: Ron Haaksman

1.2.2 How to Demonstrate

Note

In the matter of physics, the first lessons should contain nothing but what is experimental and interesting to see.

Albert Einstein

De monstrare = “Demonstrate”

“De” has the meaning of: intensification “monstrare” = to show

From the Latin version of this verb it can be seen that we aim to show phenomena in an intensified way. Ron is staff of the demonstration facility and his profession is to demonstrate.

We propose demonstrations to the professors and in consultation with them we select what will be shown. In developing, designing, and preparing the demonstrations we also make choices about how to show it effectively to our students. Finally we show the demonstrations during the lecture when it is the appropriate moment so it fits in with the matter taught during that lecture.

Currently (2025) we present around 300 demonstrations every year and this number is still increasing, because more professors see and experience the benefits of our services. Moreover also other faculties of our Technical University Delft and teachers from outside our university have found their way to our demonstration facility. Our Demonstration Room is a booming business!

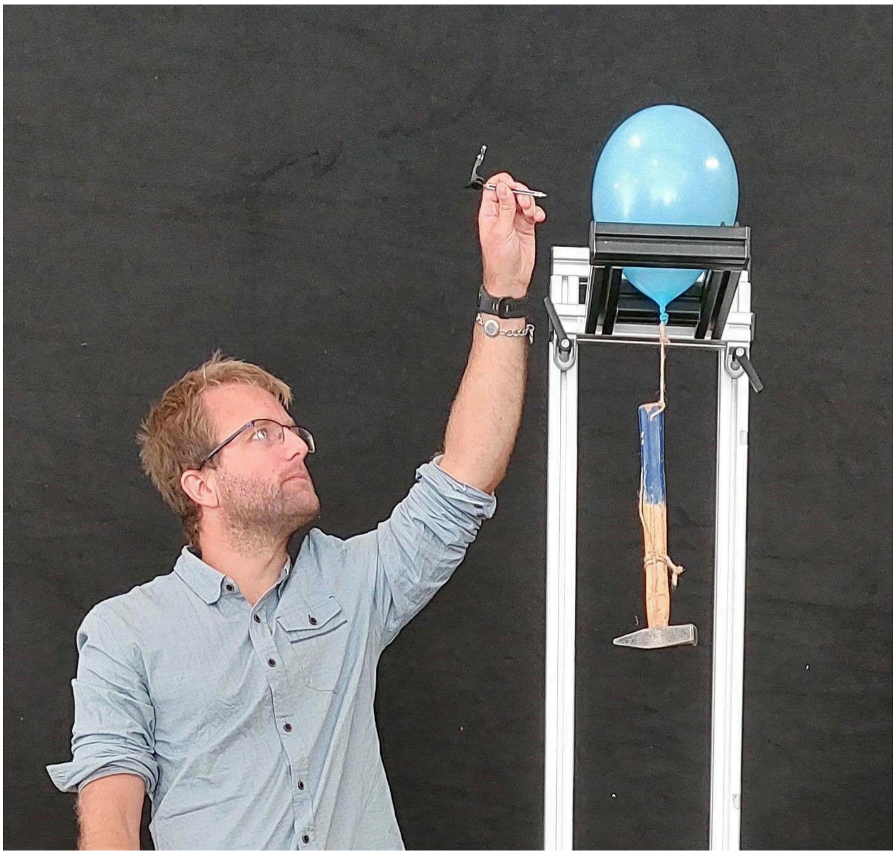


Figure 1.3: Freek Pols

1.2.3 Demonstrations

“How to demonstrate” means how to do it as effectively as possible and with “effective” we mean that students really learn from the presented demonstrations. Demonstrations are commonly believed to help students learn science and to stimulate their interest. The latter objective is generally achieved: studies show that demonstrations are among students’ favorite elements of a course. But research on the first objective also shows that traditional demonstrations do not effectively help students grasp the underlying scientific concepts or correct their misconceptions, while teachers often think the opposite. Here we refer to two studies:

- “Why may students fail to learn from demonstrations?” (Roth et al., 1997)
- “Classroom demonstrations: Learning tools or entertainment?” (Crouch et al., 2004)

These studies show that students who passively observe demonstrations understand the underlying concepts no better than students who do not see the demonstration at all! Learning is enhanced, however, by increasing student engagement. The key to an effective demonstration is interaction with the audience. Students who predict the demonstration outcome before seeing it, display significant greater understanding (Crouch et al., 2004).

Observe:

1. students observe the demonstration.
2. hear the instructor's explanation.

Predict:

1. students record their prediction (without discussion)
2. observe the demonstration.
3. hear the instructor's explanation.

Discuss:

1. students record their prediction (without discussion)
2. observe the demonstration.
3. discuss it with fellow students
4. hear the instructor's explanation.

At our department we apply the ***predict-method*** as much as possible. (The discuss-method requires too much time in our way of demonstrating). In the large lecture halls we question the prediction of the students before showing the demonstration. After a couple of minutes a multiple choice prediction is then presented to them. Then we show the demonstration and a short discussion follows.

1.2.4 References

2. Mechanics

2.1 Measurement

2.1.1 1A20 Error and Accuracy

2.1.1.1 01 Hooke's Law

2.1.1.1.1 Aim

This demonstration shows Hooke's law. However, the focus is on taking measurements, measurement uncertainty and how to interpret the results.

2.1.1.1.2 Subjects

- 1A20 (Error and Accuracy)
- 1R10 (Hooke's Law)

2.1.1.1.3 Diagram

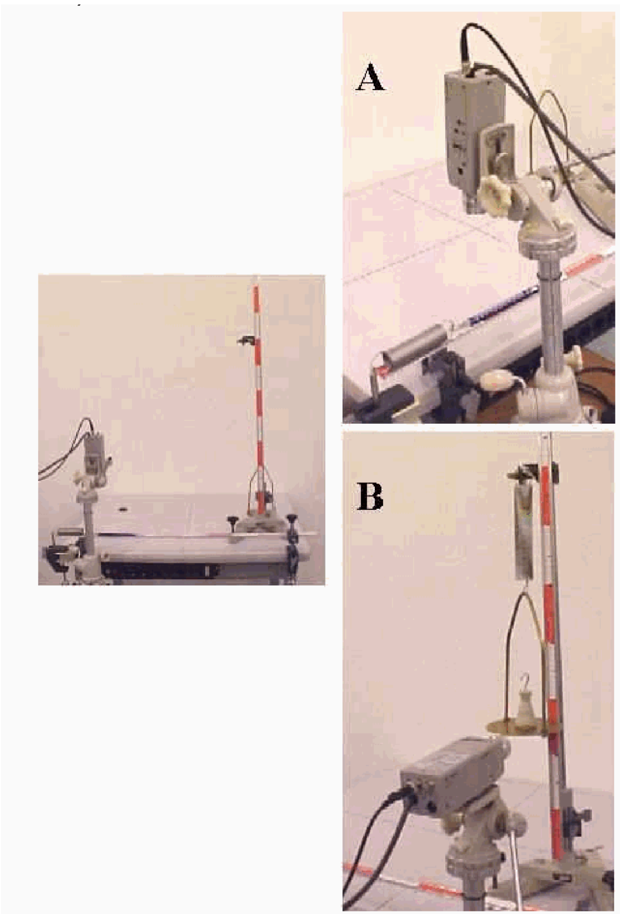


Figure 2.1: .

2.1.1.1.4 Equipment

- Spring $(k = 50N/m)$ with pre-stress $(2.5N)$.
- Two rulers.
- Spring balance, 10N.
- Scale to be attached to spring balance (heavier than 250g).
- Mass: 200.0g.
- Video-camera.
- Beamer to project camera image.

2.1.1.1.5 Presentation

One ruler is placed horizontal. The spring is fixed to the ruler and can slide along when it is pulled by the spring balance (see Diagram A). The camera is positioned in such way that the position of the spring on the ruler and the force indicated by the spring balance are recorded: all students ought to be able to read the results.

The second ruler stands vertical. The spring, with the scale fixed to it, hangs close to the ruler (see Diagram B). The camera records the position of the spring on the ruler.

We start with the horizontal arrangement. First, the equilibrium position ($F = 0N$) is read. Then the spring is given a displacement (x) of $5.0cm$ from its equilibrium. The corresponding force is read and the spring constant (k) is calculated: $k = \frac{F}{x}$. In our case, we find: $x = 5.0cm; F = 5.7N$; so $k = 114N/m$. Its associated uncertainty (u) is calculated:

$$\left(\frac{u(k)}{k}\right)^2 = \left(\frac{u(x)}{x}\right)^2 + \left(\frac{u(F)}{F}\right)^2 \tag{2.1}$$

We find: $u(x) = 0.1cm; u(F) = .1N$; so $u(k) = 3N/m$.

The spring and scale are now fixed next to the vertical ruler. The camera is turned horizontally and records the position of the spring. First, the equilibrium position (h_0) is read. Then the mass of $200.0\ g$ is placed on the scale. The displacement of the spring (h_m) is read and the spring constant (k) is calculated: $k = \frac{mg}{\mid h_m - h_o \mid}$. We find: $h_0 = 35.6cm; h_m = 38.8cm$; using $g = 9.812$; so $k = 61.3N/m$. Also the uncertainty (u) is calculated:

$$\left(\frac{u(k)}{k}\right)^2 = \left(\frac{u(m)}{m}\right)^2 + \left(\frac{u(g)}{g}\right)^2 + \left(\frac{u(v)}{v}\right)^2 \tag{2.2}$$

in which $u(v)$ is determined by $v = \mid h_o - h_m \mid$ and $u(v)^2 = u(h_o)^2 + u(h_m)^2$. We find: $u(\text{ m}) = 0.1\ g; u(h_o) = u(h_m) = 0.1cm; u(g) = 0.001\ m/s^2$; so $u(k) = 3N/m$. Terms with m and g are negligible in $u(k)$.

The two results are not in good agreement: the difference between the two calculated k-values is larger than two times the uncertainty ($\mid k_1 - k_2 \mid > 2\sqrt{u_{k_1}^2 + u_{k_2}^2}$). The students are asked to discuss the possible cause of these conflicting results. After some time the word “pre-stress” appears in the student group.

2.1.1.1.6 Explanation

The spring is pre-stressed $\left(F_p\right)$, so $k = \frac{F - F_p}{x} \cdot k$ is not proportional with F, there is only linearity between k and F. More measurements ($F = F(x)$) and making a graph will produce significant values.

In our case we find $F_p = 2.66N$ with $u(F) = 0.08N$ and $k = 56.7N/m$ with $u(k) = 1.3N/m$.

2.1.1.1.7 Remarks

- This demonstration is shown in our Introductory Laboratory Course.
- The first reading of $x = 5.0cm$ also has two error margins, so $u(x)$ is actually higher ($u(x)^2 = 0.02$), and ($u(k) = 5N/m$).

2.1.1.2 02 Determining g, with precision

2.1.1.2.1 Aim

This demonstration from ShowthePhysics (Pols, 2024) introduces students to the ideas of measurement uncertainty.

2.1.1.2.2 Subjects

- 1A20 (Error and Accuracy)

2.1.1.2.3 Diagram

Figure 2.2: .

2.1.1.2.4 Equipment

- Balloon
- Long ruler
- Phone with Phyphox app
- Hammer
- Rope
- Ladder
- Awl
- Tall tripod

2.1.1.2.5 Presentation

Inflate the balloon and hang the hammer from it with a string. Hang the whole setup on the framework and ensure the wooden plank is directly beneath the hammer. Use the acoustic chronometer in the Phyphox app with a threshold value of 0.35 and a delay of $\sim$0.3 s.

Start the demonstration by discussing what an accurate measurement entails and why an accurate value can be important. Explain the experiment: Using a single measurement and the equation, we will determine the gravitational acceleration g as accurately as possible. Popping the balloon starts the acoustic chronometer, and the hammer's BANG on the ground stops the timer.

- Is it necessary for a good measurement to have the largest or smallest possible falling height? Are there any conditions on the extreme values you choose?
- Where should you hold the phone? At the top, bottom, middle, or does it not matter? Why?
- How accurately do we measure the time and height?

Have students brainstorm answers to the questions in pairs, write down the answers, and then invite students to share their answers (think, pair, share).

After measuring the falling height (with an estimate for the uncertainty) and determining the fall time, you can start a discussion about the uncertainty in the time measurement. Is it 1.0 s, 0.1 s, 0.01 s, or 0.001 s? Or is it something in between?

Normally, you determine the uncertainty in time by repeating the experiment, but what numbers do you expect to see when you repeat the measurement? Or said differently: Which decimal digit will likely vary?

By using the code provided below, you can calculate the final value of g with its associated uncertainty. Click the rocket at the top of the page to make the Python code cell active.

```python
# Import libraries
import numpy as np

# Record your measurements here. H in cm, dt in s.
H = /100        #measured height  in cm
u_H = /100      #the estimated uncertainty in the height
dt =            #measured fall time in s (using phyphox)
u_dt =          #the estimated uncertainty in the fall time

# Function for determining the acceleration due to gravity
def g(H,dt):
    return 2*H/dt**2

print('In this experiment, g is determined to be: ', g(H,dt))
```

```
err_in_g = np.sqrt((u_H/H)**2+4*(u_dt/dt)**2)*g(H,dt)

print('In this experiment, g is determined to be: %.1f +/- %.1f m/s^2' %(g(H,dt),
err_in_g))
```

2.1.1.2.6 Explanation

Every measurement can only be performed with a certain precision. Sometimes the precision is determined by the equipment, and sometimes by the measured property. In science, the answer is always given with the associated uncertainty, where the chance that a repeated measurement falls within the value with its associated uncertainty is equal to 68% ($P(\bar{x} - \mu_x < x < \bar{x} + \mu_x) = 0.68$). When multiple quantities influence the uncertainty, as in the determination of the acceleration due to gravity, each measurement contributes to the uncertainty. The final value of the uncertainty in this equation is given by:

$$\left(\frac{\mu_g}{g}\right)^2 = \left(\frac{\mu_H}{H}\right)^2 + 4\left(\frac{\mu_{\Delta t}}{\Delta t}\right)^2 \tag{2.3}$$

The uncertainty is always given with only one significant figure. The final answer is presented with the same decimal digit (e.g., $9.8 \pm 0.3 m/s^2$).

2.1.1.2.7 Remarks

- This demonstration is shown in our Introductory Laboratory Course.

2.1.2 1A40 Vectors

2.1.2.1 01 Cross Product

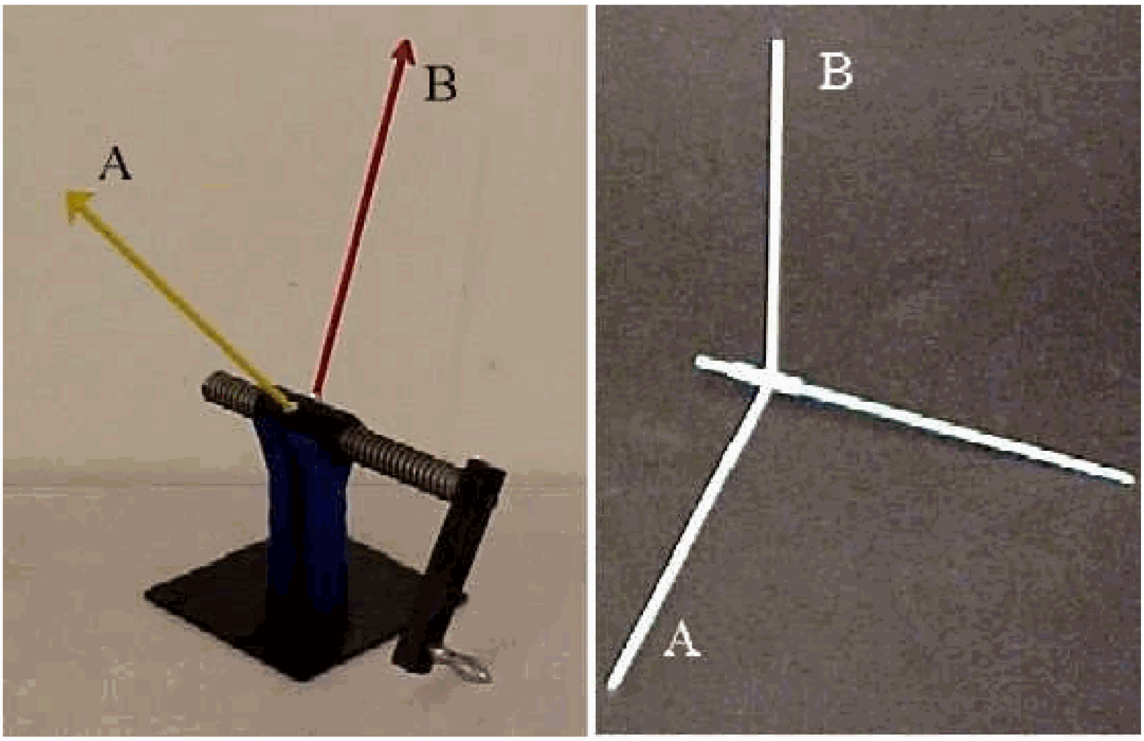
2.1.2.1.1 Aim

To visualize the result of a cross product of two vectors.

2.1.2.1.2 Subjects

- 1A40 (Vectors)
- 1E30 (Coriolis Effect)

2.1.2.1.3 Diagram



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2.1.2.1.4 Equipment

- Screw model.
- Right-hand rule model.

2.1.2.1.5 Presentation

- Rotate the screw into the direction $A \to B$. The screw moves into the direction of the result of the cross product of these two vectors. Rotating the screw in the opposite direction shows that the cross product vector points in the other direction.
- The small white model is used in case of explaining Coriolis force in combination with a globe (see Figure 2).

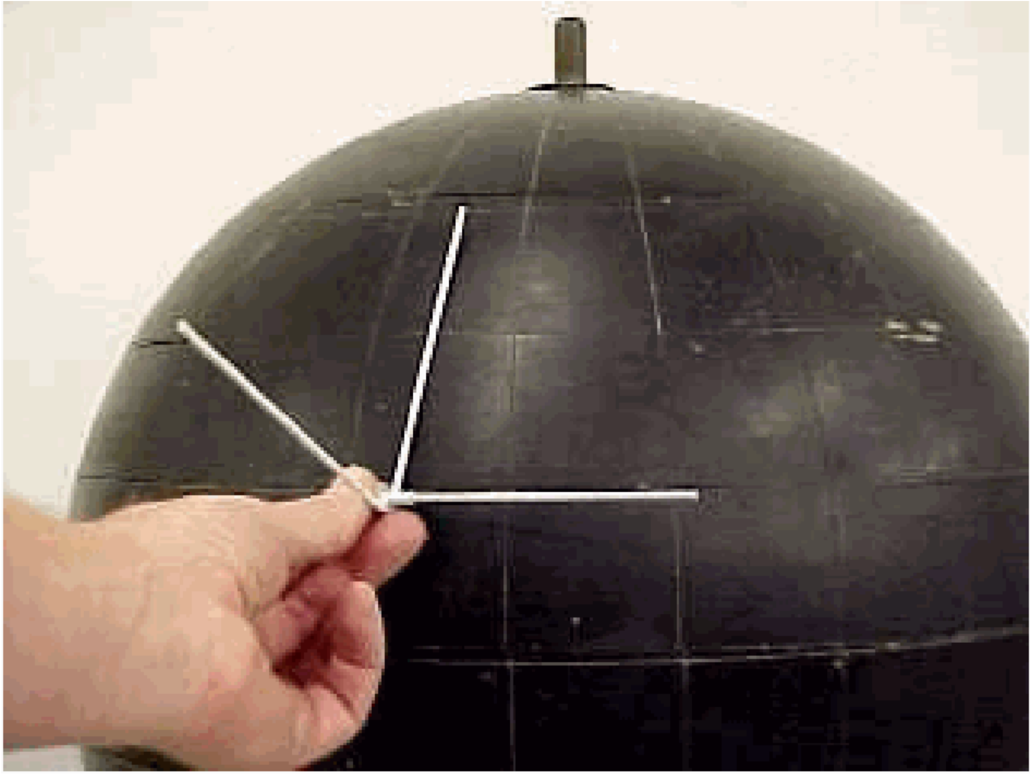


Figure 2.4: .

- This model is a handy tool; otherwise, the professor ends up twisting their fingers in all sorts of directions trying to visualise the right-hand rule. In this small model, the resulting vector of the cross product can point one way or another by shifting it through the small tube that is soldered to the fixed vectors A and B.

2.1.2.1.6 Remarks

- For more on dot- and cross products, see the work of our colleagues.

2.1.2.1.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 183 and 733

2.2 1D motion in two dimensions

2.2.1 1D40 Center of Mass

2.2.1.1 01 Centre of Mass

2.2.1.1.1 Aim
To show that the centre of mass does not change when only internal forces act.

2.2.1.1.2 Subjects
- 1D40 (Motion of the Centre of Mass)

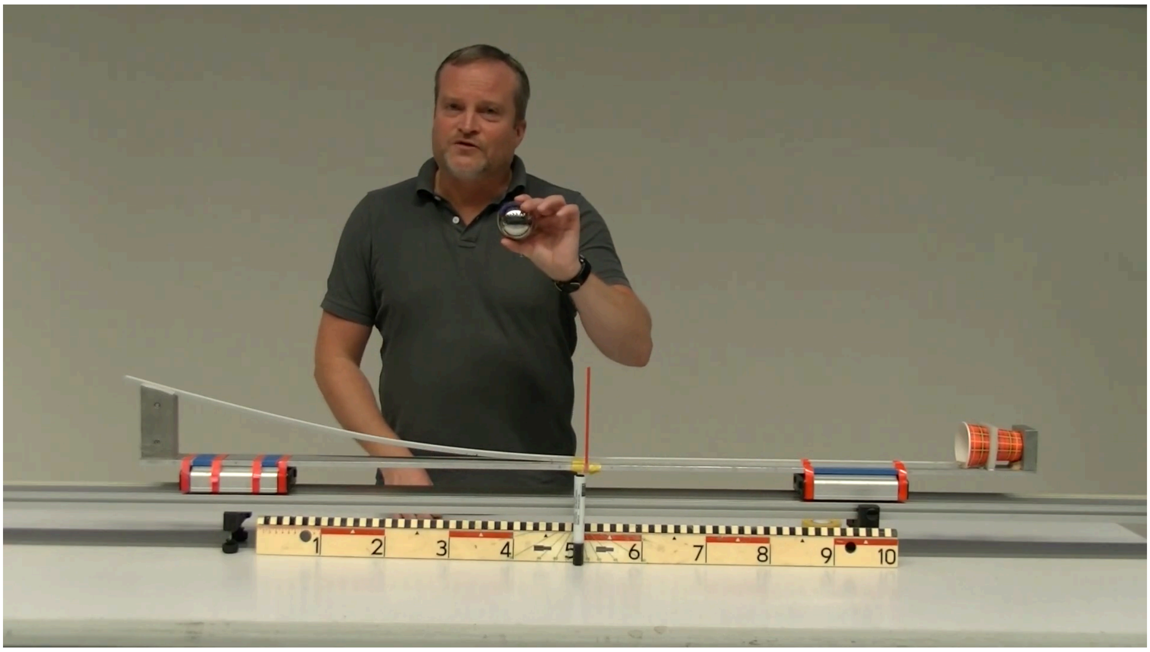
2.2.1.1.3 Diagram


Figure 2.5: Diagram of the experimental set-up

2.2.1.1.4 Equipment
- Track (2.2m, PASCO ME-9452), levelled.
- Two carts (PASCO ME-9454).
- Bent rail track on frame, with “ball catcher” (plastic coffee cup) and a pointer fixed to it (see Figure 1). The bent rail track is fixed firmly to the two carts. Ensure that the two carts are neatly aligned.
- Steel ball ($m = 1$ kg).
- Graduated ruler, $l = 1$ m.
- Small wooden beam.
- Balance or scale with a large display.

2.2.1.1.5 Safety
- Ensure that the heavy steel ball is not dropped on the floor (or your feet).

2.2.1.1.6 Presentation
The Diagram is shown to the students. Then the mass of the cart-assembly is measured by the balance (4 kg) and also that of the steel ball (1 kg). Next, the centre of mass of the cart-assembly is determined by balancing this assembly on the small wooden beam. Then the assembly is set at rest in the middle of the levelled cart-track, and the pointer is fixed to the assembly in its centre

of mass. Furthermore, this pointer position is marked on the table by placing a piece of chalk upright.

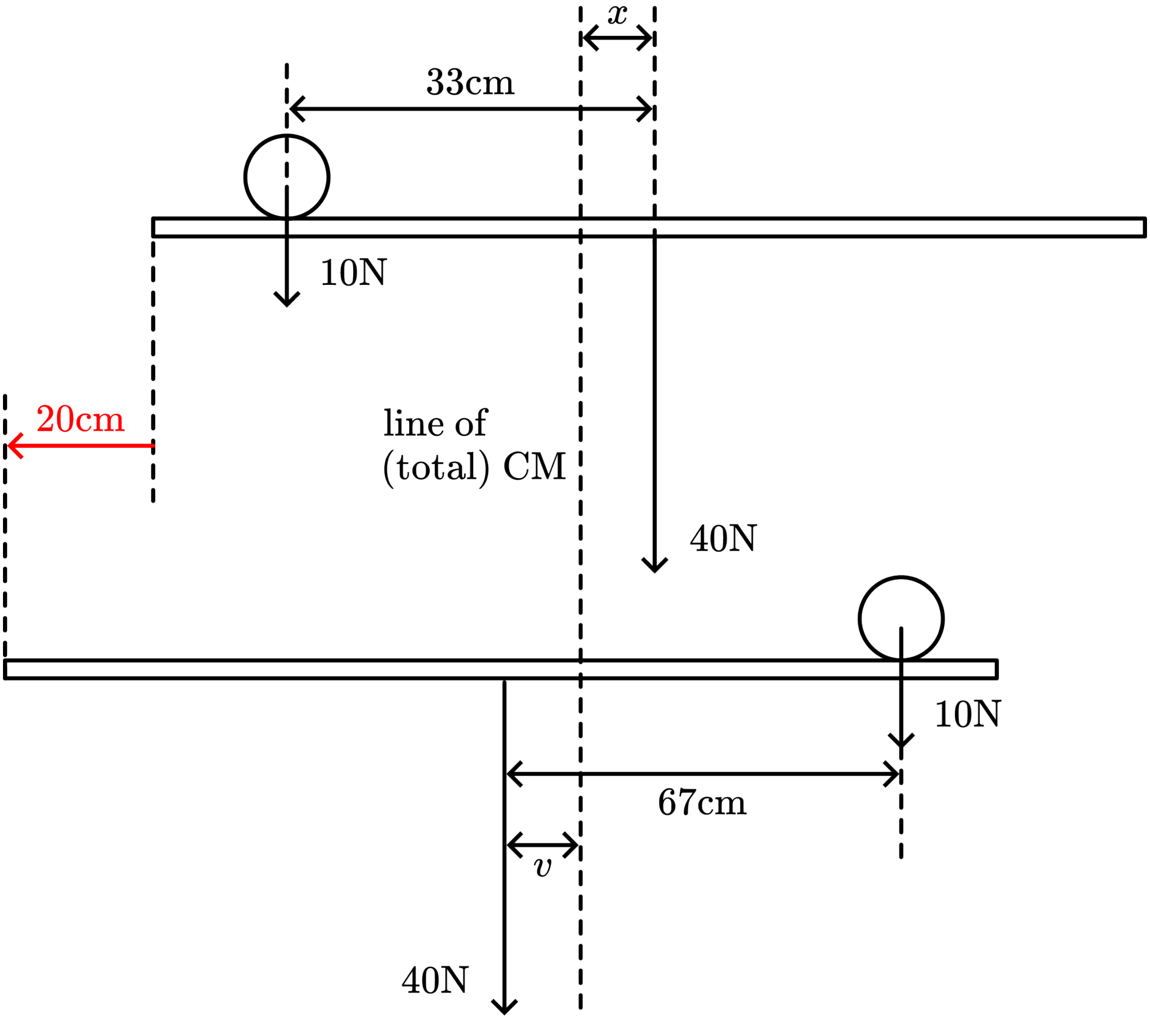


Figure 2.6: Schematic representation of the experimental setup

The steel ball is placed at the slope of the bent track. We place it about 33 cm away from the point of reference on the assembly. With our other hand, we hold the cart assembly in its resting position. The ball is released and rolls down the track. The whole assembly is moving, and the steel ball is captured in the plastic coffee cup (a small piece of modelling clay at the low side at the entrance of the cup takes care that the steel ball remains in the cup). This plastic cup is 67 cm away from the centre of mass of the cart-assembly.

When the ball is caught, the whole assembly is immediately at rest. However, the whole assembly is shifted (about) 20 cm to the side where the ball came from (see the pictures in the diagram, where the actual displacement is larger due to the higher starting point of the steel ball).

2.2.1.1.6.1 Explanation

Our steel ball has a mass of 1 kg. The cart-assembly (with carts, track, and cup, etc.) has a mass of 4 kg. With our starting position at 33 cm away from the point of reference, this gives a sketch of the situation as shown in the first picture of Figure 2.

Calculating the distances x and y gives the displacement of the cart-assembly: With m being the mass of the steel ball and $4m$ the mass of the cart-assembly, the centre of mass is at the position indicated by the dotted line, because by definition the centre of mass is positioned at $R = \frac{m_1 r_1 + m_2 r_2}{m_1 + m_2}$, relative to some origin. When that origin is taken at the dotted line, so $R = 0$, we have: $R = \frac{1(x-.33)+4(x)}{1+4} = 0$, making $x = 6.6$ cm. When the steel ball is released, no external forces act upon it, meaning that the centre of mass will not move. The bottom picture in Figure 2 shows the situation at the end and the displacement of the steel ball and cart-assembly.

Calculating again the position of the centre of mass in the same way

$$R = \frac{1(.67 - y) - 4(y)}{1 + 4} = 0 \tag{2.4}$$

yielding $y = 13.5$ cm. So the total displacement of the assembly equals $6.6 + 13.5 = 20.1$ cm. This is confirmed in our demonstration.

2.2.1.1.7 Remarks

- Take care that when you release the steel ball, you impart no horizontal momentum to the track. Practice before performing!
- In our demonstration, the reference pointer is fixed at the centre of mass of the track assembly, but this point of reference can be situated at any other position. Our choice makes calculations easy.
- When the ball hits the cup, the whole assembly should come to a full stop. But very often the assembly moves back just a little. This is caused by the friction of the carts on the track: the direction of that friction force is opposite to the displacement of the assembly. The effect of this external force becomes visible when the ball comes to a rest in the cup.

2.2.1.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 128-130.
- McComb,W.D., Dynamics and Relativity, pag. 103-105.

2.2.1.2 02 Centre of Rotation

2.2.1.2.1 Aim

To show that a free rotating body rotates around its centre of mass.

2.2.1.2.2 Subjects

- 1D40 (Motion of the Center of Mass)
- 1Q60 (Rotational Stability)

2.2.1.2.3 Diagram

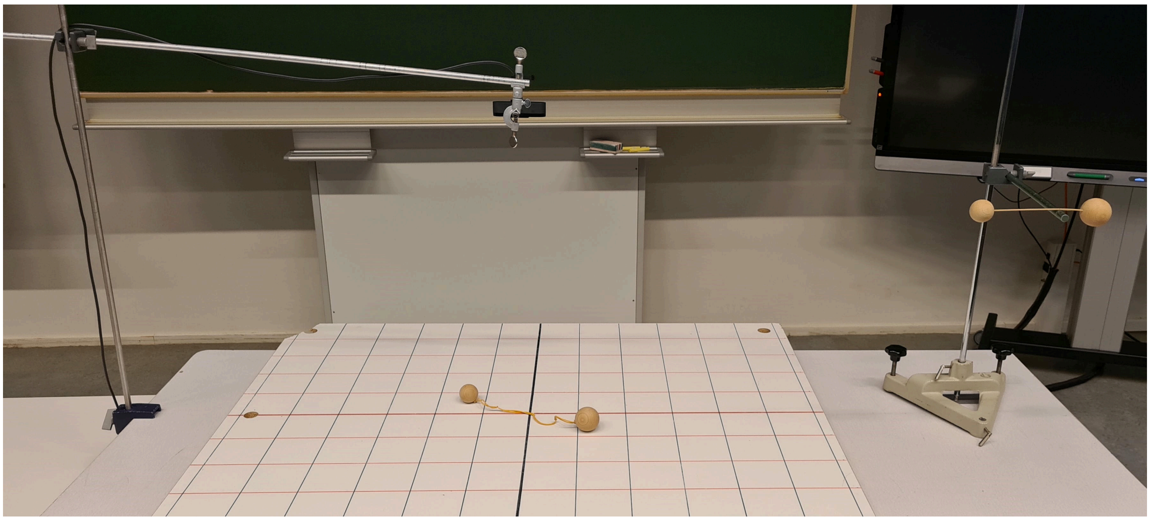


Figure 2.7: .

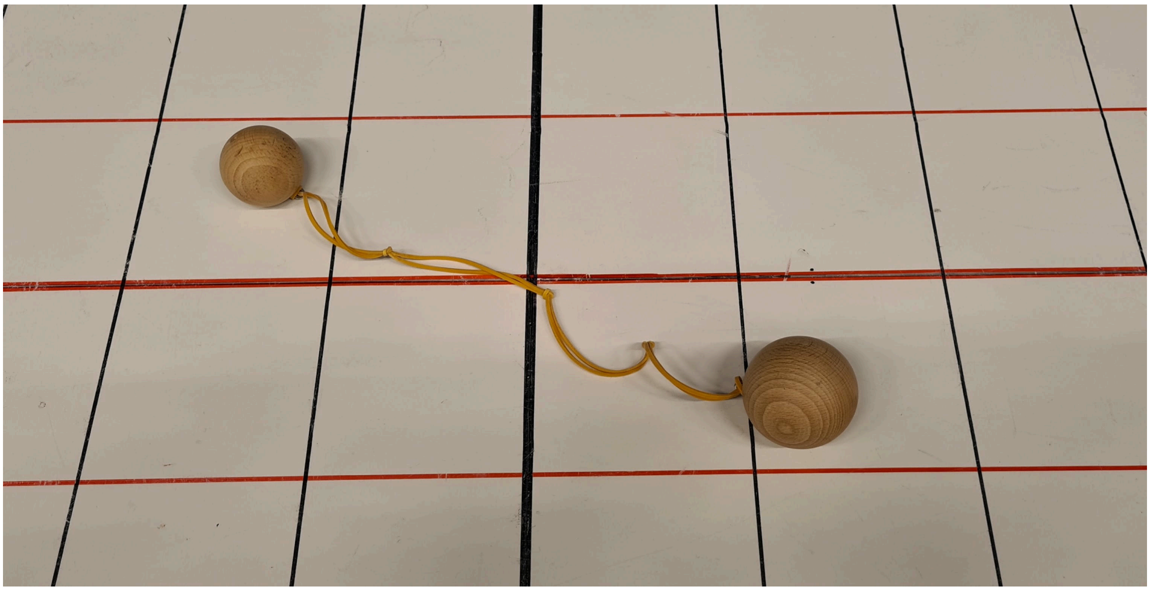


Figure 2.8: .

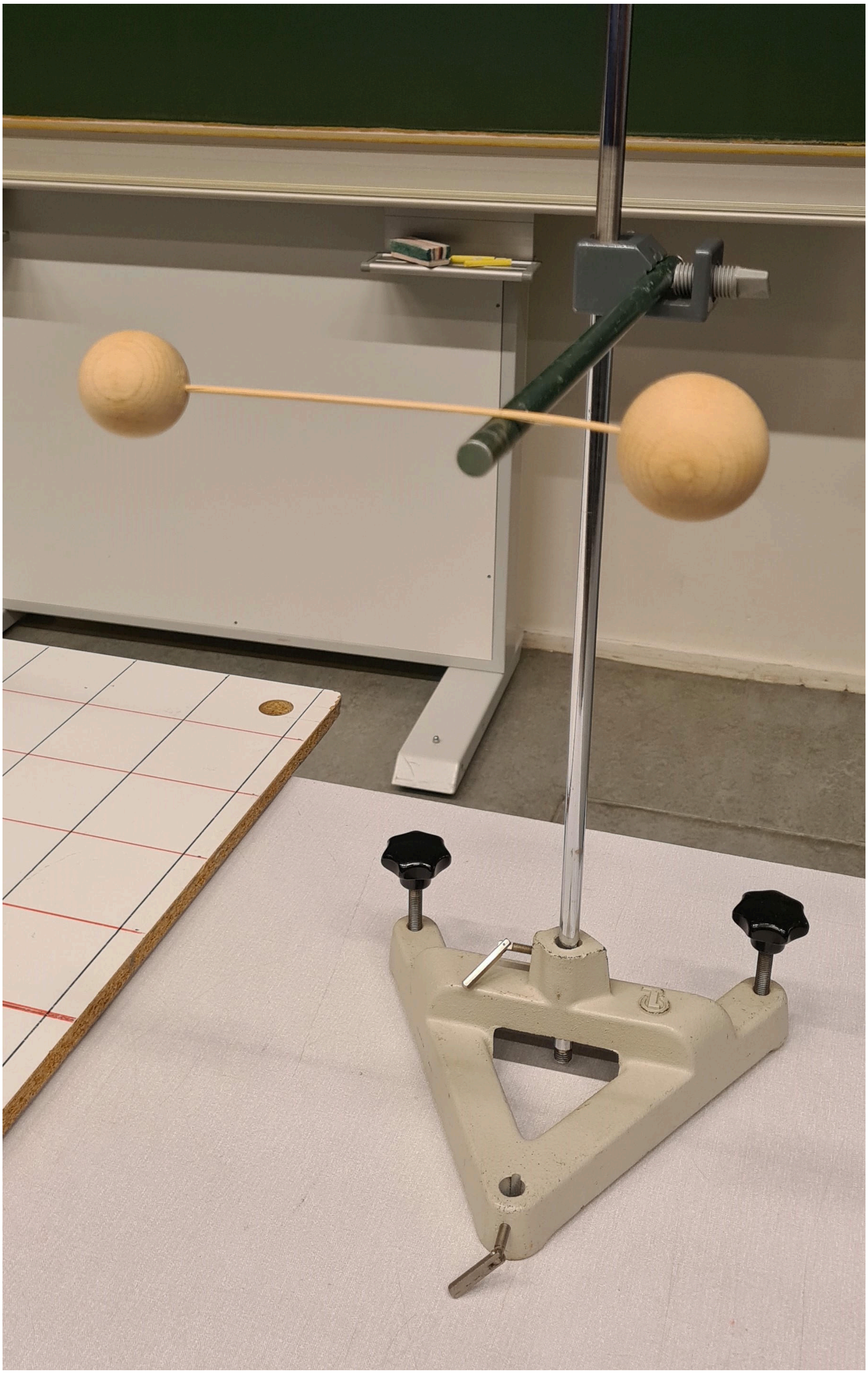


Figure 2.9: .

2.2.1.2.4 Equipment

- Two different wooden spheres ($d_1 = 5$ cm and $d_2 = 4$ cm), connected by a light stick.
- Two different wooden spheres ($d_1 = 5$ cm and $d_2 = 4$ cm), connected by a rubber band (length unwound around 50 cm).
- Board with square grid ($10 \times 10\ cm^2$).
- Video camera on tripod.

- Projector to project image of square grid to the audience.

2.2.1.2.5 Presentation

The two spheres, connected by a light stick, are balanced (see Figure 1) to show where the centre of mass (CM) is located. The location of the CM divides the distance (d) between the two centres of the spheres in roughly $\frac{1}{3}d$ and $\frac{2}{3}d$.

The system of two spheres connected by a twisted rubber band (see Figure 1 and Remarks) is placed on the gridboard, and then left by itself. The system begins to rotate as the twisted rubber band unwinds. The system rotates around a fixed point. This can be recognized as the CM. This can be related to the first part of the demonstration. Note that during the rotation, the distance between the spheres increases, but its centre of rotation keeps the ratio $\frac{1}{3} : \frac{2}{3}$!

2.2.1.2.6 Explanation

As no external forces are acting, the CM has to remain at its position on the board according to Newton's first law. (Note: When the system rotates around any other point but the CM, the CM performs a rotation, and an external torque should be needed for that.)

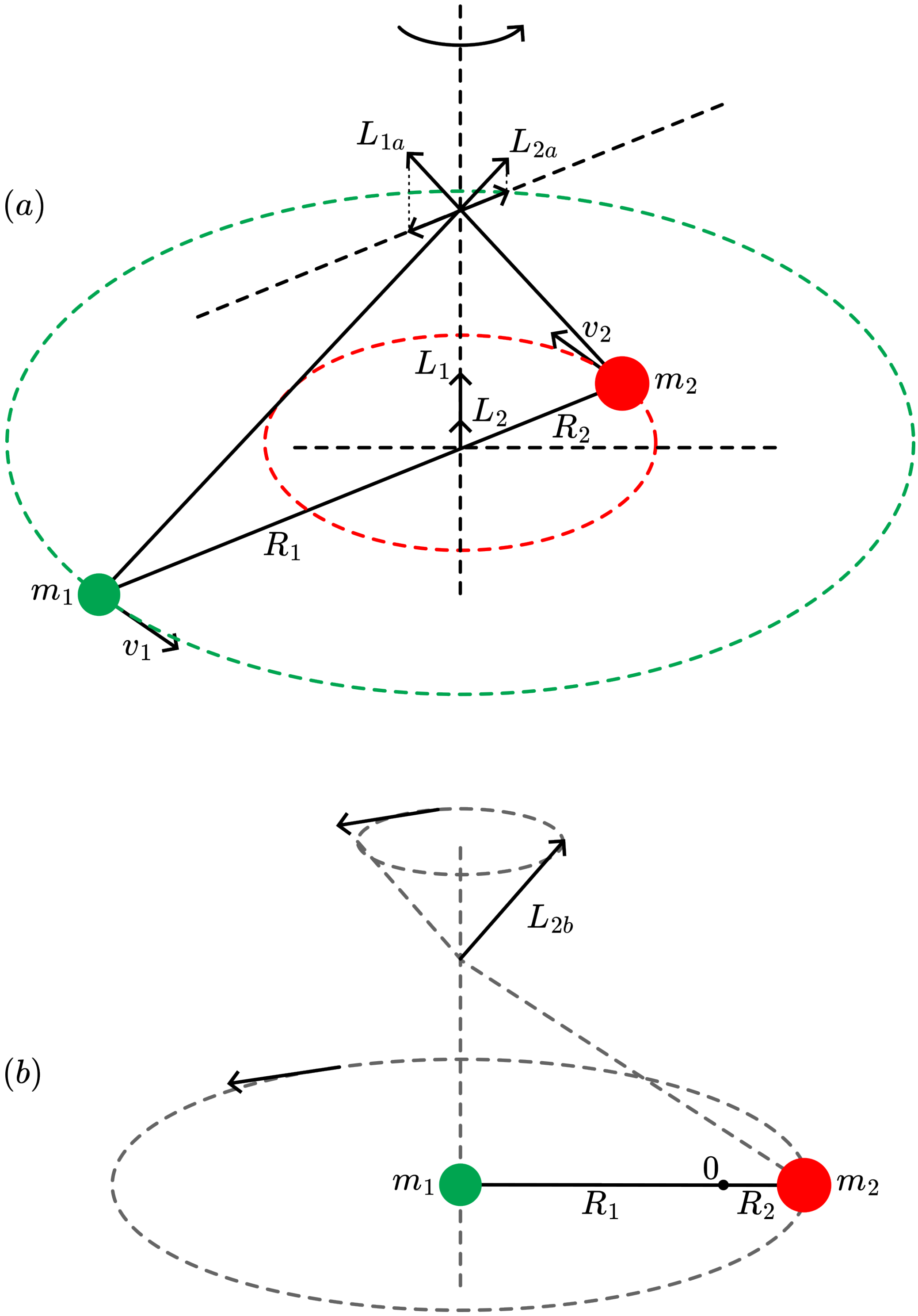


Figure 2.10: .

The body rotates around an axis perpendicular to d. When no external forces are acting, the angular momentum vector $\vec{L}$ remains constant. The body in our demonstration consists of two masses: m_1 and m_2 (see Figure 4a).

$$\begin{aligned}\vec{L} &= \vec{L}_1 + \vec{L}_2 \\ \vec{L} &= \vec{R}_1 \times m_1\vec{v}_1 + \vec{R}_2 \times m_2\vec{v}_2\end{aligned} \tag{2.5}$$

The axis of rotation characterizes itself by the fact that, at any position on this axis, $\vec{L}$ will have the same magnitude and direction (at O' the horizontal components of L_{1a} and L_{2a} cancel, and their vertical components add up to $\vec{L}$: see Sources). This means that only one axis of rotation is possible. When, for instance, an axis of rotation is chosen passing through the centre of m_1, then the total angular momentum adds up to L_{2b} (see Figure 4 b). And so, being constant in magnitude, its direction constantly changes (describing a cone). Such a situation needs an external torque.

In our demonstration, there is no external torque, and the sphere-system rotates around an axis somewhere between the two spheres (Figure 5). At O, $\vec{L} = \vec{R}_1 \times m_1\vec{v}_1 + \vec{R}_2 \times m_2\vec{v}_2$, directed along the axis of rotation. At O', the horizontal components of L_1 and L_2 need to cancel in order to keep L along the axis of rotation.

$$| \vec{L}_1 | = \frac{R_1 m_1 v_1}{\cos\alpha} \tag{2.6}$$

$$L_{1h} = \frac{R_1 m_1 v_1}{\cos\alpha}\sin\alpha = R_1 m_1 v_1 \tan\alpha = m_1 v_1 y \tag{2.7}$$

In the same way:

$$L_{2h} = m_2 v_2 y, v = \omega R, so L_{1h} = m_1 \omega R_1 y L_{1h} = m_1 \omega R_1 y \tag{2.8}$$

and

$$L_{2h} = m_2 \omega R_2 y L_{2h} = m_2 \omega R_2 y \tag{2.9}$$

These two are equal when $m_1 R_1 = m_2 R_2$, this holds when the axis of rotation passes through the CM.

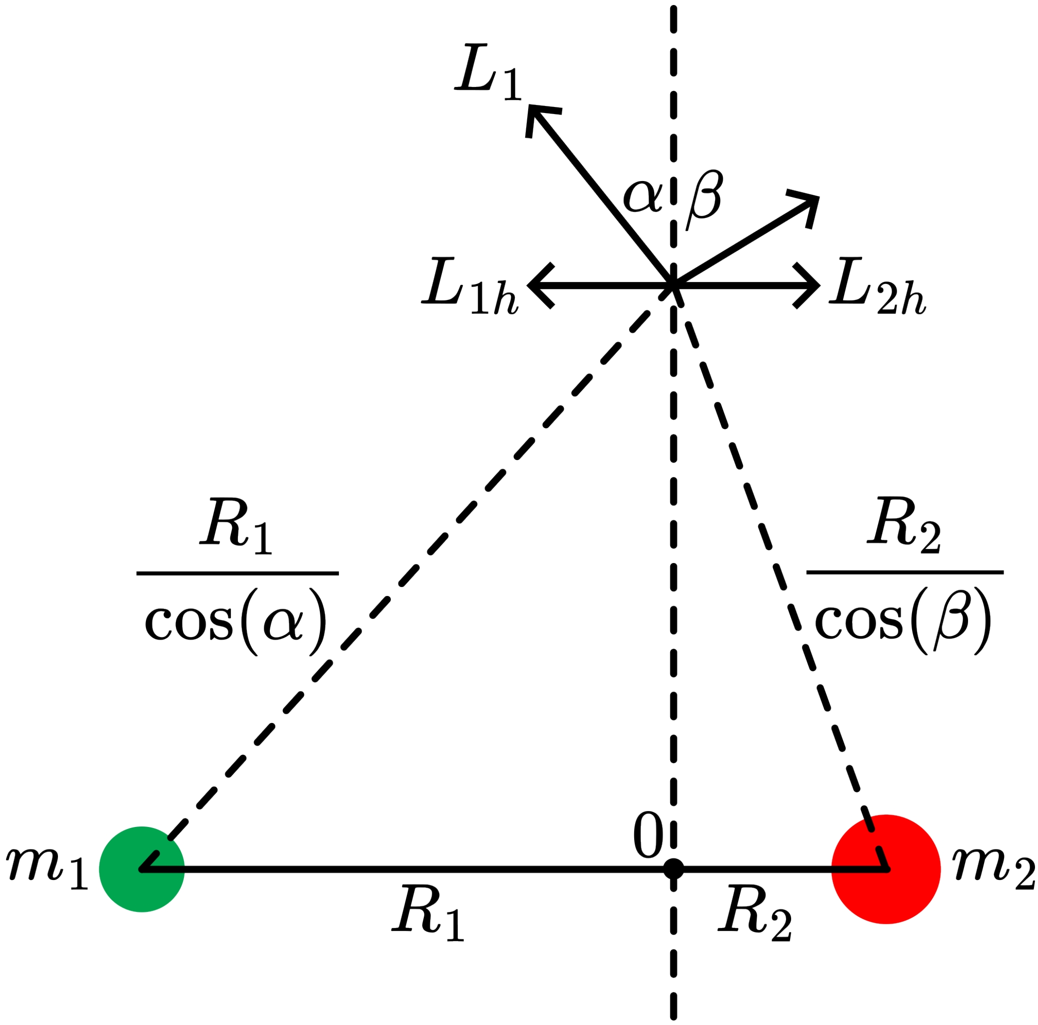


Figure 2.11: .

2.2.1.2.7 Remarks

- The easiest way to wind the rubber band: hold the small sphere in your hand and whirl the large sphere round over the ground.
- The wooden spheres having diameters of 4 — and 5 cm will have a mass ratio of 1 to 1.95 , so very close to a factor 2.
- See also the demonstration Dumb-Bell

2.2.1.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 139-141
- PSSC, College Physics, pag. 352-354

2.2.1.3 03 Student's Centre of Mass

2.2.1.3.1 Aim

To show that the centre of mass (CM) will not move when only internal forces act.

2.2.1.3.2 Subjects

- 1D40 (Motion of the Center of Mass)

2.2.1.3.3 Diagram

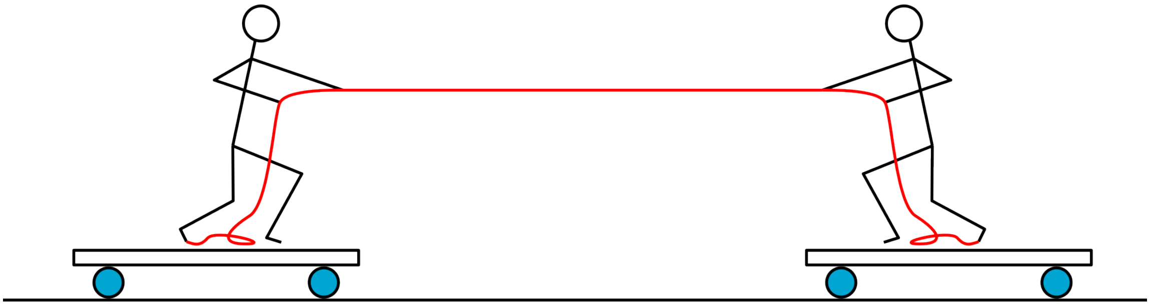


Figure 2.12: .

2.2.1.3.4 Equipment

- Two light carts (skateboards), easy rolling.
- Rope, $l = 10$ m.
- Light student.
- Heavy student.

2.2.1.3.5 Presentation

The two carts are positioned at the front of the lecture hall—one on the right side, the other on the left. Two student volunteers each stand on a cart, holding opposite ends of a rope. Knowing the students' masses, the CM can be determined, and this position is marked on the floor. When one or both students gently pull on the rope, the carts move toward each other and meet approximately at the CM.

2.2.1.3.6 Explanation

Explanation: The CM of a system of particles represents the average position of those particles. So, seen from the CM:

$$m_1 r_1 + m_2 r_2 + \ldots = 0 \tag{2.10}$$

The larger the mass (m), the smaller r will be. Since no external forces are acting, the CM will not be displaced, as this demonstration verifies.

2.2.1.3.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 128

2.2.1.4 04 Explosion

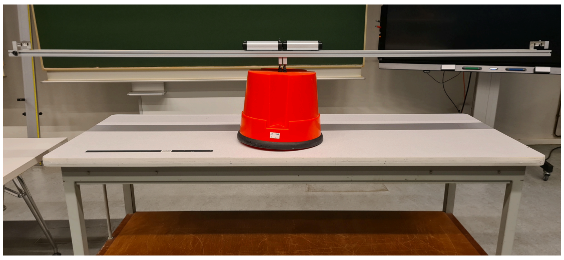
2.2.1.4.1 Aim

To demonstrate that in an explosion, the centre of mass does not move.

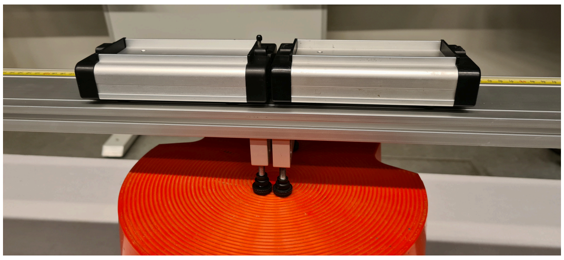
2.2.1.4.2 Subjects

- 1D40 (Motion of the Centre of Mass)
- 1N20 (Conservation of Linear Momentum)

2.2.1.4.3 Diagram



(a)



(b)

2.2.1.4.4 Equipment

- Dynamics cart.
- Masses.
- Collision cart.
- Cart-track, 2.2 m, with end-stops (with magnets).
- Small table.
- Mass balance (scale).
- Short stick.
- Air level.

2.2.1.4.5 Safety

- An assistant should be present to (potentially) catch the track.

2.2.1.4.6 Presentation

2.2.1.4.6.1 Preparation

Place the two supports of the cart track in the middle of the track, about 4 cm apart, to balance the track on the small table (see Figure 1). Use an air level to carefully balance the small table horizontally, then do the same for the track.

2.2.1.4.6.2 Presentation

The dynamic cart and the collision cart are put on the scale to show that their masses are equal. Now the plunger of the dynamic cart is pushed completely inward and latched.

1. Carefully position the dynamic cart and collision cart against each other on the balanced track. Give the plunger release button a short blow with the stick and watch the two carts move to the ends of the track. The cart-track with the moving carts remains balanced (even when the carts bounce at the end stops!)
2. Now, a mass equal to the mass of one cart is put on top of one of the carts (see Remarks to know where the CM is). The demonstration is repeated: The heavier cart is moving slower, but the track with the moving carts remains balanced!
3. The demonstration can be performed a third time with two masses put on top of one cart, making the mass-ratio between the two carts equal to $3:1$.

4. As an extra, in the second and third demonstrations, with the carts of different masses, you need to catch the track when one of the carts bumps against the end-stop, as the track will not remain balanced. Present this to the students as a challenge: *"The set-up becomes unbalanced when one of the carts bumps into the end-stop, so the centre of mass moves away from the point of support!"*

- **Question:** *"What makes the centre of mass move away?"*
- **Answer:** *"An external force."*
- **Question:** *"What and where is this external force?"*

2.2.1.4.7 Explanation

1. 2. and 3.

The centre of mass (CM) of a fixed number of particles is defined as the average position (R_{CM}) of those particles:

$$R_{cm} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2} \tag{2.11}$$

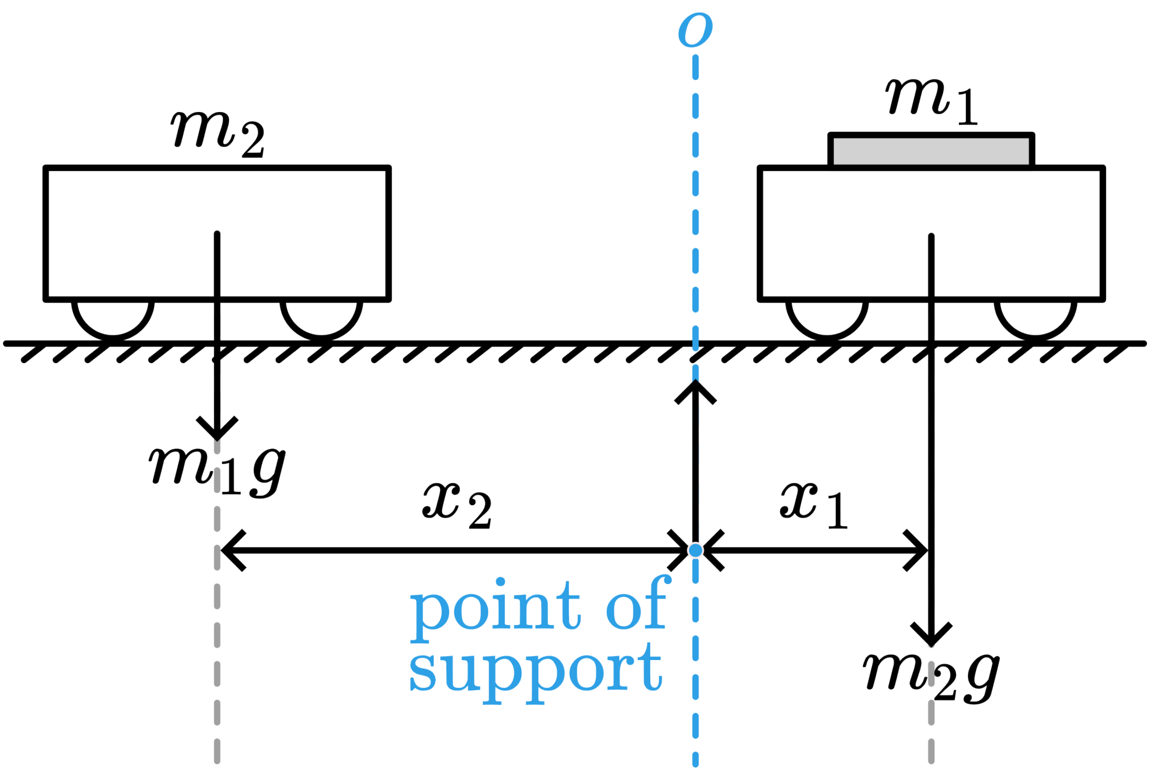


Figure 2.16: .

At the start of the demonstration (before the explosion) $R_{cm} = \frac{m_{10}+m_{20}}{m_1+m_2} = 0$ (Point of support being the zero-reference.)
After the explosion of the two carts $m_1 v_1 + m_2 v_2 = 0$ (conservation of momentum).
Since $x = vt$; $m_1 x_1 + m_2 x_2 = 0$, so $R_{CM} = 0$ and CM remains at the zero-coordinate; the track remains balanced.

Extra.

When one cart hits the end stop (m_2 in Figure 3), there is at that location a change of momentum $\Delta p = 2mv$ of the cart. The track experiences an impulse of $| \int_0^{\Delta t} F dt | = 2mv$.
There is no external impulse imparted to the track, so this impulse must be balanced somewhere.
Friction force at the support takes care for that $| \int_0^{\Delta t} F_f dt |$. And also: $F_f = -F$ (Newton 3).

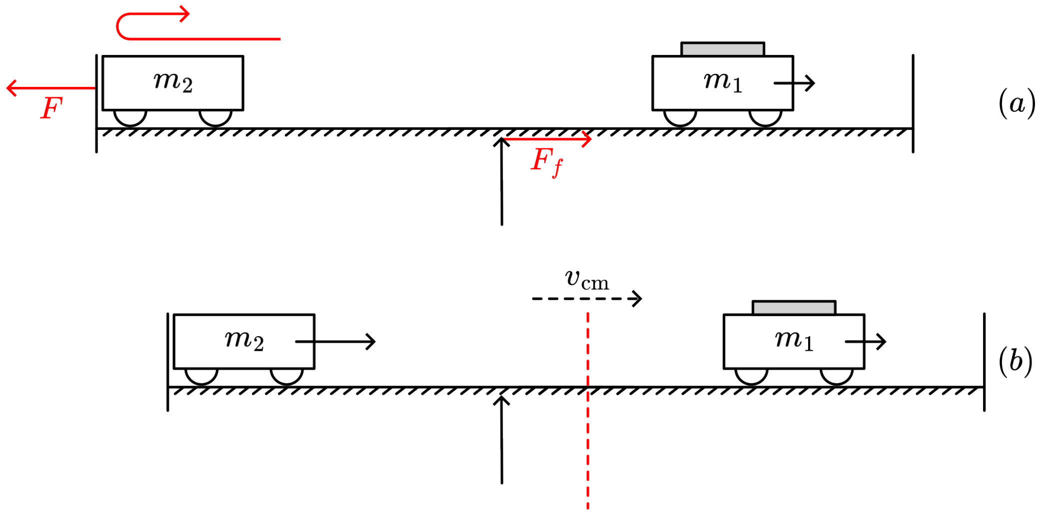


Figure 2.17: .

In Figure 3A this F_f gives the whole assembly a velocity to the right, displacing CM to the right. CM will keep on moving to the right (Newton 1), increasing the unbalance more and more.

2.2.1.4.8 Remarks

- When carts of different masses are placed on the balanced track, take care that their common centre of mass is placed right above the balanced point of the track (see Figure 4). When $m_1 = 2m_2$, then $y = 1/61$; when $m_1 = 3m_2$, then $y = 1/41$.

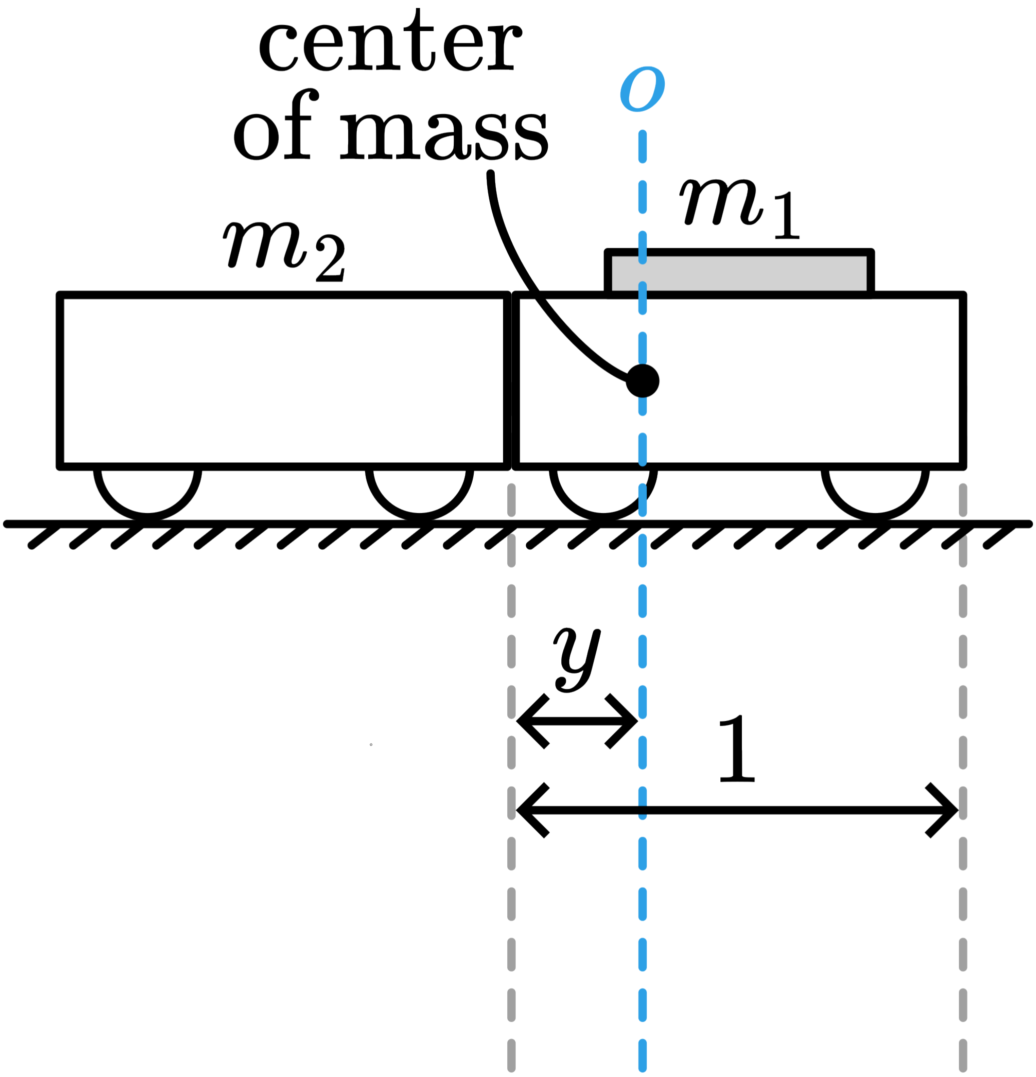


Figure 2.18: .

2.2.1.4.9 Sources

- PASCO scientific, Instruction Manual and Experiment Guide for the PASCO scientific Model ME-9458 and ME-9452, experiment 1 and 11
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 124-129

2.2.2 1D50 Central Forces

2.2.2.1 01 Going Round in Circles

2.2.2.1.1 Aim

To see/feel the centripetal force.

2.2.2.1.2 Subjects

- 1D50 Central Forces

2.2.2.1.3 Diagram

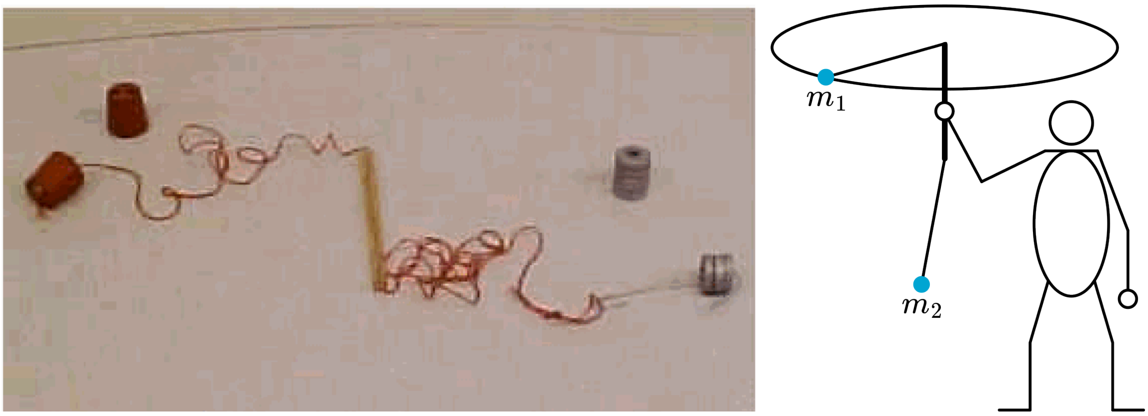


Figure 2.19: .

2.2.2.1.4 Equipment

- Tube, with rounded edges, $l = 15$ cm.
- Piece of rope, $l = 1.5$ m.
- Two rubber stoppers (m_1).
- A number of weights (m_2). We use thick washers.
- Paperclip.
- (Stopwatch).

2.2.2.1.5 Presentation

The diagram shows the components and how to use them. By swinging the tube slightly, the mass m_1 begins to move in circles above your head. The demonstrator must swing m_1 at a specific frequency to balance the system.

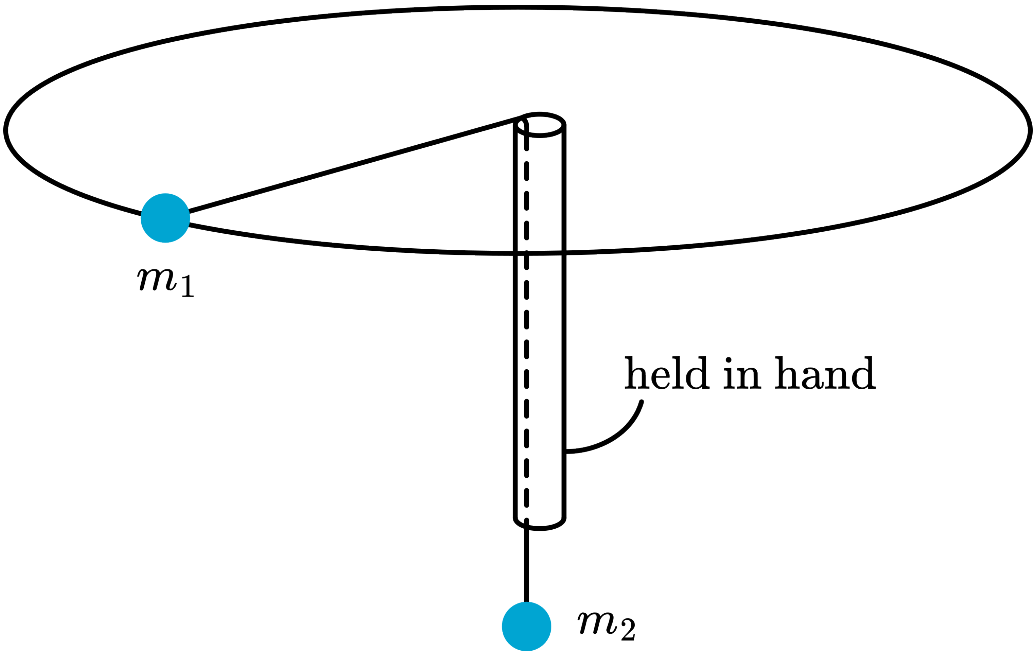


Figure 2.20: .

- When the demonstrator slows down to a lower frequency, m_2 moves downward, causing m_1's circular path to become smaller and smaller. Speeding up causes m_2 to rise, and

$$m_1 \tag{2.12}$$

moves in increasingly larger circles.

-
- The demonstrator first swings m_1 in a stable circular motion. Then, by pulling m_2 downward, m_1 speeds up dramatically, tracing tighter and tighter circles.

If time permits, the relationship between the variables in this demonstration can be verified more exactly. Just below the tubing, a paperclip is fixed to the rope used as a marker to make m_1 go round in a circle with fixed R. A stopwatch can be used to time the frequency.

1. When m_1 is doubled by adding another rubber stopper to it, a lower frequency is needed to balance the system.
2. When m_2 is increased, a higher frequency is needed to balance the system.
3. When half the rope length is used (shifting the paperclip), a higher frequency is needed to balance the system.

2.2.2.1.6 Explanation

Analysis shows that movement at a constant speed (v) of a mass (m_1) in a circle with radius R can be described by $a_c = \frac{v^2}{r}\omega^2 R$. In our demonstration the tension (T) in the string provides the force needed for $a_c : T = m_1 a_c$, and $m_2 g = m_1 a_c \Rightarrow a_c = \frac{m_2}{m_1} g$, (see Figure 3).

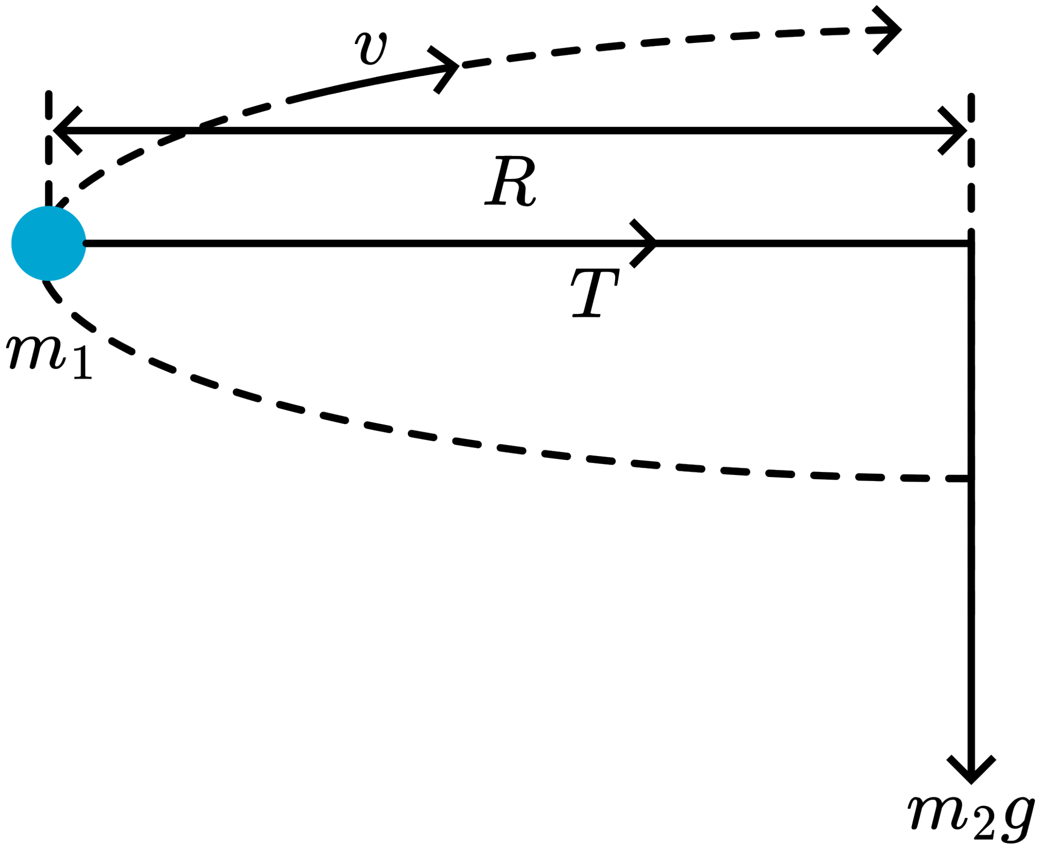


Figure 2.21: .

- First, the demonstrator showed a balanced situation, after which he slowed down ω. The centripetal acceleration, describing such a slower movement, will be lower $\left(a_c = \omega^2 R\right)$. But T is a fixed value, so T will pull m_1 inwardly. As $a_c = \omega^2 R$ shows, this proces is cumulative and m_1 ends at the centre of the circle.
- When m_2 is pulled downward, the string tension increases substantially, and so does a_c. According to $a_c = \omega^2 R$, and given that R decreases, ω increases significantly.

1. Doubling m_1 means that the centripetal acceleration a_c provided by the string tension will be halved $\left(a_c = \frac{m_2}{m_1} g\right)$. To keep m_1 moving in the same circle, ω must decrease by a factor of $\sqrt{2}$ according to $\left(a_c = \omega^2 R\right)$.
2. Increasing m_2 raises the string tension, so the provided a_c increases $(T = m_1 a_c)$. To keep m_1 moving in the same circle, ω has to increase.
3. When R is halved but the tension in the string remains the same, the provided a_c also remains constant. To keep m_1 moving in a (smaller) circle, ω must increase by a factor of $\sqrt{2}$ according to $\left(a_c = \omega^2 R\right)$.

2.2.2.1.7 Remarks

- Practice the demonstration before you show it. A practiced hand is needed to make m_1 go round properly.
- Rubber stoppers are used as masses moving in circles for safety reasons.
- The spinning mass should be light compared to the hanging weight (about a factor of 3), because otherwise the angle between the string and the vertical will not approach 90°. This leads to more friction, and due to the slanting rope (forming a cone around the circle), the analysis changes.
- In the last part of the presentation (grabbing and pulling m_2 downward), the demonstrator will feel that quite a lot of force is needed. It is, of course, most instructive for the students if they experience this force themselves (perhaps during the coffee break?).

2.2.2.1.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 72-73
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 68-71 and74-75

2.2.2.2 02 Conical Pendulum

2.2.2.2.1 Aim

To show that the period of motion of a conical pendulum changes only noticeably at large angles.

2.2.2.2.2 Subjects

- 1D50 (Central Forces)

2.2.2.2.3 Diagram

Figure 2.22: .

2.2.2.2.4 Equipment

- Ball suspended on a thread.
- Clamping material.
- Large paper circle, $r = 35$ cm.
- Small paper circle, $r = 7.5$ cm.
- Stopwatch with large display.
- A small ball suspended on a thread

2.2.2.2.5 Presentation

1. Set up the conical pendulum as shown in the diagram. Place the small paper circle under the pendulum and make the pendulum swing conically along the circumference of the

paper circle. Measure the time needed for 10 periods. Repeat this procedure, but now with the large paper circle. In our setup, the times measured are 18.2 and 17.5 seconds, respectively.

2. Take the small simple pendulum by hand and make it swing conically. Gradually increase its speed. At very large angles, the increase in angular velocity becomes easily noticeable.

2.2.2.2.6 Explanation

Theory tells us that the period (T) of a conical pendulum is given by $T = 2\pi\sqrt{\frac{l\cos\phi}{g}}$ (see Figure 2).

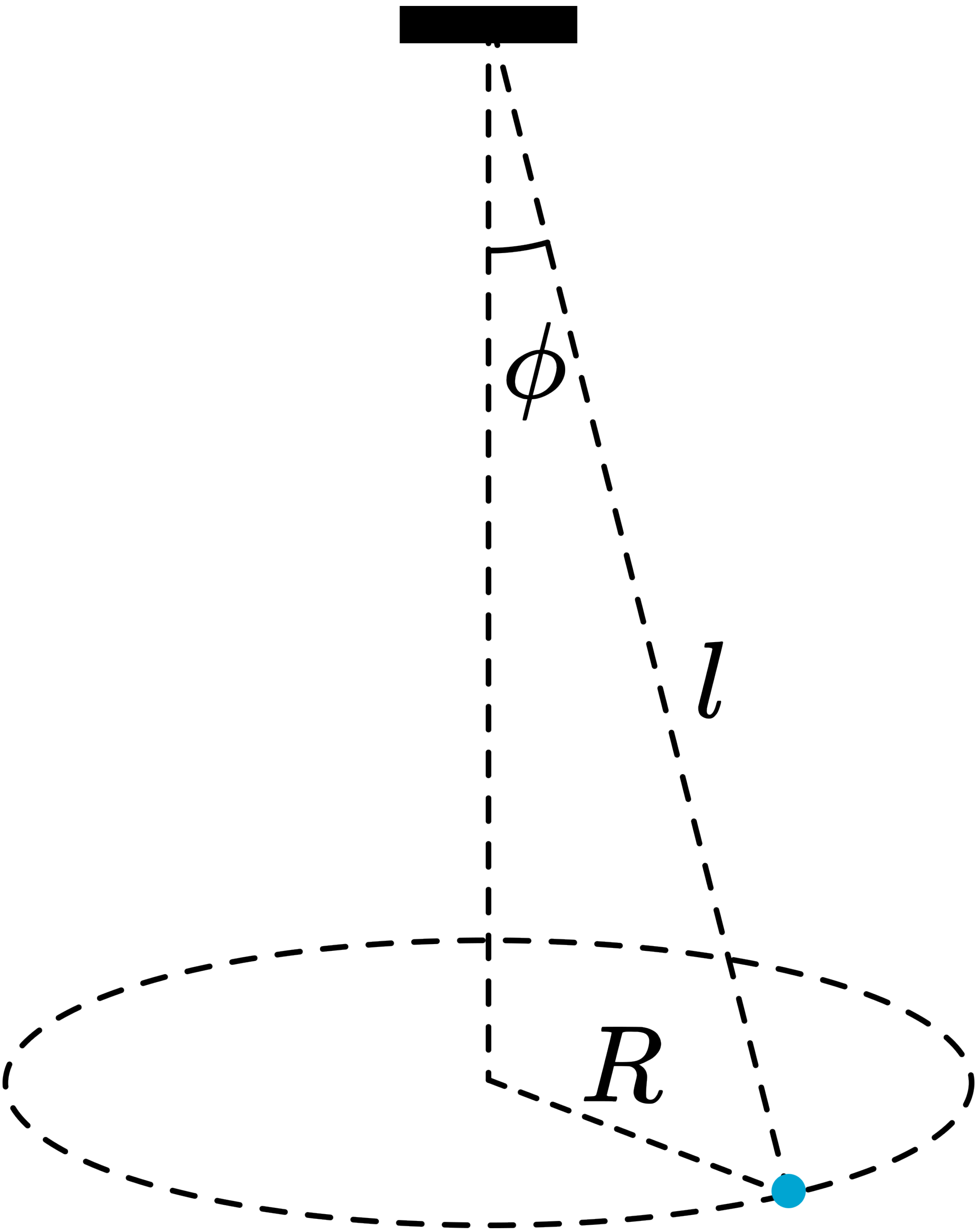


Figure 2.23: .

So $T \propto \sqrt{\cos\phi}$

The table in Table 1 shows that from 0° to 30°, $\sqrt{\cos\phi}$ only changes 7%, while from 60° to 89° this change is about 82%. So only at large angles ϕ, T changes noticeably.

$\phi(\%)$	$\sqrt{\cos\phi}$
0	1
15	0,98
30	0,93
45	0,84
60	0,71
75	0,51
80	0,42
85	0,30
89	0,13

Table 2.24: table

2.2.2.2.7 Remarks

- When the pendulum is suspended vertically and not swinging, we have marked this central position on the table. The paper circles have a hole in their center so that it is easy to position them in the right place (hole and mark coincide).
- Making the pendulum swing along the circumference of the paper circle needs some practice. Launch the suspended ball tangentially and give it a speed so that it just reaches a deflection equal to R of the paper circle (see Figure 3).

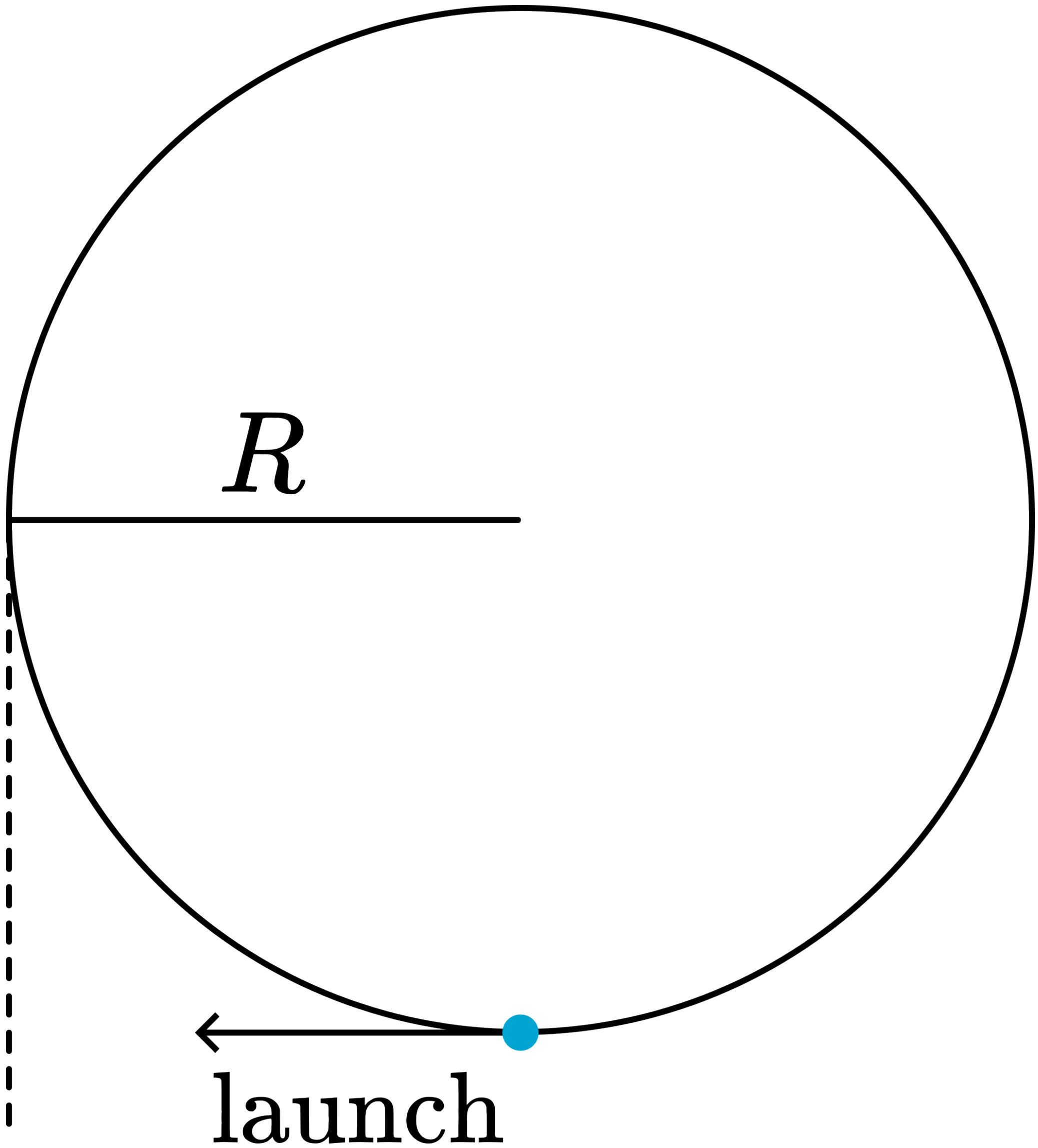


Figure 2.25: .

2.2.2.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 70
- Roest, R., Inleiding Mechanica, pag. 55-56
- Young, H.D. and Freedman, R.A., University Physics, pag. 141-142

2.2.2.3 03 Centripetal Force

2.2.2.3.1 Aim

To show an example of the centripetal force.

2.2.2.3.2 Subjects

- 1D50 (Central Forces)

2.2.2.3.3 Diagram

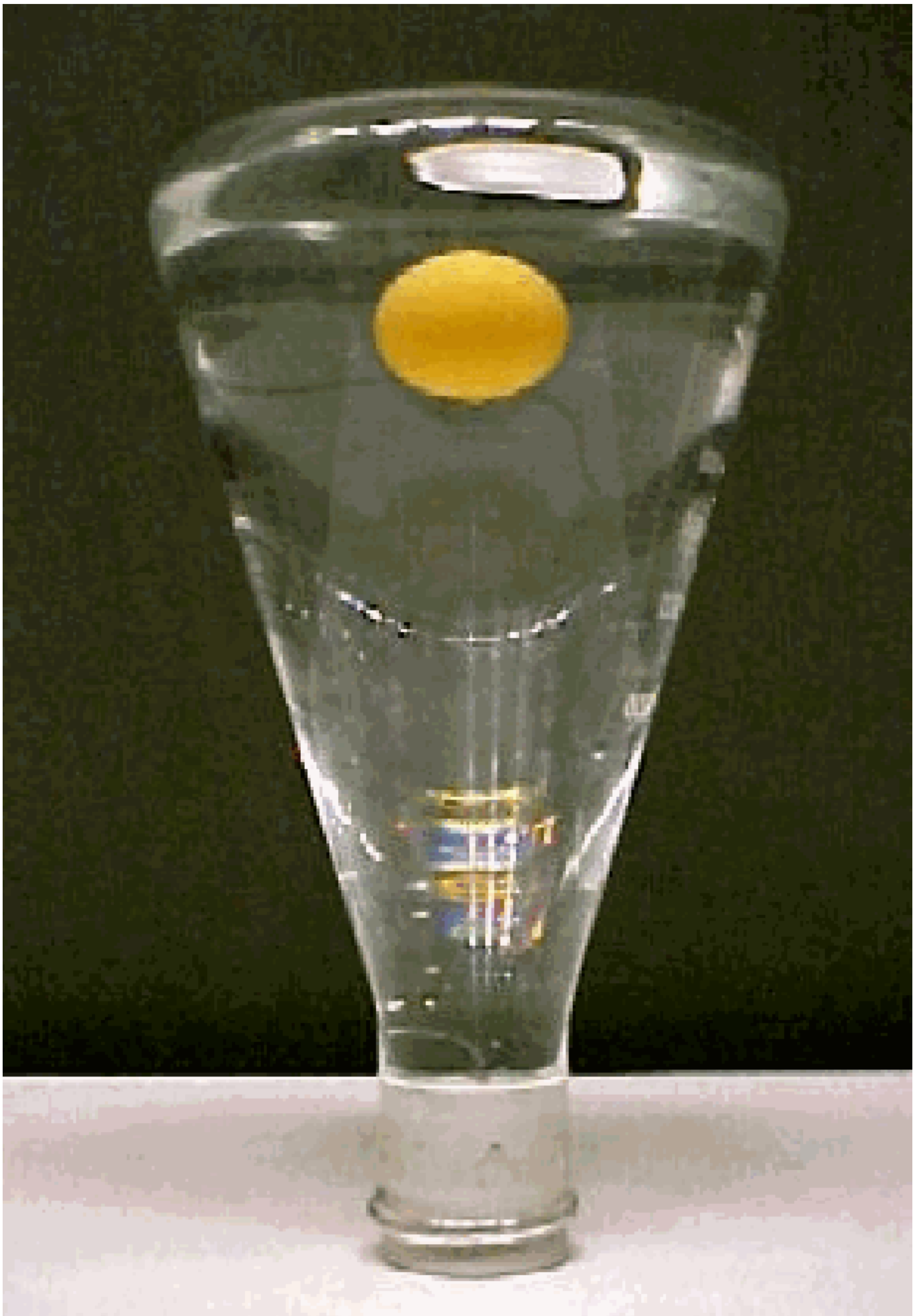


Figure 2.26: .

2.2.2.3.4 Equipment

- Conical beaker, $2l$, filled with water.
- Rubber stop.
- Ping-pong ball tied to rubber stop (see Diagram).

2.2.2.3.5 Safety

- The conical beaker filled with water is quite heavy ($m \approx 2kg$). Hold it firmly!

2.2.2.3.6 Presentation

Hold the conical beaker filled with water upside-down in your hands. The ping-pong ball floats directly above the rubber stopper. Start turning in a circle, and while turning, observe the behaviour of the ping-pong ball (see Figure 2).

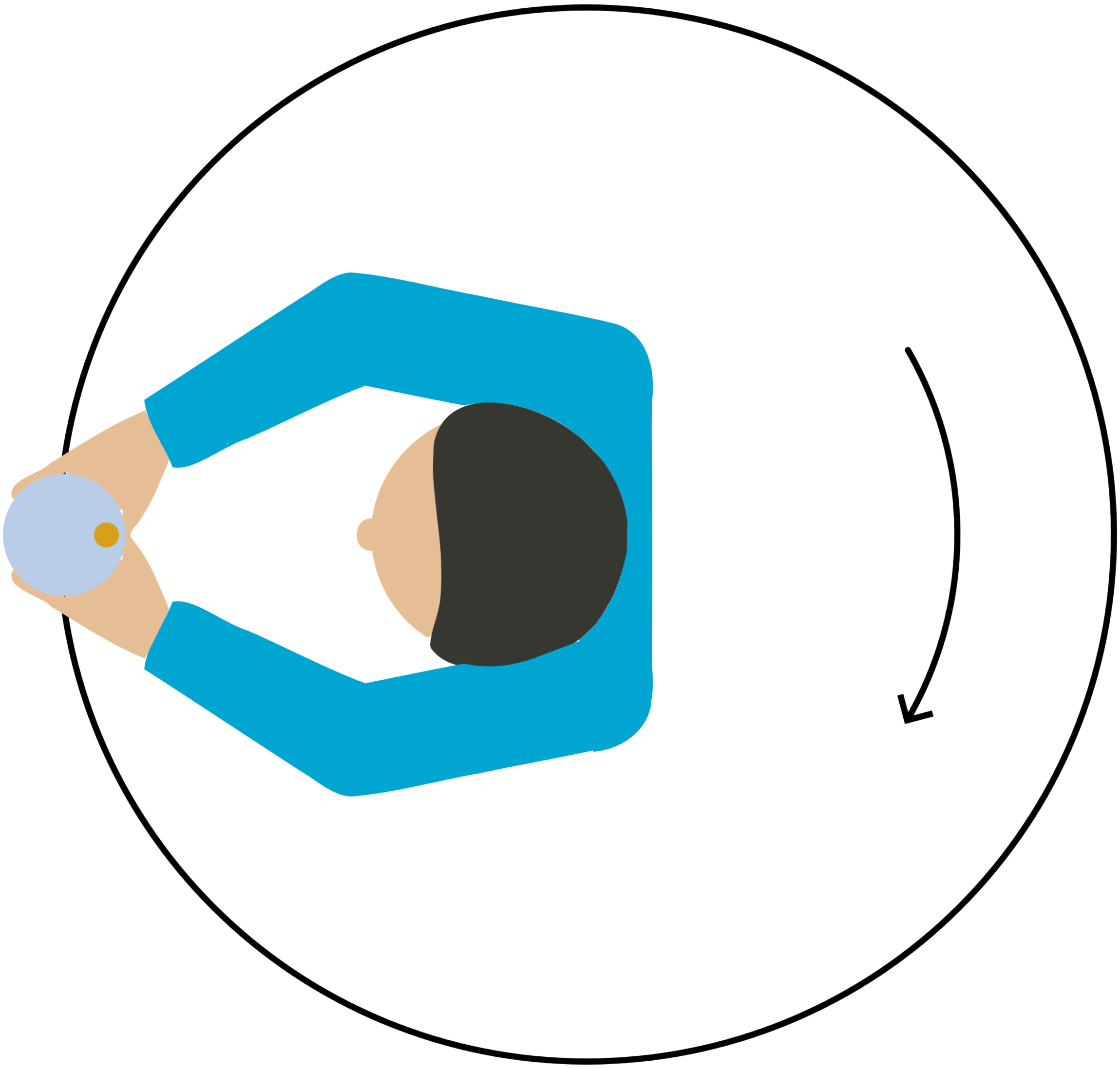


Figure 2.27: .

The ping-pong ball is displaced towards you.

2.2.2.3.7 Explanation

The ping-pong ball, being completely immersed in water, experiences an upward buoyant force F_u that is greater than its weight $m \cdot g$. The net force $(F_u - m \cdot g)$ is directed upwards. The tension T in the string prevents the ping-pong ball from floating upwards (see Figure 3a).

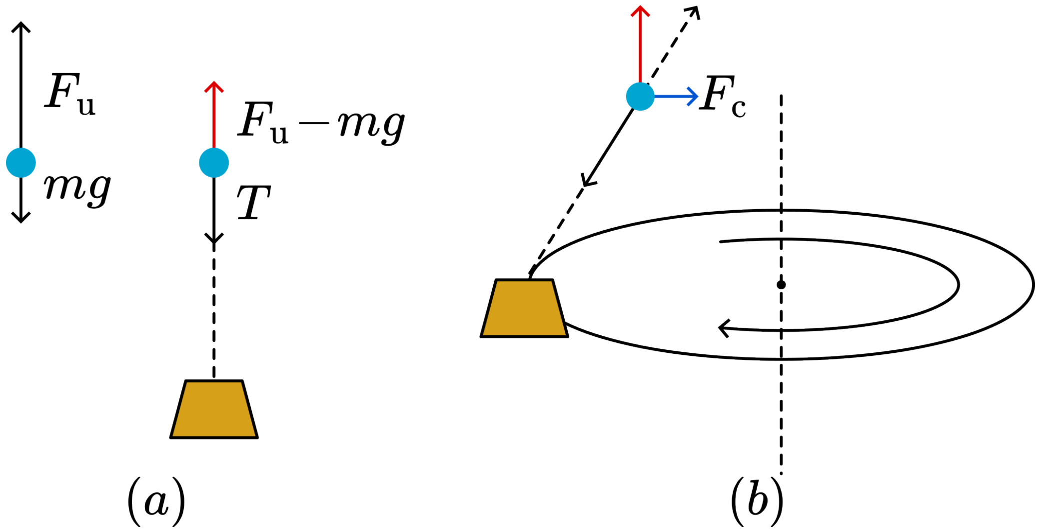


Figure 2.28: .

When turning around in circles, the ping-pong ball is forced to move in a circle. A centripetal force is needed for that. Figure 3b shows the new situation of equilibrium: the net upward force and tension are compensated by a centripetal force F_c. Any other position of the ping-pong ball is not a situation of equilibrium (drawing a free body diagram of the forces will show this).

2.2.2.3.8 Remarks

- When an air bubble is trapped in the conical beaker filled with water, this bubble will behave in the same way as the ping-pong ball does.
- When you move the system from left to right, the acceleration on the left side and the deceleration on the right side can be observed. In general, the system can be used as an acceleration meter.

2.2.2.3.9 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 31-32.

2.2.2.4 04 Force Field

2.2.2.4.1 Aim

To introduce the concept of a (radial) force field.

2.2.2.4.2 Subjects

- 1D50 (Central Forces)

2.2.2.4.3 Diagram

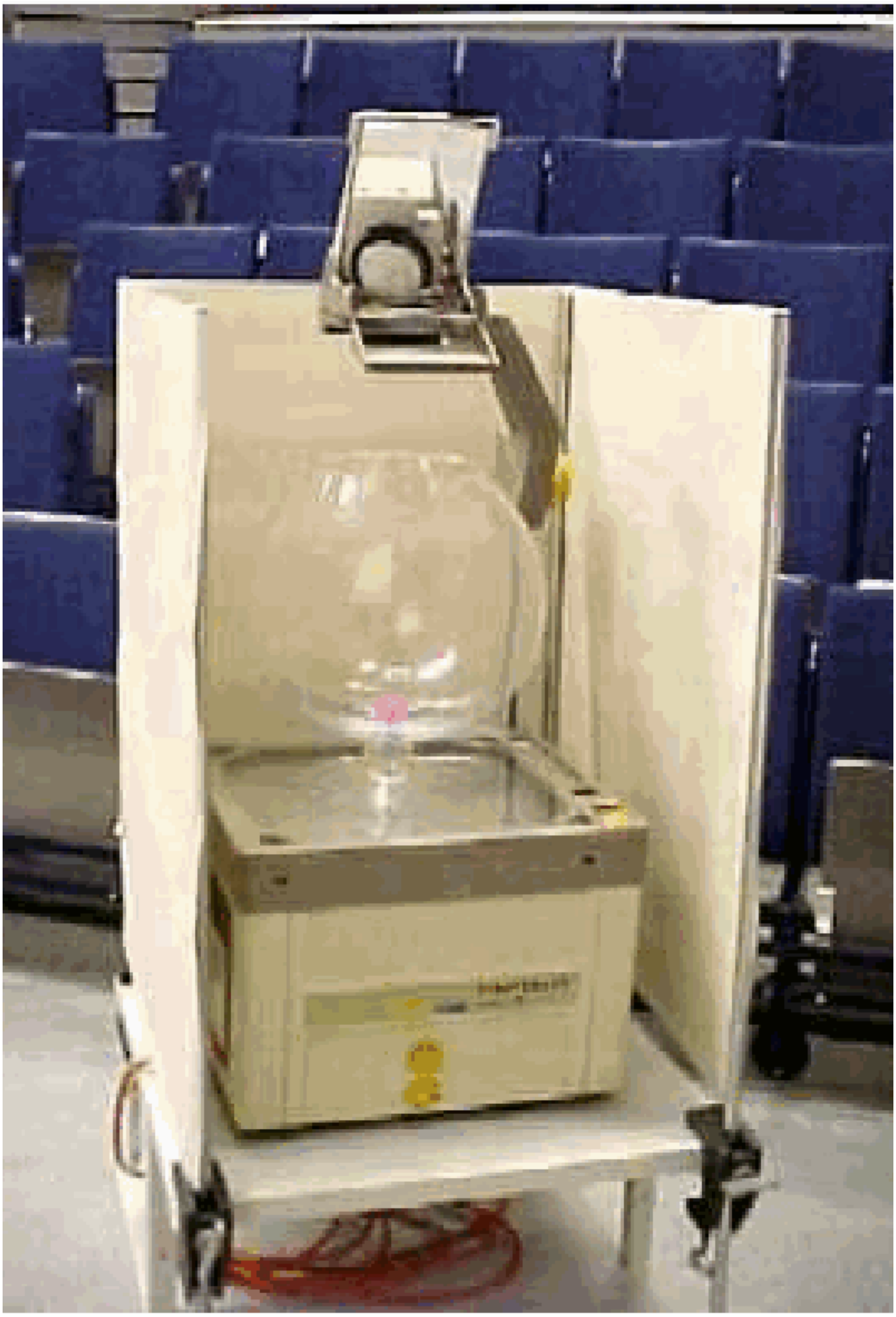


Figure 2.29: .

2.2.2.4.4 Equipment

- Large glass bowl on overhead projector.
- Screen to hide the bowl.
- Steel ball.

2.2.2.4.5 Presentation

The steel ball is held out of the centre of the bowl and released. Then the overhead projector is switched on and the image of the steel ball is projected on the screen. The spectators see the ball move in a line from one side to the other, just like there is some spring that is continuously pulling the steel ball towards the centre. The line may rotate slowly in a plane, but all the time we can describe this movement as being caused by a force that is always directed towards a centre (see Figure 2).

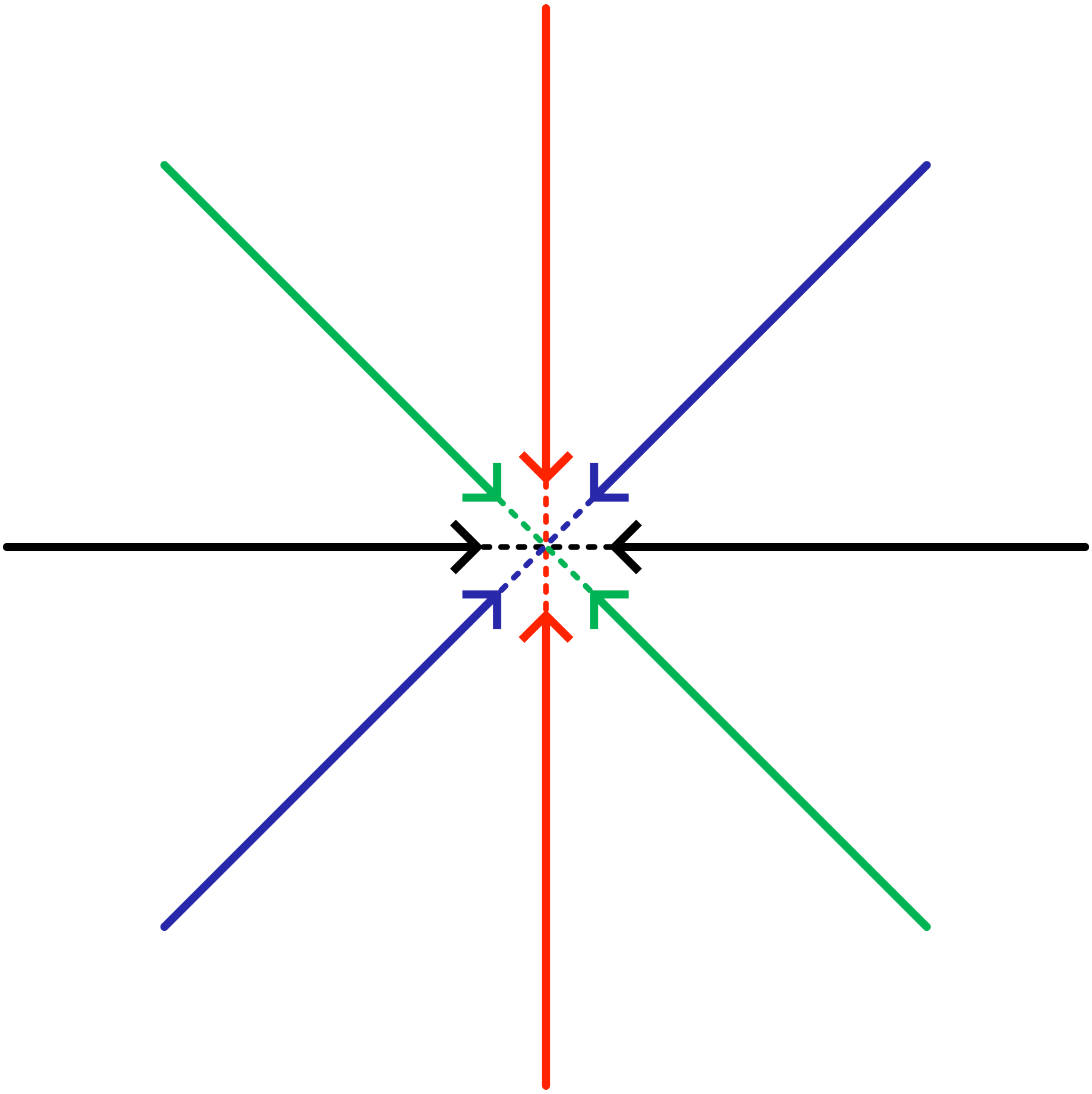


Figure 2.30: .

Also, when the ball is given a movement perpendicular to the force field, the effect of the force field on the movement can be observed (circular and elliptical orbits). When the movement is circular, it is just like there is a piece of rope connected to the centre. When the movement is elliptical, the ellipse also shows a precession, indicating that the force field is not a real inverse square force field (see also the demonstration [Precessing orbit](/book/1 mechanics/1L gravity/1L20 Orbits/1L2003 Precessing Orbit/1L2003.md).

2.2.2.4.6 Remarks

- The screen hiding the bowl is placed to prevent students from “seeing” the vertical gravitational field.

2.2.2.4.7 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 66-68
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 83-84 and 107-108
- McComb,W.D., Dynamics and Relativity, pag. 50

2.3 1F Newton’s first law

2.3.1 1F20 Inertia of Rest

2.3.1.1 01 Tablecloth Pull

2.3.1.1.1 Aim

To show an example of Newton’s first law

2.3.1.1.2 Subjects

- 1F20 (Inertia of Rest)

2.3.1.1.3 Diagram

Figure 2.31: .

2.3.1.1.4 Equipment

- Sheet of paper.
- Different objects placed on the sheet of paper.

2.3.1.1.5 Presentation

Set the table as shown in Diagram (light a candle etc.). Our tablecloth is technically not a tablecloth. We use a sheet of paper (see Diagram). Take the protruding free end of the paper in both hands and give a sharp downward jerk. The sheet of paper comes out from under the glasses and they are hardly moved. (Even the water in the glasses is not disturbed!)

2.3.1.1.6 Explanation

This is one of the many possible demonstrations to show the validity of Newton’s first law.

Also, Newton’s second law can be used to explain this demonstration:

The effect of a given force between the sheet of paper and the glasses depends on the impulse of that force ($F\Delta t$). The impulse is small when the sheet of paper moves away quickly (Δt is small). The resulting horizontal displacement will then be very small. Analysis shows that the horizontal displacement d of a mass on the sheet equals:

$d = \frac{1}{2}k_1 g\Delta t^2\left(1 + \frac{k_1}{k_2}\right)$, where k_1 is the coefficient of friction between sheet and glass and k_2 is the coefficient of friction between glass and table and Δt the time to pull the sheet from beneath the glasses. So d is very sensitive to Δt!

2.3.1.1.7 Remarks

- After the lecture students like to try the demonstration by themselves.
- This demonstration needs trying it before you show it!

2.3.1.1.8 Video Rhett Allain

(a) (b)

Figure 32: Video embedded from - Scan the QR code or click here to go to the video.

2.3.1.1.9 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 21
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 46-49
- Jones, Evan, The Physics Teacher, Vol. 15, pag. 389
- Perez, Joseph, The Physics Teacher, Vol. 15, pag. 242

2.3.1.2 02 Newton’s Hammer

2.3.1.2.1 Aim

To show an example of Newton’s first law

2.3.1.2.2 Subjects

- 1F20 (Inertia of Rest)

2.3.1.2.3 Diagram

Figure 2.35: .

2.3.1.2.4 Equipment

- Hammer
- Sheet of paper

2.3.1.2.5 Presentation

This demonstration is an exciting variant to the traditional tablecloth pull; Very little is needed to topple the balanced hammer.

The sheet op paper is placed on the table and the hammer is balanced on it (see Diagram). For the audience it is observable that it takes care to balance the hammer with its head up; a slight disturbance makes it fall.

When the hammer is balanced, take hold of the sheet of paper and with a quick jerk, you pull the sheet of paper away. The hammer remains balanced!

2.3.1.2.6 Explanation

This is one of the many possible demonstrations to show the validity of Newton's first law. We like this one, because a very small disturbance makes the hammer fall down, giving the demonstration more tension to the audience.

Also, Newton's second law can be used to explain this demonstration:

The effect of a given force between the sheet of paper and the hammer depends on the impulse of that force $(F\Delta t)$. The impulse is small when the sheet of paper moves away quickly (Δt is small). The resulting horizontal displacement will then be very small.

Analysis shows that the horizontal displacement d of the mass on the sheet equals:

$d = \frac{1}{2}k_1 g\Delta t^2\left(1 + \frac{k_1}{k_2}\right)$, where k_1 is the coefficient of friction between sheet and hammer and k_2 is the coefficient of friction between hammer and table and Δt the time to pull the sheet from beneath the hammer. So d is very sensitive to Δt !

2.3.1.2.7 Remarks

- After the lecture students like to try the demonstration by themselves.
- A successful demonstration needs trying it before you show it!

2.3.1.2.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 21
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 46-49
- Jones, Evan, The Physics Teacher, Vol. 15, pag. 389

2.3.1.3 03 Not Breaking a Wineglass

2.3.1.3.1 Aim

A demonstration of Newton's first law.

2.3.1.3.2 Subjects

- 1F20 (Inertia of Rest)

2.3.1.3.3 Diagram

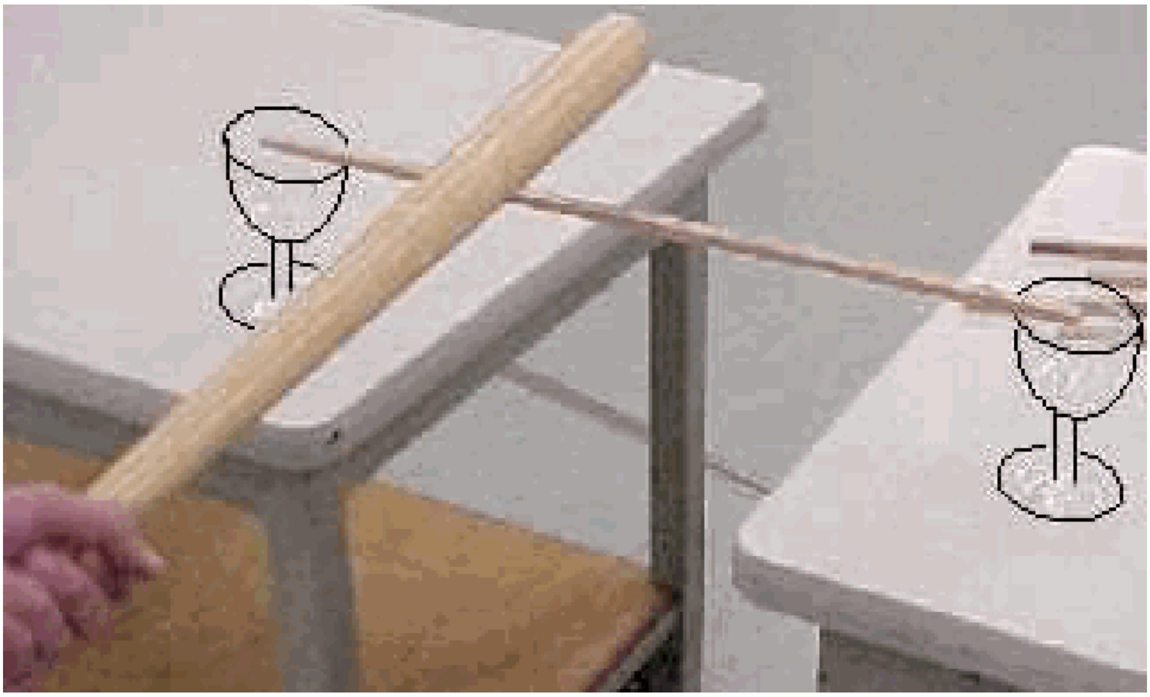


Figure 2.36: .

2.3.1.3.4 Equipment

- 2 wine glasses
- 3 wooden sticks (we use meranti multi-ply, 12 × 9 mm.)

$l_1 = 100$ cm

$l_2 = 50$ cm

$l_3 = 25$ cm

- a heavy club (we use a baseball bat).

2.3.1.3.5 Presentation

Place a wine glass on the edge of each of the two tables. Take a stick and demonstrate to the audience that it takes considerable force to break it. Let the ends of the stick l_1 with its broad side up rest on the two glasses. Now hit the middle of the thin stick with the heavy club. Giving it enough speed to break the stick but leaving the wine glasses unmoved.

Repeat this performance with l_2 and then l_3. The shorter the stick, the more surprising the experiment.

2.3.1.3.6 Explanation

When the club comes down, it touches the horizontal stick and acts on it with a force F. The effect $(m\Delta v)$ of this force depends on the impulse $F\Delta t$. The impulse is smallest when the club hits quickly, causing the least disturbance of the stick (Δt is small). For this reason, the club should be given a relatively high speed.

As soon as the horizontal stick is broken into two halves, these halves not only drop but also rotate around their center of mass. The centers of mass stay where they were just before hitting (inertia of rest). Due to this rotation, a stick-half moves away from the wineglass in an upward direction, provided the club has given it sufficient rotational speed.

When the horizontal stick between the wine glasses is chosen shorter, the effect (Δv) is small only when the contact-time between club and stick is still shorter than it was before, because the mass of the stick is smaller now. So, in this case, the club should have an even higher speed.

2.3.1.3.7 Remarks

This demonstration is a variation of the demonstration in which a penny is shot out from under a stack of pennies. The stick on the wine glasses is a horizontal version of the vertical stack of pennies.

2.3.2 1F30 Inertia of Motion

2.3.2.1 01 Galileo's Thoughts

2.3.2.1.1 Aim

To show the thought experiment of Galileo Galilei on the inertia of movement.

2.3.2.1.2 Subjects

- 1F30 (Inertia of Motion)

2.3.2.1.3 Diagram

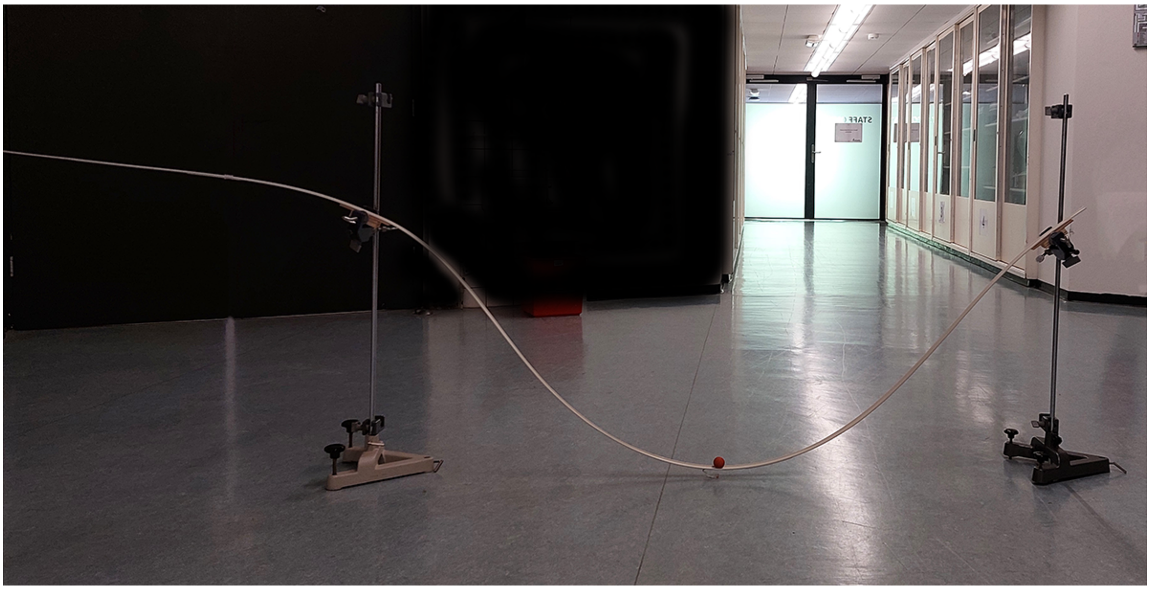


Figure 2.37: .

2.3.2.1.4 Equipment

- Gutter (a curtain rail, bend properly).
- Ball.
- Clamping material (see Diagram).

2.3.2.1.5 Presentation

The right-hand side of the gutter is placed at a steep angle. The ball is released at the top of the left-hand side of the gutter, rolls down and up on the right-hand side. It is observed that it almost reaches the same height as that at which it was released. Now the right-hand side of the gutter is made less steep by shifting the right-hand support to the right. Again, releasing the ball in the same fashion, it can be observed that it reaches almost the same height. It is also observed that the horizontal distance traveled is larger than in the first part of the demonstration.

The right-hand support of the gutter is placed in its most right position. Now the released ball travels the whole gutter.

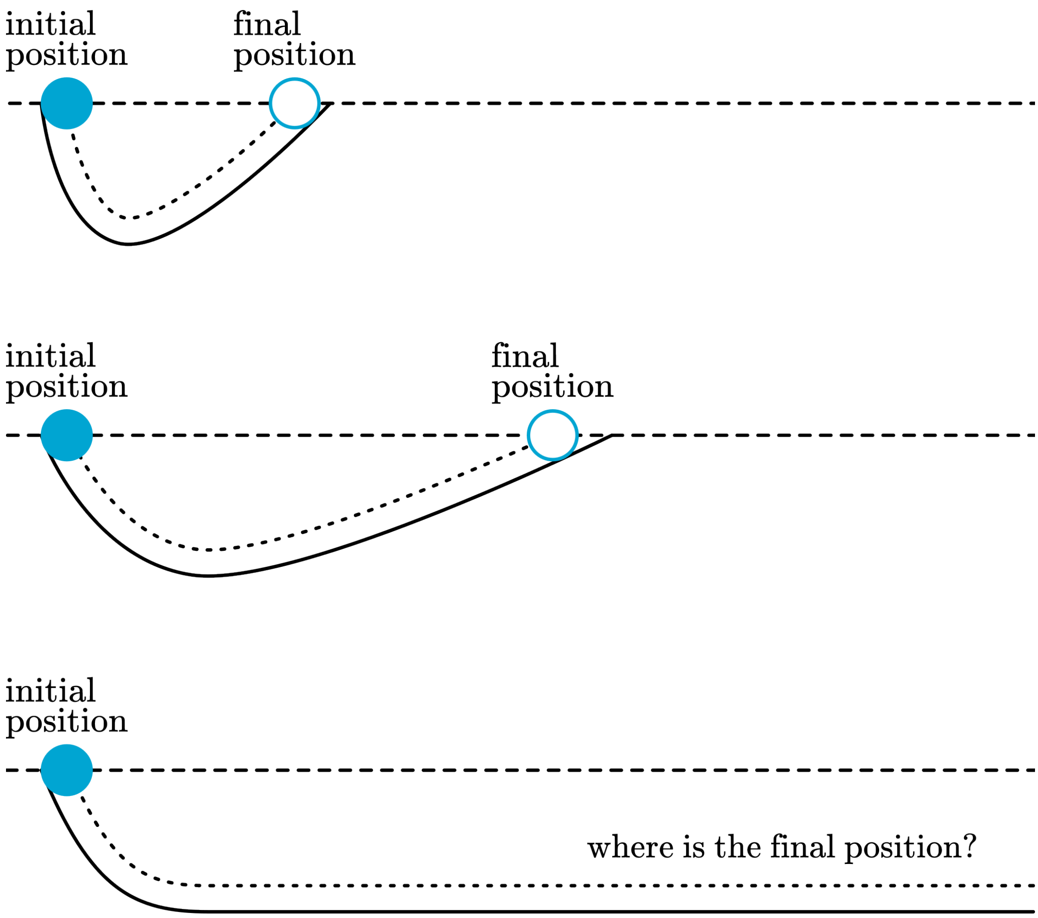


Figure 2.38: .

The right-hand side support is removed, and this part of the gutter now lies horizontally on the table. Ask the students how far the ball will travel now when released as before: "What is its final position?" (see Figure 2). After receiving their answers, the ball can be released (In our setup, the ball disappears in a sink).

2.3.2.1.6 Explanation

Galilei reasoned that when the right-hand part of the gutter is aligned horizontally, the ball can never reach the same height again. So, it will keep rolling to the right perpetually; the ball is moving and will remain in motion! This is what we have now dubbed Newton's first law.

2.3.2.1.7 Remarks

- Open the door of your lecture room, and the ball will leave the room on its way to infinity.
- Another reasoning of Galilei can also be related to this ball-and-gutter demonstration :

When the ball is going down, speed increases.

When the ball is going up, speed decreases;

So, when there is no going up or down, speed should remain the same!

2.3.2.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 37
- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 57
- PSSC, College Physics, pag. 221
- Young, H.D. and Freeman, R.A., University Physics, pag. 92

2.3.2.2 02 Walk and Ball

2.3.2.2.1 Aim

To demonstrate that vertical and horizontal motions are independent of each other

2.3.2.2.2 Subjects

- 1F30 (Inertia of Motion)

2.3.2.2.3 Diagram

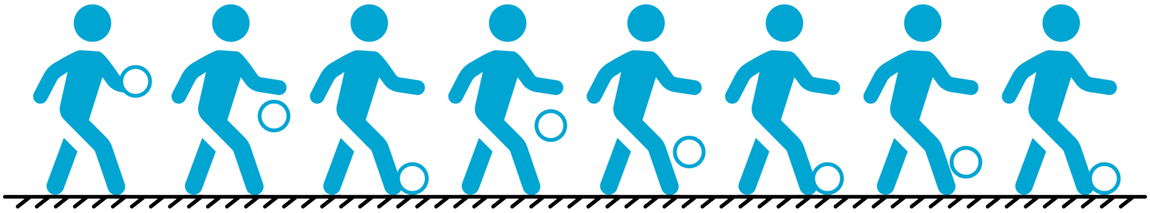


Figure 2.39: .

2.3.2.2.4 Equipment

- Basketball.
- Walking instructor.

2.3.2.2.5 Presentation

The instructor holds a basketball in his hand and walks at a constant speed in front of the lecture hall. While walking, he lets the basketball fall from his hand. The ball bounces up and down, gradually losing height, and eventually rolls along the floor. Despite this complex vertical motion, the ball keeps pace with the instructor, who continues walking at a constant speed. This shows that the horizontal velocity of the ball remains constant.

2.3.2.2.6 Explanation

In this situation, there are only forces acting in the vertical direction. In the horizontal direction, there is no force to change the horizontal movement, and so, the horizontal velocity remains the same as compared to the initial state.

2.3.2.2.7 Remarks

- The basketball will also gain some rotation upon hitting the ground. However, if you release the ball correctly (by letting it roll from your hand instead of simply dropping it), this rotation won't interfere with the demonstration. So even for this simple experiment, it's worth taking a few minutes to practise beforehand.
- If you simply drop the ball without any initial rotation, it will start rotating when it hits the ground and won't keep up with you. Of course, this phenomenon can be a great opportunity to spark a discussion with your students about energy.
- Also see the demonstration Throwing a basketball.

2.4 1G Newton's second law

2.4.1 1G10 F = ma

2.4.1.1 01 Throwing Eggs

2.4.1.1.1 Aim

To show that the force on an object is low as long as the acceleration/deceleration is low.

2.4.1.1.2 Subjects

- 1G10 (Force, Mass, and Acceleration)

2.4.1.1.3 Diagram

Figure 2.40: .

2.4.1.1.4 Equipment

- Raw eggs.
- Blanket (see Diagram).
- Clamping material.

2.4.1.1.5 Presentation

Mount the blanket in such a way that the bottom part is folded upward. Throw the egg at full speed at the blanket. On touching, the egg will not break! Invite the students to discuss why it doesn't break.

Then the explanation is given.

Finally, it is shown that when Δt is small, F will be high. This is done by throwing the same egg against the wall, and the consequences of the resulting high force are visible to all.

2.4.1.1.6 Explanation

According to Newton's second law, the force on the egg is not too large as long as it is not brought to rest too abruptly (in $F\Delta t = \mathrm{m}\Delta v$, Δt must be high). The blanket makes it slow down quietly.

2.4.1.1.7 Remarks

- Don’t hesitate to throw the eggs at high speed, as that is just the surprising part of this demonstration.
- Make sure that the bottom side of the sheet is not touching the table.

2.4.1.1.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 32-33
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 42

2.4.1.2 02 Bungee Jumper

2.4.1.2.1 Aim

To show that a bungee jumper falls with an acceleration greater than g.

2.4.1.2.2 Subjects

- 1G10 (Force, Mass, and Acceleration)
- 1D40 (Motion of the center of mass)

2.4.1.2.3 Diagram

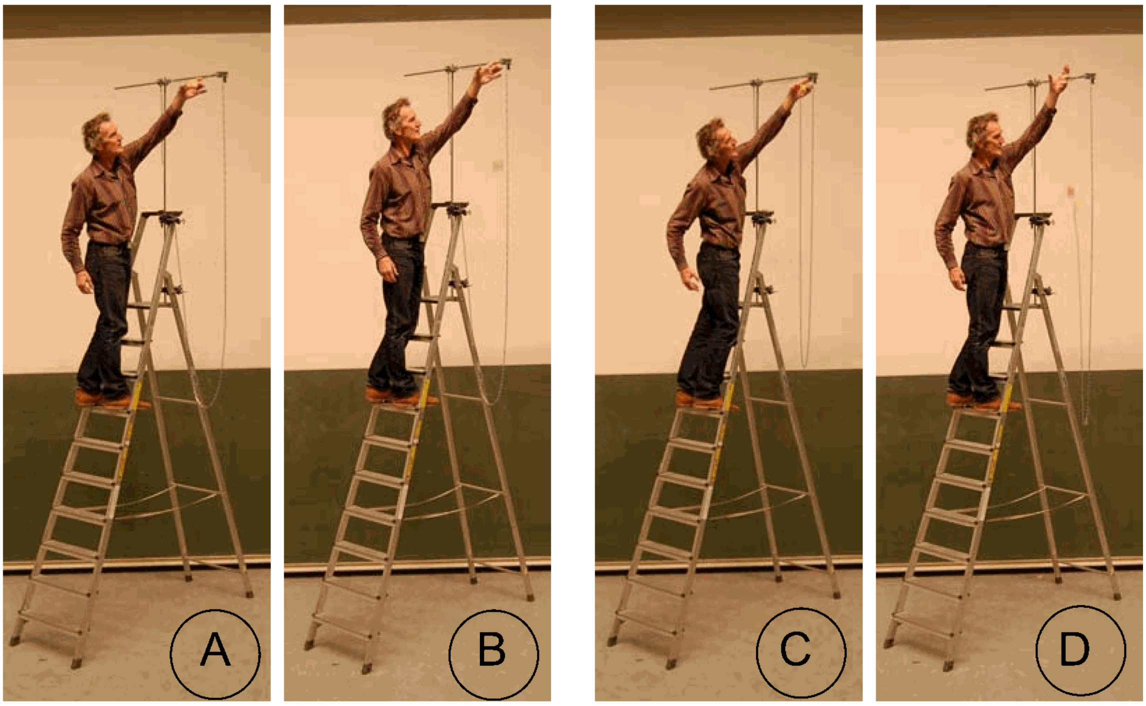


Figure 2.41: .

2.4.1.2.4 Equipment

- Chain, $l = 6$ m, a wooden block fixed to the end.
- Double ladder.
- 2 wooden blocks.
- 2 wooden blocks, one painted red, the other yellow, and fixed to the chain.
- Clamping material to attach the chain to the ladder (see Diagram).

2.4.1.2.5 Safety

- In the pictures, the demonstrator is standing with his hands free. (We did so to make the picture clearer.) **When you stand on the ladder, hold yourself!**

2.4.1.2.6 Presentation

The ladder is set up, and the chain with the yellow block is attached to it. It hangs from such a height that the yellow block just touches the ground when the chain is fully extended (see Diagram A, where the end with the yellow block is temporarily fixed to the ladder).

- Firstly, two small blocks of wood are kept fixed, squeezed between your thumb and forefinger. When you let them go, they fall together towards the ground and touch it at the same time (see Diagram B and Figure 2).

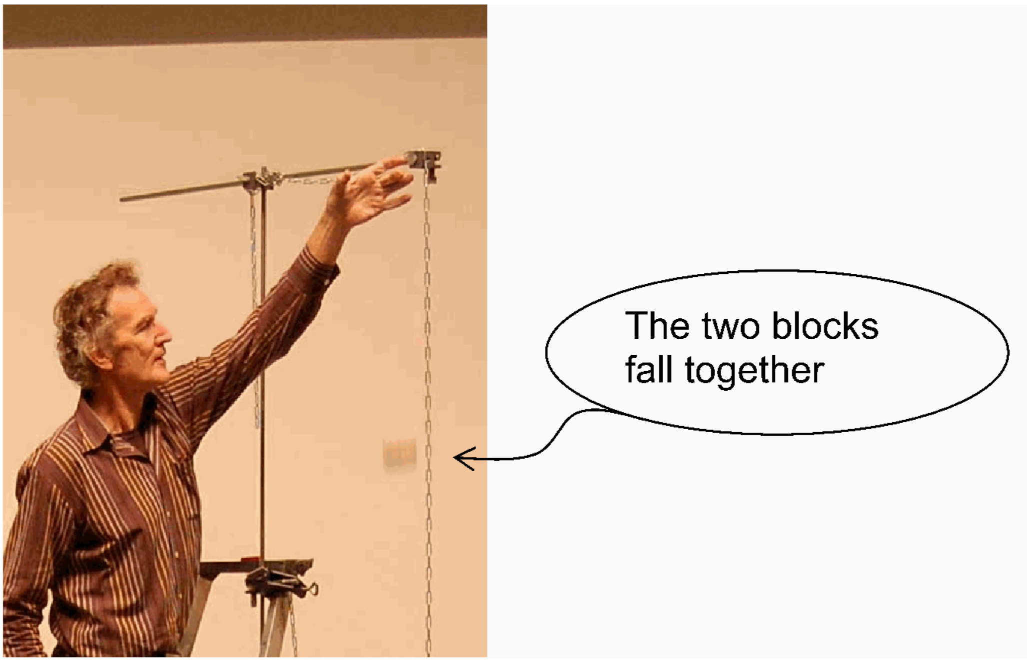


Figure 2.42: .

- The red and yellow blocks, which are attached to the chain, are held between your fingers (see Diagram C). Then, release them (see Diagram D) and observe that the yellow block touches the ground before the freely falling red block does. The difference in displacement can already be seen during the fall (see {numref}Figure {number} <1g1002_figure_2.png>), but it becomes especially clear at touchdown, when two distinct bumps are heard.

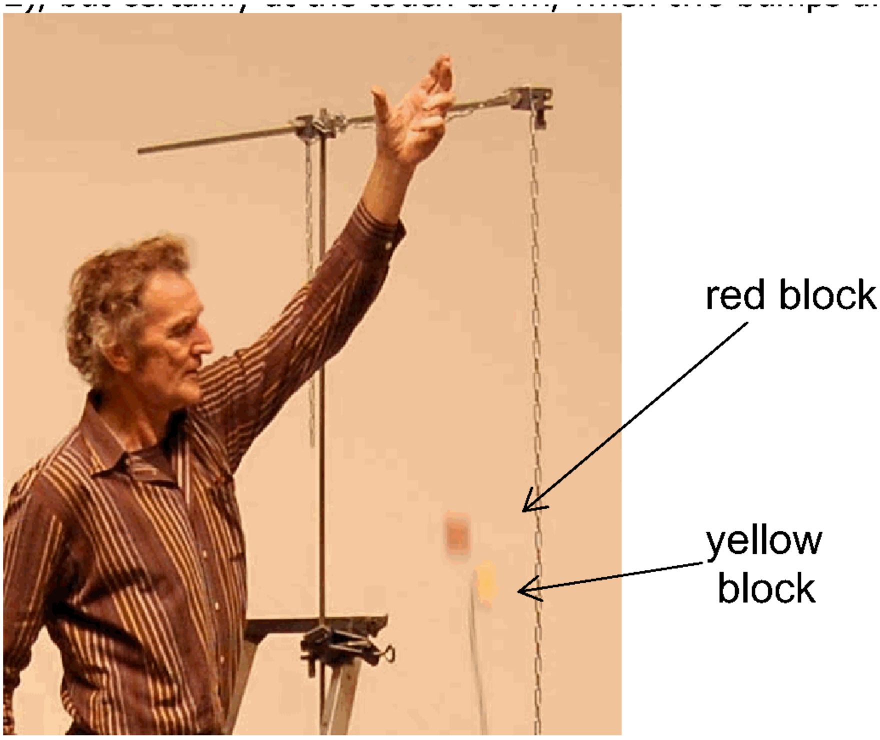


Figure 2.43: .

The block fixed to the chain reaches the ground before the free-falling block does. This means that the chained block has acceleration greater than g!

2.4.1.2.7 Explanation

The key to understanding the phenomenon is in recognizing that the mass of a real bungee cord is at least equal to the mass of the jumper. Therefore, the jumper on the end of the bungee cord can accelerate at a greater than g acceleration because the center of mass of the system is not accelerating more than g.

Approaching the problem from the point of view of energy leads to an acceleration (at the end of maximum stretch) of $a = g\left[1 + \frac{\mu(4+\mu)}{8}\right]$

where μ is the ratio of the mass of the cord to the mass of the jumper. (See Sources: The Physics Teacher) This equation shows that a is always greater than g and, depending on μ, can be substantially greater than g.

An explanation through a force model is more difficult. In the indicated literature, some intuitive insights are gleaned from the following considerations:

- The motion of a bungee cord and jumper is similar to that of a whip. When a whip is cracked, energy from the entire whip is transferred via internal forces to the tip in such a way that initial speeds of a few meters per second become supersonic at the tip.
- Continuously, the portion of the chain at the bottom of the loop is coming to rest. Since it was moving downward, an upward force is required on this part of the system. Since this upward force is an internal force, and Newton's Third Law must be satisfied, there must be an equal and opposite downward force somewhere within the system. A portion of this reaction force acts on the stationary part of the chain, but another part acts on the falling portion, causing it to accelerate.
- The falling portion of the chain can be thought of as a rocket moving downward. It is "ejecting" the chain as its "fuel" in such a way that the ejected chain is always at rest. So this ejected chain is "fired" upward, producing a downward "thrust" on the remaining portion of the moving chain.

2.4.1.2.8 Remarks:

- When the block is attached to the chain containing an acceleration sensor, its motion can be easily recorded using a data acquisition system. We often perform the demonstration this way, and the results align well with theoretical predictions.
- In this setup, no ladder is required. Dropping the block from a height of approximately 2 metres yields reliable results.

(*Note: In this version of the demonstration, the block with the sensor is prevented from reaching the ground to protect the acceleration sensor.*)

- As an alternative to using an acceleration sensor, the demonstration can also be performed with a Rotary Motion Sensor (see Sources: Pasco Newsletter).

2.4.1.2.9 Sources:

- Pronk, C./Biegstraaten,A.W.W.M., Syllabus "Inleiding Computergebruik", pag. 191-218.
- American Journal of Physics, pag 776 (Vol. 74-9; 2006).
- Pasco Newsletter, Vol. 1/Issue 1 (Fall 09), pag. 6.

2.4.1.3 03 Pulling a Thread

2.4.1.3.1 Aim

To use Newton's second law to explain a surprising demonstration.

2.4.1.3.2 Subjects

- 1G10 (Force, Mass, and Acceleration)

2.4.1.3.3 Diagram

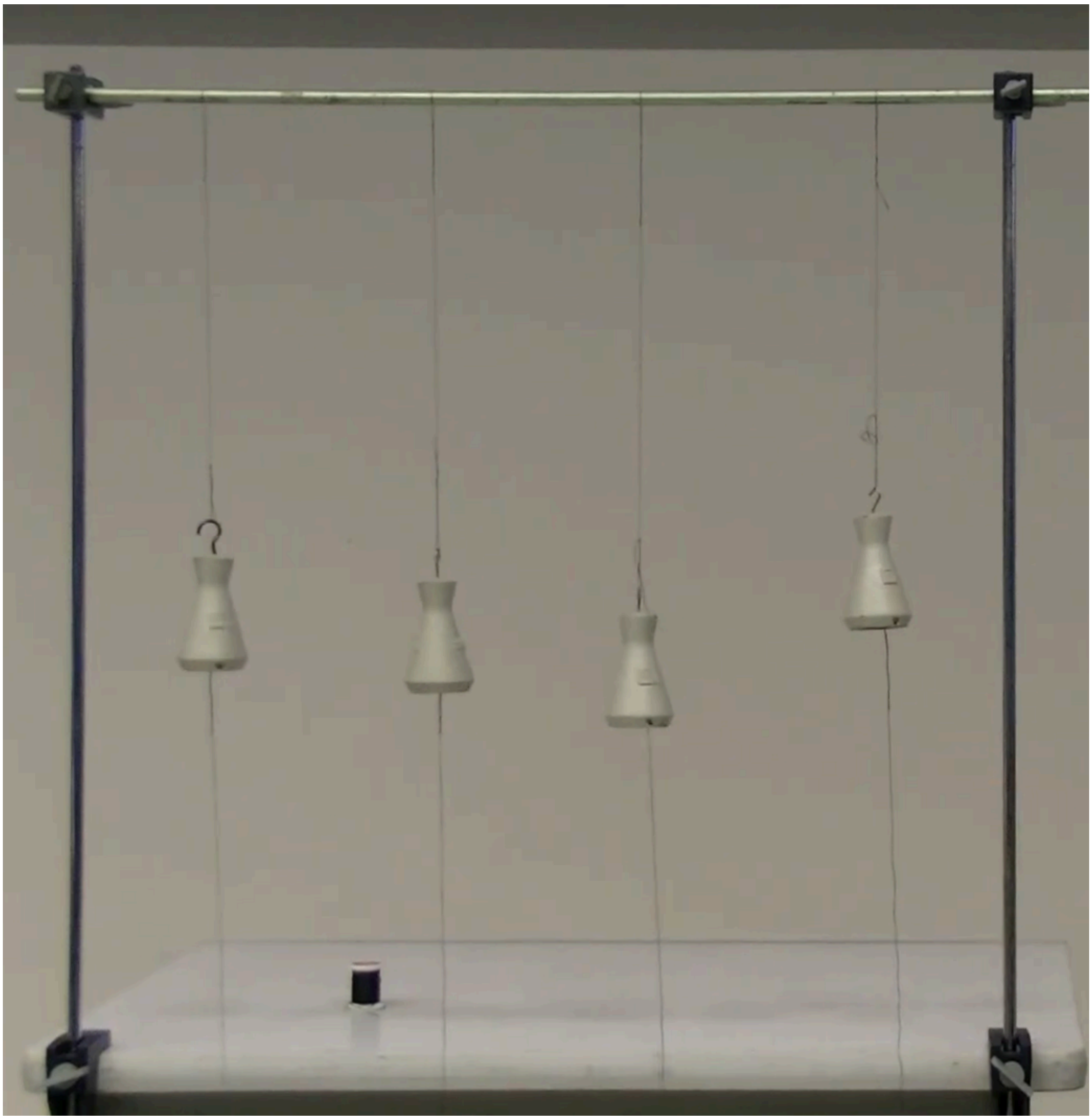


Figure 2.44: .

2.4.1.3.4 Equipment

- Mass of 5 kg.
- 4 identical masses, 1 kg each (see Remarks).
- Thin cotton thread.
- A bar to hang the masses.

2.4.1.3.5 Safety

- Mind the falling weights! You can put a foam cushion under the weights.

2.4.1.3.6 Presentation

1. The mass of 5 kg is suspended by a strong thread. Through a thin cotton thread, it can be displaced horizontally by slowly pulling on this thread. However, when a quick jerk is given, the thin cotton thread breaks.
2. Using a thin thread, the two masses of 1 kg are hung on to the bar. On the bottom side of each mass, a free-hanging thread is tied. Ask the students which thread will break, the upper or the lower, when we slowly increase the pulling force on the bottom thread. Slowly pull the lower thread of one mass. This will cause the upper thread to break. Then ask the students which thread will break when we increase the pulling force on the lower thread very fast. Pull the lower thread on the second mass rapidly. This time, the lower thread will break.

2.4.1.3.7 Explanation

1. The tension (T) in the thin thread equals the force applied to the thread: $F=T$. This force accelerates m (see Figure 2). A jerk means that a is high; a high $F(=ma)$ is needed for that. The tension in the thread will be high, resulting in the breaking of this thread.

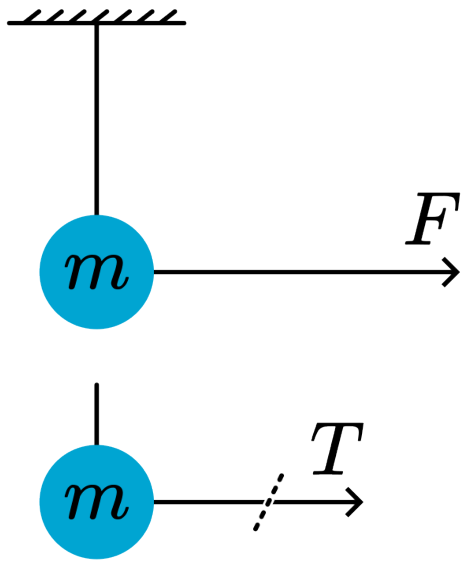


Figure 2.45: .

2.

a. A general explanation When we increase the pulling force slowly, a low acceleration a is imparted to the mass. The mass can follow this acceleration, causing a stretch in the upper thread. The upper thread also supports the weight of the mass, so it is the thread that eventually breaks. However, when we try to give the mass a high acceleration suddenly, the inertia of the mass prevents it from following the motion of our hand quickly; it lags. As a result, the thread between our hand and the mass experiences a large stretch and breaks. Meanwhile, the upper thread remains unaffected because the mass is no longer moving downwards; it only supports the weight of the mass, as it did before.

```
*b. An analytical explanation* Using Newton's second law gives still more insight.
The forces acting on $m$ are $T_{1}, T_{2}$ and $m g$ (see {numref}`Figure
{number} <1g1003_figure_2.png>`). $T_{1}$ is the tension in the upper thread. The
tension in the lower thread is $T_{2}$. The acceleration $a$ that $m$ obtains can
be determined by: $m a=T_{2}+m g-T_{1}$

It follows: $m a-m g=T_{2}-T_{1}$ or $m(a-g)=T_{2}-T_{1}$
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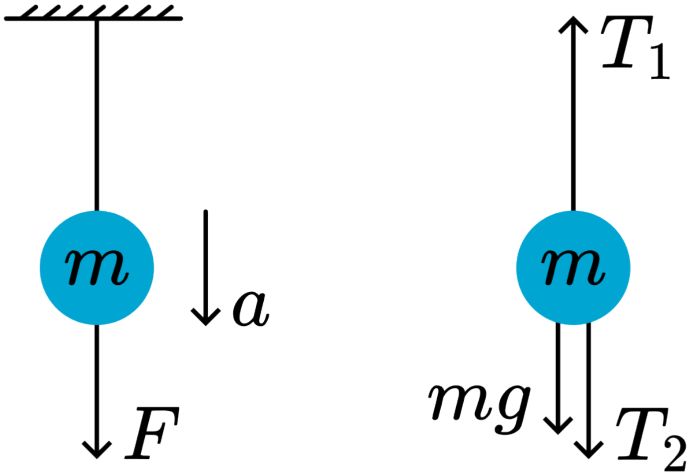


Figure 2.46: .

As long as $a < g$, then $T_2 < T_1$ and the top-thread will break. But when $a > g$, then $T_2 > T_1$ and the bottom-thread will break.

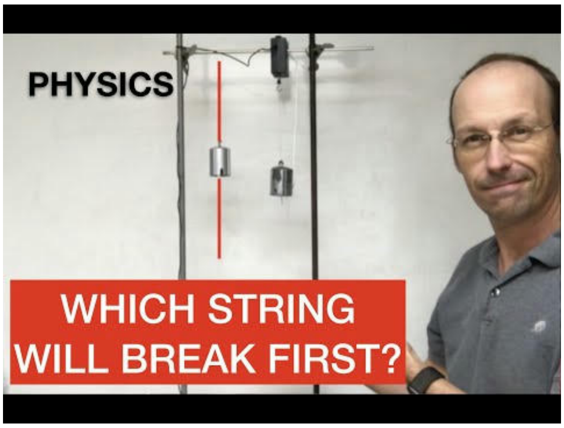
This last explanation shows the power of Newton's second law: now it is possible to say something about the acceleration a, which determines what will happen (i.e., which thread will break).

(A student asked: what will happen when $a = g$?)

2.4.1.3.8 Remarks

- We suspend 4 masses to perform the demonstration twice (without tedious knotting).
- Presentation 1 can be directly referred to the common experience that when pulling a damaged car by another car, the pulling car should start slowly, otherwise the pulling rope will break.
- A variation to presentation 1 is attaching a thread to a mass and slowly pulling upward, lifting the mass. Repeating this with a jerk will break the thread.
- In a more sophisticated analysis, also the elasticity and length of both cords should be taken into account (see AJP- and PT-articles mentioned in Remarks).

2.4.1.3.9 Video Rhett Allain



(a) (b)

Figure 45: :align: center - Scan the QR code or click here to go to the video.

2.4.1.3.10 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 30.
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 85.
- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. M16.
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 46-47.
- American Journal of Physics, pag. 860-862 (Vol. 72-7; 2004).
- The Physics Teacher, pag.504-507 (Vol. 34; Nov. 1996).

2.5 1H Newton's third law

2.5.1 1H10 Action and Reaction

2.5.1.1 01 Who is the Strongest in a Collision?

2.5.1.1.1 Aim

To show that Action=-Reaction is always true.

2.5.1.1.2 Subjects

- 1H10 (Action and Reaction)

2.5.1.1.3 Diagram

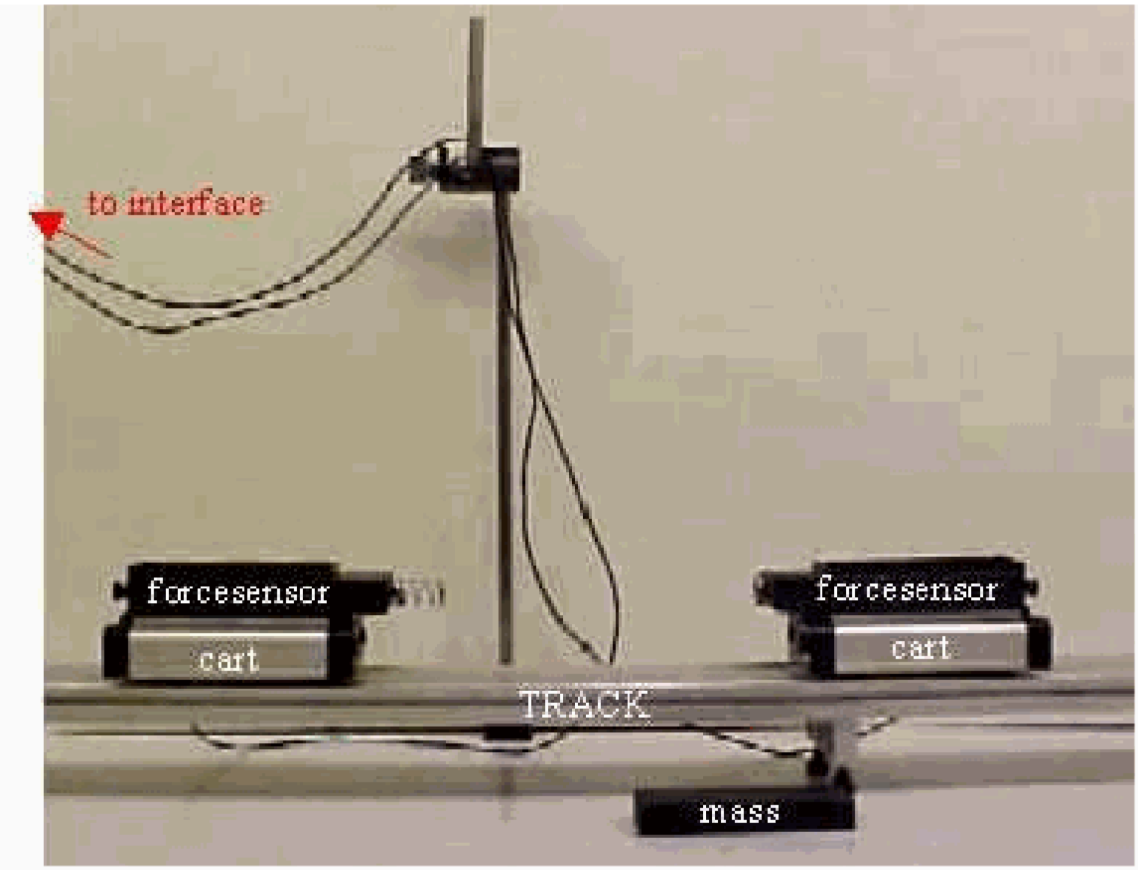


Figure 2.50: .

2.5.1.1.4 Equipment

- Track, 2.2 m.
- Two collision carts
- Two force sensors, one of them mounted with a spring.
- Mass, 1 kg.
- Interface and data-acquisition system (we use PASCO ScienceWorkshop).
- Projector to project on the monitor screen.

2.5.1.1.5 Presentation

Presentation: The force sensors are attached to each cart and connected to the interface (see Diagram). The software is prepared to read and graphically display both forces (-1 to $+12$ N) during about 10 s. Both carts are positioned on the track at about 5 m away from each other. The data recording is started, and both carts are pushed towards each other manually. The recording is stopped after a collision occurs. Students can now observerve the registered force data (see Figure 2 left).

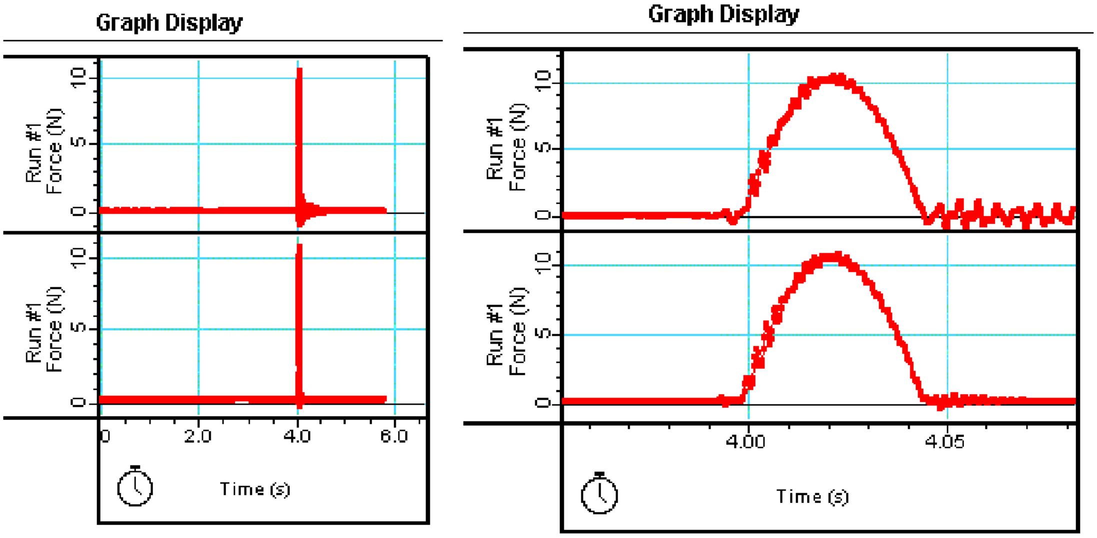


Figure 2.51: .

The part of the data that resembles the collision is magnified (see Figure 2 right). It can be seen that at any moment, the force on both carts is the same. 1 kg is added to one of the carts. The demonstration is repeated, again showing that the forces registered during the collision are the same at all times both carts!

2.5.1.1.6 Explanation

Newton's third law states $\vec{F}_{A \to B} = -\vec{F}_{B \to A}$, which is supported by the results of these demonstrations.

2.5.1.1.7 Remarks

- The speed you give the carts by hand is, of course, not important. But when students doubt, redo a run with one cart standing still or moving at a different speed in the same direction. The data-registration will always show $\vec{F}_{A \to B} = -\vec{F}_{B \to A}$.
- In the right graph of Figure 2 can be seen which cart has the spring mounted to its force sensor: A damped vibration is seen after the collision. The force sensor itself also vibrates after the collision, as shown in the graph of the other force sensor.

2.5.1.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 119

2.5.1.2 02 Who is Pulling?

2.5.1.2.1 Aim

To show the reality of Action=-Reaction.

2.5.1.2.2 Subjects

- 1H10 (Action and Reaction)

2.5.1.2.3 Diagram

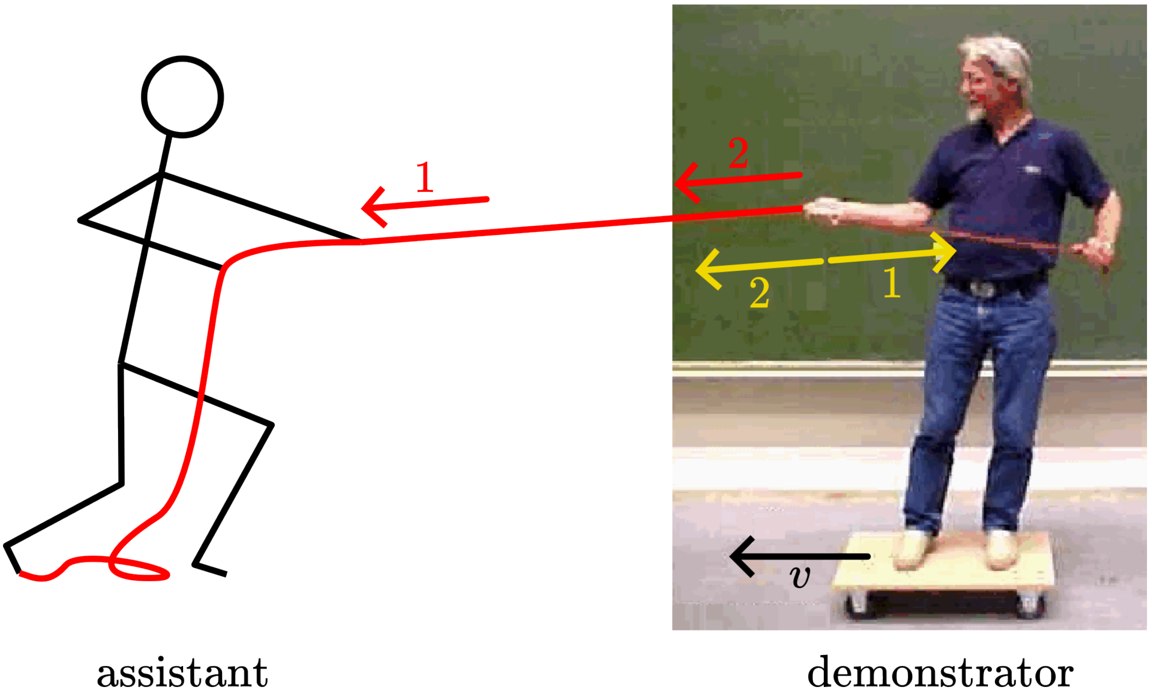


Figure 2.52: .

2.5.1.2.4 Equipment

- Light cart that rolls easily.
- Rope, $l = 10$ m.
- An assistant to the demonstrator.

2.5.1.2.5 Presentation

The demonstrator and his assistant are standing each at one side of the lecture hall. Each of them holding one end of the rope. The demonstrator steps on the cart, and then his assistant hauls in the rope. The cart with the demonstrator is approaching the assistant. The demonstrator returns to the point of departure, but now the demonstrator, on his cart, hauls in the rope. Again, the cart with the demonstrator is approaching the assistant.

(A variation to the last demonstration can be shown when instead of the assistant holding the rope, it is tied to the wall.)

2.5.1.2.6 Explanation

The demonstration shows that the effect of pulling by either the assistant or the demonstrator is the same: the cart + demonstrator moves towards the assistant. The resultant force has to be directed towards the assistant in both situations. So in both cases, the rope pulls the demonstrator toward the assistant (see Diagram; red arrows: first demonstration; yellow arrows: second demonstration). The yellow arrows show Newton's third law. (And all arrows apply in both demonstrations!)

2.5.1.2.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 119

2.5.1.3 03 Trying Hard to Pull Differently

2.5.1.3.1 Aim

To show (again) the validity of Newton's third law.

2.5.1.3.2 Subjects

- 1H10 (Action and Reaction)

2.5.1.3.3 Diagram

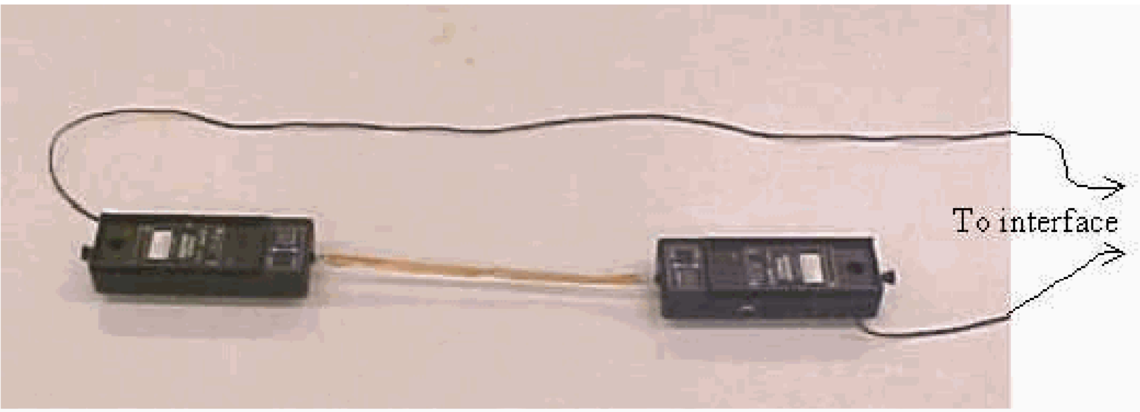


Figure 2.53: .

2.5.1.3.4 Equipment

- Two force sensors.
- Rubber band.
- Data acquisition via Science Workshop.
- Projector to project on the monitor screen
- Trying hard to pull differently

2.5.1.3.5 Presentation

On the monitor, two graphs are presented for each force sensor. The software is set in such a way that one of the sensors presents $-F$.

Two demonstrators take each of the sensors. They start both pulling randomly. The display shows clearly that whatever they do, both force sensors measure the same force: $-F$ and $-F$ (see Figure 2).

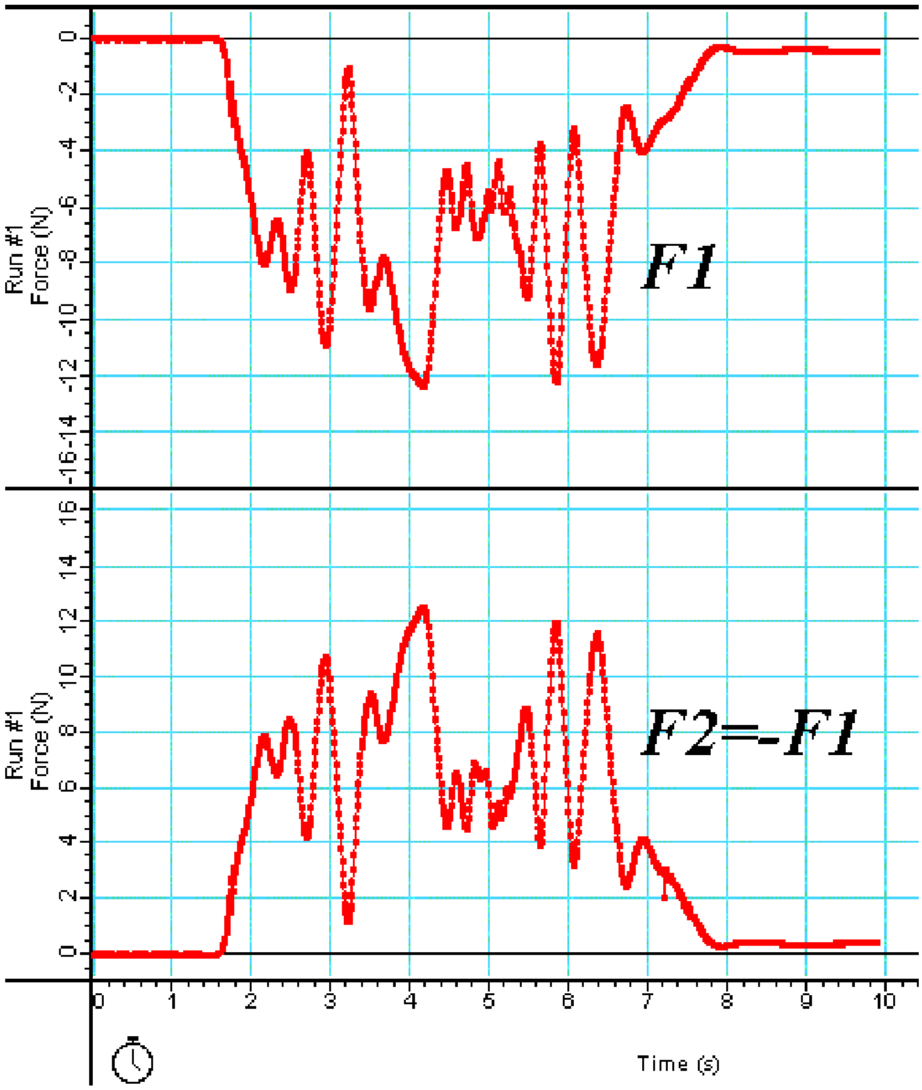


Figure 2.54: .

Also, when one of the demonstrators holds his force sensor without moving it, while the other demonstrator moves again randomly, then both force sensors register an equal F and $-F$. The registration does not reveal which of the two demonstrators is not moving his sensor.

2.5.1.3.6 Explanation

Again, the validity of Newton's third law is shown.

2.5.1.3.7 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 82
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 119
- McComb,W.D., Dynamics and Relativity, pag. 1

2.5.1.4 04 Bottle Rocket

2.5.1.4.1 Aim

- To show the effect of a (horizontal) impulse.
- To give an example of Newton's third law.

2.5.1.4.2 Subjects

- 1H10 (Action and Reaction)
- 1N10 (Impulse and Thrust)
- 1N22 (Rockets)

2.5.1.4.3 Diagram

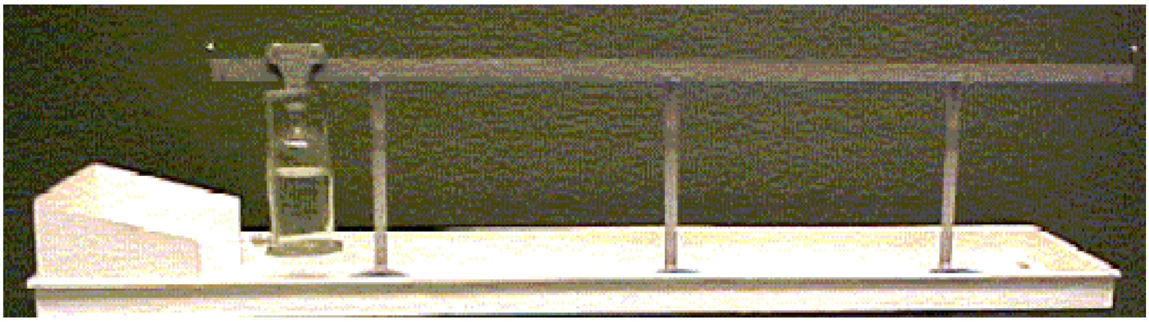


Figure 2.55: .

2.5.1.4.4 Equipment

- Rail ($l = 2.50$ m)
- A cart with wheels, hanging on the rail.
- Decantation bottle with cork in bottom opening (opening $d = 25$ mm).
- Tray as long as the rail to catch the water.
- Shield at the beginning of the tray.

2.5.1.4.5 Safety

- It is inevitable that in this demonstration, water will spill on the ground. In our lecture hall this makes the ground very slippery!

2.5.1.4.6 Presentation

The bottle is filled with water and is at rest. Then the cork is pulled out of the bottom opening. The cart with the bottle starts moving and accelerates along the rail.

2.5.1.4.7 Explanation

The cart with the bottle accelerates, meaning that a horizontal force acts on this cart. This force (F) arises due to the impulse of the water streaming out of the bottle $F = -v\frac{\Delta m}{\Delta t}$, in which v is the velocity of the water relative to the bottle and $-\Delta m$ the change in the mass of the bottle with water.

The mechanism of movement can also be explained by Newton's third law. The cart with water pushes a part of itself (water) away. Force is needed for that. Then the water exerts a reaction force on the cart.

2.5.1.4.8 Remarks

- The velocity (v) of the water flowing out of the bottle can be reduced by placing a narrow tube in the cork. The reduced velocity of the cart can be observed.
- This demonstration can be converted to an experiment by using commercial water rockets. Then the effects of the exhaust velocity and the mass ejected can be demonstrated by:

- pumping the rocket at various air pressures;
- first using only air and then using a mixture of air and water.

2.5.1.4.9 Video Rhett Allain

(a)

(b)

Figure 52: :align: center - Scan the QR code or click here to go to the video.

2.5.1.4.10 Sources

- Roest, R., Inleiding Mechanica, pag. 96.
- Borghouts, A.N., Inleiding in de Mechanica, pag. 93.
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 170.
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 33.

2.5.1.5 05 Magnet Symmetry

2.5.1.5.1 Aim

To confirm Newton's third law. To confirm conservation of angular momentum.

2.5.1.5.2 Subjects

- 1H10 (Action and Reaction)
- 1N20 (Conservation of Linear Momentum)
- 1Q40 (Conservation of Angular Momentum)

2.5.1.5.3 Diagram

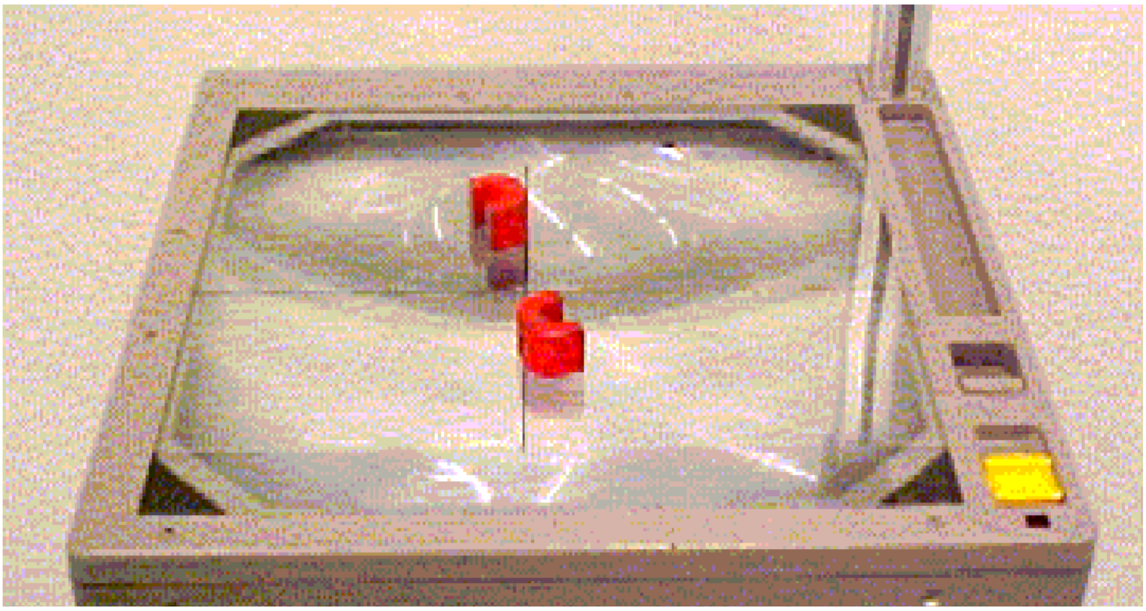


Figure 2.59: .

2.5.1.5.4 Equipment

- Two small horseshoe magnets.
- Transparency.
- Overhead projector.

2.5.1.5.5 Presentation

The axes of a rectangular coordinate system are drawn on the transparency. The transparency is placed on the overhead projector. The two horseshoe magnets are held together with like poles touching and positioned at the origin of the coordinate system. When releasing, the magnets travel a short distance. It can be observed that they always land in a symmetric pattern: symmetric in translation and rotation. (Both magnets need not be equally "strong"; usually, they are not equally "strong". This can be shown by lifting a row of paperclips by both magnets: One magnet lifts more than the other.)

2.5.1.5.6 Explanation

- The symmetric pattern shows evidence of both a mutual force as well as a mutual torque. Flying apart into a symmetric configuration confirms Newton's third law. That the magnets are not equally strong does not change the equality of action and reaction force magnitudes.
- The observed equality in rotation can also be explained using conservation of angular momentum: No external forces are acting, so angular momentum, being zero at the beginning of the demonstration, has to remain zero during the movement of the magnets. The identical magnets turn the same angle in opposite directions.

2.5.1.5.7 Remarks

- Releasing the two magnets needs some practice (see Figure 2); both fingers need to move away from the magnets simultaneously.

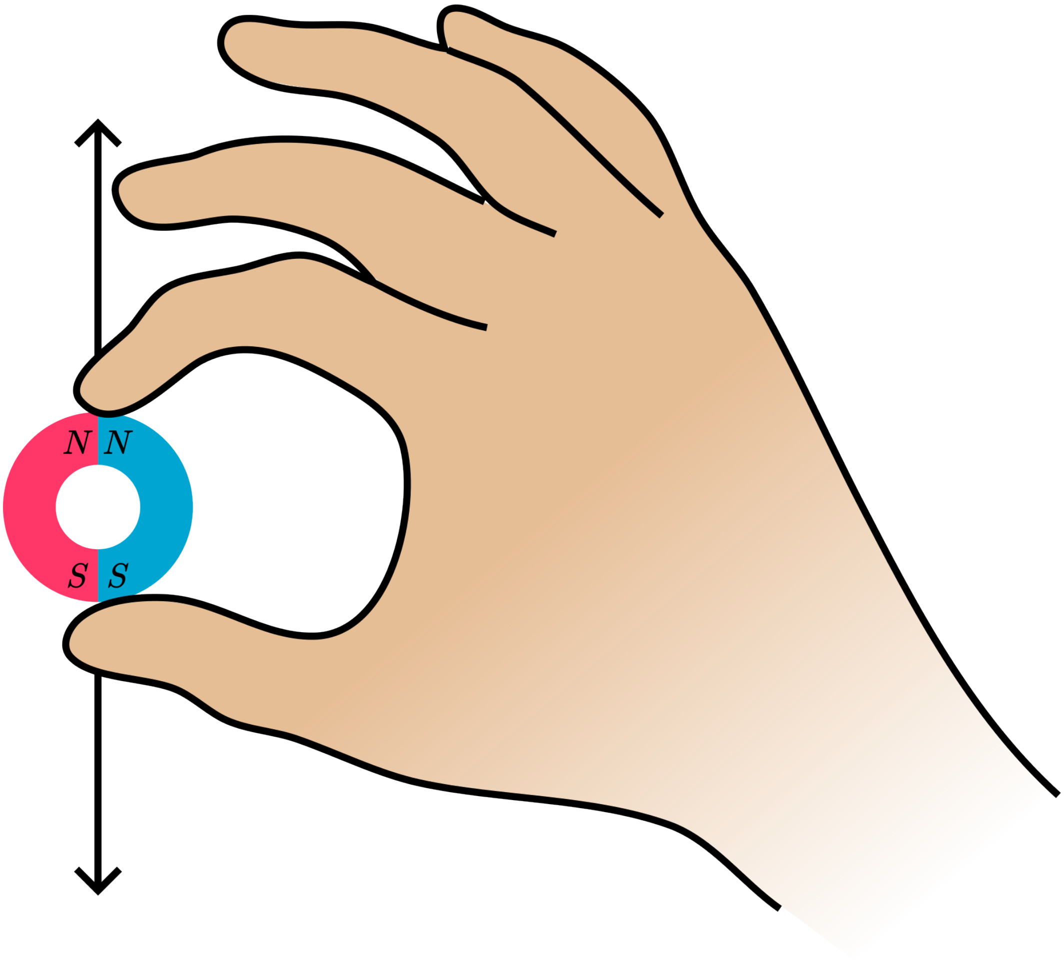


Figure 2.60: .

2.5.1.5.8 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 35-36
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 102
- Young, H.D. and Freedman, R.A., University Physics

2.5.1.6 06 Recoil of a Water Jet

2.5.1.6.1 Aim

To show an example of Newton's third law.

2.5.1.6.2 Subjects

- 1H10 (Action and Reaction)
- 1N22 (Rockets)

2.5.1.6.3 Diagram

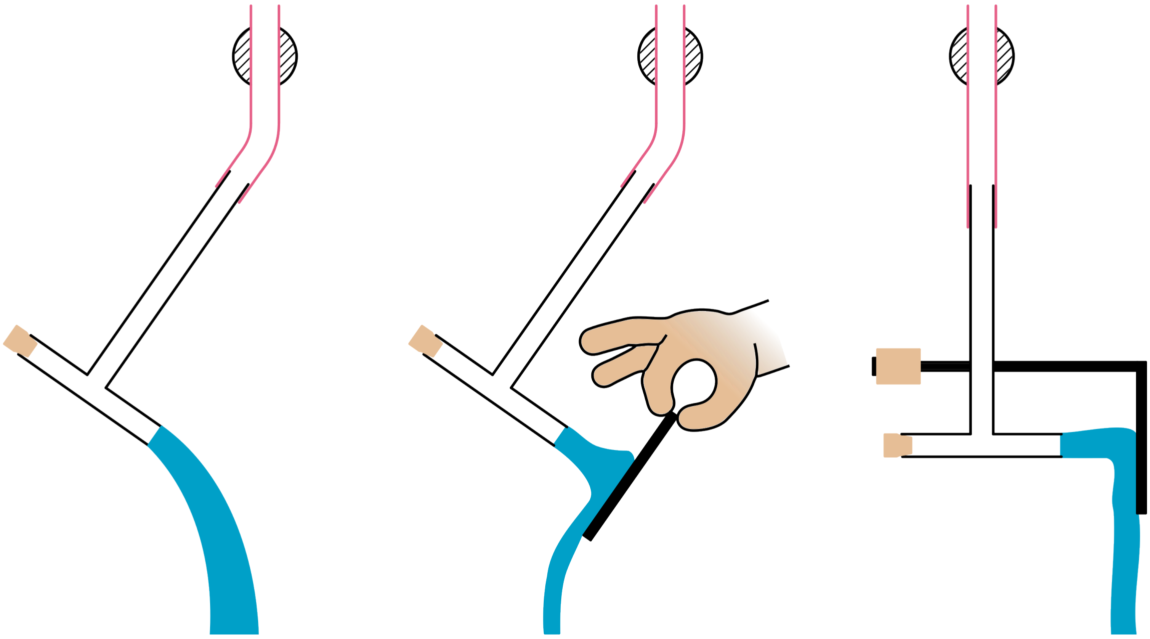


Figure 2.61: .

2.5.1.6.4 Equipment

- Tube with a T-junction, ∅10
- Rubber hose (about 2 meters)
- Faucet
- A tray to catch the water

2.5.1.6.5 Presentation

The rubber hose with a T-junction hangs vertically down. Opening the faucet makes the end of the hose move away.

Figure 2.62: .

When a plate is held in the water-jet, nothing changes.

When the plate is fixed to the end of one side of the T-junction, the hose stays vertically in its position.

2.5.1.6.6 Explanation

To convert a downward water flow into a sideways water flow, the T-junction has to exert a force on the water. The reaction to this force is responsible for the recoil to the other side. When a plate is placed in the outgoing water stream, it also exerts a force on the plate. When this plate is fixed to the T-junction, these two forces cancel, so there is no recoil

2.5.1.6.7 Remarks

This demonstration can be performed by the students themselves, by giving each of them a flexible soda straw, giving it a 90° bend (Figure 3).

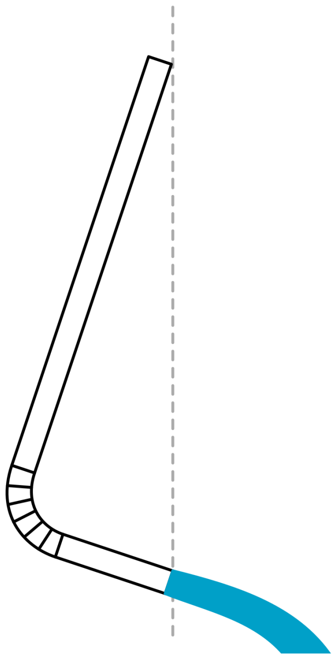


Figure 2.63: .

Blowing hard in the long part of the straw, the free end recoils. The no-recoil can be observed when a small plastic bag is attached to the end of the straw.

2.5.1.6.8 Sources

- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 169
- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 34
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 35

2.5.1.7 07 Strong Magnet, Weak Paperclip

2.5.1.7.1 Aim

To show that Newton's third law remains valid, even in the more complex cases.

2.5.1.7.2 Subjects

- 1H10 (Action and Reaction)

2.5.1.7.3 Diagram

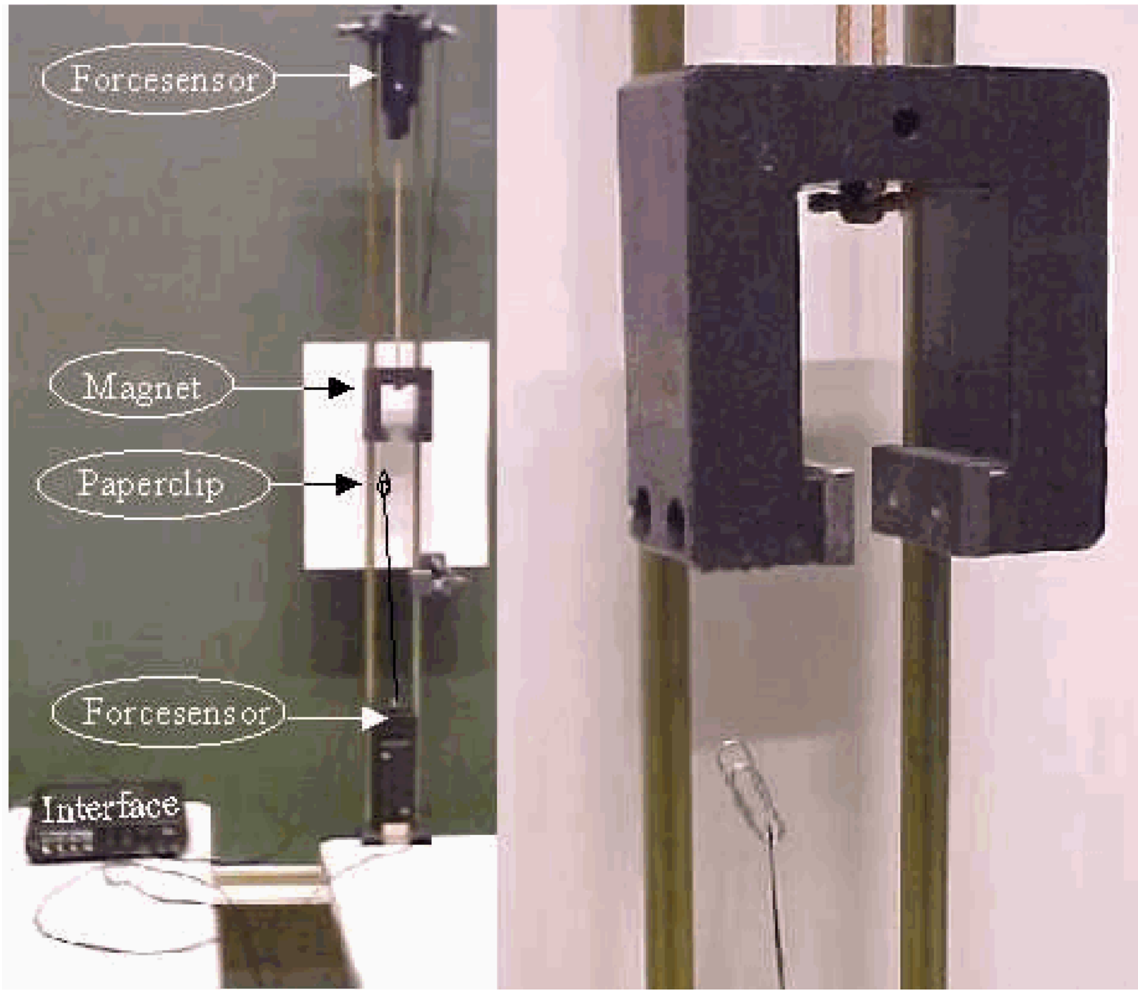


Figure 2.64: .

2.5.1.7.4 Equipment

- Strong horseshoe magnet, attached to a rope.
- Paperclip, attached to a string.
- Two force-sensors.
- Bars (aluminium) and clamps to build the set-up (see Diagram).
- Interface and computer with data-acquisition software.
- A camera and a large screen monitor.
- Projector to project the graphs.

2.5.1.7.5 Presentation

The demonstration is presented as a tug-of-war between a heavy, strong horseshoe magnet and a light paperclip. After demonstrating the strength of our magnet, the setup is as shown in the Diagram. Using a camera, the magnet and paperclip are presented in more detail on a large monitor screen. The graphs, still blank, are projected using a projector (see Figure 2).

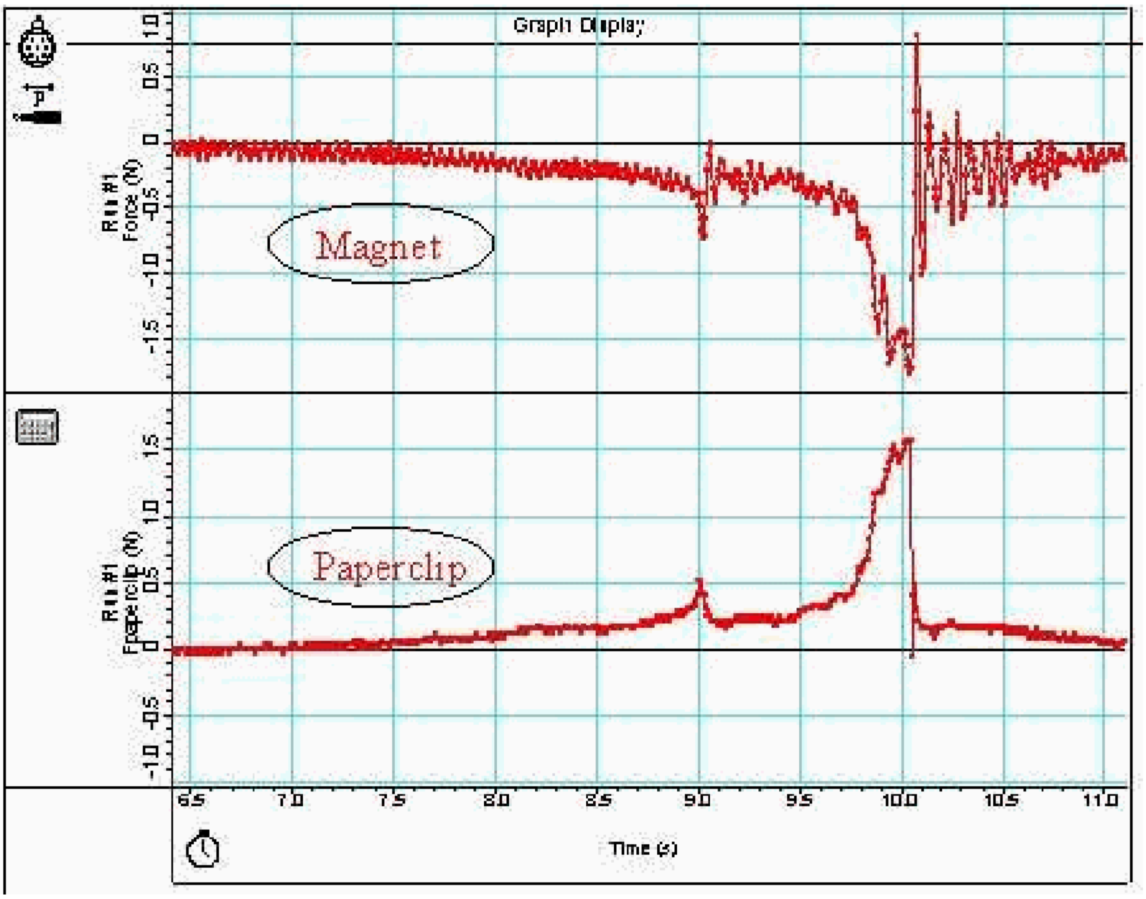


Figure 2.65: .

First, the force sensors are set to zero. Students see this in the projected graph while we use the monitor mode of the data-collection program. The effect of pulling by hand on the force sensors is shown. (We make the graphs in such a way that when pulling the magnet downward, its graph goes negative. Vise versa, when pulling the paperclip upwards, its graph goes positive.)

Then, the data is collected as a recording and is acquired by sliding the lower force sensor upward along the aluminium bars. The paperclip is brought closer to the magnet until it touches one of the poles. Afterward, the lower force sensor is lowered again (detaching the paperclip from the magnet pole) to its point of origin. The data collection is stopped.

The recorded data are discussed now; a region of interest can be selected (see Figure 2). It can be observed that the force-time relationship is a complicated one; nevertheless, Newton's third law is valid: at every moment in time, we see $F_{paperclip} = -F_{magnet}$.

2.5.1.7.6 Explanation

There is no explanation here, since Newton's laws are just a set of hypotheses which appear to agree with our everyday experience. Our demonstration is another experiment demonstrating the validity of the third law.

2.5.1.7.7 Remarks

- In the demonstration, inevitable vibrations arise, especially in the data of the force sensor with the heavy magnet. An appropriate sampling rate and data-averaging should be selected to minimize these vibrations in the presented data. However, the students could also visually take the average of the graph of the magnet and see that it is in accordance with the graph of the paperclip.

2.5.1.7.8 Sources

- The Physics Teacher, Vol.39, October2001, pag. 392-393

2.6 1J Rigid Bodies

2.6.1 1J20 Equilibrium

2.6.1.1 01 Equilibrium and Potential Energy

2.6.1.1.1 Aim

To show a counter-intuitive example of stable equilibrium that can be explained through minimum potential energy

2.6.1.1.2 Subjects

- 1J20 (Stable, Unstable and Neut. Equilibrium)

2.6.1.1.3 Diagram

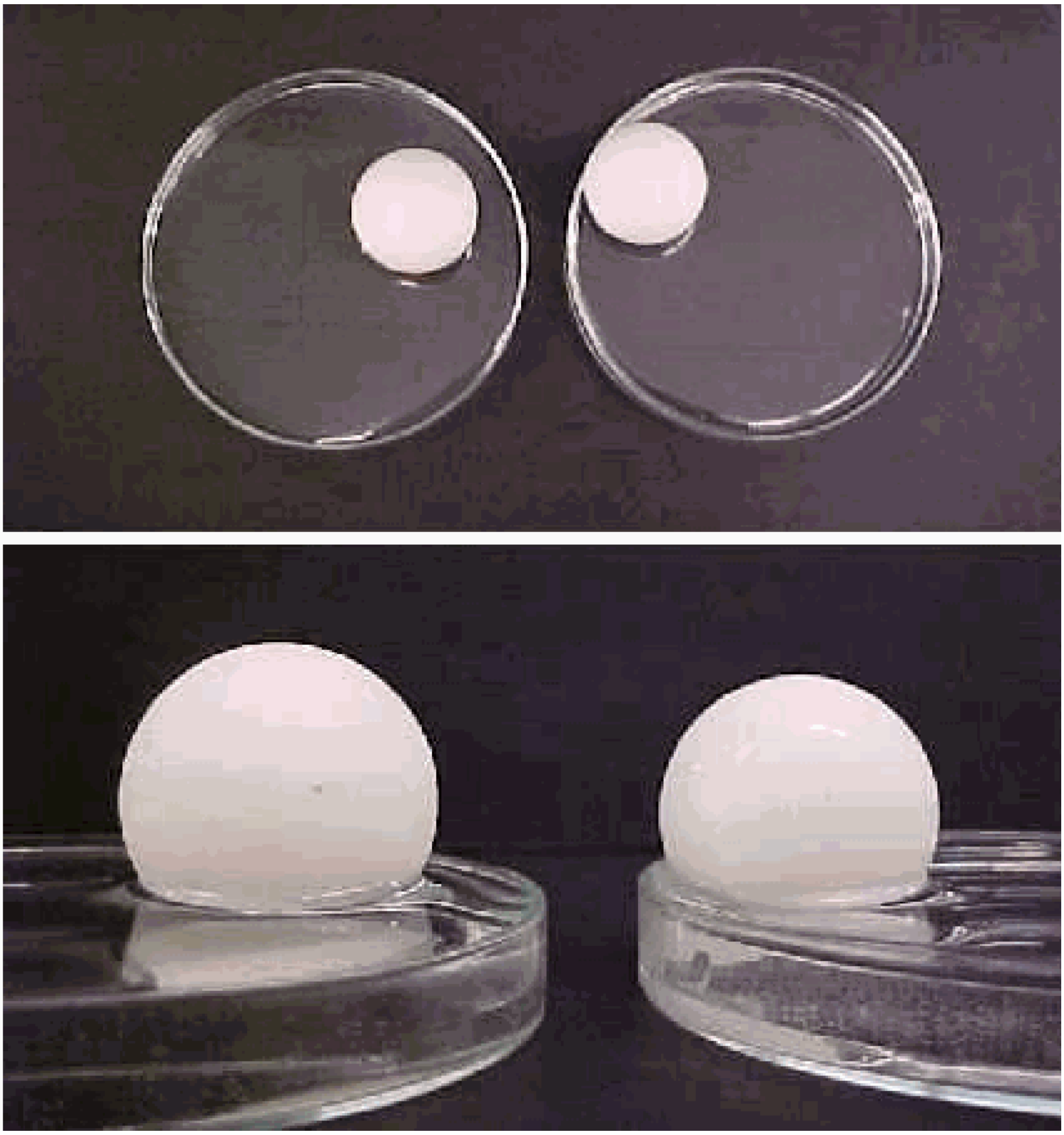


Figure 2.66: .

2.6.1.1.4 Equipment

- Two Petri dishes.
- Two table tennis balls

2.6.1.1.5 Presentation

One Petri dish is filled half with water, and the table tennis ball is floating in it. It moves a bit, and at a certain moment, it will hit the rim and stick to it. When carefully observing, as the ball approaches the rim of the petri dish, it will accelerate toward it! There is an attractive force acting.

The other Petri dish is filled with water to the rim and even a little bit more; the water level is higher than the rim. The table tennis ball is floating around but never touches the rim. Again, carefully observing the motion of the ball, it can be seen that as the ball approaches the rim, it slows down and is repelled. There is a repelling force working.

2.6.1.1.6 Explanation

The difference between the two Petri dishes is the shape of the meniscus of the water surface. The dish that is half-filled with water has a hollow meniscus, while the other one has a spherical meniscus. The ball in the half-filled dish floats upwards when approaching the rim. This is the counterintuitive part of the demonstration. The same holds for the ball floating in the filled dish; this ball “refuses” to float downwards when approaching the downward incline.

The key to understanding is the condition for equilibrium in a conservative force field, which reads: $dE_p = 0$. This equilibrium is stable when E_p (potential energy) is a minimum. Applying this to our demonstration, we have to consider not only the table tennis ball but also the water it displaces. To achieve an equilibrium, the common center of mass of these two should be positioned as low as possible, and so, the table tennis ball as high as possible. In the situation with the hollow meniscus, this is in the water at the rim. In the situation with the spherical meniscus, this is in the water away from the rim (see also Figure 2).

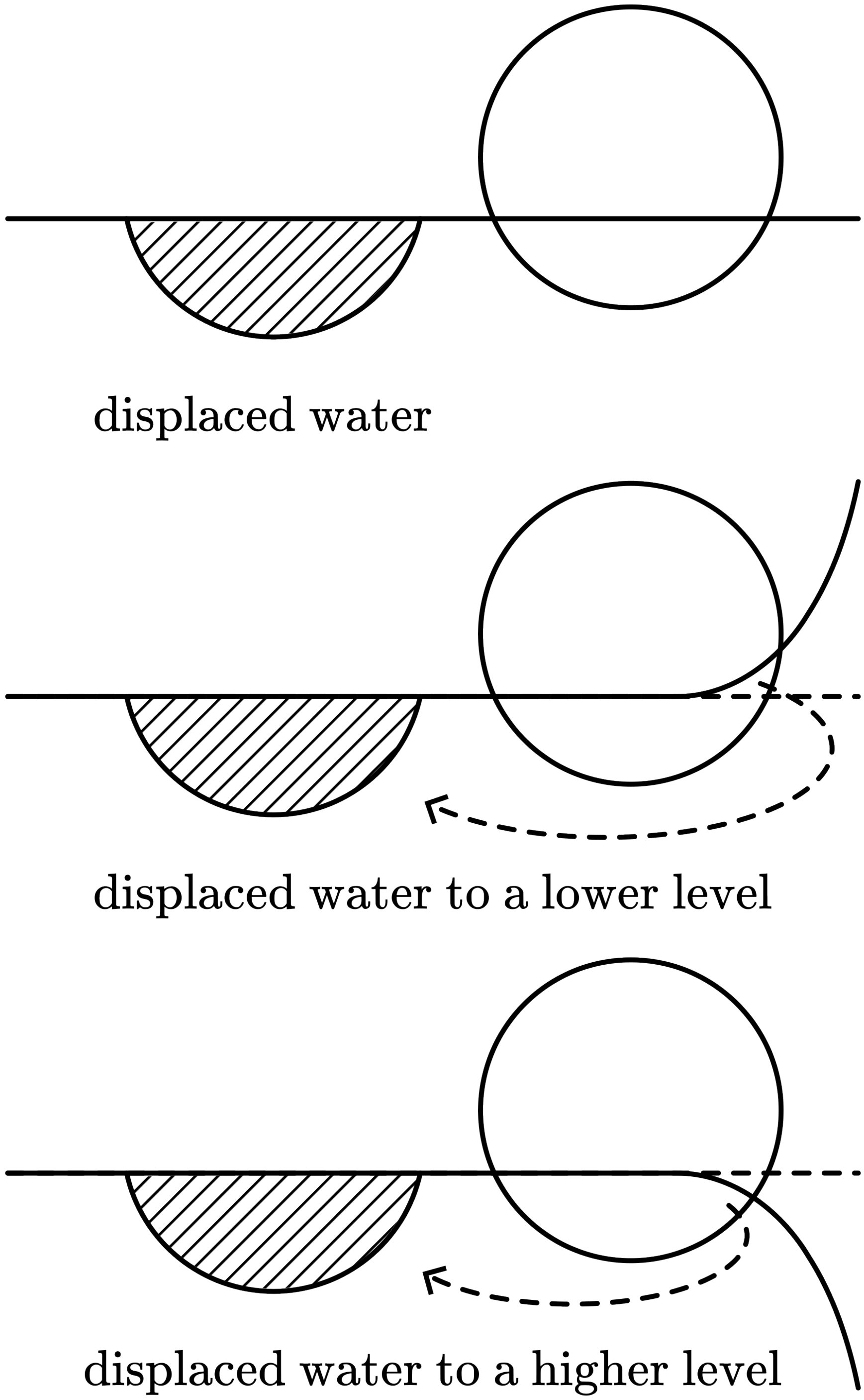


Figure 2.67: .

2.6.1.1.7 Remarks

- This demonstration can be shown on an overhead projector.
- You can also show this demonstration with one ball and a Petri dish. Place the ball in the Petri dish and slowly fill the dish with water. When the ball is floating, it will first stick to the rim, but as the filling continues, at a certain moment, the ball will float away from the rim.
- You can also place the dishes with water and balls in your lecture room. A draft in your room will make the balls float around. The performance of the balls will puzzle your students.

2.6.1.1.8 Sources

- Roest, R., Inleiding Mechanica, pag. 76-78;188-193

2.6.2 1J30 Resolution of Forces

2.6.2.1 01 Strong Professor (Weak Students)

2.6.2.1.1 Aim

To use components of force.

2.6.2.1.2 Subjects

- 1J30 (Resolution of Forces)

2.6.2.1.3 Diagram

Figure 2.68: .

2.6.2.1.4 Equipment

- Rope, about 8 m.
- Hinged bars, with a nylon thread (3 mm) between the extremities.
- Two strong students.

2.6.2.1.5 Presentation

1. The two students pull with force on the ends of the rope, keeping it in equilibrium. From above, the professor pushes downwards,in the middle of the rope, easily touching the ground, with almost no effort, while the students work extremely hard to prevent this. Both strong students give way to the weak professor. (see Figure 2)

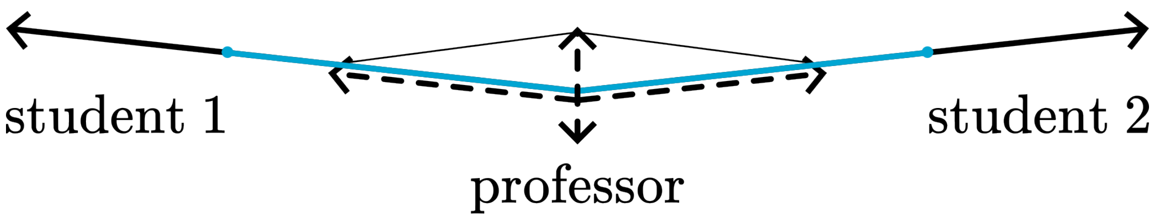


Figure 2.69: .

2. A thick nylon thread is shown and it is clear to all that by hand it cannot be broken. (The strong students can try it.) The thread is fitted between the extremities of the hinged bars (see Diagram). The professor pushes vertically downward on the joint between the bars and breaks the thread.

3. A piece of rope, that cannot be broken by hand, is tightly knotted around the top of a table (see Figure 3B). A metal bar is stuck under it and when the bar is pulled upwards, the rope breaks easily.

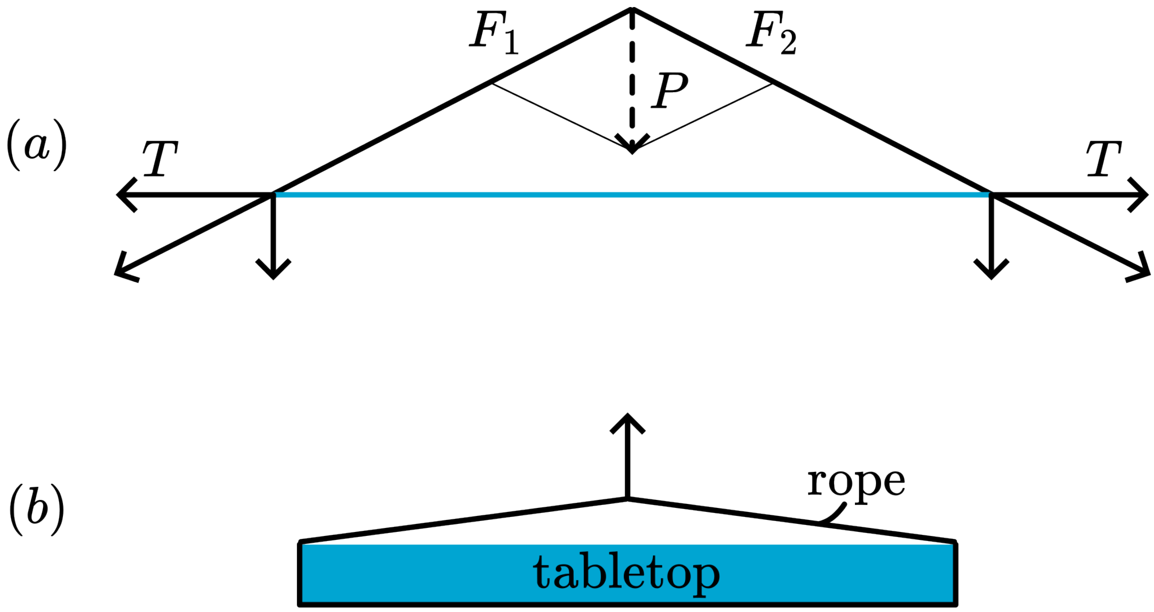


Figure 2.70: .

2.6.2.1.6 Explanation

We consider the situations as being in equilibrium.

1. Equilibrium requires that there is resolution of force (see Figure 2). The students need a large force to cancel the small force of the professor.
2. In equilibrium the force downward should be in the direction of the bars (F_1 and F_2 in Figure 3). The horizontal components of these forces give the tension T in the thread. F_1 and F_2 are the components of force along the bars of the professor's force P. The more the bars are pressed downward, the higher the components F_1 and F_2 will be and the higher the tension T in the thread.
3. The tension in the string due to the upward force is much higher than this upward force (construct the force-balance diagram to see this).

2.6.2.1.7 Remarks

There should be no knots in the nylon thread, so fixing this thread between the extremities of the bars needs to be done in a special way. We have chosen the solution shown in the detail-drawing in the Diagram.

2.6.2.1.8 Sources

- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. M-27
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 20

2.7 1K Applying Newton's Laws

2.7.1 1K10 Dynamic Torque

2.7.1.1 01 Pulling a Spool

2.7.1.1.1 Aim

Direction of rolling is determined by direction of torque.

2.7.1.1.2 Subjects

- 1K10 (Dynamic Torque)

2.7.1.1.3 Diagram

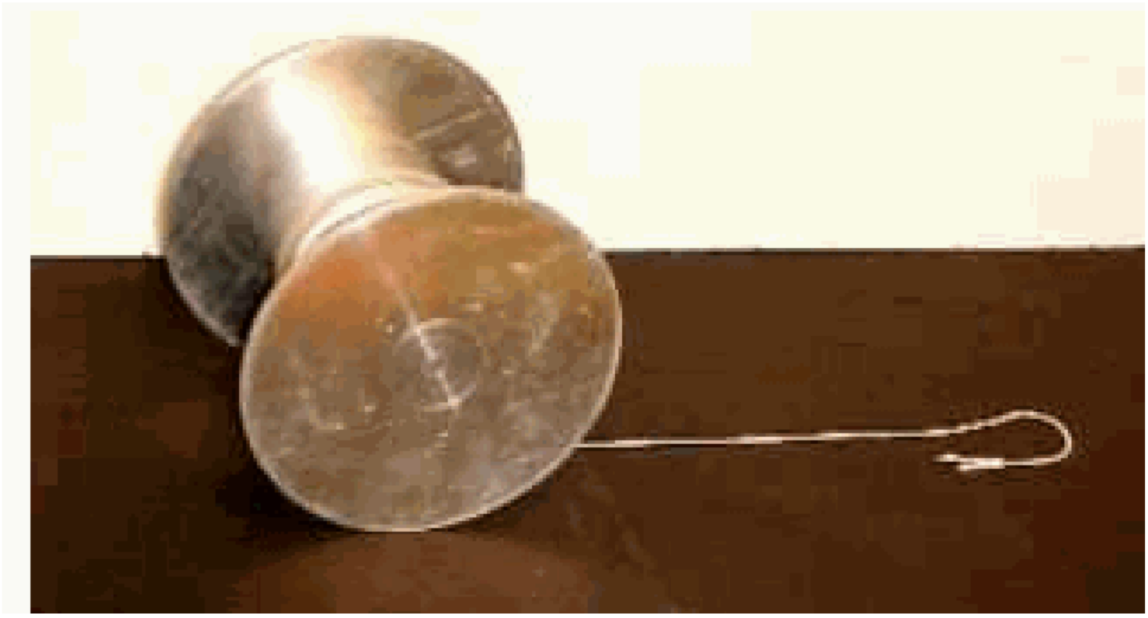


Figure 2.71: .

2.7.1.1.4 Equipment

- A (large) spool of thread.
- A thread or ribbon wound on the spool.
- Pulley.
- Mass, $m = .1$ kg.

2.7.1.1.5 Presentation

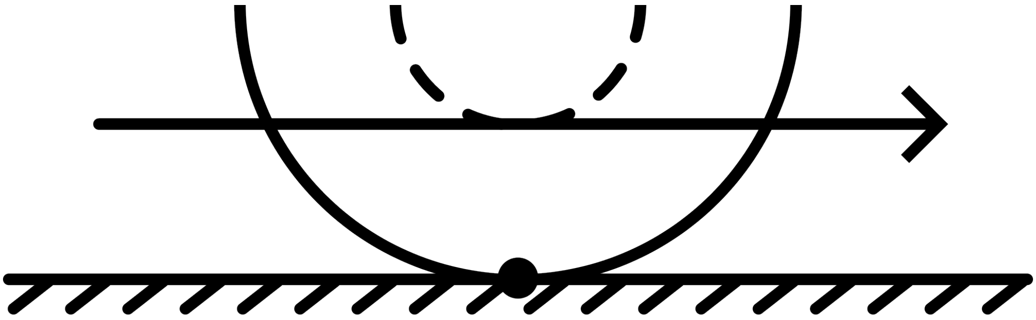
Show the simple construction of spool and wound thread to the students. The demonstrator takes the end of the thread in his hands and wants to pull in a horizontal direction. Ask the students in which direction the spool will roll. After their answers, pull .... and the spool will roll into the same direction as the demonstrator pulls.

The thread is wound to the spool again. The demonstrator takes the end of the thread in his hands and wants to pull in an upward vertical direction. Again he poses the same question. After the students' answers he pulls .... and the spool rolls into the other direction.

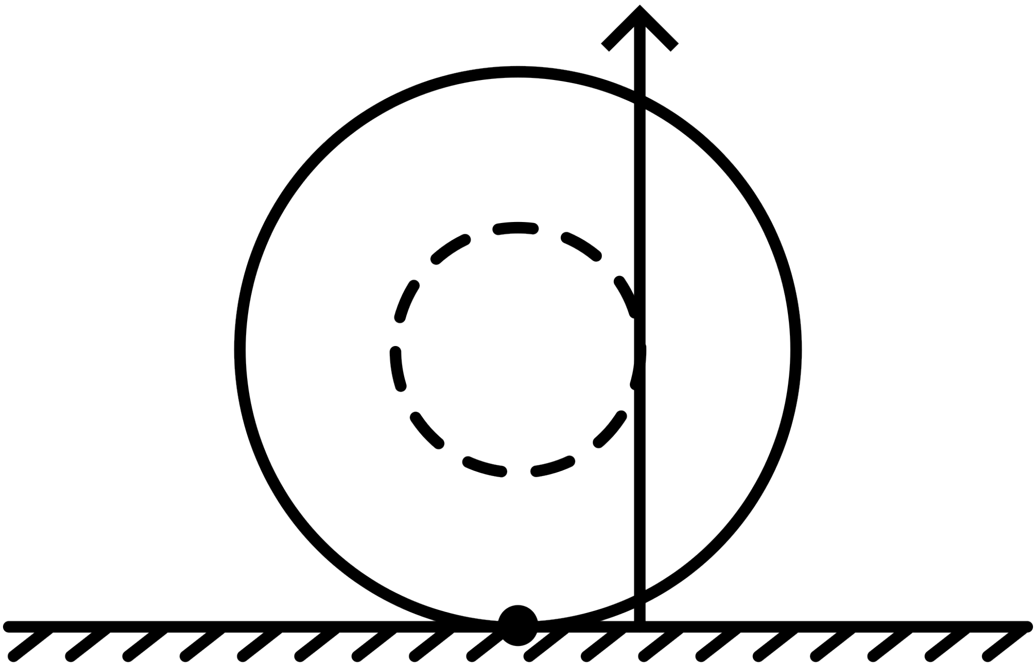
These two demonstrations induce the idea that it should be possible to pull in such a direction that the spool will not roll at all! Ask the students in which direction you need to pull the thread to get this situation. After their answers, experimentally search the right angle: the spool skids.

2.7.1.1.6 Explanation

The direction in which the spool rolls is determined by the direction of the torque on the spool about the contact point. The critical angle is defined by extending the line of the pulled thread so that this line passes through the point of contact between the spool and the table. A force directed along this line produces zero torque on the spool about the contact point. (see Figure 2)



right-hand torque



left-hand torque

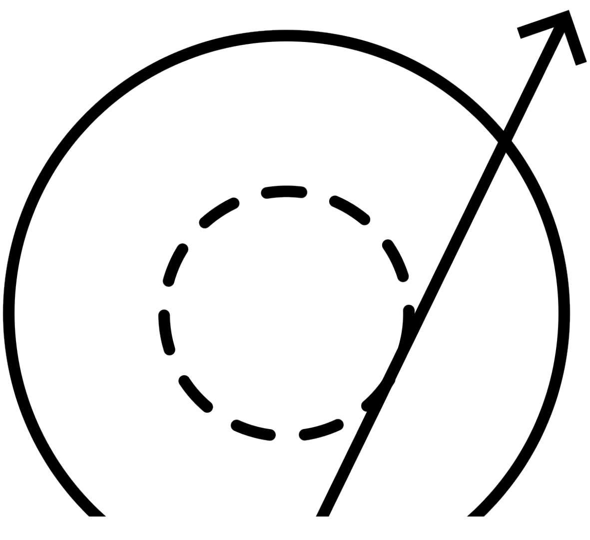


Figure 2.72: .

2.7.1.1.7 Remarks

- When pulling at very shallow angles, the spool orientation is not stable unless the thread comes off the spool at its center. This can be prevented by using a ribbon rather than a thread or using a large spool that is made in such a way that the thread can only be rolled in the centre of the spool (Figure 3).

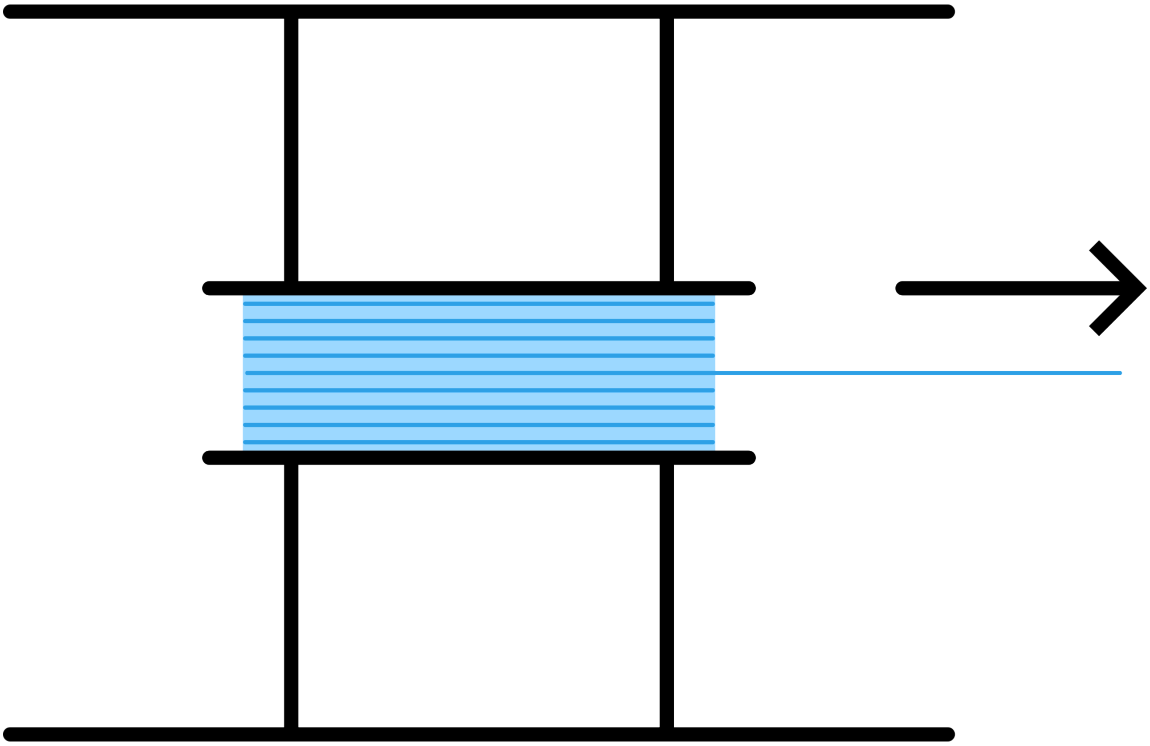


Figure 2.73: .

- A nice extension of this demonstration is to set the system up so that the string passes over a pulley and the force is supplied by hanging a weight from the end of the string (Figure 4).

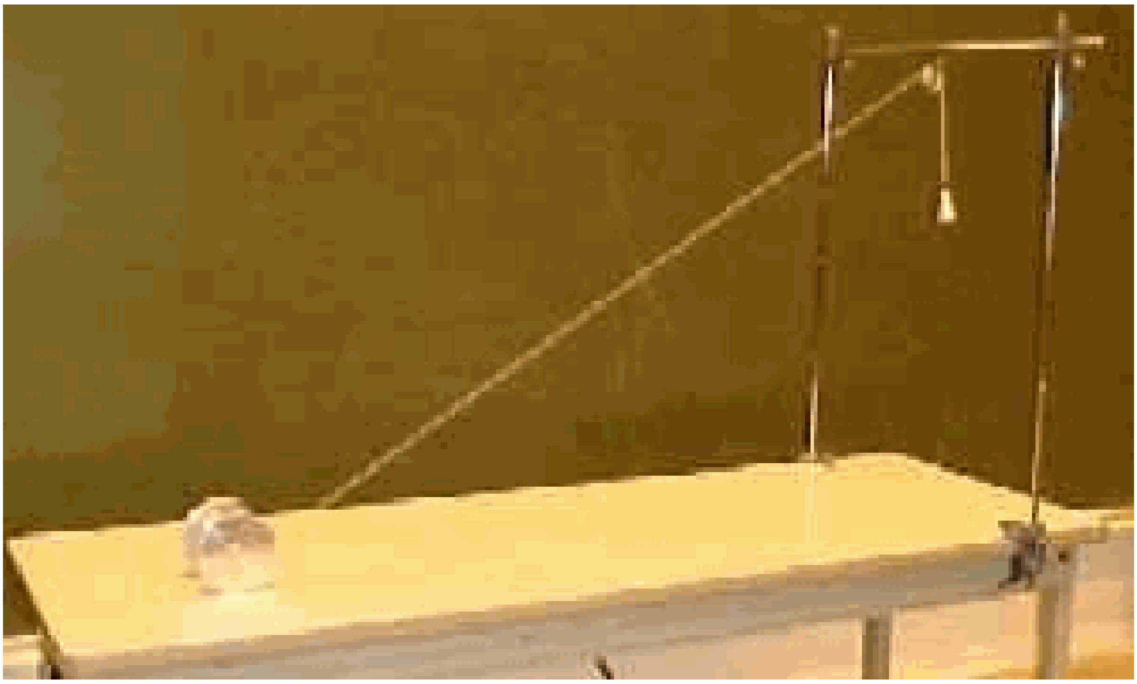


Figure 2.74: .

If the spool is moved away from its critical angle, the spool will always roll back to the position of the critical angle! It will oscillate back and forth around this equilibrium position.

2.7.1.1.8 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 65
- Jewett Jr., John W., Physics Begins With Another M… : Mysteries, Magic, Myth, and Modern Physics, pag. 115
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 102
- Young, H.D. and Freeman, R.A., University Physics, pag. 324(10-53)

2.7.1.2 02 Boomerang Ball (1)

2.7.1.2.1 Aim

To explain the very peculiar behavior of a bouncing superball.

2.7.1.2.2 Subjects

- 1K10 (Dynamic Torque)
- 1N10 (Impulse and Thrust)

2.7.1.2.3 Diagram

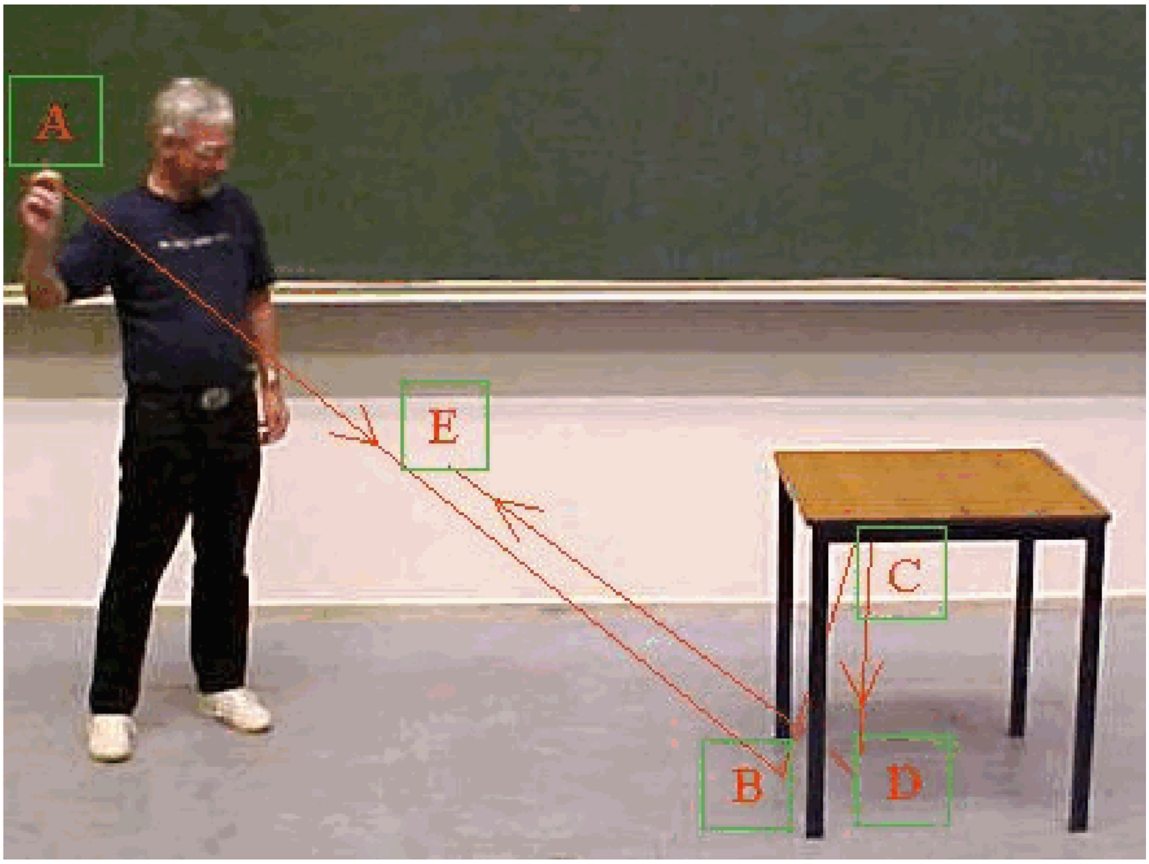


Figure 2.75: .

2.7.1.2.4 Equipment

- Superball.
- Basketball.
- Table.

2.7.1.2.5 Safety

- A superball can jump into many unexpected directions, so mind vulnerable objects in your neighborhood.

2.7.1.2.6 Presentation

The superball is thrown under the table as shown in the Diagram. Surprisingly it bounces back to the pitcher! How is this possible?

2.7.1.2.7 Explanation

As an introduction to an explanation a basketball is rolled over the floor, hitting the wall and rolling back to you. But in this rolling back it is also bouncing up and down. Confronting your students with the question “where originates this vertical momentum?” will lead them (I hope) to the answer: “the impulse of the friction force while the ball touches the vertical wall”.

As a second introduction to an explanation the basketball is thrown as shown in Figure 2A.

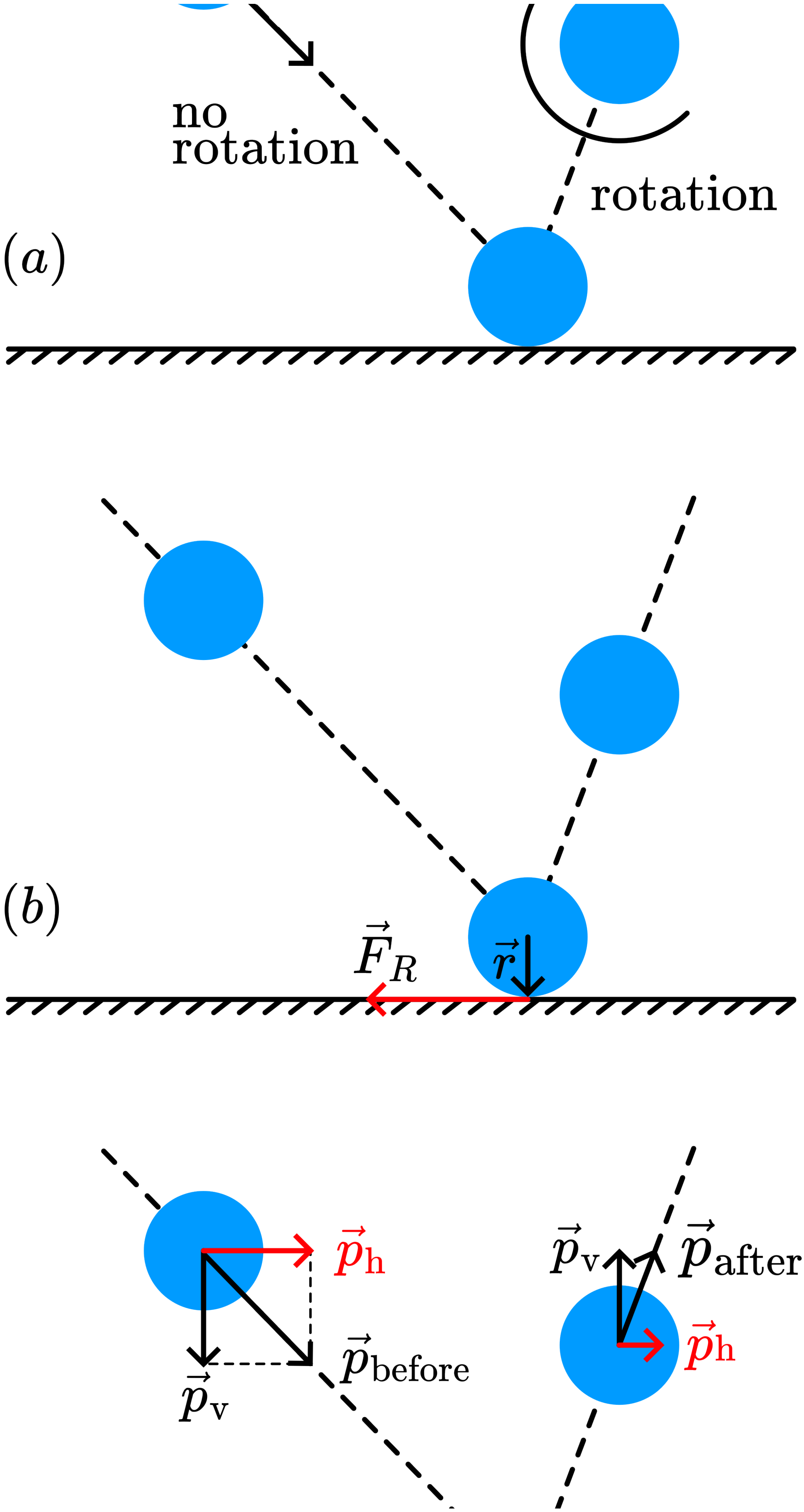

no
rotation
rotation
(a)
(b)
$\vec{F}_R$
$\vec{r}$
$\vec{p}_{\mathrm{h}}$
$\vec{p}_{\mathrm{before}}$
$\vec{p}_{\mathrm{v}}$
$\vec{p}_{\mathrm{v}}$
$\vec{p}_{\mathrm{after}}$
$\vec{p}_{\mathrm{h}}$

Figure 2.76: .

(Also see the demonstration ["Throwing a basketball"](../1K1005 Throwing a Basketball/1K1005.md)). The ball is thrown without rotation, but after bouncing it rotates (the lines on the basketball make this rotation very well visible). The cause for this rotation is the torque $\overrightarrow{M}$, due to the friction force $\vec{F_r}$: $\left(\overrightarrow{M} = \vec{r} \times \vec{F_r}\right)$ (see Figure 2B). $\vec{F_r}$, that acts during a certain time Δt, also causes a decrease of the momentum (Δp_h) in the horizontal direction of the moving ball ($\Delta \vec{p_h} = \int_0^{\Delta t} \vec{F}_R dt$). The result is that, after hitting the floor, the ball not only rotates but also rises at a steeper angle than it had in its approach. (See Figure 2C; p_v only reverses its direction and does not change its magnitude; suppose the bounce completely elastic). Figure 3 shows the ball on hitting the bottom-side of the table-top. Observing the movement of the ball's surface with respect to the bottom-side of the tabletop makes clear that the friction force is (again) directed to the left.

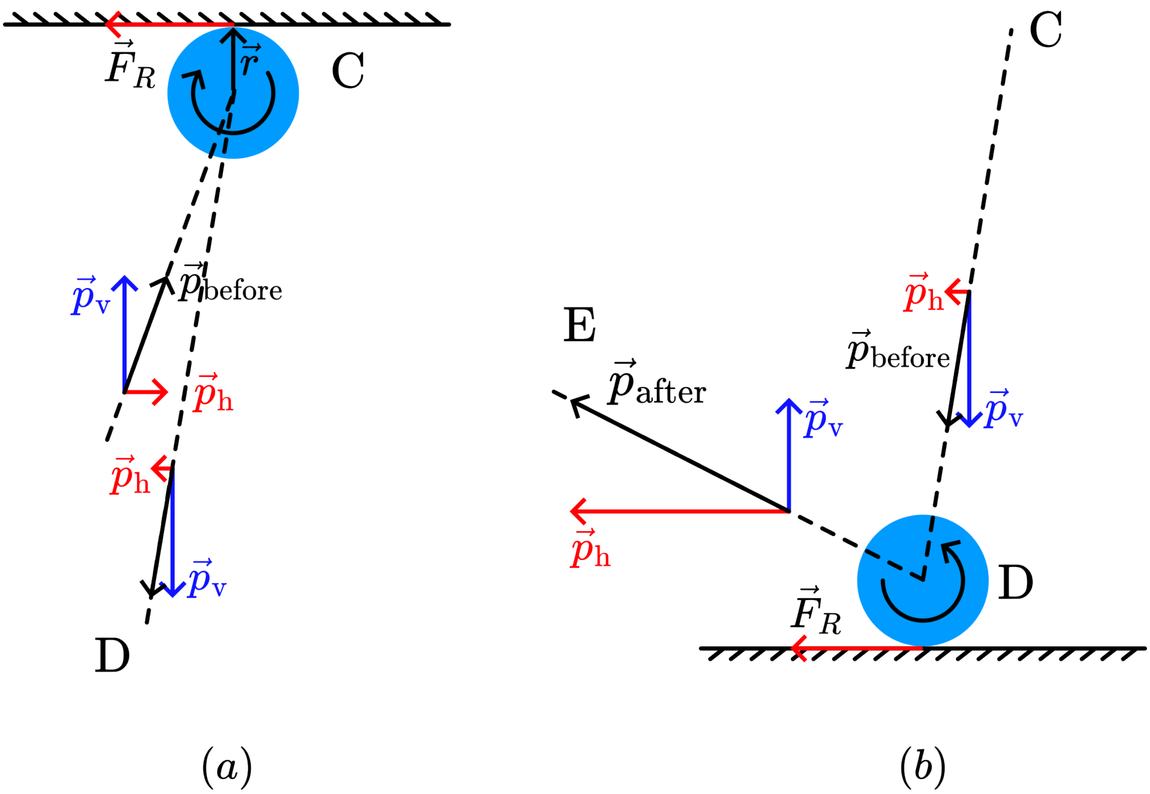


Figure 2.77: .

Due to this horizontal impulse, p_h even changes direction and bouncing from the bottom side, the ball even moves to the left. (The clockwise rotation will be slowed down, stopped or even reversed, because on hitting the bottom-side of the tabletop $\bar{M}$ is directed in the opposite direction.)

Depending on the value of p_h now, CD in Figure 3 could be a possible line of movement. Explaining line DE (towards the pitcher) will be easy when you suppose a counterclockwise rotation in the path CD, because then the friction force on hitting the floor is directed again to the left increasing the horizontal component of the ball's velocity to the left! (see Figure 3B)

2.7.1.2.8 Remarks

- In theory all balls will behave in this way. Yet a superball is needed to show this type of "boomerang-behavior". That a superball performs so well is due in the first place to its high coefficient of friction and subsequently its high friction force on horizontal contact with the floor and table. And a high friction force can change the horizontal momentum dramatically.

- It is more spectacular to throw the ball between the floor and the ceiling of the lecture room! (Even in our lecture hall that is around 7 meters high this succeeds.)
- The higher the speed of the ball that you throw, the more surprising the demonstration. But to do this, practicing is absolutely necessary. (But when you miss, this enlightens your performance in front of your students and their laughing will consolidate their reminiscence of this demonstration.)
- When you are able to keep the ball between the floor and the table (two horizontal surfaces), then the thrown ball goes to and fro quite a number of times, and eventually moves only up and down perfect vertically. The same can be tried between two vertical surfaces: the ball thrown will go up and down a number of times. So, in these two cases an oscillating displacement of the ball can be observed (see the article in AJP 72-7). When you try these possibilities the ball needs to be thrown at very high speeds.
- Many other strange bounces are possible: see Boomerang ball.

2.7.1.2.9 Sources

- Walker, J., Roundabout, the Physics of Rotation in the Everyday World, pag. 8-12
- American Journal of Physics, pag. 875-883 (Vol.72-7; 2004)
- Nederlands Tijdschrift voor Natuurkunde, 70/10(2004), pag. 347
- McComb, W. D. Dynamics and Relativity, pag. 3

2.7.1.3 03 Boomerang Ball (2)

2.7.1.3.1 Aim

The concept of impulse explains this very peculiar behavior of a bouncing ball.

2.7.1.3.2 Subjects

- 1K10 (Dynamic Torque)
- 1N10 (Impulse and Thrust)

2.7.1.3.3 Diagram

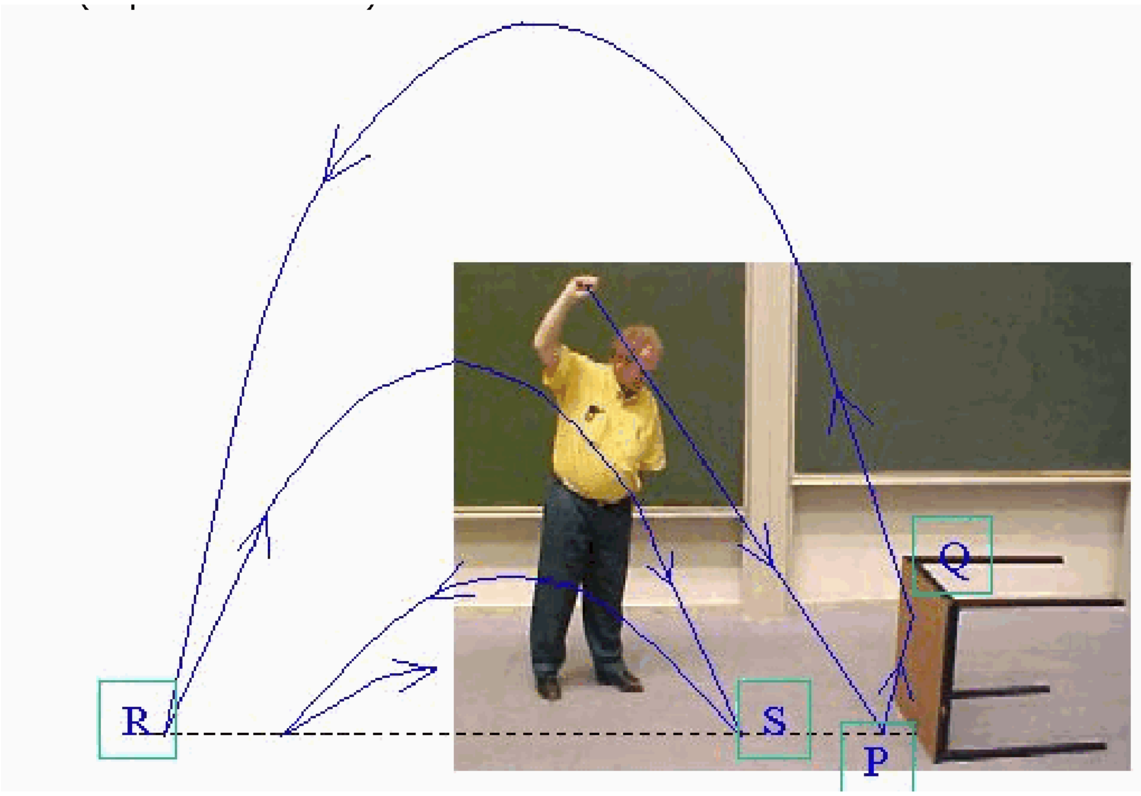


Figure 2.78: .

2.7.1.3.4 Equipment

- Superball.
- Table.

2.7.1.3.5 Safety

- A superball can jump into many unexpected directions, so mind vulnerable objects in the neighborhood.

2.7.1.3.6 Presentation

The table is positioned as shown in Diagram. The ball is thrown as shown. The ball bounces to a fro.

2.7.1.3.7 Explanation

As a basis to explanation see the demonstration Boomerang ball. Using a large basketball thrown against the floor and then bouncing against a vertical wall, shows that after hitting the vertical wall the basketball still rotates clockwise. Figure 2A shows this.

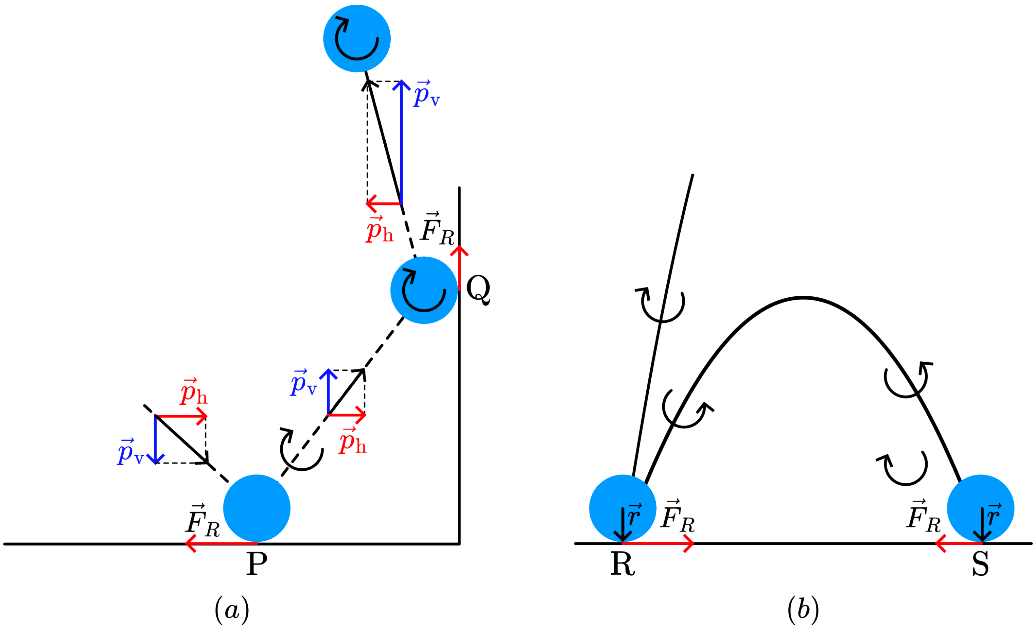


Figure 2.79: .

(The effect of the friction force F_R in Q is not that large as that of F_R in P, since the ball approaches the vertical wall with $\vec{p}_h$ and this momentum is smaller than

$\vec{p}_v$ in P.)

Having hit the vertical wall the ball climbs steep (see Figure 2A). A parabolic trajectory follows. On hitting the floor in R, the friction force is directed to the right (Figure 2B). The impulse $\int F_r dt$ is large enough to make the component

$\vec{p}_h$ change direction and $\bar{M} = \vec{r} \times \vec{F}_R$ is inducing a counter clockwise rotation. It bounces towards S and again F_R is directed to the inner side of the parabola, making the component $\vec{p}_h$ reverse direction and $\bar{M} = \vec{r} \times \vec{F}_R$ inducing clockwise rotation. And so on.

2.7.1.3.8 Remarks

- Practicing this demonstration against a real wall will learn that this part of the demonstration can also be appreciated on its own. Having the right speed and right angle, a very high climbing ball will be the result of your practicing. Figure 2A shows the explanation of this phenomenon: After bouncing at Q, $\vec{p}_v$ has a very high value.
- A nice variation to this demonstration is the “drunken student” (sorry, “drunken sailor”). To throw a ball that follows such a staggering trajectory, see Figure 3.

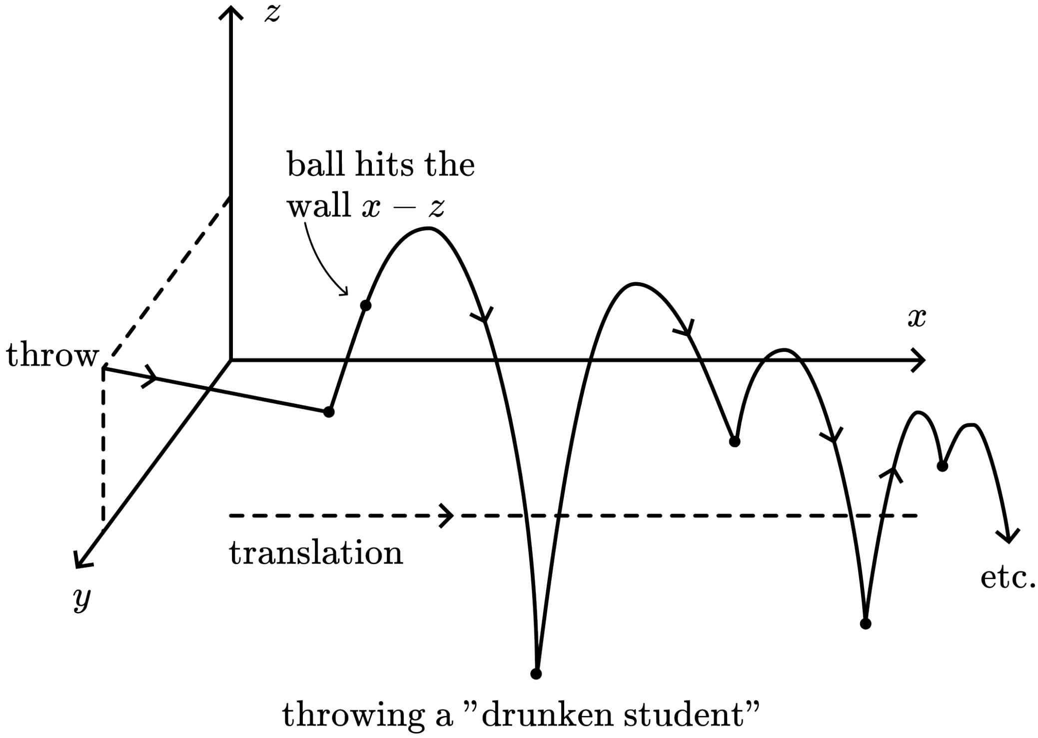


Figure 2.80: .

2.7.1.3.9 Sources

- Walker, J., Roundabout, the Physics of Rotation in the Everyday World, pag. 8-12.
- American Journal of Physics, pag. 875-883 (Vol. 72-7; 2004).

2.7.1.4 04 Falling Stick

2.7.1.4.1 Aim

To show that a movement of a tipping object is determined by friction between the object and the surface on which it falls.

2.7.1.4.2 Subjects

- 1K10 (Dynamic Torque)
- 1K20 (Friction)

2.7.1.4.3 Diagram

No diagram available

2.7.1.4.4 Equipment

Stick $(l = 2 \text{ m})$ with a wheel. It's center is clearly marked.

2.7.1.4.5 Presentation

Hold the stick so that it is standing on its wheel. Incline the stick about 20° from the vertical. Indicate to the audience the marked center of mass. This point is right in front of your belly.

Let the stick go and it will hit the floor. The marked center is right in front of your toes, so this point moved vertically down.

The demonstration is done once more but now the wheel cannot move since your foot blocks it. Let the stick go and observe that the stick falls with the center of mass on the left of yourself; it even jumps away from your right foot to the left!

2.7.1.4.6 Explanation

The behavior of the stick depends on the friction force between the tip and the floor on which it rests. When there is frictionless interaction the only forces acting on the pencil are its weight and the normal force, both of which are vertical. There are no horizontal forces on the stick. (See Figure 1.)

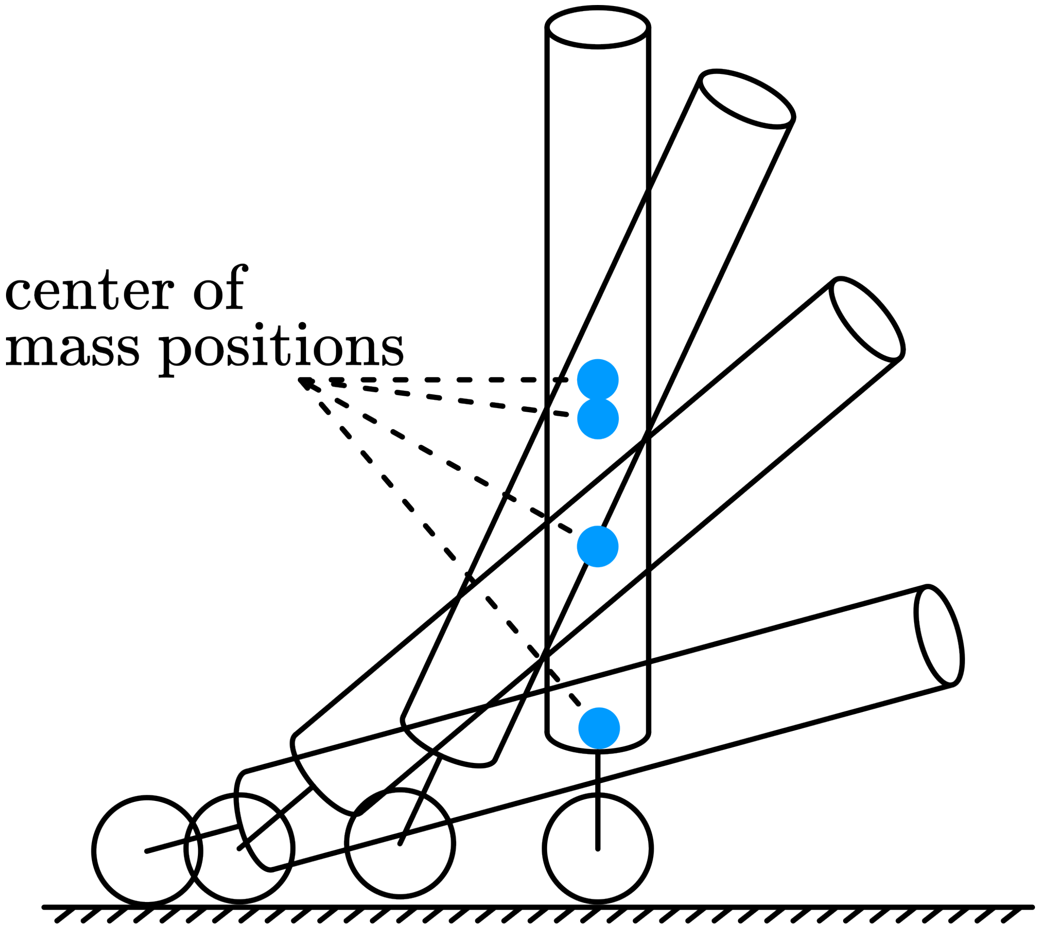


Figure 2.81: .

The 20° inclination is to skip the region where the wheel has too much friction to roll. In the first 20° the stick receives so much impulse from friction of the wheel that the centre of mass moves.

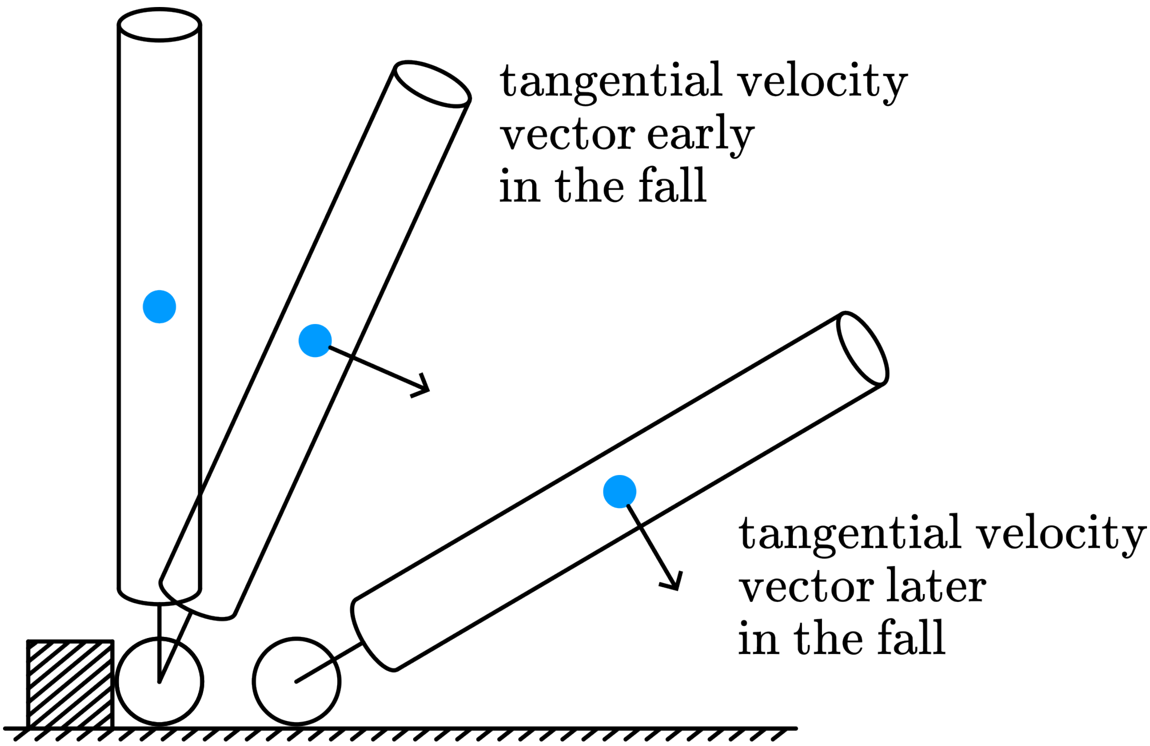


Figure 2.82: .

When there is friction (Figure 2), then, as the stick falls, the tip does not slip. The horizontal friction force causes a horizontal momentum, which increases during the fall.The velocity vector of the center of mass of the stick is approaching a vertical orientation as the stick nears the floor. In the beginning the velocity of the center of mass is increasing in the horizontal direction, but since this velocity is becoming more vertical, something must happen to maintain the horizontal momentum. As a result, the stick does not continue to rotate simply about its tip, but takes on a horizontal translational velocity in the direction of the fall.

2.7.1.4.7 Remarks

Students can perform the demonstration themselves using a pencil. For the first demonstration, the sharpened pencil rests with its point on a glass surface. For the second demonstration, the pencil rests with its rubber top on a piece of sandpaper.

2.7.1.4.8 Sources

- Jewett Jr., John W., Physics Begins With Another M… : Mysteries, Magic, Myth, and Modern Physics, pag. 91

2.7.1.5 05 Throwing a Basketball

2.7.1.5.1 Aim

To show how impulse changes the movement of a thrown basketball.

2.7.1.5.2 Subjects

- 1K10 (Dynamic Torque)
- 1K20 (Friction)
- 1N10 (Impulse and Thrust)

2.7.1.5.3 Diagram

Figure 2.83: .

2.7.1.5.4 Equipment

- Basketball.

2.7.1.5.5 Presentation

The lines on the basketball make it easy to see if the ball rotates yes or no.

Throw the basketball and observe that before hitting the ground it does not rotate, but that after rebound it rotates (see Figure 2A).

Also can be observed that after rebound the ball moves steeper than when it was in the throw (again: see Figure 2A).

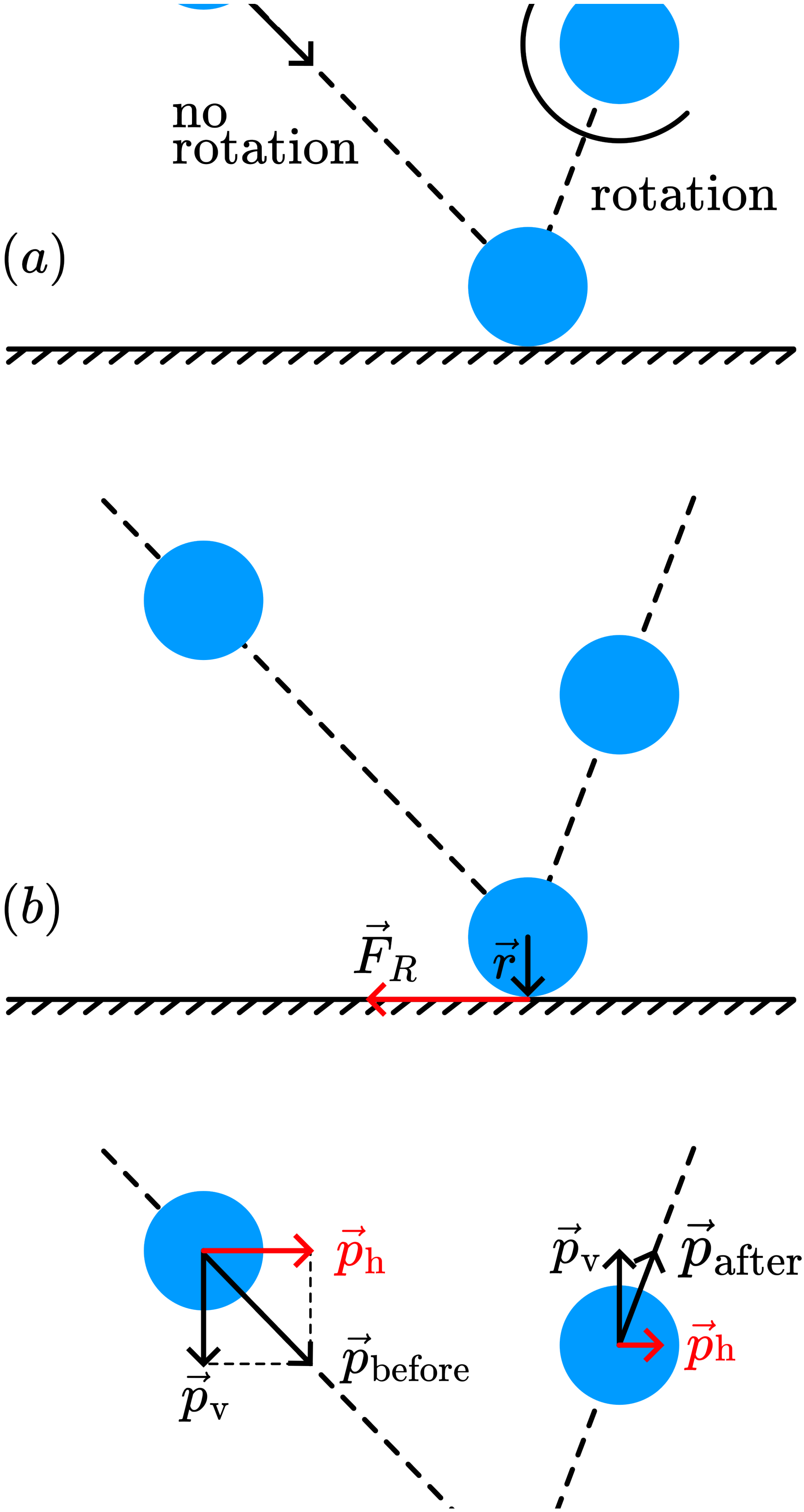

no rotation
rotation
(a)
(b)
$\vec{F}_R$
$\vec{r}$
$\vec{p}_{\mathrm{h}}$
$\vec{p}_{\mathrm{before}}$
$\vec{p}_{\mathrm{v}}$
$\vec{p}_{\mathrm{v}}$
$\vec{p}_{\mathrm{after}}$
$\vec{p}_{\mathrm{h}}$

Figure 2.84: .

2.7.1.5.6 Explanation

The ball has an impulse p, which can be looked at as consisting of a vertical component p_ν and a horizontal component p_h. When the ball hits the ground, p_ν is reversed (supposing complete elasticity). But p_h changes because the friction force F_R, that acts during a short time (Δt), reduces the horizontal impulse by an amount of $\Delta \vec{p}_h = \int_0^{\Delta t} \vec{F}_R dt$. The combination of unchanged p_v and changed p_h makes that the ball mounts steeper (Figure Figure 2C).

That it rotates as well is due to the torque during contact with the ground, changing its angular momentum by an amount of: $\Delta \vec{L} = \int_0^{\Delta t} \vec{r} \times \vec{F} dt$.

2.7.1.5.7 Sources

- American Journal of Physics, 72-7(2004), pag. 875-883
- Nederlands Tijdschrift voor Natuurkunde, 70-10(2004), pag. 347
- Walker, J., Roundabout, the Physics of Rotation in the Everyday World, pag. 8-12

2.8 1K20 Friction

2.8.1 01 Braking

2.8.1.1 Aim

To show the difference between braking on the rear wheels and braking on the front wheels. (To show an application of the difference between static- and kinetic friction.)

2.8.1.2 Subjects

- 1K20 (Friction)

2.8.1.3 Diagram

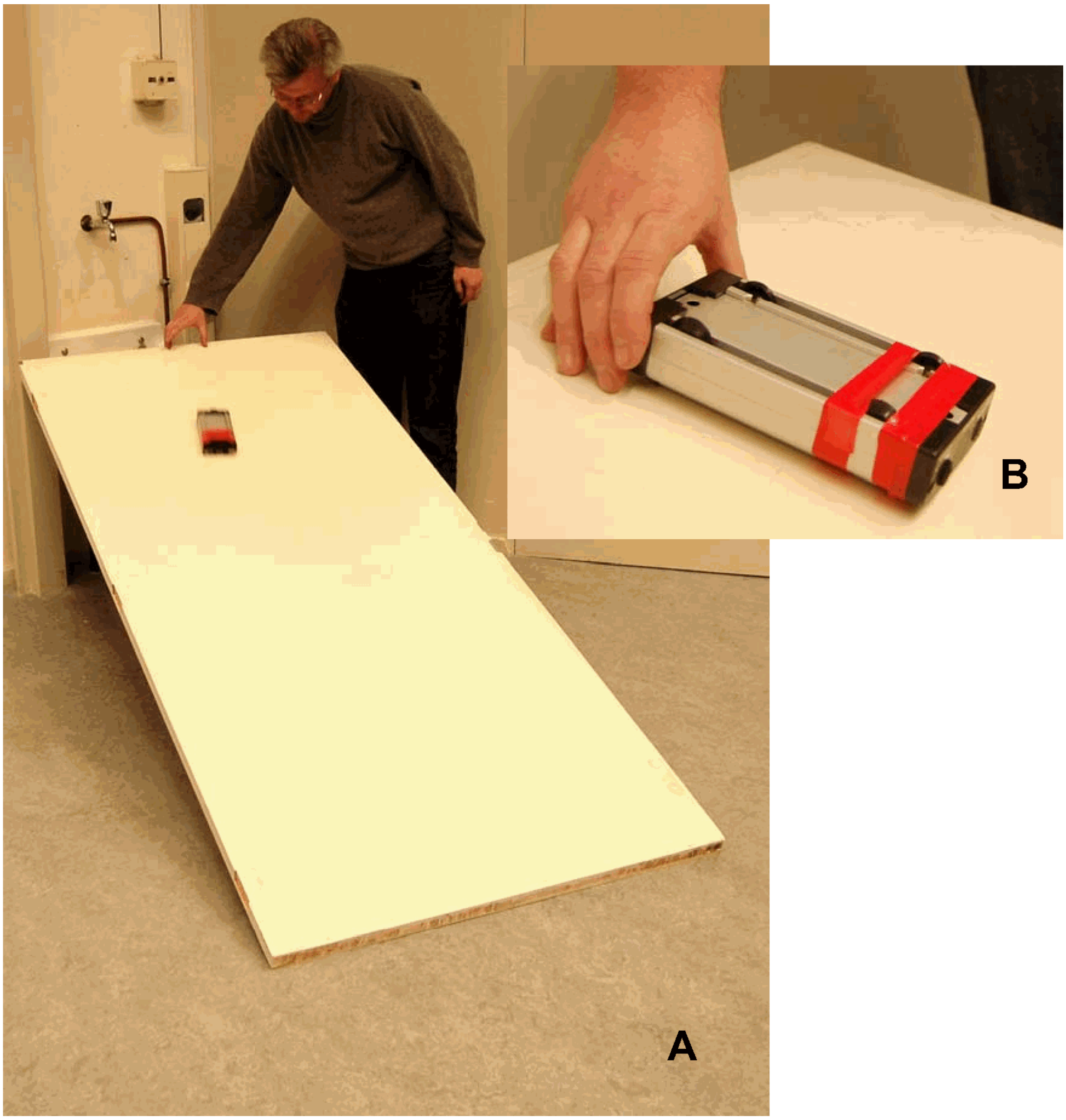


Figure 2.85: .

2.8.1.4 Equipment

- Collision cart 1.
- Collision cart 2, (the wheels of one axle are blocked using elastic tape, see B in Diagram).
- An inclined board (we use an old door).

2.8.1.5 Presentation

Roll cart 1 down the incline (all wheels free) and ask the audience: "In case of rolling down an incline is it advisable to have braking (or better: "blocking"), on the rear wheels or on the front wheels, in order to have a controlled descent?" Most people guess: "rear wheels" or "doesn't it matter which wheels you block". Then place cart 2 with the blocked wheels at the rear, on the inclined board and permit it to go down. During this run the car reverses itself and slides down rear end first (skidding). See Figure 2.

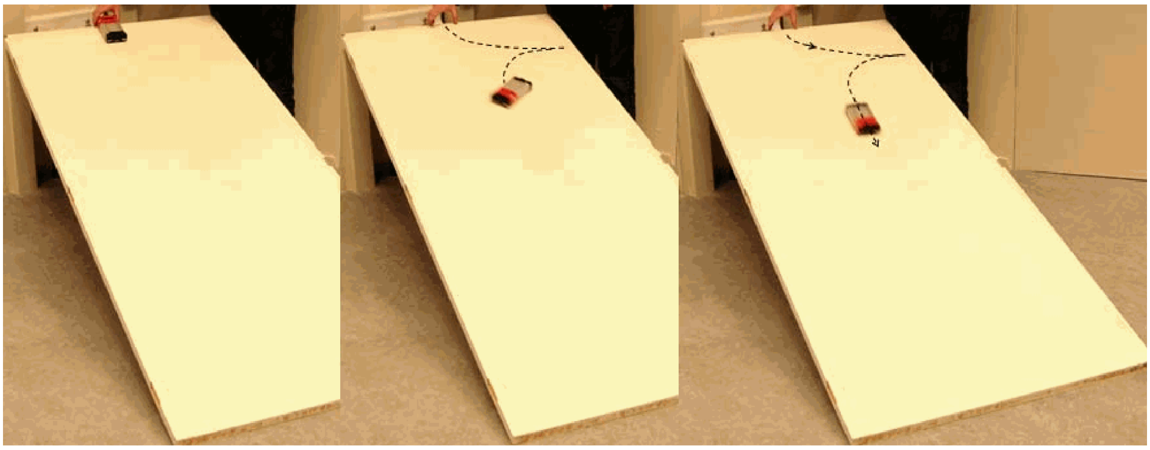


Figure 2.86: .

If the blocked wheels are at the front, the car slides down without skidding. It stays inline on the inclined plane. See Figure A in Diagram: The cart had its blocked wheels in front and is launched under a small angle with the direction of the inclined plane. During its run it lines up into the direction of the inclined plane.

2.8.1.6 Explanation

When a wheel is rolling, it is governed by static friction. When a wheel is sliding, it is governed by kinetic friction. The coefficient of static friction is higher than the coefficient of kinetic friction (see, for instance, the demonstration "Sliding towel" in this database). Figure 3 shows the effect of this on the cart in case of blocked wheels at the rear: The frictional force at the rear wheels is lower than that on the front wheels (supposing equal normal forces on the wheels), and so the resultant force into the downward direction along the plane is highest on the rear wheels. This means a higher acceleration along the plane and in due time the rear wheels will overtake the front wheels.

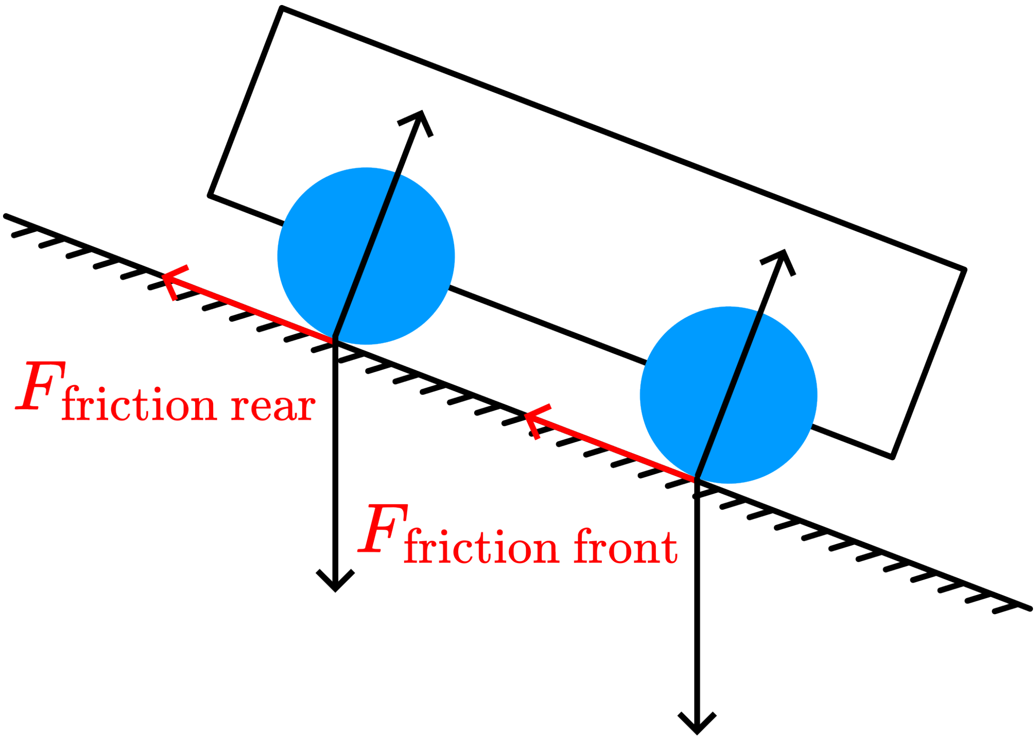


Figure 2.87: .

Now it will be easy to explain also the situation of blocked front wheels. In that situation the front wheels will have the highest acceleration, resulting in lining the car into the direction of the inclined plane

2.8.1.7 Remarks

- Students experience the most difficulty with the fact that a rolling wheel means static friction. So stress in your explanation that the local velocity of a rolling wheel at the point of contact with the road is zero. (see Sources: The Physics Teacher)
- The demo can also be done on the ground giving the cart a push. (But then students sometimes think that you trick them in the way of pushing.)
- This demonstration also leads to the answer on questions like "Should you lock your brakes when sliding?" and "Why should you steer into a skid?".
- Due to the geometry of the demonstration the normal forces on the front - and rear wheels are not equal: The normal force on the front wheels is higher than the normal force on the rear wheels. In case of locking the rear wheels the difference in the friction forces (see Figure 3) is still larger and so the skidding effect will be even stronger. But in the situation where we lock the front wheels, the difference between the normal forces is contra-productive (even a front wheel lock can then produce a skid). The longer the car, the smaller the difference between the normal forces: so use a relatively long car to have a successful demonstration. (Having done the demonstration with a long car it can be stimulating to do it also with a short one.)

2.8.1.8 Sources

- Lewett Jr., John W., Physics Begins With an M… Mysteries, Magic, and Myth, pag. 40.
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 66-67.
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 153.
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 32.
- The Physics Teacher, Vol. 25, pag. 504.

2.8.2 02 Phonebook Friction

2.8.2.1 Aim

Showing that friction force can be very large

2.8.2.2 Subjects

- 1K20 (Friction)

2.8.2.3 Diagram

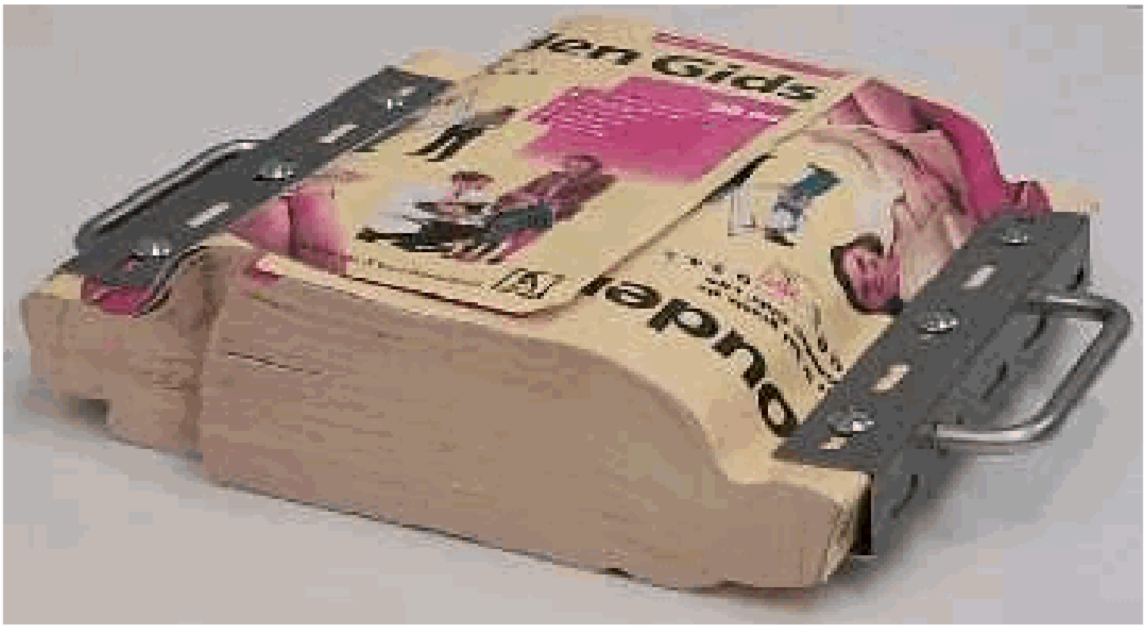


Figure 2.88: .

2.8.2.4 Equipment

- Two (equal) phonebooks, 1000 pages each.
- Two strong students.

2.8.2.5 Presentation

The two phonebooks are interleaved page by page. Ask two volunteers to grab the spines of the books and to pull them apart. This will be impossible!

2.8.2.6 Explanation

First estimate the normal force between pages. The pages at the top are pressed together with almost zero force. The pages at the bottom are pressed together with a force equal to the weight of the portions of the pages from both books that overlap. If the pages are overlapped by half of their width, then the weight on the bottom pages is the weight of one book. So in that case the normal force varies from zero at the top to W_{book} at the bottom. The average normal force between pages then is $1/2W_{book}$. For two books of 1000 pages each there are 1999 page-surfaces in contact! Supposing that the static coefficient of friction between the pages is the same as that between a book and a table, than in this case the friction force between the books equals 1999 $\times$ $\left(\mu \times \frac{1}{2}W_{book}\right)$. In our situation: $W_{book} = 15$ N and $\mu = 0.25$, so F$_{friction} \approx 3750$ N !

2.8.2.7 Remarks

The books can also be held vertical. Due to the slanting pages, there is still enough normal force to prevent the lower book from falling. (Even a mass can be hung to it.)

2.8.2.8 Sources

- Jewett Jr., John W., Physics Begins With Another M… : Mysteries, Magic, Myth, and Modern Physics, pag. 42
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 66-67

2.8.3 06 Chain Friction

2.8.3.1 Aim

Determining the coefficient of static friction.

2.8.3.2 Subjects

- 1K20 (Friction)

2.8.3.3 Diagram

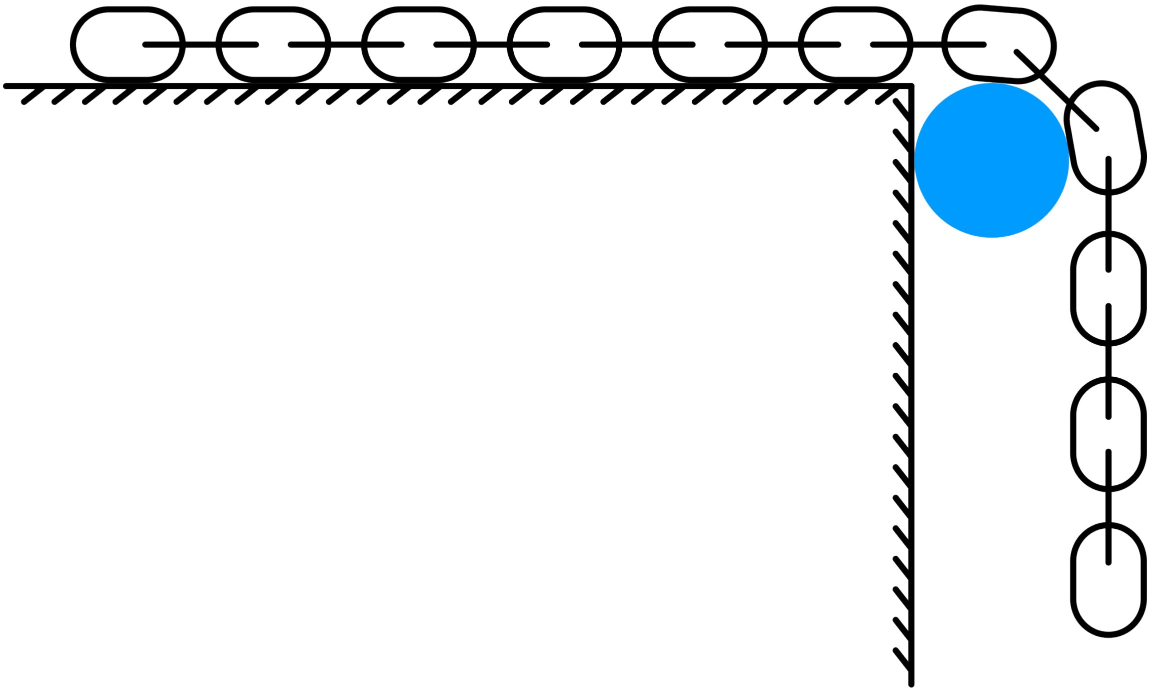


Figure 2.89: .

2.8.3.4 Equipment

- Table.
- Chain, ($l = 1.2$ m).
- Bar.

2.8.3.5 Presentation

The chain is laid out straight on a table. One end is slowly pulled over the edge until the chain just does not slip. The coefficient of friction (μ_s) between the table top and chain is then $\mu_s = \frac{l_0}{l - l_0}$, where l is the total length of the chain and l_0 the length of the overhanging portion.

2.8.3.6 Explanation

No slipping means that forces are in equilibrium: $F_1 = F_2$ (see Figure 2).

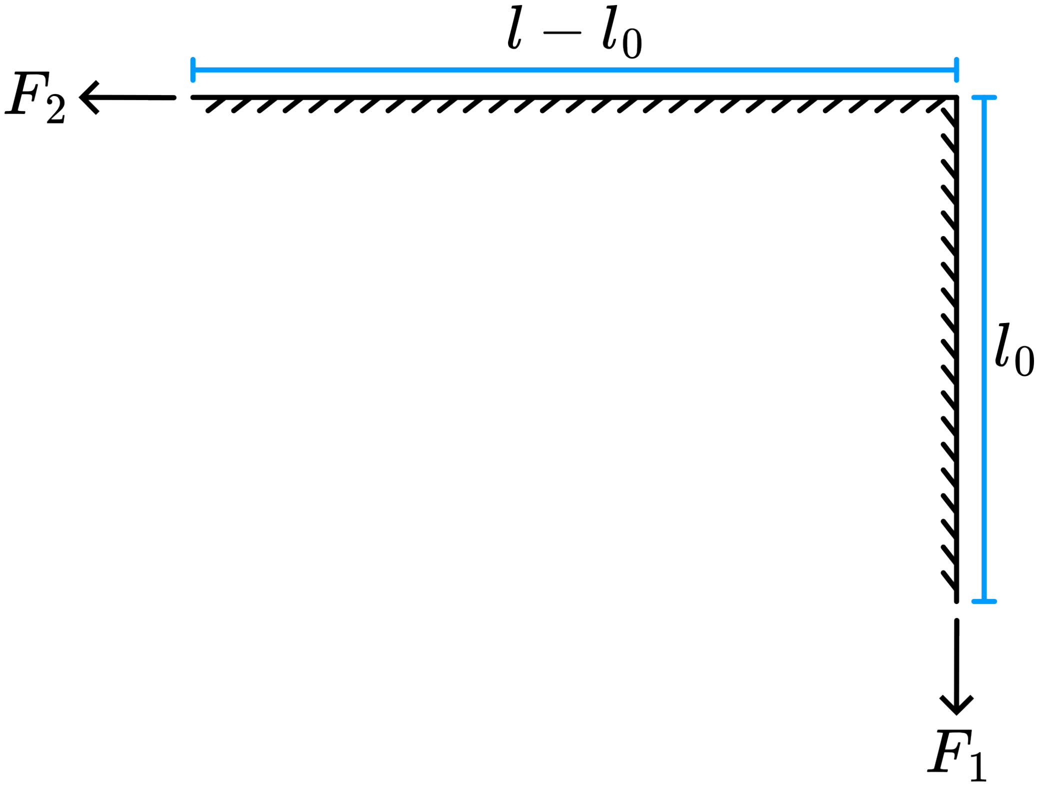


Figure 2.90: .

The mass of the part of the chain hanging over the edge equals: $m_1 = \frac{l_0}{l}m$. This makes: $l_0 F_1 = \frac{l_0}{l}mg$.

The mass of the part of the chain still on the table equals: $m_2 = \frac{l-l_0}{l}m$.

The normal force of that part of the chain equals: $F_N = \frac{l-l_0}{l}mg \to F_2 = \mu_s F_N = \mu_s \frac{l-l_0}{l}mg$.

$F_1 = F_2$ now yields: $\frac{l_0}{l}mg = \mu_s \frac{l-l_0}{l}mg$, and so: $\mu_s = \frac{l_0}{l-l_0}$.

2.8.3.7 Remarks

- It is advisable to make the corner of the table a low friction surface, e.g. rounding that corner. You can of course also make a special surface for your chain (acrylic plate, bended at one end). We used a stand bar as a low friction surface for the corner of the table.
- Instead of a chain, the demonstration can also be done with a piece of soft cloth or rope.

2.8.3.8 Sources

- Meiners, Harry F., Physics demonstration experiments, part 1, pag. 152

2.8.4 07 Moving Two Fingers under a Meterstick

2.8.4.1 Aim

Showing that the relationship between the coefficients of static- and kinetic friction explains why two fingers supporting the ends of a meterstick always meet at the center of mass of the stick.

2.8.4.2 Subjects

- 1K20 (Friction)

2.8.4.3 Diagram

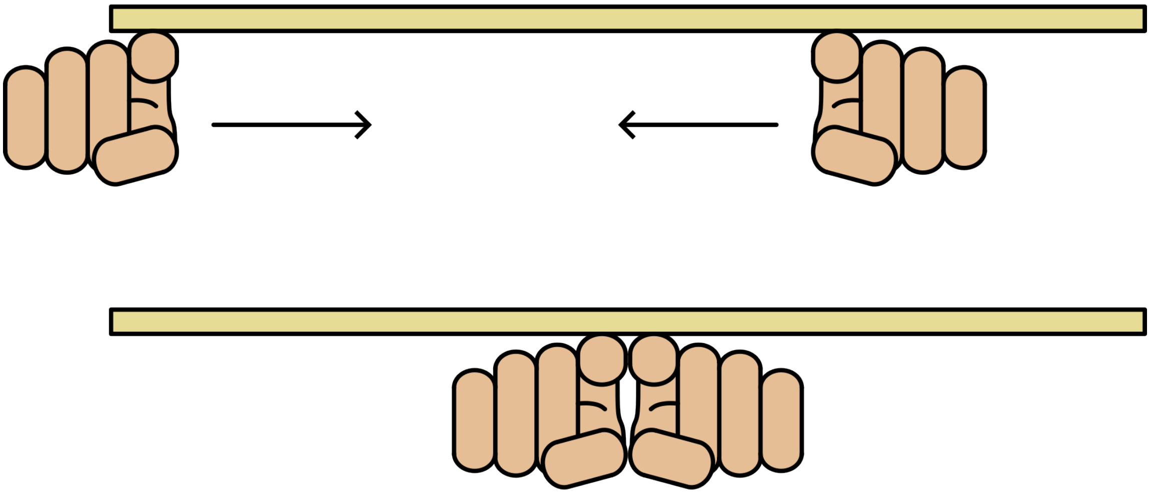


Figure 2.91: .

2.8.4.4 Equipment

- Stick, wood, about 1.5 m, with hooks at the ends, a clearly marked centre and blockmarks every 2 cm.
- Small weight with ring.
- Rubber glove or piece of rubber.

2.8.4.5 Presentation

- Let the stick rest on two fingers, so that the fingers are symmetrically near the ends of the stick. Ask the audience what will happen, when the fingers are slowly brought together (will the stick fall or not, where do the fingers meet?). The stick will not fall off the fingers. The point where the fingers meet is the point that divides the stick into two equal parts (halves).
- The stick is layed asymmetrically on the fingers and the above experiment is repeated. Ask the same question to the audience. The result is the same: the stick will not fall and in this way the middle of the stick is found. The explanation (see below) using the term 'friction' is given.
- Now friction is influenced by using one bare finger and one finger in a glove (or a piece of rubber as a finger). The same questions are asked and the same experiment is done. Probably the audience is astonished that the result remains the same, even under these circumstances.
- As a last experiment the stick is made linearly inhomogeneous by hanging a weight on one end of the stick. Ask the same questions and perform the same experiment. The result is that the stick still won't fall of the fingers but the place where the fingers meet is different this time. This part of the demonstration can also be done using a (large) broom.

2.8.4.6 Explanation

Initially the stick exerts the same force on both fingers. When the fingers are moved, the force on one of the fingers will be greater than on the other. The finger closest to the middle of the stick will have the greater force and thus the greater friction. The other finger can slide towards the middle of the stick until the force on this finger is greater. Now the friction at the first finger is less, so this finger can move towards the middle, and so on until the fingers meet under the middle of the stick.

This is independent of the starting-point of the fingers and also independent of the type of friction.

According to the second condition for equilibrium, the fractions of the meterstick's weight resting on your two fingers, W_1 and W_2, depend on the distances x_1 and x_2 to the centre, according to the relation $W_1 x_1 = W_2 x_2$. Just at the point where one finger stops moving and the other starts moving, the static-friction force of the fixed finger equals the kinetic-friction force of the moving finger: $\mu_s W_1 = \mu_k W_2$ (see Figure 2).

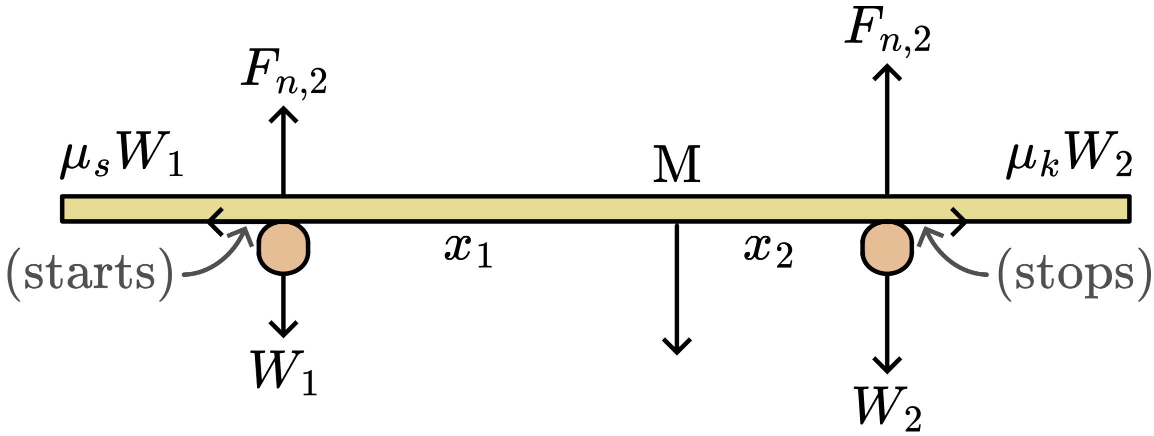


Figure 2.92: .

Combining the two preceding equations yields the condition $\mu_k x_1 = \mu_s x_2$. By observing just where one finger stops sliding and the other starts, you can measure the values of x_1 and x_2, and thereby determine the ratio of the two friction coefficients using $\mu_k / \mu_s = x_2 / x_1$.

2.8.4.7 Remarks

You can, of course, make your fingers meet at some point other than the half-way mark by suddenly accelerating one of them, because in that case the friction force each finger exerts on the stick need not be the same. According to Newton's second law, accelerations imply unbalanced forces.

2.8.4.8 Video Rhett Allain

(a)

(b)

Figure 87: :align: center - Scan the QR code or click here to go to the video.

2.8.4.9 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 49
- Taylor, Charles, Art and Science of Lecture Demonstration, pag. 47
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 130
- Vlaanderen, C.L., Physics Fair
- Borghouts, A.N., Inleiding in de Mechanica, pag. 61

2.8.5 08 No Tipping Allowed

2.8.5.1 Aim

To show that a cylinder that slides to a stop tips only if its diameter-to-height ratio is less than the reciprocal of the coefficient of kinetic friction.

2.8.5.2 Subjects

- 1K20 (Friction)

2.8.5.3 Diagram

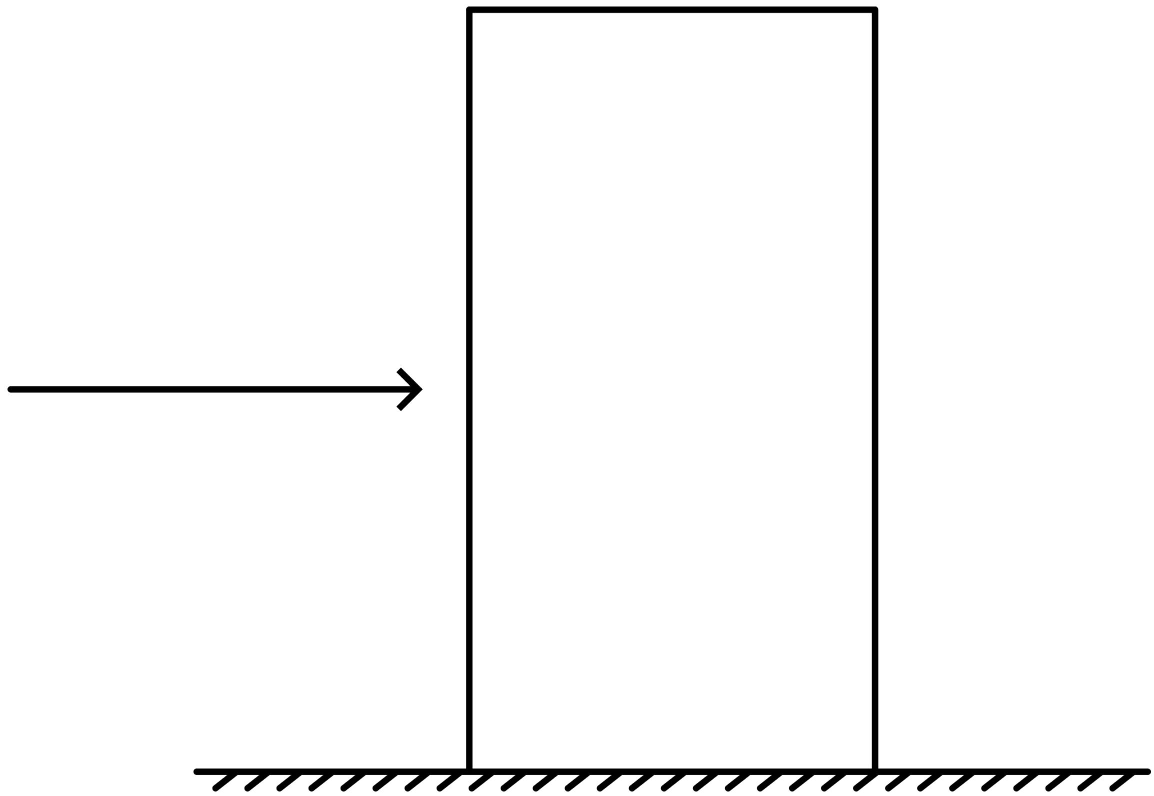


Figure 2.96: .

2.8.5.4 Equipment

- 5 pvc cylinders, $\emptyset = 80$ mm
  - $l_1 = 285$ mm
  - $l_2 = 320$ mm
  - $l_3 = 335$ mm
  - $l_4 = 350$ mm
  - $l_5 = 385$ mm
- Horizontal surface (smooth table)

2.8.5.5 Presentation

The lateral standing cylinder is given a push by hand. (Push the cylinder on the bottom half, a number of times from left to right and vice versa).

Cylinder l_1 never tips, l_5 always tips, l_2, l_3 and l_4 tip sometimes/often (l_3 tips roughly 50% of the times).

2.8.5.6 Explanation

On the verge of tipping, the upward normal force acts at the leading edge of the base (Figure 1, point A).

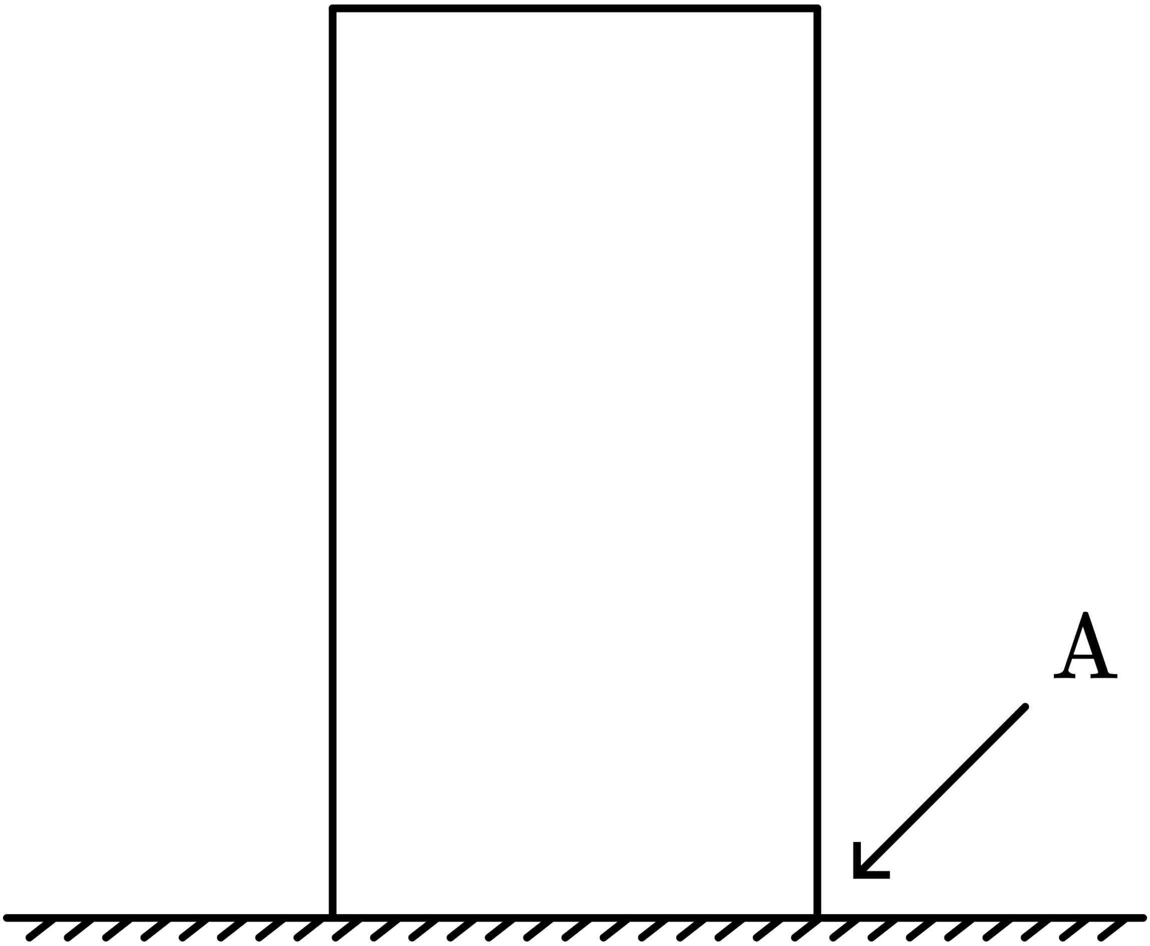


Figure 2.97: .

In the decelerating reference frame ma acts on the center of mass, along with the vertical gravitational force mg. (See Figure 3).

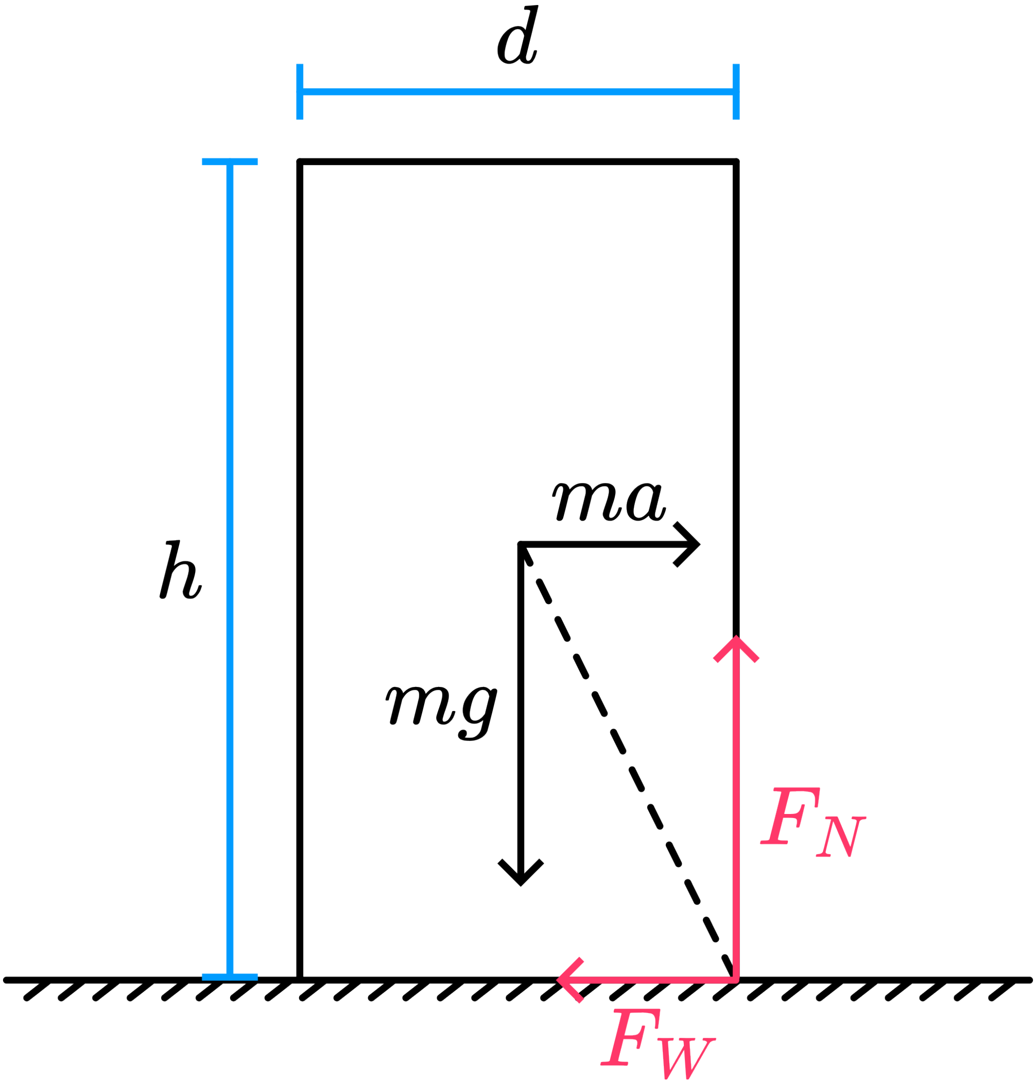


Figure 2.98: .

When the resultant of ma and mg is directed to point A, the cylinder is on the verge of tipping. Figure 3 shows that in that case $\mu_k = d/h$.

2.8.5.7 Remarks

When constructing the demonstration, you need to know the value of μ_k before you can cut the cylinder to the proper heights. μ_k can easily be determined by placing a short cylinder on an inclined board and finding the angle of incline for which the cylinder slides at constant speed after being given an initial push. $\mu_k = \tan(\alpha)$ ($\alpha =$ angle of incline).

2.8.5.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 43
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 128

2.8.6 09 Pulling a Sliding Block

2.8.6.1 Aim

Showing the difference between static and kinetic friction

2.8.6.2 Subjects

- 1K20 (Friction)

2.8.6.3 Diagram

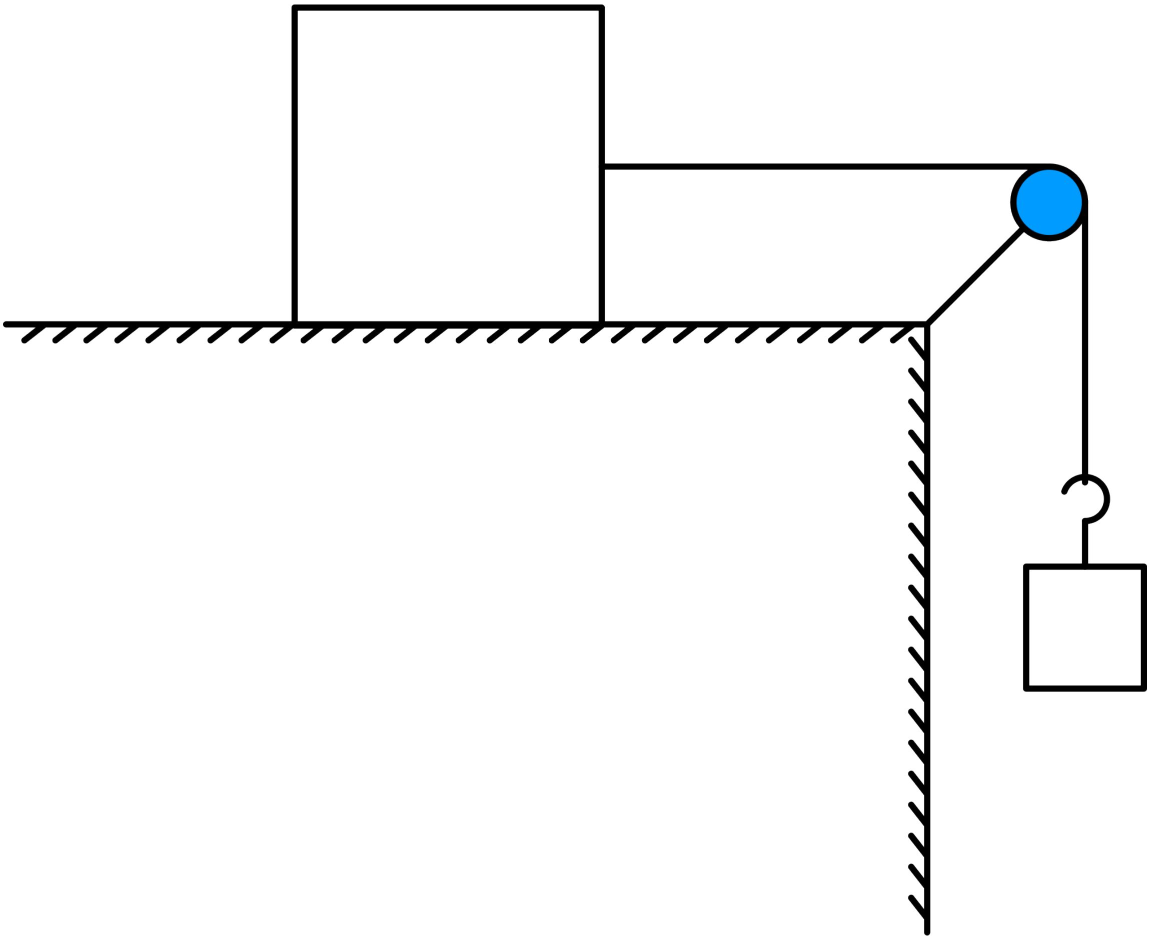


Figure 2.99: .

2.8.6.4 Equipment

- Wooden block
- Pulley
- String
- Slotted masses

2.8.6.5 Presentation

The slotted mass is made so heavy that the block just doesn't move. Then you give a smash on the table and the block will start sliding and keep on sliding.

2.8.6.6 Explanation

When the block just doesn't move, it means that F_f is almost equal to $F_{f,\max} = \mu_{stat} F_n$ (see Figure 2).

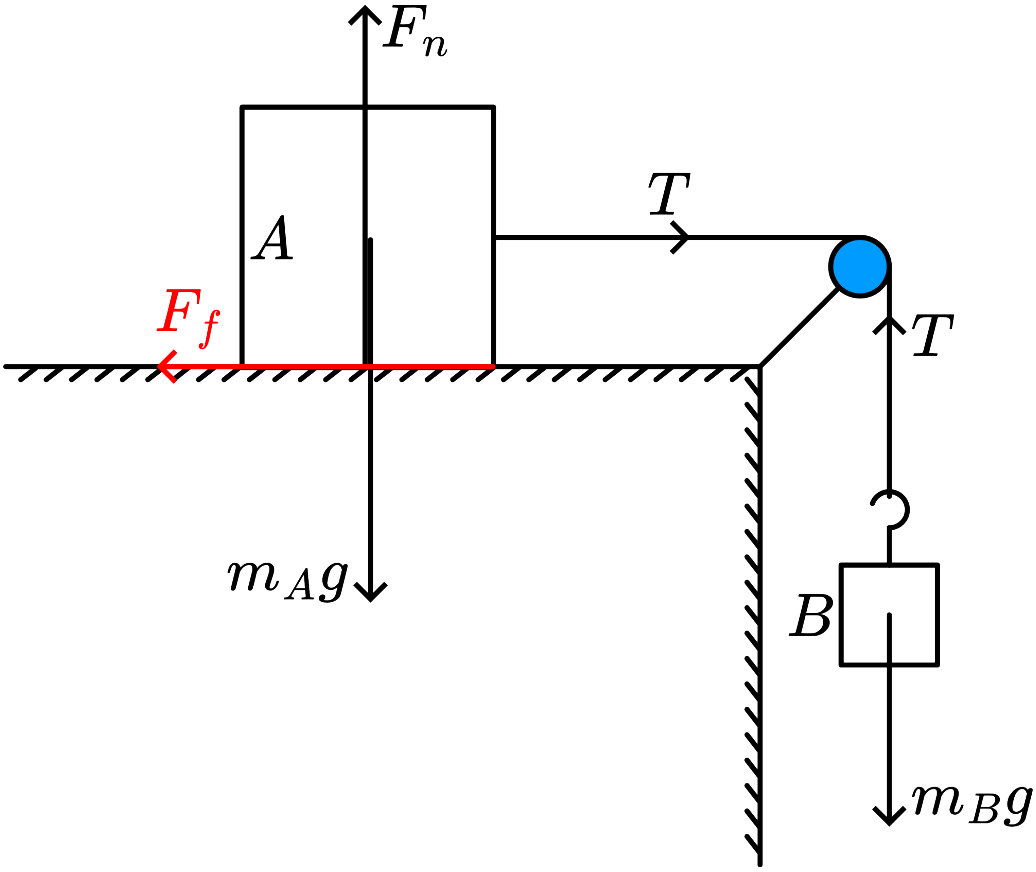


Figure 2.100: .

A smash on the table means that the block is released from the table for a short moment (at least temporarily F_n will be much smaller than $m_A g$) so A and B start moving. Since A and B continue to move, it means that $\mu_{kin} F_n (= m_B g)$ is lower than $\mu_{stat} F_n$.

2.8.6.7 Remarks

- The ring for fixing the string can be moved vertically in order to maintain the pulling string horizontal when the block is moving.
- A wetted bottom of the block makes this demonstration somewhat easier.

2.8.6.8 Sources

- Roest, R., Inleiding Mechanica, pag. 63

2.8.7 10 Rolling Up-and-Down, Again and Again

2.8.7.1 Aim

Determining the coefficient of rolling friction and to give an impression how low the coefficient of rolling friction is.

2.8.7.2 Subjects

- 1K20 (Friction)

2.8.7.3 Diagram

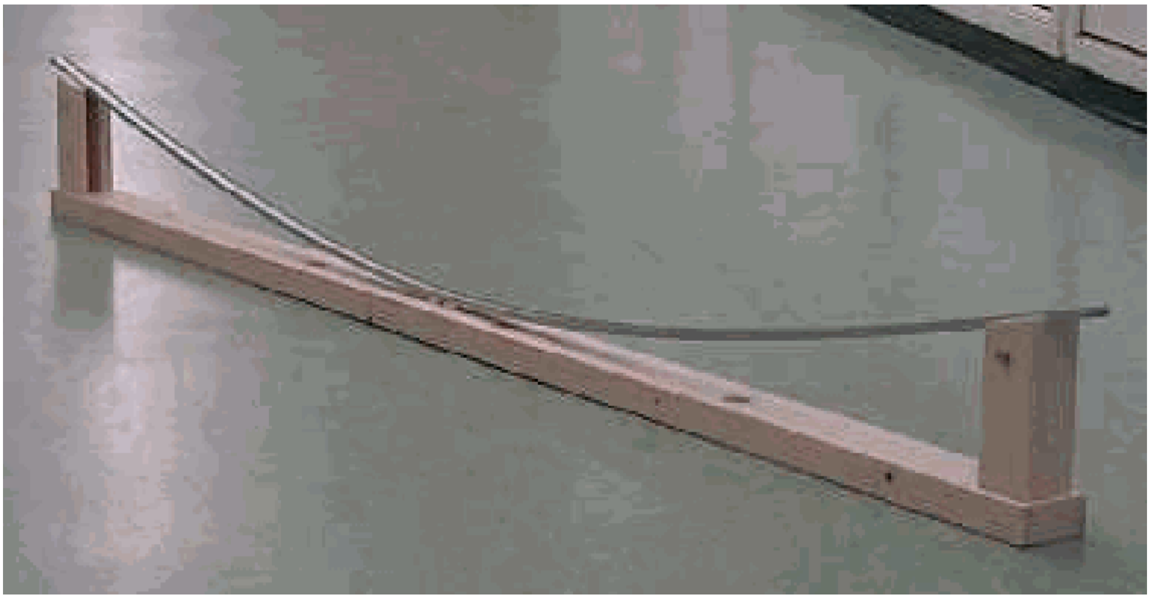


Figure 2.101: .

2.8.7.4 Equipment

- U-shaped railtrack
- Metal ball

2.8.7.5 Presentation

Release the ball and it will roll down the track, climb the other track, and so on. But gradually the distance it rolls reduces (due to rolling friction).

After n runs the coefficient of rolling friction can be determined by measuring the distance the ball travels upward in the n-th run.

2.8.7.6 Explanation

The potential energy of the ball equals (see Figure 2 and Figure 3)

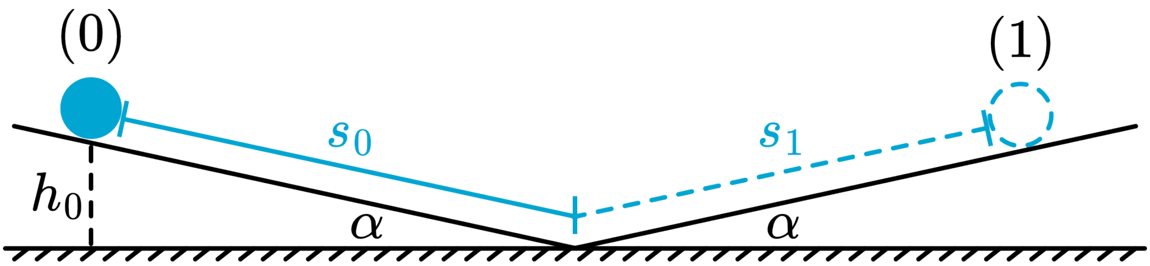


Figure 2.102: .

$U_p(0) = mgs_0 \sin(\alpha) = Fs_0$

Reacting the other side (1): $U_p(0) - U_p(1) = F_f(s_0 + s_1)$

So: $F(s_0 - s_1) = F_f(s_0 + s_1)$

$s_1 = s_0 \left[\frac{F - F_f}{F + F_f}\right] = s_0 \left[\frac{1 - \frac{F_f}{F}}{1 + \frac{F_f}{F}}\right] = s_0 b$

Rolling back (s_1) and up (s_2) again:

$s_2 = s_1 \cdot b = s_0 \cdot b^2$

The coefficient of friction (μ) is by definition F_f / F_N.

In this case (see Figure 3): $\mu = \frac{F_f}{F} \tan \alpha$.

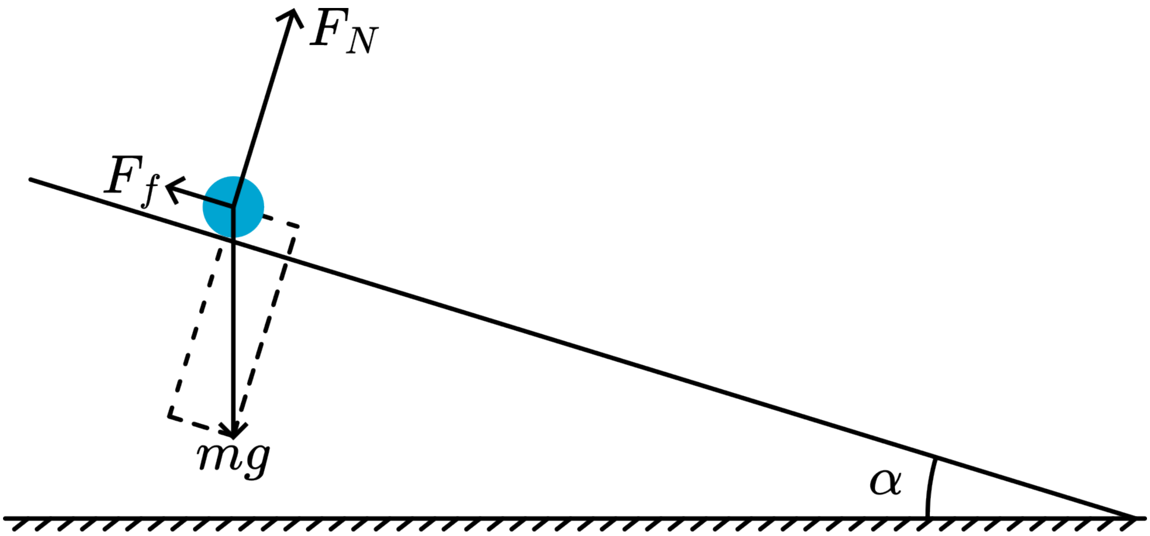


Figure 2.103: .

So the coefficient of friction can be determined by measuring s_0, s_2 and α and using the formulas above.

2.8.7.7 Sources

- Jordens, H.

2.8.8 11 Rope on a Table

2.8.8.1 Aim

To show that by means of the difference in friction forces, the behavior of a rope with knots can be predicted.

2.8.8.2 Subjects

- 1K20 (Friction)

2.8.8.3 Diagram

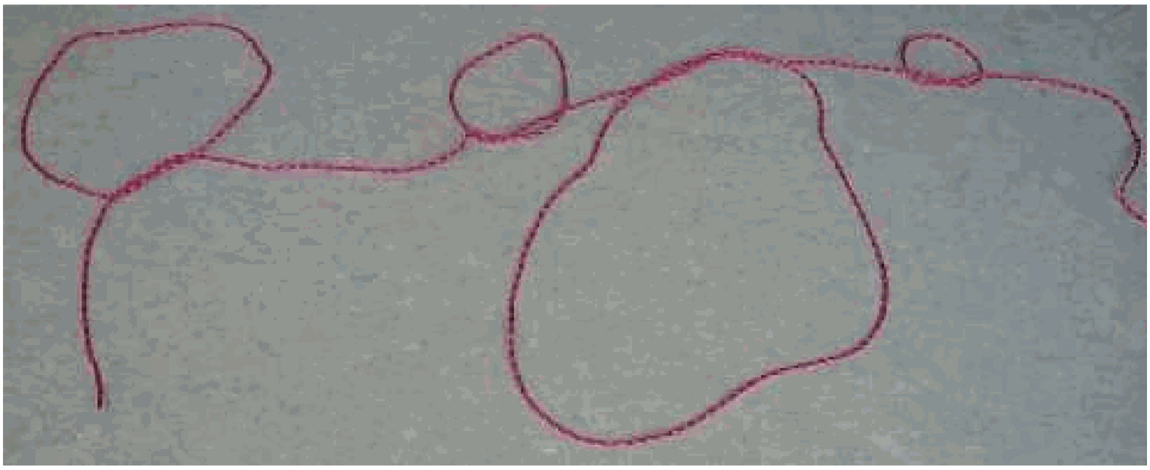


Figure 2.104: .

2.8.8.4 Equipment

4 meter of (mountain climbing) rope.

2.8.8.5 Presentation

1. The rope is laid on a table with loops and loose knots like shown in the diagram. The loops have different sizes.

Ask the audience in what order the loops tighten to knots when pulling the ends of the rope.

Then perform the experiment and carefully observe that the largest loop always moves first, ending in closing all together at the same moment (see Figure 2).

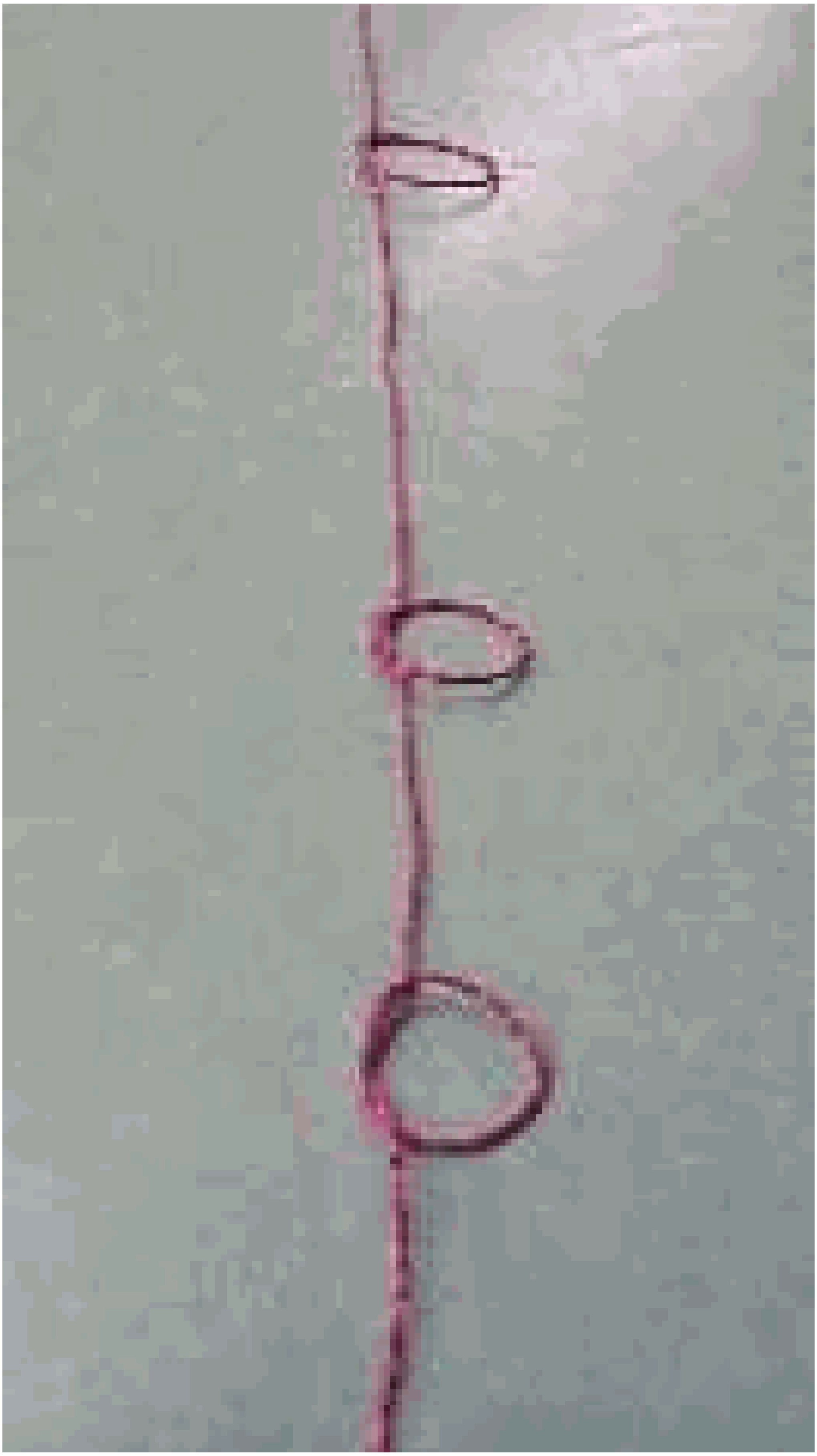


Figure 2.105: .

2. The rope with loops of different sizes is hung horizontally. Again ask the audience in what order the loops will tighten to knots when pulling the ends of the rope. Then perform the experiment and observe that the small loops move first to knots and the largest loops last!

2.8.8.6 Explanation

1. In the small loops the parts of the rope forming the knot press stronger together. This makes that the friction force in the knots with the smaller loops is larger than the friction force in the knots with the larger loops. Sliding occurs first in those places where the opposing friction force is lowest, so the larger loops move first.
2. When the rope is hung horizontally, the larger loops are heavier than the smaller ones. This makes that the friction force in the knots of the larger loops is larger.

2.8.8.7 Remarks

- The rope must be very flexible.
- The knots in the rope should not be too small.

2.8.9 12 Sliding Towel

2.8.9.1 Aim

Showing the difference between static and dynamic coefficient of friction.

2.8.9.2 Subjects

- 1K20 (Friction)

2.8.9.3 Diagram

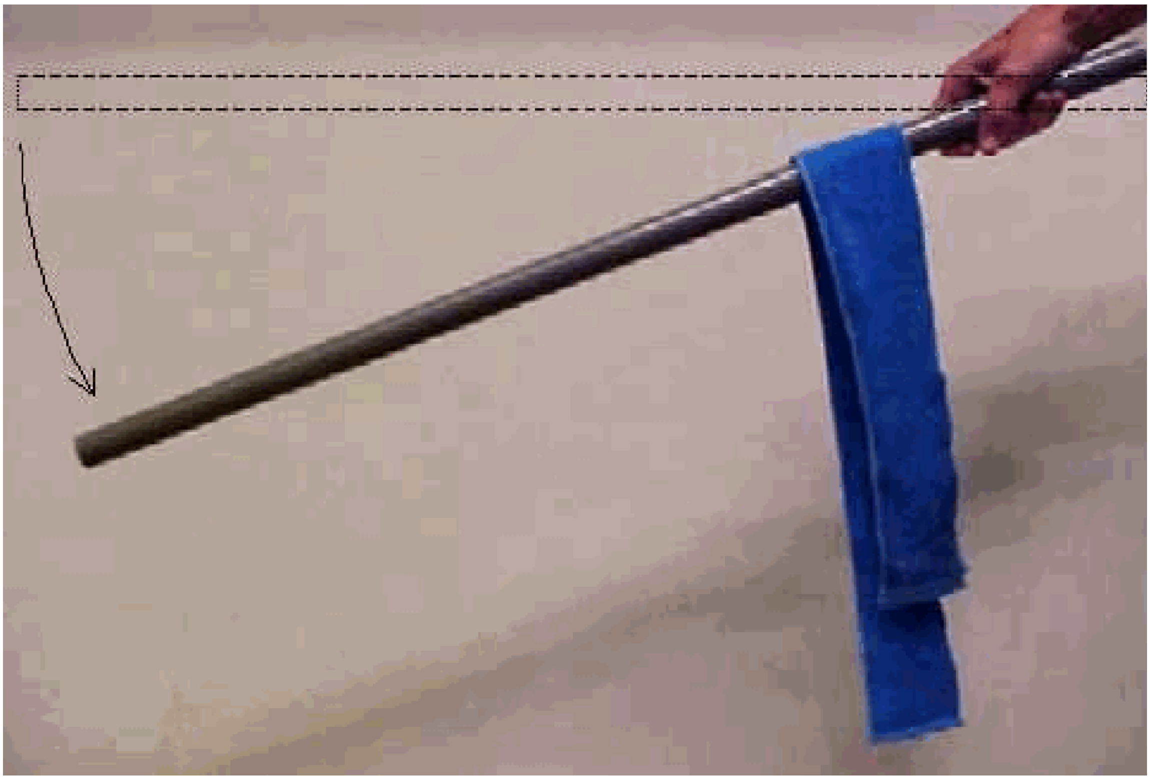


Figure 2.106: .

2.8.9.4 Equipment

- Smooth round tube or stick.(We use a pvc-tube, $\emptyset = 32$ mm.)
- Soft cloth or soft towel.

2.8.9.5 Presentation

A towel hangs across the horizontal round stick. One end hangs lower than the other, such that the towel just does not slip away radially.

Slowly tilt the stick. At a certain angle, the towel starts sliding along the stick and at the same time slips away radially.

It is advisable to repeat the experiment and stress to the students that in this demonstration the radial movement of the towel is the important one to look at.

2.8.9.6 Explanation

When the towel is not moving, it does not slip away radially. Static friction holds it where it is. When it moves along the stick it also slips away radially, so now the friction force is not high enough to prevent radial movement. This means that the friction force in the second part of the demonstration (the kinetic situation) is lower than in the beginning of the demonstration (the static situation): $\mu_k < \mu_s$.

2.8.9.7 Sources

- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 136
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 66-67

2.9 1L Gravity

2.9.1 1L10 Universal Gravitation

2.9.1.1 01 Weighing the Earth

2.9.1.1.1 Aim

To show the experiment of Cavendish.

2.9.1.1.2 Subjects

- 1L10 (Universal Gravitational Constant)

2.9.1.1.3 Diagram

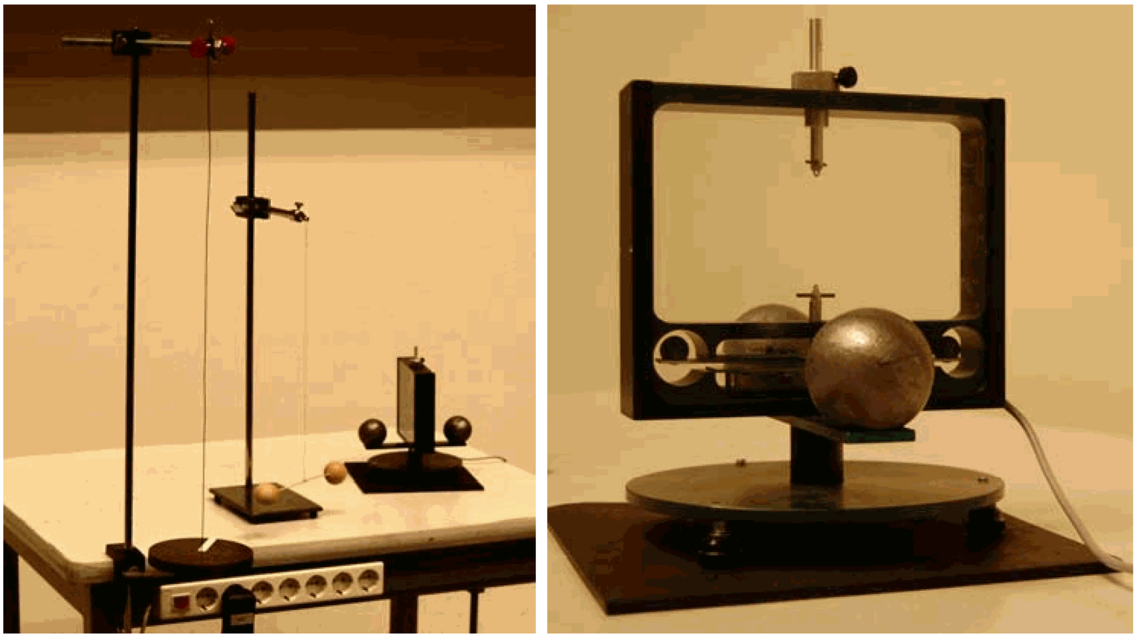


Figure 2.107: .

2.9.1.1.4 Equipment

- Computerized Cavendish Balance.
- Data-acquisition system.
- Some models of torsion balances (see Diagram A).

2.9.1.1.5 Safety

- You are manipulating lead balls in this experiment. So wash your hands after you have performed the demonstration.

2.9.1.1.6 Presentation

First a short historical survey is presented to the students:

- **1687:** Newton's law on gravitation published in his "Philosophia Naturalis Principia". In this "Principia" he considers that the attraction of a pendulum (that hangs straight downwards) by a mountain could be used as a practical demonstration of his theory (see Figure 2), but pessimistically he thought that any real mountain would produce too small a deflection to measure.

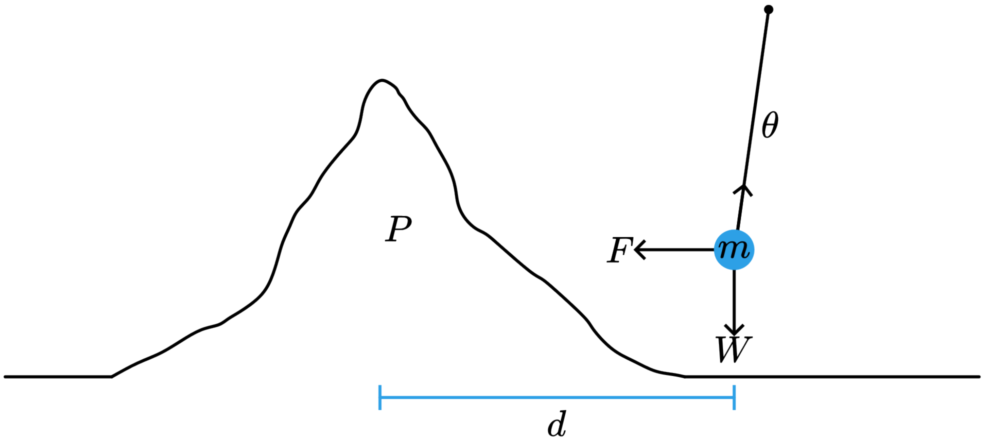


Figure 2.108: .

- An experiment to test Newton's gravitational law would provide an estimate of the mass and density of the Earth. Since, by that time, the masses of astronomical objects were known in terms of relative ratios, the mass of the Earth would provide reasonable values of density and mass to the other planets, their moons, and the Sun.
- **1738**: A French team performs plumb-line measurements next to the volcano Chimborazo in Ecuador. They determined a deflection of 8 seconds of arc, but doubted the reliability of their results (they measured in very difficult circumstances).
- **1774**: The plumb-line experiment is conducted around the Scottish mountain of Schiehallion. A deflection of 11.6 seconds of arc is measured (the sum of the north - and south deflections). Based on these measurements Hutton determined in 1778 that the earth had a mean density of about 9/5 of that of the mountain, and announced that the mean density of the Earth is $4,500\ \mathrm{kg/m^{-3}}$. He also gives a density table for the other planets and the Sun.
- **1783**: John Michell, a geologist, invents the torsion balance (independent of Coulomb in France) in order to measure the force of gravity between masses in the laboratory. He dies in 1793 before he could begin the experiment. His apparatus was sent to Cavendish who performed and completed the experiment in 1798.

Pictures of Cavendish balance are shown to the students (see Figure 2).

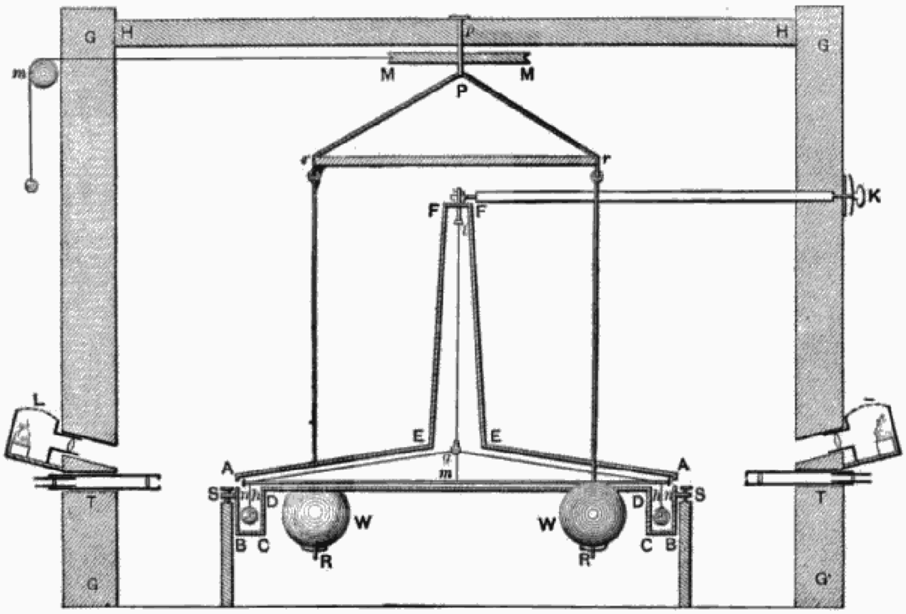


Fig. 1

Figure 2

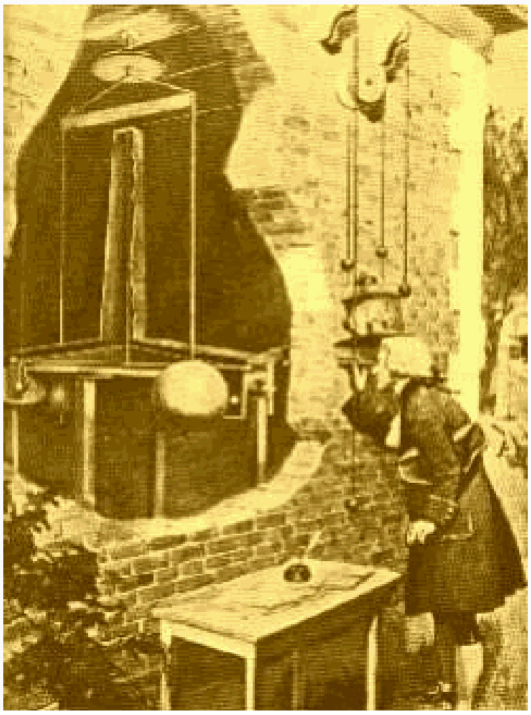


Figure 2.109: .

Our instrument (see Diagram B) is explained to the students and compared with Cavendish's construction:

It is essentially a torsion pendulum in which two small lead balls (15 gram each) rest on the ends of a light aluminium boom. This boom is suspended in the centre by a thin tungsten wire (diameter is 25 micron). All this is mounted inside a draft proof case. On the outside of the case two larger lead balls (1 kilogram each) can be swivelled from one side to the other (see Figure 4).

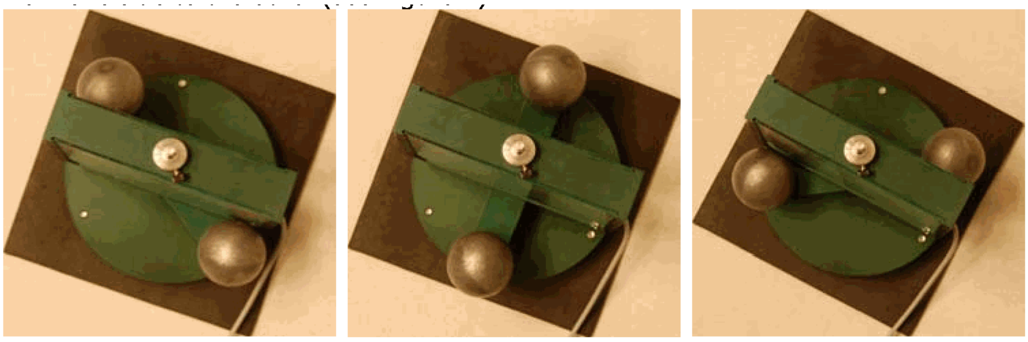


Figure 2.110: .

The position of the boom is measured in a capacitive way: the boom is suspended between capacitor plates mounted in the aluminium case. This transducer comprises two sensors to eliminate noise due to vibrations. The transducer output is proportional to the angular movement of the boom. The angular displacement appears on the monitor screen as a function of time (see Figure 5).

At the beginning of the lecture a small displacement of the boom is given (for instance by a little “shock” to the table). It takes quite a long time before the boom is at rest again (see the example in Figure 5, in which it took around 3000 seconds before the boom was damped enough to perform the demonstration). In this damping the students can clearly observe the torsional vibration of the boom.

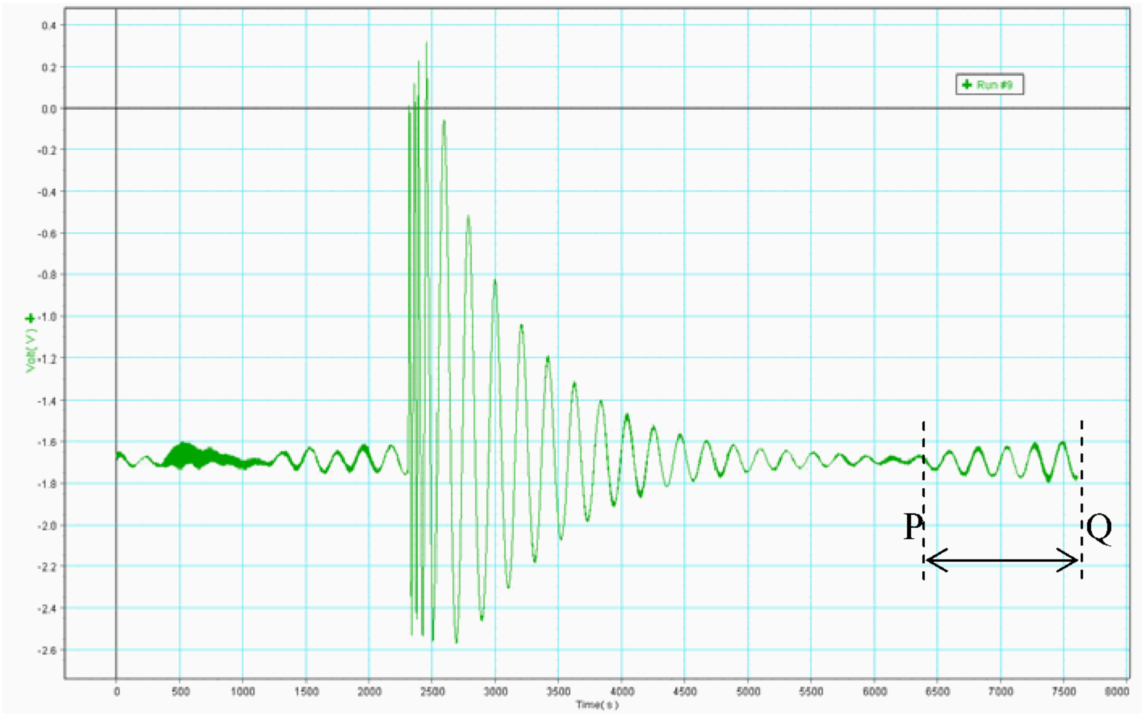


Figure 2.111: .

(Giving the model torsion-balances a small deflection will strengthen their imagination of what is happening inside the casing of our instrument.)

In P — Q we swivel the lead balls in the right rhythm from one position to the other in order to drive the boom to higher amplitudes (swivel from one side to the other when the indicated amplitude is at its extreme value). This part shows clearly that there must be an attractive force that is responsible for the increasing amplitude.

2.9.1.1.7 Explanation

The mountain experiment (see Figure 2):

$F = G\frac{mM_M}{d^2}$ And $W = G\frac{mM_E}{r_E^2}$. This leads to: $\frac{F}{W} = \frac{M_M}{M_E}\left(\frac{r_E}{d}\right)^2 = \frac{\rho_M V_M}{\rho_E V_E}\left(\frac{r_E}{d}\right)^2$

$\frac{F}{W} = \tan\theta$, so $\frac{\rho_M}{\rho_E} = \frac{V_E}{V_M}\left(\frac{d}{r_E}\right)^2 \tan\theta$.

Since the volumes of the Earth and mountain are known as are r_E and d, then $\frac{\rho_M}{\rho_E}$ is determined in measuring the angle of the plumb-line with the vertical. Knowing ρ_M (soil drilling), ρ_E is determined.

Cavendish experiment:

In order to know the force between the lead balls, the torsion constant of the wire needs to be known. Oscillation experiments yield this value (see manual). Quite a lot of calculation is needed, also for the determination of G out of the oscillations. So this is not suitable when demonstrating. The demonstration just shows that here is an attractive force working.

Once G has been found, the attraction of an object (m) at the Earth's surface to the Earth itself can be used to calculate the Earth's mass and density:

$$mg = G\frac{mM_E}{r_E^2}; so M_E = \frac{gr_E^2}{G}, and \rho_E = \frac{M_E}{V_E} = \frac{M_E}{\frac{4}{3}\pi r_E^3} = \frac{3g}{4\pi r_E G} \tag{2.13}$$

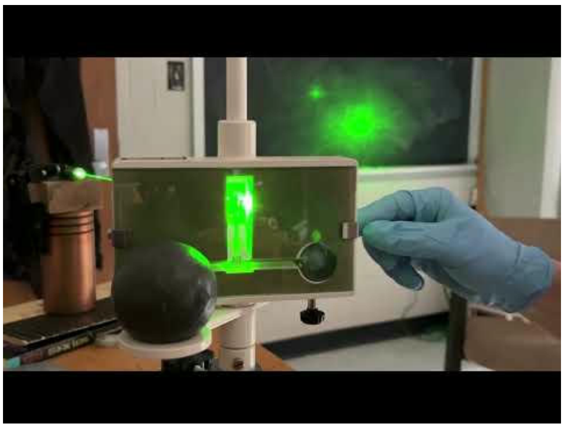
In this way Cavendish found that the Earth's density is 5.448 times that of water. (Cavendish was not interested in the value of G. To him was just a proportionality constant, in which he was not specifically interested. To us that is different.)

2.9.1.1.8 Remarks

- Treat the Cavendish balance carefully, it is a sensitive instrument.
- Fix the table to the floor and be sure it is a massive floor the assembly is standing on (a wooden floor moves too much).

2.9.1.1.9 Video Rhett Allain

(a)



(b)

Figure 104: :align: center - Scan the QR code or click here to go to the video.

2.9.2 1L20 Orbits

2.9.2.1 01 Kepler's Second Law

2.9.2.1.1 Aim

To verify Kepler's second law

2.9.2.1.2 Subjects

- 1L20 (Orbits)
- 8A10 (Solar System Mechanics)

2.9.2.1.3 Diagram

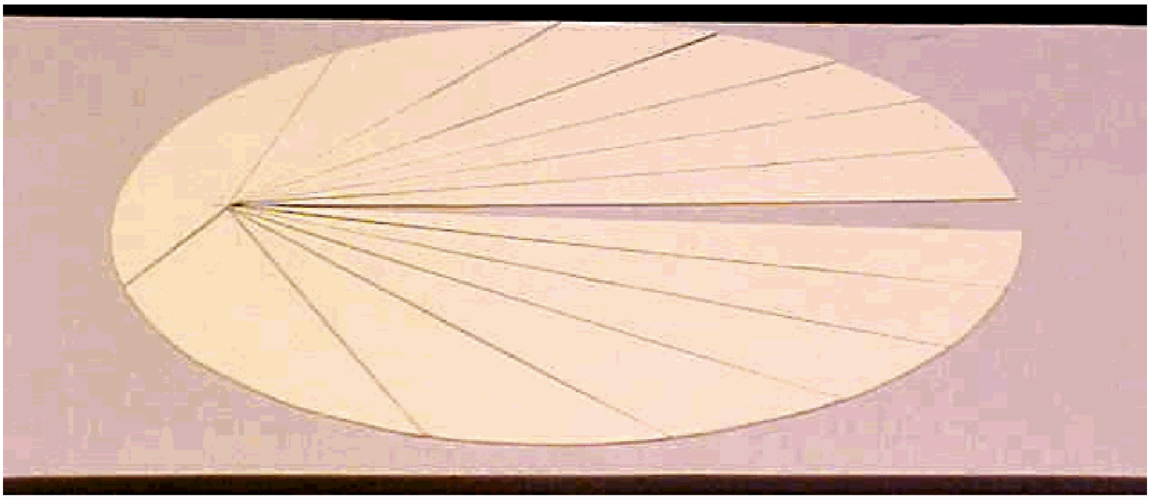


Figure 2.115: .

2.9.2.1.4 Equipment

- Board-model with "Kepler-areas" (see Diagram).
- Balance, with large display.
- Software program (we use Interactive Physics) drawing the position of a planet around a central mass at a couple of time-intervals.
- Projector, to project the monitor-image on a large screen.

2.9.2.1.5 Presentation

By means of the software program an elliptical orbit is projected (see Figure 2A). The speed in the orbit is visualized when in the orbit points are plotted at constant time-intervals. This orbit is also plotted when the time-interval applied is 16 times larger (Figure 2B).

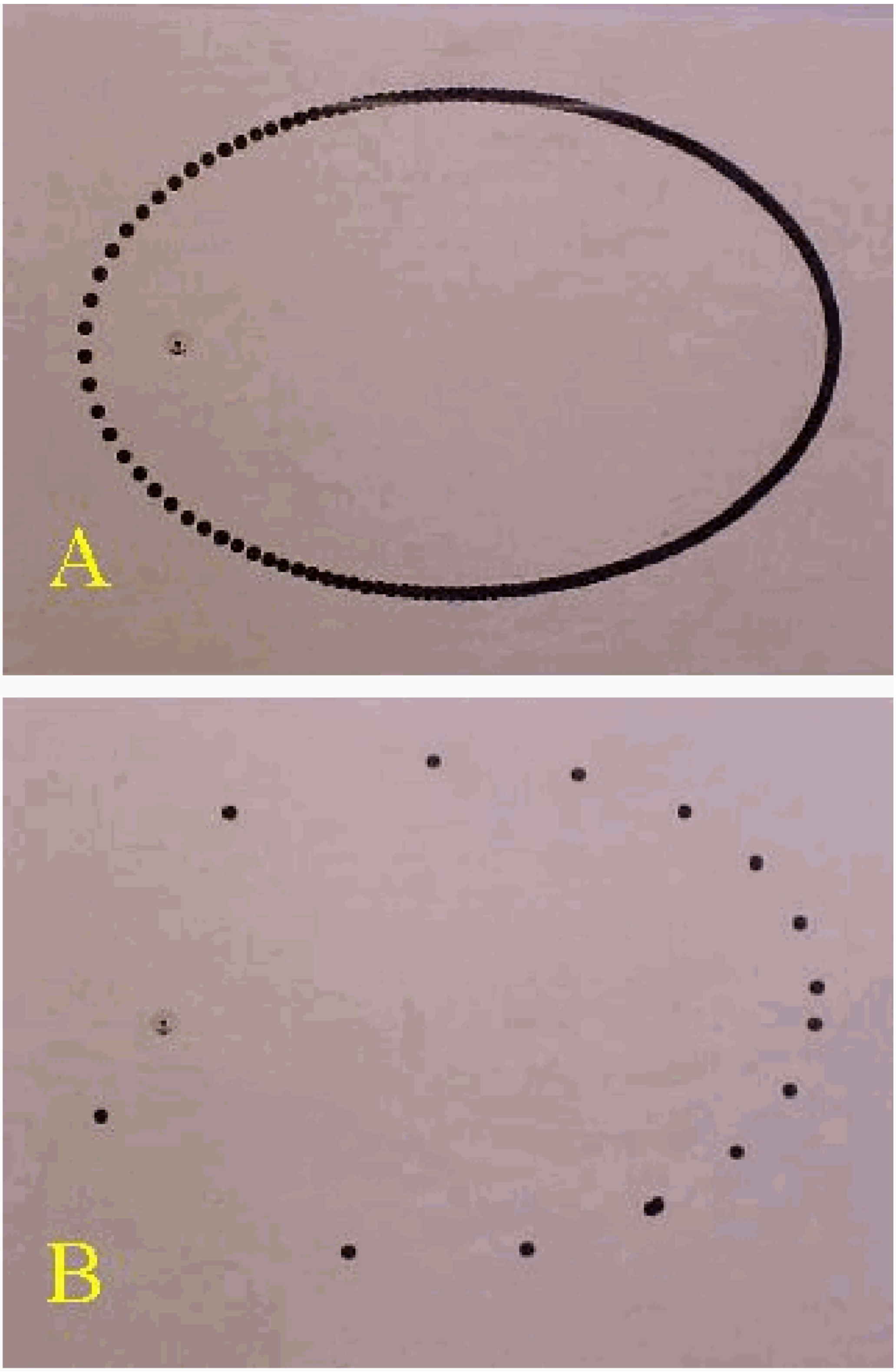


Figure 2.116: .

Before, we had this figure projected on a large sheet of cardboard and the elliptical time-segments were cut out (see Diagram). The similarity between the software-image and the cardboard-model is shown to the students. When the segments are placed one after the other on the balance, equal mass is observed. This also means that the areas of the segments are equal (Kepler's second law).

2.9.2.1.6 Explanation

Kepler "found" his law while working on the astronomical data of Tycho Brahe. So in our demonstration the law should arise from watching the areas and "seeing" the equality. Since Newton we can use the law of conservation of angular momentum. Using this law we can explain the statement of Kepler's second law.

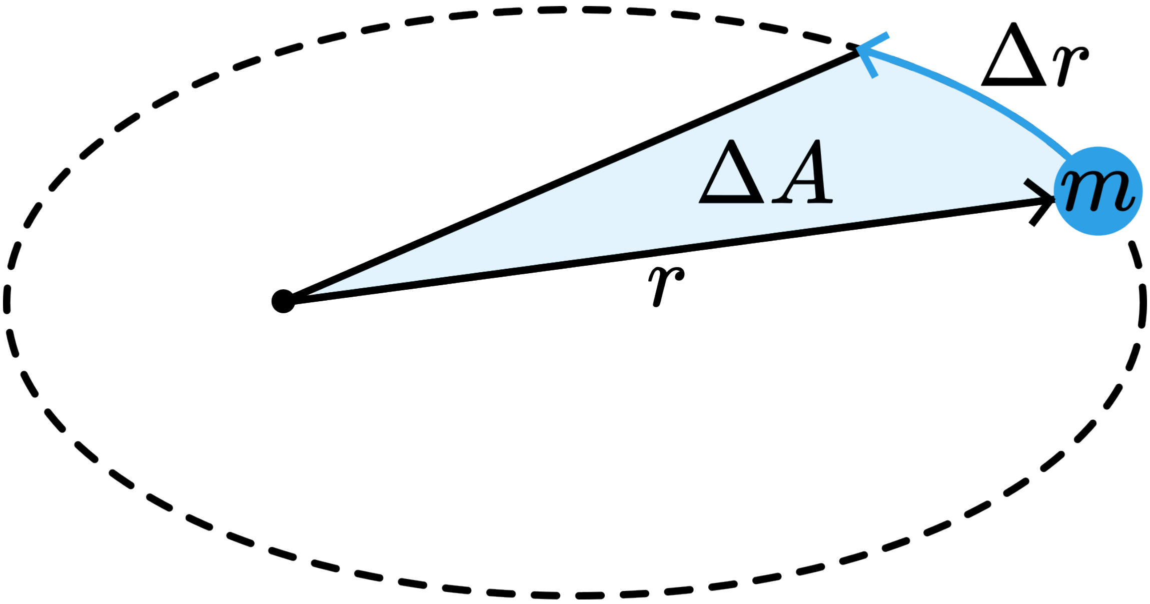


Figure 2.117: .

Consider the area in Figure 3 swept by the vector r in a time Δt.

$$\Delta A = \frac{1}{2} \mid \vec{r} \times \Delta \vec{r} \mid \tag{2.14}$$

$$\frac{\Delta A}{\Delta t} = \frac{1}{2} \mid \vec{r} \times \frac{\Delta \vec{r}}{\Delta t} \mid = \frac{1}{2} \mid \vec{r} \times \Delta \vec{v} \mid \tag{2.15}$$

Since $\vec{L} = m\vec{r} \times \vec{v} = const. \rightarrow \frac{\Delta A}{\Delta t} = \frac{1}{2} \frac{\mid \vec{L} \mid}{m} = const.$

So, when Δt is constant (equal time-intervals), then ΔA is constant.

2.9.2.1.7 Simulations

On the internet you can find many simulations that are appropriate. For instance on:

- www.walter-fendt.de

2.9.2.1.8 Remarks

- $\vec{L}$ being constant means also that m moves in a fixed, flat plane, since $\vec{L}$ will not change its direction

2.9.2.1.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, edition 1998, pag. 105-106.
- McComb,W.D., Dynamics and Relativity, edition 1999, pag. 71.
- Roest, R., Inleiding Mechanica, vijfde druk, pag. 100-102.
- Stewart, J, Calculus, edition 1999, pag. 866-867.

2.9.2.2 02 Kepler's Third Law

2.9.2.2.1 Aim

To show empirically that Kepler's third law is true.

2.9.2.2.2 Subjects

- 1L20 (Orbits)
- 8A10 (Solar System Mechanics)

2.9.2.2.3 Diagram

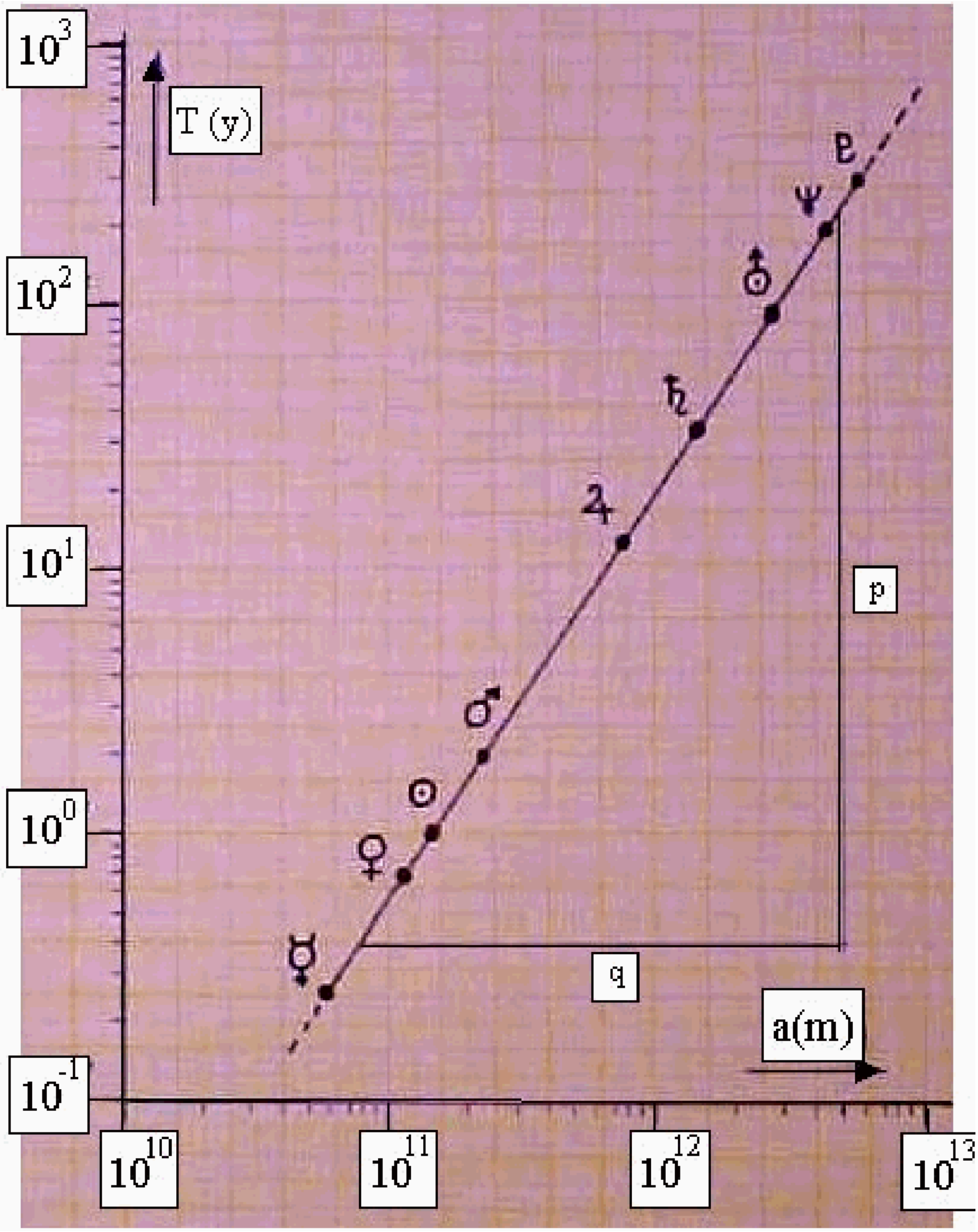


Figure 2.118: .

2.9.2.2.4 Equipment

- Graph on overhead sheet, $T = f(a)$, T and a both scaled logarithmically.
- Table with data of the planetary system (see Sources).

2.9.2.2.5 Presentation

The graph is projected by means of an overhead sheet. The relationship with the table of planetary data is elucidated. Clearly can be observed that the data fit on a straight line in such a double logarithmic graph. The slope of this line (p/q) equals 1.5. This is the relationship of the powers in Kepler's third law: $T^2 \propto a^3$

2.9.2.2.6 Explanation

Kepler's third law states $T^2 = c \times a^3$ with c a constant. Taking logarithms on both sides, we can also write:

$$2 \log T = \log c + 3 \log a \tag{2.16}$$

and:

$$\log T = \frac{1}{2} \log c + \frac{3}{2} \log a \tag{2.17}$$

So when T and a are graphed logarithmically (with $x-$ and y-decades equally spaced), we see a line whose slope ($\frac{3}{2}$) is the power-relationship in the original function.

2.9.2.2.7 Simulations

ISSUE: SIMULATION NEEDED

2.9.2.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, edition 1998, pag. 106-107 and 741 (planetary data).
- BINAS tabellenboek, vijfde druk, tabel 31.
- McComb, W.D., Dynamics and Relativity, edition 1999, pag. 72-74.
- Roest, R., Inleiding Mechanica, vijfde druk, pag. 257-258.
- Stewart, J, Calculus, edition 1999, pag. 867.

2.9.2.3 03 Precessing Orbit (1)

2.9.2.3.1 Aim

To show that the orbit of a ball on a concave surface will precess in a predictable manner.

2.9.2.3.2 Subjects

- 1L20 (Orbits)
- 8A10 (Solar System Mechanics)

2.9.2.3.3 Diagram

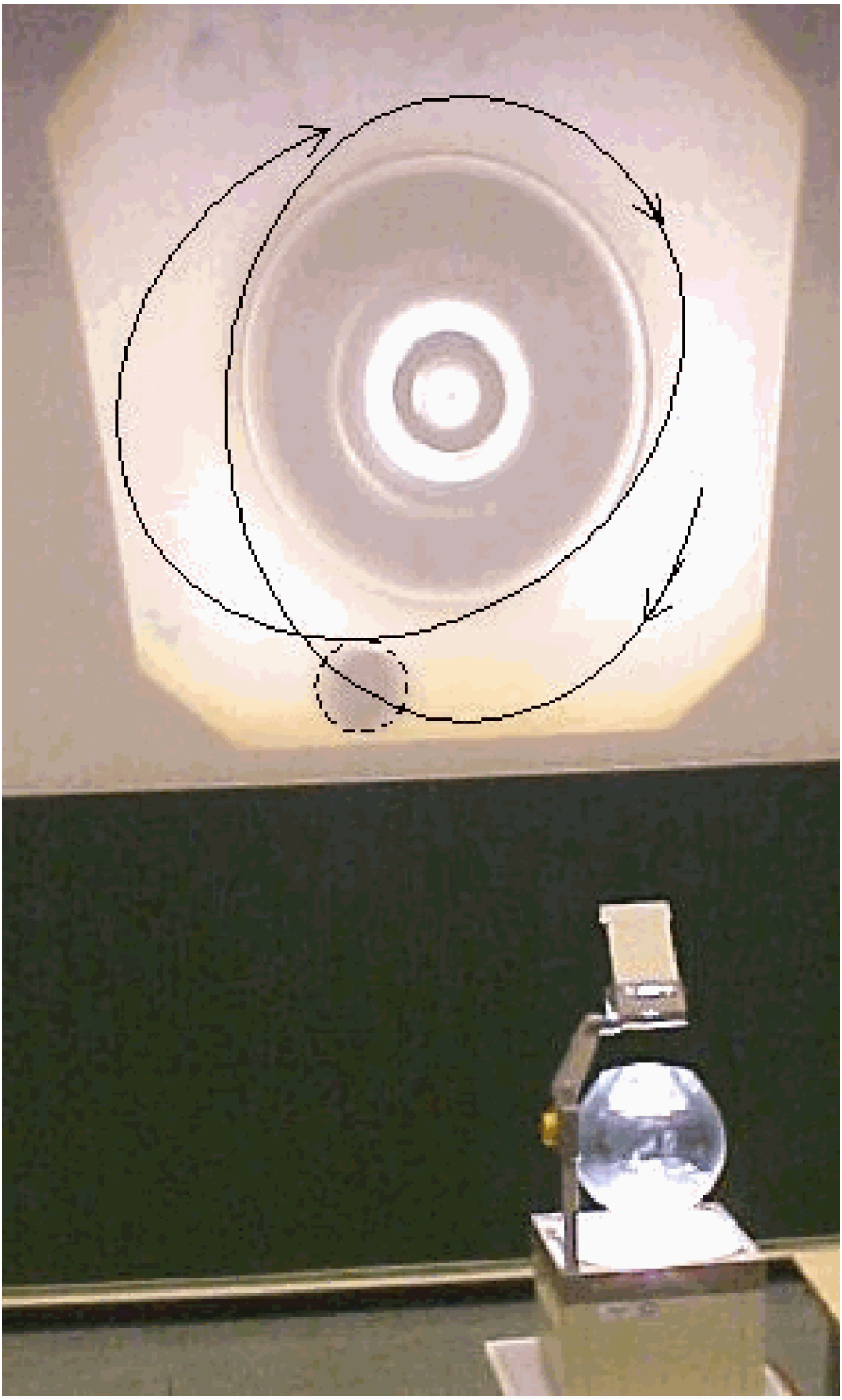


Figure 2.119: .

2.9.2.3.4 Equipment

- Bowl.

- Steel ball, diam. around 2 cm.
- Overhead projector.

2.9.2.3.5 Presentation

Use the overhead projector to show the two-dimensional image of the ball in the bowl (see also the demonstration Force field). Shaking the bowl gently you should be able to achieve orbits that are either circular, linear or elliptical depending on the ball's speed and direction.

Make an elliptical orbit. Observe that the orbit does not close, but precesses into the direction of the ball's rotation (see orbit drawn in Diagram).

Also can be shown:

- Zero precession for a straight line orbit;
- stronger precession for ellipses that are less eccentric;
- stronger precession for larger ellipses.

2.9.2.3.6 Explanation

Precession in this demonstration happens due to the bowl's shape. But be careful with this analogy! The bowl's shape is NOT such that the potential energy corresponds to an r^{-1} variation! (see Sources).

The next is just an attempt to say something more about it:

For the concave bowl we can write for this type of potential (Maclaurin series):

$$U(r) = U(0) + \frac{U'(0)}{1!}r + \frac{U''(0)}{2!}r^2 + \frac{U'''(0)}{3!}r^3 + \ldots \tag{2.18}$$

When $U(0) = 0$ and $U'(0) = 0$ (minimum at $r = 0$, the center of the bowl) and when r is relatively small, so we can neglect the higher-order terms, then: $U(r) = \frac{1}{2}U''(0)r^2$.

This is a harmonic potential, and when moving in a line with small amplitudes, we'll see a harmonic motion. This harmonic potential $\left(r^2\right)$ is clearly NOT a r^{-1}-potential.

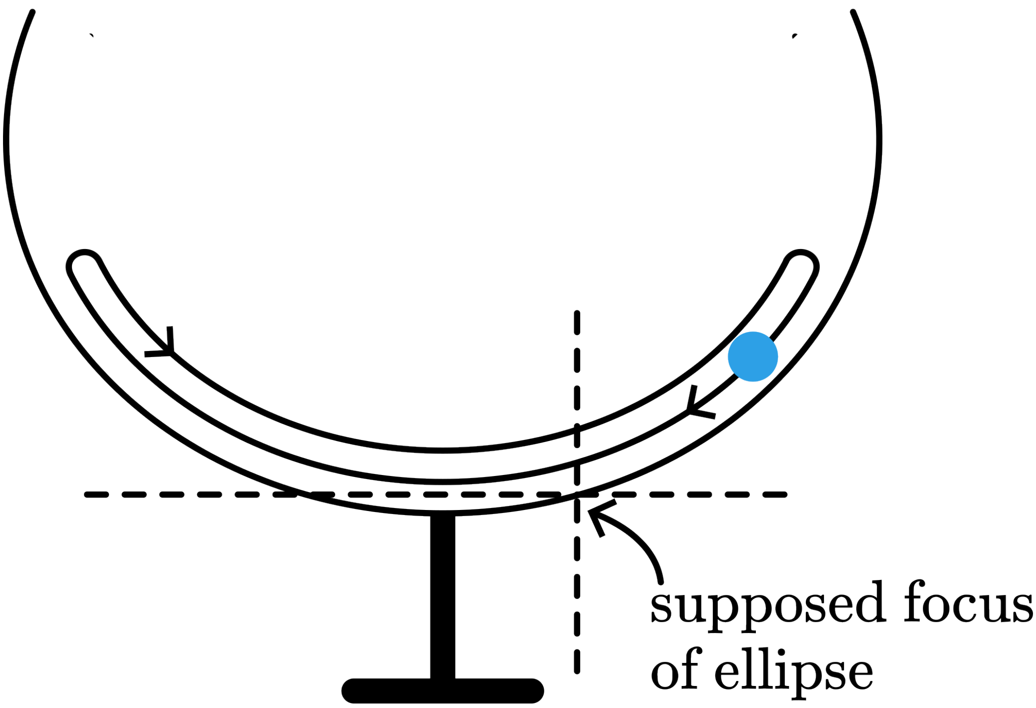


Figure 2.120: .

In case of an ellipse, the situation becomes even worse. Now one focus of the ellipse is off the center of the bowl (see Figure 1) and at $r = 0, U(0) = 0$, but $U'(0)$ is not 0 ! So now:

$$U(r) = U'(0)r + \frac{1}{2}U''(0)r^2 + \frac{1}{6}U'''(0)r^3 ... \tag{2.19}$$

showing that expressing the potential with respect to a focal point, this potential is still farther away from a r^{-1}-potential. Conclusion is that the bowl only suggests planetary motion (but is in the same time a wrong example of such a motion). The only reason to show it, is to challenge the mind of the students with the question how the shape of the bowl ought to be for a real r^{-1}-potential.

2.9.2.3.7 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 66-68
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 13-14
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 107-108
- McComb,W.D., Dynamics and Relativity, pag. 34

2.10 1M Work and Energy

2.10.1 1M10 Work

2.10.1.1 01 How much Work to Break a Soup Tureen?

2.10.1.1.1 Aim

To show the influence of the distance on the work done by a constant force.

2.10.1.1.2 Subjects

- 1M10 (Work)

2.10.1.1.3 Diagram

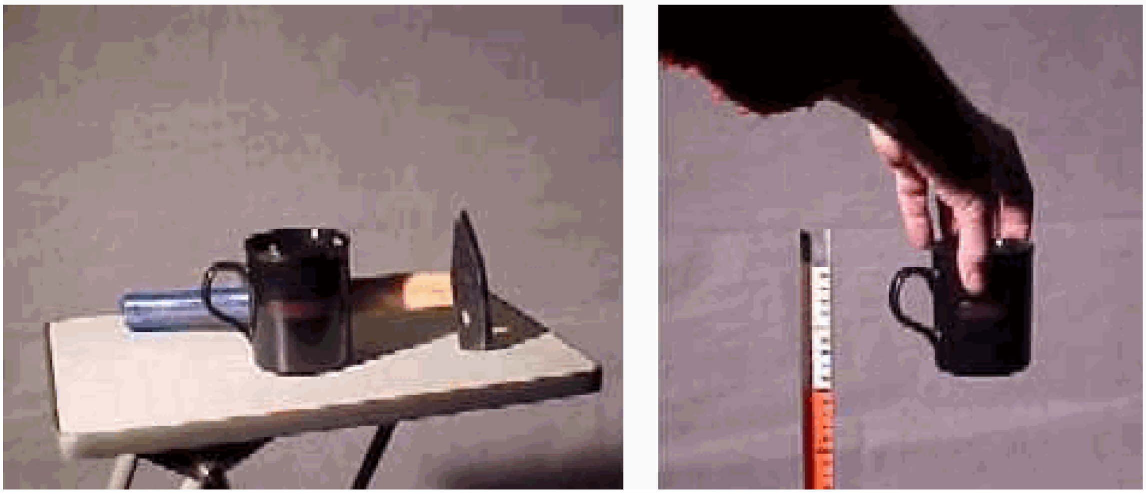


Figure 2.121: .

2.10.1.1.4 Equipment

- Two identical soup-tureens.(Instead of soup-tureens also cheaper coffee-mugs can be used, or whatever ceramic object you prefer.)
- Hammer.
- Meterstick.

2.10.1.1.5 Presentation

Take hammer and soup-tureen and knock the soup-tureen in one blow to pieces. Then ask the students how much work it took to do this. Probably they will have no idea. Then the demonstration is performed in a controlled way:

First place the soup-tureen on the balance to determine its weight ($F_w = mg$). Then drop the soup-tureen on the ground from about 10cm height: The soup-tureen will survive. Next, repeating the demonstration, increase the height of fall in regular steps until the soup-tureen breaks.

Clearly the distance traveled by the constant force (mg) determines the work on the soup-tureen.

In this way we strengthen the idea that it makes sense that the work done by a constant force depends on the distance, an idea that is rather intuitive at the outset.

2.10.1.1.6 Explanation

From the first demonstration it is clear that a certain amount of work is needed to break the soup-tureen.

In the second demonstration the force on the soup-tureen during the fall equals $F_w = mg$, and during the fall this force is constant. The only variable in the demonstration is the distance of fall. So this demonstration illustrates that the amount of work, which is dissipated in the soup-tureen when it hits the ground, depends on the distance traveled: A certain distance has to be traveled to equal the effect of the blow of the hammer.

Using $W = F_w \cdot h_{fatal}$ and $h_{fatal} = 1$ m and $F_w = 3$ N (coffeemug), we find $W = 3$ J.

2.10.1.1.7 Remarks

- Take care that in all demonstrations you drop the object in the same way, so that it will hit the ground in the same way. The way the ceramic object hits the ground depends on its orientation just before ground contact. (We make it fall bottom down.)

2.10.2 1M40 Conservation of Energy

2.10.2.1 02 Kinetic Energy in an Elastic Collision

2.10.2.1.1 Aim

To show conservation of mechanical energy in an elastic collision.

2.10.2.1.2 Subjects

- 1M40 (Conservation of Energy)

2.10.2.1.3 Diagram

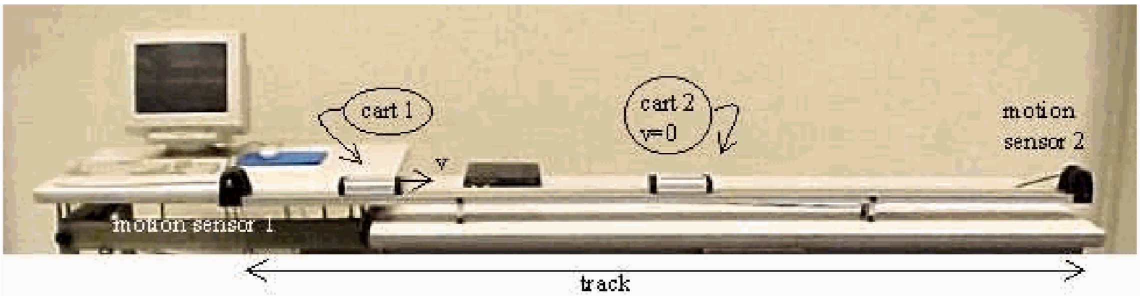


Figure 2.122: .

2.10.2.1.4 Equipment

- Track (2.2 m), levelled.
- Two carts with magnetic repelling bumpers.
- Two motion sensors.
- Data-acquisition system and computer with software.
- Projector to project the monitor screen.

2.10.2.1.5 Presentation

Set up the equipment as shown in Diagram. Set up Scientific Workshop so that it shows four graphs: velocity of cart 1, kinetic energy of cart 1, kinetic energy of cart 2, sum of both kinetic energies (see Figure 2).

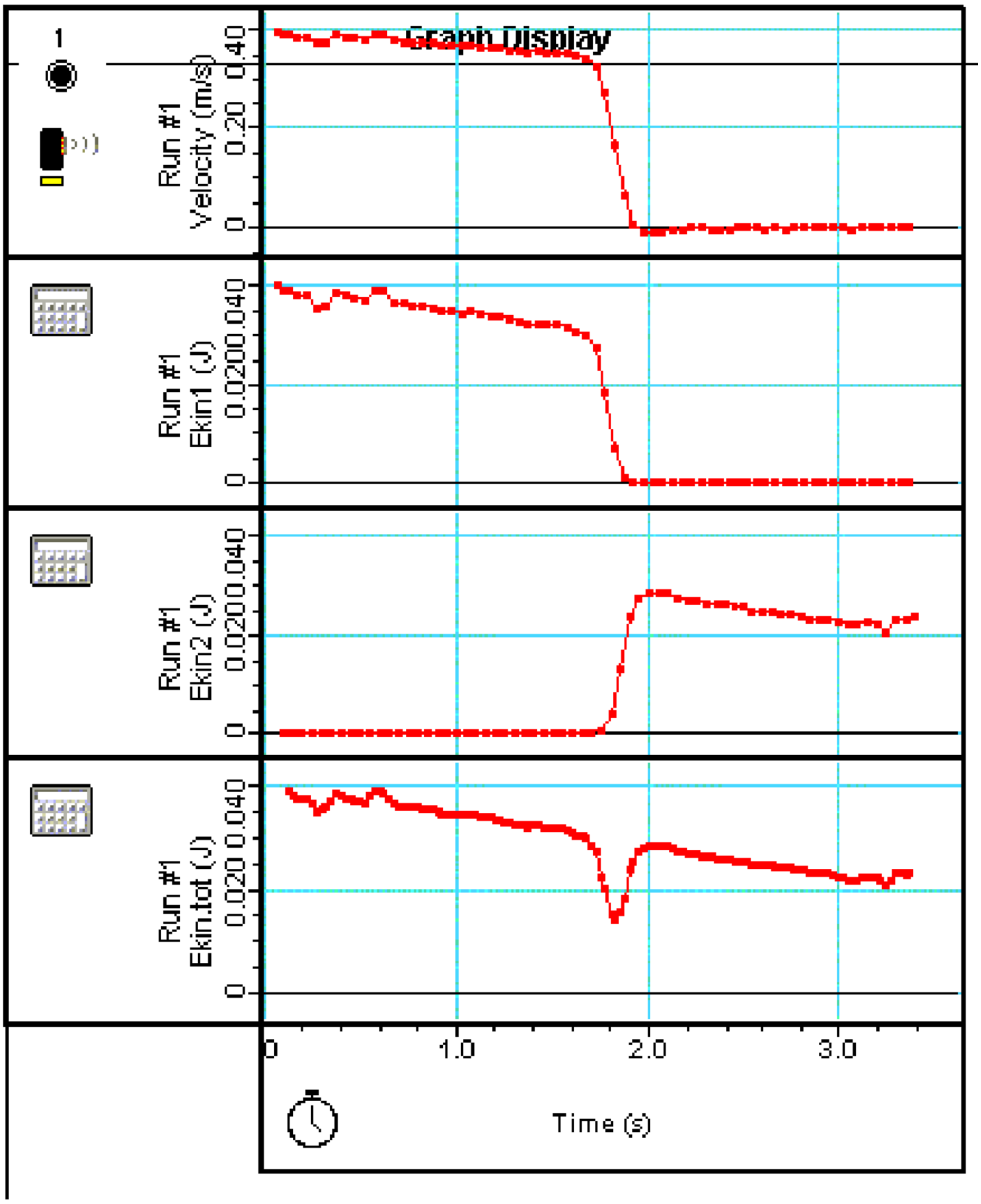


Figure 2.123: .

First show the elastic collision without using the data-acquisition system. Let the students observe that the velocities of cart 1 before the collision and of cart two after the collision are the same: conservation of kinetic energy. Do the demonstration again, but now collect data. On the screen the mentioned graphs appear. The results can be discussed. Observing the graph of $E_{kin,1}$ and $E_{kin,2}$ shows at first sight conservation of kinetic energy in this demonstration. But the graph of $E_{kin,1} + E_{kin,2}$ shows a remarkable dip: observe that kinetic energy disappears and comes back again. Ask the students if there is a temporarily violation of the law of conservation of mechanical energy.

2.10.2.1.6 Explanation

During the collision potential energy is stored in the magnetic field of the bumpers.

2.10.2.1.7 Remarks

- The magnetic bumpers can be replaced by mounting a spring on one of the carts, but this makes the demonstration easier to understand by the students. Not seeing the elastic bumper, they have to reason that there must be somewhere a potential storage.

- The downward slope of the E_{kin}-graphs shows that some energy is dissipated (friction).

2.10.2.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 91

2.10.2.2 03 Mortar

2.10.2.2.1 Aim

To show an example in which the principle of conservation of mechanical energy is very helpful.

2.10.2.2.2 Subjects

- 1M40 (Conservation of Energy)

2.10.2.2.3 Diagram

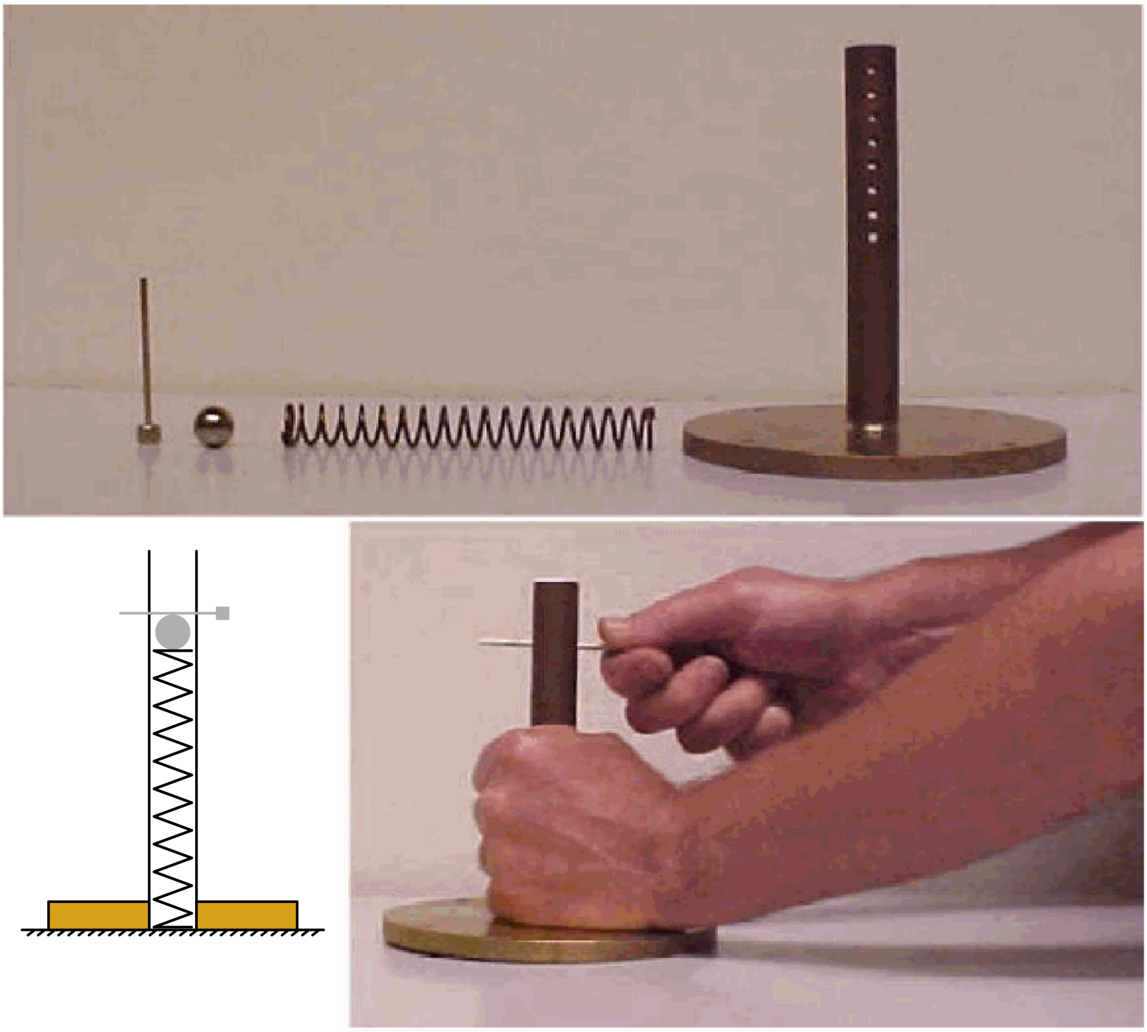


Figure 2.124: .

2.10.2.2.4 Equipment

- Compression spring (we use $k = 2500$ N/m).
- Launching tube ($\emptyset = 19$ mm), soldered into heavy base.
- Steel ball, ($\emptyset = 18$ mm).
- Steel pin.
- Measuring tape.
- Helmet (see Safety).

2.10.2.2.5 Safety

- The steel ball leaves the launching tube with high speed: do not cast a glance into the launching tube and be away with your head when launching.
- What goes up will come down. Wear your helmet when you make high launches.

2.10.2.2.6 Presentation

The dimensions of the components are such that when the mortar is assembled, the top of the steel ball is just level with the top of the launching tube (see Figure 2).

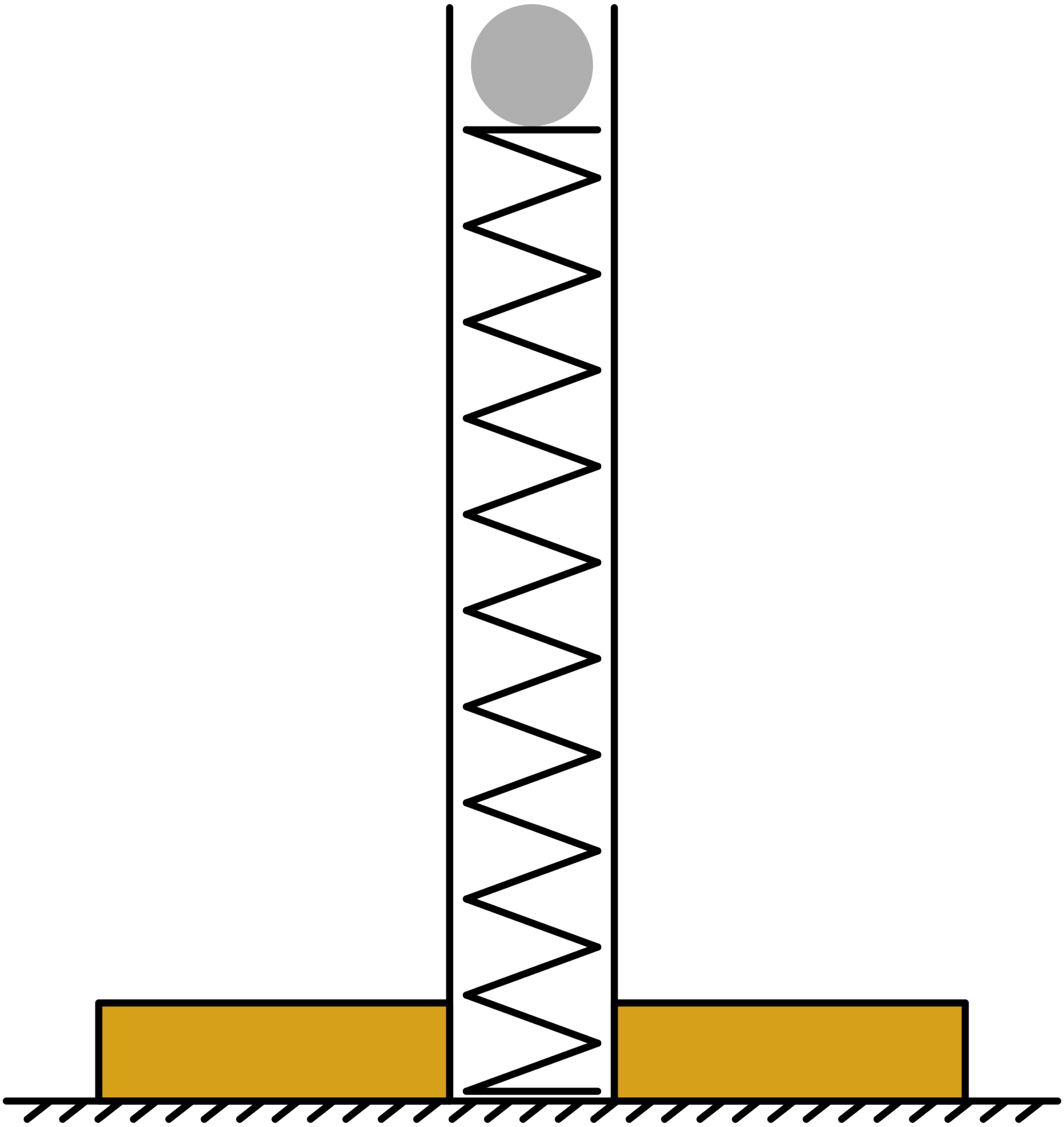


Figure 2.125: .

The launching tube has holes drilled in it at every cm, starting from the top. The steel pin is placed at 1 cm from the top; the ball and spring are placed into the launching tube from the bottom side. The base is hold by hand and firmly holds the launching tube down (see Diagram). In this situation the spring is compressed 1 cm. By means of your other hand the steel pin is pulled out and the steel ball is launched: it just climbs a couple of centimeters. By repeating the demonstration, a numerical value of the elevation can be given.

The whole procedure is repeated but now the steel pin is placed 2 cm from the top (and so the spring is compressed 2 cm). Before launching it, make your students predict the maximum height of the steel ball. After their prediction put on your helmet. The ball is launched and the maximum height determined; the prediction is checked (it will be around four times higher).

To complete the demonstration the spring is compressed 4 cm (this needs quite some force). Make students predict that the ball easily reaches the top of the lecture hall. The ball is launched, climbs really high, but does not reach the ceiling as predicted. Repeat the experiment and make the students observe that also the compression spring is launched out of the tube: so part of the potential spring energy is transferred into translational kinetic energy of the spring.

2.10.2.2.7 Explanation

1. When the spring is compressed it will have a potential energy of $U_p = 1/2\mathrm{k}\delta^2$. (δ is the compression of the spring.) When all this potential energy is transferred to the steel ball, the velocity of the steel ball, when leaving the launching tube, can be determined by $1/2m_{b(all)}v_i^2 = 1/2k\delta^2$. The maximum height reached (h_m) can be determined by $1/2m_b v_i^2 = m_b g h_m$. So, $h_m = \frac{k\delta^2}{2m_b g}$, showing the fourfold in h_m when δ is doubled.
2. But also the spring is launched! At the moment of launching the top of the spring has a speed v_i (same speed as the steel ball). At that moment the bottom of the spring is still at rest. Every part of the spring has a different speed during the launching process, so in order to determine the kinetic energy of the spring we consider a part (dm) of it (see Figure 3):

$$dm = \frac{m_{s(pring)}}{l}dy.K_{spring} = \int_0^l \frac{1}{2}\frac{m_s}{l}v(y)^2 dy \tag{2.20}$$

At the moment of launching

$v_l = v_i$ and $v_y = y/l.v_i$

Then:

$$K_{spring} = \frac{1}{2}\frac{m_v}{l}\frac{v_i^2}{l^2}\int_0^l y^2 dy = \frac{1}{6}m_s v_i^2 \tag{2.21}$$

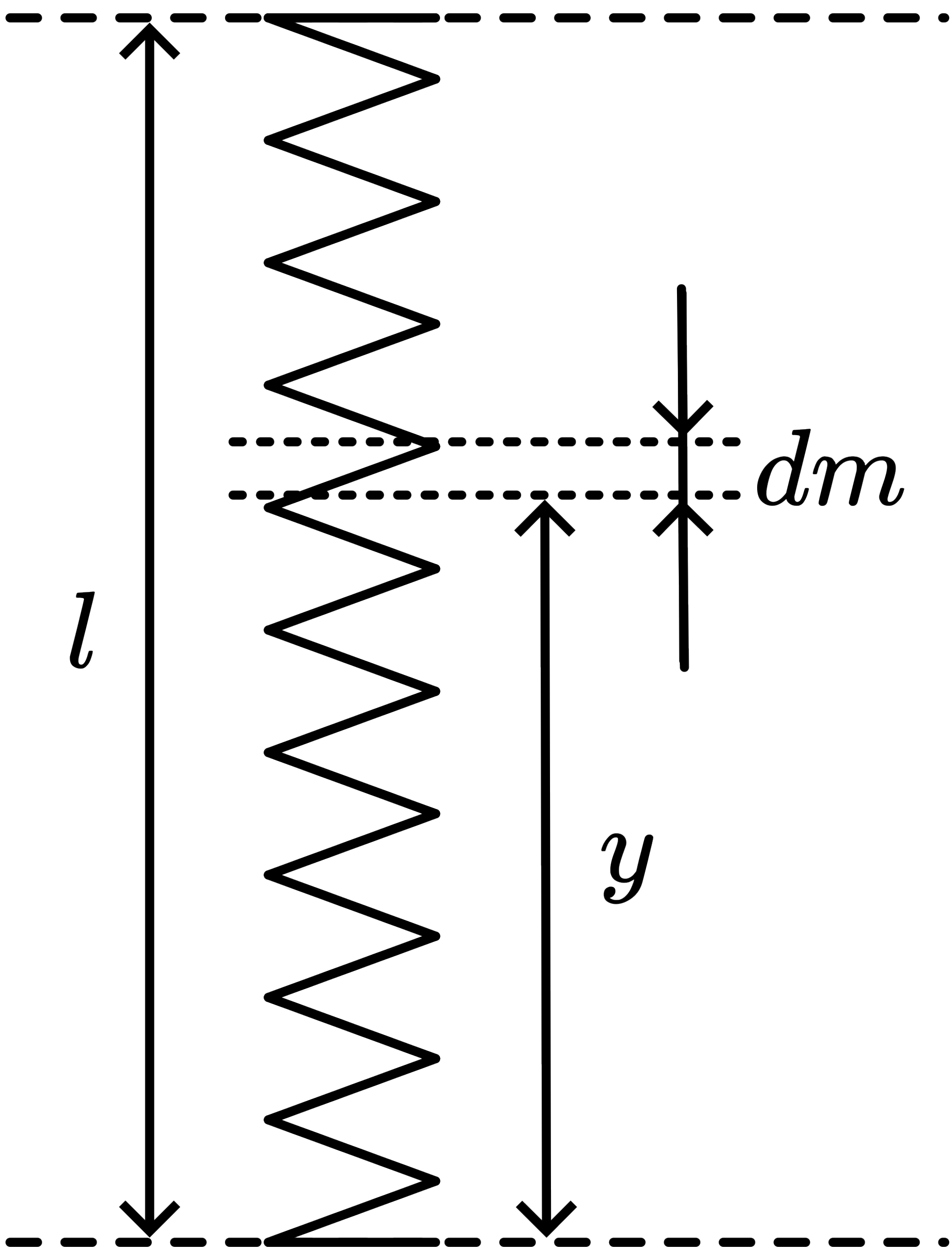


Figure 2.126: .

In our demonstration spring and steel ball have equal mass, so we have that 1/4 of the potential spring energy is transferred into translational kinetic energy of the spring and 3/4 is left as kinetic energy for the steel ball. The energy-balance equals $m_b g h_m + \frac{1}{6} m_s v_i^2 = \frac{1}{2} k \delta^2$ and it is clear that doubling δ no longer doubles h_m.

2.10.2.2.8 Remarks

- Using the value of the spring constant given in Equipment, hm can also be calculated in advance and checked in the demonstration.
- When we simulate this demonstration in a program like Interactive Physics we observe that the spring not only obtains translational kinetic energy but also vibrational kinetic energy. So the analysis is still a bit more complicated than given in our Explanation. (Adding this simulation to your demonstration shows the value of such a simulation program, since it extends your analysis of the demonstration.)

2.10.2.2.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 60-62 and 87-92.
- McComb,W.D., Dynamics and Relativity, pag. 32-35.
- Roest, R., Inleiding Mechanica, pag. 49-51; 72-73 and 81-83.

2.10.2.3 04 Galileo's Pendulum

2.10.2.3.1 Aim

To show a phenomenon that can be explained using "conservation of energy".

2.10.2.3.2 Subjects

- 1M40 (Conservation of Energy)

2.10.2.3.3 Diagram

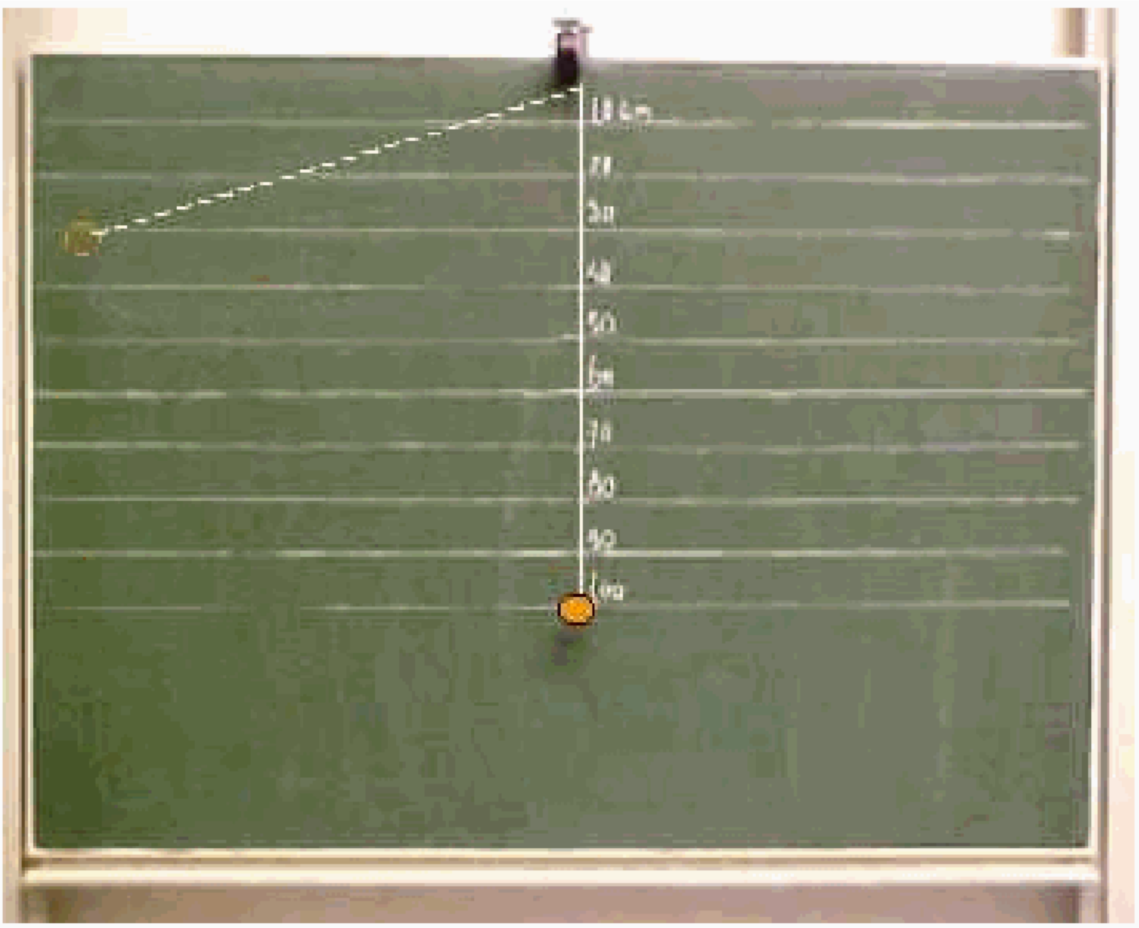


Figure 2.127: .

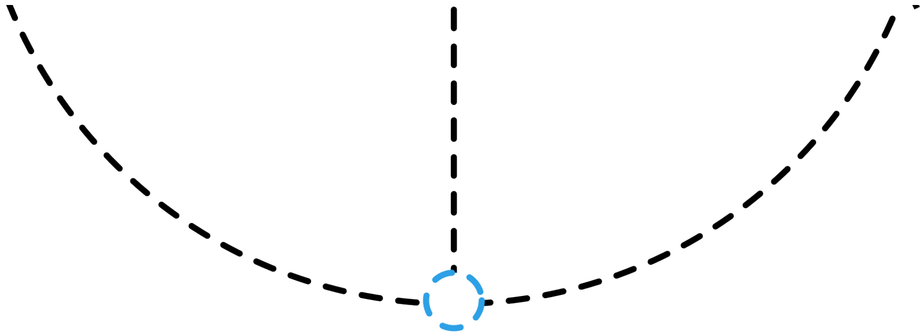
2.10.2.3.4 Equipment

- Simple pendulum, a ball connected to a string, $l = 1$ m.
- Clamping material.
- A peg.
- Air level.

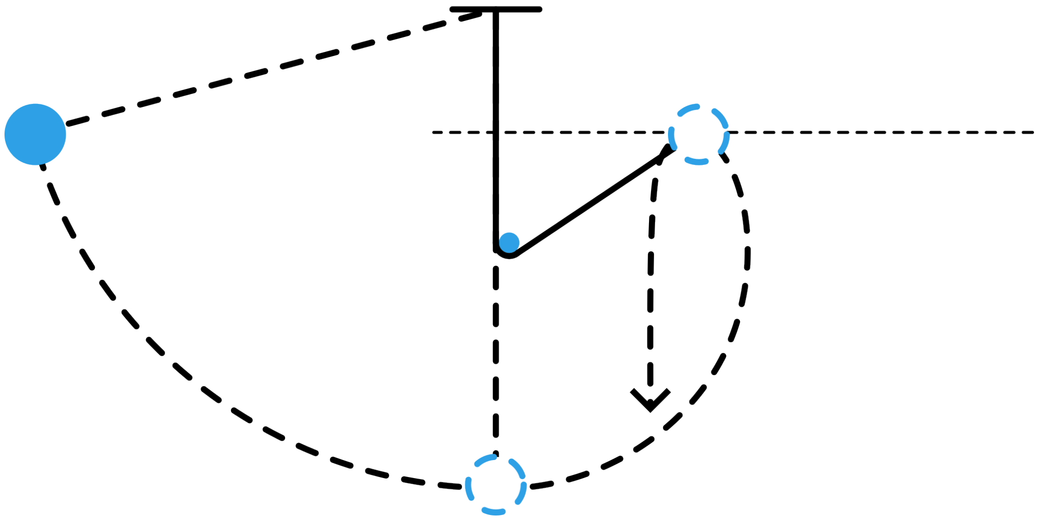
2.10.2.3.5 Presentation

The pendulum is connected to the blackboard, hanging a couple of cm's in front of it. On the blackboard, using the air-level, at every 10 cm downwards horizontal lines are drawn (see Diagram).

The pendulum is pulled aside upwards to the 30 cm line. Before releasing the pendulum, students are asked how far the pendulum will go upward on the other side.



(a)



(b)

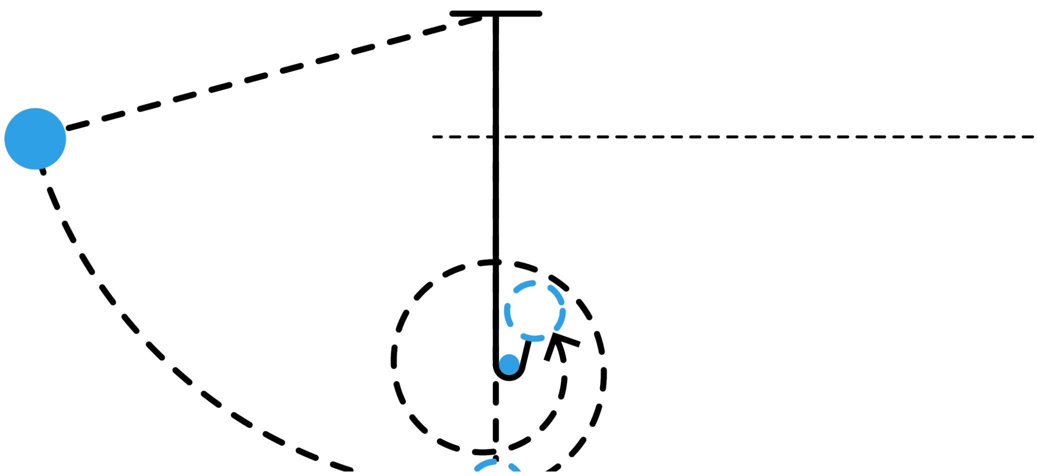


Figure 2.128: .

Then it is released and almost reaches the 30 cm line on the other side (see Figure 2A). A peg is placed at 50 cm below the point of suspension, blocking the pendulum's thread when the pendulum is released (we use a piece of chalk holding it there by hand). Again the pendulum is pulled aside upwards to the 30 cm line. Students are asked how high the pendulum will climb now on the other side when the pendulum is released. After their answers the pendulum is released and climbs almost to the 30 cm line again (see Figure 2B).

Then the peg is placed at 70 cm (or lower). It is clear now that the pendulum released at the 30 cm line can never reach the same line on the other side, the thread is too short. So, ask the students to predict what will happen to the pendulum now. After their answers the pendulum is released and winds itself around the peg! (see Figure 2C).

2.10.2.3.6 Explanation

In this situation (conservative field), total mechanical energy is constant:

$$E = constant = K + U \tag{2.22}$$

Before releasing the pendulum, there is only potential energy, U (zero reference at the 100 cm line). When the pendulumbob reaches the 30 cm-line on the other side there is again only potential energy. In between these two extremes the bob moves and has kinetic energy K. (When the pendulum is at its lowest point, there is no potential energy anymore, $E = K$ and the pendulum moves at it highest possible speed.)

When a peg is placed at the 50 cm-point below the suspension point, there is no restriction for the bob to raise again to the 30 cm-line on the other side. It can also be observed that when it reaches that line, the speed of the bob wil be zero $K = 0$ and the ball drops down vertically (giving a strong jerk to the thread).

When the peg is placed at 70 cm below the suspension point, the released ball can only go upwards to the 40 cm-line. At that point the ball still has an amount of kinetic energy, its velocity will be in the horizontal direction and the ball winds around the peg. This continues since at every turn the winding thread becomes shorter and the pendulum bob will reach a lower highest point: the pendulum will wind itself faster and faster around the peg.

2.10.2.3.7 Remarks

- We use an air-level to draw the horizontal lines because our blackboard is not level.
- Make your peg not too thin, because otherwise the thread will not wind itself completely around it. (On every turn the height-loss has to be that large as to compensate at least the "normal" energy-loss of the pendulum.)

2.10.2.3.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 90-92
- McComb,W.D., Dynamics and Relativity, pag. 32-34
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 59

2.10.2.4 05 Pendulum of Death

2.10.2.4.1 Aim

To show that we really trust the law of conservation of energy.

2.10.2.4.2 Subjects

- 1M40 (Conservation of Energy)

2.10.2.4.3 Diagram

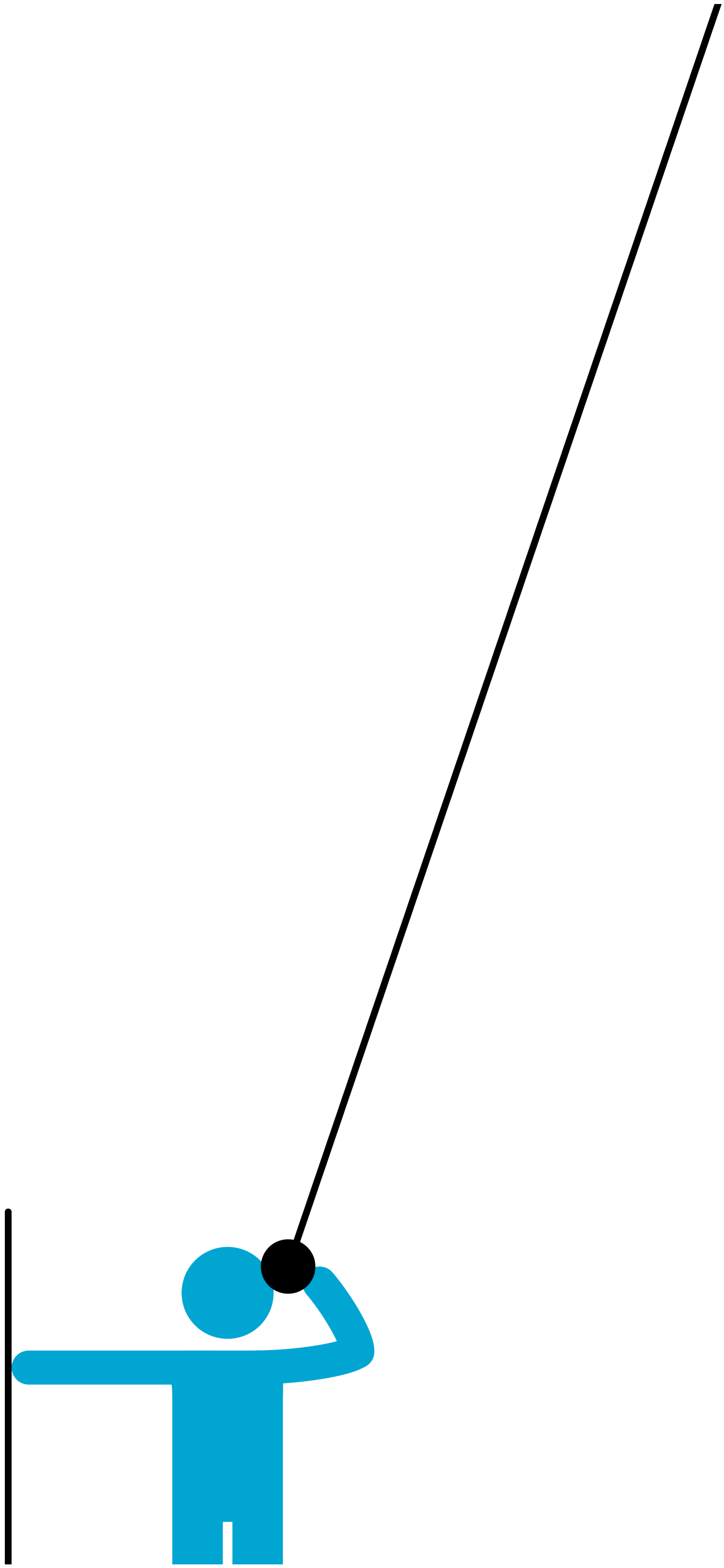


Figure 2.129: .

2.10.2.4.4 Equipment

- Long pendulum suspended from the ceiling of the lecture hall.
- Some kind of support.

2.10.2.4.5 Presentation

A long pendulum is suspended from the ceiling of the lecturehall. The pendulum bob is a heavy cast-iron sphere. The demonstrator draws the bob to one side and puts his head immediately adjacent to it and steadies himself against some support. Then he releases the ball, and keeping his eyes fixed on the audience, he explains that he is willing to risk his head to demonstrate that the law of conservation of energy applies! Meanwhile, the ball has been swinging far out, and is returning to his head threateningly. But the ball slows down as it regains its original level and barely touches the head. The law of conservation of energy has given a correct prediction: the demonstrator survives.

2.10.2.4.6 Explanation

Mechanical work done by a field force in moving a body between A and B is defined as: $W_{AB} = \int_A^B \vec{F} d\vec{s} = U(\vec{r}_A) - U(\vec{r}_B)$, (independent of the path taken: conservative force field). $U(\vec{r})$ is called the potential energy function.

Also can be shown (using $\vec{F} = m\vec{a}$) that $\int_A^B \vec{F} d\vec{s} = \frac{1}{2}mv_B^2 - \frac{1}{2}mv_A^2 = K_B - K_A . K$ is called: kinetic energy.

Combining these two equations: $U_A + K_A = U_B + K_B$.

So the pendulum bob moves in such a way that $U + K = E =$ constant. On release the bob has only potential energy $E = U_A$. When it returns to its original height it has the same amount of potential energy, so then $K = 0$, and $v = 0$. Reaching a point higher than A should mean that E has to increase, which violates $U + K = E =$ constant.

2.10.2.4.7 Remarks

- When the demonstrator is not sure about the result of the demonstration he will, just before the final moment, steal a glance at the approaching pendulum, and he will involuntarily recoil! It surely will enlighten the demonstration when the first time you do it in this way.
- When letting the pendulum go be sure not to give it some push. Conservation of energy still applies, but your head will not appreciate this. Be careful.

2.10.2.4.8 Video Rhett Allain

(a) (b)

Figure 120: :align: center - Scan the QR code or click here to go to the video.

2.10.2.4.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 87 and 90-91
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 74 and 179

2.10.2.5 01 Dropping Rolls of Toilet Paper

2.10.2.5.1 Aim

To show that for a free falling object the rotational acceleration reduces the linear acceleration.

2.10.2.5.2 Subjects

- 1M40 (Conservation of Energy)
- 1Q20 (Rotational Energy)

2.10.2.5.3 Diagram

Figure 2.133: .

2.10.2.5.4 Equipment

- Two equal rolls of toilet paper.

2.10.2.5.5 Presentation

Two rolls of toilet paper are dropped simultaneously from the same height (≈ 2 m), one of them while holding on to the paper-end of the roll. This roll hits the floor later than the other.

2.10.2.5.6 Explanation

When you drop the toilet paper roll while holding on to one end, the roll is momentarily rotating about an axis at the edge of the roll. The angular acceleration (α) of the roll during its fall can be found from $\alpha = \frac{\tau}{I}$, where the net torque is given by $\tau = mgr_2$ (see Figure 2).

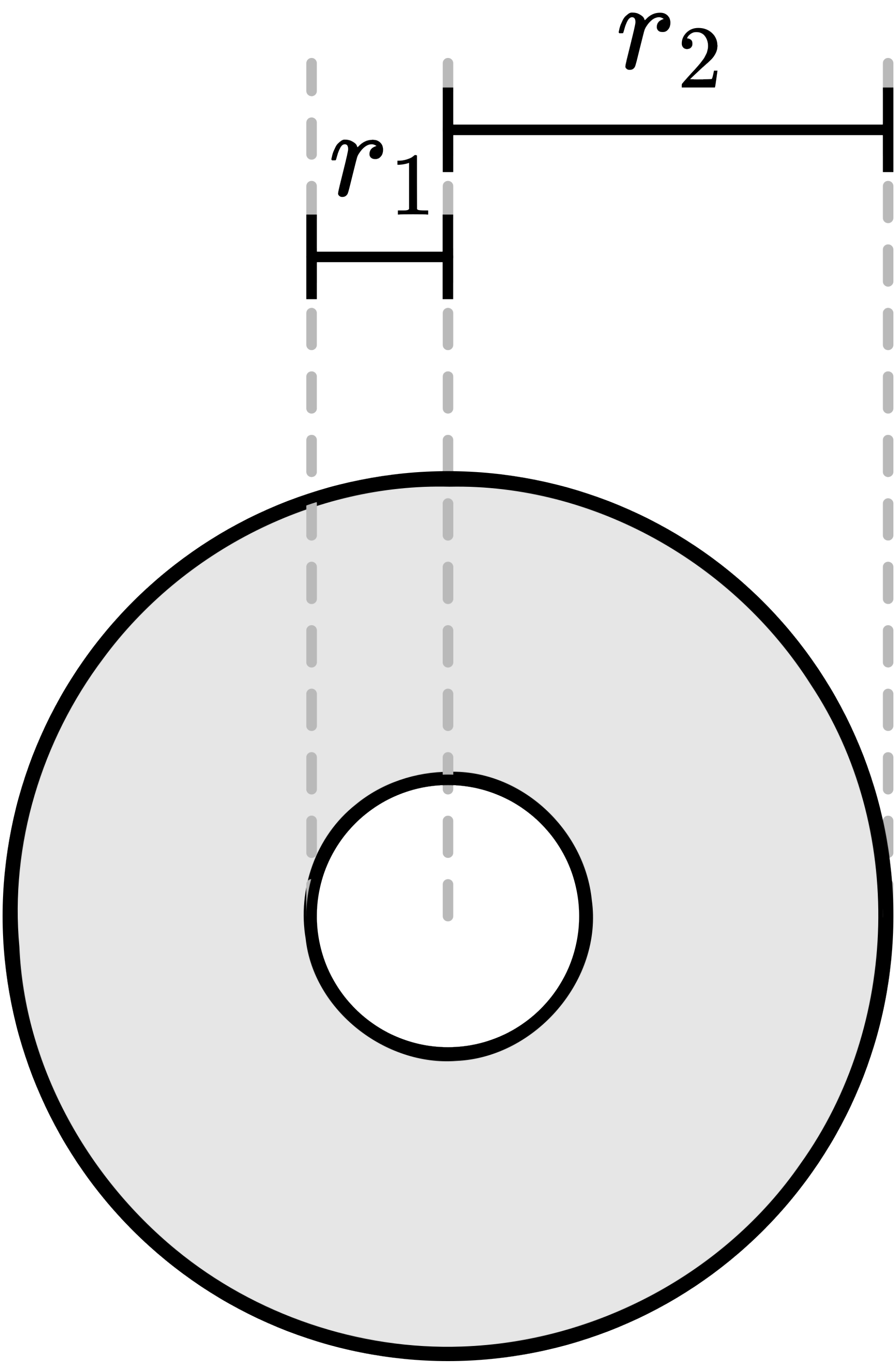


Figure 2.134: .

The acceleration of the center of mass (a) is related to the angular acceleration of the roll by $a = \alpha r_2$, so the roll accelerates downward by $a = \frac{mgr_2^2}{I}$.

Since $I > mr_2^2 \left(I = \frac{m}{2(r_1^2+r_2^2)} + mr_2^2 \right)$, we find that $a < g$.

2.10.2.5.7 Remarks

- Working with the above formulas, it can easily be shown that $a = \frac{2}{3+R^2} g$, where $R = \frac{r_1}{r_2}$. For our toilet rolls $R = 0.4$, so $a = 0.63$ g.

This means that when the paper-end held roll is dropped from a height of about 1.25 m and the other roll from a height of about 2 m, both rolls hit the floor simultaneously.

2.10.2.5.8 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 97

2.11 1N Linear Momentum and Collisions

2.11.1 1N10 Impulse and Thrust

2.11.1.1 02 Boomerang Ball (1)

See Boomerang Ball

2.11.1.2 03 Boomerang Ball (2)

See Boomerang Ball

2.11.1.3 04 Throwing a Basketball

2.11.1.3.1 Aim

To show how impulse changes the movement of a thrown basketball.

2.11.1.3.2 Subjects

- 1K10 (Dynamic Torque) 1K20 (Friction) 1N10 (Impulse and Thrust)

2.11.1.3.3 Diagram

Figure 2.135: .

2.11.1.3.4 Equipment

- Basketball.

2.11.1.3.5 Presentation

The lines on the basketball make it easy to see if the ball rotates yes or no.

Throw the basketball and observe that before hitting the ground it does not rotate, but that after rebound it rotates (see Figure 2A).

Also can be observed that after rebound the ball moves steeper than when it was in the throw (again: see Figure 2A).

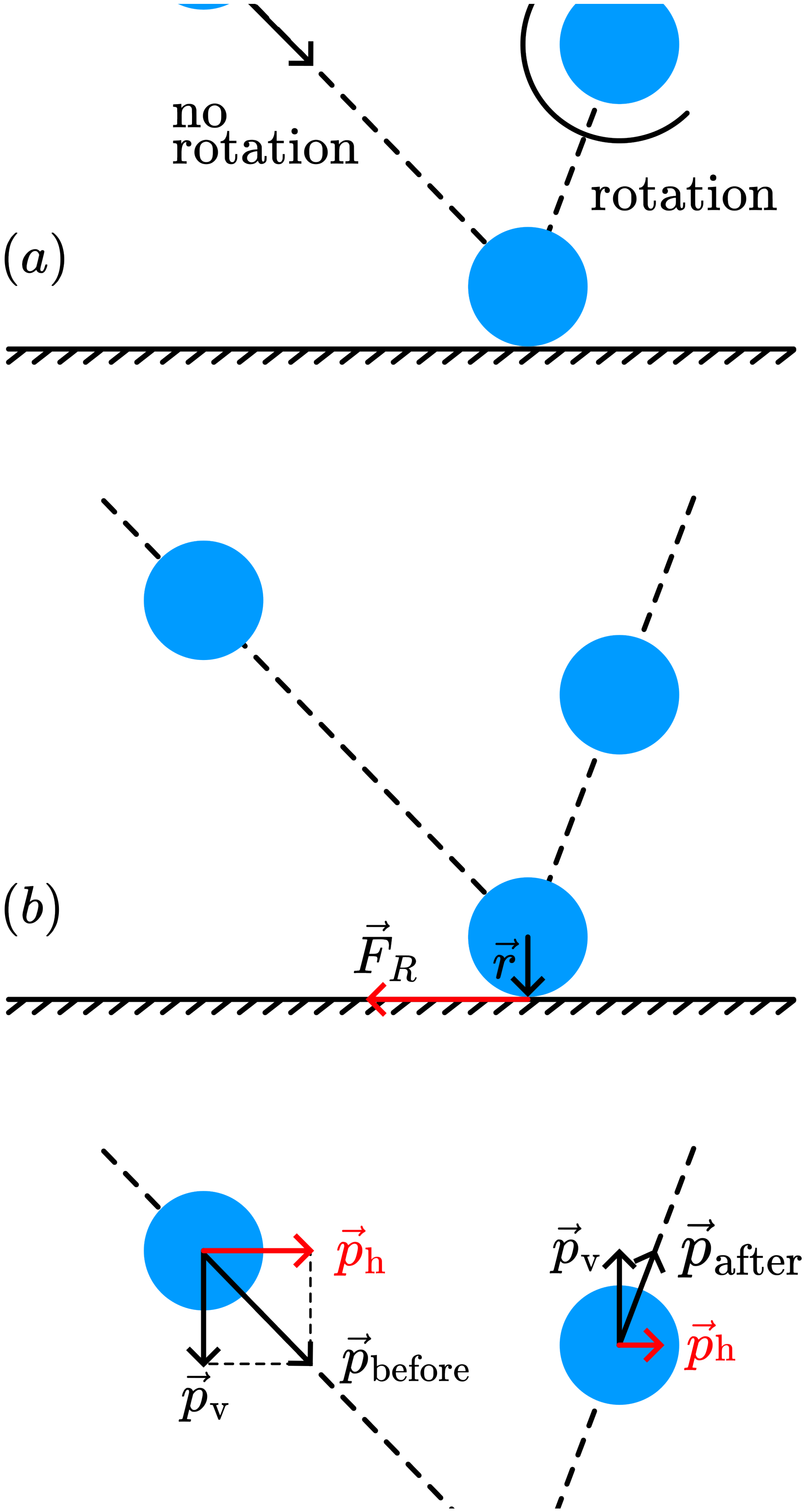

no rotation
rotation
(a)
(b)
$\vec{F}_R$
$\vec{r}$
$\vec{p}_\mathrm{h}$
$\vec{p}_\mathrm{before}$
$\vec{p}_\mathrm{v}$
$\vec{p}_\mathrm{v}$
$\vec{p}_\mathrm{after}$
$\vec{p}_\mathrm{h}$

Figure 2.136: .

2.11.1.3.6 Explanation

The ball has an impulse p, which can be looked at as consisting of a vertical component p_ν and a horizontal component p_h. When the ball hits the ground, p_ν is reversed (supposing complete elasticity). But p_h changes because the friction force F_R, that acts during a short time (Δt), reduces the horizontal impulse by an amount of $\Delta \vec{p}_h = \int_0^{\Delta t} \vec{F}_R dt$. The combination of unchanged p_v and changed p_h makes that the ball mounts steeper (Figure 2C).

That it rotates as well is due to the torque during contact with the ground, changing its angular momentum by an amount of: $\Delta \vec{L} = \int_0^{\Delta t} \vec{r} \times \vec{F} dt$.

2.11.1.3.7 Sources

- American Journal of Physics, 72-7(2004), pag. 875-883
- Nederlands Tijdschrift voor Natuurkunde, 70-10(2004), pag. 347
- Walker, J., Roundabout, the Physics of Rotation in the Everyday World, pag. 8-12

2.11.1.4 05 Sliding Ladder

2.11.1.4.1 Aim

To show an example where the concept ‘impulse’ explains the phenomenon.

2.11.1.4.2 Subjects

- 1N10 (Impulse and Thrust)

2.11.1.4.3 Diagram

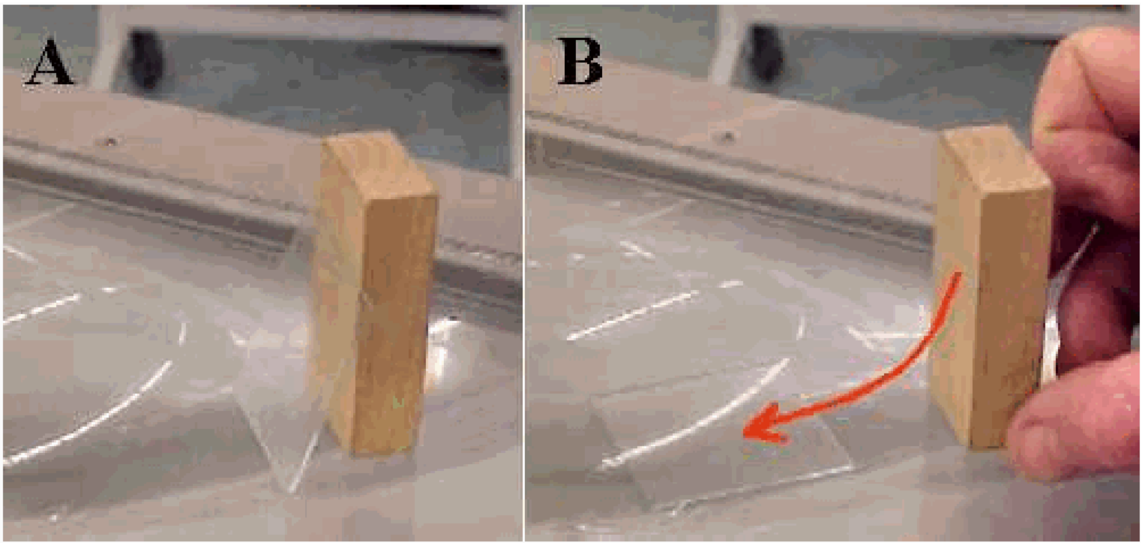


Figure 2.137: .

2.11.1.4.4 Equipment

- Cover glass (we use $50 \times 50 \times 1$ mm).
- Wooden block (we use $7 \times 3.5 \times 2$ cm7×3.5×2 cm).
- Overhead projector.

2.11.1.4.5 Presentation

Preparation

The glass of the overhead projector and the cover glass are cleaned and polished.

Presentation

The cover glass rests against the wooden block (see Figure 1A). By hand, the inclination of the cover glass is decreased by pulling the wooden block very slowly to the right (see Figure 1B). At a certain moment the cover glass starts sliding: It moves downwards and away from the wooden block. Pose the question to the students: “What makes the cover glass move away from the wooden block?”

2.11.1.4.6 Explanation

During the sliding movement, five forces are acting: The weight G, the normal forces N_A and N_B and the friction forces in A and B (see Figure 2; the friction forces are neglected).

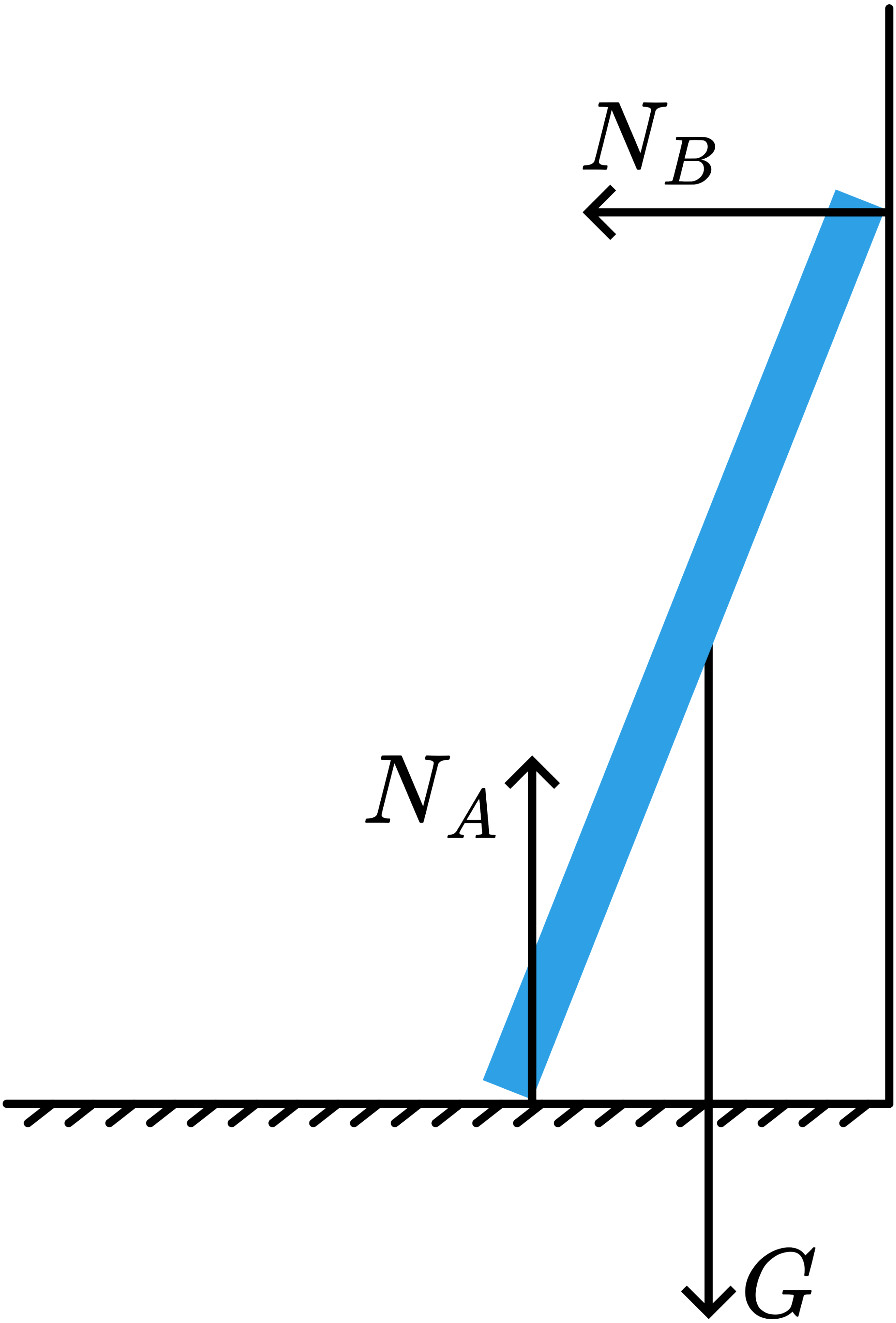


Figure 2.138: .

At a certain moment in the movement, B leaves the wooden block. This is only possible if the cover glass has a component in its velocity that is directed to the left and correspondingly a momentum to the left. The only force directed to the left is N_B. N_B itself is not moving to the left, but gives the cover glass an impulse to the left equal to $\int_{t_1}^{t_2} N_B dt$, $t_2 - t_1$ being the time that B slides the vertical wall. (Will the cover glass leave the vertical wall before point B hits the ground?)

After some time the movement to the left stops due to friction forces between the horizontally sliding cover glass and the glass of the overhead projector.

2.11.1.4.7 Remarks

- Notice that the force N_B does no work!
- This demonstration can be easily performed in a simulation program. The advantage then is that the friction on the ground can be made zero and the ladder (cover glass) will continue moving over the ground. Such a simulation is a useful follow-up of the demonstration in our real world. Also the question raised in the Explanation about the sliding point B can be answered by observing the movement of point B in that simulation.

2.11.1.4.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 92
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 123
- Young, H.D. and Freeman, R.A., University Physics, pag. 228-229

2.11.2 1N20 Conservation of Momentum

2.11.2.1 01 Elastic Collisions

2.11.2.1.1 Aim

To explore the conservation of momentum in elastic collisions.

2.11.2.1.2 Subjects

- 1N20 (Conservation of Linear Momentum)

2.11.2.1.3 Diagram

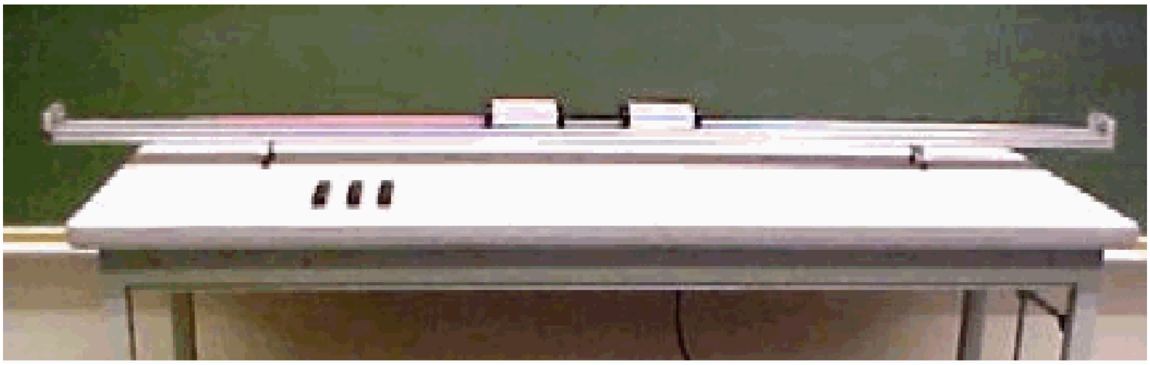


Figure 2.139: .

2.11.2.1.4 Equipment

- Two collision carts with magnetic bumpers on both ends.
- Masses for carts.
- Cart track, 2.2 m, with end-stops.
- Mass balance.

2.11.2.1.5 Presentation

The cart track is carefully leveled (by setting a cart on the track to see which way it rolls).

- One cart is placed in the middle of the track. Give the other cart an initial speed towards the cart at rest. Observe that after the collision the second cart moves with the speed of the first and that the first cart stops. When the second cart rebounds elastically at the end-stop this phenomenon repeats.
- Both carts are given a certain speed towards the middle of the track; Equal speeds: Then after collision they recede with equal speeds. Different speeds: Then after collision they have interchanged their speeds.
- By means of the extra masses, one of the carts (mass $= m$) is given a mass of $2m$ or $3m$. Now the next demonstrations can be performed:

(Let students predict what will happen before showing the concerned demonstration.)

1. The $2m$-cart stands at rest in the middle of the track. The $1m$-cart approaches at a certain speed. Observe that after the collision the $1m$-cart reverses its direction of movement and is slowed down and that the $2m$-cart is launched and has a higher speed then the $1m$-cart after the collision (actually the $\mathbf{2m}$-cart is two times as fast as the Im-cart).

as can be observed rather convincingly.

1. The $3m$-cart stands at rest in the middle of the track. The $1m$-cart approaches at a certain speed. Observe that after the collision, the $1m$-cart reverses its direction of movement and is slowed down and that the $3m$-cart is launched. It can also be observed that both carts have the same speed.

2. The $1m$-cart stands at rest at one third of the track. The $2m$-cart approaches at a certain speed. Observe that after the collision the $2m$-cart continues moving in the same direction but is slowed down substantially and that the $1m$-cart is launched with very high speed (actually, after the collision the $\mathbf{1m}$-cart is $\mathbf{4}$ times as fast as the $2m$-cart).
3. ***a.*** The $\mathbf{1m}$-cart stands at rest at one third of the track. The $3m$ cart approaches at a certain speed. Observe that after the collision the $3m$-cart continues moving in the same direction but is slowed down and that the $\mathbf{1m}$-cart is launched with a very high speed. (The difference in speed between the two carts is less than in situation 3.)

b. A nice extra demonstration is the following:
Place the $1m$-cart close to the end of the track. The $3m$-cart approaches at a certain speed (not so high). After the collision, the $1m$-cart bounces four times between the end-stops of the track and the still moving $3m$-cart, but after that sequence the $1m$-cart stands still and the $3m$-cart moves with the same speed (opposite direction) it had before the collision.

2.11.2.1.6 Explanation

In explaining the situations demonstrated, a rule introduced by Huygens can be used: *"If in an elastic collision the sum of the impulses equals zero, then both objects reverse and have the same speed after the collision as before the collision."* (CM coordinate system.)

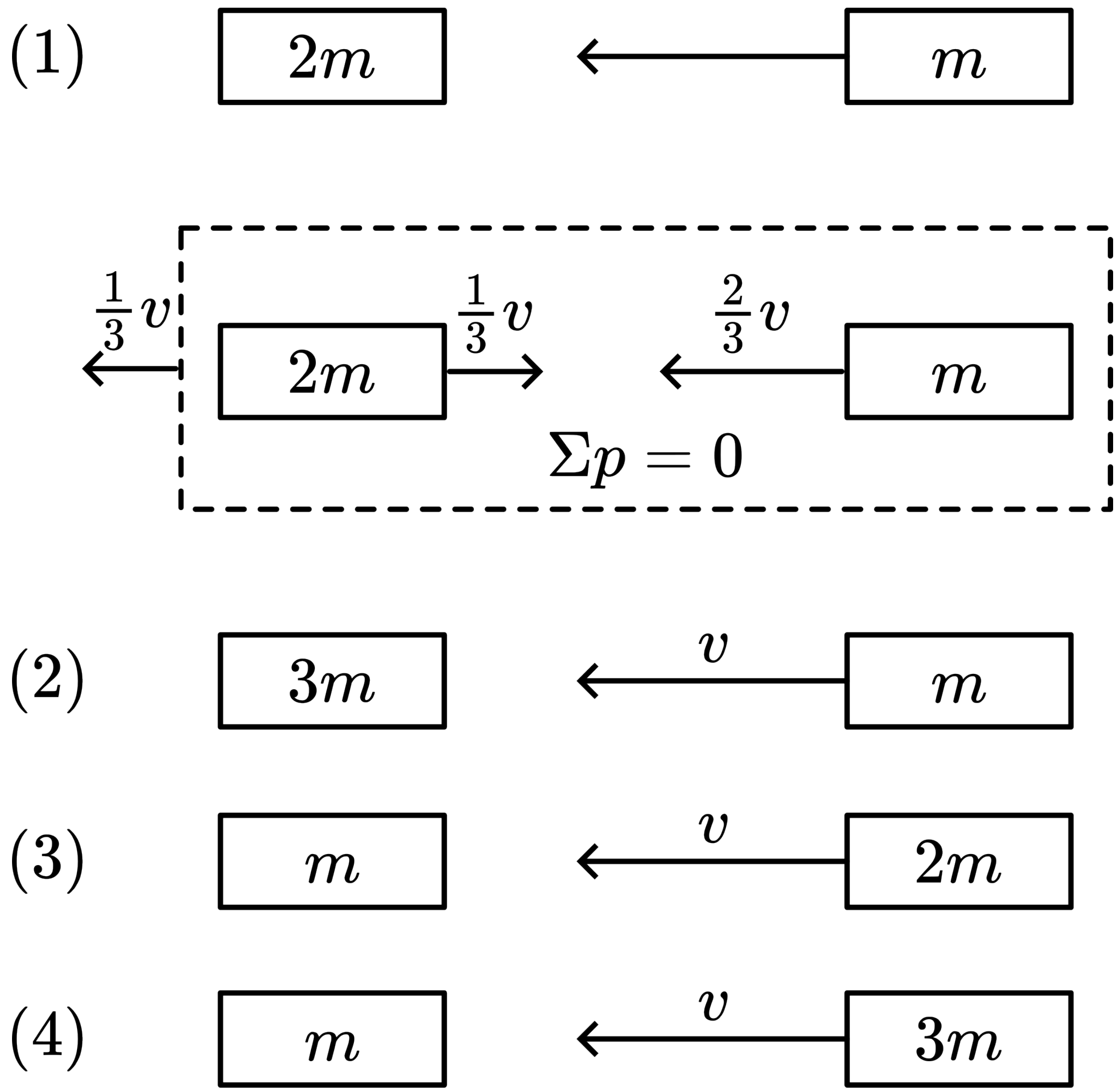


Figure 2.140: .

This rule can easily be verified in applying conservation of momentum and conservation of kinetic energy. This method is shown here for situation 1 only, for the other situations the result is shown (see Figure 2 and Figure 3). Figure 3 shows the observed $-v_1$ and v_2 after the collision.

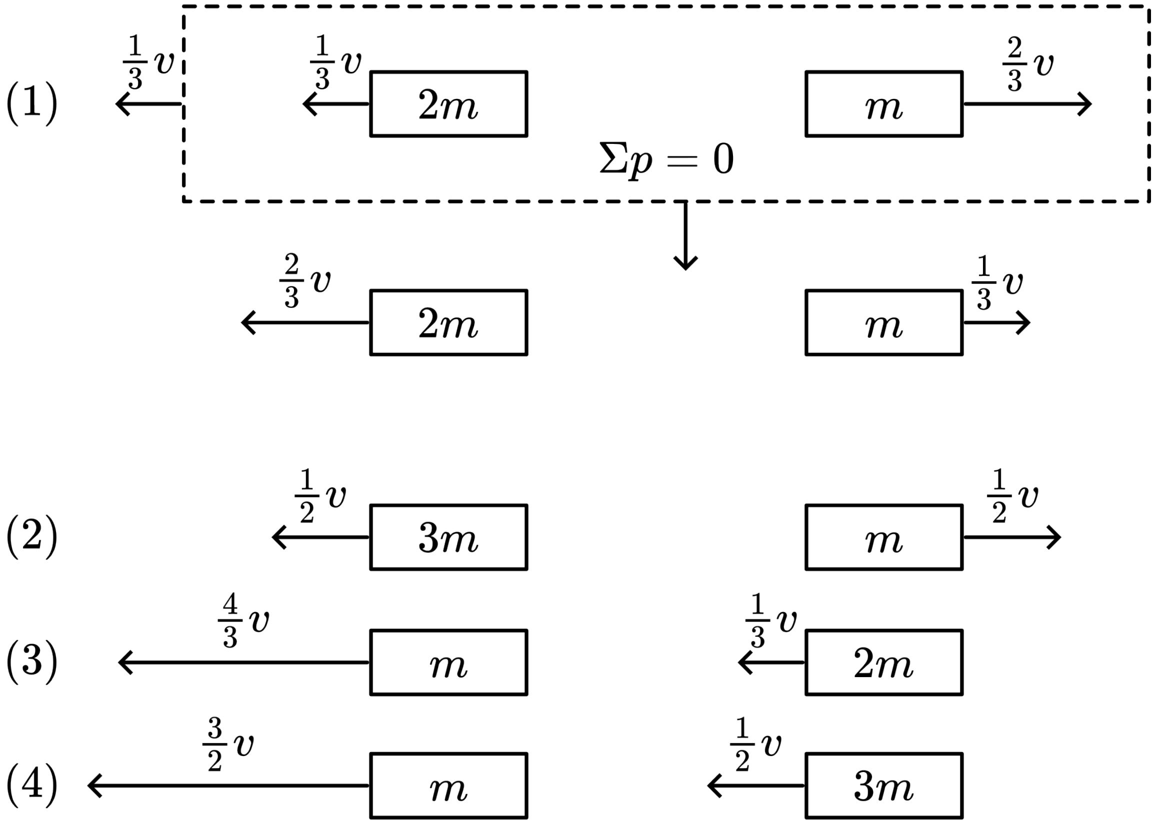
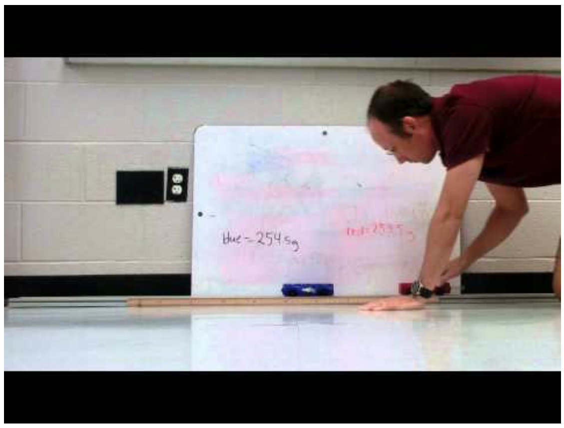


Figure 2.141: .

2.11.2.1.7 Video Rhett Allain

(a)



(b)

Figure 130: :align: center - Scan the QR code or click here to go to the video.

2.11.2.1.8 Remarks

- Run each demonstration a couple of times to get agreement with your students on the observations.

- The cart launched by hand should not be given too much speed, otherwise both carts touch each other and the collision is not completely elastic anymore. The carts might even derail.
- $v_2' = v_1\left(\frac{2m_1}{m_1+m_2}\right)$ means that when $m_2 \ll m_1$ then $v_2' \approx 2v_1$. In our demonstration sequence we approach v_2 'up to $1.5v_1$

2.11.2.1.9 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 148.
- Mansfield, M and O'Sullivan, C., Understanding physics, 1998, pag. 126-128 and 135-136.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, third edition, pag. 212-217.

2.11.2.2 02 Inelastic Collisions

2.11.2.2.1 Aim

To explore the conservation of momentum in inelastic collisions.

2.11.2.2.2 Subjects

- 1N20 (Conservation of Linear Momentum)

2.11.2.2.3 Diagram

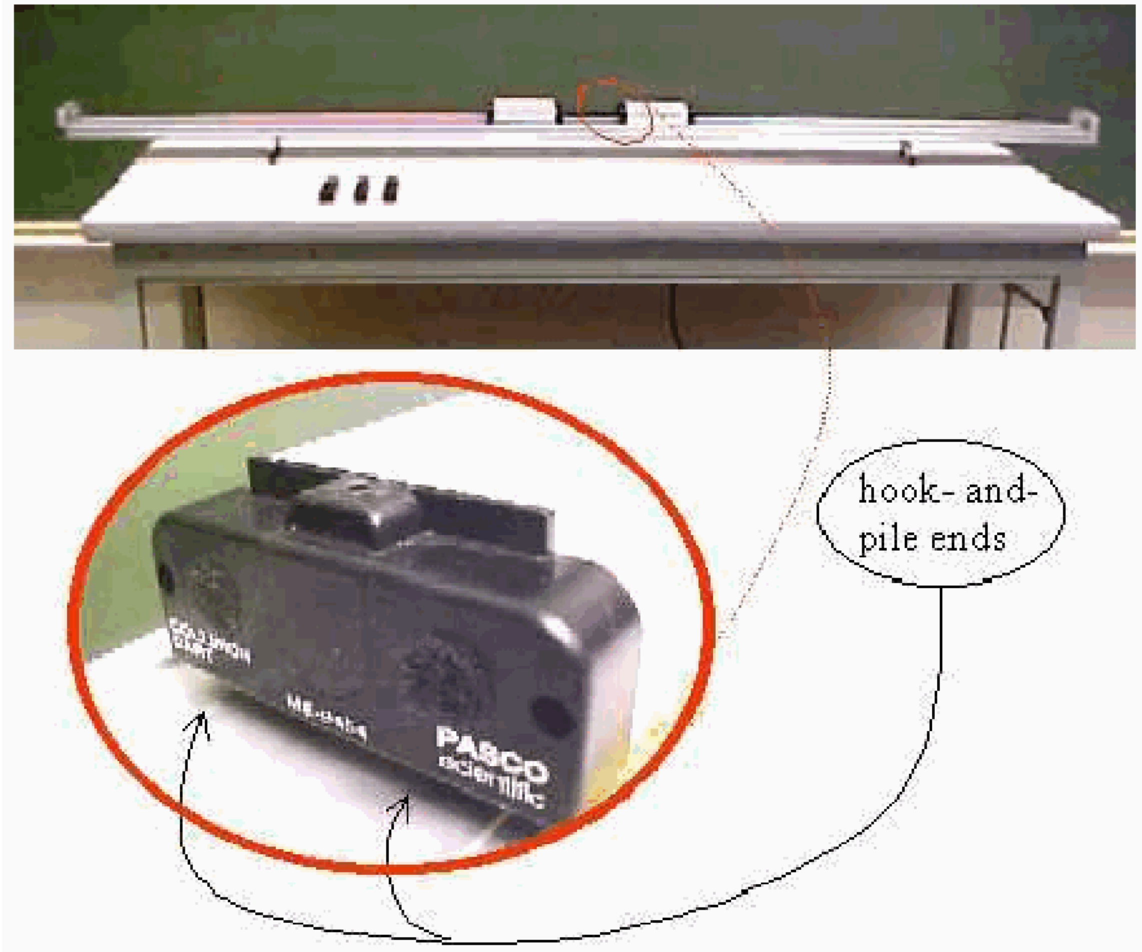


Figure 2.145: .

2.11.2.2.4 Equipment

- Collision cart.
- Dynamic cart.
- Masses for carts.
- Cart track, 2.2 m, with end-stops.
- Mass balance.

2.11.2.2.5 Presentation

The cart track is carefully levelled (by setting a cart on the track to see which way it rolls). Both carts have hook-and-pile ends (not magnets!) so they stick together after collision.

1. Place both carts at the track ends and give them by hand a low equal speed toward each other. (It is surprisingly easy to make the two speeds roughly the same by moving your hands in mirror image motions.) In the middle of the track both carts collide and stop.

2. One cart stands at rest in the middle of the track. The other cart approaches at a certain speed (v). After collision, both carts together move at a lower speed ($v/2$).
3. One cart stands at rest in the middle. The other cart has mass added to it ($2m$) and approaches at a certain speed (v). After collision, both carts together move on. The speed is reduced a little.
4. As 3, but now a 3 m-cart approaches. After collision, both carts together move on. The speed is hardly changed.
5. The 2 m-cart stands at rest in the middle of the track. The other cart (m) approaches at a certain speed (v). After collision, both carts stick together and move on at a much lower speed.
6. As 5, but now with a 3 m-cart in the middle. After collision, both carts stick together and hardly move any longer.

2.11.2.2.6 Explanation

In presentation 1, the total momentum equals zero and remains so after the collision. In presentations 2 to 6, conservation of momentum leads to the diagrams shown in Figure 2 (before collision) and Figure 3 (after collision).

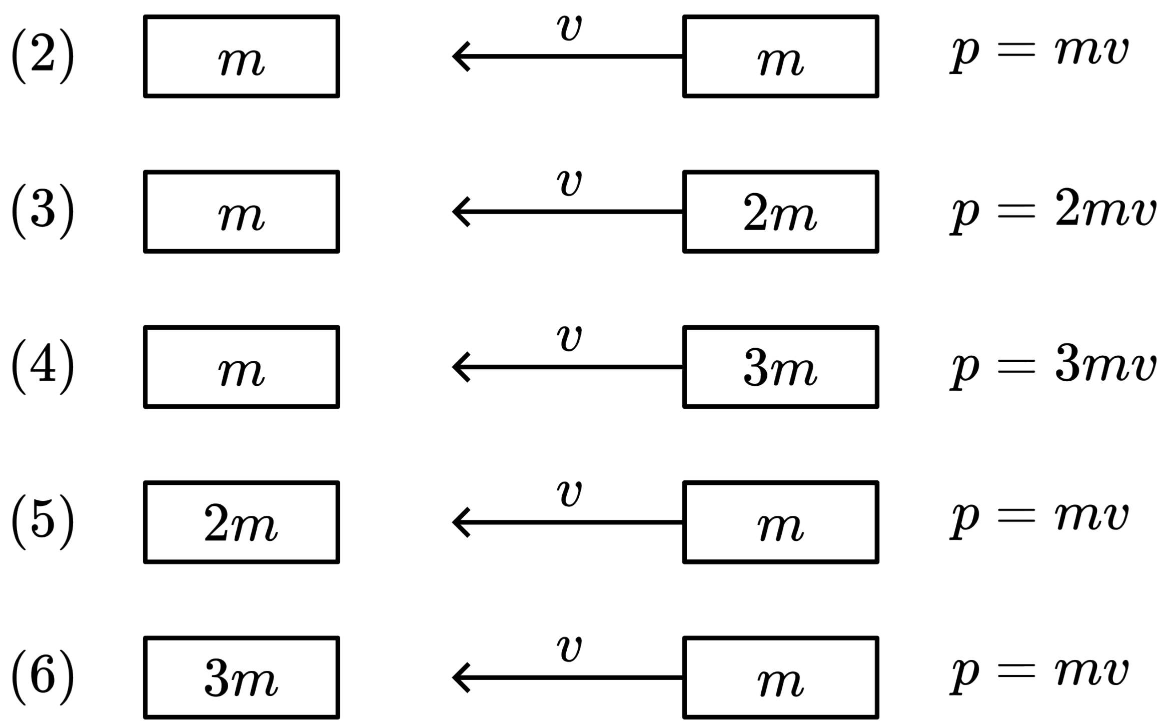


Figure 2.146: .

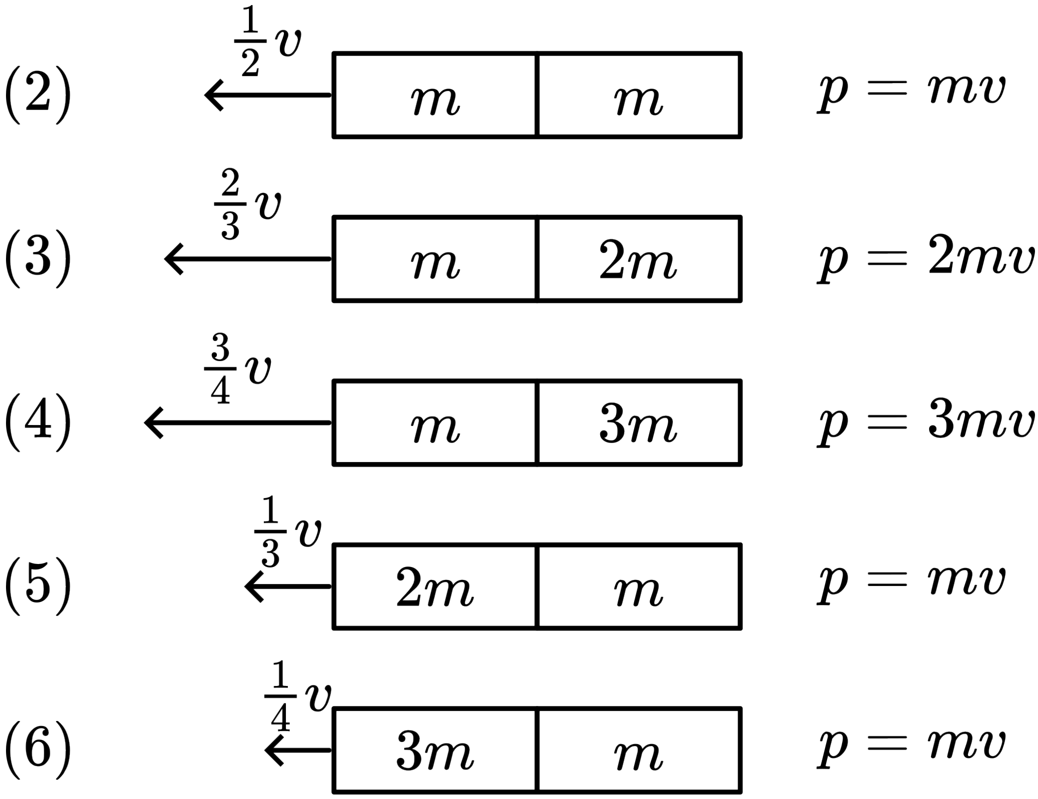
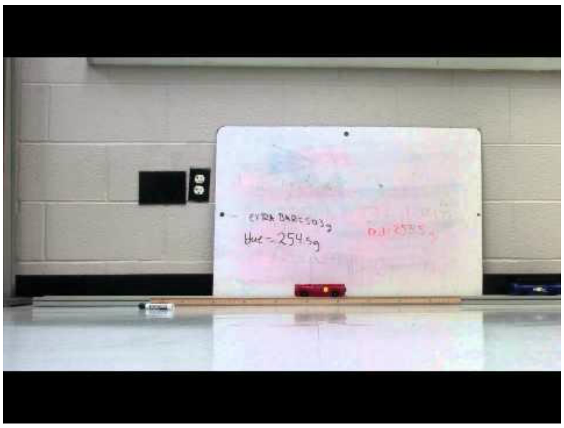


Figure 2.147: .

2.11.2.2.7 Video Rhett Allain

(a)



(b)

Figure 134: :align: center - Scan the QR code or click here to go to the video.

2.11.2.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 126-128
- PASCO scientific, Instruction Manual and Experiment Guide, pag. ME-9458

2.11.2.3 03 Explosion

See Explosion

2.11.2.4 04 Colliding Balls (1)

2.11.2.4.1 Aim
To demonstrate many combinations of elastic collisions. To test momentum conservation.

2.11.2.4.2 Subjects
- 1N20 (Conservation of Linear Momentum)

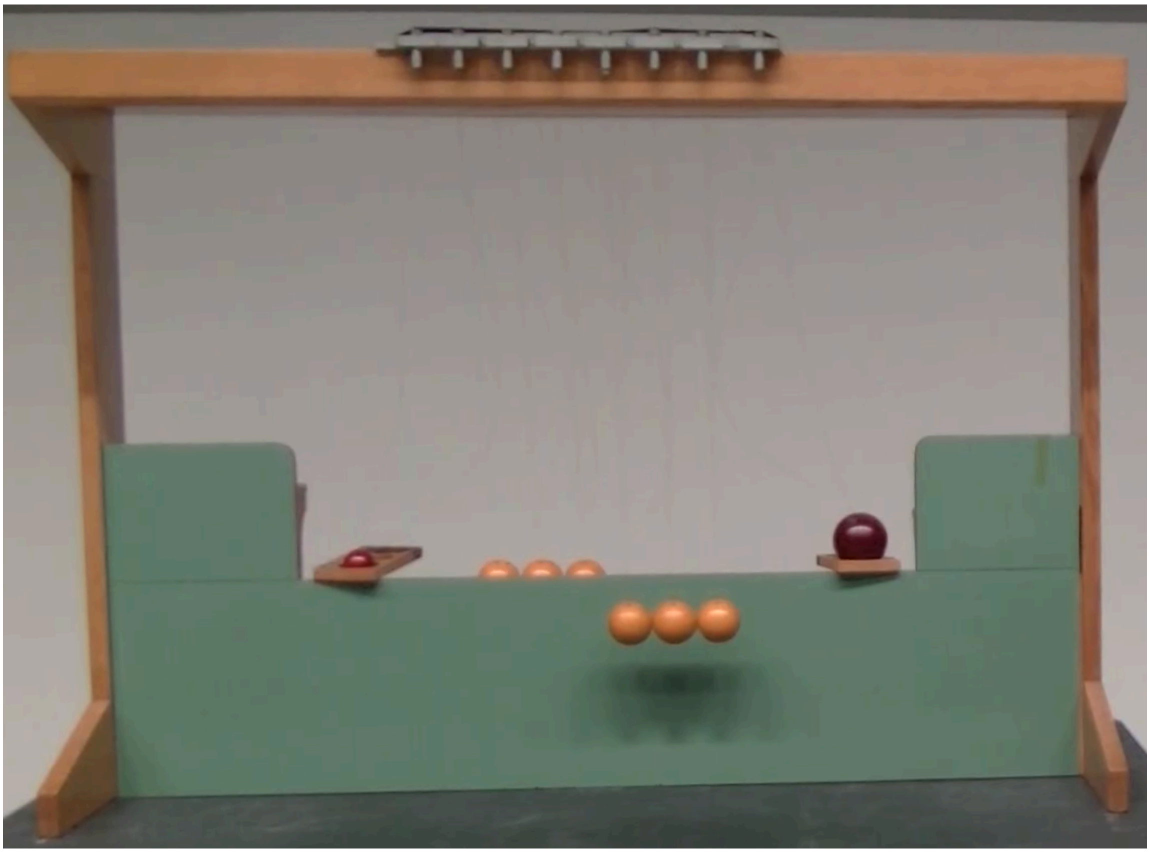
2.11.2.4.3 Diagram


Figure 2.151: .

2.11.2.4.4 Equipment
Elastic balls hanging from a frame ("Newton's cradle")

2.11.2.4.5 Presentation
The identical balls are bifilarly suspended in a straight row. In horizontal equilibrium the balls are just in contact. Speeds at the time of contact are, to a first approximation, proportional to the horizontal displacement from rest position.

1. *Two balls are suspended.* One ball is pulled out and released. It hits the other and this one bounces out to the other side; the first ball being at rest now. (See Figure 2.)

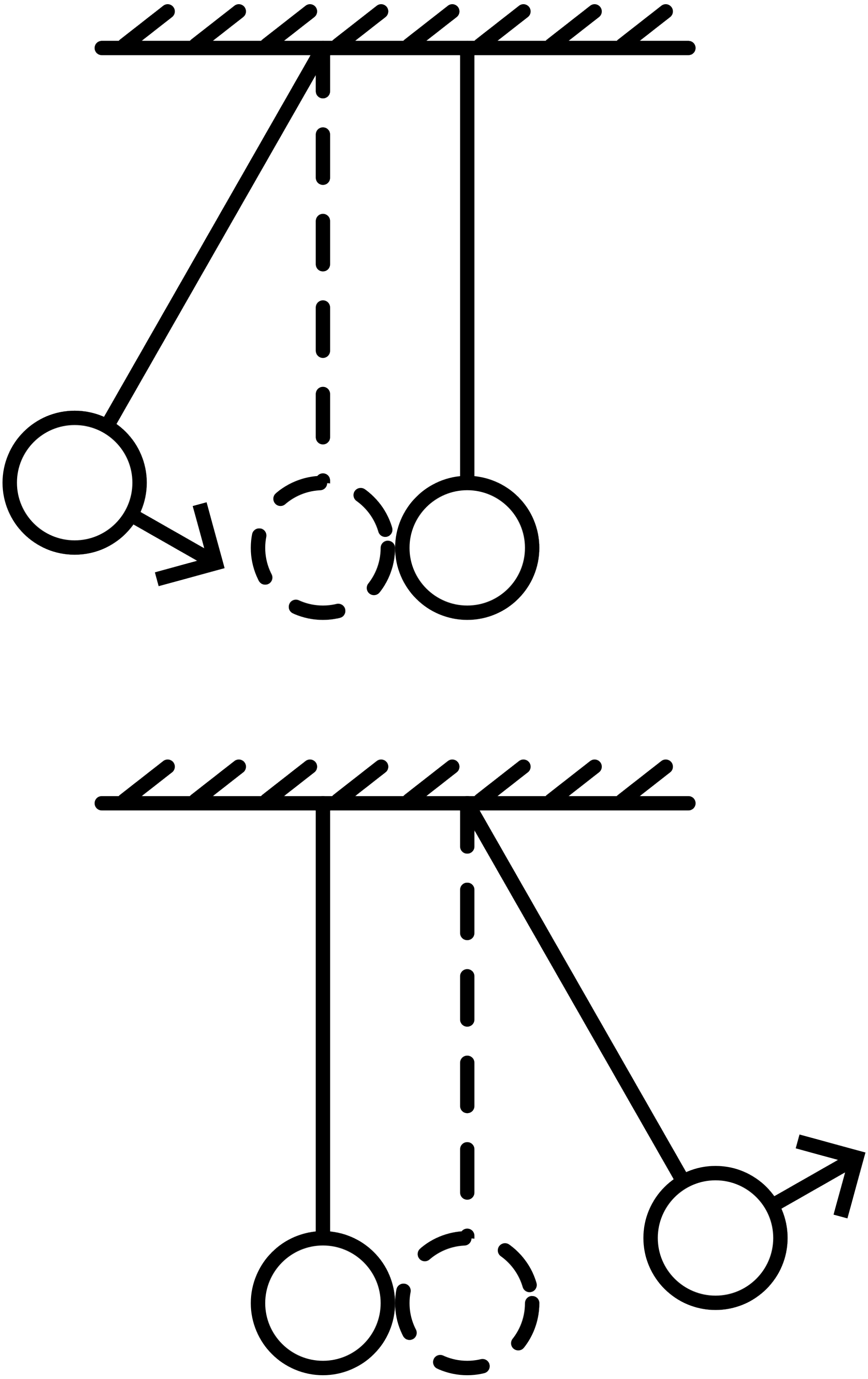


Figure 2.152: .

Both balls are pulled out and released. They hit and both rebounce almost to the original height. (See Figure 3.)

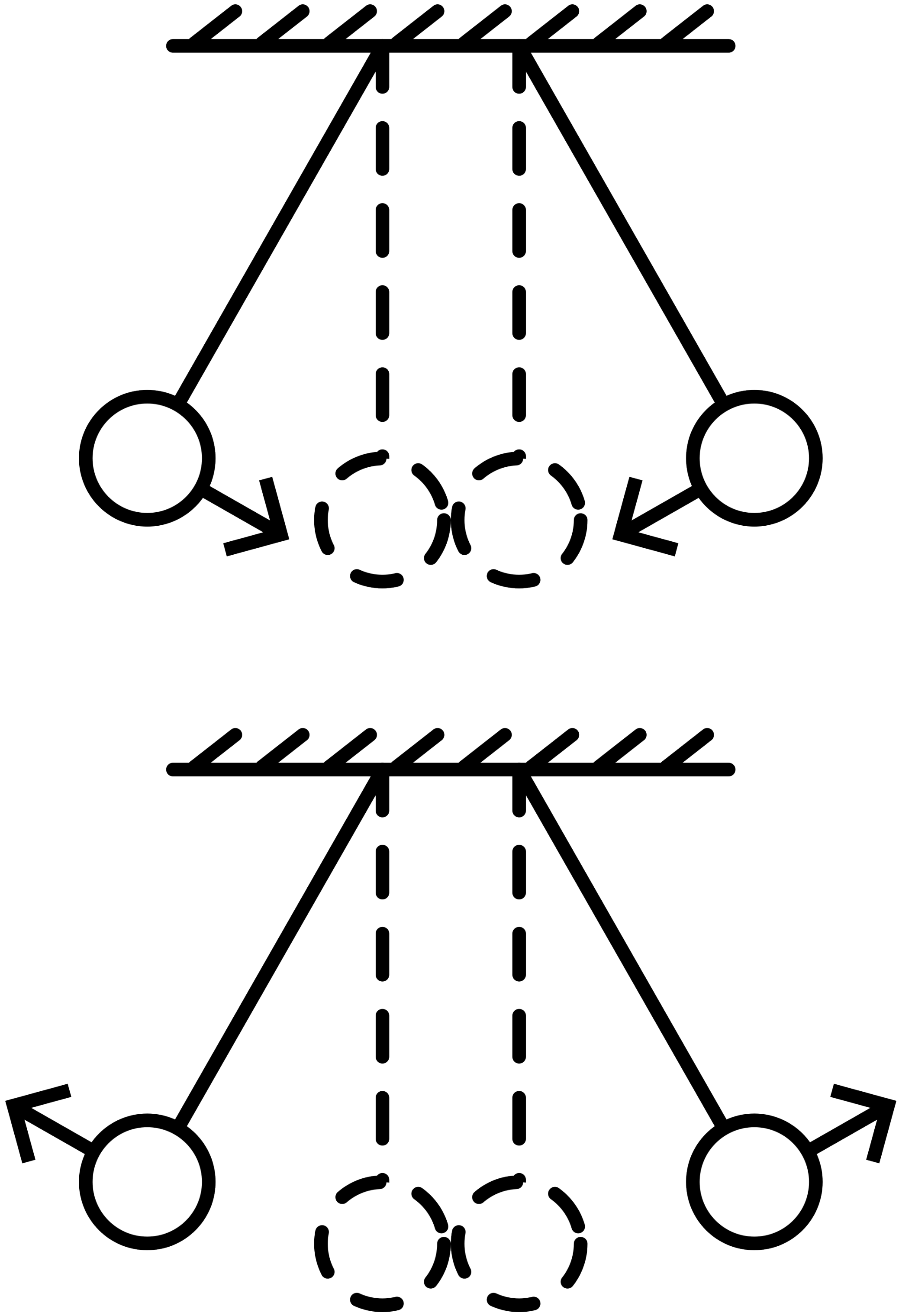


Figure 2.153: .

Both balls are pulled out but one ball more than the other. In this way the two balls will have different speeds. They are released, hit, and it can be observed that after the collision the two balls have interchanged their speeds. (See Figure 4.)

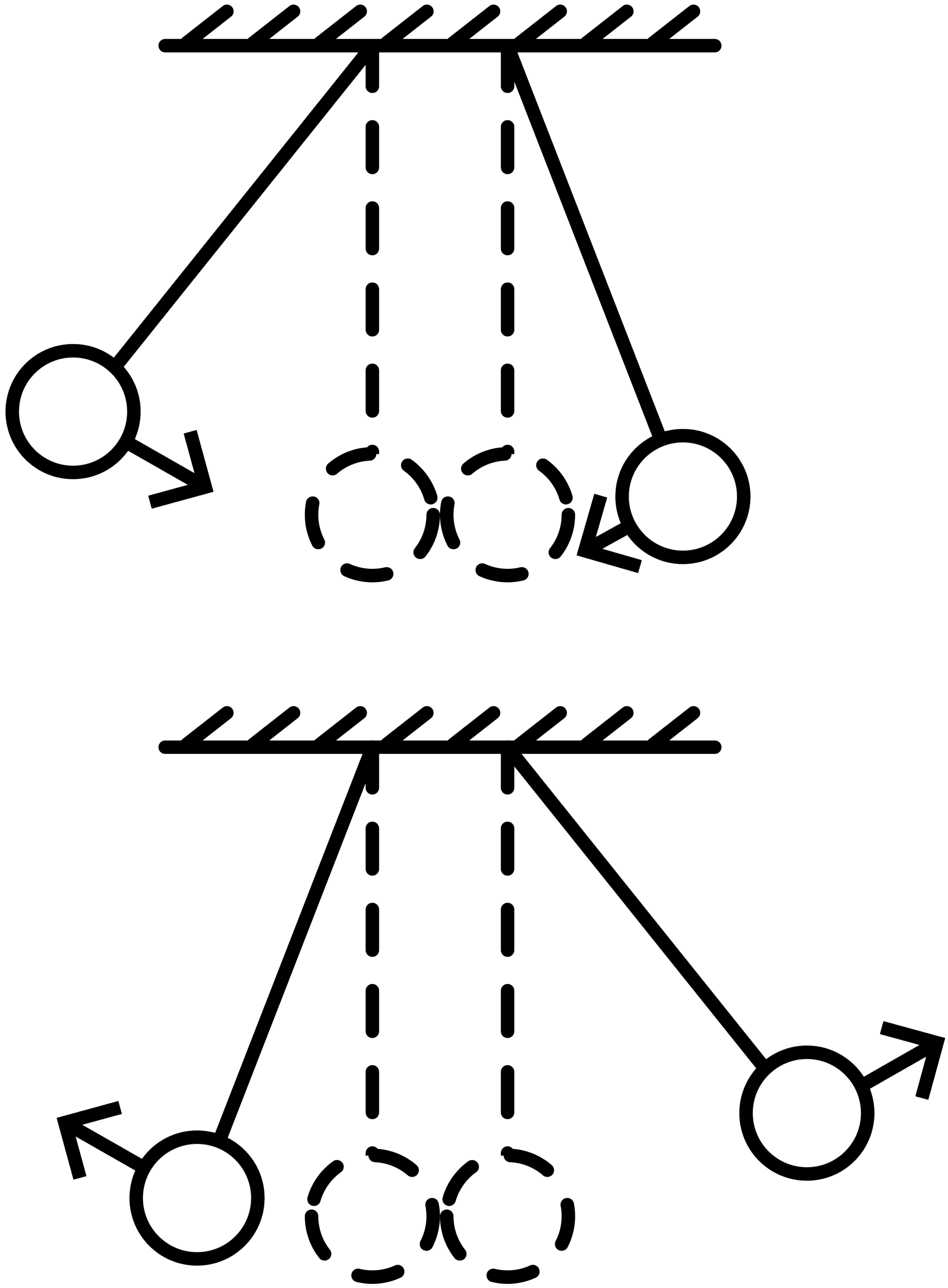


Figure 2.154: .

2. *More balls are suspended.*

When 3 (or 4 , or 5 , etc.) balls are suspended the demonstrations performed with two balls can be repeated. The observed phenomena are similar. The balls between the two outer balls are not taking part in the movements. (See Figure 5.)

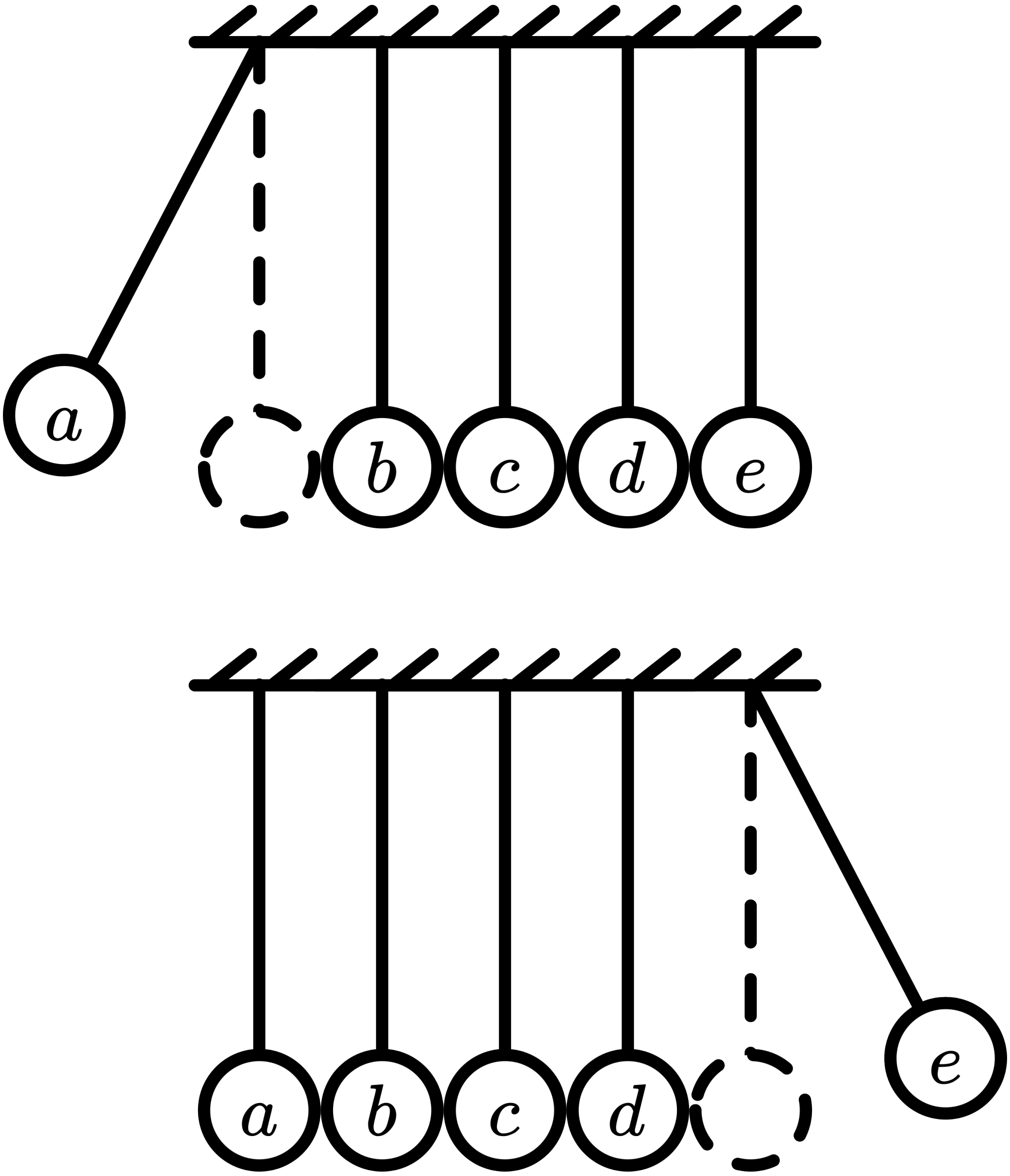


Figure 2.155: .

When two balls are pulled out and released, they hit the others and two balls bounce out to the other side. With three, three bounce out, etc. It is always the same number of balls. (See Figure 6.)

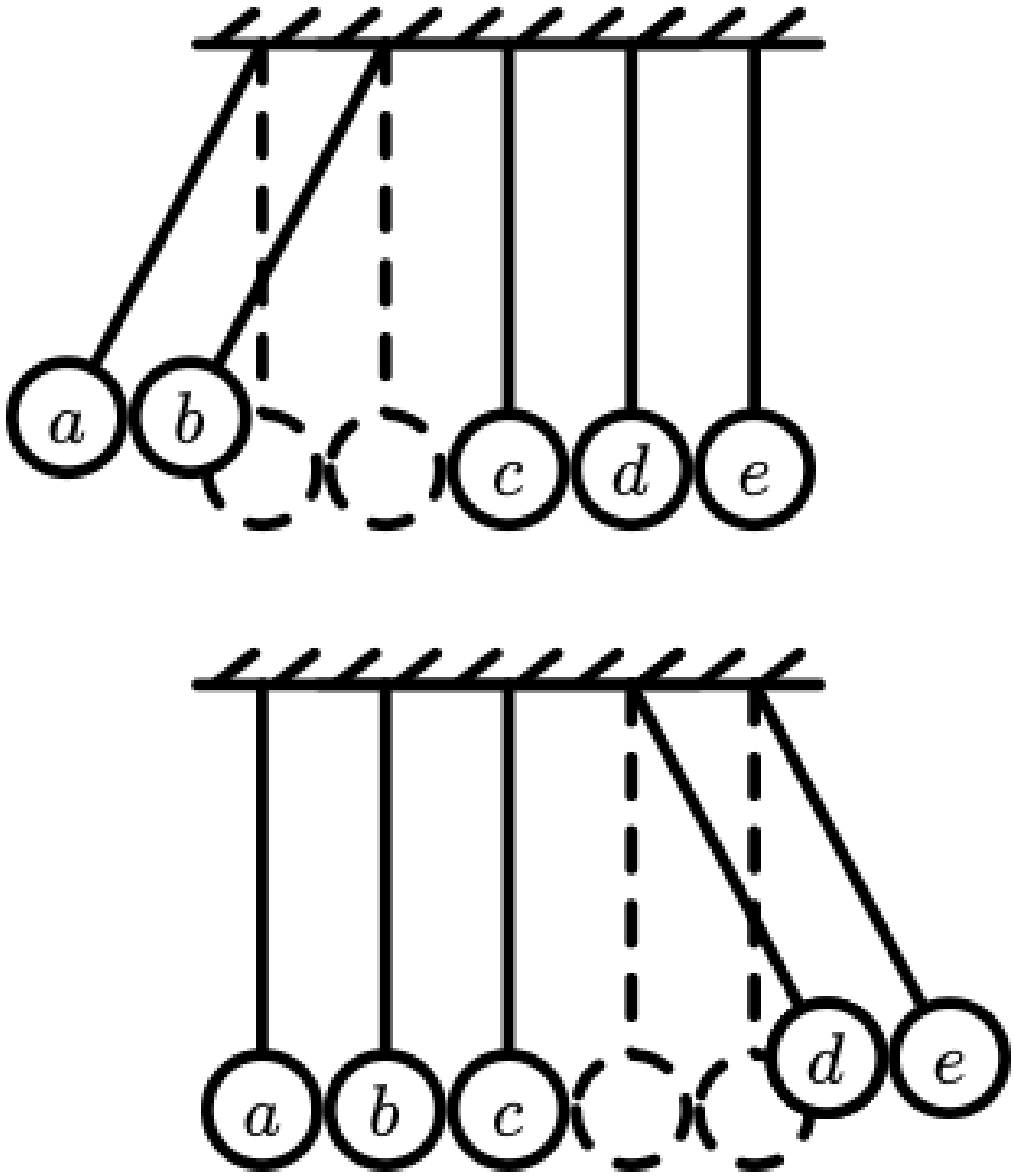


Figure 2.156: .

3. Two balls of *different mass* (m and $3m$).

    3. m is hanging in its rest position and $3m$ is pulled out and released. After the collision m is launched and $3m$ follows it but with reduced speed. After reversing their direction, they collide again in the middle and after this second collision m hangs at rest and $3m$ rebounces to its original height.
    4. $3m$ is hanging in its rest position and m is pulled out and released. After the collision, $3m$ is launched and m rebounces but not to its starting position. Both masses have the same speed when they collide again exactly in the rest position and after this second collision $3m$ is at rest and m rebounces to its starting position.
    5. Both balls are pulled out and released at the same height, so they have the same speed. After the collision, $3m$ is at rest and m bounces to a much higher height. m reverses its direction and there is a second collision. Now both balls rebounce to their original height.

In all three demonstrations the starting position returns after two collisions.

2.11.2.4.6 Explanation

Figure 7 shows the situation before and after an elastic collision. In an elastic collision, both momentum and kinetic energy are conserved. This means that v_{rel} will not change: $u_2 - u_1 = V_{rel}$

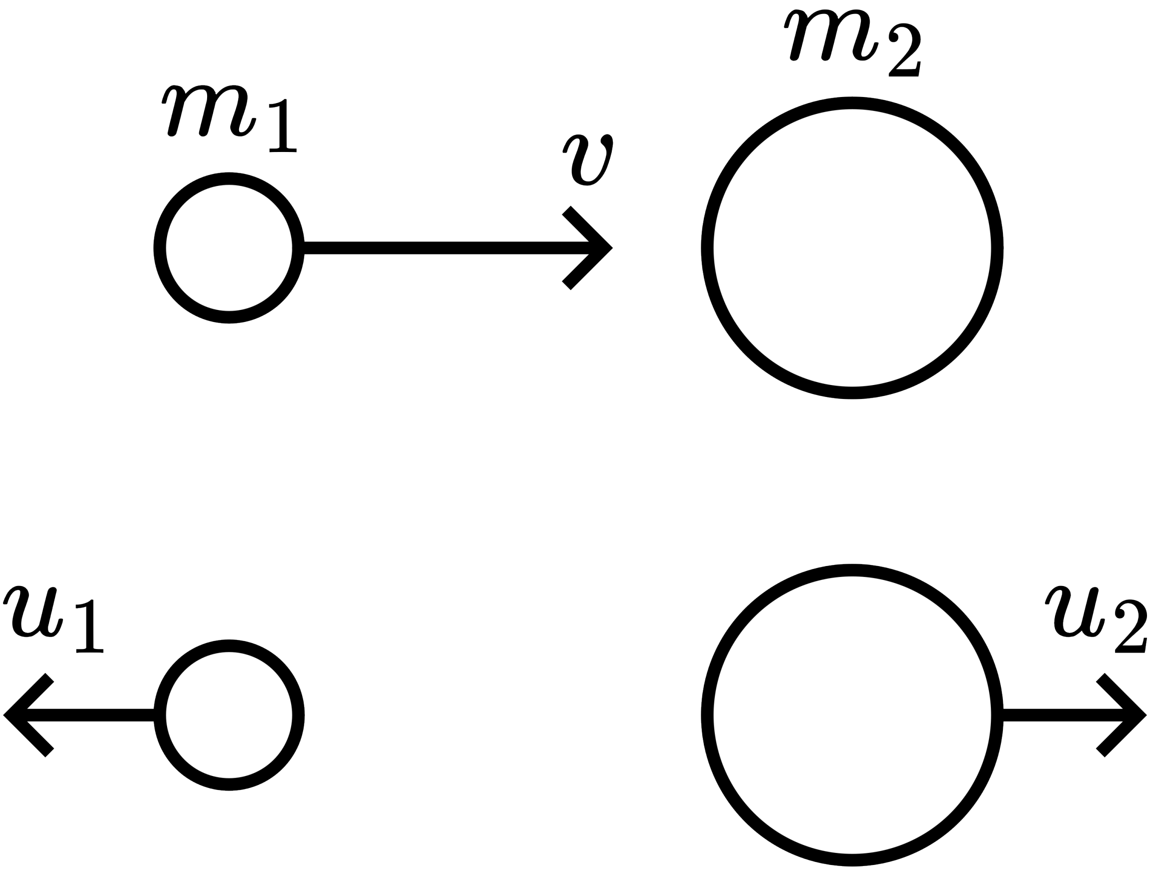


Figure 2.157: .

Momentum is conserved:

$$m_1 u_1 + m_2 u_2 = m_1 v_{rel} \tag{2.23}$$

These two equations give us:

$$u_1 = \frac{m_1 - m_2}{m_1 + m_2} v_{rel} \tag{2.24}$$

and

$$u_2 = \frac{2m_1}{m_1 + m_2} v_{rel} \tag{2.25}$$

The next table shows the results of different situations concerning our demonstrations.

m_1/m_2	u$_1$	u$_2$
$1/3$	$-1/2v$	$\underline{1/2v}$
1	0	$\underline{v}$
3	$1/2 \quad v$	$\underline{3/2v}$

This table explains the behavior shown in presentation 1 and 3 .

In the demonstration of Figure 5, a hits b. b gets the speed of a (see table) and immediately hits c. b comes to rest and c gets the speed of b and immediately hits d etc. At the end, e is launched with the speed v that a originally had.

In the demonstration of Figure 6 , the first thing that happens is that b hits c. b comes to rest and finally e is launched. In the meantime a hits b and a comes to rest and finally d is launched.

If not reasoning step by step, the question could be raised why ball e is not coming out with double velocity. After all this would conserve momentum. But checking kinetic energy will show that in that case kinetic energy is not conserved.

2.11.2.4.7 Remarks

In succession to demonstration 2 (in the end with three balls), one ball with mass 3 m and speed v hits the row of balls at rest. It can be seen that in this case not the last three balls are launched with speed v, but that all balls are moving now with different speeds and also the $3m$-ball is still moving.

2.11.2.4.8 Sources

- Jewett Jr., John W., Physics Begins With an M… Mysteries, Magic, and Myth, pag. 74, 83
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 56
- Roest, R., Inleiding Mechanica, pag. 118-119
- Borghouts, A.N., Inleiding in de Mechanica, pag. 103-104
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 58
- Leybold-Heraeus, Physikalische Handblätter, pag. DK 531.662; a

2.11.2.5 05 Demonstrator and Cart

2.11.2.5.1 Aim

To show an example in which only conservation of momentum predicts how the demonstration ends.

2.11.2.5.2 Subjects

- 1N20 (Conservation of Linear Momentum)

2.11.2.5.3 Diagram

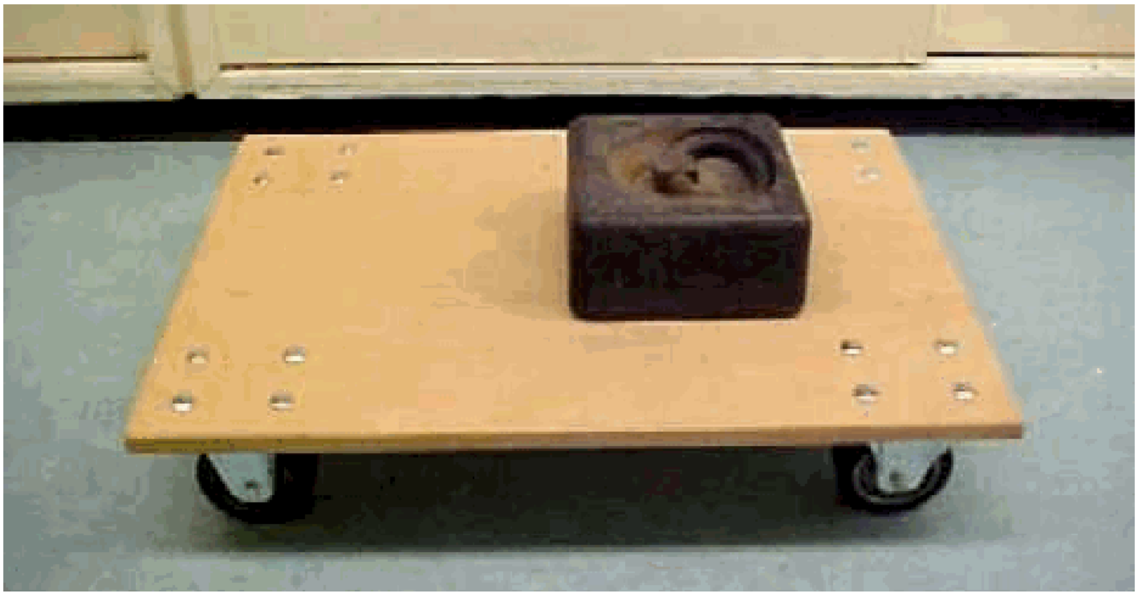


Figure 2.158: .

2.11.2.5.4 Equipment

- Light cart, easy rolling.
- Heavy weight (25 kg).
- An assistant to the demonstrator.

2.11.2.5.5 Presentation

The cart is placed centrally in front of the lecture hall. From one side the demonstrator and his assistant walk together towards the cart. Arriving at the cart the demonstrator steps on it, his assistant keeps on walking. The students will observe that the demonstrator still has the same speed; he keeps pace with the still walking assistant. The heavy weight is placed on the cart (see Diagram). Again the demonstrator and his assistant start walking towards the cart and on arrival the demonstrator steps on it (the assistant keeps on walking). Now the students will observe that the cart+demonstrator has a lower speed; the still walking assistant being his reference.

2.11.2.5.6 Explanation

The cart (m) and demonstrator (M) is considered as one system. Before he jumps on the cart the total momentum equals Mv. After he is jumped on it the total momentum equals

$$(M+m)v \tag{2.26}$$

So:

$$v' = \frac{M}{M+m}v \tag{2.27}$$

When the cart is light: $v' = v$ (the first part of the demonstration).

When m cannot be neglected v' will be smaller than v.

2.11.2.5.7 Remarks

- When you step on the cart you easily give it an extra push. This should not happen. Some practicing is really needed before showing it to an audience!
- v' is calculated using conservation of (linear) momentum. As can be shown there is no conservation of (kinetic) energy (K) in this demonstration:

Before jumping on the cart: $K = \frac{1}{2}Mv^2$.

After jumping on the cart: $K = \frac{1}{2}(M+m)v^2$, and substituting v' will give:

$K = \frac{M}{M+m}\frac{1}{2}Mv^2$.

While jumping on the cart part of the energy is lost in friction. (When there would be no friction then you would glide over the cart and leave it undisturbed.) This all shows that conservation of energy cannot be used in calculating v :

(In our demonstration $M = 75$ kg and m $= 25$ kg. Conservation of momentum gives $v' = \frac{3}{4}\nu$, while applying conservation of energy gives $v' = \sqrt{\frac{3}{4}}v = 0.87v$ which is wrong.)

In calculating energy before and after it is of course possible to show how much energy is “lost” in friction.

2.11.2.5.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 92-93
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 126-127
- Roest, R., Inleiding Mechanica, pag. 118-119

2.11.2.6 06 Knock-Out

2.11.2.6.1 Aim

To show that when two balls, having equal momentums, collide with a block, the one that recoils with greater momentum imparts more momentum to the block.

2.11.2.6.2 Subjects

- 1N20 (Conservation of Linear Momentum)
- 1N30 (Collisions in One Dimension)

2.11.2.6.3 Diagram

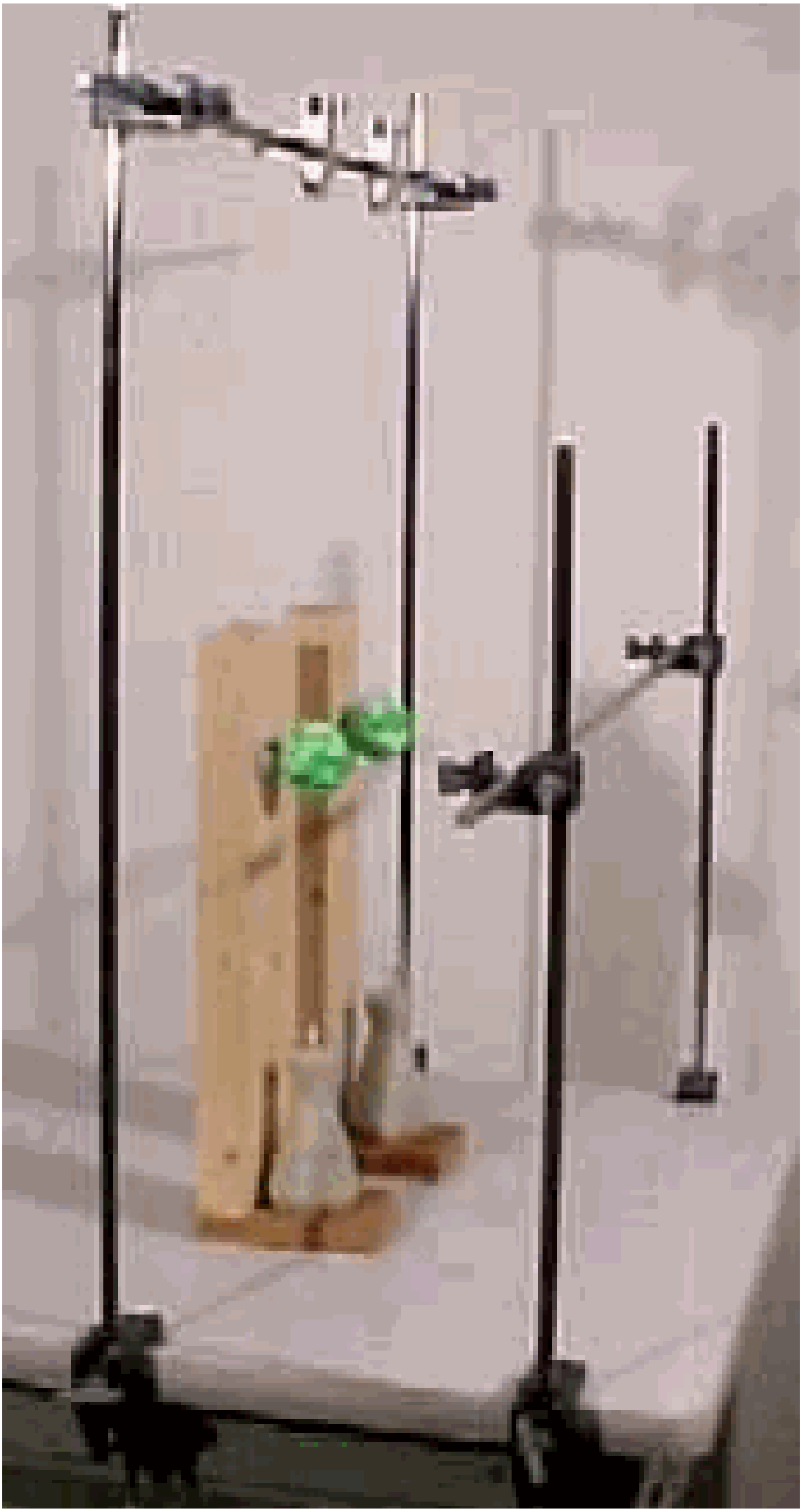


Figure 2.159: .

2.11.2.6.4 Equipment

- 2 Superballs on strings ($l=45\mathrm{~cm}).
- 2 Wooden blocks ($4\times9\times45\mathrm{~cm}), hinged on base.
- Masses or clamps to fix the bases.
- Modelling-clay.
- Support-rods and table-clamps.

2.11.2.6.5 Presentation

Preparation:

One of the wooden blocks has a piece of modelling-clay stuck to it on the place where the ball hits the block. A ball can be given a deflection by holding it against a support-rod. By means of this support-rod, both balls can be given the same starting position. By trial and error the support-rod is placed in such a position that after launching the balls the block without the clay is just knocked down.

Presentation:

One ball is given a deflection by pressing it to the support-rod. With your other hand you hold the wooden block fixed in position. Letting the ball go, it hits the wooden block. Doing this with one block after the other it is clearly observed that the collision with the clayed block is less elastic than the collision with the other block (the ball bounces less far). Now the students are asked which block will be knocked down when both balls are released. After their prediction both balls are launched simultaneously and only the block without the clay is knocked down. The presentation can be discussed now, focussing on the idea that the concept of change in impulse is relevant.

2.11.2.6.6 Explanation

When the ball hits the wooden block, the block experiences a force depending on the momentum $\int F dt$. The elastic collision imparts more momentum to the block because the ball changes its momentum from $+mv$ to $-mv$ (a change of $-2mv$), while the ball hitting the clayed block changes its momentum from $+mv$ to 0 (a change of $-mv$). So $\int F dt$ is twice as high in the first situation.

2.11.2.6.7 Remarks

- Sticking the piece of clay to the wooden block, we model it in a sharp way (see Figure 2).

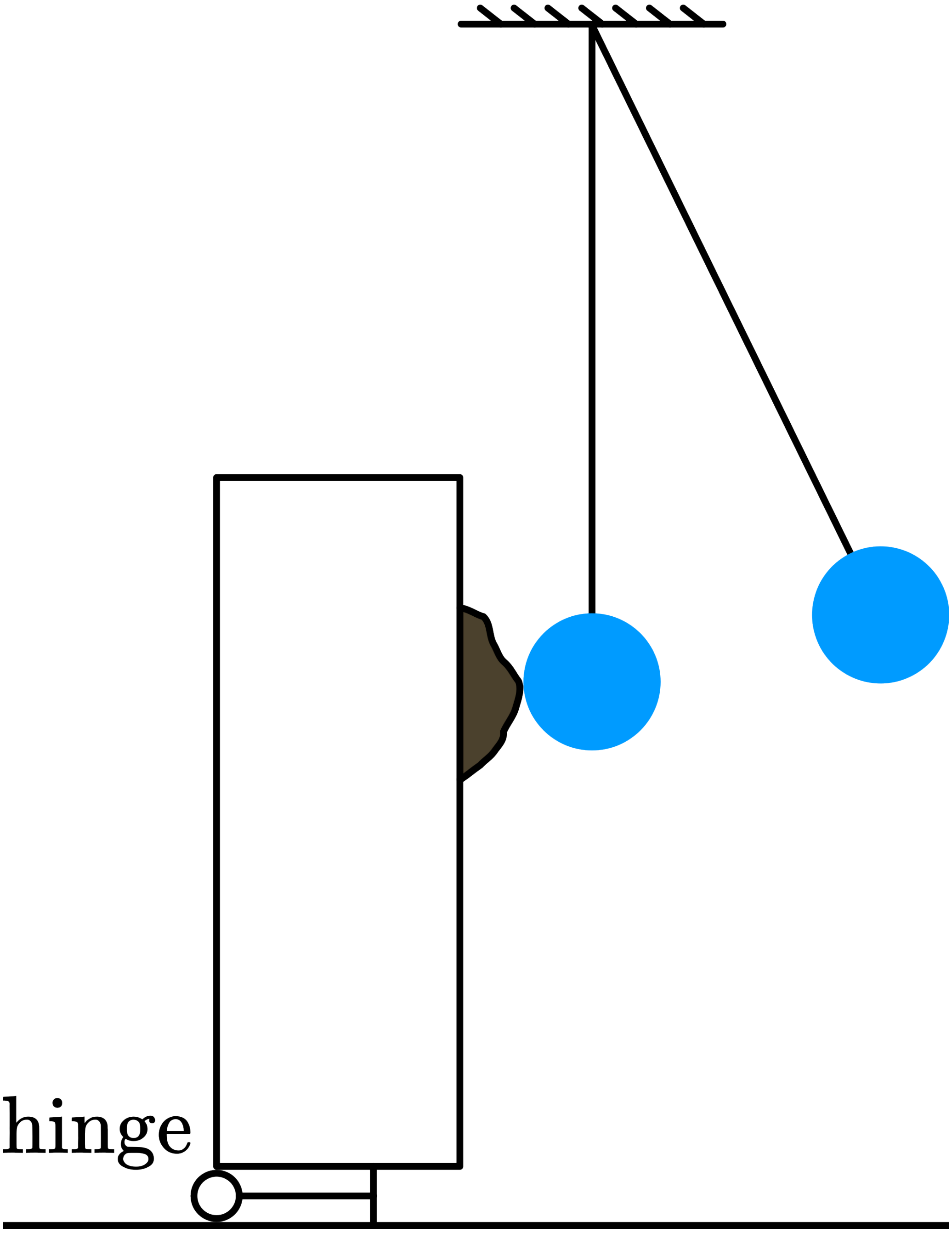


Figure 2.160: .

- Flattening the clay-surface makes it more elastic.

2.11.2.6.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 27-28

2.11.2.7 07 Pulling a Slackened Rope

2.11.2.7.1 Aim

To show that only a short impulse is needed to make a student move.

2.11.2.7.2 Subjects

- 1N20 (Conservation of Linear Momentum)

2.11.2.7.3 Diagram

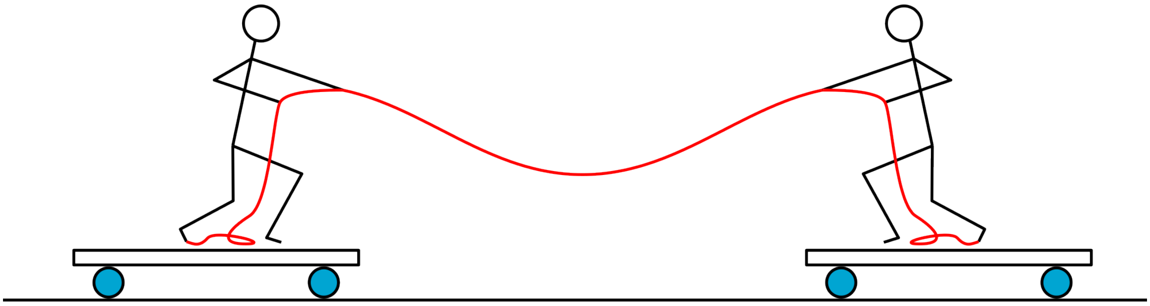


Figure 2.161: .

2.11.2.7.4 Equipment

- Two light carts, easily rolling.
- Rope; $l = 10$ m.
- Two students.

2.11.2.7.5 Presentation

The two students stand each on a cart. Between them is a slackened rope. Slowly they increase the tension in the rope and at a certain moment both carts start moving towards each other. The rope slackens again, but both carts keep on moving. (Eventually friction will stop their movement.)

When there is a clear mass difference between the two students, the difference in their respective speeds will be clearly observable.

2.11.2.7.6 Explanation

The tension in the rope implies an impulse $F\Delta t$ to the cart + student. This impulse changes the momentum $p = m_1\Delta v_1$ of the cart + student. Applying Newton's second law we can say: $F\Delta t = m_1\Delta v_1$. When the initial velocity is zero, then m_1 will move with v_1 after the short impulse is over.

Applying 'conservation of linear momentum' to the whole system it is clear that the change of momentum of m_2 is $-\Delta p = m_2\Delta v_2$. v_2 will be opposite to v_1 and when $m_2 > m_1$, v_2 will be lower than v_1.

2.11.2.7.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 122-123

2.11.2.8 08 Spinning Bouncing Ball

2.11.2.8.1 Aim

To show the power of the correspondence between translational and rotational motion.

2.11.2.8.2 Subjects

- 1N20 (Conservation of Linear Momentum)
- 1Q40 (Conservation of Angular Momentum)

2.11.2.8.3 Diagram

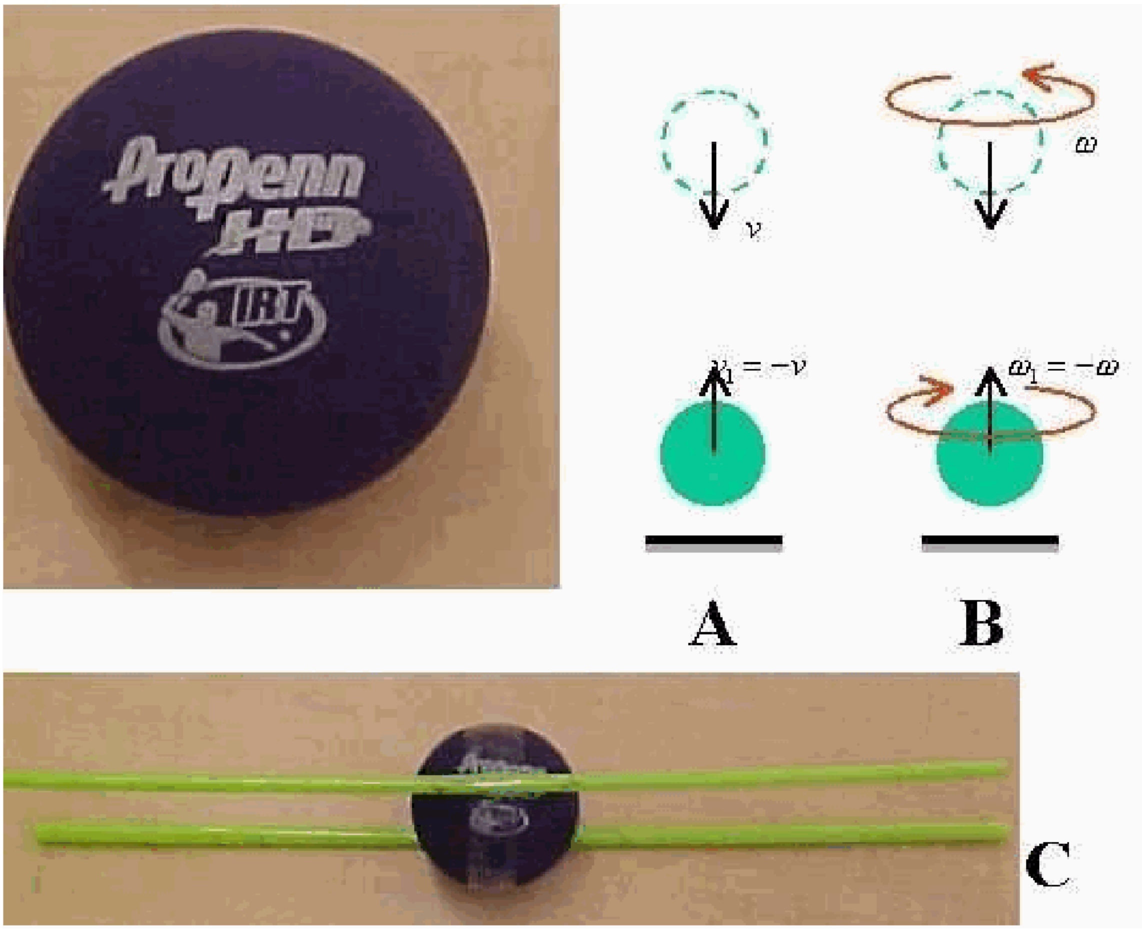


Figure 2.162: .

2.11.2.8.4 Equipment

- Racquetball.
- Racquetball with straws (Diagram C).
- Superball (see Explanation).
- Basketball (see Explanation).
- Camera
- Projector, to project the image of the bouncing ball to a large audience.

2.11.2.8.5 Presentation

The racquetball is dropped straight down from your hand and bounces back (see drawing A in Diagram). This is a well known phenomenon. The laws of mechanics explain the reversal of the velocity (see Figure 2).

$$m_1 v = m_1 v_1 + m_2 v_2$$

$$\frac{1}{2} m_1 v^2 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2$$

$$v_1 = v \frac{m_1 - m_2}{m_1 + m_2}$$

$$v_2 = v \frac{2m_1}{m_1 + m_2}$$

$$\boxed{\begin{aligned} &m_2 >> m_1 \\ &v_1 = -v \\ &v_2 = 0 \end{aligned}}$$

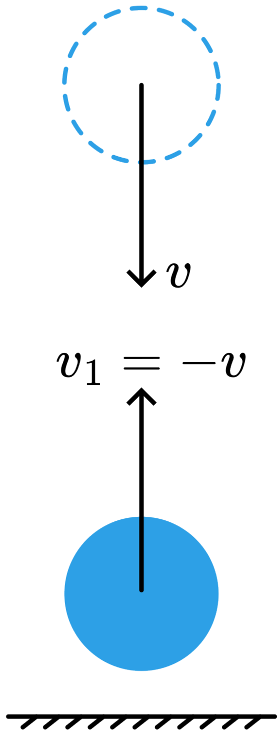


Figure 2.163: .

There is a strong correspondence between the formalisms of translational and rotational mechanics. Awareness of this correspondence leads us to the prediction that when the bouncing ball is spinning in one direction when dropped, it has to spin in the opposite direction after bouncing! (see drawing B in Diagram.)

We try this and it really works that way! (The camera looks down on the bouncing ball and "sees" the label on the ball rotate in one direction and after bouncing in the other direction, and so on, while bouncing.)

2.11.2.8.6 Explanation

Figure 3 shows the explanation from a point of view of rotational dynamics. In order to perform this demonstration you really need a racquetball.

$$I_1\omega = I_1\omega_1 + I_2\omega_2$$

$$\frac{1}{2}I_1\omega^2 = \frac{1}{2}I_1\omega_1^2 + \frac{1}{2}I_2\omega_2^2$$

$$\omega_1 = \omega\frac{I_1 - I_2}{I_1 + I_2}$$

$$\omega_2 = \omega\frac{2I_1}{I_1 + I_2}$$

$$\boxed{\begin{aligned} &I_2 >> I_1 \\ &\omega_1 = -\omega \\ &\omega_2 = 0 \end{aligned}}$$

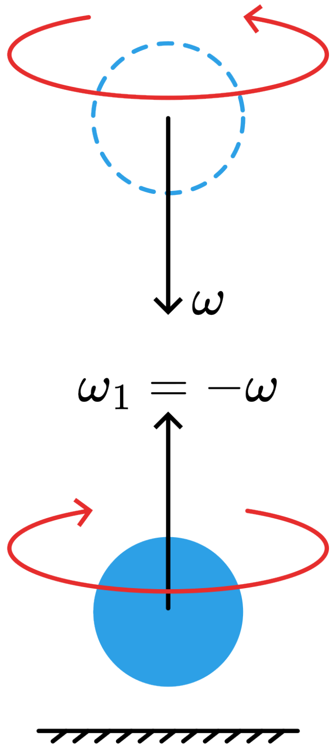


Figure 2.164: .

When, for instance, you use a superball, the ball continues to rotate in the same direction after bouncing. In order to get a reversal of the sense of rotation it is wise to study again the correspondence between translational and rotational laws:

In translational situations we get a reversal of velocity due to the elastic bounce on the floor; temporarily the kinetic energy is stored in potential energy of the materials (linear springs: $U = 1/2kx^2$). To get at bouncing such a situation for rotation we need to store the rotational energy by means of torsion ($U = 1/2c\theta^2$). When using a superball, this material is too massive, too stiff, in order to store the rotational energy in torsion. The ball slips over the floor and looses part of its rotational energy in that dynamic friction before it bounces up again. After a couple of bounces all rotation is lost. From a point of view of rotation, a bouncing superball bounces not elastically.

When trying a basketball we will see that it shows the predicted change of direction of rotation just a little (when the speed of rotation is not too high). The difference, when compared to the superball, is that a basketball is thin-walled, while the superball is massive. The thin walled basketball can make a little torsion at its bouncing contact while the superball cannot. This leads us finally to the racquetball that can make a relatively large torsion (in combination with a high coefficient of static friction with the floor). To show this torsion we have a racquetball with two straws stuck to it (see Diagram C). While the camera sees the two straws in line, one behind the other, you can show the possible torsion by forcing it that way by your hands.

2.11.2.8.7 Sources

- The Physics Teacher, pag. 550-551 (Vol.42), Vol. 42
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 166

2.11.2.9 10 Magnet Symmetry

See Magnet Symmetry

2.11.3 1N22 Rockets

2.11.4 1N30 Collisions

2.11.4.1 02 Super Balls, Double Ball Drop

See Super Balls, Double Ball Drop

2.12 1Q Rotational Dynamics

2.12.1 1Q10 Moment of Inertia

2.12.1.1 01 Bicycle Wheel Pendulum

2.12.1.1.1 Aim

A qualitative demonstration of the parallel axis theorem.

2.12.1.1.2 Subjects

- 1Q10 (Momentum of Inertia)

2.12.1.1.3 Diagram

Figure 2.165: .

2.12.1.1.4 Equipment

- Bicycle wheel with leaded rim.
- Suspension-bracket with blocking-nuts.
- Large frame to suspend the bracket and bicycle wheel.

2.12.1.1.5 Presentation

The wheel is free to rotate about its axis. Then the wheel is swung as a pendulum. The period of oscillation is noted. (It can also be shown that the period is independent of the speed of rotation of the wheel.) Now the wheel is fixed by turning the nuts in the bracket holding the wheel rim (see Figure 2).

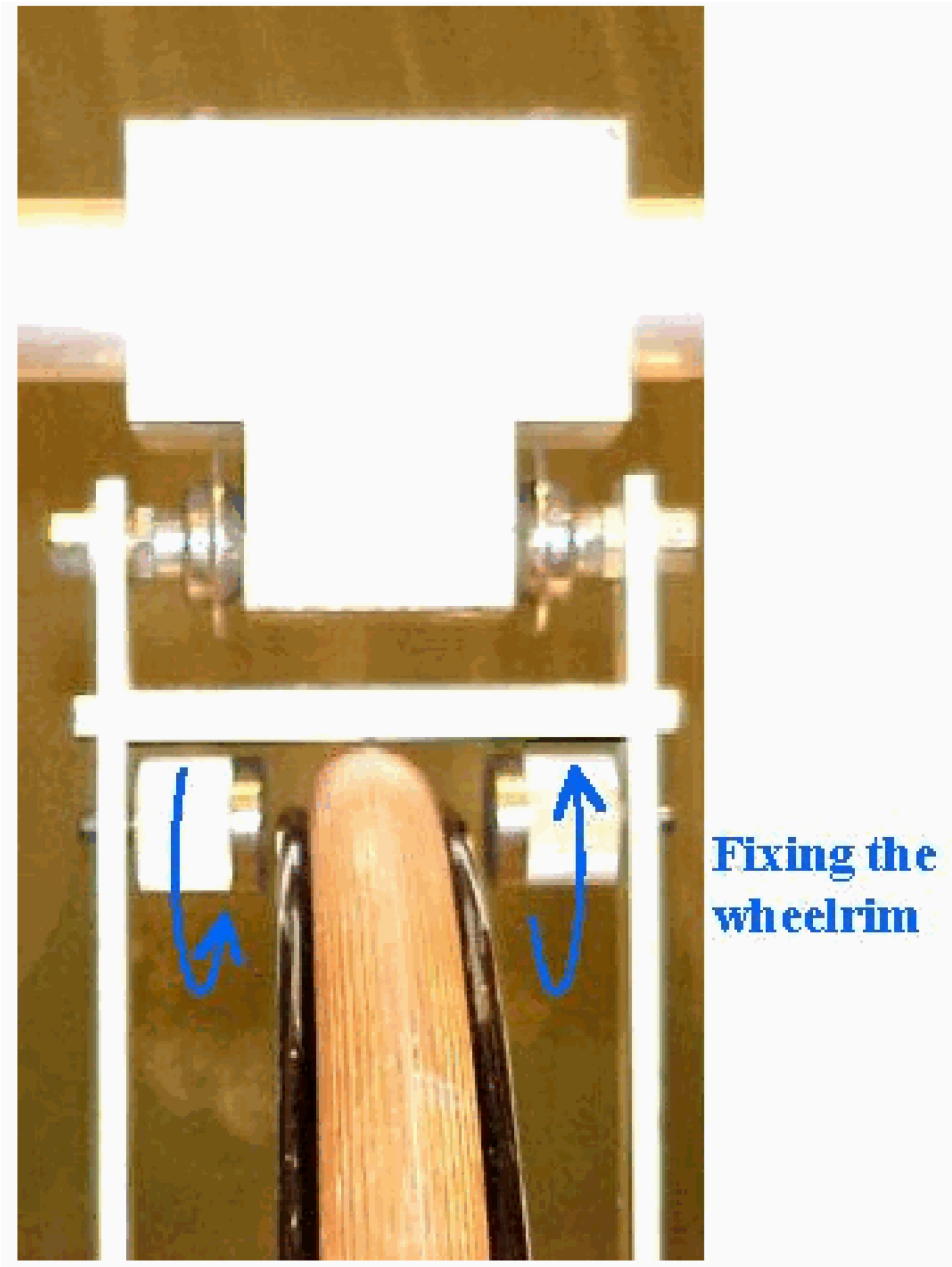


Figure 2.166: .

Again the apparatus is swung as a pendulum. The period observed is longer than that in the previous case.

2.12.1.1.6 Explanation

In the first part of the demonstration, the wheel can rotate about its axis and thus acts as though all its mass were concentrated at its axis. $I = MR^2$.

In the second part, the wheel swings as a rigid body and the total rotational inertia now includes the rotational inertia of the wheel about an axis through its centre of mass, I_c, plus $MR^2 . I_c = MR^2$, so $I_{tot} = 2MR^2$, making it a slower pendulum. Since the period of a physical pendulum equals $T = 2\pi\sqrt{\frac{I}{mgR}}$, the pendulum is 41% slower $\left(\sqrt{2} = 1.41\right)$.

2.12.1.1.7 Sources

- Meiners, Harry F., Physics demonstration experiments, part I, pag. 280.
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 155-157.
- Roest, R., Inleiding Mechanica, pag. 163-164 en 169.

2.12.1.2 02 Physical Pendulum (2)

2.12.1.2.1 Aim

To show the validity of the parallel axis theorem (Steiner's law).

2.12.1.2.2 Subjects

- 1Q10 (Momentum of Inertia)
- 3A15 (Physical Pendula)

2.12.1.2.3 Diagram

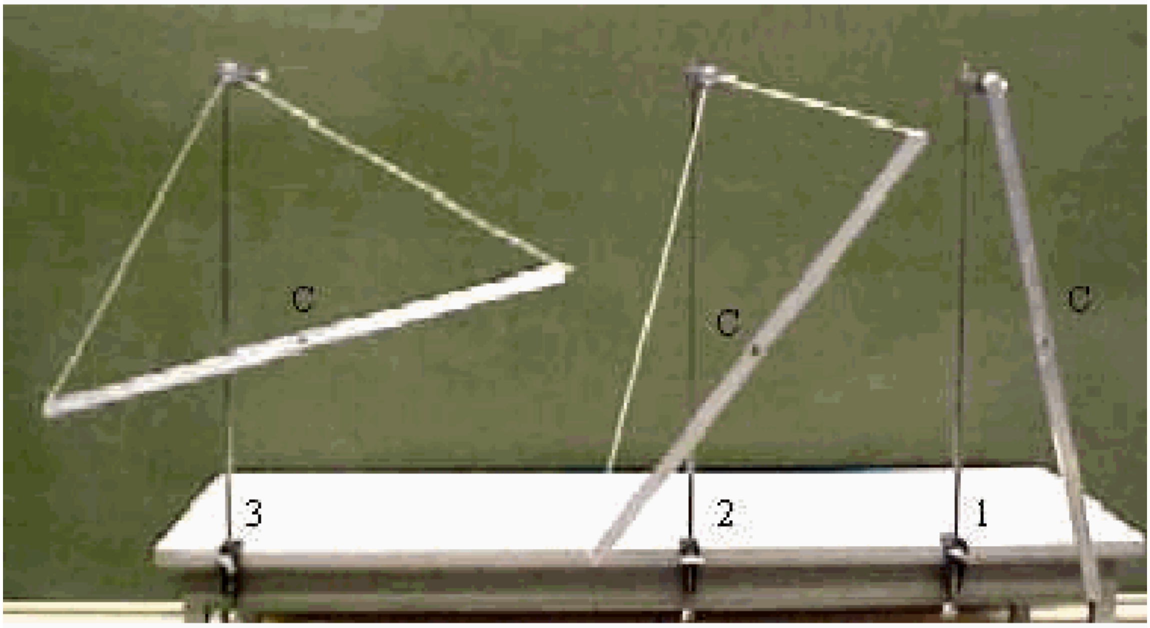


Figure 2.167: .

2.12.1.2.4 Equipment

- 4 sticks, one meter each, with holes at the ends.
- 1 meter stick for measurements.
- suspension wires for sticks (see Diagram).

2.12.1.2.5 Presentation

Pendulum 1 and 2 are swinging. It can be observed that they have the same period. Pendulum 1 and 3 are swinging. Again the same period is observed.

All three pendulums have the same period. Once started, they keep swinging in the same way together (observe the three centres of mass, C).

2.12.1.2.6 Explanation

For a physical pendulum the period T is given by: $T = \frac{2\pi}{\sqrt{g}}\sqrt{\frac{I_A}{ms}}$ (see Physical pendulum.

Also, $I_A = I_C + ms^2$ (Steiner), so T is constant as long as s is constant.

The suspension of the three pendulums is chosen such that the distance s is always the same because they are situated on a circle through C (see Figure 2). $s = 50$ cm.

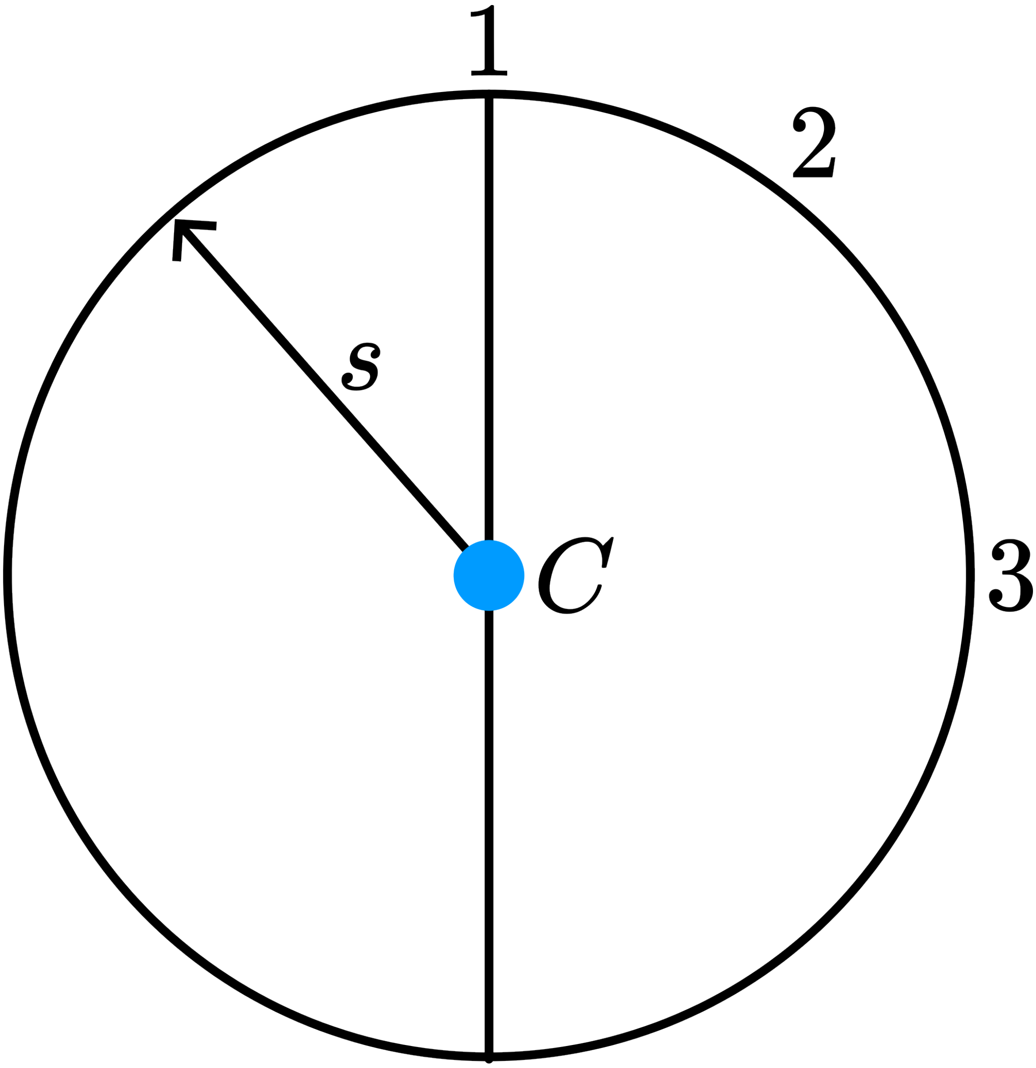


Figure 2.168: .

2.12.1.2.7 Remarks

We also have a suspension as shown in Figure 3. Now the suspension point is 0.167 m away from C and again T is the same because now the pendulum swings through the point of its reduced length (see demonstration "Physical pendulum (1)").

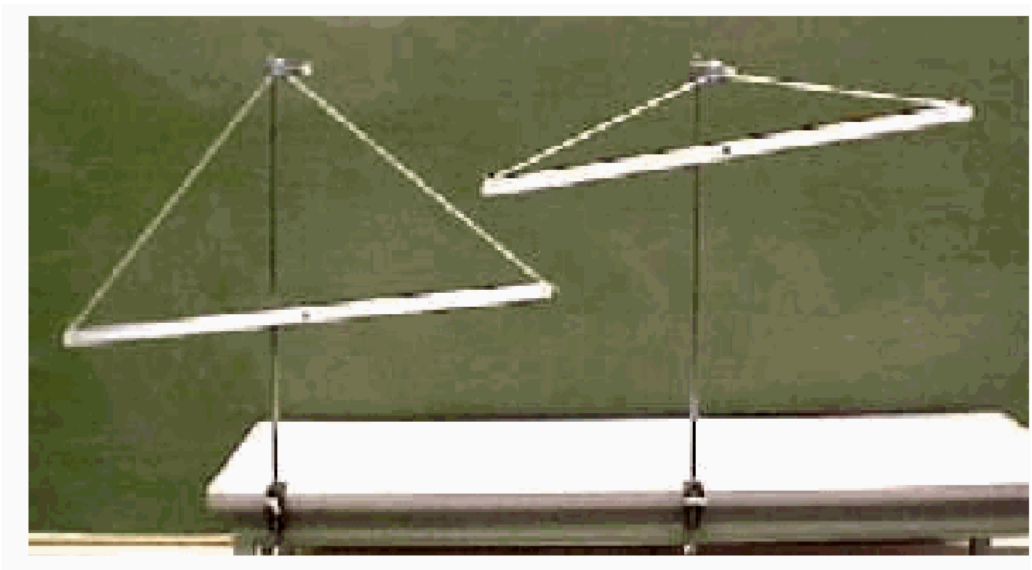


Figure 2.169: .

2.12.1.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 154-156
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 277-278

2.12.1.3 03 Maximum Rotational Inertia

2.12.1.3.1 Aim

To show that an object prefers to rotate around an axis with largest moment of inertia.

2.12.1.3.2 Subjects

- 1Q10 (Momentum of Inertia)
- 1Q60 (Rotational Stability)

2.12.1.3.3 Diagram

Figure 2.170: .

2.12.1.3.4 Equipment

- Electric hand drill (or other electric motor).
- Aluminium bar ∅12 mm, $l = 180$ mm with string $l = 200$ mm.
- A rope, $l = 500$ mm.
- A chain, $l = 500$ mm.
- Transparent screen

2.12.1.3.5 Presentation

The bar hung from a string is fixed to the drill and set spinning. The bar starts to rotate and will not remain vertical, but rises. Finally, the bar spins in a horizontal plane (see Diagram).

A rope suspended in the drills head will climb very fast to a rotation in a horizontal plane (passing through an interesting sequence of movement).

When a chain is used, this chain will also finally rotate in a horizontal plane, but it takes much more time to go from the vertical suspension to the horizontal rotation. (Now a study of the sequence in between is possible.)

Figure 2 shows several objects that can be used in this demonstration.

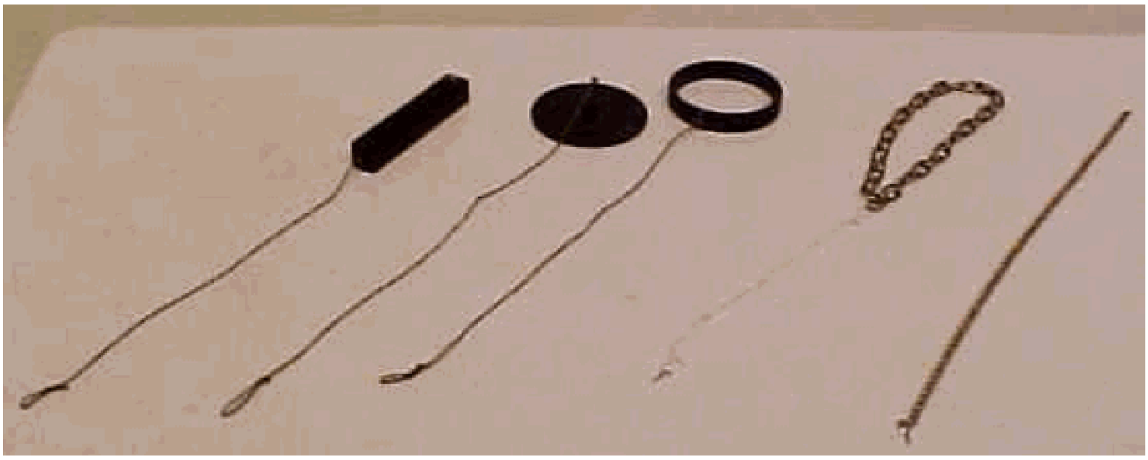


Figure 2.171: .

2.12.1.3.6 Explanation

- When the vertical bar is just a little out of its equilibrium, then due to opposing centripetal forces on the upper and lower part of the bar, the bar will eventually align itself horizontally.
- The angular velocity vector ω points vertically downward. The angular vector momentum does not, because the rotational inertia of the bar is greater about an axis perpendicular to the bar. The downward impulse $\vec{L}\Delta t$ attempts to align the angular momentum with ω.

2.12.1.3.7 Remarks

- While rotating the bar, rope or chain, take care that these objects, while rotating horizontally, leave enough free space. A transparent screen between the rotating objects and the observers is advised.

2.12.1.3.8 Sources

- Meiners, Harry F., Physics demonstration experiments, part I, pag. 275
- Roest, R., Inleiding Mechanica, pag. 216-222

2.12.1.4 04 Rolling Down a Wide Gutter

2.12.1.4.1 Aim

To show the effect of rolling radius on the amount of rotational kinetic energy.

2.12.1.4.2 Subjects

- 1Q10 (Momentum of Inertia)
- 1Q20 (Rotational Energy)

2.12.1.4.3 Diagram

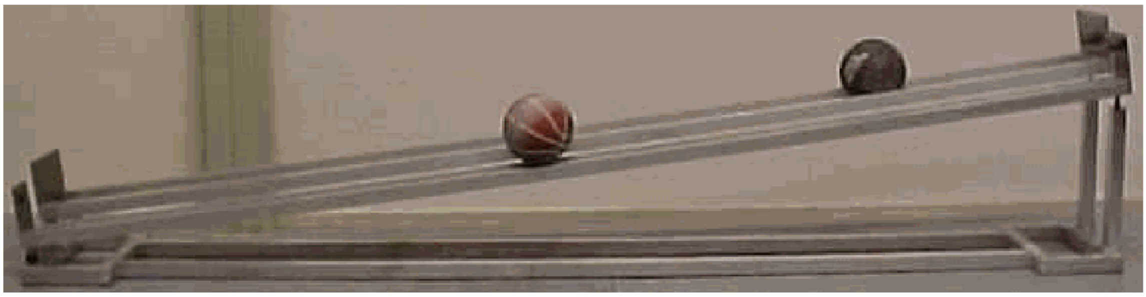


Figure 2.172: .

2.12.1.4.4 Equipment

- Two gutters of different width.
- Two equal, large basketballs.

2.12.1.4.5 Presentation

Both gutters are inclined about 7°. The balls start rolling down at the same time. The ball that rolls down the wider gutter takes much more time to reach the horizontal plane as the one rolling down the narrow gutter.

2.12.1.4.6 Explanation

One ball ('A') rolls with a larger radius than the other ('B'). So 'A' makes less rotations along the ramp than 'B'. That's why ball 'A' needs a smaller part of the available potential energy for its rotation to reach the end of the track and so more energy is available for its translation.

$E_{pot} = E_{transl} + E_{rot}$

$E_{transl} = 1/2mv^2$; $E_{rot} = 1/2I\omega^2$, with $I = 2/3mR^2$ (thin-walled hollow sphere).

When a ball rolls down the gutter, then $v = \omega r$ (r being the radius of rotation) and we find: $E_{transl}/E_{rot} = (3/2)(I^2/R^2)$.

When the gutter is very narrow, $r = R$ and $E_{transl}/E_{rot} = 3/2$. So 60% of the pot. energy is transformed in translation of the ball and 40% in rotation.

Our wider gutter has dimensions such that $r = 1/2R$, and so $E_{transl}/E_{rot} = 3/8$. Now 27% of the pot. energy is transformed into translation of the ball and 73% in rotation.

Comparing these two rolling balls, ball 'A' obtains 2.2 times as much energy for its translation as ball 'B' does. This means that ball 'A' has at the end of the gutter a transl. speed almost 50% higher than ball ' B ' $\left(2.2^{1/2} = 1.48\right)$. Then the time ball ' B ' needs to travel along the gutter will also be 50% higher.

2.12.1.4.7 Remarks

- The balls must be pumped firmly, otherwise the ball in the wide gutter will experience too much friction.

2.12.1.4.8 Sources

- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 212
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 53-55

2.12.1.5 05 Pirouette

2.12.1.5.1 Aim

To show an example of conservation of angular momentum, and the effect of the moment of inertia on rotational movement.

2.12.1.5.2 Subjects

- 1Q10 (Momentum of Inertia)
- 1Q40 (Conservation of Angular Momentum)

2.12.1.5.3 Diagram

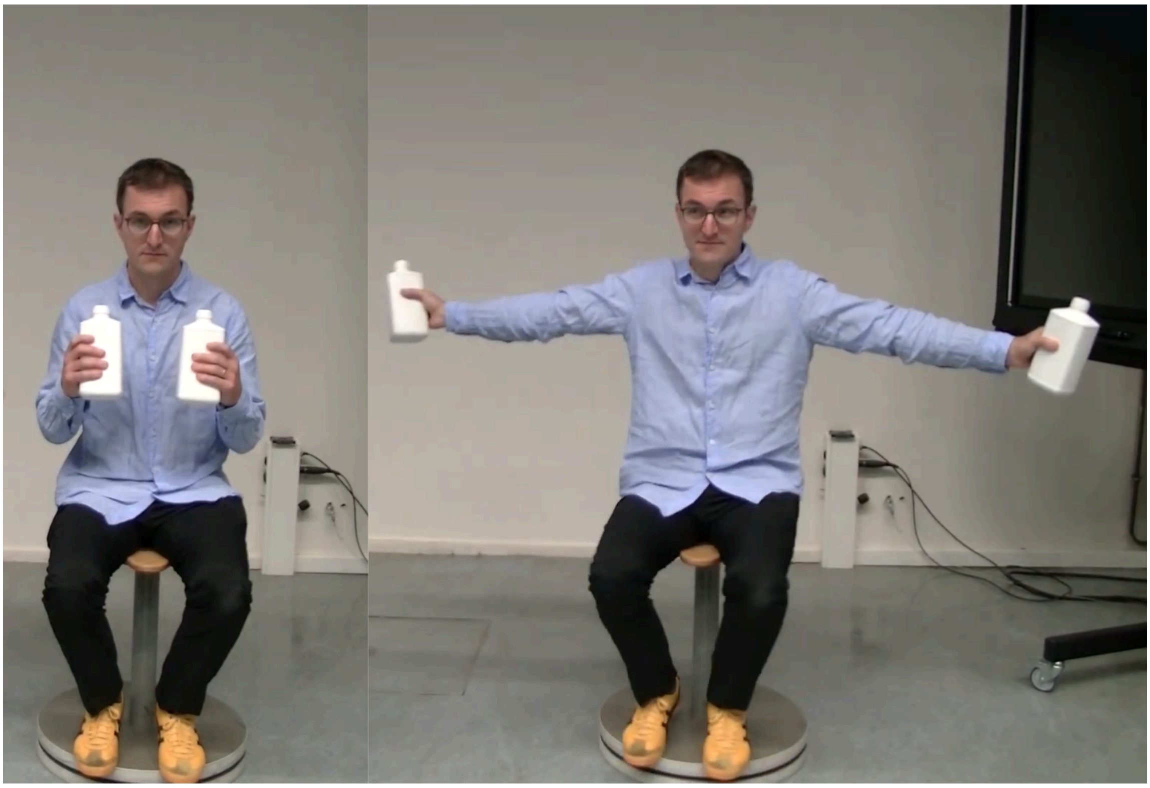


Figure 2.173: .

2.12.1.5.4 Equipment

- Swivel chair
- 2 masses, 1 kg each.

2.12.1.5.5 Presentation

The presentator sits on the swivel chair, holding in each hand a 1 kg mass. His hands rest in his lap. He is given angular speed by an assistant. While rotating, he extends his arms. Clearly can be observed that his angular velocity reduces. Returning his hands to his lap will increase the angular velocity again.

2.12.1.5.6 Explanation

During the experiment, there are no external forces applied. $\vec{L} = I\vec{\omega} = \text{const.}$. When moving the arms outward, $\vec{L}$ should remain constant (no external torque). The moment of inertia (I) of the rotating system increases, so $\vec{\omega}$ has to decrease and so the demonstration shows us.

2.12.1.5.7 Remarks

- You should not explain this demonstration using the basic $\vec{L} = \vec{r} \times m\vec{v} = const.$: An increase in r does predict a decrease in v, but a convincing change in v is difficult to observe in this demonstration (an observed reduced ω can also be caused by a v that remains constant!); a changing ω is observable convincingly.

- The effect of the demonstration is best observed when doing it yourself. It is remarkable how much better the change in angular velocity is felt than observed from the outside. So it is advisable that all students do the experiment themselves (for example during coffee-break of the lecture).
- It might be challenging to start the experiment at high moments of inertia. But then the increase of angular velocity may become very uncomfortable.

2.12.1.5.8 Video Rhett Allain

An extra demostration of the same principle as in the demonstration.

(a)

(b)

Figure 158: :align: center - Scan the QR code or click here to go to the video.

2.12.1.5.9 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 171
- Leybold Didactic GmbH, Gerätekarte, pag. 33166/-69, 33166
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 103-104 and 158-159
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 75

2.12.1.6 06 Rolling Downhill

2.12.1.6.1 Aim

To show, qualitatively, the influence of the moment of inertia in rolling downhill.

2.12.1.6.2 Subjects

- 1Q10 (Momentum of Inertia)
- 1Q20 (Rotational Energy)

2.12.1.6.3 Diagram

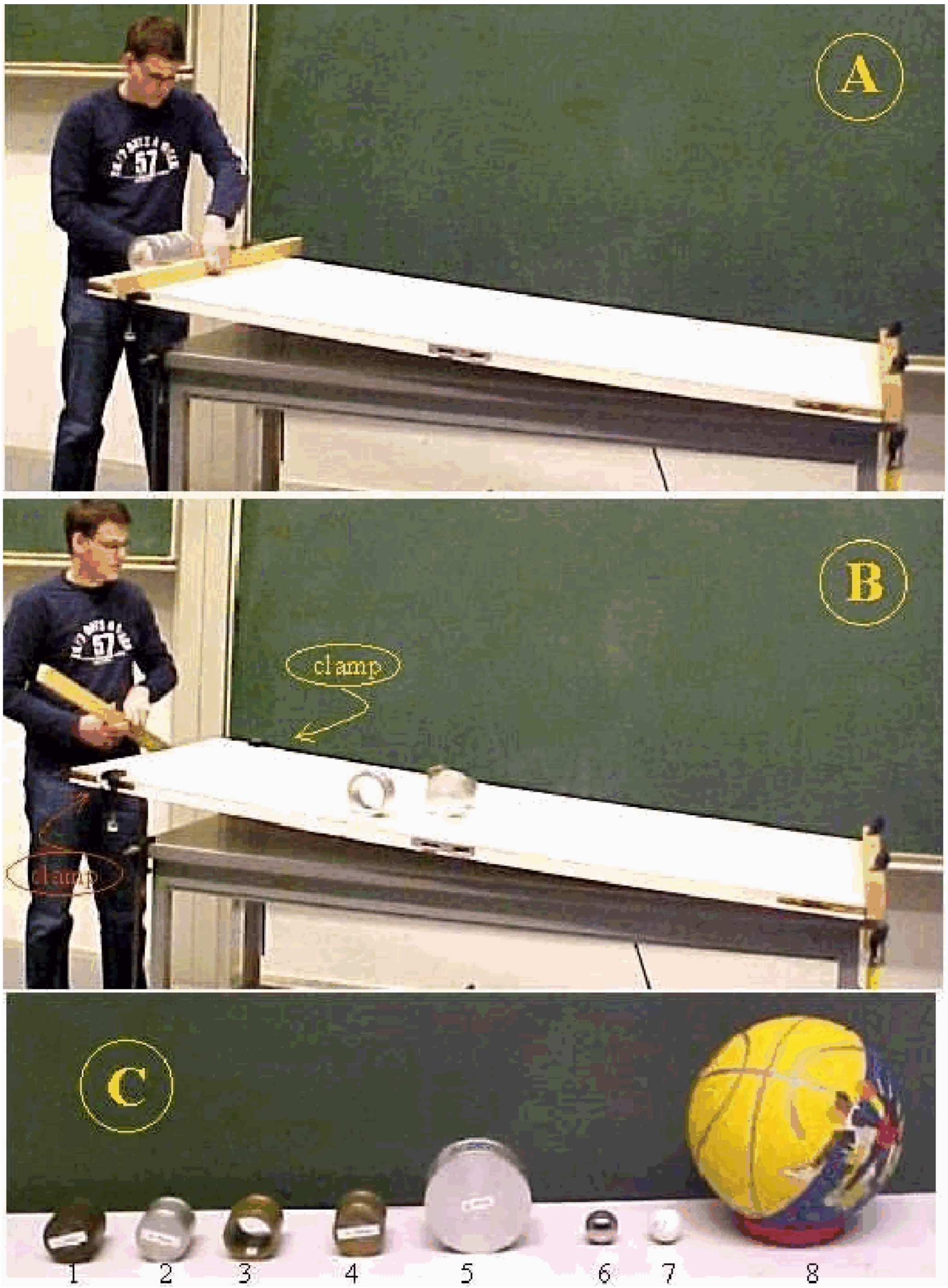


Figure 2.177: .

2.12.1.6.4 Equipment

- Inclined ramp ($l = 2$ m; we use a flat door).

- Rolling objects
    1. m_1 cilinder of wood with lead in the center ($\emptyset 60$ mm; $m = 424$ g); $C = 0.21$
    2. m_2 solid aluminum cilinder ($\emptyset 60$ mm; $m = 424$ g) $C = 0.5$
    3. m_3 hollow brass cilinder ($\emptyset 60$ mm, d = 5 mm; $m = 424$ g); $C = 0,83$
    4. m_4 solid brass cilinder ($\emptyset 60$ mm; $m = 1.3$ kg); $C = 0,5$
    5. m_5 solid aluminum cilinder ($\emptyset 120$ mm; $m = 1.7$ kg); $C = 0,5$
    6. m_6 steel ball ($\emptyset 40$ mm; $m = 230$ g); $C = 0,4$
    7. m_7 ping pong ball ($\emptyset 37.5$ mm; $m = 2$g); $C = 0,67$
    8. m_8 basketball; $C = 0.67$
- Overhead sheet with list of moments of inertia of rolling objects.
- Balance with large display.

2.12.1.6.5 Presentation

2.12.1.6.5.1 Preparation

The ramp has to be adjusted horizontally in its cross direction, using an air-level. The two clamps (see Diagram B) are placed in such a way that in starting, the shelf, while pressed against these clamps, is nicely perpendicular to the long side of the ramp. A heavy wooden beam keeps the ramp at the end of the table. This beam also stops the rolling objects.

2.12.1.6.5.2 Presentation.

Different races are presented to the students. Before each race, the mass of the racing objects is determined by placing each object on the balance. Then students are asked to predict the result of that race: Is there a winner/loser? When the answer is yes, which object will be the winner/loser?

- Race 1:

m_1, m_2 and m_3 race down the ramp together, starting at the same time. m_1 is the winner, m_3 the loser. (Most students predict the right answer. Evidently the distribution of mass is important.)

- Race 2:

m_2 and m_4 race down the ramp together. There is no winner. (Most students predict the wrong answer. Evidently mass is not important in this demonstration. It makes me remember Galileo dropping objects from the tower of Pisa, in which experiment mass has also no influence on the downward acceleration.)

- Race 3:

m_2, m_4 and m_5 race down the ramp together. They arrive together; there is no winner. (Many students don't dare to predict. Evidently radius R is of no importance in this experiment.)

Now an overhead sheet is presented to the students that shows a table of the expressions of moments of inertia of the various rolling objects. When mass m and radius R are of no importance in these downhill races then the difference will be found in the factor ahead of mR^2 in the expressions of the moment of inertia. After this observation the next races will be predicted right by (almost) all students.

- Race 4:

m_2, m_6 and $m_7 . m_6$ is the winner, m_7 the loser.

Figure 2 shows a summary. ‘

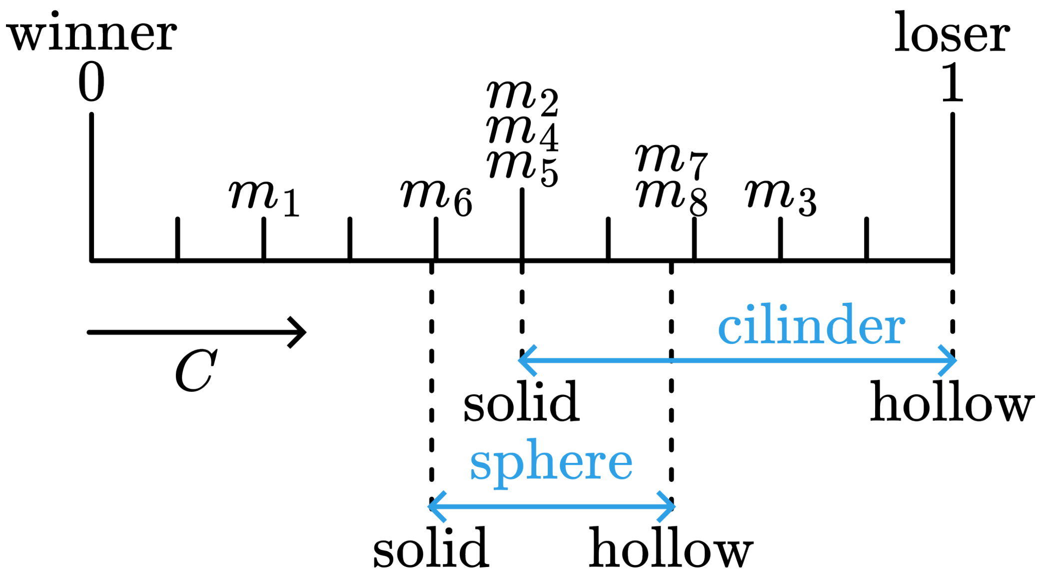


Figure 2.178: .

2.12.1.6.6 Explanation

Rolling down means translational acceleration plus rotational acceleration. The more energy is needed for rotational acceleration, the less energy is left for translational acceleration.

Conservation of energy tells us: $1/2mv_c^2 + 1/2I\omega^2 + mgh = \text{constant}$.

By $v_c = \omega R$, $h = s\sin\gamma$ and differentiating, we find $a_c = \frac{g\sin\gamma}{1+\frac{I_c}{mR^2}}$

The moment of inertia of objects with circular symmetry can be written as: $I = CmR^2$, where C is a constant. From tables we know (see Figure 2):

- solid sphere, $C = 2/5$
- solid cilinder, $C = 1/2$
- hollow sphere, $C = 2/3$
- hollow cilinder, $C = 1$
- cilinder with thickness $(R_2 - R_1)$, $C = \frac{1}{2}\left(1 + \left(\frac{R_1}{R_2}\right)^2\right)$

Using C in the expression above, we find: $a_c = \frac{g\sin\gamma}{1+C}$

The larger C, the smaller a_c. Also note that a_c does not depend on m or R!

2.12.1.6.7 Remarks

- To have a fair race you need to have a good starting procedure. We get the best start by using a shelf, blocking the objects in the starting position. Starting is done by very quickly moving the shelf away into the direction of the descending ramp.
- When racing the basketball and ping pong ball (Race 5) there is no winner. Makes sure that in starting, the basketball is not ahead of the ping pong ball.

2.12.1.6.8 Sources

- Jewett Jr., John W., Physics Begins With Another M… : Mysteries, Magic, Myth, and Modern Physics, pag. 113-114
- Young, H.D. and Freeman, R.A., University Physics, pag. 304
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 263

2.12.1.7 07 Matchbox and Wineglass

2.12.1.7.1 Aim

To show an example in which conservation of angular momentum explains the trick.

2.12.1.7.2 Subjects

- 1Q10 (Momentum of Inertia)
- 1Q40 (Conservation of Angular Momentum)

2.12.1.7.3 Diagram

Figure 2.179: .

2.12.1.7.4 Equipment

- Heavy mass (wineglass).
- String, 1 m.
- Stick ($\approx$ 50 cm long).

2.12.1.7.5 Presentation

See Diagram. The wineglass hangs straight down a few centimeters below the pencil, the matchbox is held so that its string is nearly horizontal. Now release the matchbox and ... the wineglass will not hit the floor!

2.12.1.7.6 Explanation

As the heavy mass descends and pulls the light mass towards the pencil, the rotational velocity of the light mass increases rapidly, first because it is swinging like a pendulum and secondly because for a given value of angular momentum, any decrease in radial distance must result in an increase in the angular speed: $\vec{L} = I\omega = const.$. Were it only for the pendulum motion, the light mass would swing only up to its original height. But due to the second cause of increase in angular speed, the string goes over the top of the pencil and wraps itself around it a number of times (enough to create a large frictional force). When you do the demonstration once more, the speeding up of the empty matchbox is very good observable.

2.12.1.7.7 Remarks

- We do this demonstration at the beginning of the lecture on 'moment of inertia', just to awaken students' interest in the subject. At the end of the lecture an explanation follows.

- Every now and then the demonstration fails because the matchbox hits the thread the wineglass is hanging to. The effect is that the wineglass hits the floor and breaks. So keep a spare wineglass at hand.

We always hope that the demonstration happens in this way: first a broken wineglass and next a perfect demonstration, because such a failed demonstration is better remembered by the students.

2.12.1.7.8 Sources

- Acheson, D.J. and Mullin, T., Nature, Vol.366, vol. 63, nr. 9, pag. 854-855, Comment on “A surprising mechanics demonstration”, R.E.J. Sears
- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 74

2.12.2 1Q20 Rotational Energy

2.12.2.1 02 Yo-Yo

2.12.2.1.1 Aim

To show the movement of a yo-yo and the force it exerts on the string that is holding it.

2.12.2.1.2 Subjects

- 1Q20 (Rotational Energy)

2.12.2.1.3 Diagram

Figure 2.180: .

2.12.2.1.4 Equipment

- Yo-yo.
- Force sensor.
- Data-acquisition system.
- Projector to project monitor image.

2.12.2.1.5 Presentation

We all know the yo-yo: Two circular discs with a common shaft and a string several times wrapped around it. Hold the end of the string stationary and release the yo-yo. The string unwinds as the yo-yo drops and rotates with increasing speed. When the unwrapping is completed, the yo-yo climbs again, comes to a stop and starts over again. etc.

Suspending the yo-yo to a force sensor, a registration of the tension in the string is made (red graph in Figure 2 left). When, finally, the yo-yo has come to rest, such a registration is repeated (green line in Figure 2 left).

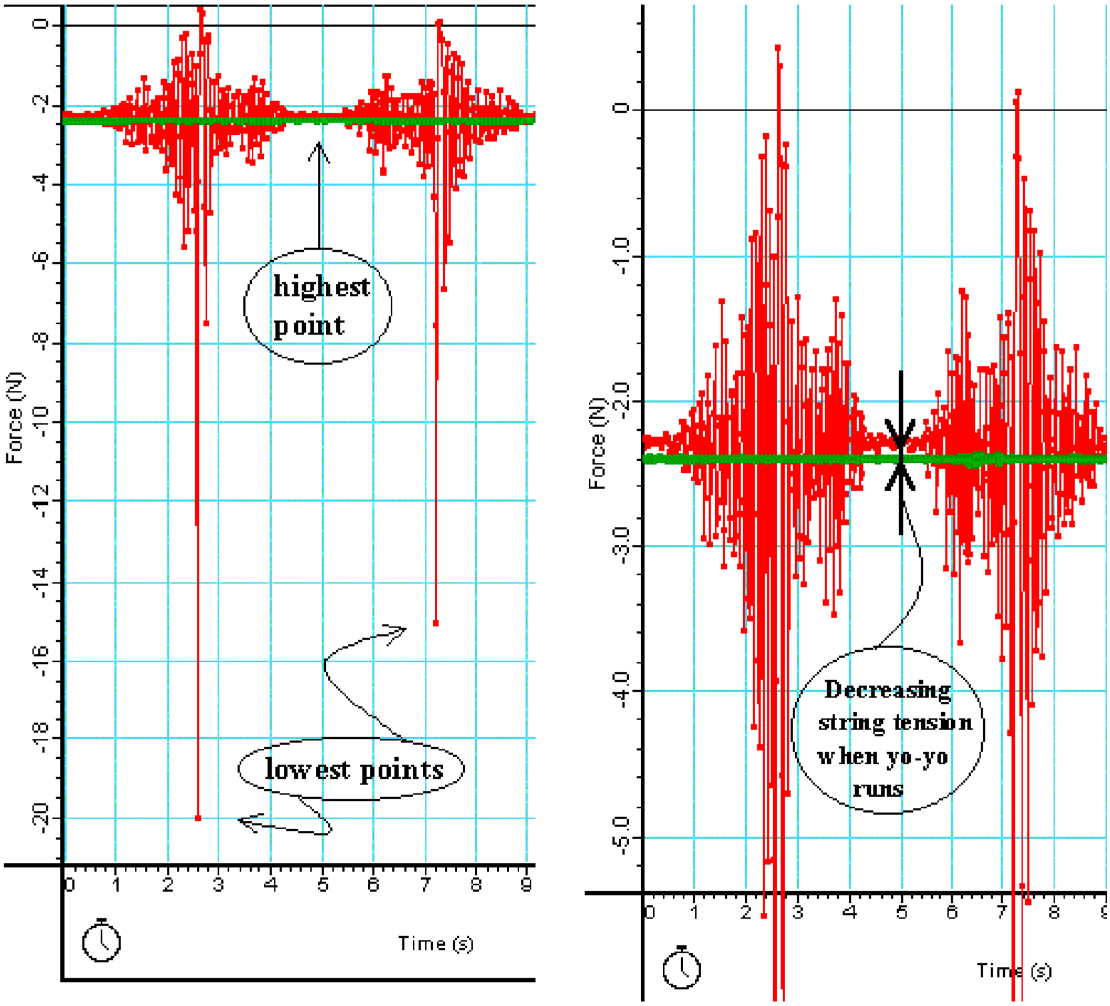


Figure 2.181: .

When studying these graphs, the jerk at the turning point is clearly observed. (Also a strong vibration.) See that the jerk at the turning point is much higher than the weight of the yo-yo.

Going from one jerk to the next, the highest position of the yo-yo is halfway between the two jerks. When a complete cycle is enlarged (see Figure 2 right), it is clear that during the complete cycle the string tension is lower than the weight of the yo-yo.

2.12.2.1.6 Explanation

The yo-yo accelerates (a) due to a force $ma = mg - F_s$(F_s being the string tension and m the mass of the yo-yo.)

When there is no string, then $F_s = 0$ and $a = g$ (free fall);

With a string, a is always smaller than g :

$a = g - \frac{F_s}{m}$

When F_s is just a little smaller than mg, then a will be very small.

The angular acceleration (α) of the roll during its fall can be found from $\alpha = \frac{\tau}{I}$, where

the net torque (τ) is given by $\tau = mg$.

The acceleration of the center of mass (a) is related to the angular acceleration of the yo-yo by $a = \alpha r$, so the yo-yo accelerates downward by $a = \frac{mgr^2}{I}$.

Our yo-yo is a simple double disc, so $I_{CM} = \frac{1}{2}mR^2$. It rolls at the circumference of the shaft (radius r), that's why $I = \frac{1}{2}mR^2 + mr^2$, and we find for the acceleration:

$a = \frac{2g}{2+\frac{R^2}{r^2}}$.

Because $R >> r, a << g$.

With our yo-yo we have $R = 150$ mm and $r = 12$ mm, so $a = 0.012$ g.

Also the string tension can be calculated now: $F_s = mg - ma$, so: $F_s = mg - 0.012mg$, showing that the string tension is just a little lower than the weight of the yo-yo.

2.12.2.1.7 Remarks

- A worthwhile observation is, that when the string is unwrapped completely and the yo-yo starts climbing again, that the yo-yo's translational velocity changes its direction ($-v$ to $+v$) but keeps its rotation in the same direction. In other words: its momentum changes direction ($-mv$ to $+mv$), but there is no change in angular momentum. The large change of momentum ($2mv$) at this point of the yo-yo's movement explains the jerk (the change of momentum takes place in a very short time).
- See also the demonstration Maxwheel in this database in order to link the measured string tension to the acceleration of the yo-yo. Usually we show these two demonstrations together.

2.12.2.1.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 186-187
- Roest, R., Inleiding Mechanica, pag. 183-185
- Young, H.D. and Freeman, R.A., University Physics, pag. 303

2.12.2.2 03 Maxwheel

2.12.2.2.1 Aim

- To show the conversion of potential energy into rotational kinetic energy and vice-versa.
- To show the effect of a large moment of inertia.

2.12.2.2.2 Subjects

- 1Q20 (Rotational Energy)

2.12.2.2.3 Diagram

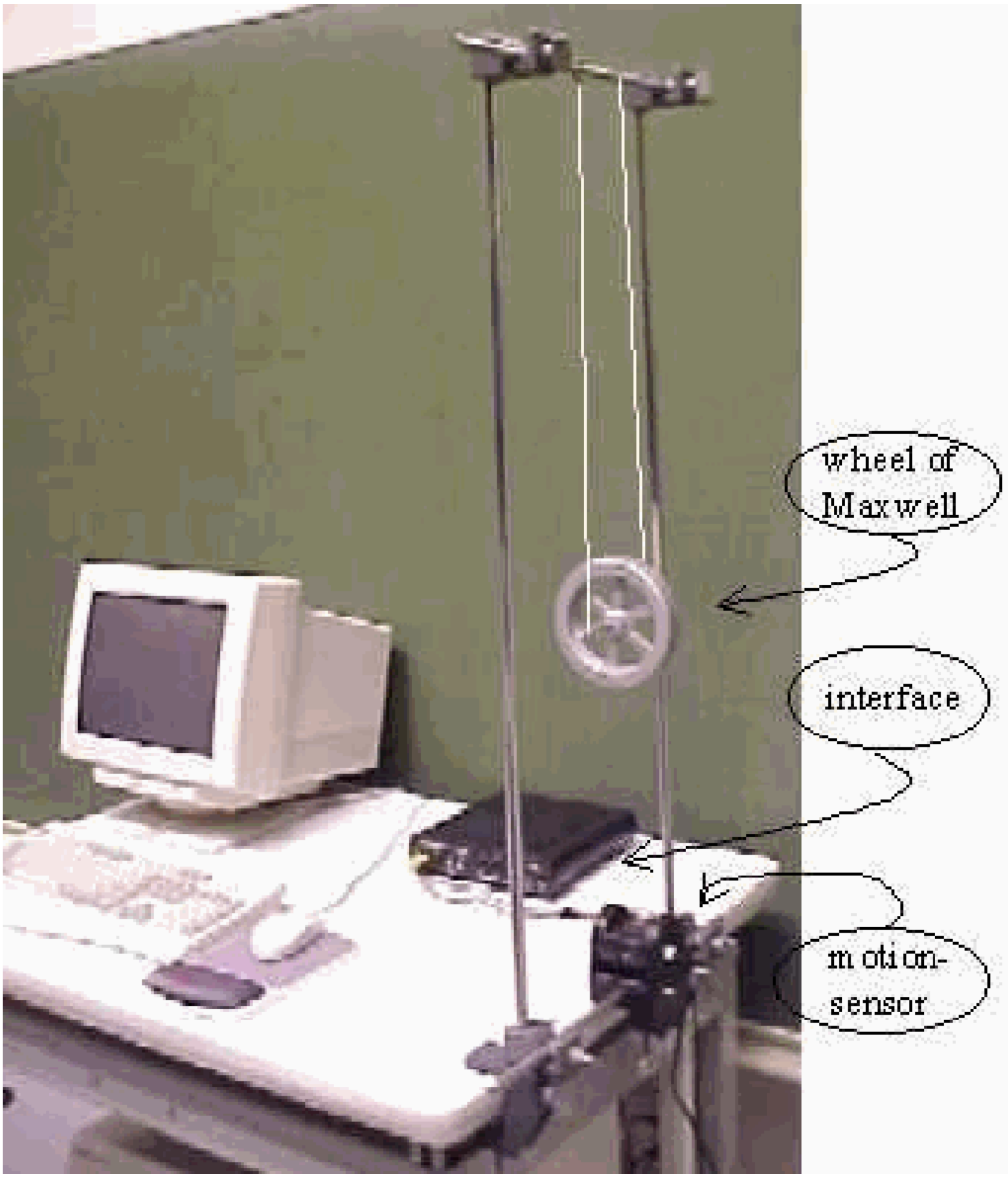


Figure 2.182: .

2.12.2.2.4 Equipment

- Wheel of Maxwell.
- Motion sensor.
- Data-acquisition system.

- Projector, to project monitor-image.
- Overheadsheet with the dimensions of the wheel.

2.12.2.2.5 Presentation

The wheel is rolled by hand to its uppermost position. When released, the wheel moves downward slowly and starts rotating. In its lowest position, the speed of rotation is maximum and the wheel rolls upward again, almost reaching the starting position. This pattern repeats itself.

Going through its lowest position, a strong jerk can be observed.

Using a motionsensor, placed under the wheel (see Diagram), the position of the wheel can be measured continuously using a data-acquisition system. Such a system enables to calculate velocity and acceleration and display these variables graphically while the wheel is running up and down (see Figure 2). After a couple of periods data-acquisition is stopped and the results can be discussed:

From the position-graph (see Figure 2) we read $\Delta h = 0.7m$, giving that E_{pot} changes an amount $\Delta E_{pot} = mg\Delta h = mg \cdot 0.7$, so around 7 m[J].

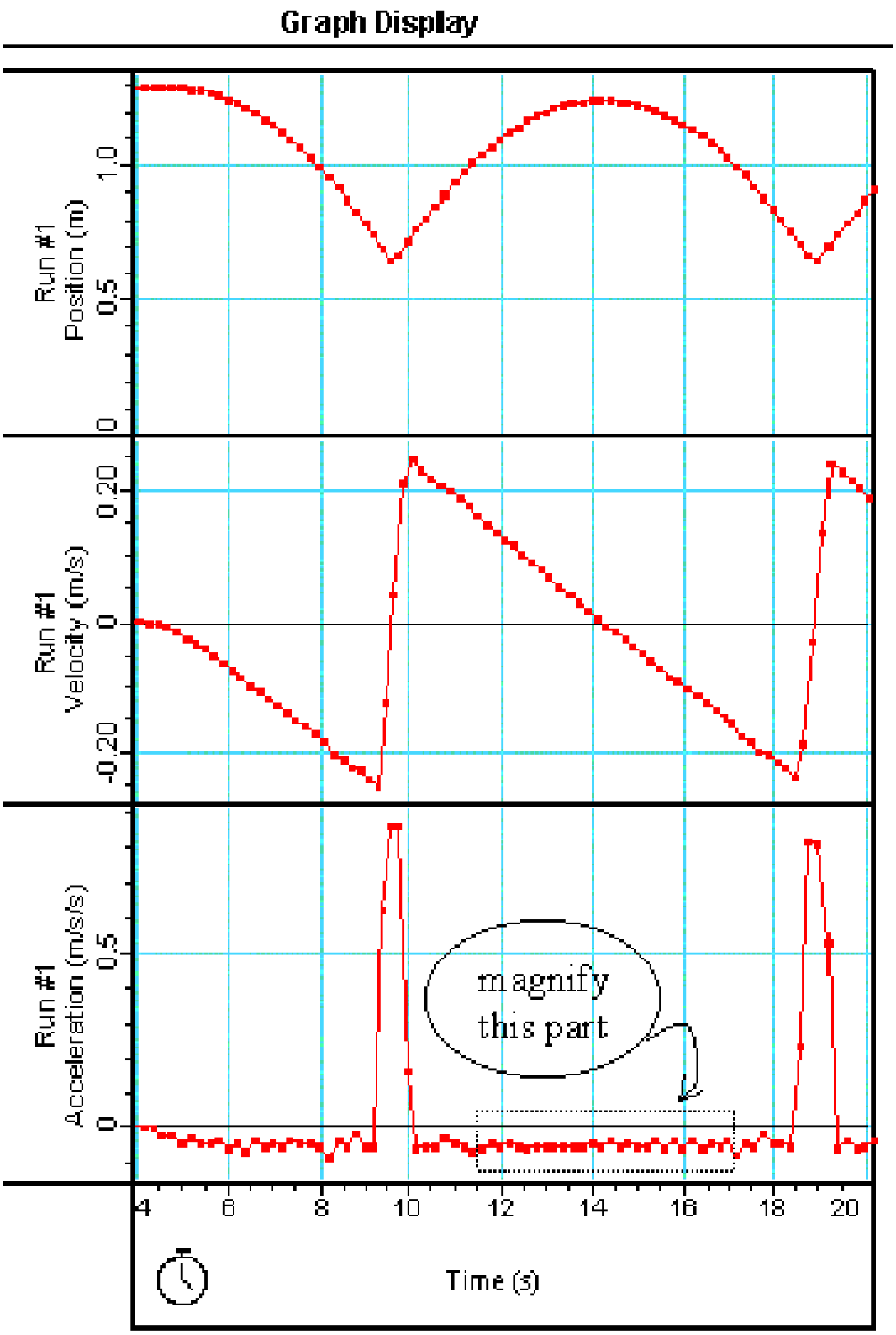


Figure 2.183: .

Out of the velocity graph, at the end of the descent we read that the absolute value of the velocity is around 0.25 m/s. So $E_{trans} = 1/2mv^2$, so around 0.03 m[J] !.

These numbers show that in this demonstration only a very small part (1/244) of the potential energy appears as translational kinetic energy. The rest will appear as rotational kinetic energy; almost all the energy is transformed into the rotation of the wheel.

Part of the graph of the acceleration is magnified in order to read the value of the acceleration. Also this experimental value can be checked by calculation (see Explanation).

2.12.2.2.6 Explanation

While moving downwards, a large portion of the potential energy is converted into rotational kinetic energy rather than into translational kinetic energy.

$\Delta E_{pot} = E_{trans} + E_{rot}$, so

$mgh = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$, with $\omega = \frac{v}{r_1}$ and $I = m(R^2 + r_1^2)$.

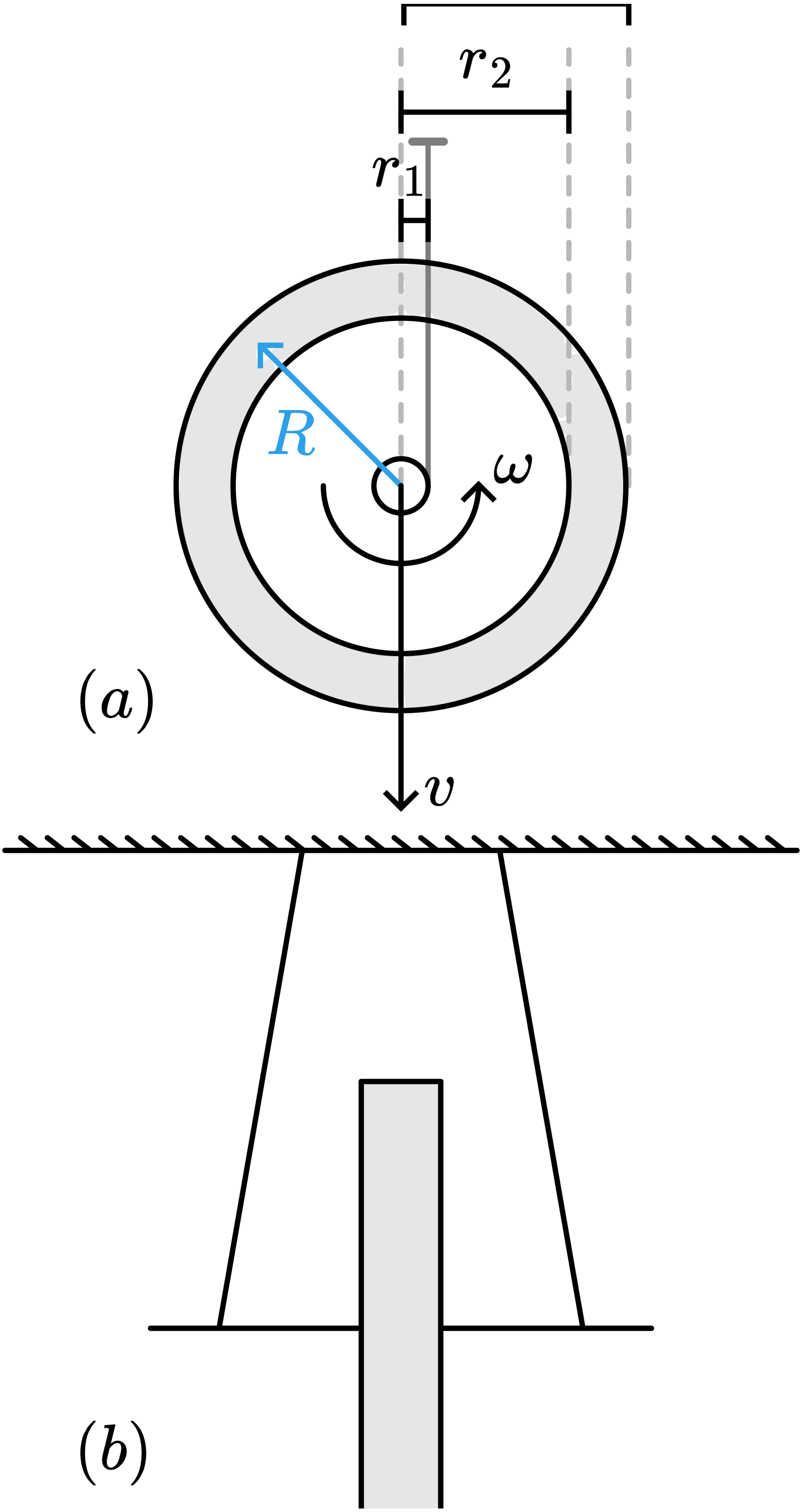

r_2
r_1
R
ω
(a)
v
(b)

Figure 2.184: .

We find:

$$E_{pot} = \frac{1}{2}mv^2 + \frac{1}{2}m\left(\frac{R^2}{r^2} + 1\right)v^2 \tag{2.28}$$

In our demonstration $r_1 = 3.5$ mm and R = 57 mm, and so we have.

$$E_{pot} = \frac{1}{2}mv^2 + 266\frac{1}{2}mv^2 \tag{2.29}$$

We see that only a very small amount of the potential energy is converted into translation, the difference being indicated by the factor 266 . The translational acceleration will be a factor 267 times smaller than g. This statement is confirmed by the acceleration-graph (see magnified part to read a significant value).

(For a quick calculation we use $R = 50$ mm and $r = 3.5$ mm, giving $R^2/r^2 = 200$.)

Passing through its lowest point, the wheel changes its momentum from $-mv$ to $+mv$ (total change of $2mv$). Quite a large force F is needed for this because the time Δt in which the change in momentum takes place is small. The impulse $F\Delta t$ is delivered by the threads in which, during half a period of rotation, a higher tension occurs.

2.12.2.2.7 Remarks

- Care must be exercised so that the two threads always have the same length and so there is no overlapping on the spindle which would change r_1. In our wheel, overlapping is prevented by giving different lengths to the spindle and suspension bar (see Figure 3B).
- When measuring r_1 do not forget the thickness of the thread!
- As an introduction to this experiment see the demonstration "Yo-yo" in this database. Doing so, the measured acceleration can be related to the force of the strings holding the wheel.

2.12.2.2.8 Sources

- Meiners, Harry F., Physics demonstration experiments, part I, pag. 286
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 214
- Roest, R., Inleiding Mechanica, pag. 183-185
- Young, H.D. and Freeman, R.A., University Physics, pag. 303

2.12.2.3 05 Rolling Down a Wide Gutter

See Rolling Down a Wide Gutter

2.12.3 1Q40 Conservation of Angular Momentum

2.12.3.1 02 Colliding Magnets

2.12.3.1.1 Aim

To show that a linearly moving mass also can possess angular momentum.

2.12.3.1.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.1.3 Diagram

Figure 2.185: .

2.12.3.1.4 Equipment

- Two large ceramic ring magnets, $\emptyset = 70$ mm.

2.12.3.1.5 Presentation

Slide across the table (or floor) one ring towards the other to make a glancing collision. The two magnets stick together and rotate about their common center of mass (see Figure 2). (No rotation is observed for head-on collisions.)

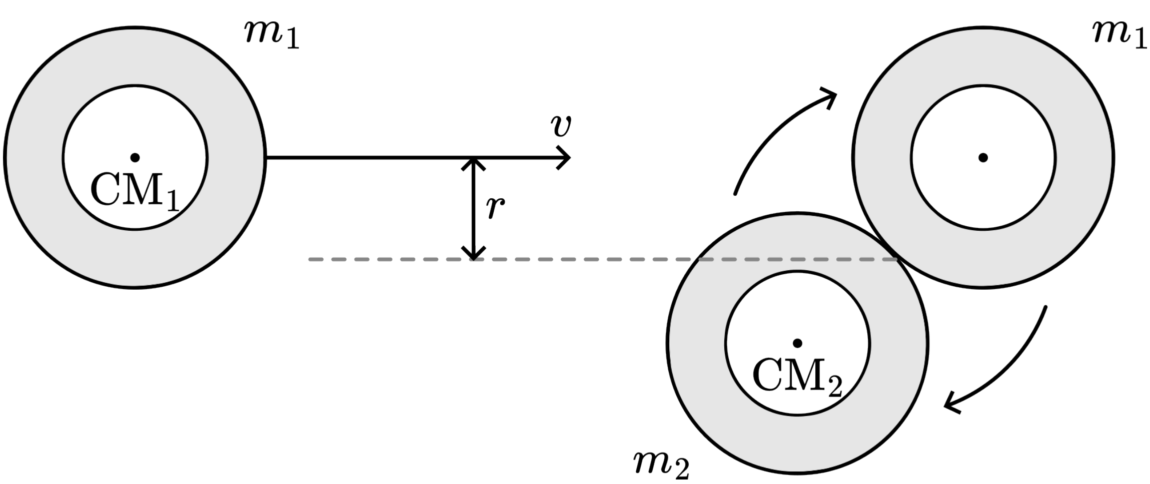


Figure 2.186: .

In the beginning there is no rotation, so the question to the students is: “From where does this rotation emerge? Is this demonstration violating the law of conservation of angular momentum?”

2.12.3.1.6 Explanation

A linearly moving object possesses angular momentum $\vec{l} = \vec{r} \cdot \vec{p}$ where $\vec{p}$ is the linear momentum and $\vec{r}$ is the position vector relative to some axis ($| \ \vec{r} \ |$ is the amount of glancing). The centre of mass of the moving magnet (CM1) has angular momentum relative to the common centre of mass of both magnets. During the whole experiment this angular momentum is conserved and due to the sticking together this angular momentum is visible as a rotation around the common centre of mass. (Also the amount of linear momentum is visible in the linear movement of the pair of magnets after the collision.)

2.12.3.1.7 Remarks

- Because the magnet is fired by hand, some practice is needed to make nice glancing collisions.
- We have taped the sides of the magnets in order to prevent damage when the magnets collide. (See Figure 2)

2.12.3.1.8 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 66
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 103

2.12.3.2 03 Matchbox and Wineglass

See Matchbox and Wineglass

2.12.3.3 04 Sweet Spot

2.12.3.3.1 Aim

To show where a batter needs to hit a ball in order to transfer maximum energy to it.

2.12.3.3.2 Subjects

- 1M40 (Conservation of Energy) 1Q40 (Conservation of Angular Momentum)

2.12.3.3.3 Diagram

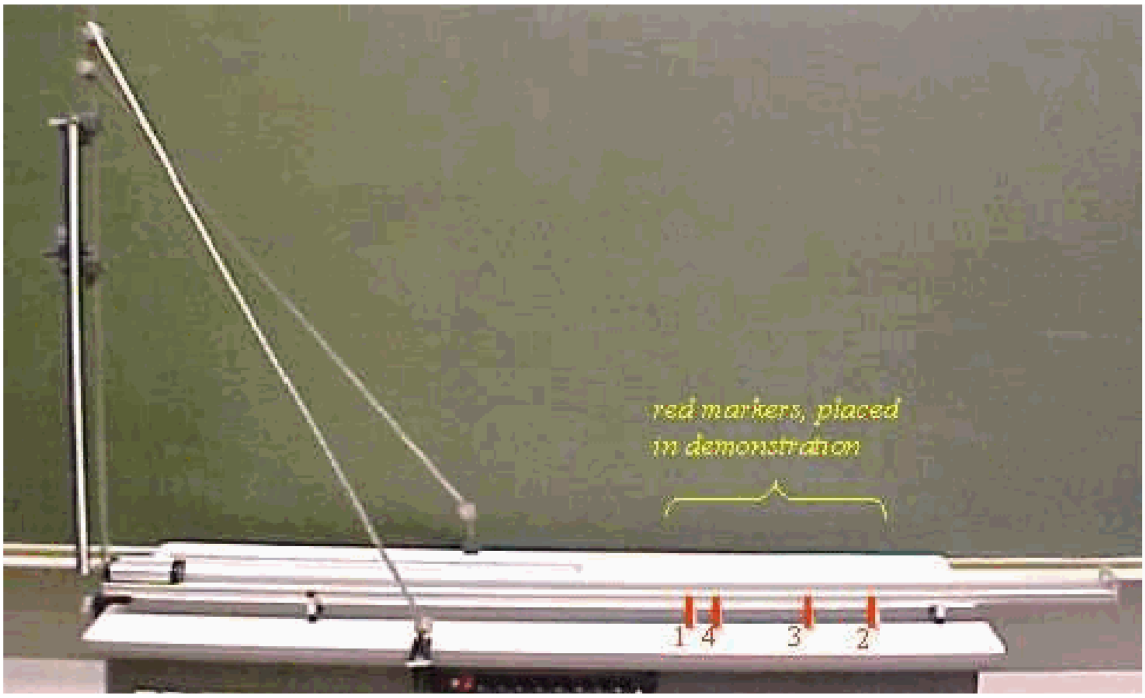


Figure 2.187: .

2.12.3.3.4 Equipment

- 2.2 m track (PASCO-ME9452) with end stop.
- Plunger cart (PASCO-ME9430), $m = .51$ kg. The plunger is connected to a compression spring (see Figure 3)
- Meterstick, pertinax, $m = .42$ kg.
- Meterstick, aluminum, $m = 1.64$ kg.
- Clamping material to fix metersticks as pendulums and to limit its initial amplitude (see detail in Figure 2).
- 4 wooden markers, triangular shaped.

2.12.3.3.5 Presentation

In the demonstration Percussionpoint it is shown to the students that a ball hitting a baseball bat will cause no impulse to your hands when you hold the bat at the percussion point. While presenting this demonstration, students often ask if this situation is also the “best” point for hitting the ball, meaning: where do we need to hit the ball to transfer maximum kinetic energy to it. Demonstration will show that this so-called “sweet spot” is not the same as the one related to the percussion point. Set up the demonstration as shown in the Diagram. The meterstick-pendulum has a limited amplitude thanks to a little bar functioning as a stop (see Figure 2). Clamp A and B shown in this figure can be used to shift the complete pendulum-system up and down. This makes it possible to choose where the meterstick-pendulum will hit the plunger cart.

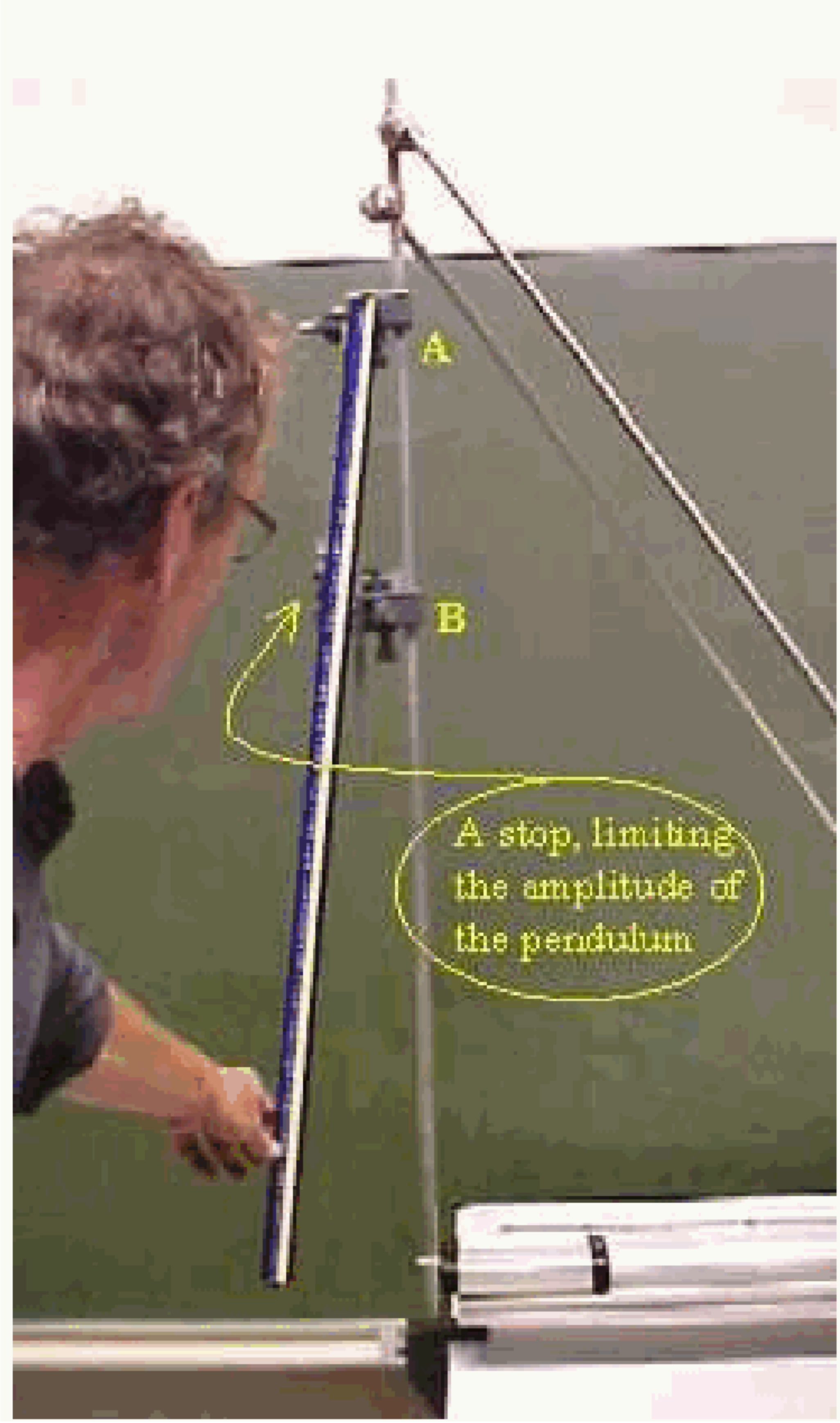


Figure 2.188: .

First we use the pertinax meterstick. The stick hits the plunger of the cart at around 25 cm distance from its point of suspension. After the collision, the cart moves along the track and stops at point 1 (see Diagram). This distance is a measure for the amount of kinetic energy the cart got initially at launching. A marker is placed at this point. The procedure is repeated for the stick hitting at 50,67 (corresponding to the percussion point) and 100 cm. The markers 2, 3 and 4 in the Diagram show the respective distances traveled by the cart. Clearly, the second situation imparts most kinetic energy to the cart, and not the one hitting at the percussion point (marker 3). The sequence is repeated, but now also the movement of the meterstick after collision is observed. Students will observe that at 25 cm, the meterstick continues swinging in the same direction after the collision, while at 100 cm the meterstick bounces back. Asking what will happen at around 50 cm will make them easily predict that the meterstick will stand still after the collision. Next this can be verified.

The whole experiment can be repeated with the heavier aluminum stick. This will show a sweet spot at the end of the stick (100 cm).

2.12.3.3.6 Explanation

See Figure 3.

Supposing that the collision is completely elastic, we apply conservation of angular momentum and conservation of energy.

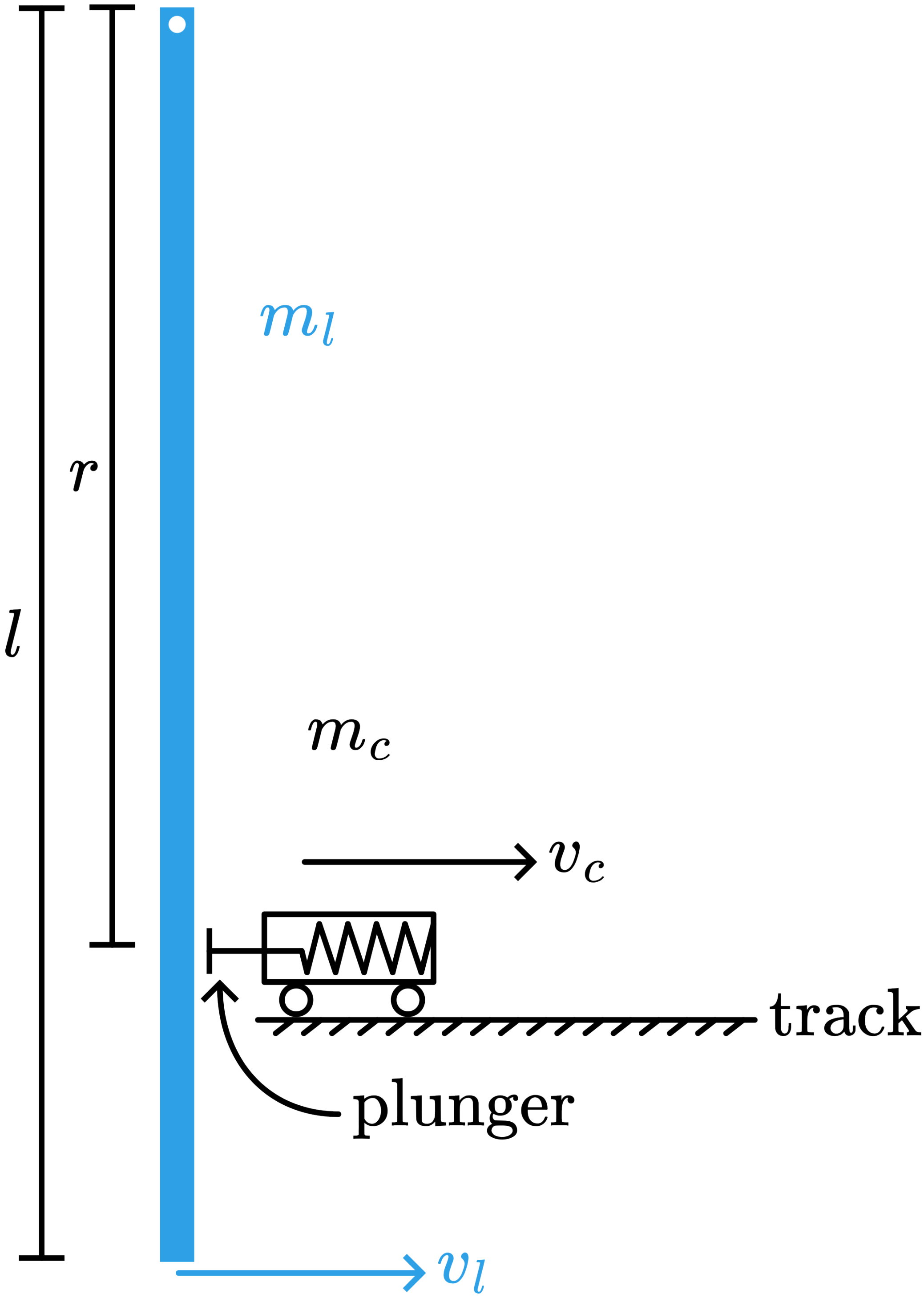


Figure 2.189: .

Conservation of angular momentum: $\frac{1}{3}m_l l v_l = \frac{1}{3}m_l l v_l' + m_c r v_c$ (v' being the velocity of the meterstick after collision)

Conservation of kinetic energy: $\frac{1}{6}m_l v_l^2 = \frac{1}{6}m_l v_l'^2 + \frac{1}{2}m_c v_c^2$.

In this elastic collision the meterstick will have transferred all its kinetic energy to the cart if after the collision $v' = 0$. Then the equation of angular momentum gives:

$v_c = \frac{1}{3}\frac{m_l}{m_c}\frac{l}{r}v_l$, and this combined with the energy-equation: $\frac{1}{6}m_l v_l^2 = \frac{1}{2}m_c v_c^2$ will give

$r = \sqrt{\frac{1}{3}\frac{m_l}{m_c}}l$. So the point on the stick of maximum energy transfer (sweet spot) depends on the mass-relationship between stick (baseball bat) and cart (ball).

Applying the masses of the meter sticks and cart used in our demonstration we find $r_{pertinax} =$ 52 cm and $r_{aluminum} = 103$ cm (in correspondence to our presentation).

2.12.3.3.7 Remarks

- Repeating the same situation a couple of times will show a distribution in the results of how far the cart rolls before it stops. In our demonstration this distribution is not disturbing the "one-run" presentations. However, take care not to take the different r-distances too close to each other.
- As $r = \sqrt{\frac{1}{3}\frac{m_l}{m_c}}l$ shows, the sweet spot and percussion point will be the same distance r at $m_c = \frac{3}{4}m_l$.
- The vertical shafts are not round but square. This enables easy positioning when shifting a pendulum up or down.

2.12.3.3.8 Sources

- PASCO scientific, Instruction Manual and Experiment Guide, pag. ME9430, exp.5

2.12.3.4 05 Balls on a Rotating Ramp

2.12.3.4.1 Aim

To show conservation of angular momentum.

2.12.3.4.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.4.3 Diagram

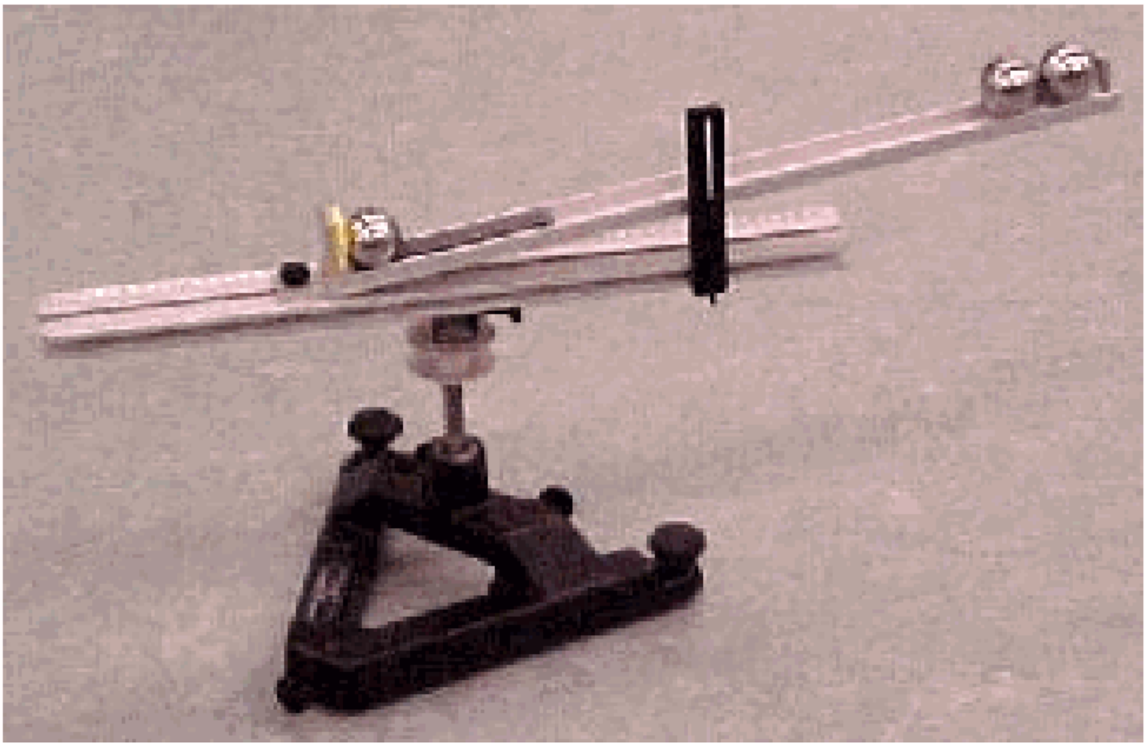


Figure 2.190: .

2.12.3.4.4 Equipment

- Rotating platform.
- Ramp.
- 3 steel balls (we use: $d = 37.5$ mm).
- (Video camera + monitor).

2.12.3.4.5 Presentation

The ramp is mounted on the platform. The steel balls are placed on it and the ramp pivot is shifted until the middle ball is at the center of rotation. The ramp is given minimum angle (about 9 degrees) and is fixed. The three steel balls are held at the top of the ramp against the post and the platform is given a rotation fast enough so that no balls roll down the ramp.

Very slowly the speed of rotation reduces and after some time the lowest ball rolls down the ramp. At the same time it can be observed that the angular speed of the platform increases.

It takes quite some time before the platform slows down enough to make the second ball roll down the ramp. Again the angular speed increases. The last ball makes a similar performance, only now the increase in angular speed is even more visible.

2.12.3.4.5.1 Extra:

Careful observation (do the demonstration a second, third, ... time) makes it possible to see also the next phenomena:

1. The first ball descends faster than the last ball does.
2. The downward acceleration on the ramp shows itself especially in the second part of its run: there is an increase in linear acceleration along the ramp.
3. The last ball descends in steps. During its descent it even goes upward on the ramp every now and then! The ball is oscillating down the ramp. This effect is shown more clear when the slope of the ramp is decreased

2.12.3.4.6 Explanation

The three balls and the track form a system. If there is no external torque on the system, the total angular momentum of the system will not change as a ball rolls down the ramp. As one ball rolls down the ramp, the rotational inertia of the system decreases, resulting in an increase in angular speed as angular momentum does not change. The angular speed at which a ball will roll down the ramp is determined by the distance the ball is from the axis of rotation. So, as the rotating platform slows due to friction, the innermost ball will fall first, while the other two balls stay in place because they are at a greater initial radius. But since the platform speeds up as the first ball rolls down, it will take even longer before the second ball begins to roll down.

2.12.3.4.6.1 Angular acceleration:

Since $L = /\omega =$ constant, we see that ω depends on $/$. A change in ω is given by a change in I: $d\omega = -\frac{L}{I^2} dI$. This shows that the largest change in ω is obtained at low $/$-values. This is when a descending ball approaches the axis of rotation. So, the largest angular acceleration is obtained in the end of the run down the ramp. This also explains why the last ball causes the largest change in ω, since / then approaches its lowest value.

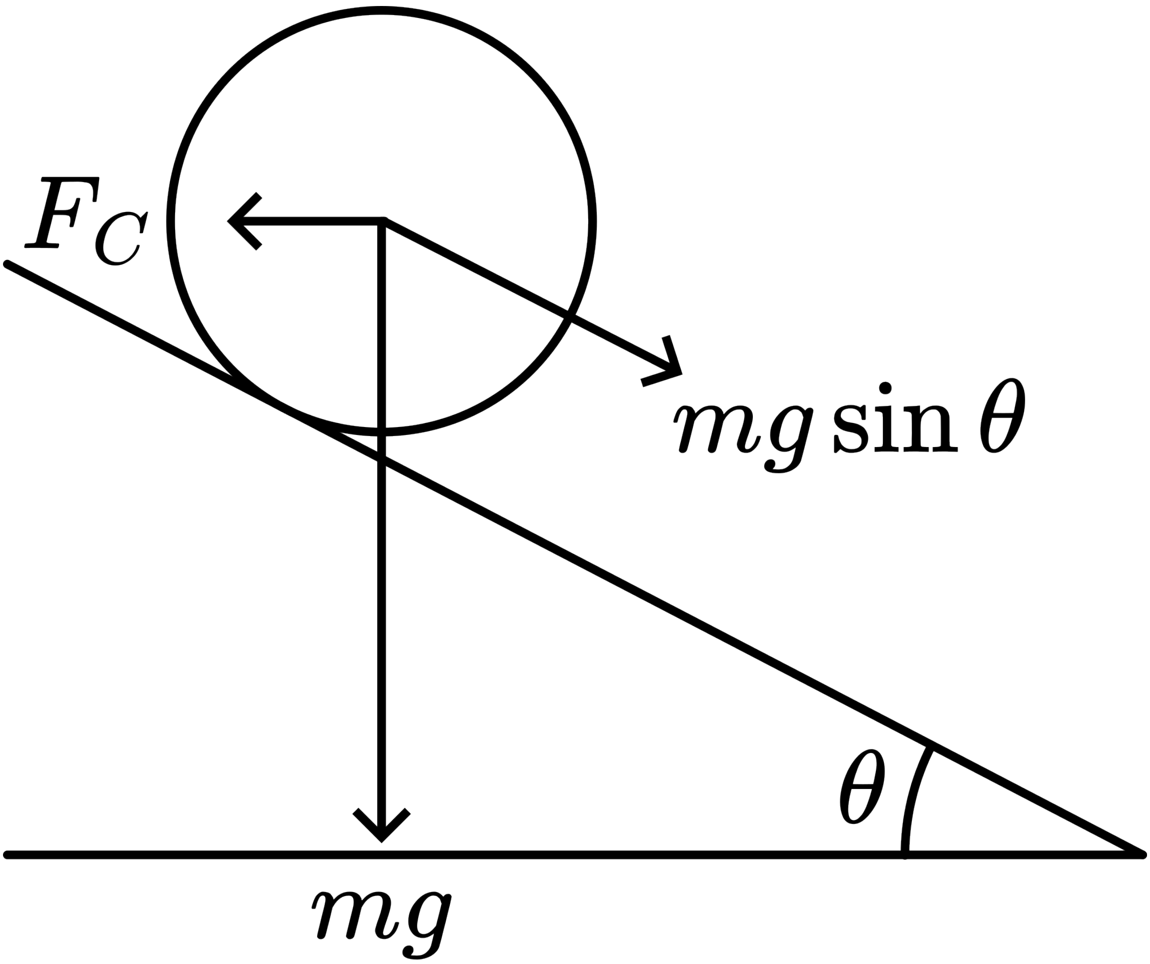


Figure 2.191: .

2.12.3.4.6.2 Acceleration along the ramp:

The centrifugal force (F_C) acting on the ball is given by $F_C = mR\omega^2$ (R being the perpendicular distance from the axis of rotation to the center of the ball). The force on the ball along the ramp is $F_r = mg\sin\theta - \cos\theta$ (see Figure 2). So:

$F_r = k - mR\omega^2\cos\theta$. When rolling down, R reduces, but at the same time ω increases: $L = I\omega =$ constant; $I = mR^2$, so: $mR^2\omega = L, \omega = \frac{L}{mR^2}$. This gives for F_r :

$F_r = k - \frac{C}{R^3}$

When R is large, F_r is small and the acceleration along the ramp will be small. When R is small, F_r is large and the acceleration along the ramp will be large (see points 1 and 2 of the extra presentation).

It can also happen that the ball moves down the ramp 'too much', due to its linear inertia along the ramp. Then the rotation of the platform speeds up that much that due to the increase in centrifugal force the ball moves upwards again! Then the ball 'oscillates' down the ramp (see point 3 of the extra presentation).

2.12.3.4.7 Remarks

It is necessary to carefully level the platform before performing the demonstration. If the rotating platform is not level, the performance will be substantially affected.

2.12.3.4.8 Sources

- PASCO scientific, Instruction Manual and Experiment Guide, pag. 13.

2.12.3.5 06 Counter Rotating Disks

2.12.3.5.1 Aim

Showing that two disks spinning in opposite directions at the same angular speed add up to zero angular momentum

2.12.3.5.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.5.3 Diagram

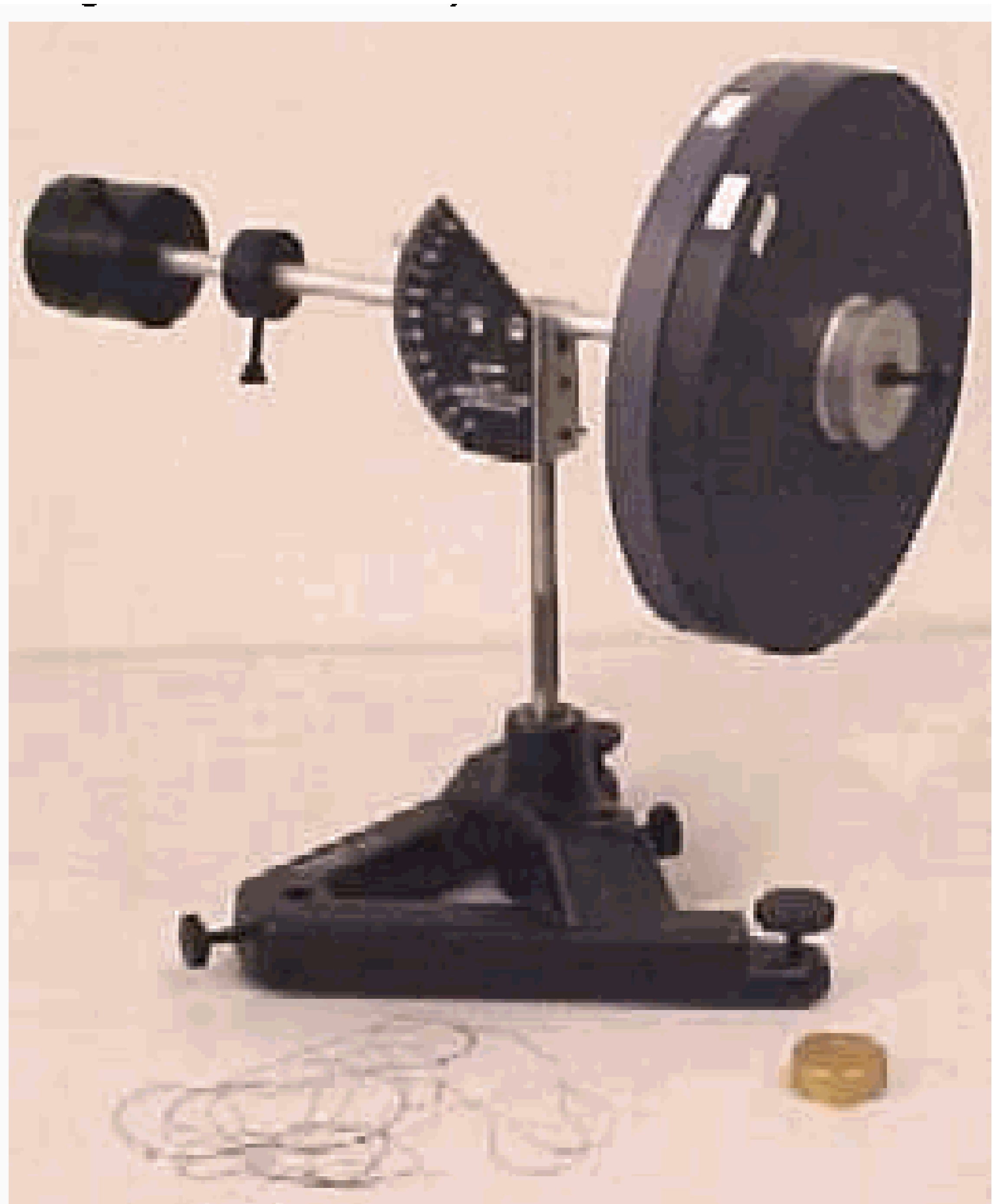


Figure 2.192: .

2.12.3.5.4 Equipment

- Demonstration gyrosCope.

- Accessory disk and counterweight.
- Thread, approximately 2.5 m long with loops in the ends.
- Slotted mass (150 g).

2.12.3.5.5 Presentation

The gyroscope is set up with two rotating disks and has its counterweights adjusted until the gyroscope is balanced (see Diagram). Show that the gyroscope is statically balanced in any orientation.

Unbalance the gyroscope by placing the slotted mass on the end of the axis and show that, when released, the disk-side falls downward vertically.

Hold the gyroscope and place the loops of thread around the pulleys. Both disks are made spinning in the same direction. Releasing the gyroscope will show that there is precession.

Stop the disks, hold the gyroscope and place the loops of thread around the pulleys in such a way that both disks are made spinning in opposite directions (and at the same speed). Ask your students what will happen when you release this “gyroscope”. On releasing, there is no precession at all: the disk-side falls downward vertically as the gyroscope did when it was not spinning at all.

2.12.3.5.6 Explanation

The opposite rotating disks have opposite angular momenta. Having the same speed these momenta add to zero. When a force or torque is applied the resulting movement is not influenced by an angular momentum that equals zero.

2.12.3.5.7 Remarks

- When in the last demonstration one of the opposite rotating disks is slowed down, precession is there again. Reduce the speed of one of the disks by hand and ask your students in which direction precession will occur.
- Both disks can be given the same angular speed by winding the same amount of turns around the pulleys

2.12.3.6 07 Dumb-Bell

2.12.3.6.1 Aim

To show that change in direction of angular momentum needs a torque.

2.12.3.6.2 Subjects

- 1Q40 (Conservation of Angular Momentum) 1Q60 (Rotational Stability)

2.12.3.6.3 Diagram

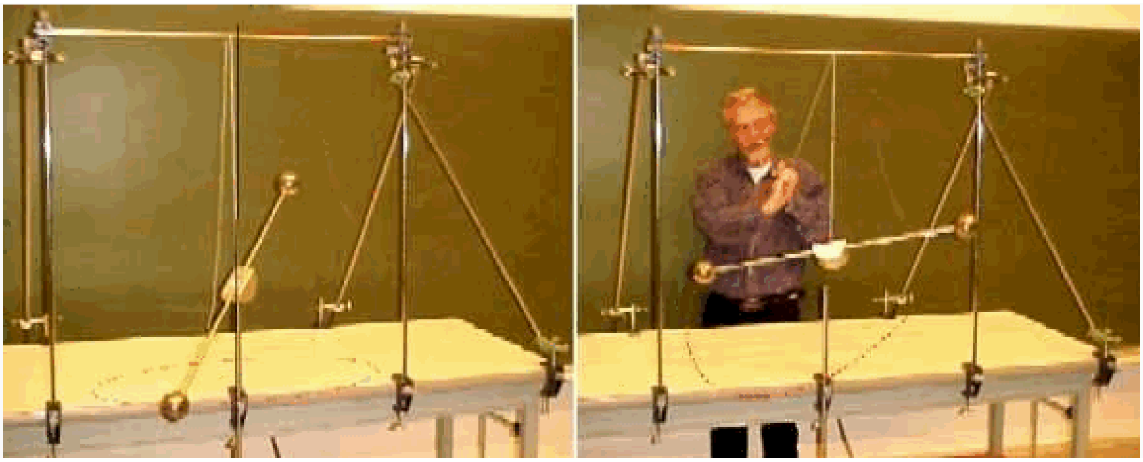


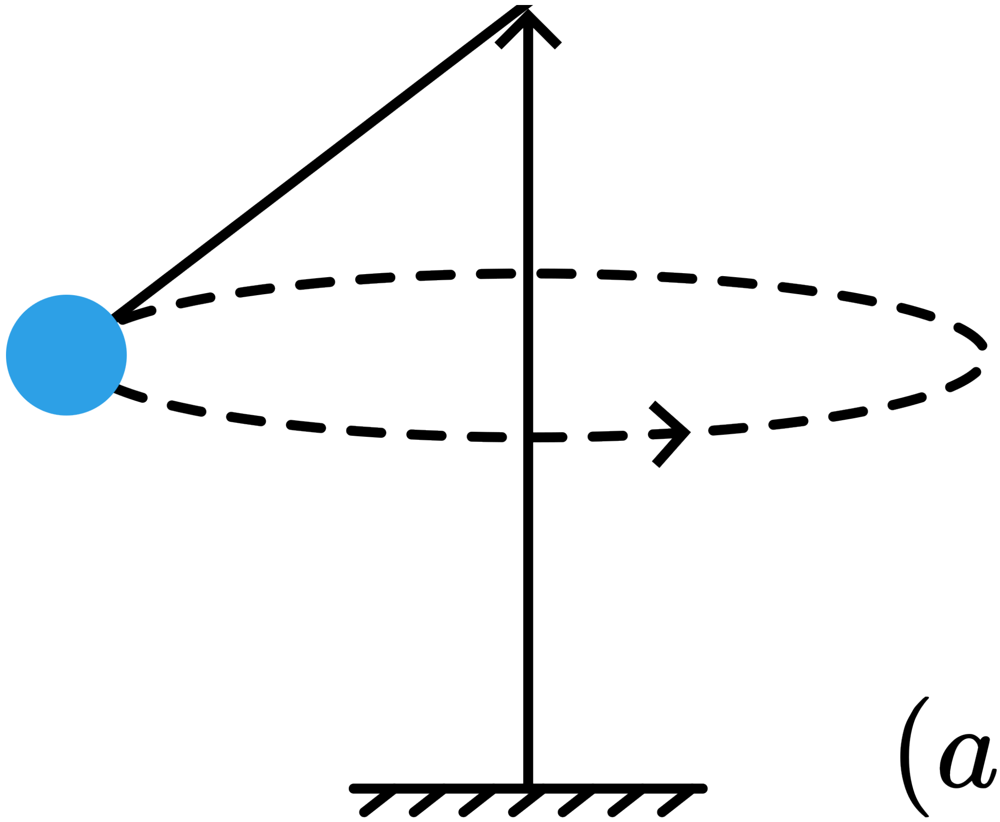
Figure 2.193: .

2.12.3.6.4 Equipment

- Dumbbell pivoted on a support at a non-symmetry axis through the center of mass.
- Frame in order to lift off the dumbbell from the support

2.12.3.6.5 Presentation

The dumbbell is placed on top of the support. A thread is fixed to the center of mass and thrown over the top of the frame and hold slack, away from the dumbbell. The dumbbell is given a rotation by hand. Make the students observe that the two masses of the rotating dumbbell describe two horizontal circles (Figure 2a).



(a)

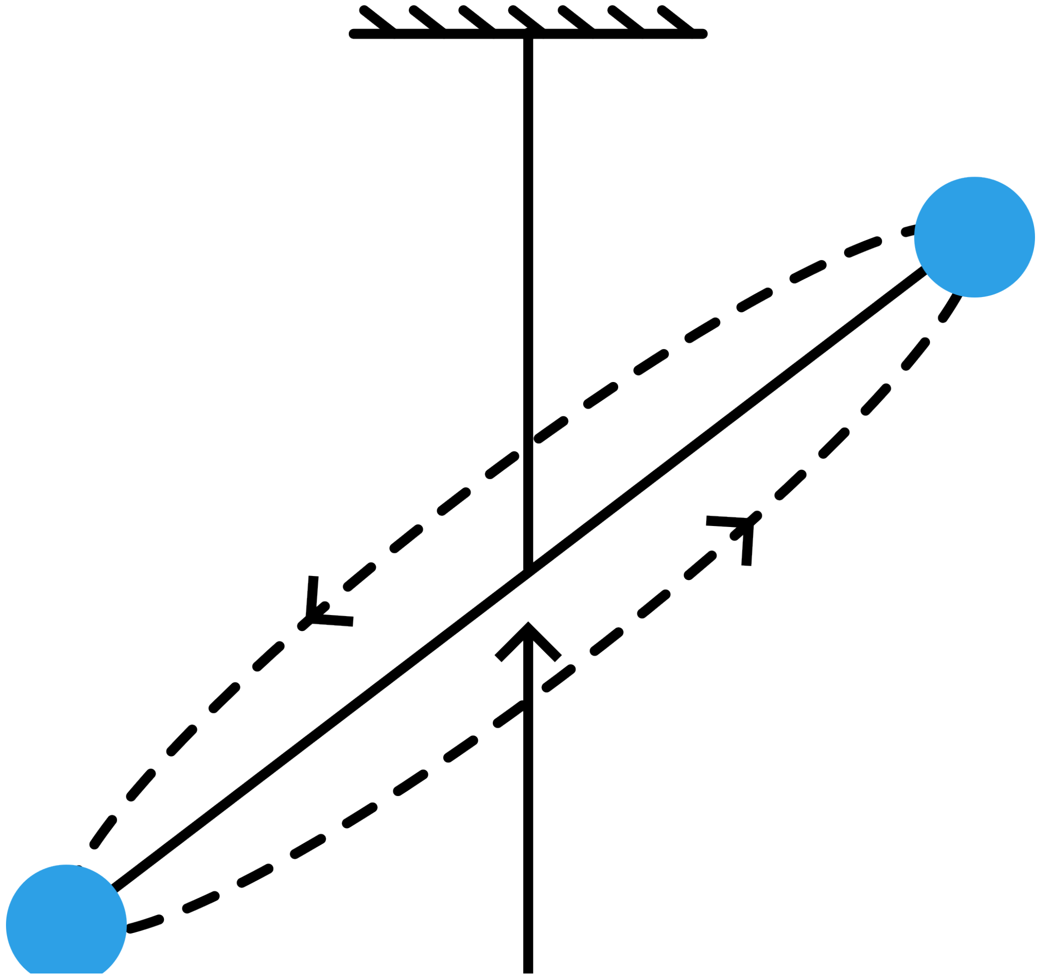


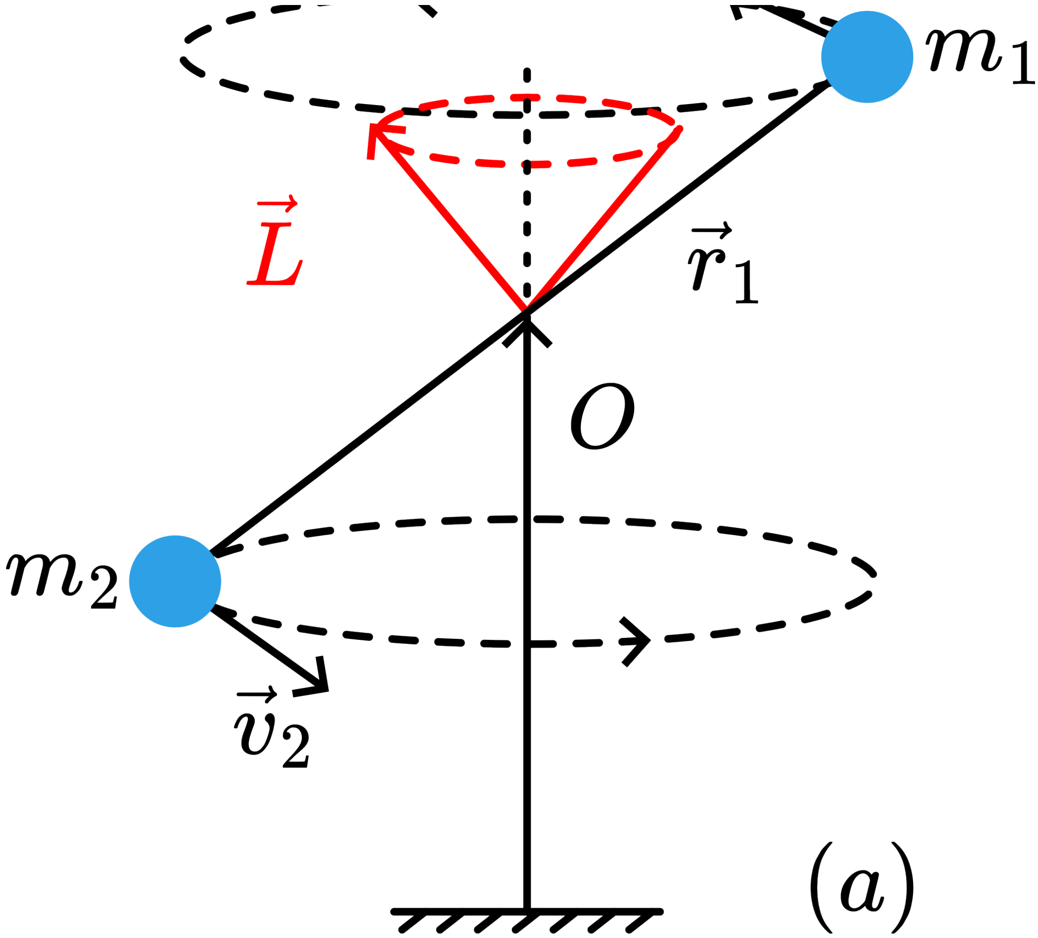
Figure 2.194: .

Lift the dumbbell from its support. Almost immediately it can be seen that now the rotation of the dumbbell takes place in one slanting plane (Figure 2b).

Before lift-off it can be seen that while the dumbbell rotates, the vertical support shaft oscillates/shakes/wobbles strongly and yet it is a thick and strong steel shaft!

2.12.3.6.6 Explanation

The dumbbell-shaped object rotates about a non-symmetry axis through the center of mass O. Figure 3a shows the angular momentum vector of the rotating dumbbell relative to O at the instant drawn and while the dumbbell rotates the angular momentum vector describes a cone. So the angular momentum changes direction continuously. To do this a torque is needed. The ballbearing support at O gives that torque: A centripetal force F_c is needed to move m around in a circle (see Figure 3b). This needs a torque $\vec{F}_c \times \vec{r}$. (Also $\overrightarrow{M} = \frac{d\vec{L}}{dt}$ gives this result.)



(a)

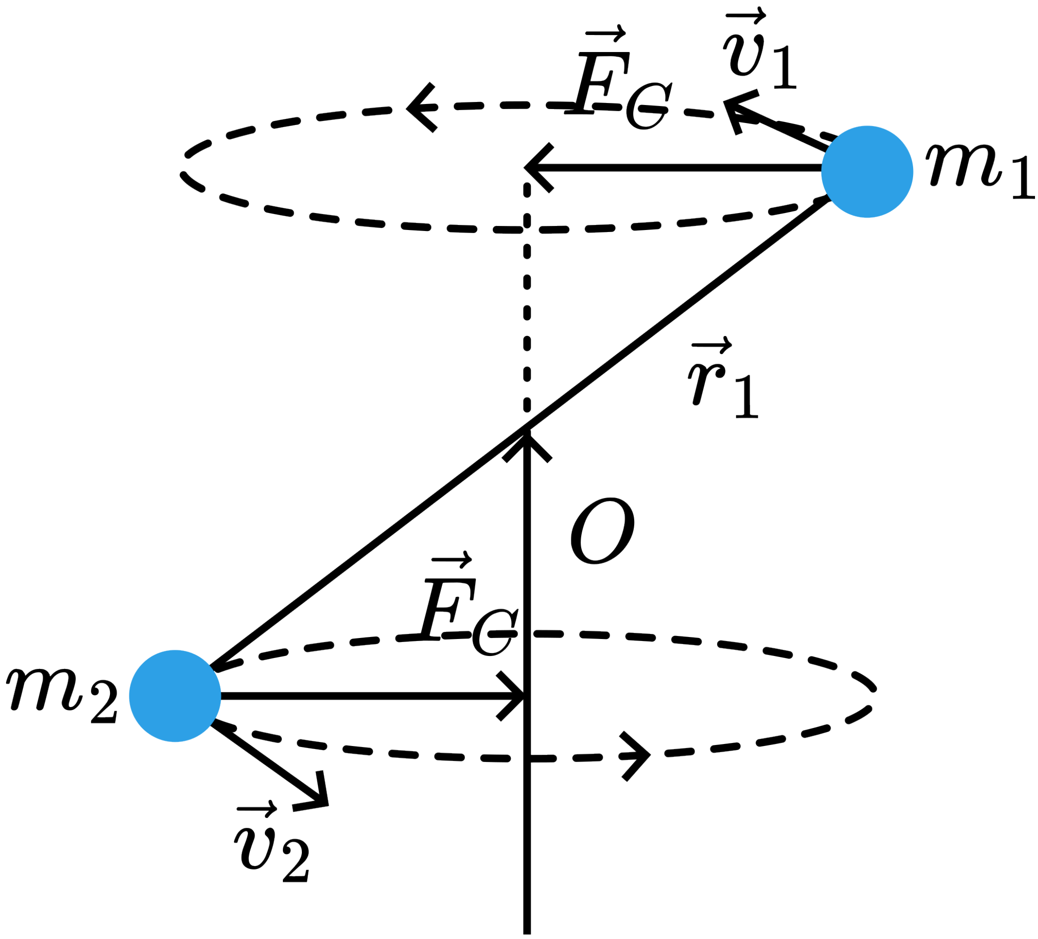


Figure 2.195: .

This torque also makes the support shaft wobble. The dumbbell needs to rotate in such a way as the direction of $\vec{L}$ dictates at the moment of lift-off.

2.12.3.6.7 Remarks

- The wobbling of the support shaft can also be described in terms of dynamical unbalance: The angular momentum ($\vec{L}$) and the angular velocity ($\vec{\omega}$) are not parallel.

2.12.3.6.8 Sources

- Alonso, M/Finn, E. J., Fundamentele Natuurkunde, part 1, Mechanica, pag. 215-217
- Borghouts, A.N., Inleiding in de Mechanica, pag. 221-223
- PSSC, College Physics, pag. 352-355 and 366-367
- Roest, R., Inleiding Mechanica, pag. 212-213
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 287

2.12.3.7 08 How an Astronaut can Turn Around in Free Space

2.12.3.7.1 Aim

To explain a phenomenon using conservation of angular momentum.

2.12.3.7.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.7.3 Diagram

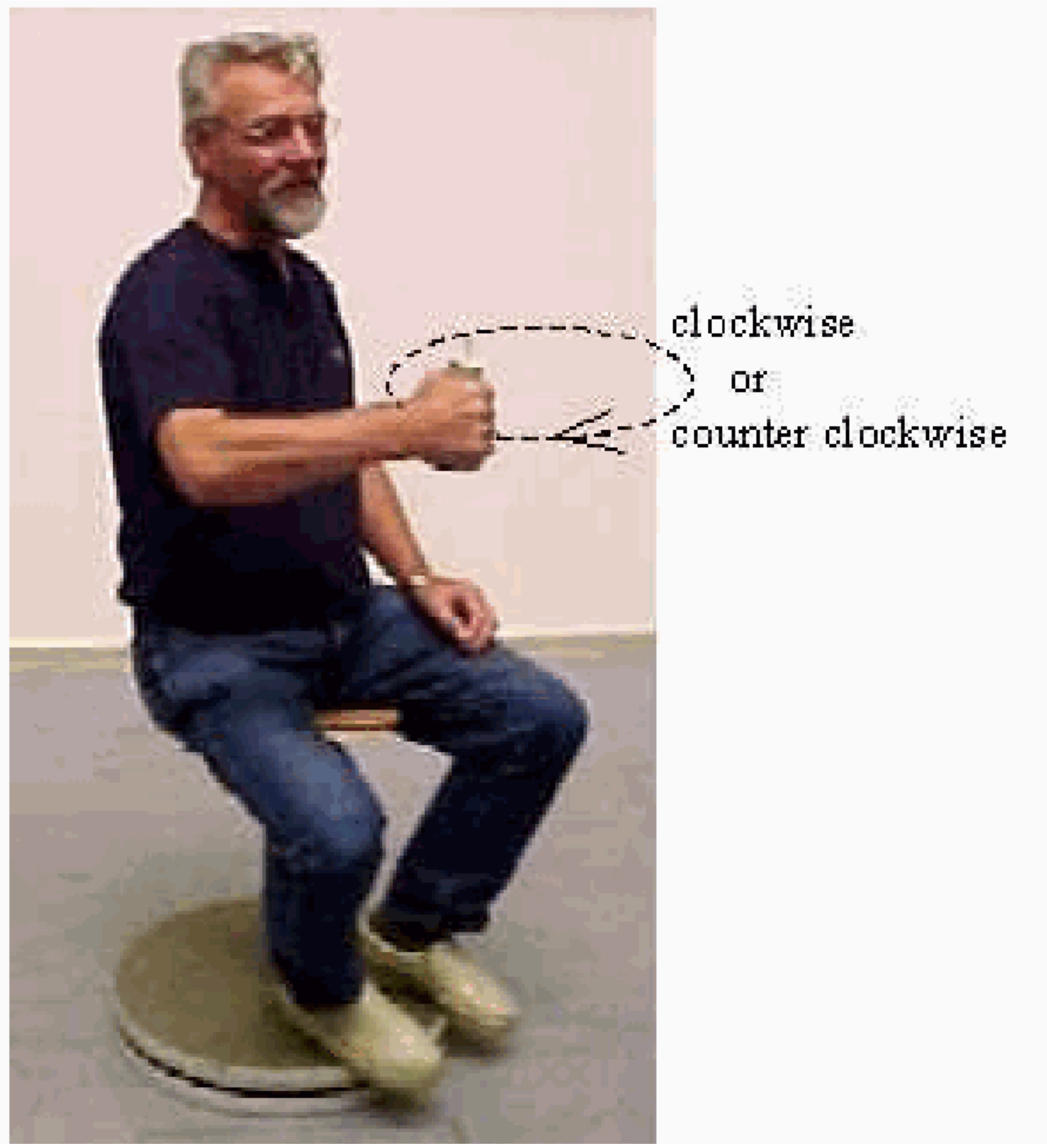


Figure 2.196: .

2.12.3.7.4 Equipment

- Swivel chair
- (mass of 1 — or 2 kg)

2.12.3.7.5 Presentation

The demonstrator, holding the heavy mass in his hand sits on the swivel chair and, while stretching his arm, moves the mass in a horizontal plane from right to left and vice versa. The swivel chair always displaces itself in the opposite direction. The demonstrator can also rotate the mass in a circle in the horizontal plane, continuously making complete turns. Then the swivel chair turns round continuously in the opposite sense

2.12.3.7.6 Explanation

During this demonstration no external forces are applied. In the beginning the total amount of angular momentum is zero and conservation of angular momentum tells us that this remains so. So as the mass is given angular momentum in one direction, something else must acquire equal angular momentum in the opposite direction: that is you and the swivel chair. This can be observed at any instant. Also the moment the demonstrator stops his arm movement, the movement of the swivel chair stops.

2.12.3.7.7 Remarks

- The demonstration can also be performed without holding a mass (no astronaut will hold one), but then the bearing of the swivel chair needs to be of a high quality (very low friction; that is true for an astronaut) and you will need to make more turns by hand to make the swivel chair go round one time.
- This demonstration also “explains” how a cat can turn around in midair and land on his paws.
- Also Newton’s third law can be observed in this demonstration.

2.12.3.7.8 Sources

- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 103-104
- Leybold Didactic GmbH, Gerätekarte, pag. 33166/-69, 33166
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 74

2.12.3.8 09 Playing Tennis

2.12.3.8.1 Aim

To show an example of conservation of angular momentum.

2.12.3.8.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.8.3 Diagram

Figure 2.197: .

2.12.3.8.4 Equipment

- Revolving platform.
- Tennis racket (or baseball bat)

2.12.3.8.5 Presentation

The demonstrator stands upon the revolving platform and swings the tennis racket (baseball bat). While the swing lasts, the swivel chair moves in the opposite direction. Swinging back brings the swivel chair back to the initial position. (Swinging fanatically is not conductive to the maintenance of professorial dignity, but necessary for a good demonstration.)

2.12.3.8.6 Explanation

During the experiment, no external forces are applied. In the beginning the total amount of angular momentum is zero and conservation of angular momentum tells us that this remains so. So as the tennis racket is given angular momentum in one direction, something else must acquire equal angular momentum in the opposite direction (you and the platform).

2.12.3.8.7 Remarks

- This experiment also explains what happens when a dog wags his tail. (Or is it: the tail wags the dog; conservation of angular momentum cannot tell the difference.)
- Also Newtons's third law can be observed in this experiment.

2.12.3.8.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 103-104
- Leybold Didactic GmbH, Gerätekarte, pag. 33166/-69, 33166
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 73

2.12.3.9 11 Pulling the Rug

2.12.3.9.1 Aim

To show a counterintuitive demonstration that can be explained using conservation of angular momentum.

2.12.3.9.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.9.3 Diagram

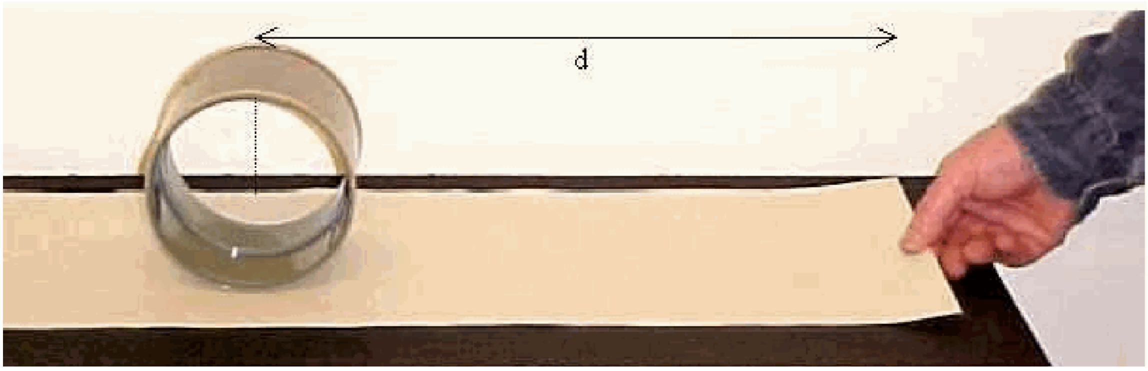


Figure 2.198: .

2.12.3.9.4 Equipment

- Piece of tube ($\emptyset = 125$ mm, $l = 120$ mm). We use a pvc coupling sleeve.
- Two rubber bands, fixed around the ends of the tube.
- Paper sheet. We use 90×25 cm^2.
- Air level.
- Solid cylinder.

2.12.3.9.5 Presentation

- Accurately level the table. Place the tube on the sheet of paper and position a stick on the table to indicate the starting position of the tube.

The sheet of paper is pulled horizontally out from under the tube. The observed movement of the tube is puzzling to the students, so the demonstration has to be repeated in order to make them describe exactly what they see:

- At first the tube is at rest.
- Pulling the sheet to the right makes the tube turn counter clockwise and there is a translation to the right (see Figure 2).
- When the sheet leaves from under the tube, immediately the tube stops its rotation and translation!

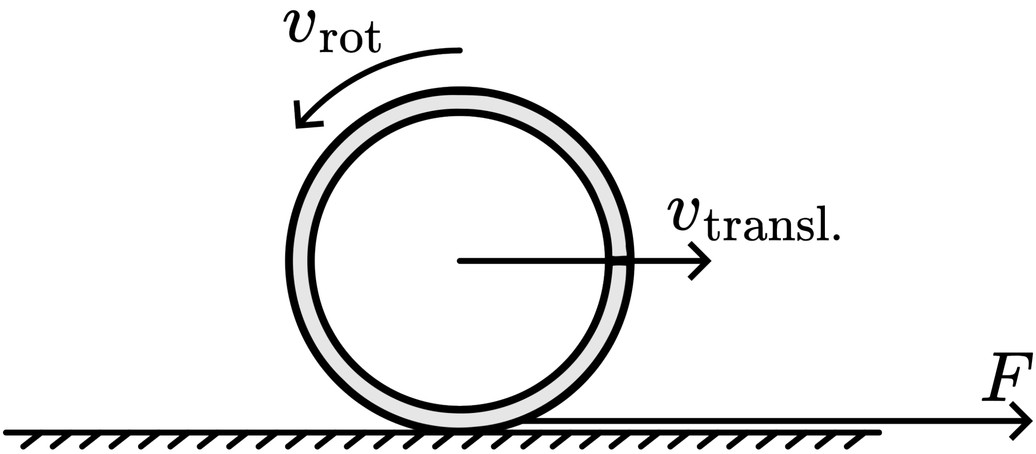


Figure 2.199: .

- When a tube and a solid cylinder are placed side by side on the sheet of paper the distances traveled in the direction of the pull will differ from each other: the tube will travel farther than the solid cylinder!

2.12.3.9.6 Explanation

- When the sheet is pulled to the right, the tube wants to stay where it is due to its inertia. But due to friction the tube will slide along with the sheet. Seen from a point on the table this means a clockwise rotation. Yet, there is no torque applied to the tube, since the sheet is very thin! The only way not to violate conservation of angular momentum (which is zero all the time during this demonstration) means that the tube itself has to turn counter clockwise (see Figure 2).
- The angular momentum due to the translation of the centre of mass of the object and due to the rotation of the object about its centre of mass must be equal in magnitude and opposite in direction.
- When the tube leaves the sheet the only way for the tube to continue moving would mean that the two components of angular momentum should have the same direction. Since the net angular momentum is zero, movement is not possible any longer.

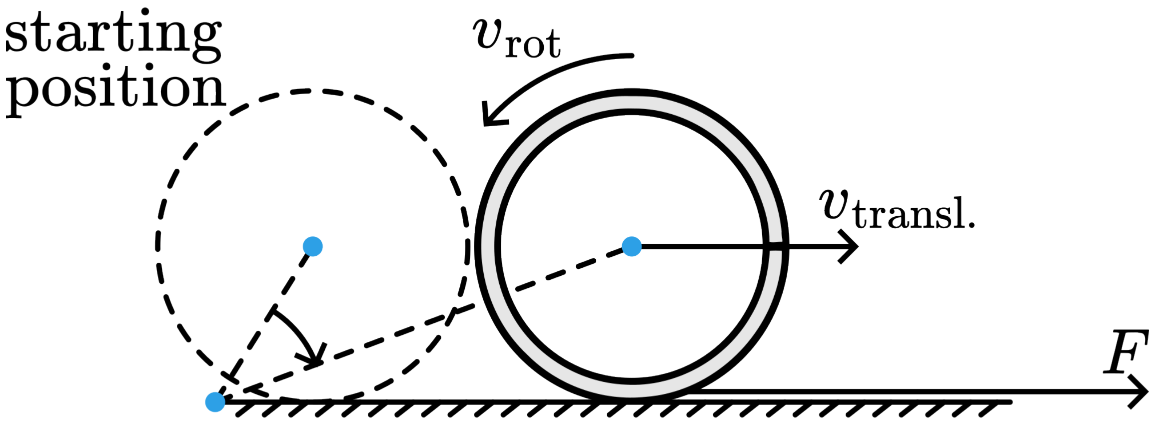


Figure 2.200: .

- The race between tube and solid cylinder seems to give a contrast with the results of Rolling downhill. But realizing that the tube has, relatively to its mass, a higher moment of inertia (ideal tube: MR^2;solid cylinder: $1/2MR^2$) will give the insight that the mechanism is the same: The angular acceleration of the tube will be smaller than that of the solid cylinder and so the tube is taken further into the direction of translation. (Figure1 and 2 show that v_{rot} gives a displacement opposite to the direction of F, so the lesser the object rotates the larger the displacement into the direction of F will be.)

Analysis will show that an ideal tube has a horizontal displacement $D = d$ and a solid cylinder $D = 1/2d$ (see Sources). So the (ideal) tube will be twice as far as the solid cylinder from their common starting point on the table.

2.12.3.9.7 Sources

- Roest, R., Inleiding Mechanica, pag. 181-182
- The Physics Teacher, Vol.39, April2001, pag. 224-225

2.12.3.10 12 Tippe Top

2.12.3.10.1 Aim

To show and explain the fascinating behaviour of a tippe top

2.12.3.10.2 Subjects

- 1Q40 (Conservation of Angular Momentum) 1Q60 (Rotational Stability)

2.12.3.10.3 Diagram

Figure 2.201: .

2.12.3.10.4 Equipment

- 3 tippe tops (see Diagram).
- White standard board (about). $50 \times 50\ \mathrm{cm}^2$
- Spray can with paint.
- Overheadsheet, showing that picture of Pauli and Bohr observing a spinning tippe top.
- Round transparent disc with arrow painted on it to show the sense of rotation.

2.12.3.10.5 Presentation

- Spin the tippe top (nr.1) with a quick snap of your fingers. It will spin with its hemispherical bottom downwards. After a short time the top turns over and spins on the stem. It continues to rotate on its stem, slows down and finally falls, resuming its position with stem up.
- Take tippe top nr.2, with the arrows painted on it. Repeat what seems to be the motion of the top without actually releasing it, that is: hold the stem of the top in the normal starting position (stem up) and twist the stem between thumb and forefinger, in the direction of the arrows painted on it. At the same time rotate the hand slowly to invert the top. The audience can clearly see that the inverted top continues to rotate in the direction of the arrow, but seen from the outside the sense of rotation is in the opposite direction. When you show this to a large audience you can use the transparent disc with the arrow painted on it to show this.

Now spin the arrowed top as in the first demonstration and when it inverts itself ask the audience to determine the actual direction of spin by close observation. Everybody can see that the inverted top is spinning opposite the direction of the arrows painted on it!

- Take tippe top nr.3, with the lines painted on it. Spin this top with a quick snap of your fingers. First the top spins on its hemispherical bottom and the lines appear blurred. When the top has inverted itself and spins on its stem the lines also appear blurred. But in between these two positions lines can be seen on the top, so in this in-between position the top is not spinning around its body axis. This happens when the top has its body-axis more or less horizontal.

- Take the white board and spray a paint-layer on its surface. Take tippe top nr. 1 and spin it in the normal way on this painted surface. After it has spun with finally stem up take the top and observe the track on its sphere (see picture in Diagram). Clearly can be seen that going from hemisphere to stem there is an inversion of direction (close to the equatorial line on the tippe top; the spinning position with body-axis horizontal).

2.12.3.10.6 Explanation

The top consists of a hollow sphere that is sliced off with a stem attached to it. This top is in stable static equilibrium when it points its stem upward, so the centre of mass (CM) is below the centre of curvature (C). This top is given a spin ω_0 (see Figure 2).

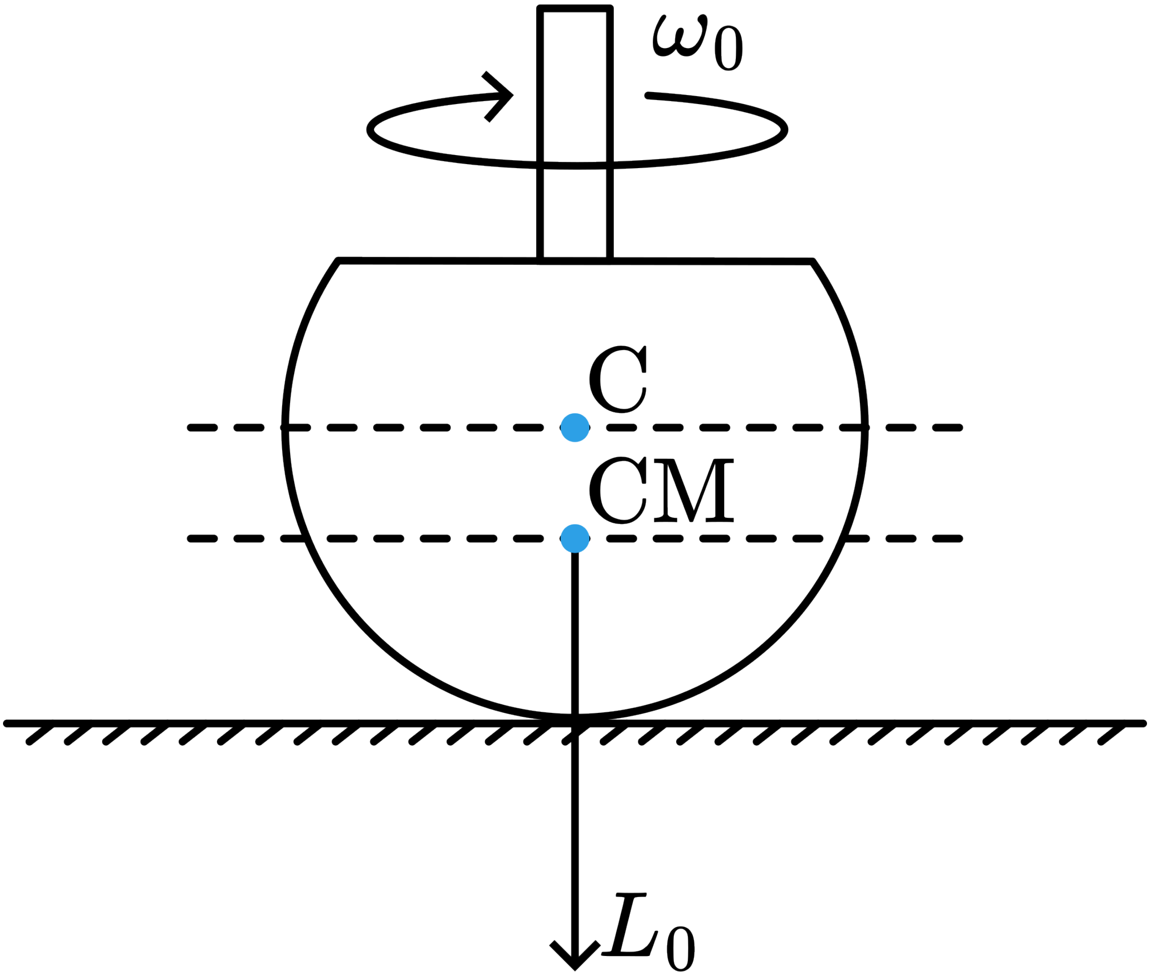


Figure 2.202: .

Now the tippe top has an amount of angular momentum (L_0). The demonstrations with tippe top nr. 2 , nr. 3 and nr. 1 on the painted board, show that this vertical angular momentum remains predominantly in that direction during the entire inversion process: L_0 keeps during this demonstration the same direction. (Thus the direction of rotation of the tippe top with respect to the coordinates fixed in its body is reversed.)

During inversion the centre of mass of the tippe top is elevated; it follows that the rotational kinetic energy decreases during inversion in order to provide the potential energy involved in this raising of the centre of mass. This implies that the total angular velocity and the total angular momentum decrease during the inversion process. However, a reduction in angular momentum requires the action of a torque. The only external forces acting on the top are gravity, the normal force exerted by the table at the point of contact and friction. Gravity and normal force point along the vertical, hence, they cannot be responsible for the decrease of angular momentum. Only friction force can produce a torque along the z-axis.

A complete analysis to account for the behavior of the top is quite elaborate (see Sources). Next a simplified explanation is attempted:

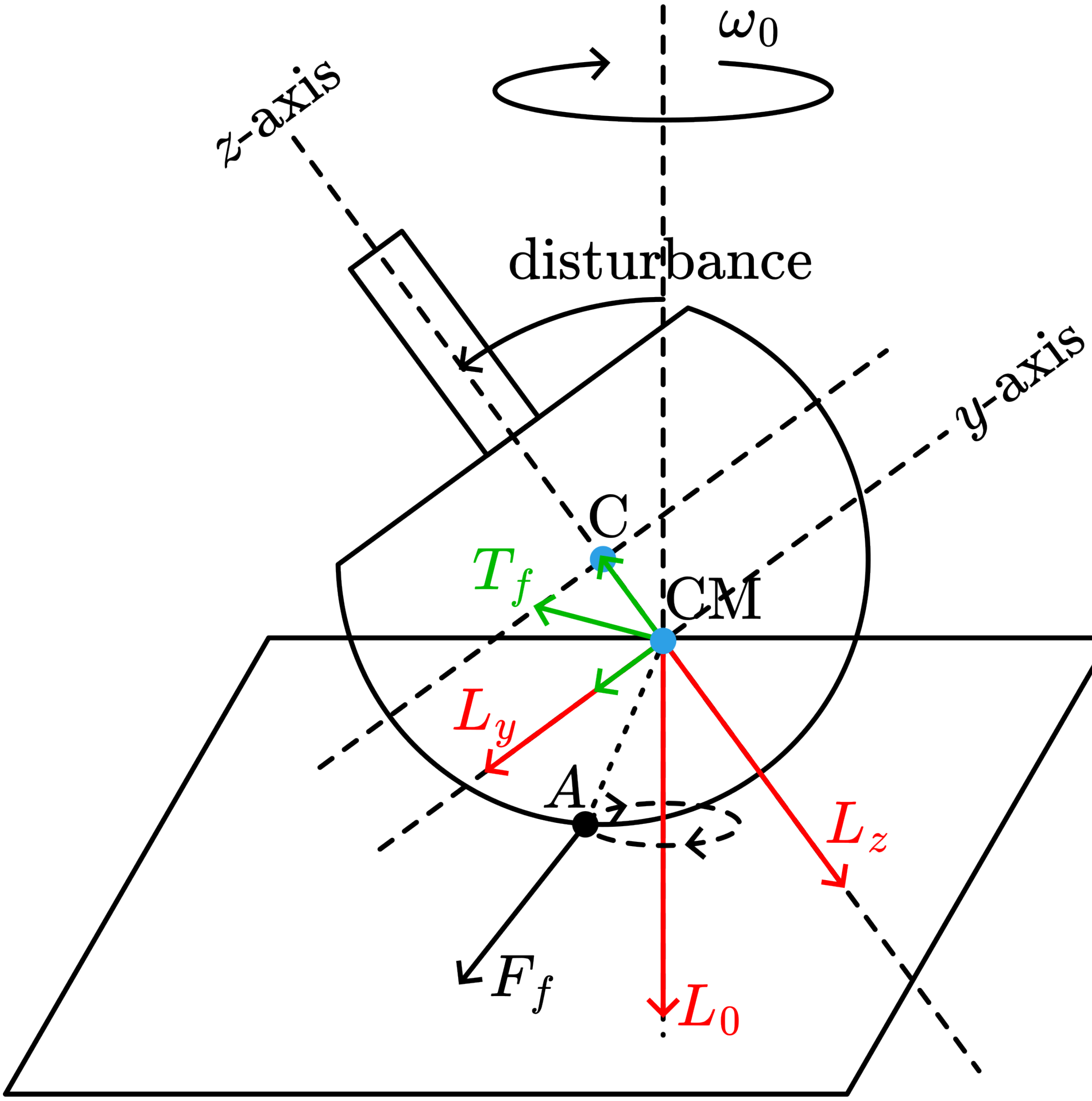


Figure 2.203: .

When a disturbance moves the top away from its initial vertical orientation with its stem up, the situation as shown in Figure 3 will occur. The tippe top remains spinning around its centre of mass CM and point A, perpendicular below C, slips over the floor. (Figure 4 shows a photograph of the circular slip track made by a tippe top on a freshly painted surface.)

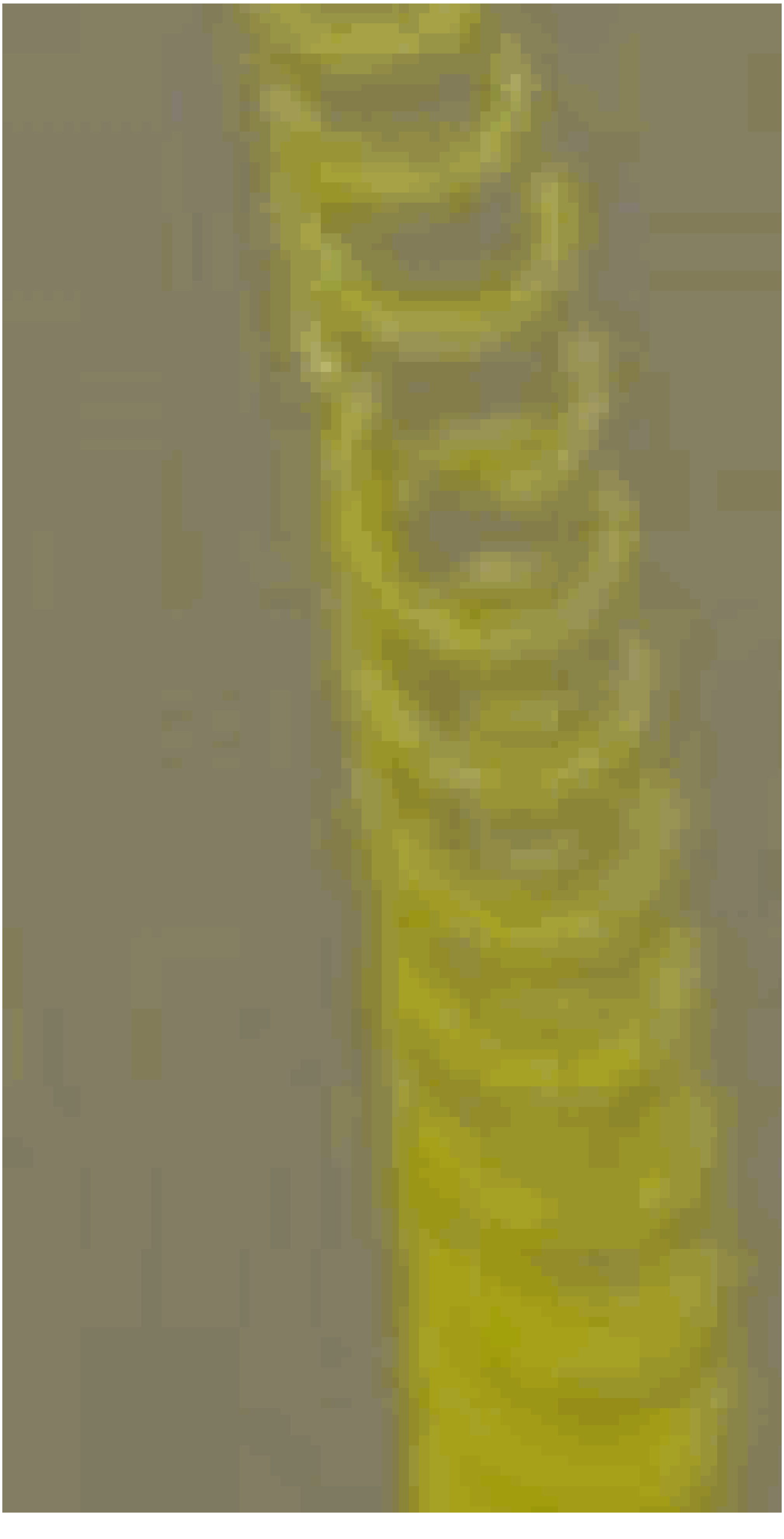


Figure 2.204: .

The friction force in A on the tippe top is pointing contrary to its direction of slip (so in Figure 2 towards the reader). The torque of this friction force is almost perpendicular to L_0, trying to change $L_0(L_z$ becomes smaller, L_y larger: see the y - and z-component of T_f). But since L_0 is conserved this change can only be reached by increasing the initial disturbance, so tilting the tippe top still more. This continues until the tippe top is spinning on its stem.

This analysis of the tippe top differs from the analysis of a rising conventional top, because the analysis of a rising conventional top depends on the fact that the angular momentum points predominantly along the symmetry axis of the top (see the demonstration Sleeper, whereas the angular momentum of the tippe top points along the vertical during the entire inversion process.

2.12.3.10.7 Remarks

- The flip of the tippe top occurs as a result of a frictional torque at the point of contact, so it should take longer to occur if the top is spun on a very smooth surface (may be even not flipping at all).
- Since CM is close to C, precession due to gravitational torque is neglected in our explanation.

2.12.3.10.8 Sources

- American Journal of Physics, Vol. 20 (1952), pag. 517-518
- American Journal of Physics, Vol. 22 (1954), pag. 28-32
- American Journal of Physics, Vol. 45 (1977), pag. 12-17
- American Journal of Physics, Vol. 68 (2000), pag. 821-828
- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 183-184
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 234
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 297-299

2.12.3.11 13 Vibrating Stopwatch

2.12.3.11.1 Aim

To show an example of conservation of angular momentum.

2.12.3.11.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.11.3 Diagram

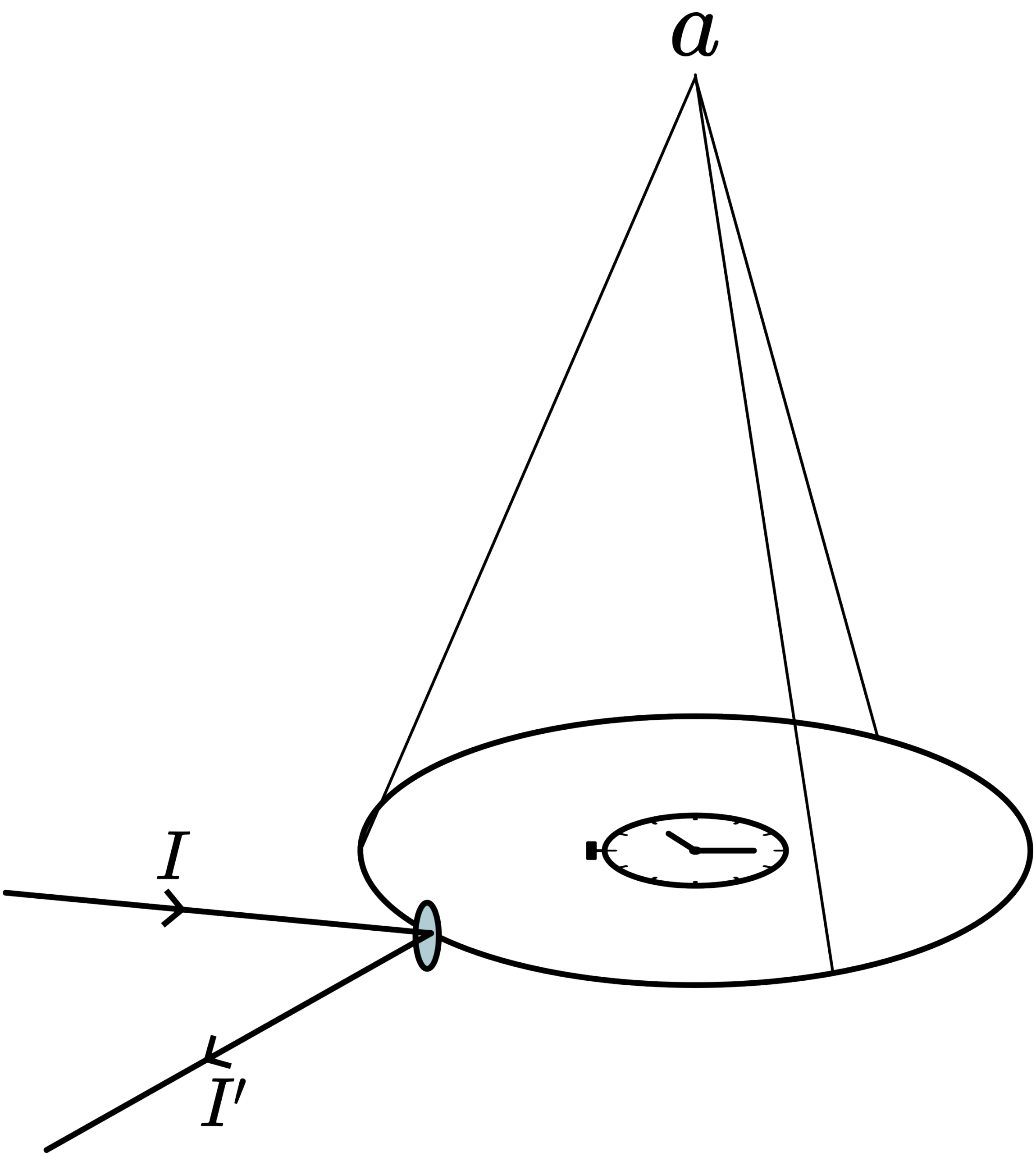


Figure 2.205: .

2.12.3.11.4 Equipment

- Mechanical stopwatch
- Mirror attached to the stopwatch
- Laser

2.12.3.11.5 Presentation

The running stopwatch is hung on three strings, so it can rotate easily. The whole assembly is mounted inside a transparent acrylic tube, to prevent movements due to airflows. The laser beam projects a spot via the mirror on the wall a couple of meters away. Observing the laser spot on the wall it can be seen that the total system vibrates. Observing the fly of the stopwatch and the movement of the laser spot, it can be seen that these directions of movement are opposite.

2.12.3.11.6 Explanation

No external force is applied to this system. The casing of the stopwatch has to move opposite to the fly. Since the casing has a larger mass than the fly, the observed deflections will be small.

2.12.3.11.7 Remarks

Since this set-up is very sensitive (e.g. to air movements), it is advisable to place the experiment in a show case. Pushing a knob activates the laser.

2.12.3.11.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 175

2.12.3.12 14 Pulling a Spool (a.k.a. Oma's Garenklosje)

2.12.3.12.1 Aim

Direction of rolling is determined by direction of torque.

2.12.3.12.2 Subjects

- 1K10 (Dynamic Torque)

2.12.3.12.3 Diagram

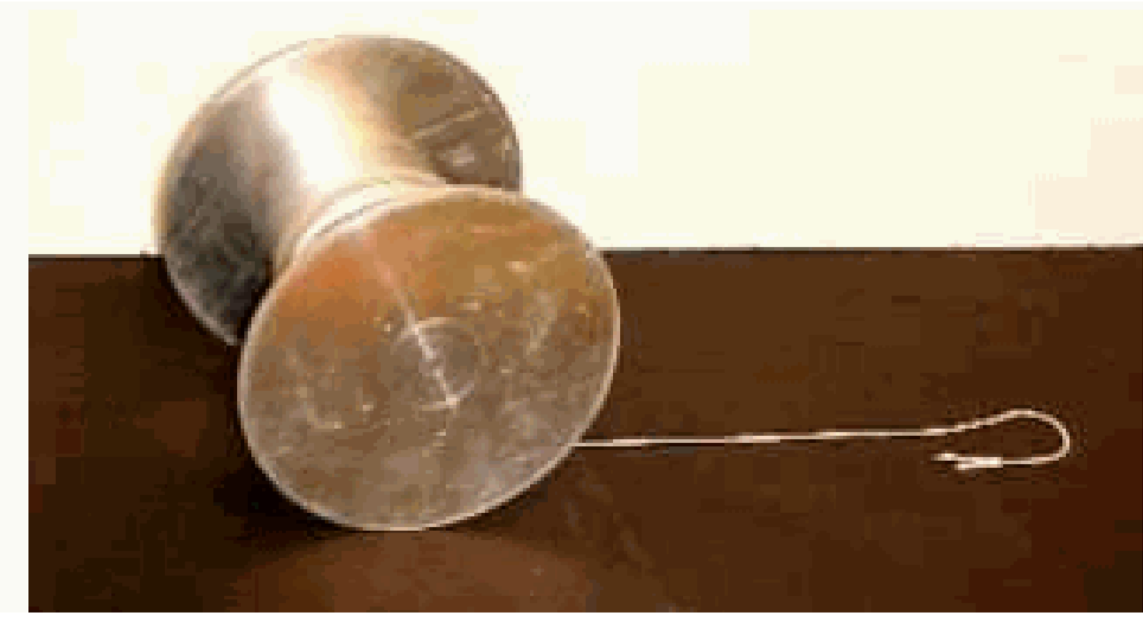


Figure 2.206: .

2.12.3.12.4 Equipment

- A (large) spool of thread.
- A thread or ribbon wound on the spool.
- Pulley.
- Mass, $m = .1$ kg.

2.12.3.12.5 Presentation

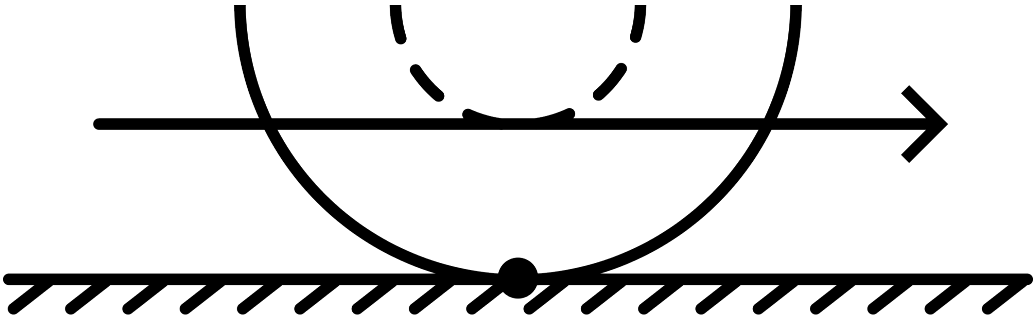
Show the simple construction of spool and wound thread to the students. The demonstrator takes the end of the thread in his hands and wants to pull in a horizontal direction. Ask the students in which direction the spool will roll. After their answers, pull .... and the spool will roll into the same direction as the demonstrator pulls.

The thread is wound to the spool again. The demonstrator takes the end of the thread in his hands and wants to pull in an upward vertical direction. Again he poses the same question. After the students' answers he pulls .... and the spool rolls into the other direction.

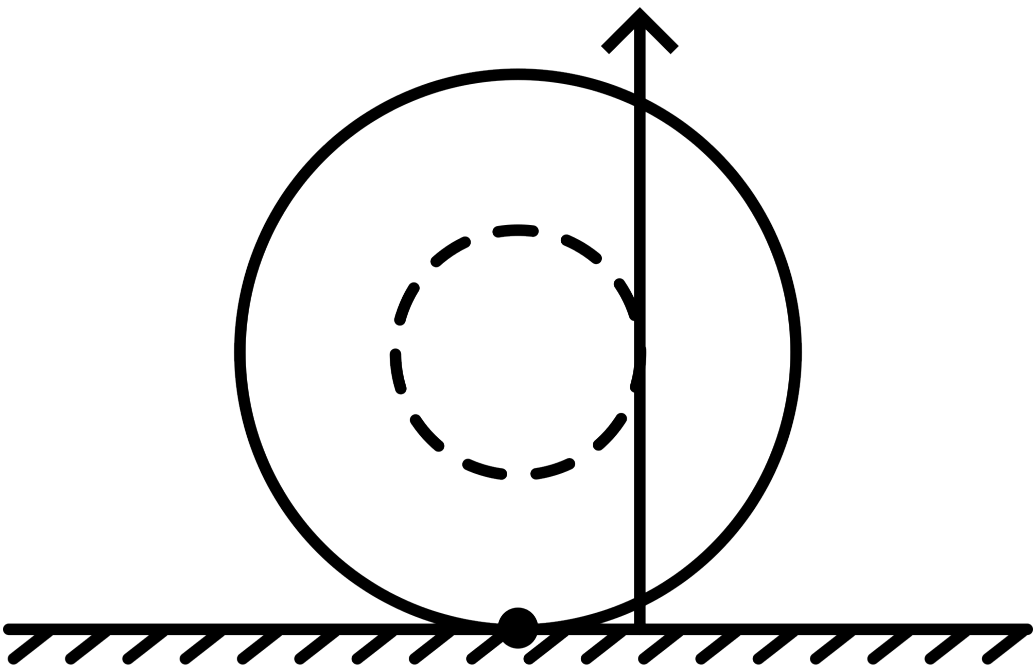
These two demonstrations induce the idea that it should be possible to pull in such a direction that the spool will not roll at all! Ask the students in which direction you need to pull the thread to get this situation. After their answers, experimentally search the right angle: the spool skids.

2.12.3.12.6 Explanation

The direction in which the spool rolls is determined by the direction of the torque on the spool about the contact point. The critical angle is defined by extending the line of the pulled thread so that this line passes through the point of contact between the spool and the table. A force directed along this line produces zero torque on the spool about the contact point. (see Figure 2)



right-hand torque



left-hand torque

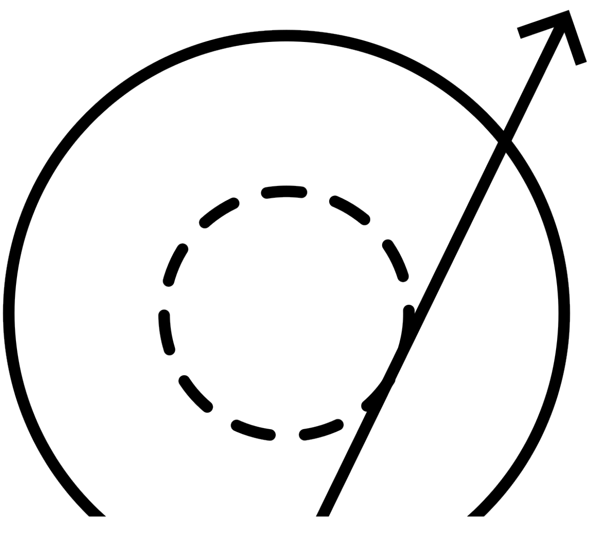


Figure 2.207: .

2.12.3.12.7 Remarks

- When pulling at very shallow angles, the spool orientation is not stable unless the thread comes off the spool at its center. This can be prevented by using a ribbon rather than a thread or using a large spool that is made in such a way that the thread can only be rolled in the centre of the spool (Figure 3).

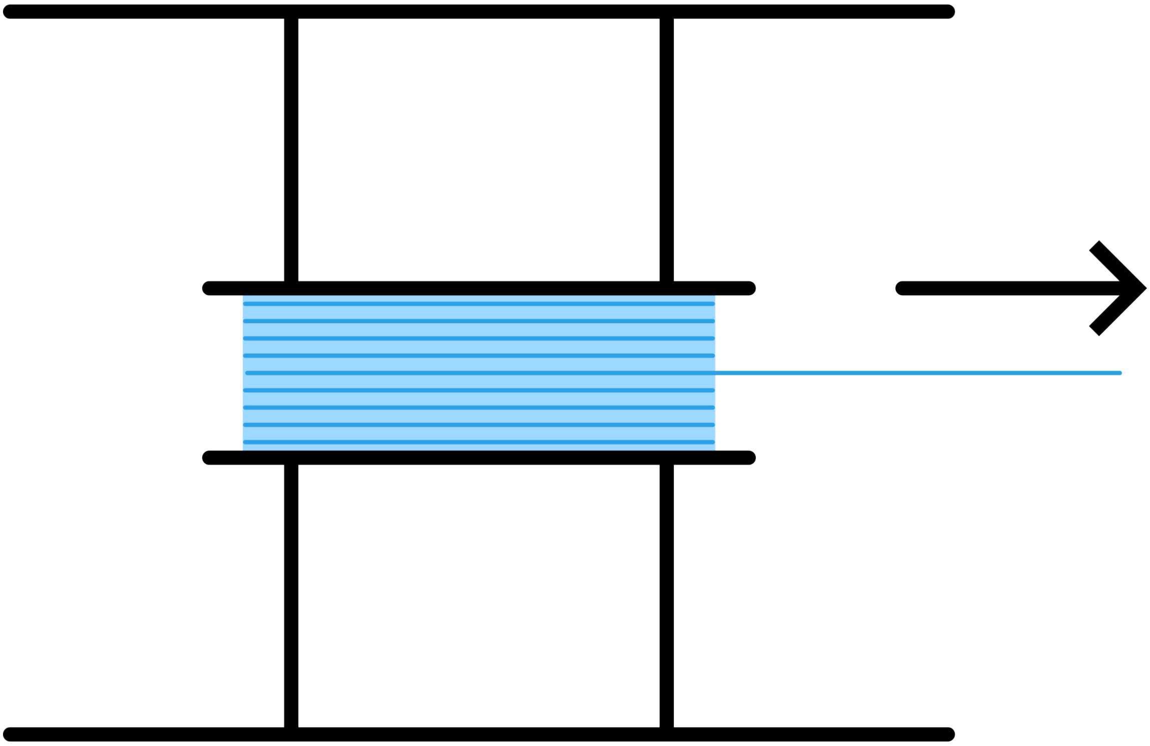


Figure 2.208: .

- A nice extension of this demonstration is to set the system up so that the string passes over a pulley and the force is supplied by hanging a weight from the end of the string (Figure 4).

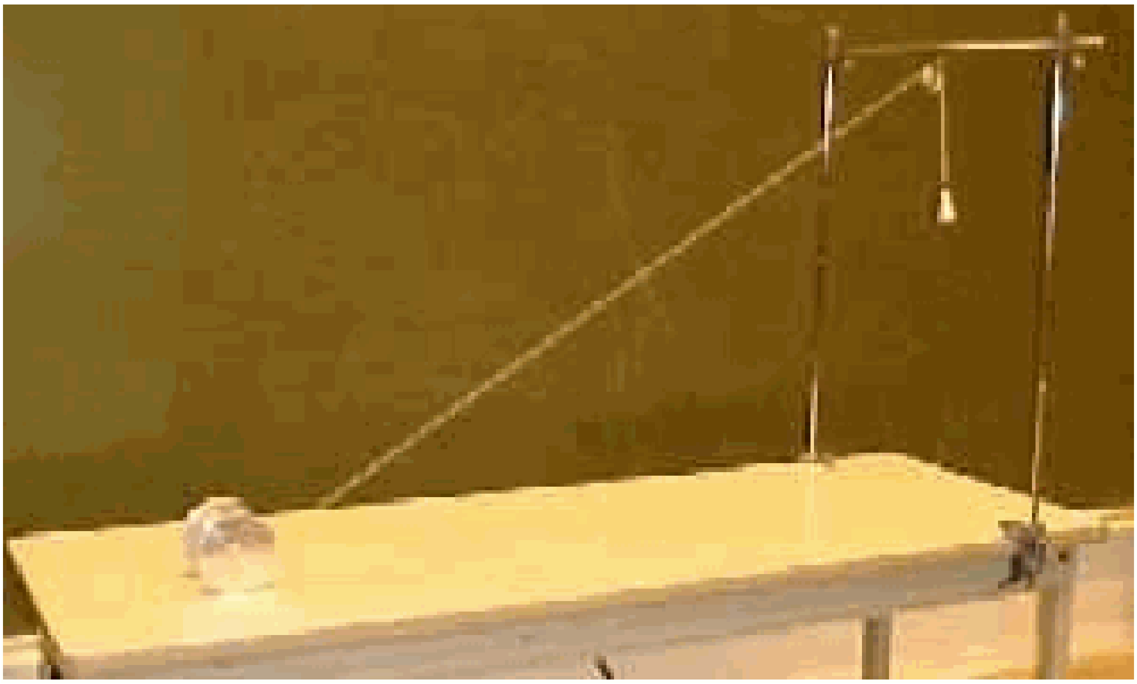
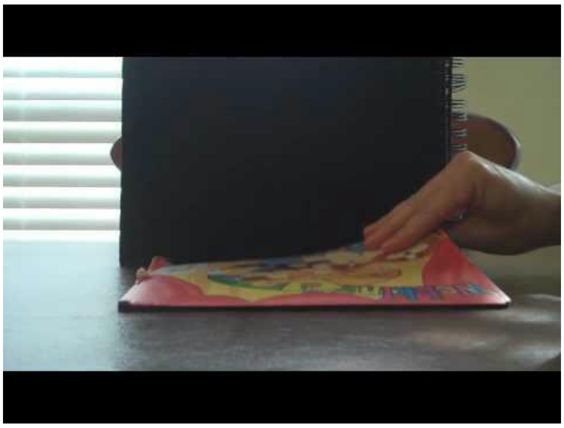


Figure 2.209: .

If the spool is moved away from its critical angle, the spool will always roll back to the position of the critical angle! It will oscillate back and forth around this equilibrium position.

2.12.3.12.8 Video Rhett Allain

(a)



(b)

Figure 192: :align: center - Scan the QR code or click here to go to the video.

2.12.3.12.9 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 65
- Jewett Jr., John W., Physics Begins With Another M… : Mysteries, Magic, Myth, and Modern Physics, pag. 115
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 102
- Young, H.D. and Freeman, R.A., University Physics, pag. 324(10-53)

2.12.3.13 15 Spinning Bouncing Ball

See Spinning Bouncing Ball

2.12.3.14 16 Bicycle Wheel and Swivel Chair

2.12.3.14.1 Aim

- To show conservation of angular momentum.
- To clarify the vector characteristics of angular momentum. (In this demonstration especially the direction of angular momentum is important.)

2.12.3.14.2 Subjects

- 1Q40 (Conservation of Angular Momentum)

2.12.3.14.3 Diagram

Figure 2.213: .

2.12.3.14.4 Equipment

- Swivel-chair.
- Bicycle wheel with handles and leaded rim.

2.12.3.14.5 Safety

- When handling the bicycle wheel for the first time, practice with it standing firmly on the ground and not on the swivel-chair, because the direction of the experienced forces might take you by surprise and hurt you.
- When you want to stop the bicycle wheel, slowing it down to a stop with your hand, be careful not to burn your hand.

2.12.3.14.6 Presentation

1. The demonstrator sits on the swivel-chair and holds the bicycle wheel in front of him. The wheel is held with its axis vertical. The demonstrator spins the wheel and immediately he starts rotating in the opposite sense. When by hand he stops the wheel, also the swivel chair stops.
2. The demonstrator sits on the swivel chair. An assistant hands him the bicycle wheel that is spinning already around the vertical axis. Before doing so, ask the audience what will happen? Answer: nothing! But when the demonstrator slows down the bicycle wheel by braking it, the swivel-chair with demonstrator will start turning round in the same direction as the bicycle wheel did.
3. The demonstrator sits on the swivel chair. An assistant hands him the bicycle wheel that is spinning already around the horizontal axis. Again nothing happens. But if he then turns the spinning wheel to a vertical position of its axis, he will rotate in the opposite sense to the spin of the wheel. Turning the wheel another 90° , so the axis is horizontal again, it brings him back to a stop. Turning the wheel another 90° makes him turn again but now in opposite direction.

When the demonstrator continuously turns the axis of the spinning wheel, then the swivel-chair will turn in one sense and then to the other and so on.

1. Again the assistant hands a spinning bicycle wheel to the demonstrator that sits on the swivel chair (wheel axis vertical again). When the demonstrator on the swivel-chair turns the axis 90° then the demonstrator starts turning. When he turns it another 90° then he rotates even faster! ($2x$)
2. When there is time to practice with your assistant, you can continue this demonstration in the following way:

Start in the same way. (The demonstrator sits on the swivel chair; the assistant hands over the turning bicycle wheel - axis vertical -; the demonstrator turns it 180°.) Now the demonstrator, while rotating on the swivel-chair, hands the wheel back to his assistant, who in turn rotates the axis through 180° and again hands it to the demonstrator on the swivel chair. When the demonstrator now turns the spinning wheel over a second time, his angular velocity increases (doubles). Additional “quanta” may be given to him by repeating this process.

If, however, the assistant fails to turn the wheel over once but turns it over each time thereafter, the process becomes subtractive.

2.12.3.14.7 Explanation

1. Making the wheel turn, it obtains an angular velocity ω and an angular momentum $L = /\omega$.

Then the swivel chair has to turn in the opposite sense with an angular velocity ω', whose angular momentum equals -/ ω (see Figure 2b), because the total angular momentum of the system has to remain zero as it is in the beginning of the demonstration (Figure 2a).

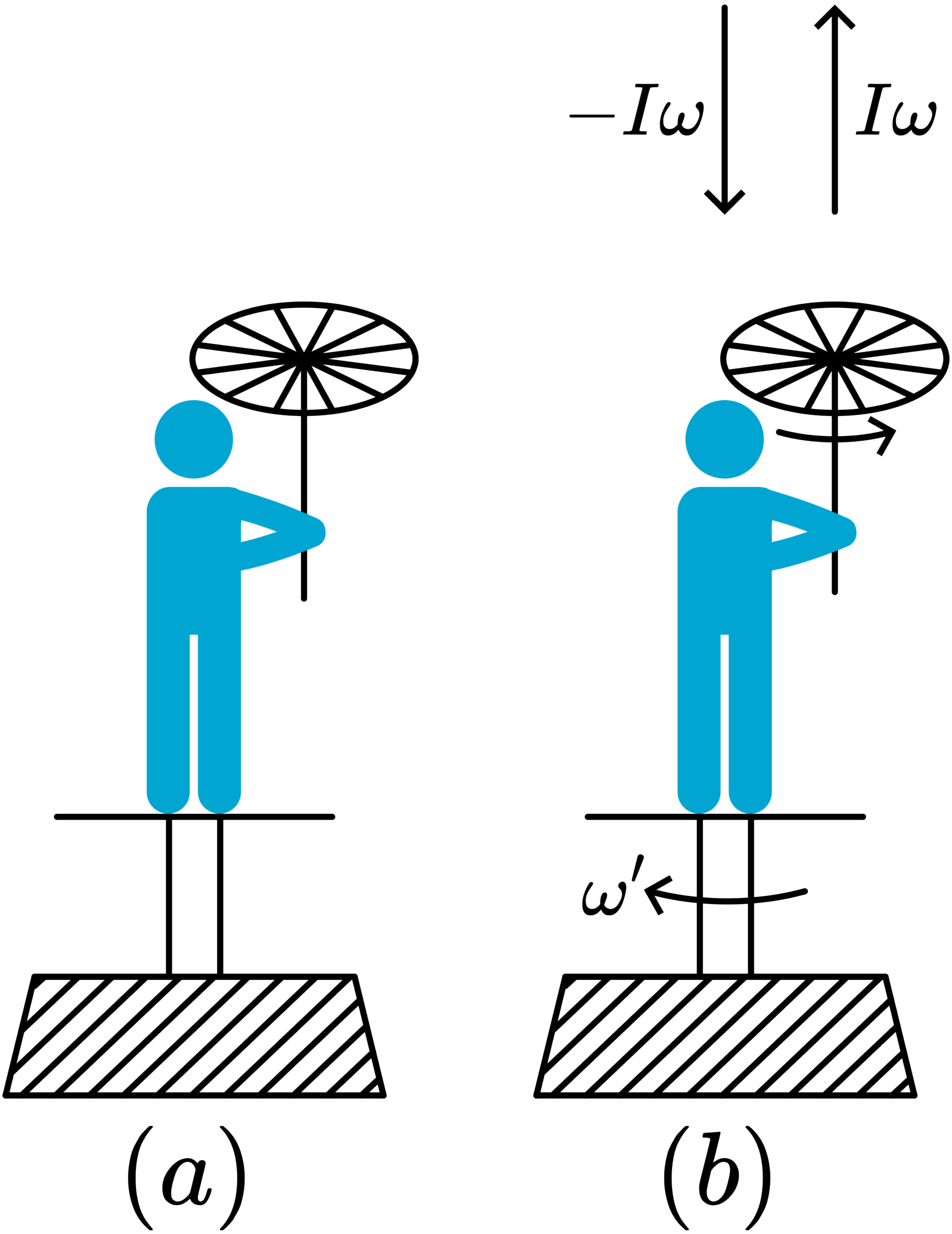


Figure 2.214: .

2. The wheel has an angular momentum of $L = /\omega$ (see Figure 3a). This angular momentum is conserved, so when the wheel stops, the swivel chair with demonstrator will start to rotate (see ω' in Figure 3b) in the same direction as ω.

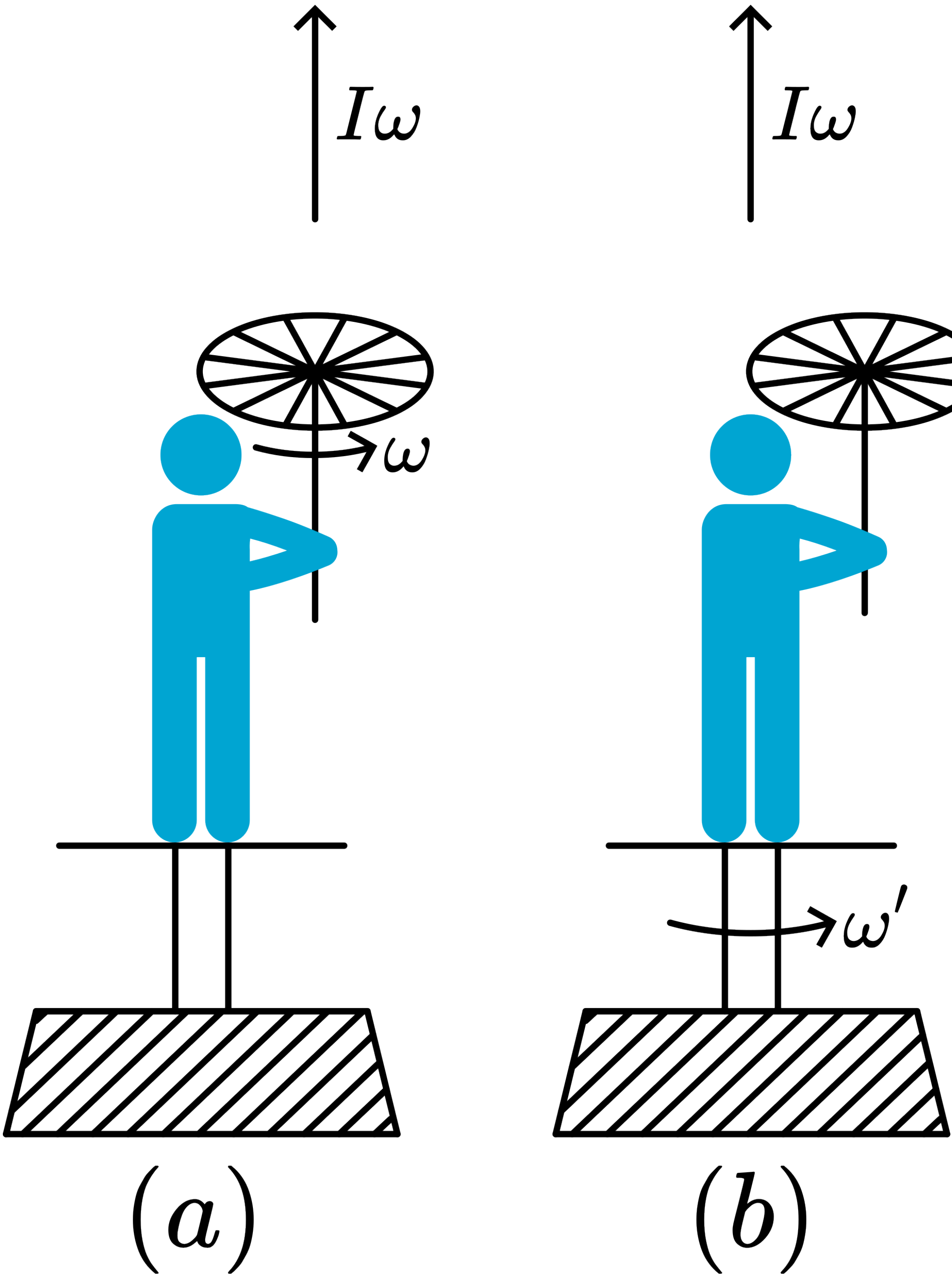


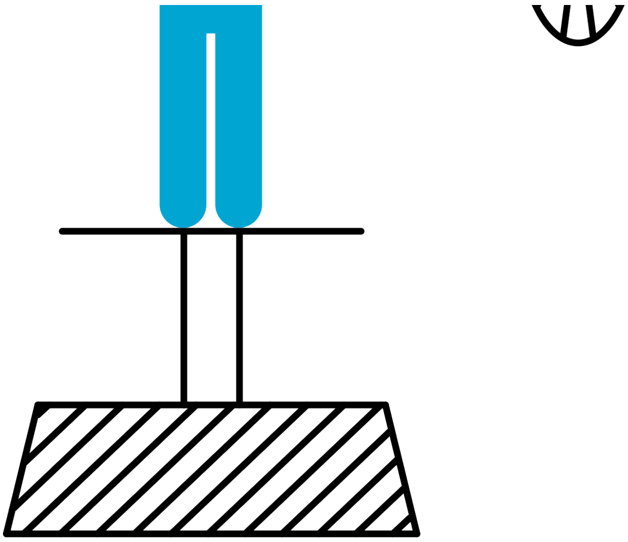
Figure 2.215: .

3. When the rotating wheel has its axis in horizontal position (Figure 4a), then there is no angular momentum in the vertical direction. The swivel chair is not rotating.

Turning the wheel 90 upwards (Figure 4b), then an angular momentum is introduced in the vertical direction (/ /ω). This has to be compensated by another angular momentum of the same amount (-/ /ω) in order to keep the total angular momentum in the vertical direction zero: the swivel chair and demonstrator will rotate (ω' in Figure 4b).

Bringing the wheel down (see Figure 4c) will make the swivel chair turn into the other direction.

(The disappearance of $I\omega$ in the horizontal direction has no rotating effect, because the set up cannot rotate around a horizontal axis. The only effect is a torque felt by the demonstrator.)



(a)

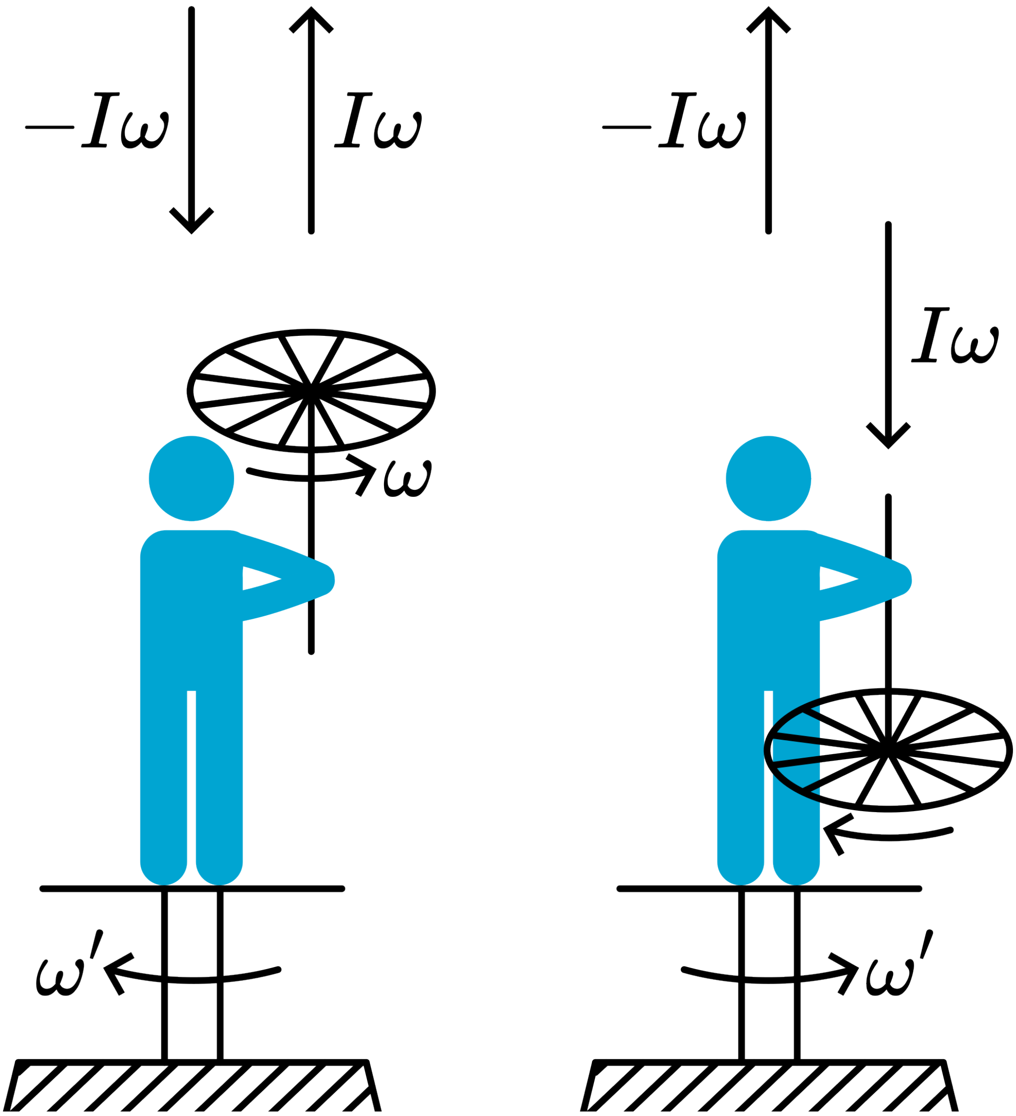
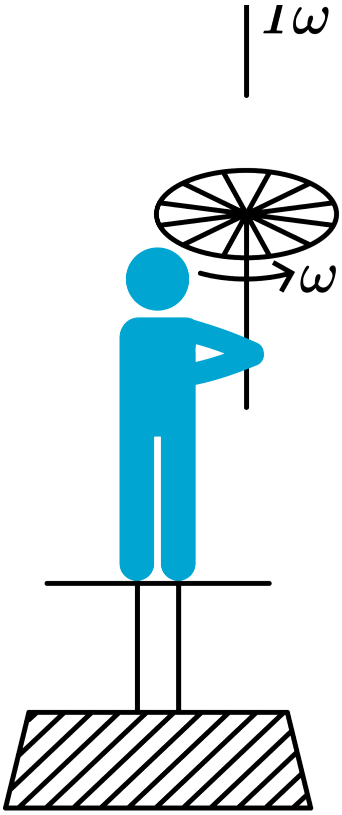


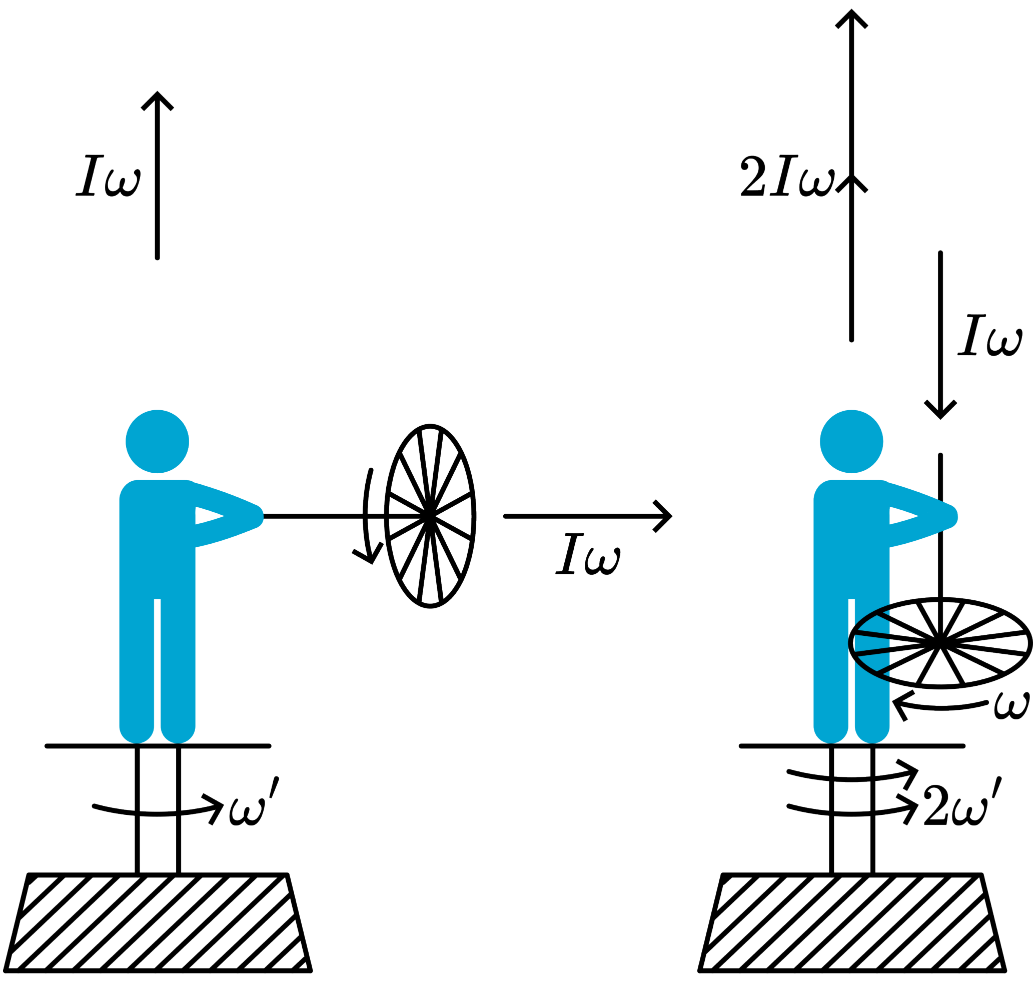
Figure 2.216: .

4. In the beginning the wheel is turning, so there is an amount of angular momentum: $L = /\omega$, and the swivel chair is standing still (see Figure 5a). Bringing the rotating wheel to a horizontal position removes that angular momentum from the system, but since angular momentum needs to be conserved, the whole system starts rotating (ω') in the same direction as ω. When the wheel is lowered once more (Figure 5c), the figure makes clear that the swivel chair has to speed op to 2ω.



$I\omega$
ω

(a)



$I\omega$
$I\omega$
ω'
$2I\omega$
$I\omega$
ω
$2\omega'$

Figure 2.217: .

5. This is repeating the procedure of situation 4 a number of times. In the beginning the swivel chair is not rotating. At the end of the first round it rotates with 2ω. Then after the second run it rotates with 4ω, after the third run with 6ω, and so on.

2.12.3.14.8 Remarks

- After the demonstration we have more bicycle wheels and swivel chairs in our lecture hall so the students can practice themselves and experience those ‘strange’ forces/torques.

2.12.3.14.9 Video Rhett Allain

(a)

(b)

Figure 198: :align: center - Scan the QR code or click here to go to the video.

2.12.3.14.10 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 173, 174.
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 75, 76.
- Leybold Didactic GmbH, Gerätekarte, 33166.
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 105.

2.12.3.15 17 Train and Track

2.12.3.15.1 Aim

To show: Action and Reaction, or: Stable equilibrium, or: Conservation of Angular Momentum. So this is a versatile assembly!

2.12.3.15.2 Subjects

- 1H10 (Action and Reaction)
- 1J20 (Stable, Unstable and Neut. Equilibrium)
- 1Q40 (Conservation of Angular Momentum)

2.12.3.15.3 Diagram

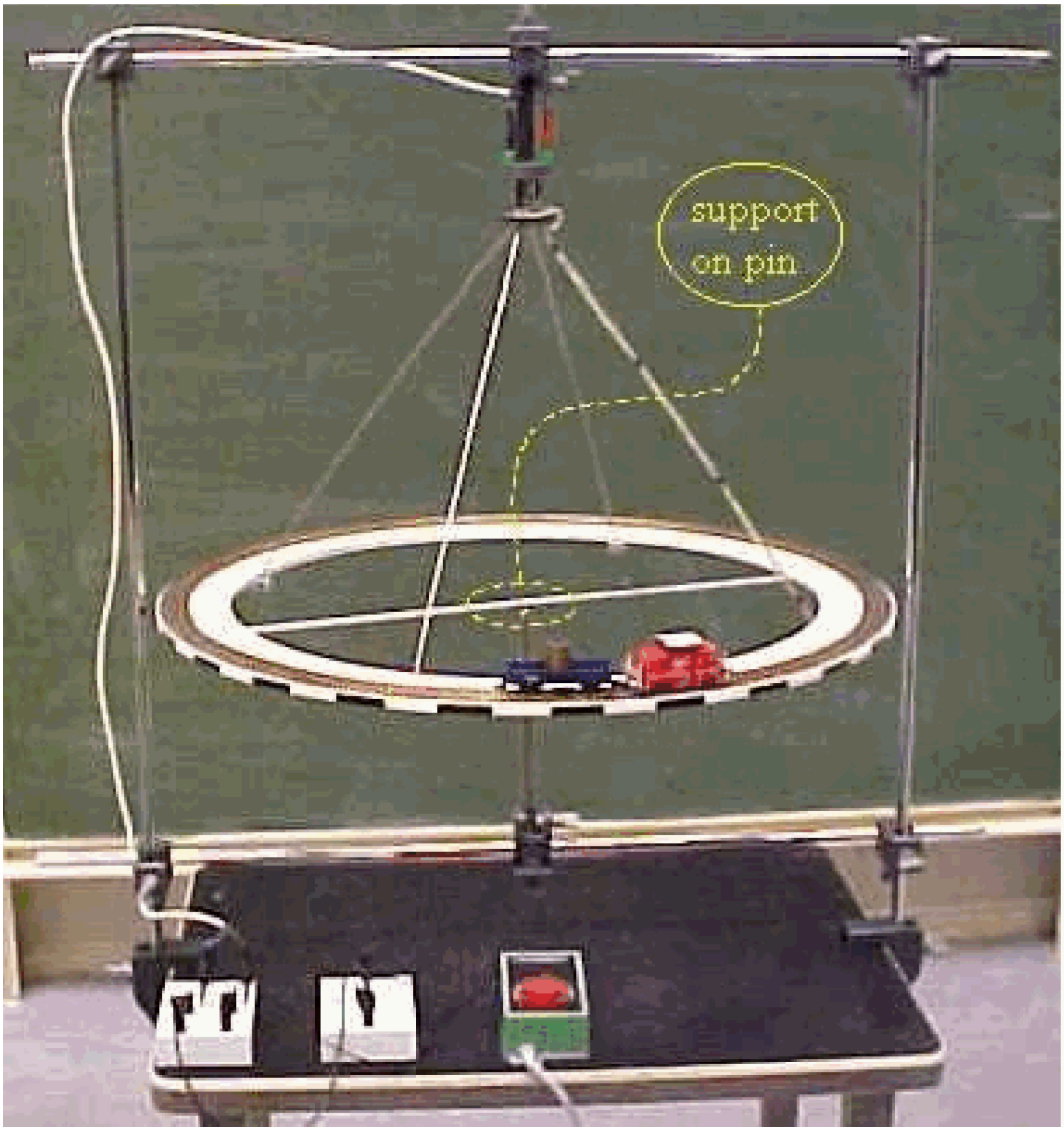


Figure 2.221: .

2.12.3.15.4 Equipment

- Electric toy locomotive.
- Trailer, with mass.
- Round electric toy-train track.
- DC power supply.

- Two switches, ON-OFF and TWO-WAY.
- Table with adjustable tabletop.
- Support material.

2.12.3.15.5 Presentation

2.12.3.15.5.1 Preparation

The track and toy train are mounted as shown in the Diagram. The track is levelled carefully. To do this, first the complete frame is mounted and fixed to the table as level as possible. When the complete set is brought into the lecture-hall, further levelling is performed by means of the adjustable tabletop only.

2.12.3.15.5.2 Presentation

1. When power is switched on, the train runs along the track and the track moves into the opposite direction. When switching off, both train and track stop their movement immediately. (Using the two-way switch, the demonstration can also be shown when the train runs into the other direction.)
2. The train is running and by hand the rotation of the track is prevented (block it during a short while). The train is running around at a constant speed and in our frame of reference the track is at rest.

When the power is switched off, the train stops on the track and track-and-train will start rotating into the same direction as the train did, but at a lower speed.

While holding the train, the power is switched on. The track is rotating and in our frame of reference the train is at rest.

When the power is switched off, the track stops under the train and track-and-train will rotate together into the same direction as the track did before, but at a lower speed now.

1. The track (at rest) is given a small gradient and students are asked to predict what will happen now. (Switching on the power will make the track rotating and the train remains in the lowest position of the track.)

2.12.3.15.6 Explanation

1. First: that both train and track move when power is switched on, shows that

Remarks: when there is action, there is also a resultant reaction.

Second: When there is no power switched on, the assembly is at rest and the total angular momentum equals zero. When the train starts going round there is an internal amount of angular momentum. Since externally no torque has been applied, total angular momentum should still be zero. This is so since the track rotates into the other direction.

When switching off the train looses his angular momentum. Since total angular momentum must be zero, also the track has to stop

2. When the train goes round and the track is at rest in our frame of reference, the total system has a certain amount of angular momentum. When the train stops, this amount should be conserved. (The train is not stopped by an external torque.) Conservation of angular momentum shows up in the rotation of the complete system now. (It has to move slower, because more mass is rotating now: the moment of inertia has increased.)

The same holds when the track goes round and the train is at rest in our frame of reference.

3. This is a demonstration of stable equilibrium, when the system has its lowest gravitational potential energy.

2.12.3.15.7 Remarks

- When doing presentation 1 the track will stop rotating after some time due to friction in its bearings. So make not run your toy train too long and so “spoil”
- When the train rotates at a high speed, it may fall from the track due to centrifugal forces.
- For demonstration 1 and 2 the track should be levelled carefully. Otherwise, even at a small gradient you will get demonstration 3 . (When the gradient is hidden it can be amusing to make a “professional” audience make the wrong prediction before the demonstration is shown.)

2.12.3.15.8 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 55

2.12.4 1Q50 Gyroscopes

2.12.4.1 01 Precession (1)

2.12.4.1.1 Aim

To show the relationship between gravitational torque and precession.

2.12.4.1.2 Subjects

- 1Q50 (Gyros)

2.12.4.1.3 Diagram

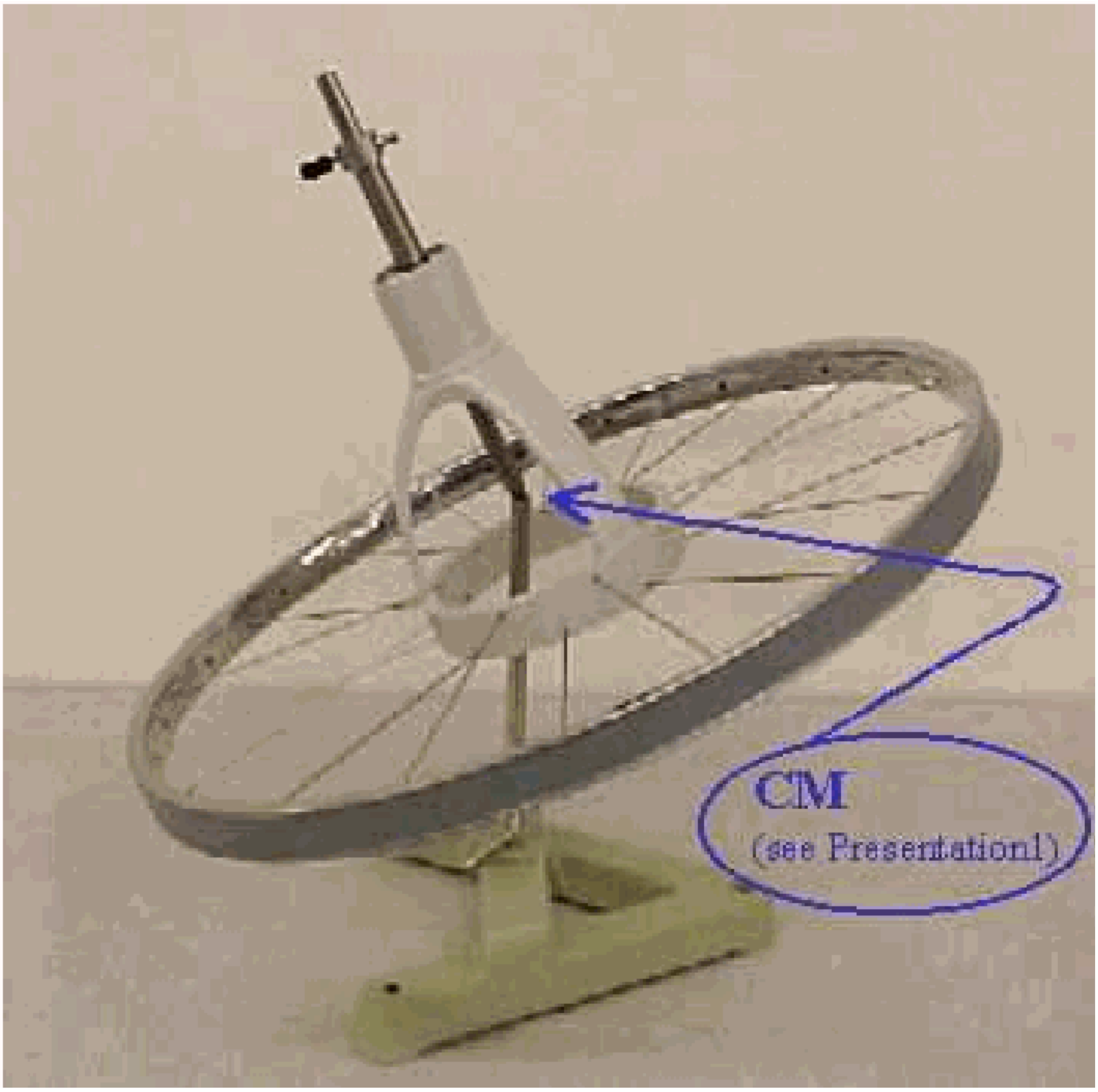


Figure 2.222: .

2.12.4.1.4 Equipment

- Large gyroscope (Laybold 34818)
- Pointed rod
- Rod with cup Precession (1)

2.12.4.1.5 Presentation

1. The pointed support-rod is shifted so that the gyroscope is supported at its centre of mass (CM). Show this to the students by placing this axis in different orientations and observe

that any orientation is in neutral equilibrium. Now the gyroscope is made spinning and given an angle of about 20° with the vertical. The spinning gyroscope will remain stationary in space.

2. The ball-bearing of the gyroscope is gripped (while the gyroscope is spinning) and the gyroscope is lifted somewhat so now its centre of mass is above its point of support. The gyroscope performs its rotary motion on a cone-shaped shell. This motion along the cone-surface is called precession.
3. The ball bearing of the still rotating gyroscope is gripped again and the gyroscope is lowered somewhat such that now its centre of mass is below its point of support. The spinning gyroscope shows again precession, but now in the other direction.

While the gyroscope slows down, it can be observed that the angular velocity of precession increases.

Also can be shown that the angular velocity of precession is proportional to the moment of the applied force by repeatedly varying the position of the point of support of the gyroscope.

2.12.4.1.6 Explanation

Since angular momentum is a vector quantity that may be represented by a vector parallel to the axis of spin, the combination of two angular moments may be treated by the parallelogram law. The spinning gyroscope has an angular momentum of $I\omega_0$. This is represented by a vector parallel to the axis of spin (see Figure 2a).

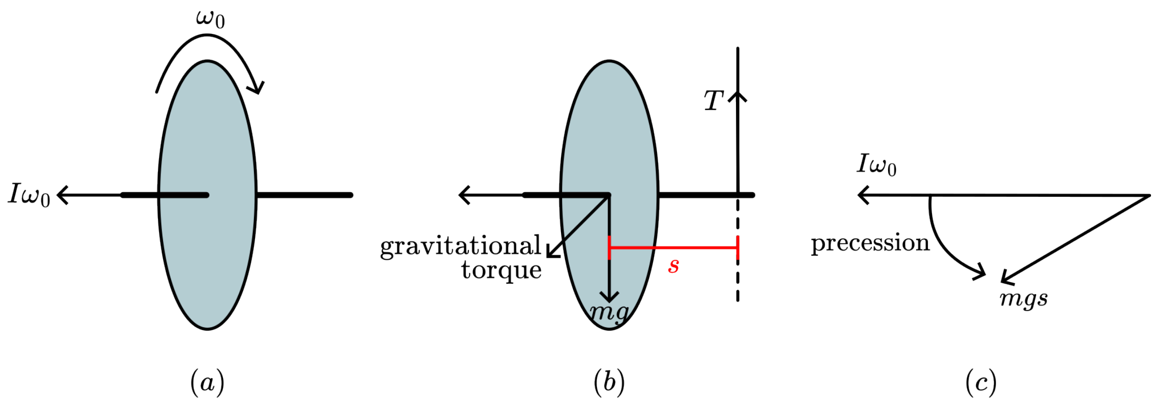


Figure 2.223: .

When the centre of mass (CM) is above the point of support, then there is a gravitational torque mgs (see Figure 2b), pointing away from you.

This torque tends to change $I\omega_0$, so $I\omega_0$ moves into the direction of mgs (see Figure 3),

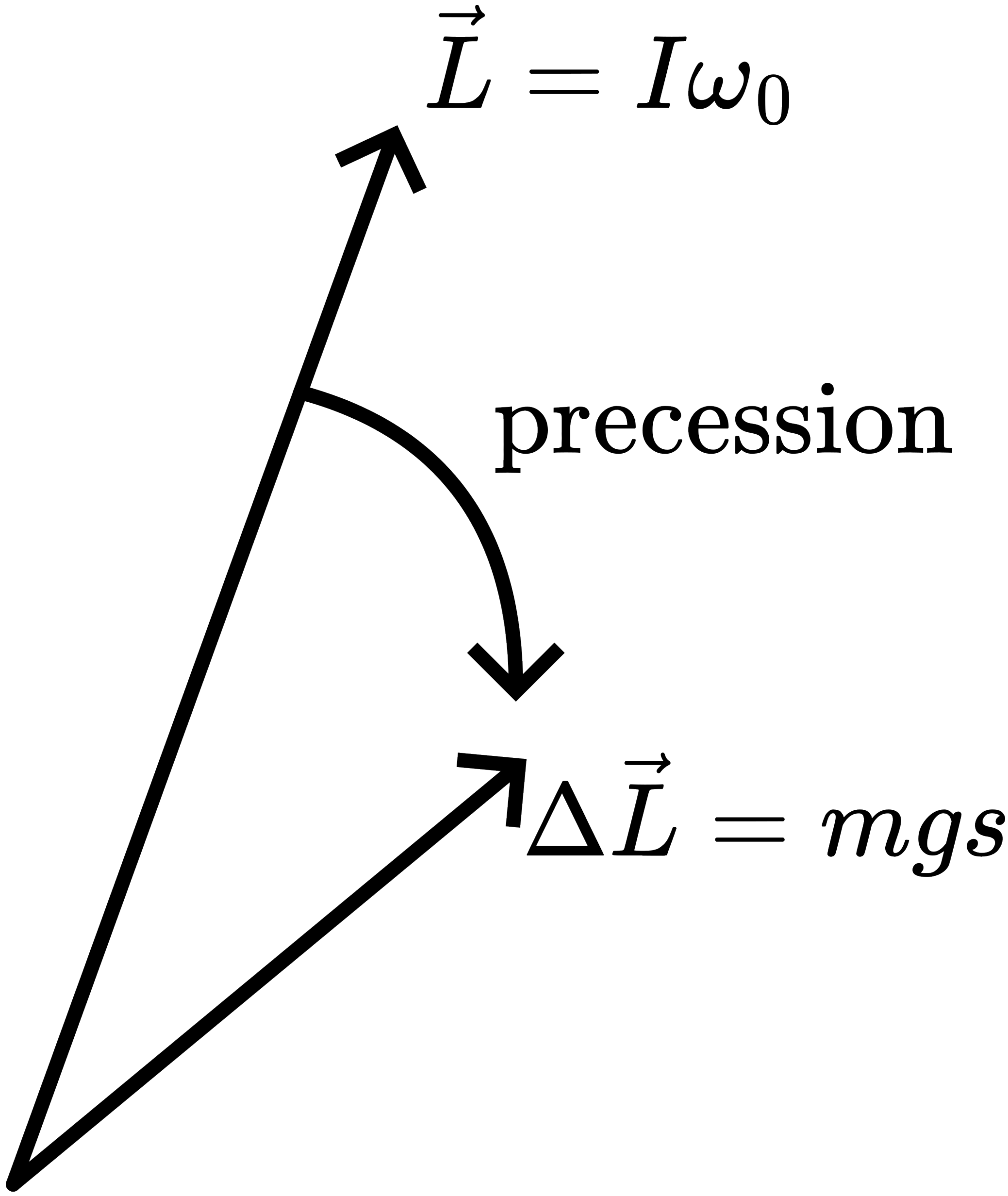


Figure 2.224: .

and in that way changes the axis of rotation of the wheel (precession). The speed of precession (ω_p) equals $\omega_p = \frac{mgs}{I\omega_0}$, so:

- increasing s, increases ω_p;
- positioning s above the CM changes direction of ω_p;
- slowing down of ω_0 , as will inevitably happen during the demonstration, increases ω_p as the formula shows.

2.12.4.1.7 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 79
- Leybold Didactic GmbH, Gerätekarte, pag. 34818
- Roest, R., Inleiding Mechanica, pag. 226-228

2.12.4.2 02 Precessing Orbit (1)

2.12.4.2.1 Aim

To show that the orbit of a ball on a concave surface will precess in a predictable manner.

2.12.4.2.2 Subjects

- 1L20 (Orbits)
- 8A10 (Solar System Mechanics)

2.12.4.2.3 Diagram

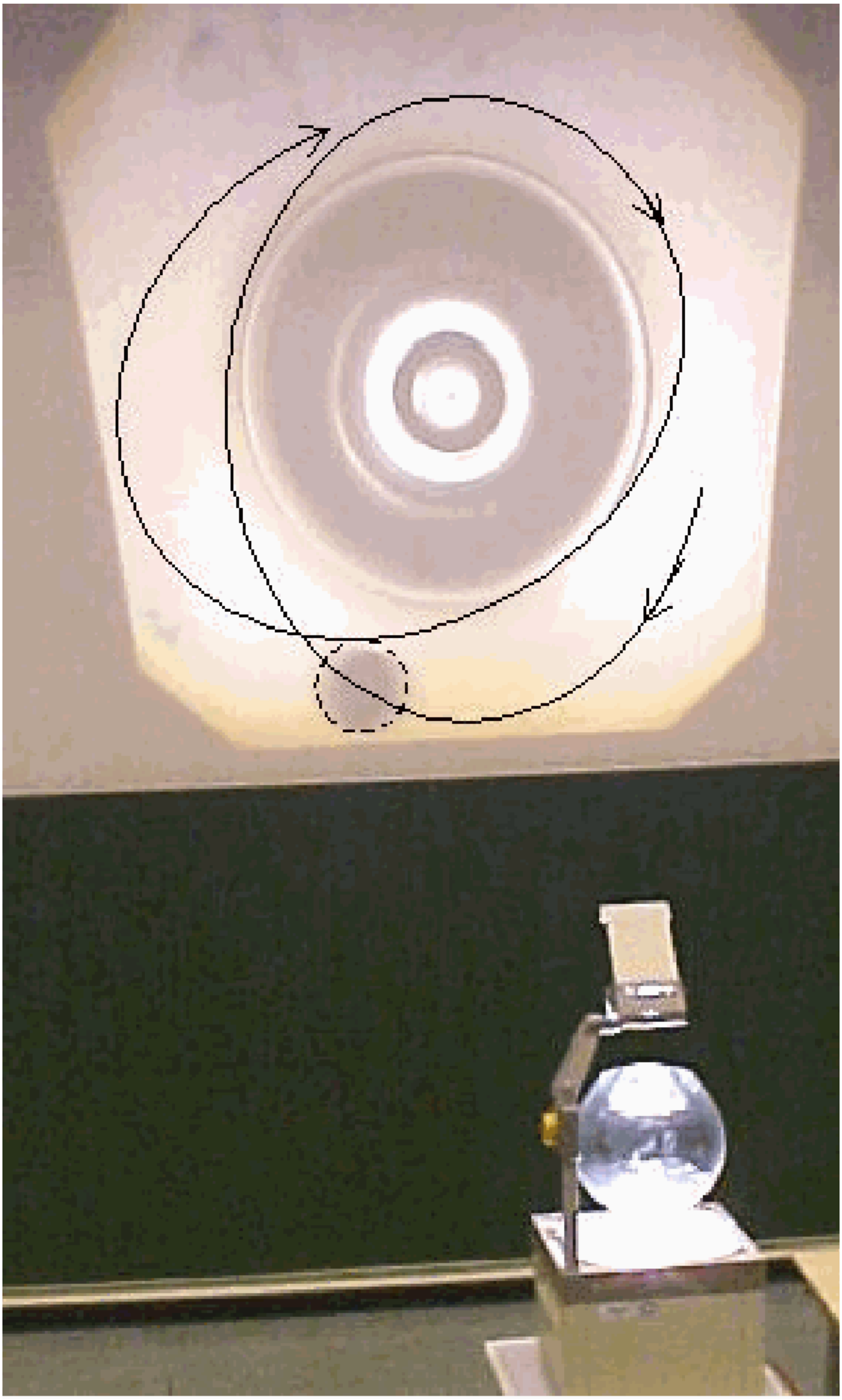


Figure 2.225: .

2.12.4.2.4 Equipment

- Bowl.

- Steel ball, diam. around 2cm.
- Overhead projector.

2.12.4.2.5 Presentation

Use the overhead projector to show the two-dimensional image of the ball in the bowl (see also the demonstration Force field. Shaking the bowl gently you should be able to achieve orbits that are either circular, linear or elliptical depending on the ball's speed and direction.

Make an elliptical orbit. Observe that the orbit does not close, but precesses into the direction of the ball's rotation (see orbit drawn in Diagram).

Also can be shown:

-Zero precession for a straight line orbit;

-stronger precession for ellipses that are less eccentric;

-stronger precession for larger ellipses.

2.12.4.2.6 Explanation

Precession in this demonstration happens due to the bowl's shape. But be careful with this analogy! The bowl's shape is NOT such that the potential energy corresponds to an r^{-1} variation! (see SourcesXX).

The next is just an attempt to say something more about it:

For the concave bowl we can write for this type of potential:

$U(r) = U(0) + \frac{U'(0)}{1!}r + \frac{U''(0)}{2!}r^2 + \frac{U'''(0)}{3!}r^3 + \ldots$ (Maclaurin series).

When $U(0) = 0$ and $U'(0) = 0$ (minimum at $r = 0$, the center of the bowl) and when r is relatively small, so we can neglect the higher-order terms, then: $U(r) = \frac{1}{2}U"(0)r^2$.

This is a harmonic potential, and when moving in a line with small amplitudes, we'll see a harmonic motion. This harmonic potential $\left(r^2\right)$ is clearly NOT a r^{-1}-potential.

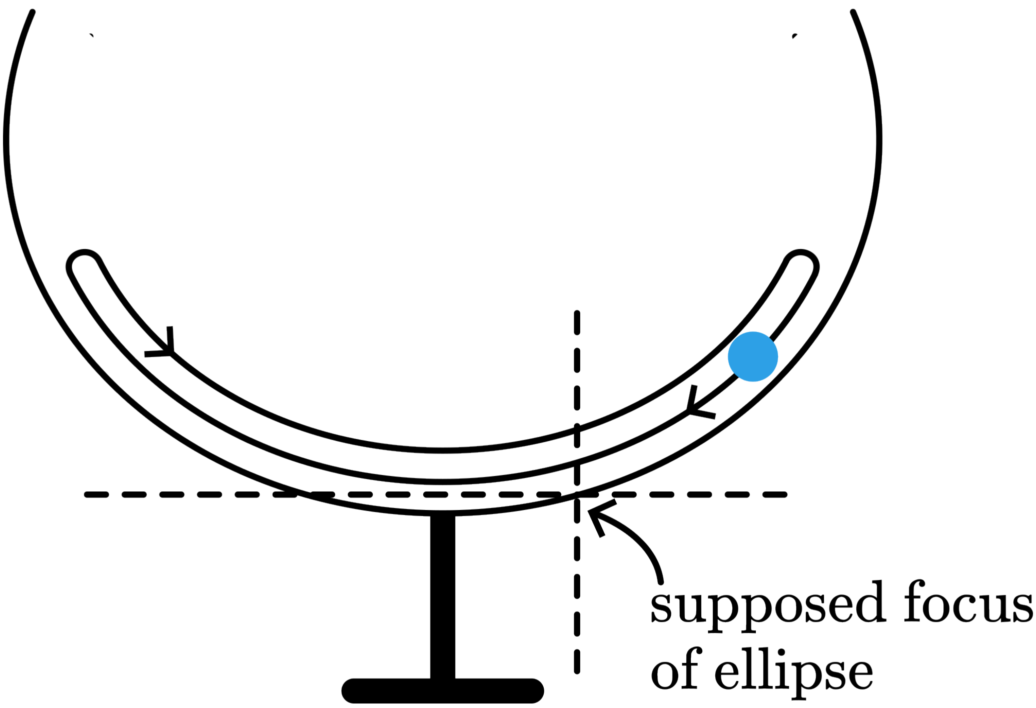


Figure 2.226: .

In case of an ellipse, the situation becomes even worse. Now one focus of the ellipse is off the center of the bowl (see Figure 1) and at $r = 0, U(0) = 0$, but $U'(0)$ is not 0 ! So now:

$$U(r) = U'(0)r + \frac{1}{2}U''(0)r^2 + \frac{1}{6}U'''(0)r^3 ... \tag{2.30}$$

, showing that expressing the potential with respect to a focal point, this potential is still farther away from a r^{-1}-potential. Conclusion is that the bowl only suggests planetary motion (but is in the same time a wrong example of such a motion). The only reason to show it, is to challenge the mind of the students with the question how the shape of the bowl ought to be for a real r^{-1}-potential.

2.12.4.2.7 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 66-68
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 13-14
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 107-108
- McComb,W.D., Dynamics and Relativity, pag. 34

2.12.4.3 03 Precession (4) AND Nutation (3)

2.12.4.3.1 Aim

- To show the combination of nutation and precession.
- To show (pseudo)regular precession.

2.12.4.3.2 Subjects

- 1Q50 (Gyros)

2.12.4.3.3 Diagram

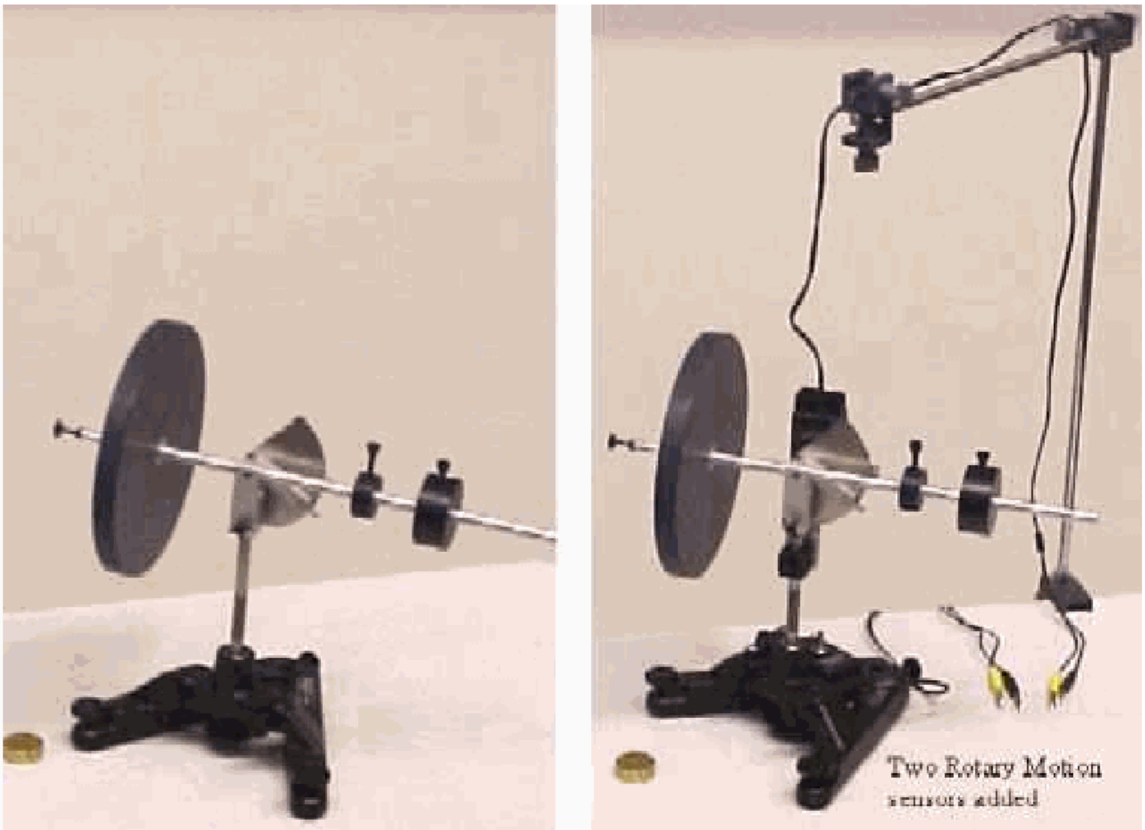


Figure 2.227: .

2.12.4.3.4 Equipment

- Demonstration gyroscope.
- Thread, approximately 1.5 m long, with a loop in the end.
- Slotted mass (150 g).

2.12.4.3.5 Presentation

The gyroscope has its base levelled and its counterweights adjusted until the gyroscope is balanced. The loop of thread is put around the pulley and pulled, to give the disk a high speed of rotation. Observe the direction of rotation and place the gyroscope-axis horizontal. The gyroscope is balanced in this situation.

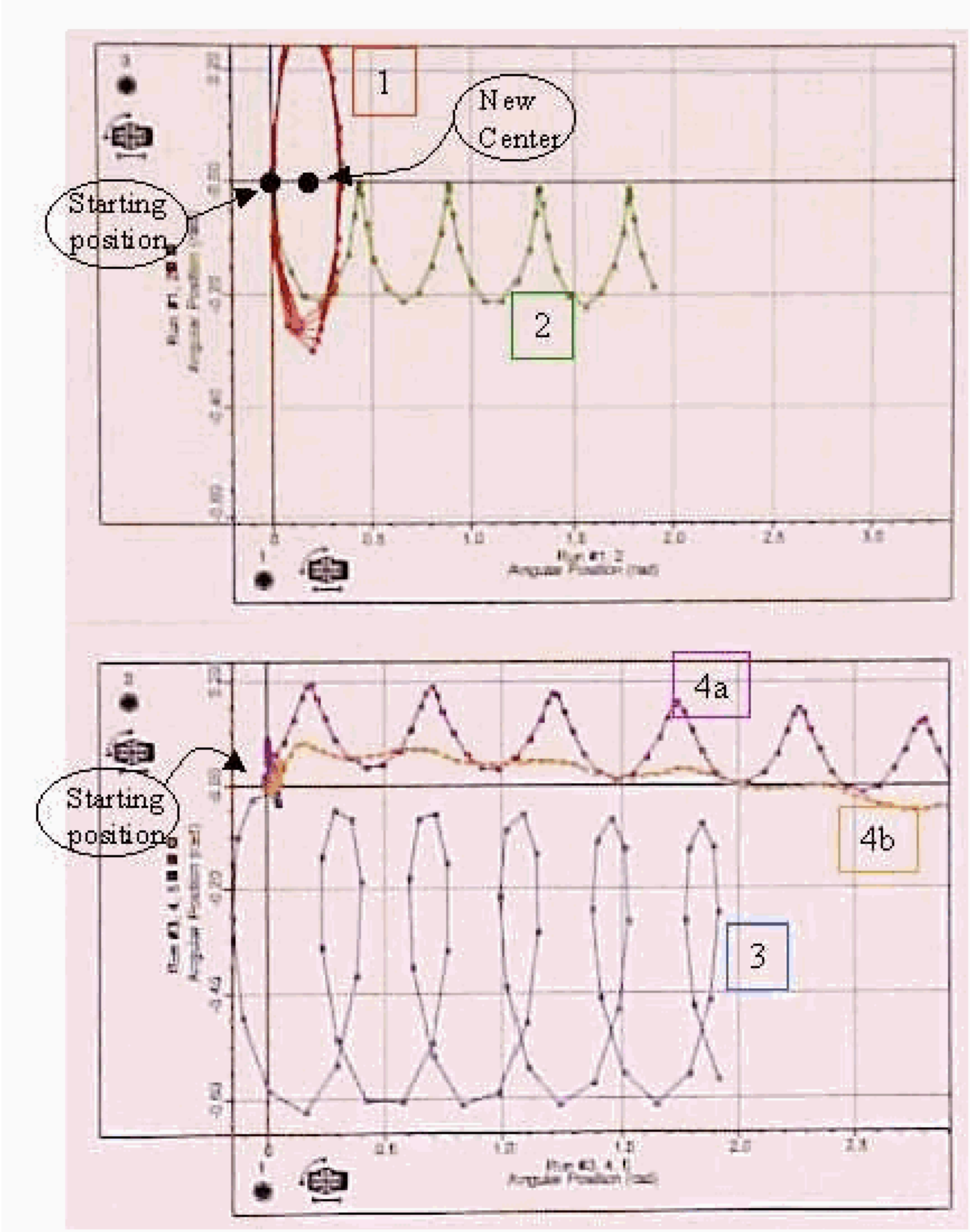


Figure 2.228: .

1. Give by hand a sharp downward blow at the end of the gyroscope-axis. Now the axis moves conically around a fixed center (nutation). This center is a little to the right or to the left (depending on the direction of the disk's rotation) of the initial starting position of the gyroscope-axis (see Figure 2–1; looking at the axes makes that the red figure is in reality a circle).

When this demonstration is repeated with a slower rotating gyroscope-disk, then it will be observed that the resulting nutation frequency is lower.

1. Restart the original horizontally balanced gyroscope rotation at a not too fast speed. While holding the rotation-axis in the horizontal position, the slotted mass is placed on the end of the axis. The gyroscope is released and shows now nutation and precession at the same time. The axis of rotation shows a cycloidic displacement (see Figure 2–2).
2. Restart the original horizontally balanced gyroscope at a not too fast speed. Place again the slotted mass and hold the axis in the horizontal position. Release the gyroscope and on

releasing give it a slight push in the direction opposite to the precession. The cycloidic nutation-pattern will have loops now (see Figure 2–3).

3. Restart the original horizontally balanced gyroscope at a not too fast speed. Place again the slotted mass and hold the axis in the horizontal position. Release the gyroscope and on releasing give it a slight push in the direction of the precession. The sharply-pointed cycloidic pattern becomes more wave-like now (see Figure 2–4a).
4. The slight push in the direction of precession can be made that strong that the nutation (almost) disappears (see Figure 2–4b). This situation is called “regular precession”.

2.12.4.3.6 Explanation

- See Nutation 1 and Nutation 2.
- Ad1. The frequency of nutation (ω_{nu}) equals: $\omega_{nu} = \frac{I_z}{\sqrt{I_x I_y}}\omega_z$

So, ω_{nu} is proportional to the rotational speed of the gyroscope

- Ad2., 3., and 4. See Literature.
- Adding a weight simulates (in an extreme way) the general situation of unbalanced massdistribution. For this reason all rotating real objects show nutation (for instance, the Earth).

2.12.4.3.7 Remarks

- Figure 2 contains data registered on the demonstration gyroscope by using two Rotary Motion sensors (PASCO CI-6538) in combination with PASCO-software (Science Workshop).
- When you are experienced, step 2 - 5 in the Presentation can be performed in one run of the gyroscope, provided the gyroscope is not slowing down too much. But remenber that the audience is not experienced and needs time to digest four different demonstrations! So , no need to hurry.

2.12.4.3.8 Sources

- Magnus, K., Kreisel, pag. 117
- Phywe, University Laboratory Experiments, part Vol. 1-5, pag. 1.2.8.
- Roest, R., Inleiding Mechanica, pag. 222-226

2.12.4.4 04 Precession (2)

2.12.4.4.1 Aim

To show precession (and to show the validity of vector-addition)

2.12.4.4.2 Subjects

- 1Q50 (Gyros)

2.12.4.4.3 Diagram

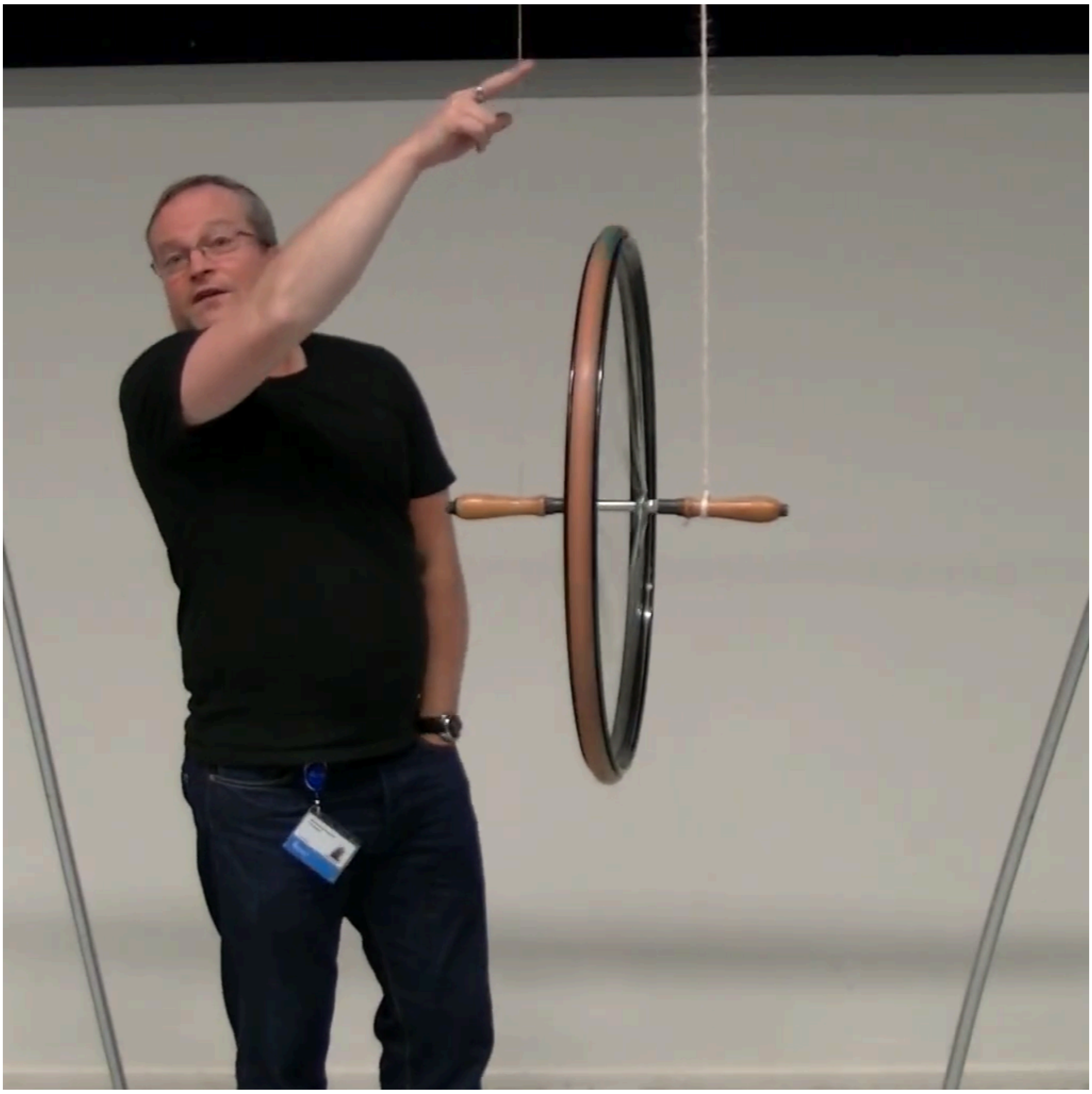


Figure 2.229: .

2.12.4.4.4 Equipment

- Bicycle-wheel with handles.
- 2 pieces of rope.
- Pair of scissors.

2.12.4.4.5 Presentation

The wheel is supported by strings tied to both handles. The wheel is given a fast spin by hand. Now one of the supporting strings is cut. The wheel starts to precess about a vertical axis (while its own horizontal axis of spin slowly descends toward the vertical). As the spin of the wheel diminishes, the wheel precesses more rapidly.

2.12.4.4.6 Explanation

Since angular momentum is a vector quantity that may be conveniently represented by a vector parallel to the axis of spin, the combination of two angular momenta may be treated by the parallelogram law. Thus, whenever a gyroscope is acted upon by a torque tending to produce rotation about an axis perpendicular to the axis of spin, the gyroscope will precess about a third axis perpendicular to the other two.

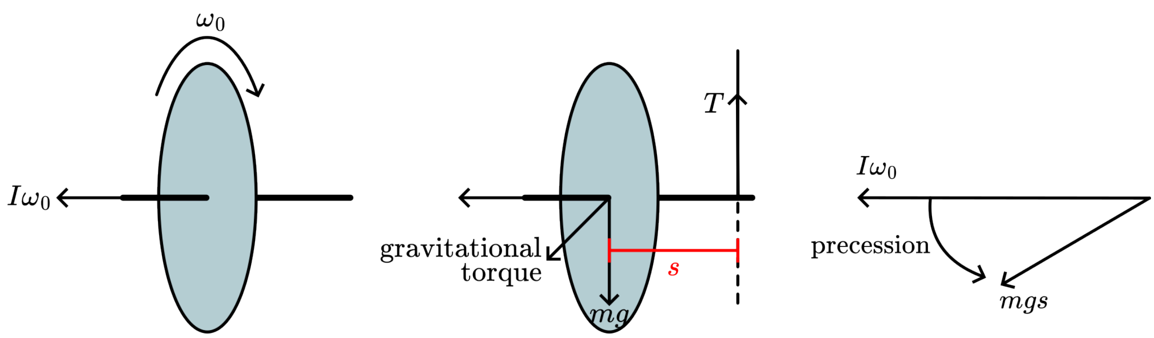


Figure 2.230: .

The spinning wheel has an angular momentum of $I\omega_0$. This is represented by a vector parallel to the axis of spin (see Figure 2 a). When one of the strings is cut, then gravitational torque (mgs) is added to the system (see Figure 2 b). This torque tends to change $I\omega_0$, so $I\omega_b$ moves into the direction of mgs (see Figure 2 c).

It can be shown that the speed of precession $\left(\omega_p\right)$ is given by $\omega_p = \frac{mgs}{I\omega_f}$, so slowing down of ω_0 increases ω_0. The precession will also be more rapid by adding a weight to the unsupported handle.

2.12.4.4.7 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 79

2.12.4.5 06 Nutation (1)

2.12.4.5.1 Aim
To show nutation.

2.12.4.5.2 Subjects
- 1Q50 (Gyros)

2.12.4.5.3 Diagram

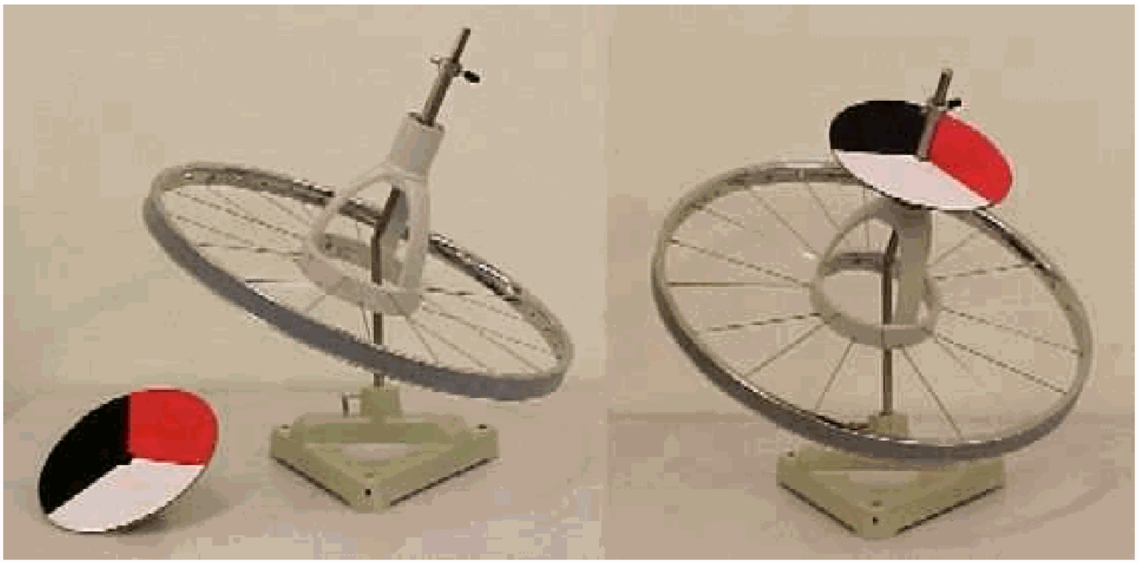


Figure 2.231: .

2.12.4.5.4 Equipment
- Large gyroscope (Leybold 34818)
- Pointed rod
- Rod with cup
- Round disk with red, white and black segments

2.12.4.5.5 Presentation
The pointed support is shifted so that the gyroscope is supported at its centre of gravity. The gyroscope is made spinning at an angle of about 20° with the vertical. The spinning gyroscope remains steady in space.

Now a short blow is given to the axis of the spinning gyroscope. It now performs an additional rotary motion; the axis moves conically. This movement is called nutation. If the colored segment is fixed on the top-side of the ball bearing, the instantaneous axis of spin is made visible. (Individual colors will be seen, but everywhere else they will merge to a uniform 'grey'.)

2.12.4.5.6 Explanation
When the gyroscope is spinning, it has an angular momentum of $I_0\omega_0$ (see Figure 2a). When a short blow is given, an extra angular momentum ($\triangle L$) is added to the spinning wheel (see Figure 2b; the short blow is given to the upper part of the axis in the direction of the observer). This leads to a total angular momentum L, which is constant from then on.

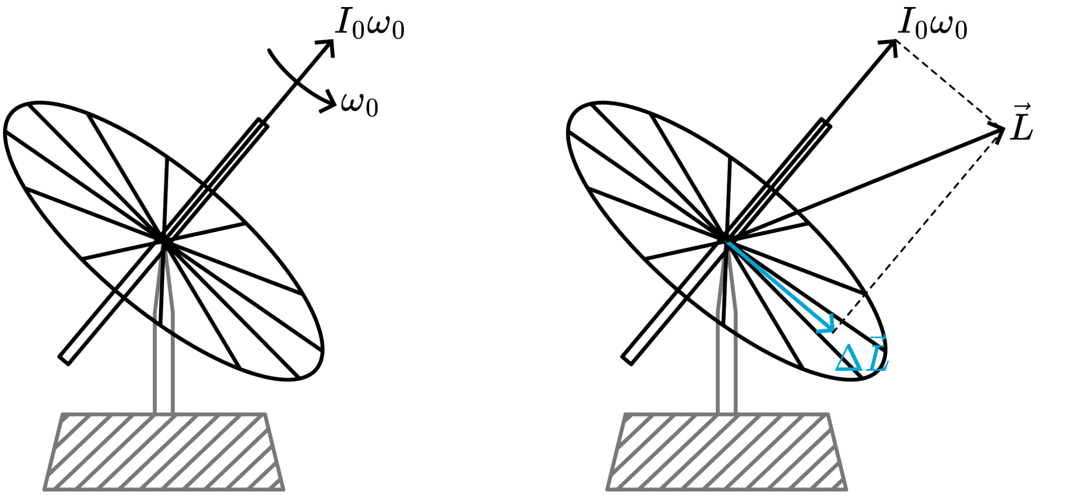


Figure 2.232: .

ΔL corresponds with a rotation $\omega' = \frac{\Delta L}{I'}$. The resultant of ω_0 and ω' is the momentary angular velocity ω (see Figure 3a). This resultant ω does not have the same direction as L, since $I' < I_0$. The constant $\angle$ is, at any moment, the resultant of $I_0\omega_0$ and $I'\omega'$. This is reached only when the gyroscope moves in such a way that in the parallelogram of Figure 3b, the axis of momentary angular velocity moves in a cone around the fixed axis of L. Then also the symmetry-axis of the gyroscope moves in a cone around the axis of L. This cone is called the cone of nutation.

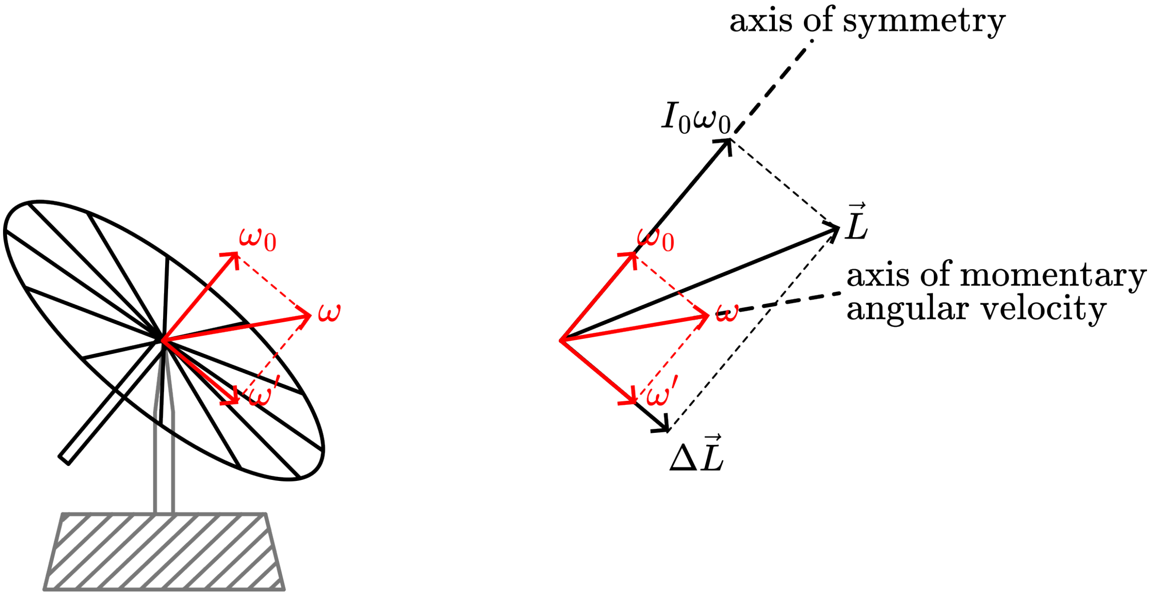


Figure 2.233: .

For the observer in the laboratory, this results in a rotation of the coplanar vectors ω_b, $I_0\omega_b, \omega$, ΔL and ω' around L. The cone described by the symmetry-axis around L is called the cone of nutation; the cone described by ω around L is called the space cone. For the observer in the rotating frame (e.g. seated on the symmetry-axis), the vector ω rotates around this axis, thus describing the so-called body cone. For the observer in the laboratory, this cone is not stationary, but moves around the space cone. Notice that the space cone and the body cone have the vector win common.

2.12.4.5.7 Remarks

- See also the description of the demonstration Nutation.

2.12.4.5.8 Sources

- Roest, R., Inleiding Mechanica, pag. 223
- Borghouts, A.N., Inleiding in de Mechanica, pag. 225
- Leybold Didactic GmbH, Gerätekarte, 34818

2.12.4.6 07 Nutation (2)

2.12.4.6.1 Aim

To give a geometric description of nutation

2.12.4.6.2 Subjects

- 1Q50 (Gyros)

2.12.4.6.3 Diagram

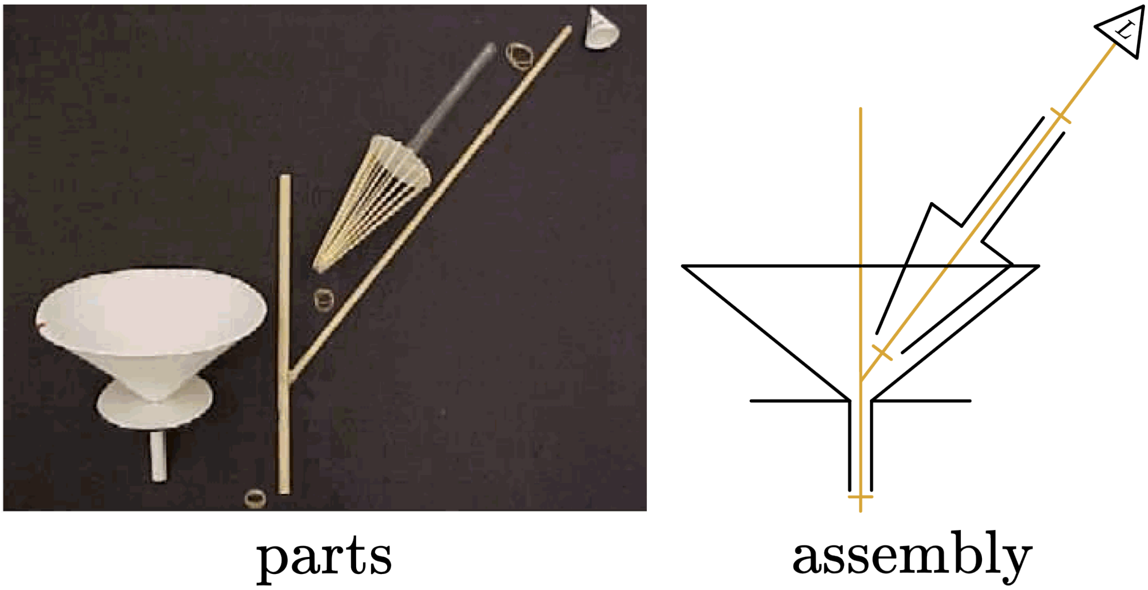


Figure 2.234: .

2.12.4.6.4 Equipment

- Model (see Diagram and Figures).

2.12.4.6.5 Presentation

Watching a nutating object we observe that the body-axis makes a conical movement (see Nutation. This movement of the body-axis is visualized in our model by rotating the L-axis by hand (see Figures).

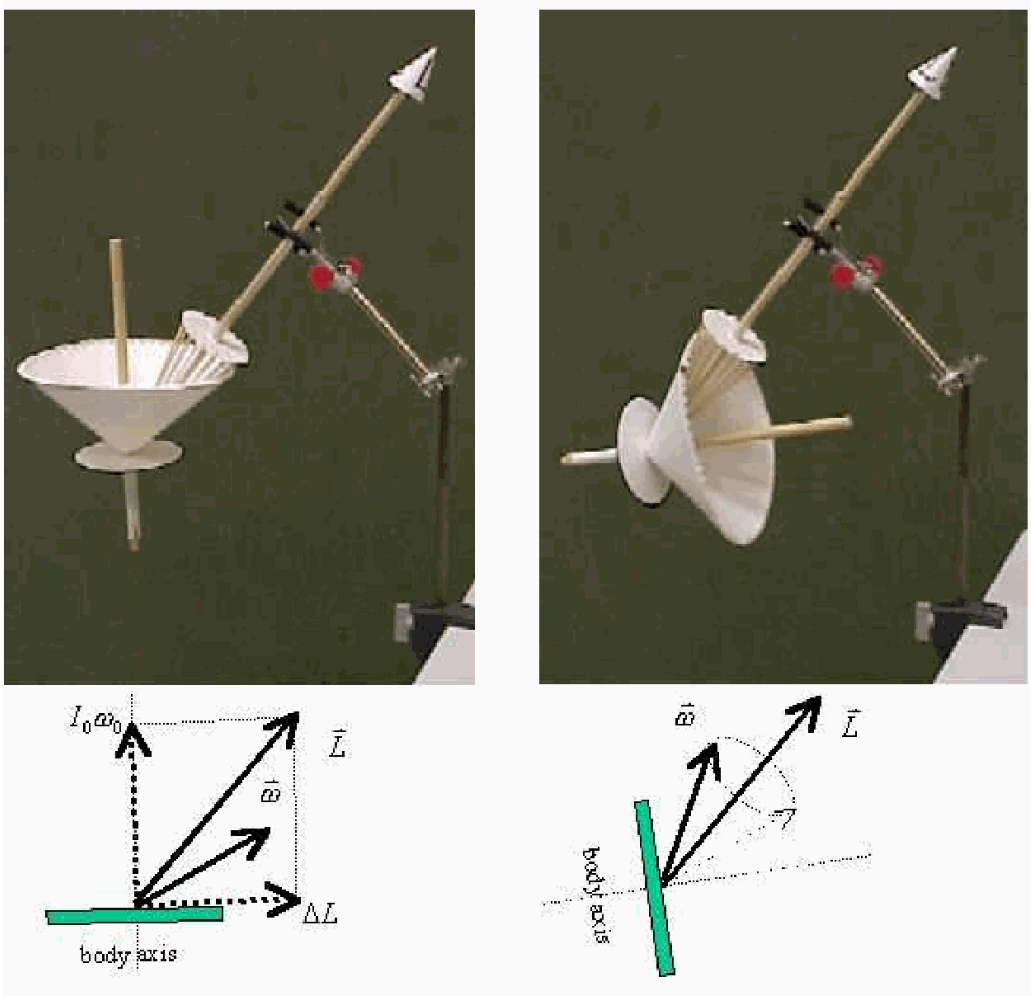


Figure 2.235: .

2.12.4.6.6 Explanation

L, wand body-axis are in one plane. While moving, L remains fixed in space, so movement of that plane has to take place around L.

The fixed cone (so-called "space cone") contains wand this ω turns around L. To show the position of ω with rerspect to the body axis, a cone around the body-axis (so-called body-cone) is visualized. This body-cone also contains ω. So in our model the position of ω is seen where the two cones touch each other. While rotating, the movement of the body-axis around L (nutation) and the movement of the momentary rotation-axis (ω) around the symmetry-axis can be observed.

2.12.4.6.7 Remarks

- The model is made in such a way that the two cones grip each other (teeth on the inside of the rim of the body-cone grip the wooden bars of the space-cone), so that the cones are not slipping. This is needed since there is only one ω while in our model ω is in two cones.
- Our model represents the movement of a disk-shaped nutating object ($I_3 > I_1$). Visualizing of a nutating bar-shaped object ($I_1 > I_3$) needs a model having the body-cone revolving with its outside around a fixed space-cone.

2.12.4.6.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 224-227
- Roest, R., Inleiding Mechanica, pag. 222-226 Nutation (2)

2.12.4.7 08 Precession (3a)

2.12.4.7.1 Aim

To show how a rotating wheel reacts to an applied torque.

2.12.4.7.2 Subjects

- 1Q50 (Gyros)

2.12.4.7.3 Diagram

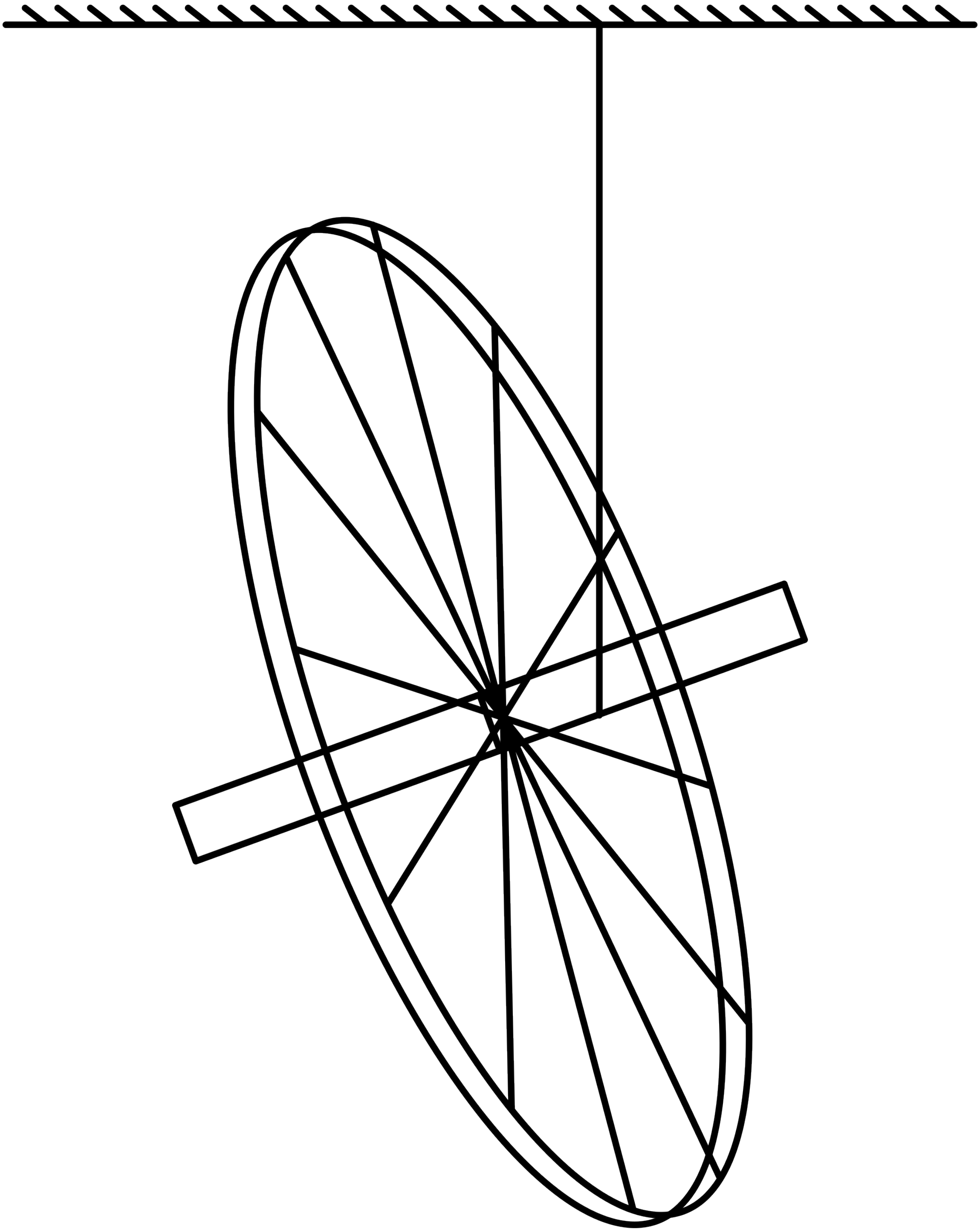


Figure 2.236: .

2.12.4.7.4 Equipment

- bicycle wheel with handles

- 1 piece of rope
- 1 stick

2.12.4.7.5 Presentation

The wheel is rotating and held by a string. The rotating wheel has an angle of about $45° - 60°$ with the vertical. The wheel will precess about a vertical axis. When the instructor pushes with the side of his hands or a stick against one of the handles of the wheel in the direction of precession, then the rotating wheel will rise to a more vertical position. This can be continued, even passing the vertical.

2.12.4.7.6 Explanation

The rotating wheel will precess due to gravitational torque, mgs ($I\omega_0$ moves in the direction of this gravitational torque; precession) (see Figure 2a).

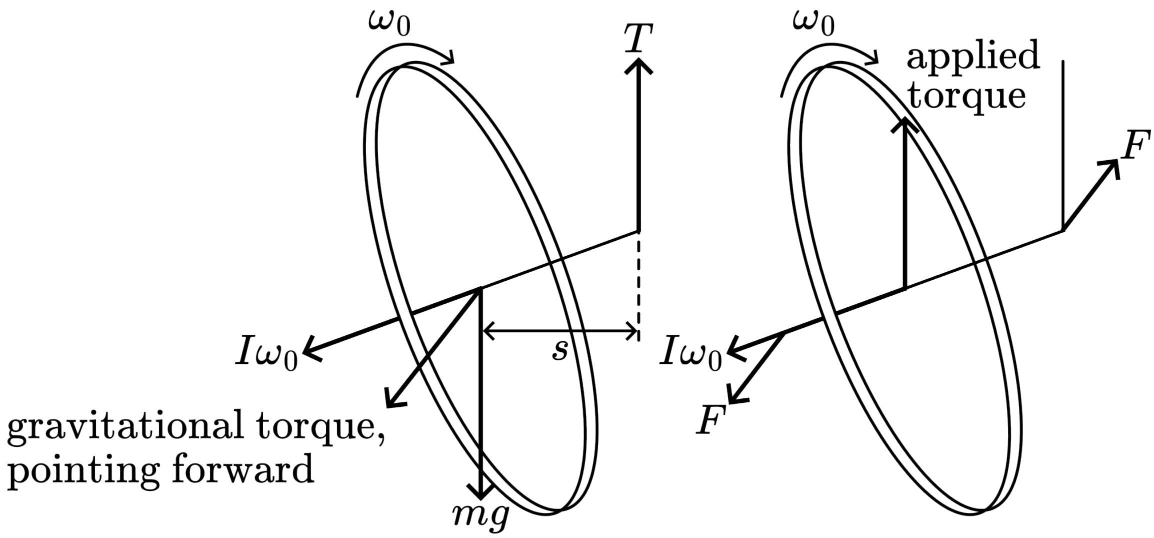


Figure 2.237: .

F is the applied force in the direction of precession (see Figure 2b). The applied torque is pointing vertically upward, so now $I\omega_0$ moves also upward.

2.12.4.7.7 Video Rhett Allain

(a)

(b)

Figure 216: :align: center - Scan the QR code or click here to go to the video.

2.12.4.7.8 Sources

- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. M-53
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 79

2.12.4.8 09 Precession (3b)

2.12.4.8.1 Aim
To show how a rotating wheel reacts to an applied torque.

2.12.4.8.2 Subjects
- 1Q50 (Gyros)

2.12.4.8.3 Diagram


Figure 2.241: .

2.12.4.8.4 Equipment

- bicycle wheel with handles
- rotating platform
- support rods and clamps
- rotatable (hinged) clamp

2.12.4.8.5 Presentation

The bicycle wheel with handles is vertically mounted on a rotating platform in such a way that one handle is fixed in a hinged clamp and the other handle rests on a support (see diagram). The bicycle wheel is made fast spinning.

Now the rotating platform is slowly turned round by hand, trying both directions of rotation. In one direction of rotation, the spinning bicycle wheel will lift its free handle upwards from the support.

As soon as you stop speeding up the rotating platform, the lifting of the spinning bicycle wheel will stop also.

Leaving the spinning bicycle wheel to itself now, it slowly comes down, and the rotating platform speeds up.

2.12.4.8.6 Explanation

The spinning bicycle wheel has an angular momentum of $I_1\omega_0$. Rotating the platform, introduces a torque T. This torque tends to change $I_1\omega_0$, so $I_1\omega_b$ moves into the direction of T. So, when T is pointing upward, $I_1\omega_0$ moves upward: the bicycle wheel handle lifts itself from the support. (See Figure 2a.)

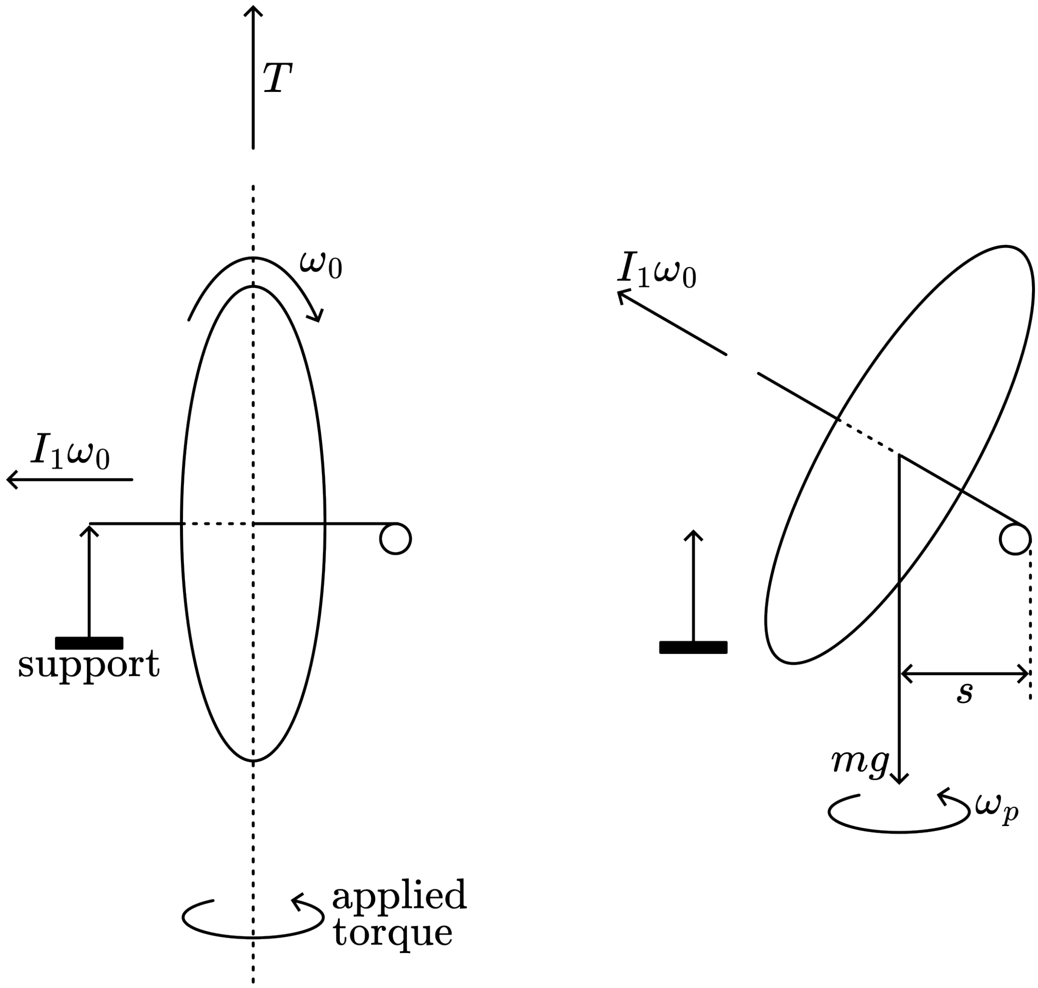


Figure 2.242: .

While the platform is freely rotating, gravitational torque mgs is acting (see Figure 2b). In Figure 2b this torque is pointing out to the reader. $I_1\omega_0$ moves into the direction of mgs, keeping the platform rotating (precession). In this process, increases because the bicyclewheel is coming down. Since $\omega_p = \frac{mgs}{I_0\omega_0}$, ω_p increases due to s becoming larger (and also a little due to ω_0 becoming smaller).

2.12.4.8.7 Remarks

- Our setup is in such a way that s changes substantially when the wheel comes down. When our wheel is at about 45°, $s = 0$.
- Take care that the bicycle wheel is not lifted more than 45°, because then it surpasses the hinge and falls down to the other side, slamming the support-rods and clamps!

2.12.4.8.8 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 79

2.12.5 1Q60 Rotational Stability

2.12.5.1 02 Dumb-Bell

See [Dumb-Bell](../../1Q40 Cons of Angular Momentum/1Q4007 Dumb Bell/1Q4007.md)

2.12.5.2 03 Stable Wheel

2.12.5.2.1 Aim

To show how a rolling bicycle wheel “organizes” its stability.

2.12.5.2.2 Subjects

- 1Q60 (Rotational Stability)

2.12.5.2.3 Diagram

Figure 2.243: .

2.12.5.2.4 Equipment

- Small bicycle wheel; $\emptyset = 40$ cm (or any other wheel or disc).

2.12.5.2.5 Presentation

- Place the wheel upright on the floor. On release it falls down immediately.
- Then the wheel is released while turning. It rolls over the floor and remains upright for a much longer time.

The second observation made is that it will follow a curve when it starts falling down. Also notice that the curve it makes, is into the direction of the “falling down” (see Figure 2).

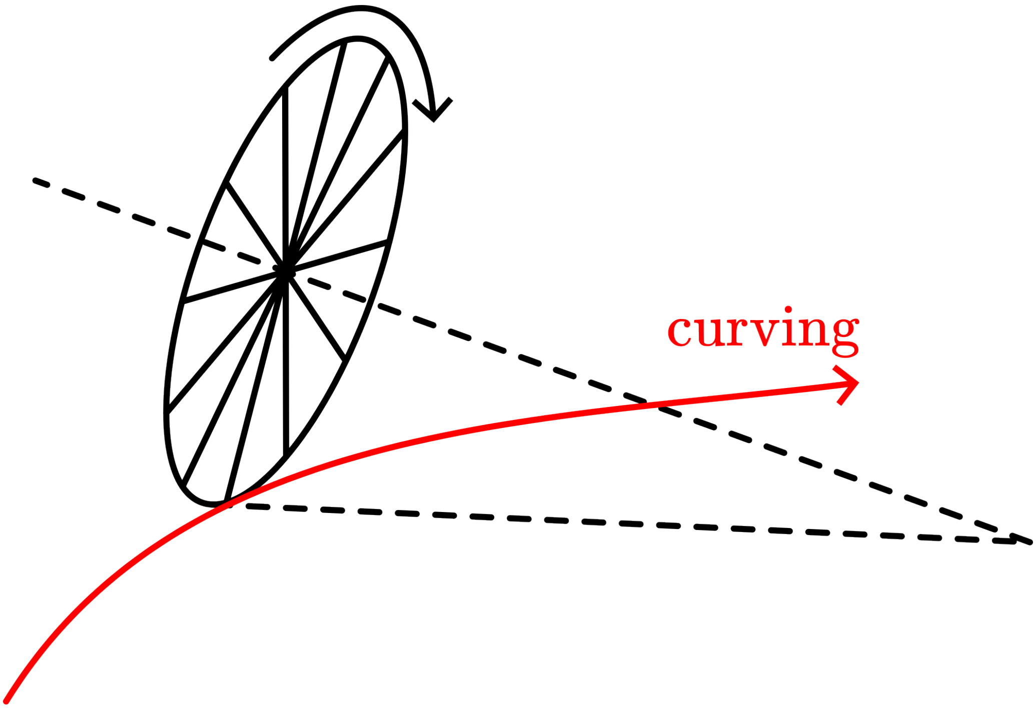


Figure 2.244: .

2.12.5.2.6 Explanation

Figure 3A shows the wheel turning. The rotation is indicated by means of the vector $\underline{\omega}$. Due to some disturbance, the wheel inclines due to gravity: a torque (τ) is acting on the wheel (see Figure 3).

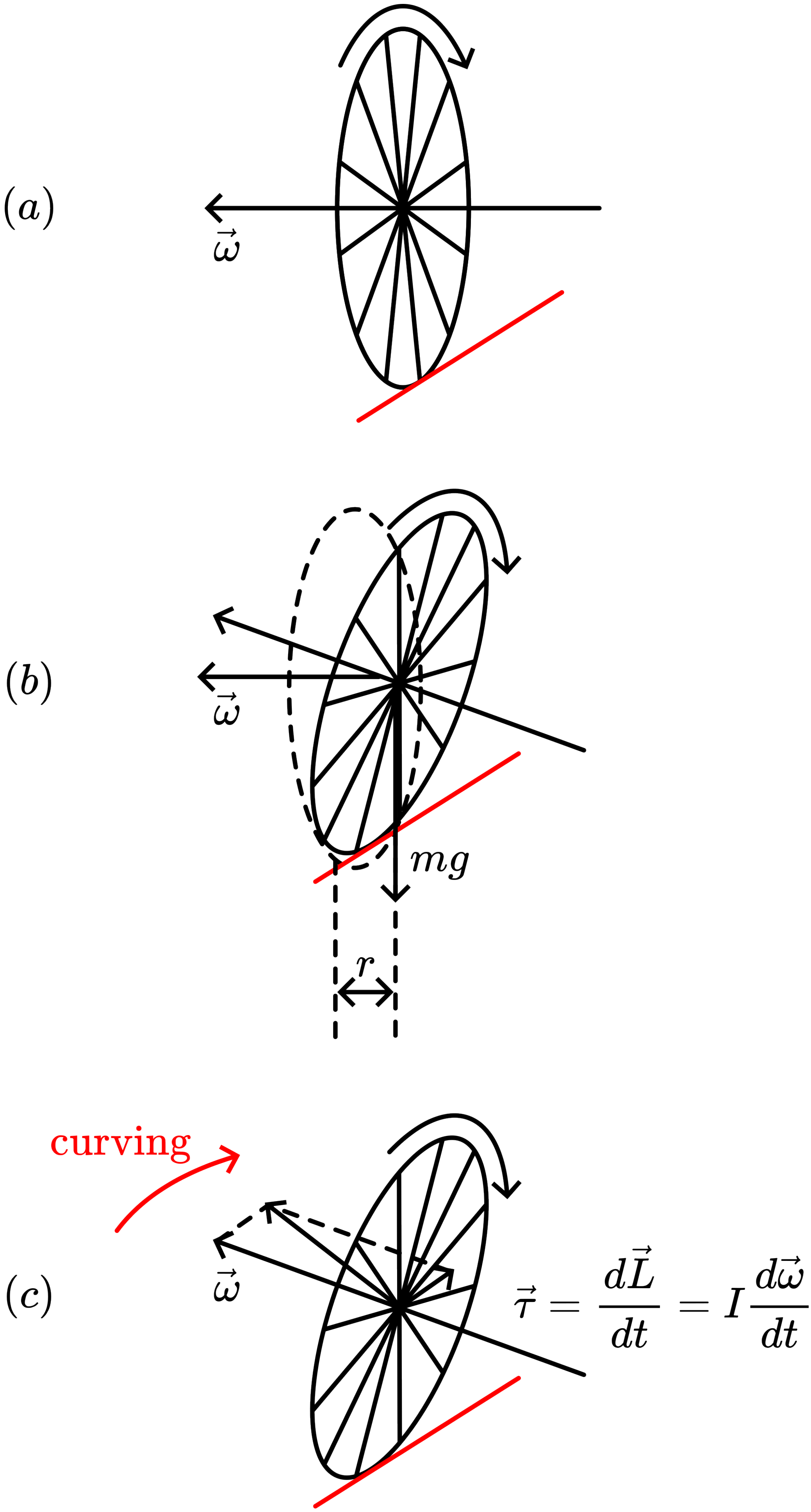

(a)
$\vec{\omega}$
(b)
$\vec{\omega}$
mg
r
curving
(c)
$\vec{\omega}$
$\vec{\tau} = \frac{d\vec{L}}{dt} = I\frac{d\vec{\omega}}{dt}$

Figure 2.245: .

Due to this torque the direction of the vector $\underline{\omega}$ is changed: $\underline{\omega}$ is changed into the direction of τ (see Figure 3C), so the wheel will make a curve while rolling. This continues because the vectors $\underline{\omega}$ and τ remain perpendicular to each other.

Also can be seen now that the larger the inclination, the sharper the curve it will make since vector $\vec{r}$ increases, making $\overrightarrow{tau}$ larger.

2.12.5.3 04 Percussionpoint (1)

2.12.5.3.1 Aim

To show the behavior of a stick to a short impulse.

2.12.5.3.2 Subjects

- 1Q60 (Rotational Stability)

2.12.5.3.3 Diagram

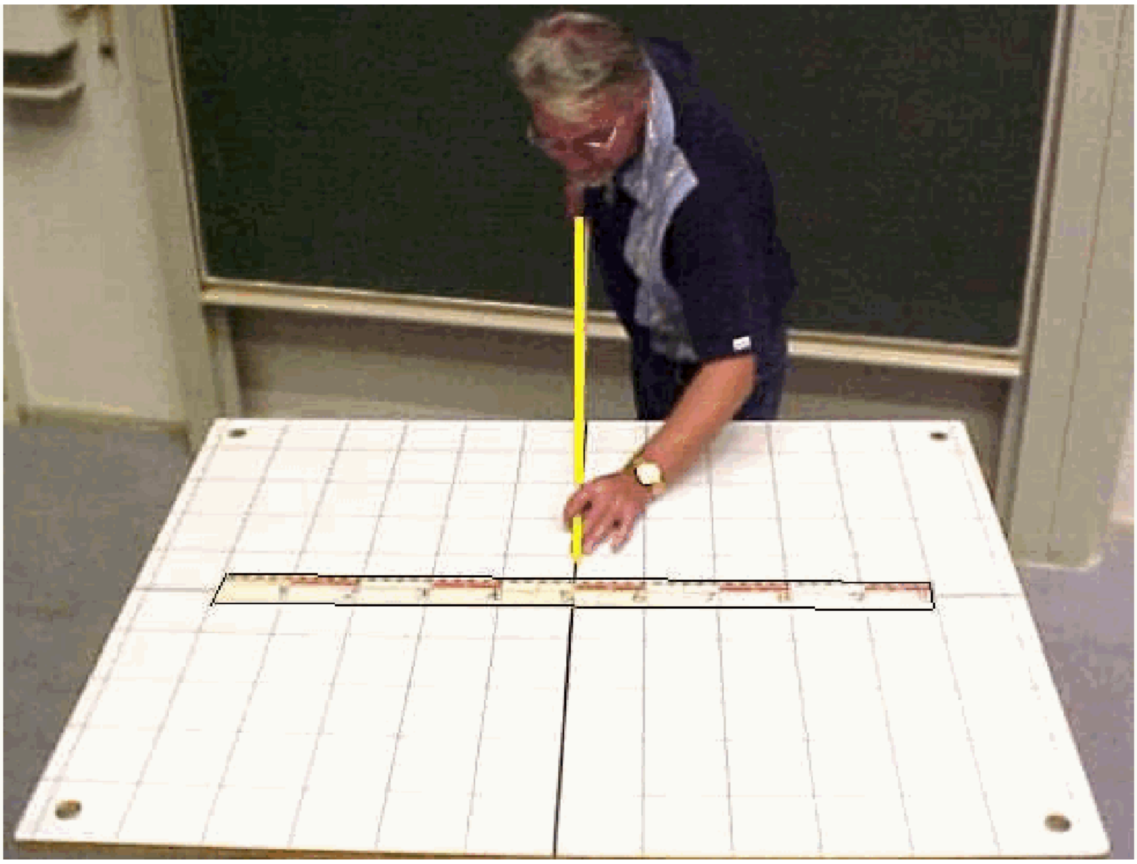


Figure 2.246: .

2.12.5.3.4 Equipment

- Platform with grid, used as reference.
- Ruler, 1 m.
- Stick.

2.12.5.3.5 Presentation

1. Place the ruler with its centerline on the thick centerline of the grid (see Diagram). With the stick you give a short blow to the center of the stick (a movement like you are playing pool-billiards). There will result a translation of the stick.
2. Again place the ruler with its centerline on the grid. With the stick you give a short blow to the ruler e.g. at 60 cm. There will result a translation and rotation of the stick.
3. With the stick you give a short blow to the ruler at 100 cm. There will result a translation and rotation of the stick. Special is that it rotates around the point of 33 cm on the ruler.
4. With the stick you give a short blow to the ruler at 67 cm. There will result a translation and rotation of the stick. Special is that it rotates around the beginning of the stick.

The point, around which the stick rotates is called "percussion point". In point 3 and −4 , this point is on the stick; in point 2 it is outside the stick.

2.12.5.3.6 Explanation

Due to the short blow, the ruler performs a movement that can be considered as consisting of two movements: a translation and rotation around its center of mass CM (see Figure 2).

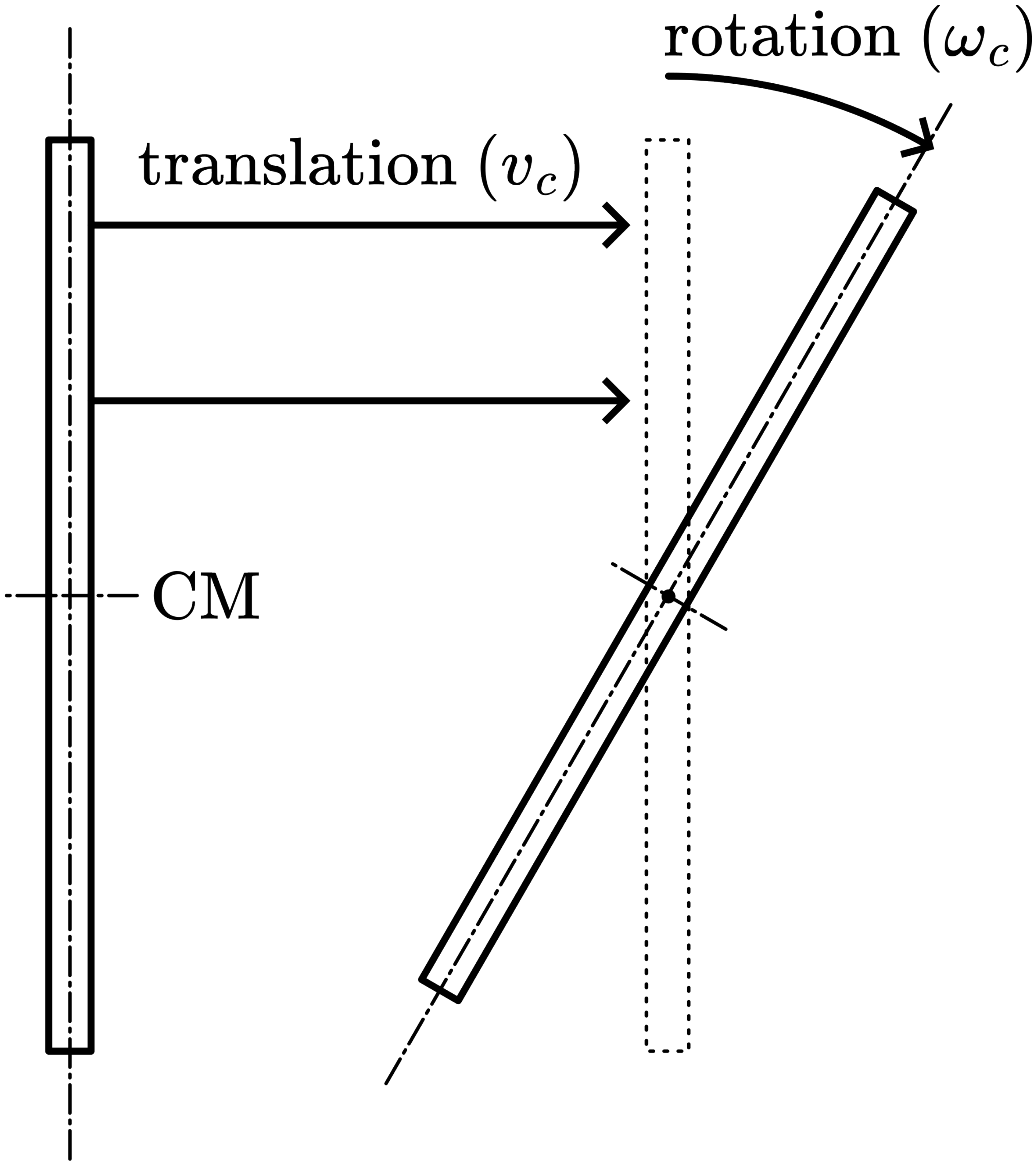


Figure 2.247: .

During the short blow force acts on the ruler. The total momentum of this force is $\int F dt = p$. The ruler gets a speed v_c, so the momentum of the ruler is mv_c. This makes $v_c = p/m$.

Relative to CM the ruler has also an angular momentum $I_c\omega_c = bp$ (see Figure 3). So $\omega_c = bp/I_c$ On one side of CM, v_c and ω_c have the same direction; on the other side v_c and ω_c are opposite to each other. Looking at point A: $v_A = v_c - \omega_c x$. When point A remains at rest after the blow (A is then the so-called percussion point) then $0 = v_c - \omega_c x$. This happens at $x = \frac{v_c}{\omega_c} = \frac{p/m}{bp/I_c} = \frac{I_c}{mb}$. For this ruler: $I_c = 1/12ml^2$, making $x = \frac{1}{12}\frac{l^2}{b}$.

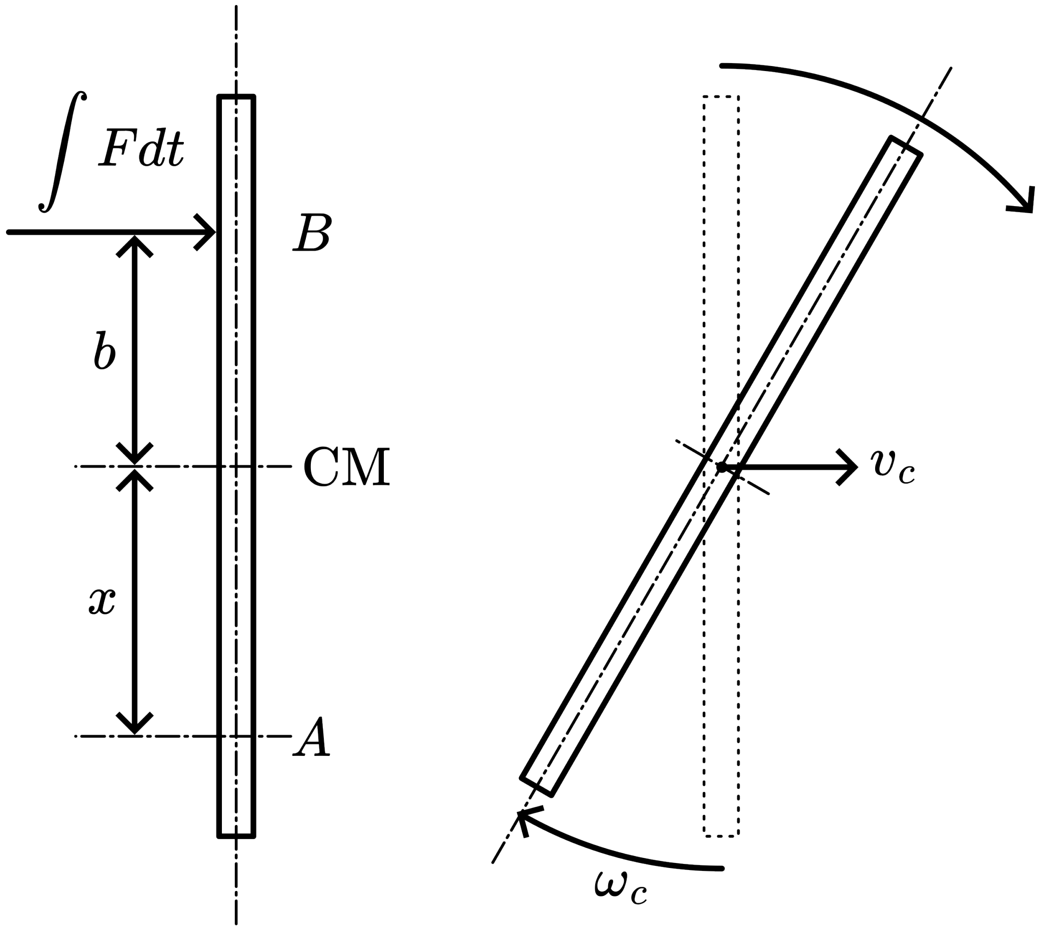


Figure 2.248: .

Applying this to the different situations of the Presentation shows the observed percussion points: in PresentationXX point 1 ($b = 0$), point 3 ($b = .5$ m) and point 4 ($b = .17$ m). In PresentationXX ($b = .1$ m), the percussion point is outside the ruler ($x = .83$ m).

2.12.5.3.7 Remarks

- Playing billiards with a stick instead with a ball needs practice!

2.12.5.3.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 182-183
- Roest, R., Inleiding Mechanica, pag. 172-173 and 176-177

2.12.5.4 05 Percussionpoint (2)

2.12.5.4.1 Aim

To show what any batter can tell you: if you hit the ball at a certain point, there will be no impulse transferred to your hands (the batter experiences no “sting”).

2.12.5.4.2 Subjects

- 1Q60 (Rotational Stability)

2.12.5.4.3 Diagram

Figure 2.249: .

2.12.5.4.4 Equipment

- Baseball bat and “cradle” (see Figure 2A).
- Meter stick.
- Mathematical pendulum.
- Rubber hammer.

2.12.5.4.5 Presentation

1. The meterstick is suspended as a physical pendulum. The point of suspension is the percussion point when the stick is hit at about 67 cm (see demonstration Percussion point. The distance of 67 cm is also the reduced length of this pendulum (see demonstration Physical pendulum (1). This is quickly shown by suspending a “mathematical” pendulum close to the suspended stick (see the arrangement on the left side of Diagram) and making both swing: when the “mathematical” pendulum has a length of 67 cm, they will have the same period; swinging together, they stay together. The conclusion can be that when you hit the stick at the point of reduced length, the point of suspension will be the percussion point.
2. The baseballbat has a hole drilled in its shaft at the point between the two hands that would grasp the bat. In this hole a bar is stuck, extending on both sides. These ends rest on the flat surfaces of the “cradle” (see Figure 2A), so the bat can rock to and fro.

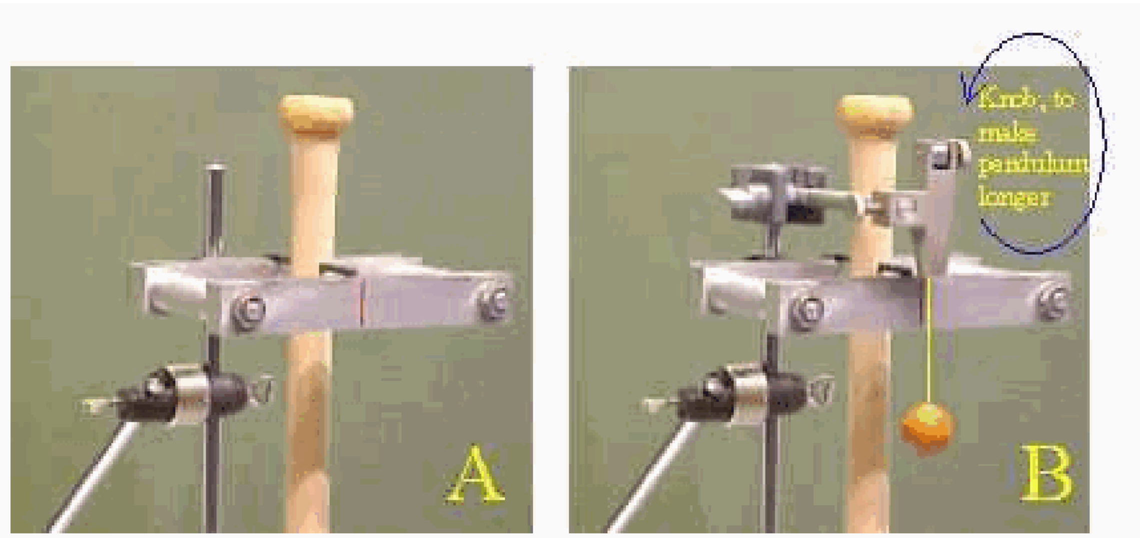


Figure 2.250: .

Using the rubber hammer, the bat is hit close to its point of suspension: The bat swings and on its horizontal surfaces of suspension it also displaces itself into the direction the hammer was hitting.

Then the hammer hits the bat at its lowest point. Again the bat swings, but now the displacement on the surface of suspension is into a direction opposite to the hitting hammer.

Conclusion will be that somewhere in between, the bat can be hit causing only a rotation at the suspension point. (By trial and error this point can be located.) We mount the mathematical pendulum close to the bat (see Figure 2 B) and increase its length until it swings with the same period as the free suspended bat does. Then we hit the bat at the point indicated by the bob of the mathematical pendulum, and the bat only rotates at the suspension point; there is no translation.

2.12.5.4.6 Explanation

In the Explanation of the demonstration Physical pendulum (1), it is shown that the reduced length of a physical pendulum equals $\frac{I_c}{\mathrm{ms}} + c$. In the Explanation of the demonstration

Percussion point it is shown that $x = \frac{I_c}{mb}$, while the percussion point is b + x away from the point of hitting. Comparing both explanations, it is easy to see that $\frac{I_c}{mc} + s = \frac{I_c}{mb} + b$:

The distance to the percussion point is equal to the reduced length.

2.12.5.4.7 Remarks

- The flat surfaces of the cradle are covered with sandpaper and the extending shafts of the bat are fitted with a tight rubber hose. This is done to have just enough friction.
- Use a water level to mount the cradle. That's why we install the extra slanting shaft that is protruding backward (see Diagram).
- The situation where the percussion point is at the point of suspension is not the situation for maximum energy transfer to the ball (see demonstration Sweet spot in this database).
- In some literature not the point of pure rotation is called percussion point. Then that name is given to the point where the ball hits the bat and makes it rotate around the point of suspension without translation; so just the other way round.

2.12.5.4.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 182-183
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 355
- Roest, R., Inleiding Mechanica, pag. 176-177
- Young, H.D. and Freeman, R.A., University Physics, pag. 327-328

2.12.5.5 06 Sleeper

2.12.5.5.1 Aim

To show how a spinning top rises itself to a vertical spin

2.12.5.5.2 Subjects

- 1Q60 (Rotational Stability)

2.12.5.5.3 Diagram

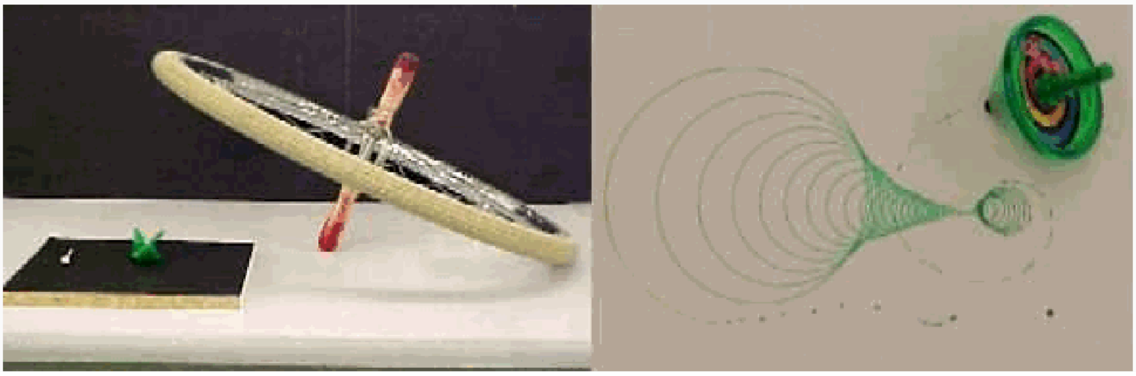


Figure 2.251: .

2.12.5.5.4 Equipment

- Small top
- Top with felt-pen
- Bicycle wheel with handles, the handles fixed
- Hard surface to spin the tops on
- White standard hardboard (about $50 \times 50\ \mathrm{cm}^2$)

2.12.5.5.5 Presentation

- Spin the small top with a quick snap of your fingers, in such a way that the top starts spinning having its spinning axis make a quite large angle with the vertical. The top runs in an arc and very soon stands vertically upright. When disturbing this upright position the vertical position returns very quickly; the vertical position appears to be very stable.
- Take the top with the felt-pen and spin this top with a quick snap of your fingers on the white hardboard. This top will move in the same way as the small top we started the demonstration with, but now it traces the way the top moves because it is drawing its track on the white hardboard. We see that the top moves in a converging spiral, meanwhile lifting itself to the vertical. (See Diagram. In this figure the spiral moves to the right, because the board is not completely horizontal.)

When the top slows down, it increases its angle with the vertical and finally topples down (see the last part of the track in Diagram).

- The same demonstration as the foregoing can be done with a bicycle wheel with handles, having the handles fixed to the wheel. The handles should be smoothly rounded and the bicycle wheel should be carefully dynamically balanced. With this bicycle wheel the same observations can be made as with the foregoing demonstrations. However, one observation can be added: When finally the bicycle wheel spins with its axis vertical, after some time it will slow down and the spinning axis moves away from the vertical but then suddenly the supporting handle slips strongly and immediately the spinning wheel lifts itself again. This repeats itself a number of times until finally the wheel topples. (When the bicycle wheel is spinning on a table you can also hear the moments the wheel slips strongly. Then this sound is immediately accompanied with the lifting to the vertical of the bicycle wheel.)

2.12.5.5.6 Explanation

The top, being almost a free body, moves around its centre of mass (CM), which remains stationary.

Due to its tilted position, the spinning top will precess ($I_0\omega_0$ moves into the direction of gravitational torque T_p, see Figure 2a.).

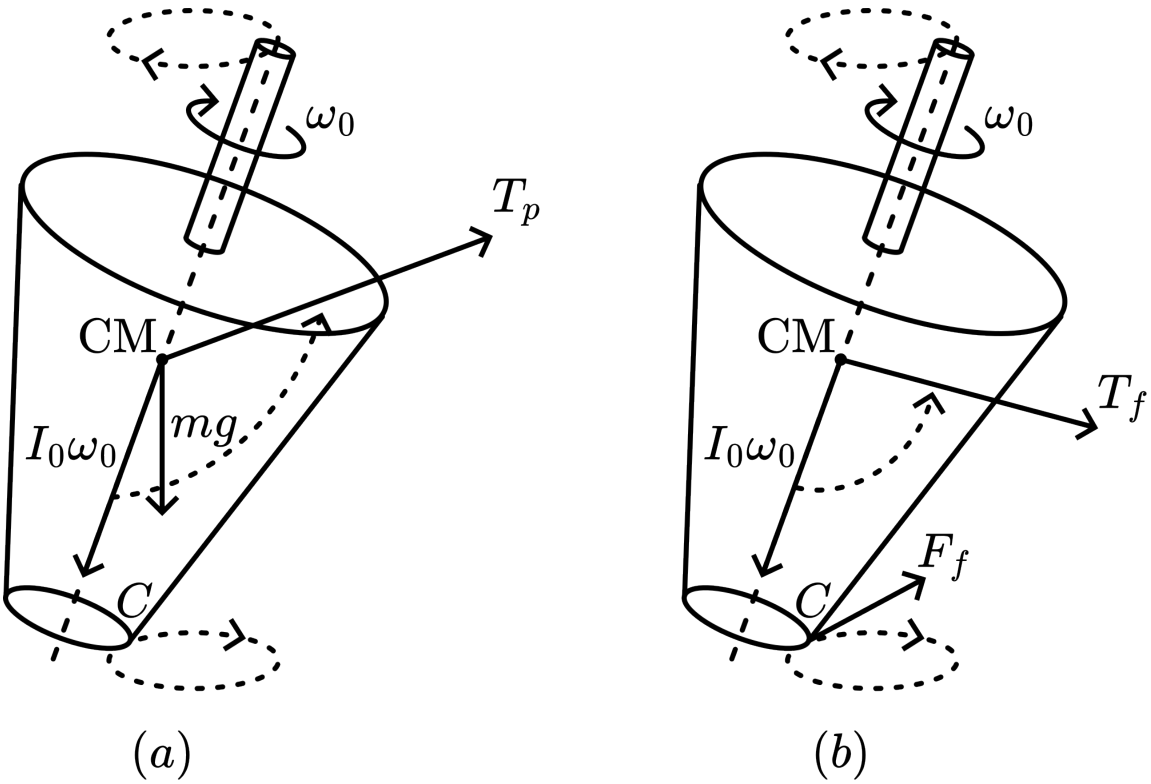


Figure 2.252: .

As a result the rounded stem of the top is attempting to roll over the floor in two ways: one due to the spin of the top around its body-axis and the other due to precession driving the stem over the floor. The first way is much faster than the second and so the rounded stem slips: it slips into the direction of spin. The friction force on the stem in point C is opposite to the slip, so friction is directed backwards (see Figure 2b). The torque of this friction force (T_f) is almost perpendicular to $I_0\omega_0$, so $I_0\omega_0$ continues to rise until the top is positioned vertical (T_f will tend to align $I_o\omega_0$). The orientation of the top follows that of $I_0\omega_0$, and the top rights itself.

Once perfectly vertical the friction force is no longer present, but any disturbance moving the top away from the vertical immediately introduces a raising torque again, restoring its vertical position.

While moving to the vertical the track of precession will have a smaller radius of curvature, so while raising, we will see a converging spiral ending in a point.

Due to dissipation the spin of the top is slowed down and a point will be reached when slipping stops. Consequently the raising torque is no longer present: the top topples.

2.12.5.5.7 Remarks

- Tops having a large radius of curvature have more trouble to rise to the vertical. (They loose too much energy while slipping before reaching the vertical.)

- When you have enough experience throwing the top with the felt-pen you can make it turn on an overhead-projector, so a large group of students can see the spiral-movement.
- See also the demonstrations Precession 3a and Precession 3b in this database where it is shown how a precessing object reacts to an applied torque.

2.12.5.5.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 230-232
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 233-234
- Roest, R., Inleiding Mechanica, pag. 230-231

2.12.5.6 07 Tippe Top

2.12.5.6.1 Aim

To show and explain the fascinating behaviour of a tippe top

2.12.5.6.2 Subjects

- 1Q40 (Conservation of Angular Momentum) 1Q60 (Rotational Stability)

2.12.5.6.3 Diagram

Figure 2.253: .

2.12.5.6.4 Equipment

- 3 tippe tops (see Diagram).
- White standard board (about). 50×50 cm^2
- Spray can with paint.
- Overheadsheet, showing that picture of Pauli and Bohr observing a spinning tippe top.
- Round transparent disc with arrow painted on it to show the sense of rotation.

2.12.5.6.5 Presentation

- Spin the tippe top (nr.1) with a quick snap of your fingers. It will spin with its hemispherical bottom downwards. After a short time the top turns over and spins on the stem. It continues to rotate on its stem, slows down and finally falls, resuming its position with stem up.
- Take tippe top nr.2, with the arrows painted on it. Repeat what seems to be the motion of the top without actually releasing it, that is: hold the stem of the top in the normal starting position (stem up) and twist the stem between thumb and forefinger, in the direction of the arrows painted on it. At the same time rotate the hand slowly to invert the top. The audience can clearly see that the inverted top continues to rotate in the direction of the arrow, but seen from the outside the sense of rotation is in the opposite direction. When you show this to a large audience you can use the transparent disc with the arrow painted on it to show this.

Now spin the arrowed top as in the first demonstration and when it inverts itself ask the audience to determine the actual direction of spin by close observation. Everybody can see that the inverted top is spinning opposite the direction of the arrows painted on it!

- Take tippe top nr.3, with the lines painted on it. Spin this top with a quick snap of your fingers. First the top spins on its hemispherical bottom and the lines appear blurred. When the top has inverted itself and spins on its stem the lines also appear blurred. But in between these two positions lines can be seen on the top, so in this in-between position the top is not spinning around its body axis. This happens when the top has its body-axis more or less horizontal.

- Take the white board and spray a paint-layer on its surface. Take tippe top nr. 1 and spin it in the normal way on this painted surface. After it has spun with finally stem up take the top and observe the track on its sphere (see picture in Diagram). Clearly can be seen that going from hemisphere to stem there is an inversion of direction (close to the equatorial line on the tippe top; the spinning position with body-axis horizontal).

2.12.5.6.6 Explanation

The top consists of a hollow sphere that is sliced off with a stem attached to it. This top is in stable static equilibrium when it points its stem upward, so the centre of mass (CM) is below the centre of curvature (C). This top is given a spin ω_0 (see Figure 2).

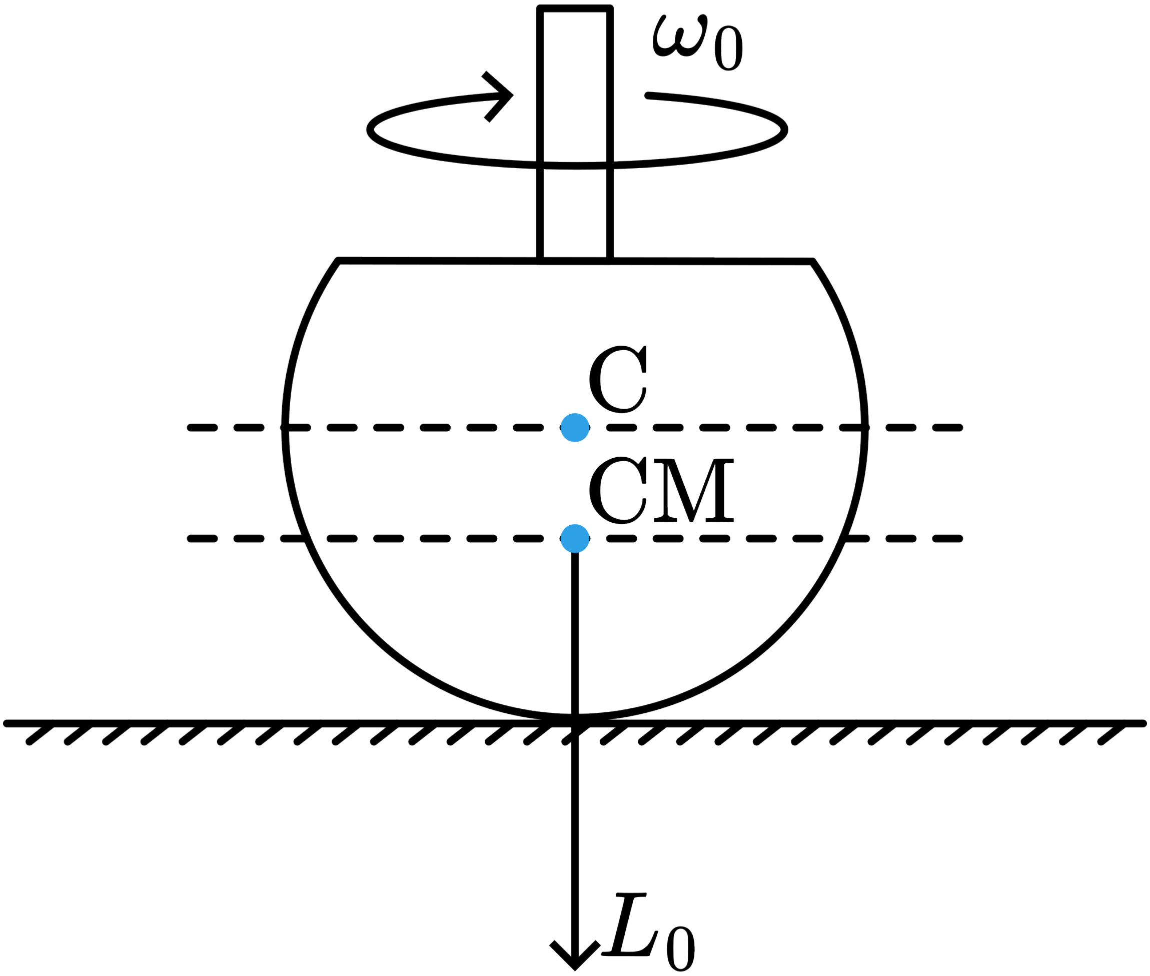


Figure 2.254: .

Now the tippe top has an amount of angular momentum (L_0). The demonstrations with tippe top nr. 2 , nr. 3 and nr. 1 on the painted board, show that this vertical angular momentum remains predominantly in that direction during the entire inversion process: L_0 keeps during this demonstration the same direction. (Thus the direction of rotation of the tippe top with respect to the coordinates fixed in its body is reversed.)

During inversion the centre of mass of the tippe top is elevated; it follows that the rotational kinetic energy decreases during inversion in order to provide the potential energy involved in this raising of the centre of mass. This implies that the total angular velocity and the total angular momentum decrease during the inversion process. However, a reduction in angular momentum requires the action of a torque. The only external forces acting on the top are gravity, the normal force exerted by the table at the point of contact and friction. Gravity and normal force point along the vertical, hence, they cannot be responsible for the decrease of angular momentum. Only friction force can produce a torque along the z-axis.

A complete analysis to account for the behavior of the top is quite elaborate (see SourcesXX). Next a simplified explanation is attempted:

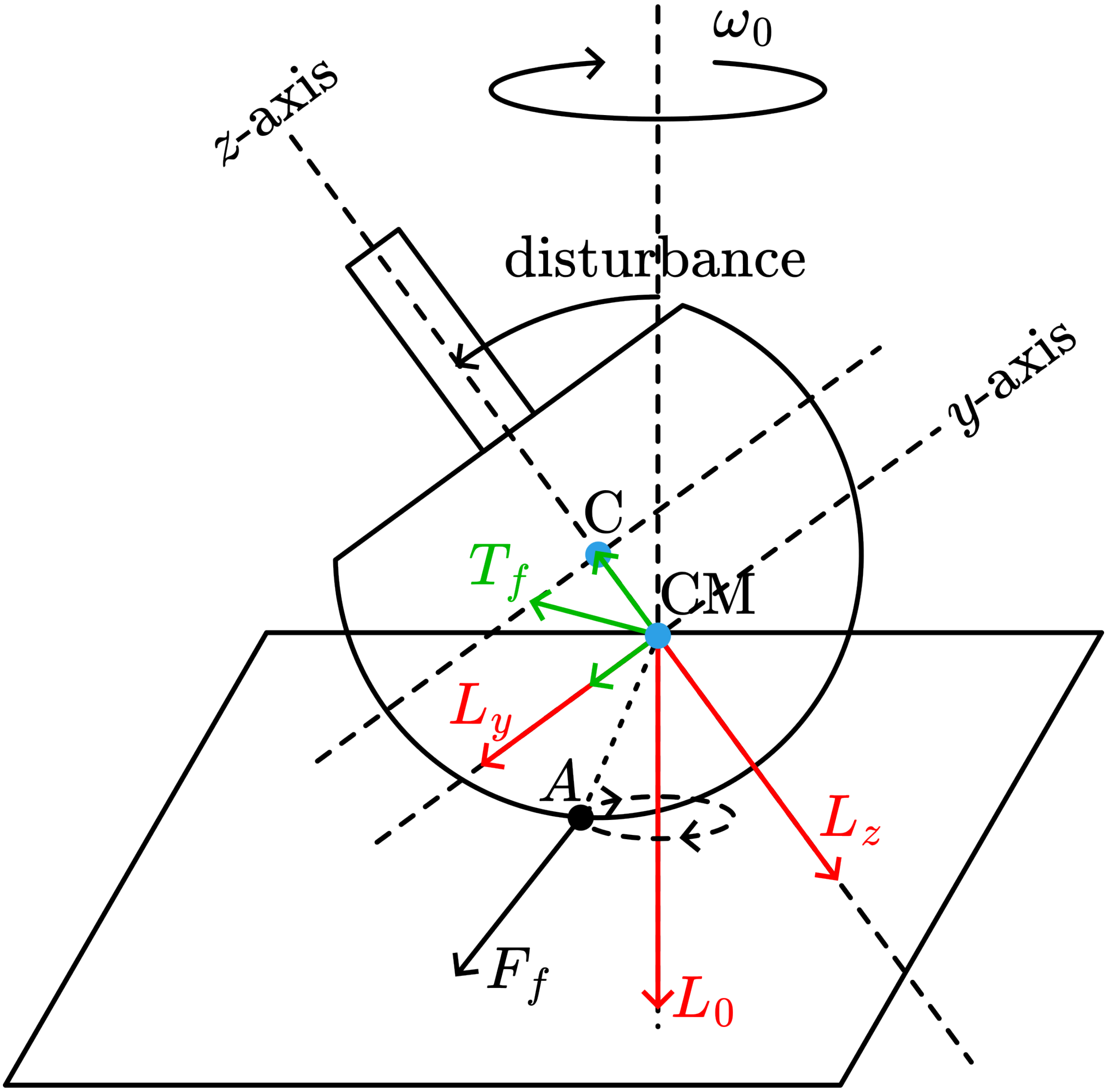


Figure 2.255: .

When a disturbance moves the top away from its initial vertical orientation with its stem up, the situation as shown in Figure 3 will occur. The tippe top remains spinning around its centre of mass CM and point A, perpendicular below C, slips over the floor. (Figure 4 shows a photograph of the circular slip track made by a tippe top on a freshly painted surface.)

Figure 2.256: .

The friction force in A on the tippe top is pointing contrary to its direction of slip (so in Figure 2 towards the reader). The torque of this friction force is almost perpendicular to L_0, trying to change $L_0(L_z$ becomes smaller, L_y larger: see the y - and z-component of T_f). But since L_0 is conserved this change can only be reached by increasing the initial disturbance, so tilting the tippe top still more. This continues until the tippe top is spinning on its stem.

This analysis of the tippe top differs from the analysis of a rising conventional top, because the analysis of a rising conventional top depends on the fact that the angular momentum points predominantly along the symmetry axis of the top (see the demonstration Sleeper in this database), whereas the angular momentum of the tippe top points along the vertical during the entire inversion process.

2.12.5.6.7 Remarks

- The flip of the tippe top occurs as a result of a frictional torque at the point of contact, so it should take longer to occur if the top is spun on a very smooth surface (may be even not flipping at all).
- Since CM is close to C, precession due to gravitational torque is neglected in our explanation.

2.12.5.6.8 Sources

- American Journal of Physics, Vol. 20 (1952), pag. 517-518
- American Journal of Physics, Vol. 22 (1954), pag. 28-32
- American Journal of Physics, Vol. 45 (1977), pag. 12-17
- American Journal of Physics, Vol. 68 (2000), pag. 821-828
- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 183-184
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 234
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 297-299

2.12.5.7 08 Rugbyball

2.12.5.7.1 Aim

To show how a rotating rugby ball lifts itself

2.12.5.7.2 Subjects

- 1Q60 (Rotational Stability)

2.12.5.7.3 Diagram

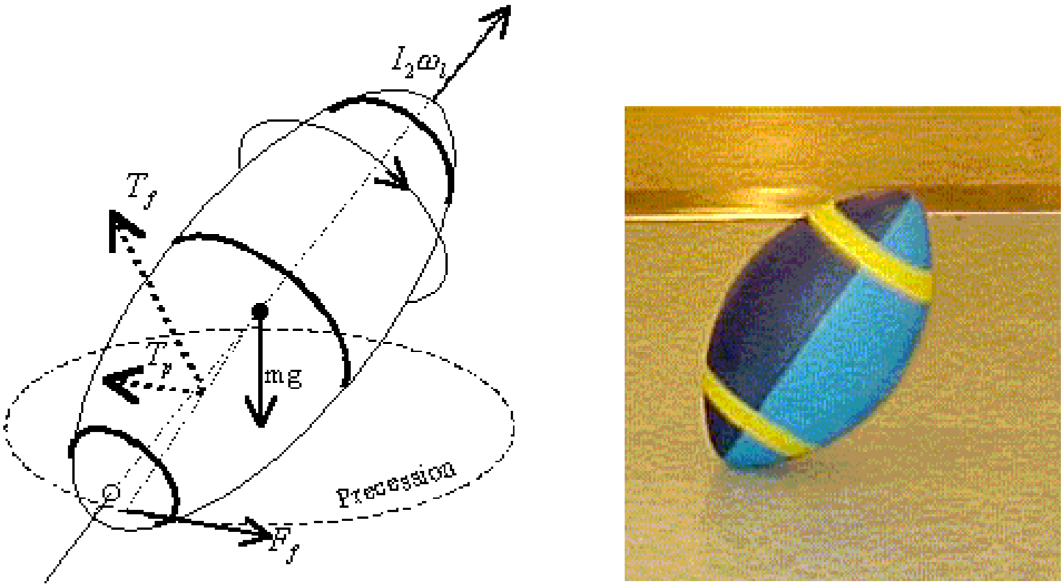


Figure 2.257: .

2.12.5.7.4 Equipment

- Rugby ball

2.12.5.7.5 Presentation

The rugby ball lies on the floor. By hand it is given a fast spin around its short axis (see Figure 2).

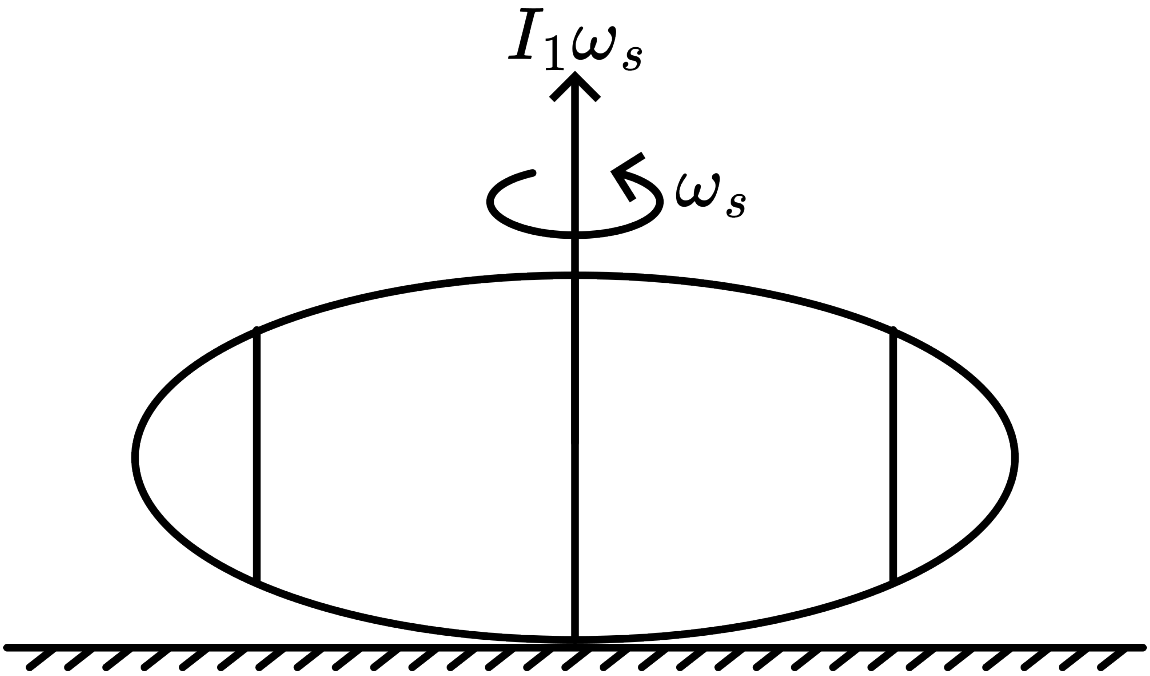


Figure 2.258: .

When the ball has made some turns it lifts itself, finally standing on its nose (tail) and rotating around its long axis.

2.12.5.7.6 Explanation

- When the ball turns around its short axis (ω_s) it will tilt its long axis a little due to unbalanced mass distribution. Then spinning around its long axis $\left(\omega_l\right)$ will start (see Figure 3) and at the same time, the long axis starts a precession ($I_2\omega_1$ moves into the direction of T_p).

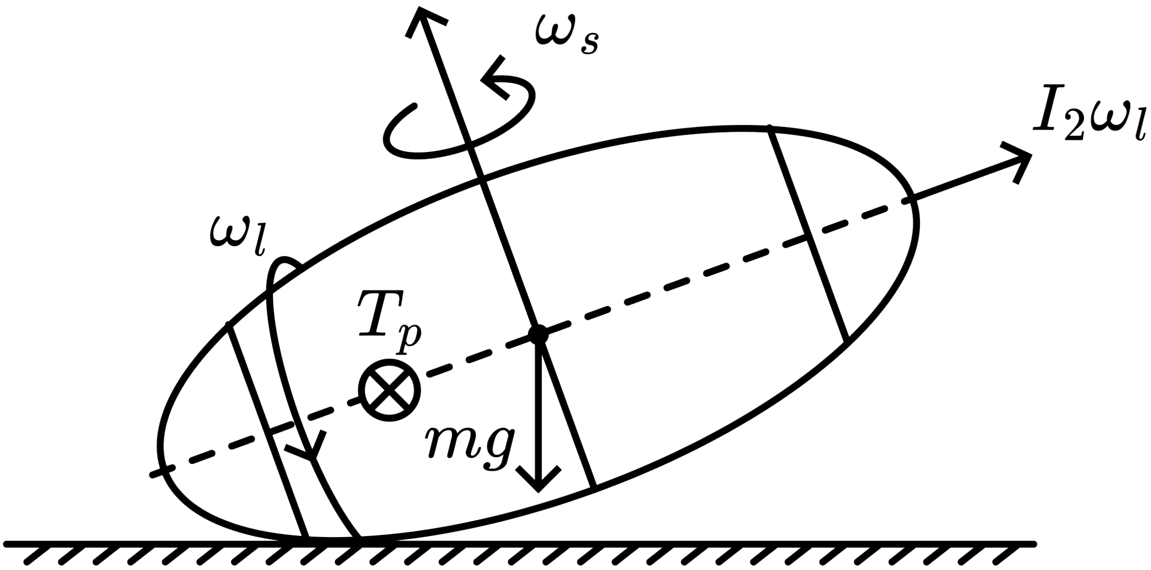


Figure 2.259: .

- The point of contact slips on the floor (see Diagram). The friction force $\left(F_f\right)$ on the ball is pointing in the same direction as its direction of precession. The torque (T_f) of this friction force is pointing upward (see Diagram), almost perpendicular to $I_2\omega_\nu$. So the friction force gives a torque that erects the ball ($I_2\omega/$ moves into the direction of T_f).
- See also the demonstrations Precession 3a and Precession 3b in this database where it is shown how a precessing object reacts to an applied torque.

2.12.5.7.7 Remarks

- Friction between ball and floor must be high enough to make this demonstration successful.
- This demonstration can also be done with a hardboiled egg. Doing it on my kitchen table, the angular speed of the egg must be quite high to reach the lifting effect.

2.12.5.7.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 230-231
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 2, Mechanik der festen Körper, pag. 233-235
- Roest, R., Inleiding Mechanica, pag. 230-231

2.13 1R Properties of Matter

2.13.1 1R10 Hooke's Law

2.13.1.1 01 duplicate

3. Fluid Mechanics

3.1 2B Statics

3.1.1 2B20 Static Pressure

3.1.1.1 01 Rotating Liquid

3.1.1.1.1 Aim

To show that the surface of a rotating liquid forms a paraboloid

3.1.1.1.2 Subjects

- 1E20 (Rotating Reference Frames)
- 2B20 (Static Pressure)

3.1.1.1.3 Diagram

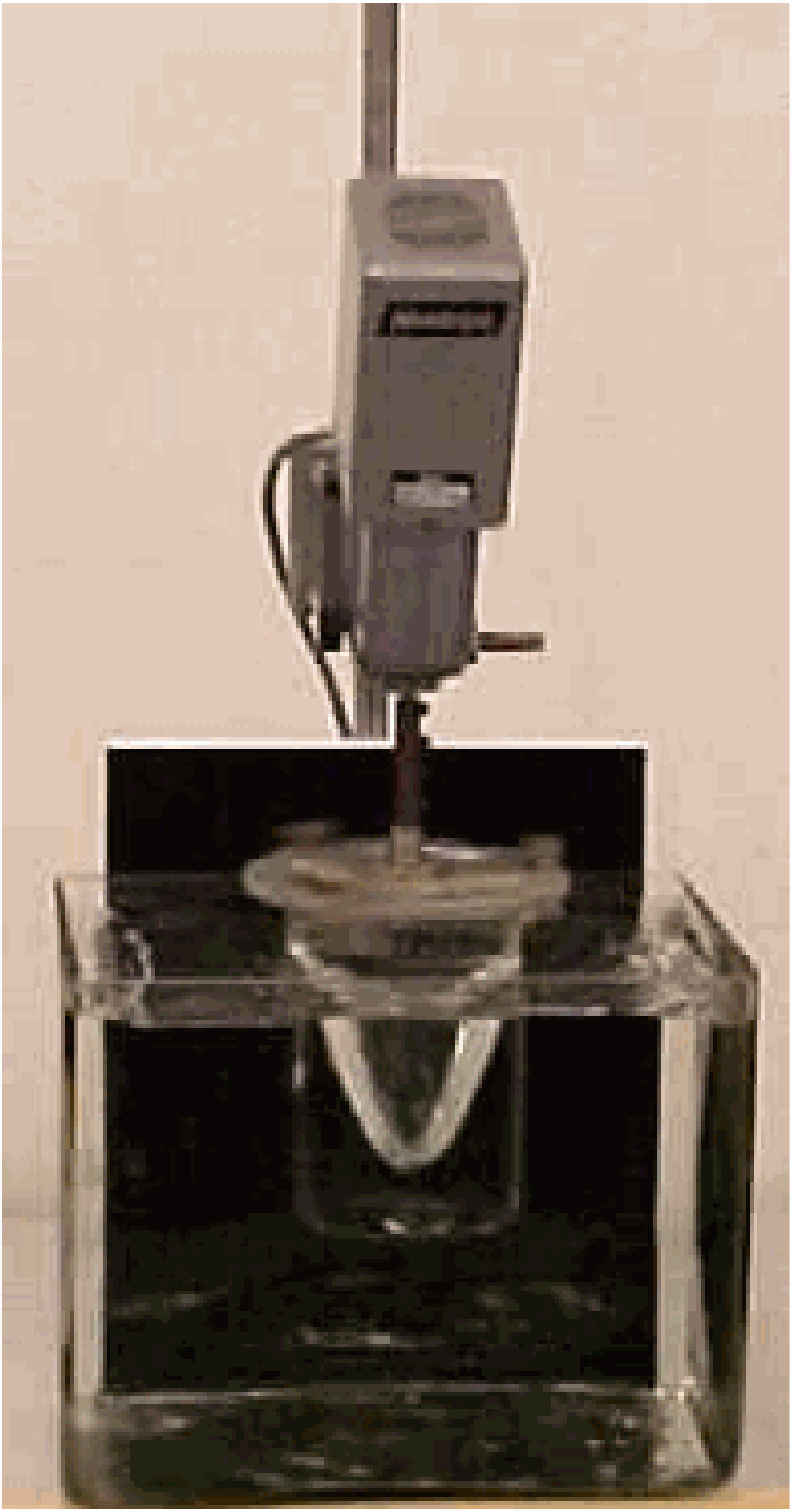


Figure 3.1: .

3.1.1.1.4 Equipment

- Glass beaker, 1 l, fixed to an electric motor, variable speed (see Diagram)
- Rectangular reservoir
- Black screen

3.1.1.1.5 Presentation

The glass beaker is half filled with water. The beaker is submerged in a square reservoir (see Diagram). By means of the electric motor the glass is made rotating. Gradually the liquid climbs the wall of the beaker until it settles itself. The paraboloidic shape can be seen clearly. By means of a videocamera and projector, the paraboloid is projected on the blackboard. Chalk is used to draw the shape of the parabola on the blackboard. Now it is checked that the drawn shape is really paraboloidic by looking for the focal point (F) and course line(c). Our experience is that the positions of this point and line are found quickly by trial and error (until the distances of focal point and course line to the drawn line are equal: see Figure 2).

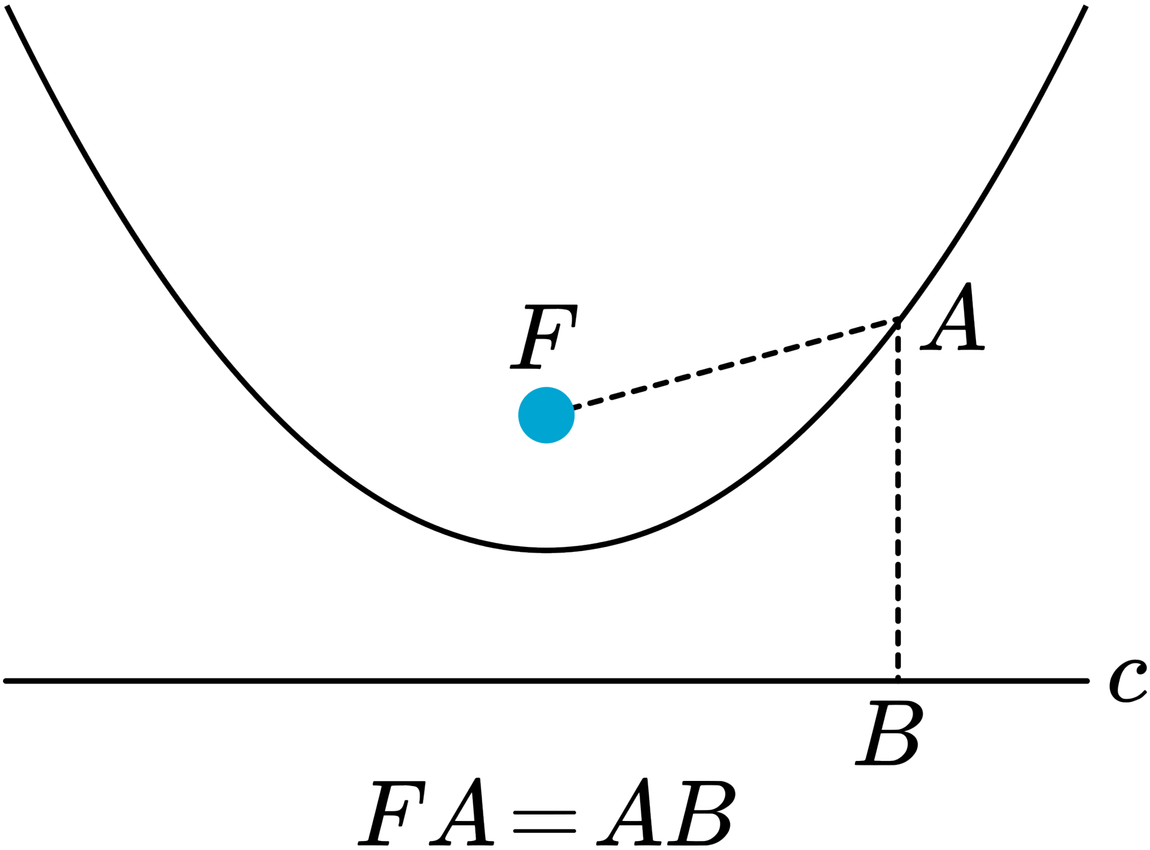


Figure 3.2: .

3.1.1.1.6 Explanation

1. In a rotating reference frame the liquid is in static equilibrium. In this reference frame the sum of the forces acting on the particles in the surface will be perpendicular to that surface. Two forces are acting on such a particle dm: gravity, $F_1 = dmg$ and the centrifugal force, $F_2 = dm\omega^2$ r. Figure 3 shows: $\tan\alpha = \frac{dy}{dx} = \frac{\omega^2 x}{g}$ and from this $y = \frac{1}{2}\frac{\omega^2 x^2}{g} + c$. This is the formula of a parabola.

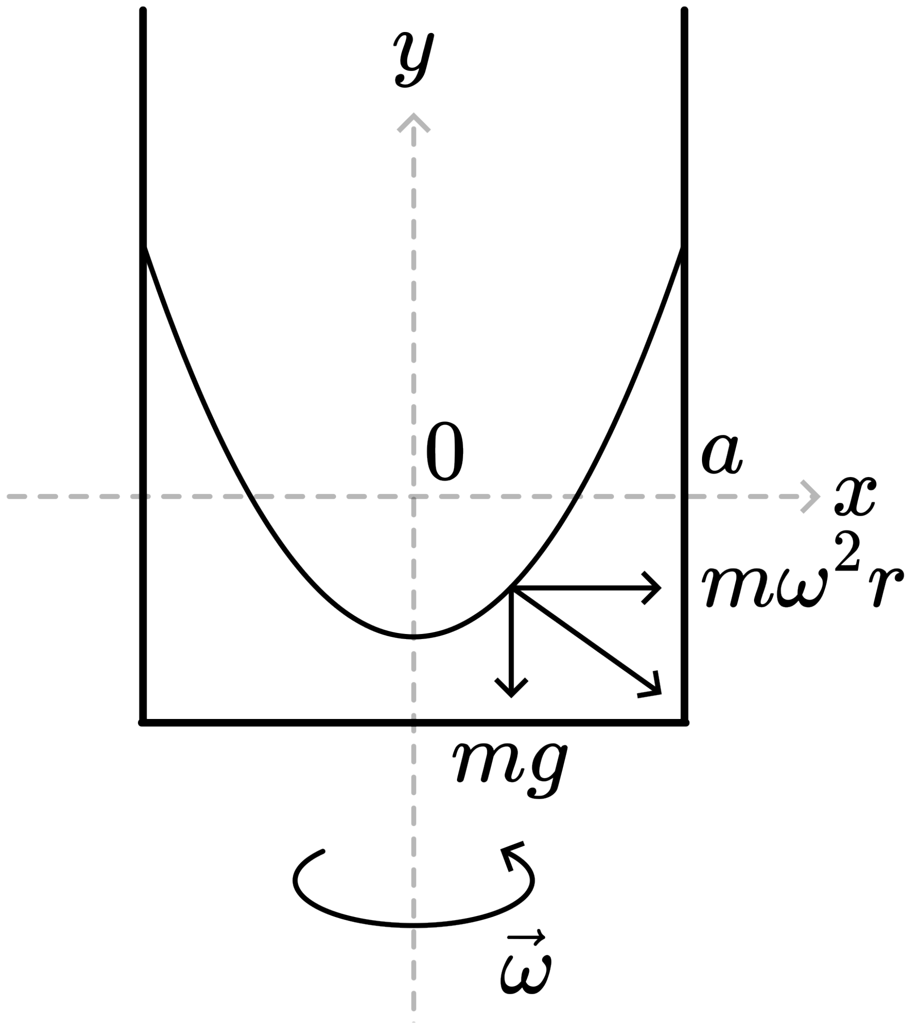


Figure 3.3: .

The constant c indicates the position of the lowest point of the rotating liquid. If the x axis in Figure 2 is located in the surface of the liquid at $\omega = 0$, then because of the conservation of mass and the assumed incompressibility of the water, one obtains: $\int_0^a y dx = 0$ After integration we find: $c = -\frac{1}{6}\frac{\omega^2 a^2}{g}$

2. Explaining can also be done from the point of view of hydrostatics (see Figure 4).

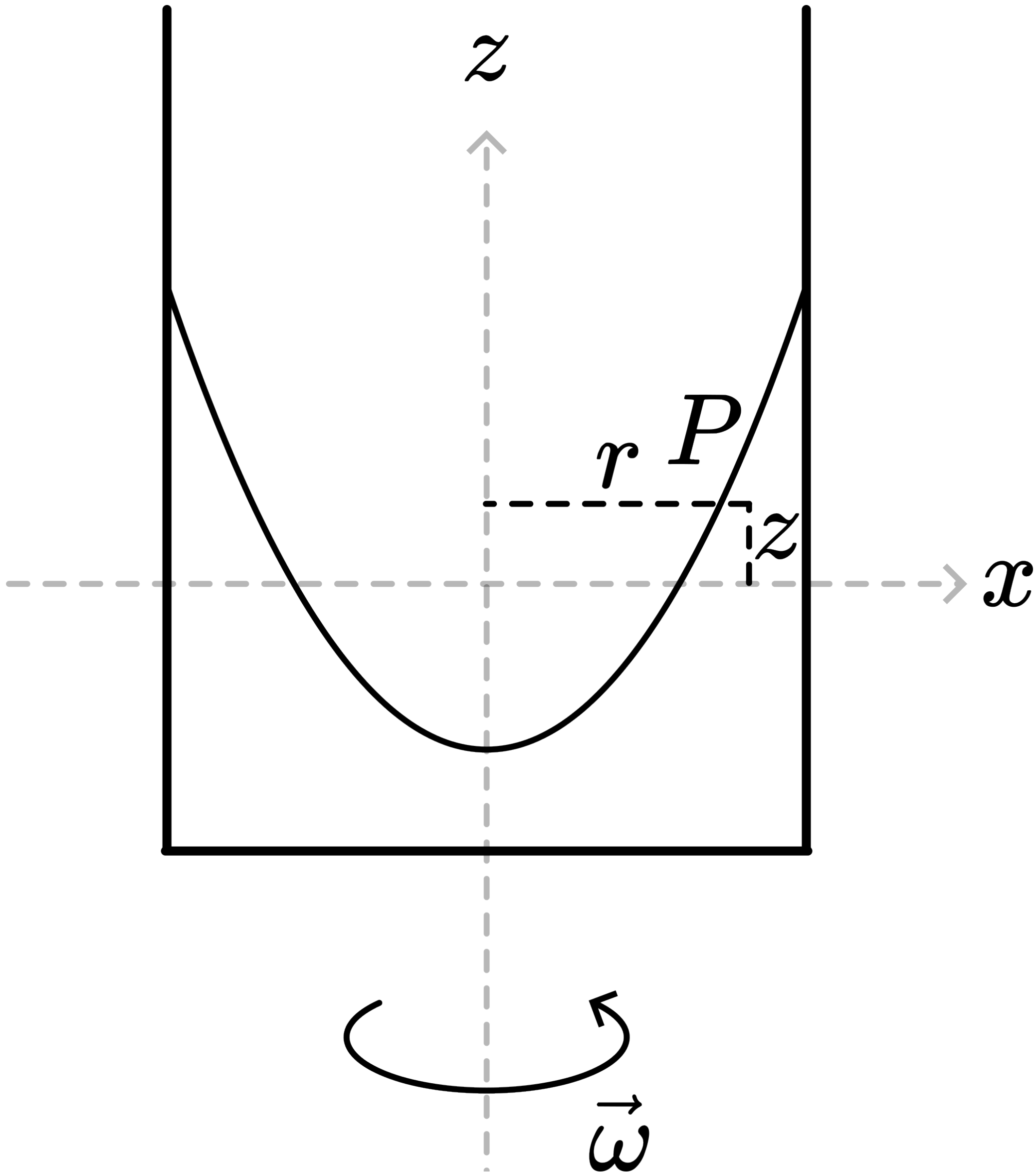


Figure 3.4: .

Pressure in the liquid is a function of r and z. When rotating, the forcefield has two components: gravity, $\frac{\partial p}{\partial z} = -\rho g$ and centrifugal, $\frac{\partial p}{\partial r} = \rho\omega^2 r$. So $dp = -\rho g dz + \rho\omega^2 r dr$. After integration: $p = -\rho g z + \frac{1}{2}\rho\omega^2 r^2 + c$. So surfaces with equal pressure are determined by $z = \frac{\omega^2}{2g} r^2 + const.$, showing the parabolic relationship.

3.1.1.1.7 Remarks

- When not using the rectangular resevoir, only the central portion of the rotating beaker produces a satisfactory image, but what is happening to the liquid inside the beaker near the edge of the beaker, is observed distorted. The rectangular reservoir corrects this; the square reservoir functions as an optical corrector.
- When the rotational speed can be varied, the lowering of the liquid (c) with the square of the rotational speed (ω) can be observed.
- The German company 'Phywe', has in its laboratory equipment a rotating liquid cell (part number 02536.01) by means of which the paraboloidic shape and the location of the lowest point can easily be determined.

3.1.1.1.8 Sources

- Roest, R., Inleiding Mechanica, pag. 323-325

- Borghouts, A.N., Inleiding in de Mechanica, pag. 217 and 309
- Phywe, University Laboratory Experiments, part Vol. 1-5, pag. 1.3.2

3.2 2C Dynamics

3.2.1 2C20 Bernoulli Force

3.2.1.1 01 Magnus Effect (1)

3.2.1.1.1 Aim

To show, qualitatively, the lift force on a translating and rotating cylinder.

3.2.1.1.2 Subjects

- 2C20 (Bernoulli Force)

3.2.1.1.3 Diagram

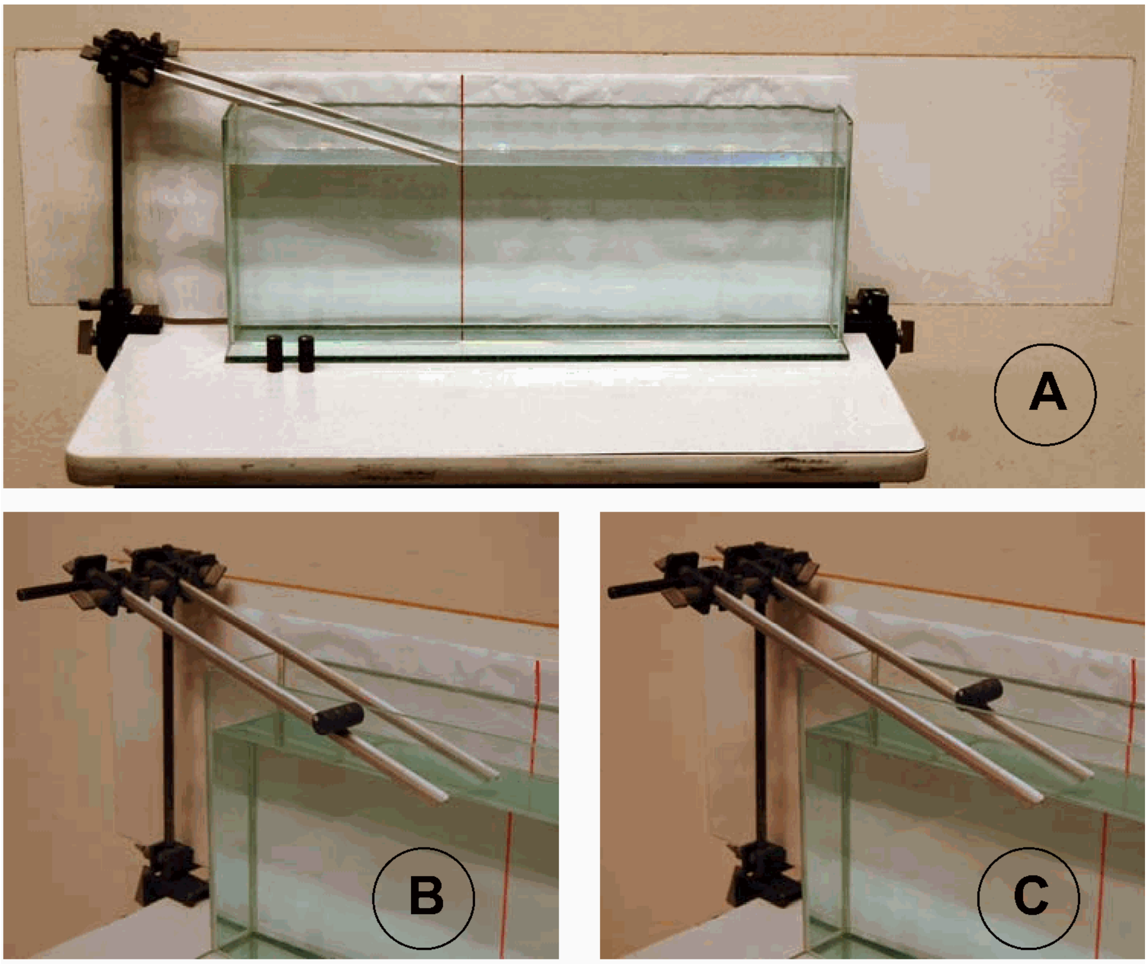


Figure 3.5: .

3.2.1.1.4 Equipment

- 2 inclined U-profiles ($\phi \approx 20°; I = 50$ cm).
- 2 PVC cylinders ($\emptyset = 2$ cm), with grooves fitting the U-profile.
- Basin (we use $80 \times 30 \times 10$ cm^3), filled with water.
- White shelf and sheet of paper with red line.

3.2.1.1.5 Presentation

The first cylinder is placed on the inclined U-profile that is outside the water basin (see Diagram B). It rolls downwards in a way everybody expects. Mark the place where it hits the table.

The second cylinder will roll down the inclined U-profile that ends in the water basin. Before doing it, ask the students where this second cylinder will end. (Same way as first cylinder? Or somewhere else?) After their answers this second cylinder is rolled down the incline (see Diagram C) and drops into the water. Instead of following the trajectory of the first cylinder, it moves in a opposite direction (see Figure 2).

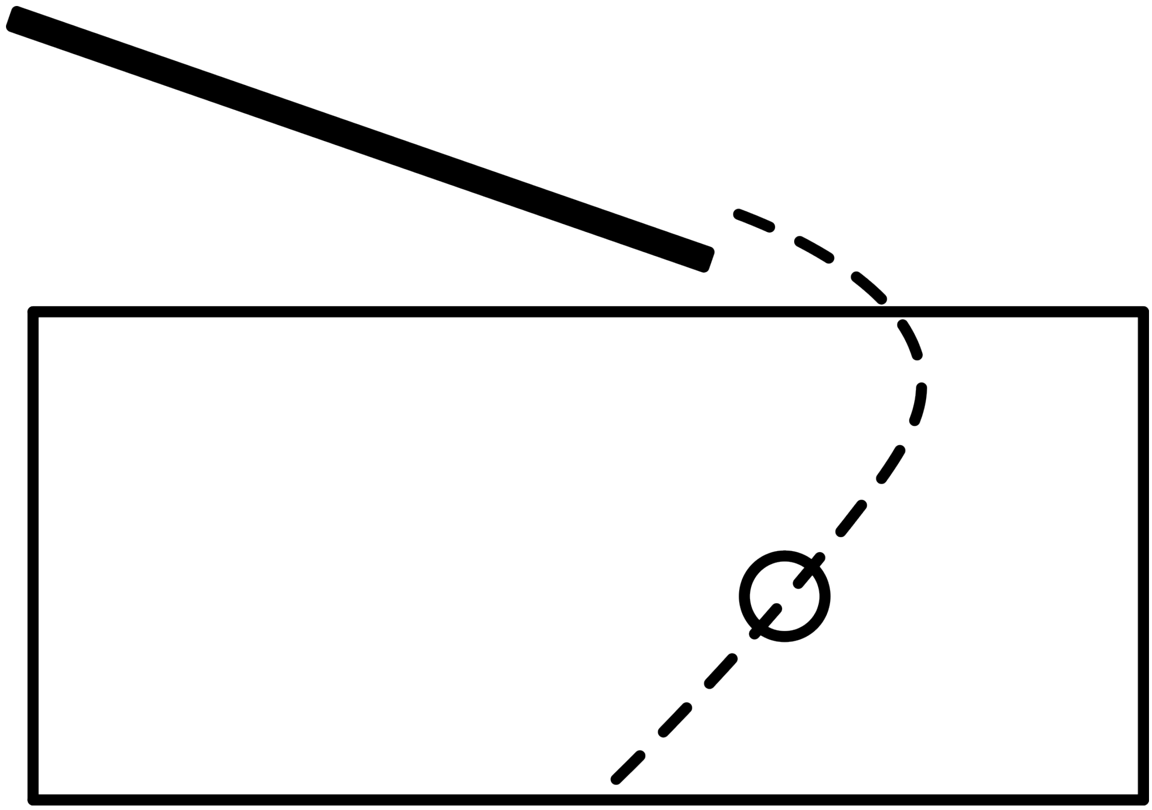


Figure 3.6: .

3.2.1.1.6 Presentation

The first cylinder is placed on the inclined U-profile that is outside the water basin (see Diagram B). It rolls downwards in a way everybody expects. Mark the place where it hits the table. The second cylinder will roll down the inclined U-profile that ends in the water basin. Before doing it, ask the students where this second cylinder will end. (Same way as first cylinder? Or somewhere else?) After their answers this second cylinder is rolled down the incline (see Diagram C) and drops into the water. Instead of following the trajectory of the first cylinder, it moves in a opposite direction (see Figure 2).

3.2.1.1.7 Explanation

A rotating cylinder, moving in a medium (e.g. water) drags that medium round with it. The medium flows in the opposite direction of translation of the cylinder (see Figure 3).

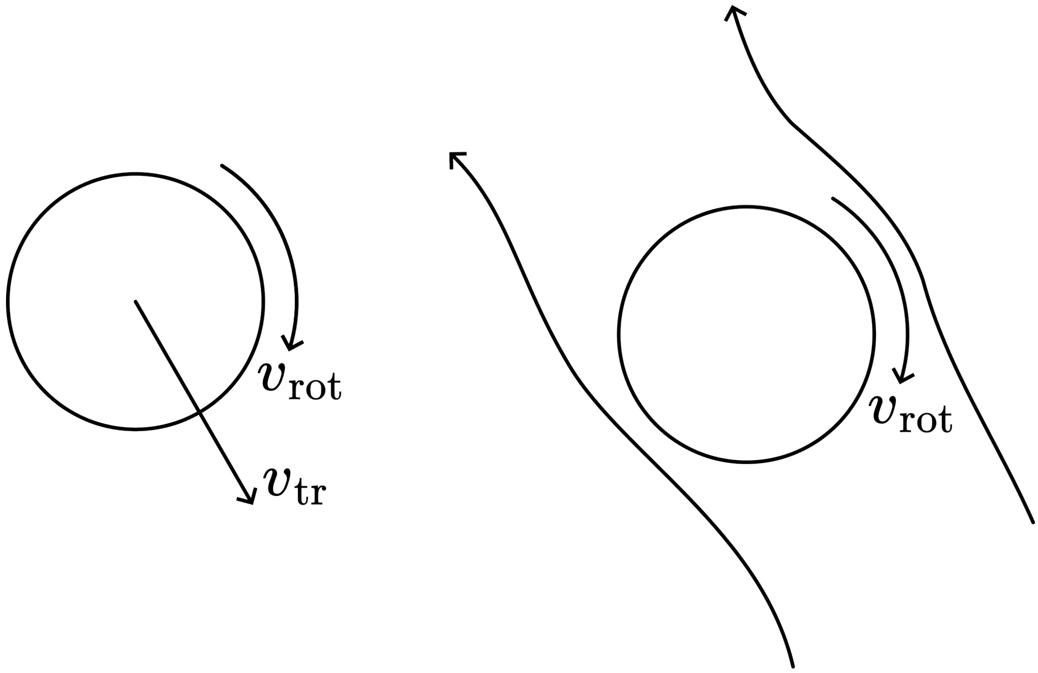


Figure 3.7: .

On the right side of the cylinder, the rotation causes the medium to flow slower, while on the other side the medium flows faster. This difference in speed causes a pressure difference; according to Bernoulli's equation: $\Delta p = \frac{1}{2}\rho(V_{left}^2 - V_{right}^2$. Since $v_{left} > V_{right}$, the net lift-force due to Δp is pointing to the left and proportional to $\rho\left(v_{left}^2 - v_{right}^2\right)$. Also since $v_{left} = v + \omega r$ and $v_{riaht} = \nu - \omega r$, F_{lift} is proportional to $2\rho\omega v_{tr}$. Because the density of water equals 10^3 kg/m^3, the lift-force is considerable. Therefore the effect of this force is clearly visible as a deviation of a trajectory without rotation.

3.2.1.1.8 Remarks

- PVC or perspex is used for our cylinder, because the specific density of these materials is just a little higher than that of water. Therefore the time it takes to sink to the bottom is high and so the deflection will be high when the bottom is reached.

3.2.1.1.9 Sources

- Edge, String & sticky tape experiments, pag. 3.12
- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. F15; F17
- Grimsehl, Lehrbuch der Physik, part 1, pag. 288-291 and 617
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 240
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 116-117
- Vogel, H, Physik, pag. 98-99

3.2.1.2 02 Magnus Effect (2)

3.2.1.2.1 Aim

To show, qualitatively, the lift force on a translating and rotating cylinder.

3.2.1.2.2 Subjects

- 2C20 (Bernoulli Force)

3.2.1.2.3 Diagram

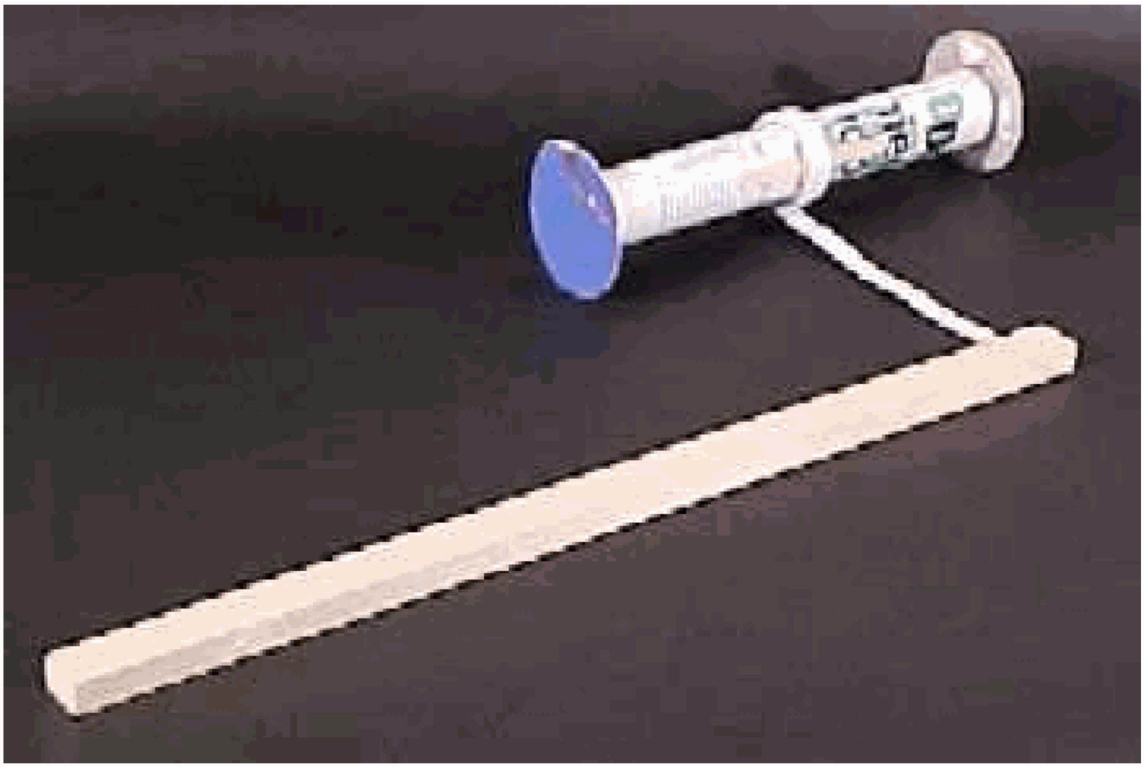


Figure 3.8: .

3.2.1.2.4 Equipment

- light cylinder, constructed of paper (see diagram)
- 1 meter of wide cloth tape, fixed to a stick

3.2.1.2.5 Presentation

The cloth tape is wrapped around the middle of the cylinder. The cylinder is laid on a table or on the ground, so that the tape will unwind from the bottom. The stick is pulled giving the cylinder linear and spin velocity. The cylinder lifts itself and describes a loop (see Figure 2).

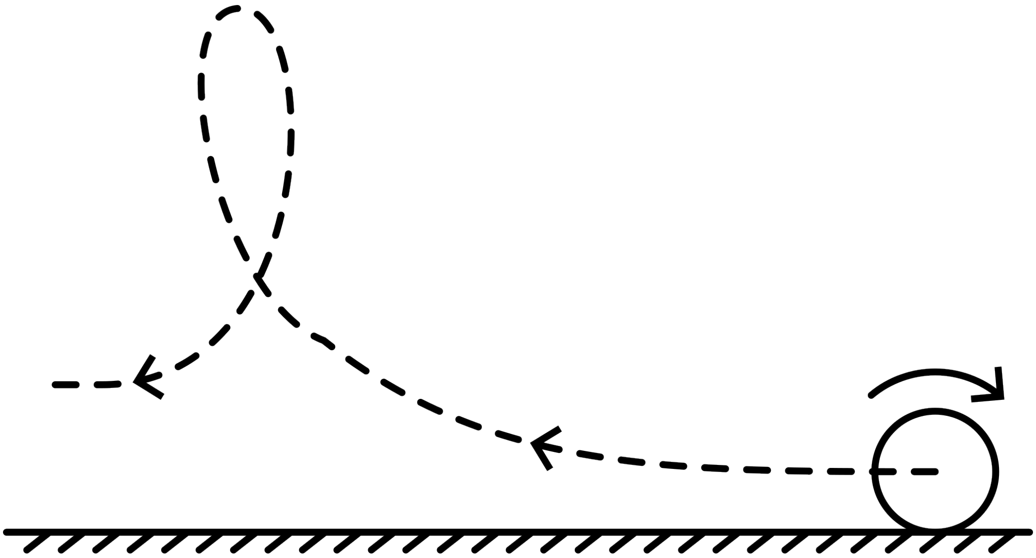


Figure 3.9: .

3.2.1.2.6 Explanation

The rotating cylinder drags the air round with it. The air flows in the opposite direction of translation of the cylinder. On the topside of the cylinder, the rotation causes the air to flow faster, while on the bottom side the air flows slower. This difference in speed causes a pressure difference; according to Bernoulli's equation: $\Delta p = 1/2\rho(V_{top}^2 - v^2 \text{ bottom })$. Since $v_{top} > v_{bottom,}$ the net liftforce is pointing upward and proportional to $20\omega r v_{tr}$ (see Magnus effect. Since v_{tr} slows down in the beginning of the movement, the cylinder climbs more and more in a vertical trajectory; then it falls down and thus speeding up it moves more and more horizontal: a loop-like trajectory is made by the moving cylinder.

3.2.1.2.7 Remarks

- In the middle of the cylinder a light piece of wood is stuck to it. Under this piece of wood the cloth tape can be fixed when wrapping it around the cylinder (see Figure 3). When the tape is pulled, the end loosens itself easily from the cylinder.

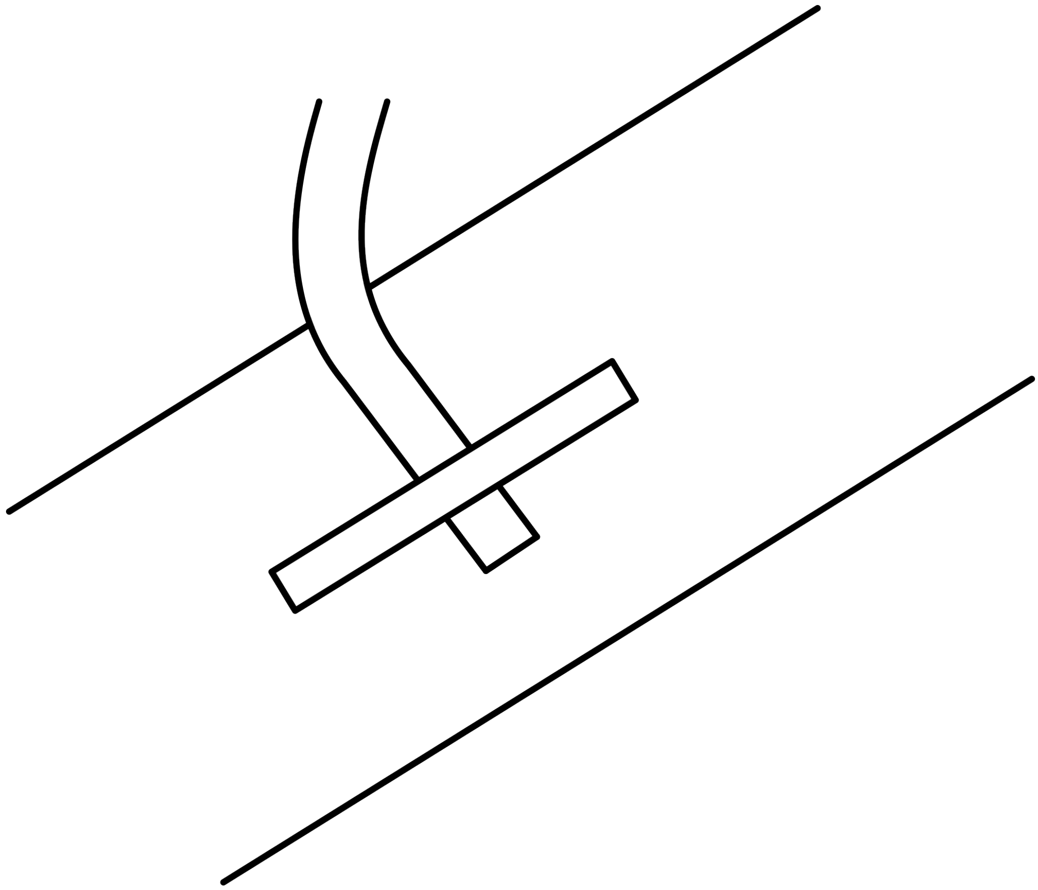


Figure 3.10: .

3.2.1.2.8 Sources

- Edge, String & sticky tape experiments, pag. 3.12
- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. F15; F17
- Grimsehl, Lehrbuch der Physik, part 1, pag. 288-291
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 240
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 117
- Vogel, H, Physik, pag. 98-99

3.2.2 2C40 Turbulent

3.2.2.1 Tornado Tower

4. Oscillations and Waves

4.1 3A Oscillations

4.1.1 3A10 Pendula

4.1.1.1 01 Mathematical Pendulum (1) Simple Harmonic Motion

4.1.1.1.1 Aim

To show the relationship between position, velocity and acceleration of a simple pendulum.

4.1.1.1.2 Subjects

- 3A10 (Pendula)
- 3A40 (Simple Harmonic Motions)

4.1.1.1.3 Diagram

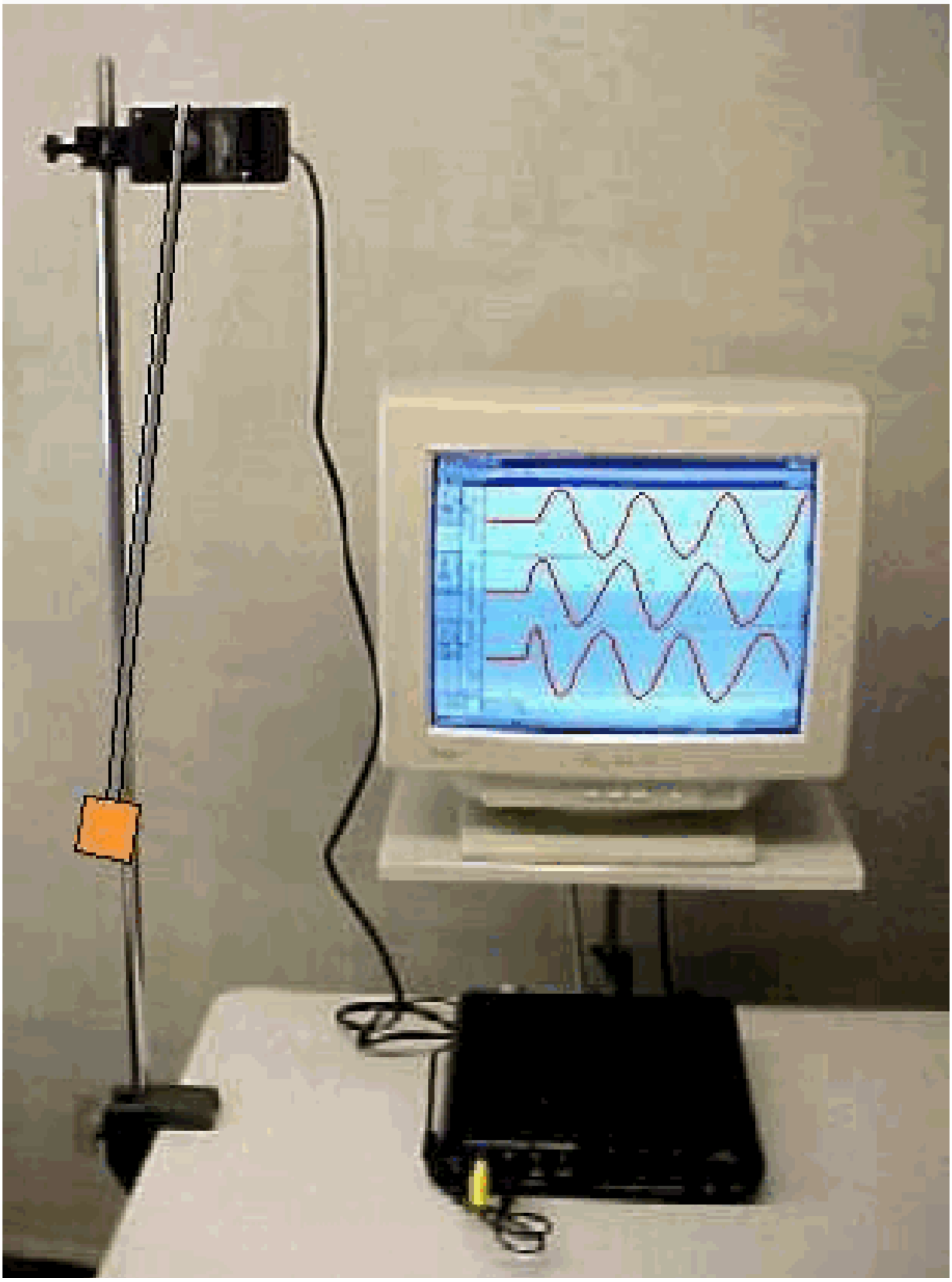


Figure 4.1: .

4.1.1.1.4 Equipment

- Simple pendulum: aluminum tube with brass mass.
- Rotary motion sensor (we use Pasco CI-6538).
- Data-acquisition system and computer with software (we use 'Science Workshop').
- Projector to project the monitorscreen.

4.1.1.1.5 Presentation

Set up the software to display graphically angular position, angular velocity and angular acceleration of the pendulum. When the pendulum is in its vertical position at rest, we start data collection. We give the pendulum a small amplitude and let it swing. When we have collected about four complete cycles, the data-acquisition is stopped.

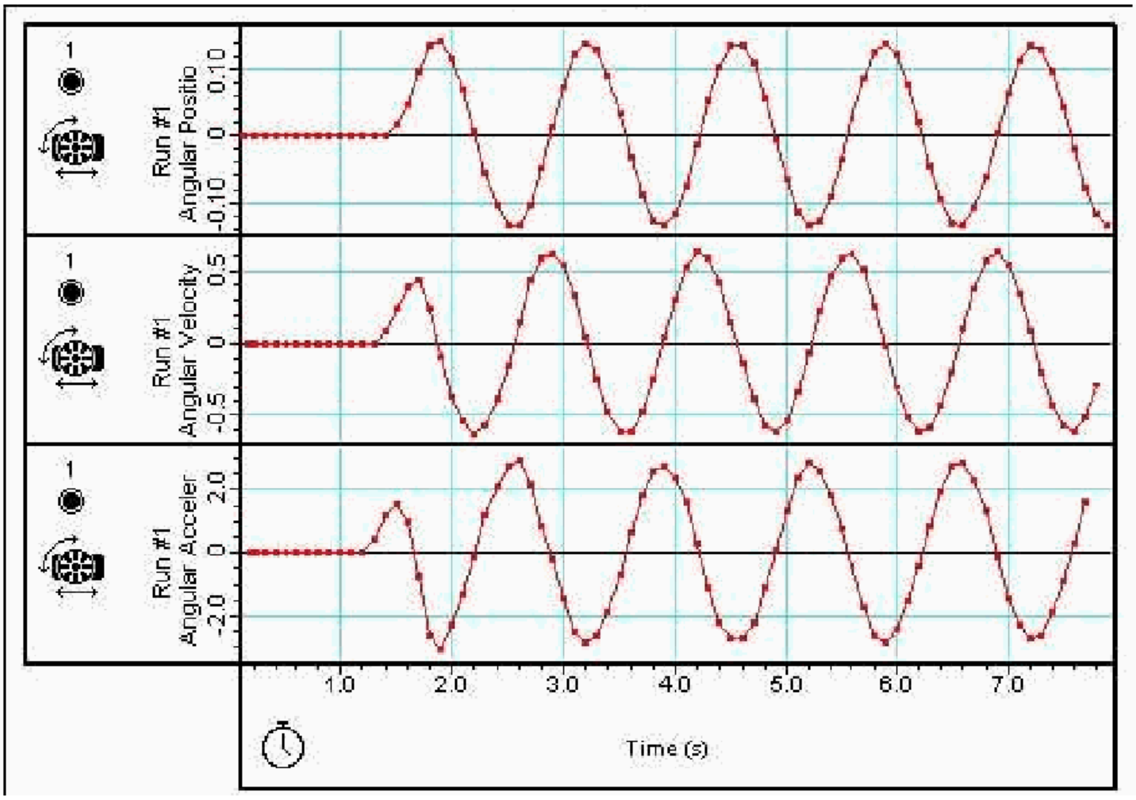


Figure 4.2: .

Already at first glance this registered graph shows its sine-shaped appearance. To have a more convincing conclusion the software can apply a mathematical curve-fit to the registered position-graph, to show that a sinusoidal equation "covers" the position-graph very good. So a sine-function describes the behavior (position-time) of this pendulum very good. A second run of the oscillations is registered, but now with a higher amplitude. Clearly can be observed now that the motion is no longer sinusoidal Trying a sine-fit will confirm this (read the chi2-value). Make a third run again with small amplitude and check the differential relationships between 'position', 'velocity' and 'acceleration': e.g.

- The points of zero-velocity correspond with maximum - and minimum position;
- The acceleration-graph is an inverse "copy" of the position-graph;
- ……….

4.1.1.1.6 Explanation

The equation that describes the motion of the mass m is given by $a_x = \frac{d^2s}{dt^2} = -g\sin\theta$.

This is not a simple harmonic motion since $\sin\theta$ is not proportional to s.

Only for small amplitude oscillations $\sin\theta \approx \theta = \frac{s}{l}$ and the equation of motion reduces to $\frac{d^2s}{dt^2} = -\frac{g}{l}s$ This is the differential equation for simple harmonic motion, giving our observed sinusoidal graphs.

For further explanation see: SourcesXX.

4.1.1.1.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 48-52
- Young, H.D. and Freeman, R.A., University Physics, pag. 398-399

4.1.1.2 02 Mathematical pendulum (2) Large angle

4.1.1.2.1 Aim

To show that the period of motion of a simple pendulum depends on the angle the pendulum makes with the vertical.

4.1.1.2.2 Subjects

- 3A10 (Pendula)

4.1.1.2.3 Diagram

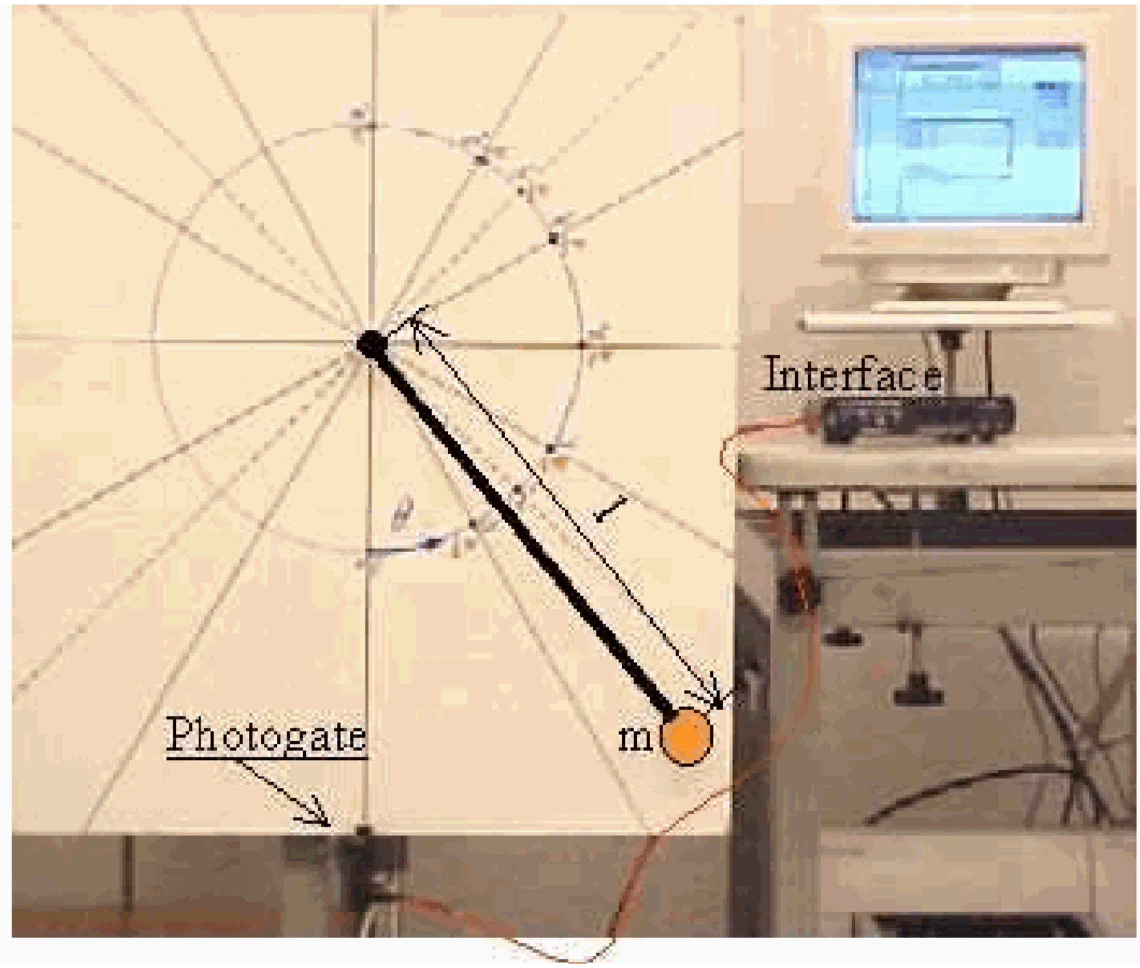


Figure 4.3: .

4.1.1.2.4 Equipment

- Pendulum; brass bob attached to a threaded rod ($I = 50$ cm) and connected to a support with ball bearing.
- Large cardboard with the principal angles of deflection indicated on it (see Diagram).
- Photogate
- Computerinterface.
- Computer with data-acquisition system. (we use PASCO Science Workshop)

4.1.1.2.5 Presentation

The photogate is placed just offset the rest-position of the pendulum. The data-acquisition system is set up in such a way that a graph of periodtimes can be presented. The data-acquisition is started, and by hand the pendulum is given a deflection of almost 180° and released. When θ has reached angles smaller than 90°, the data-acquisition is stopped. During the data-acquisition the students observe the graph displayed (see red line in Figure 2).

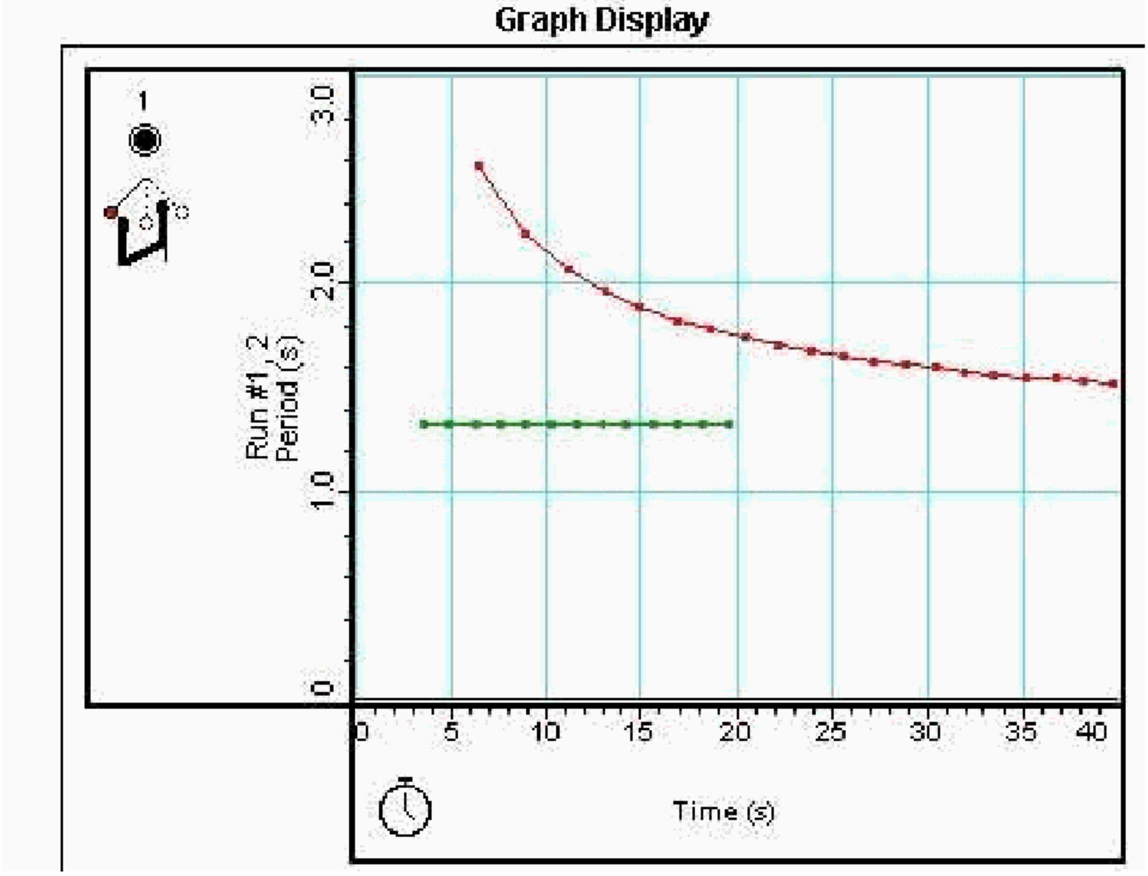


Figure 4.4: .

(This means that the expected range of the axes of the graph have to be prepared before the demonstration is started.)

A second run is made, giving the pendulum the smallest deflection possible. After about $10 - 20$ registrations of T the data-acquisition is stopped. The complete graph can be observed and discussed now.

4.1.1.2.6 Explanation

The equation that describes the motion of the mass m is given by $a_x = \frac{d^2s}{dt^2} = -g\sin\theta$ (x-direction along the tangent of the circle; see Figure 3A). This is not a simple harmonic motion since $\sin\theta$ is not proportional to s.

Only for small amplitude oscillations $\sin\theta \approx \theta = \frac{S}{l}$ and the equation of motion reduces to $\frac{d^2s}{dt^2} = -\frac{g}{l}s$ This is the differential equation for simple harmonic motion. Then the period is given by $T = 2\pi\sqrt{\frac{l}{g}}$

For large amplitudes we need $a_x = -g\sin\theta$ in stead of $a_x = -g\theta$. Since $\sin\theta < \theta$, this means that a_x is smaller than the small-amplitude equation indicates: The mass will need more time than $T = 2\pi\sqrt{\frac{l}{g}}$ to reach its maximum deflection. In other words: T is larger than $2\pi\sqrt{\frac{l}{g}}$.

(For an exact solution to the equation of motion: see SourcesXX.)

4.1.1.2.7 Remarks

- Also see the demonstration “Mathematical pendulum (1) - Simple harmonic motion”. With that demonstration the effect on the acceleration a can be observed very well.
- When you observe the pendulum directly by eye it can be seen directly that the period of oscillation is larger at larger angles.

- The software is setup in such a way that the period is presented after the pendulum has passed three times through the photogate. Every next period is presented after every second passage (see Figure 3B).

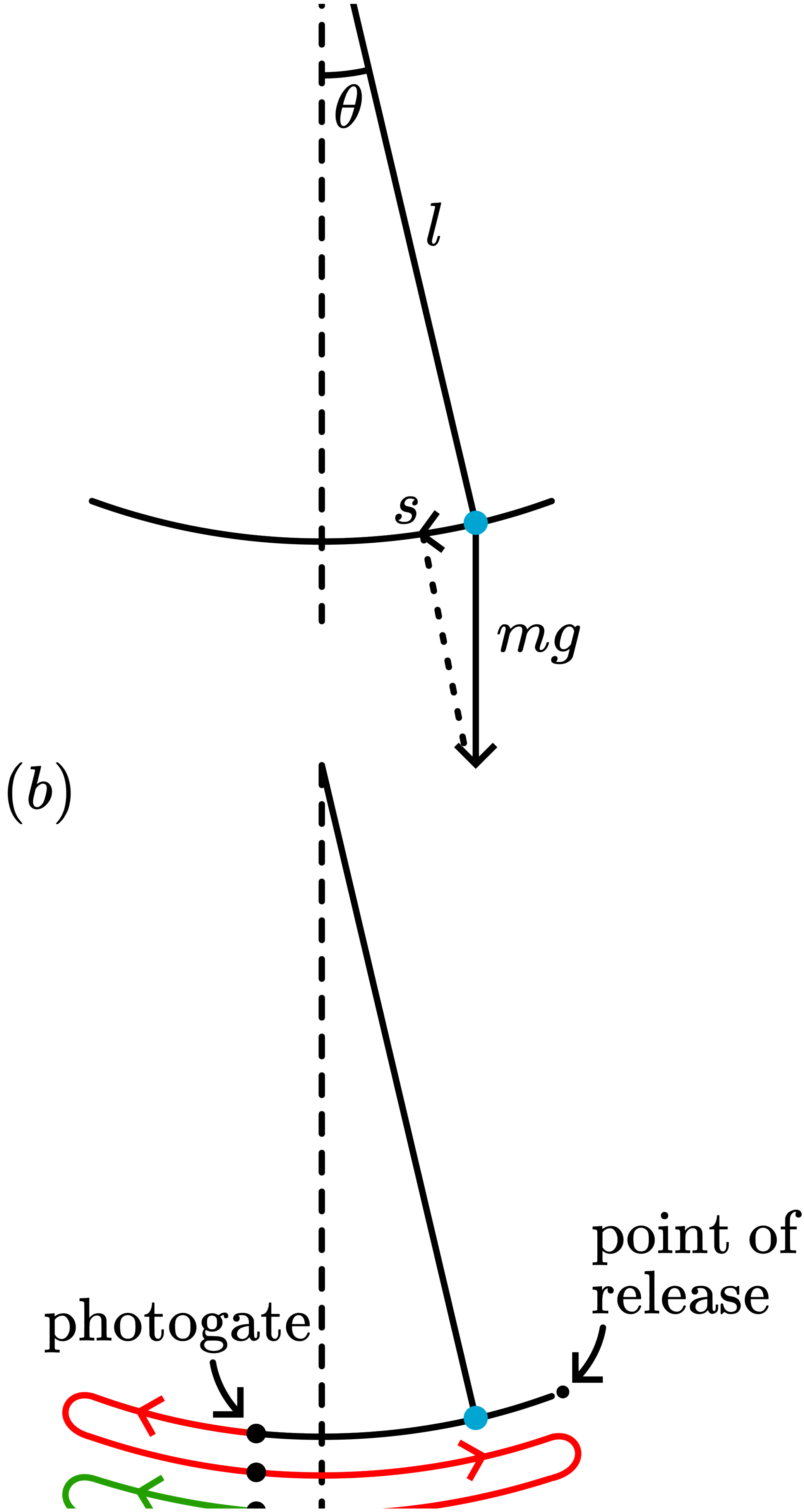

θ
l
s
mg
(b)
point of release
photogate

Figure 4.5: .

- Since the system measures the complete period the position of the photogate can be at any arbitrary point along the arc of motion.

4.1.1.2.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 129-131
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 72-73
- Roest, R., Inleiding Mechanica, pag. 91-93

4.1.1.3 03 Mathematical Pendulum (3) Determining g

4.1.1.3.1 Aim

To determine g by measuring the period of a simple pendulum.

4.1.1.3.2 Subjects

- 3A10 (Pendula)
- 3A40 (Simple Harmonic Motions)

4.1.1.3.3 Diagram

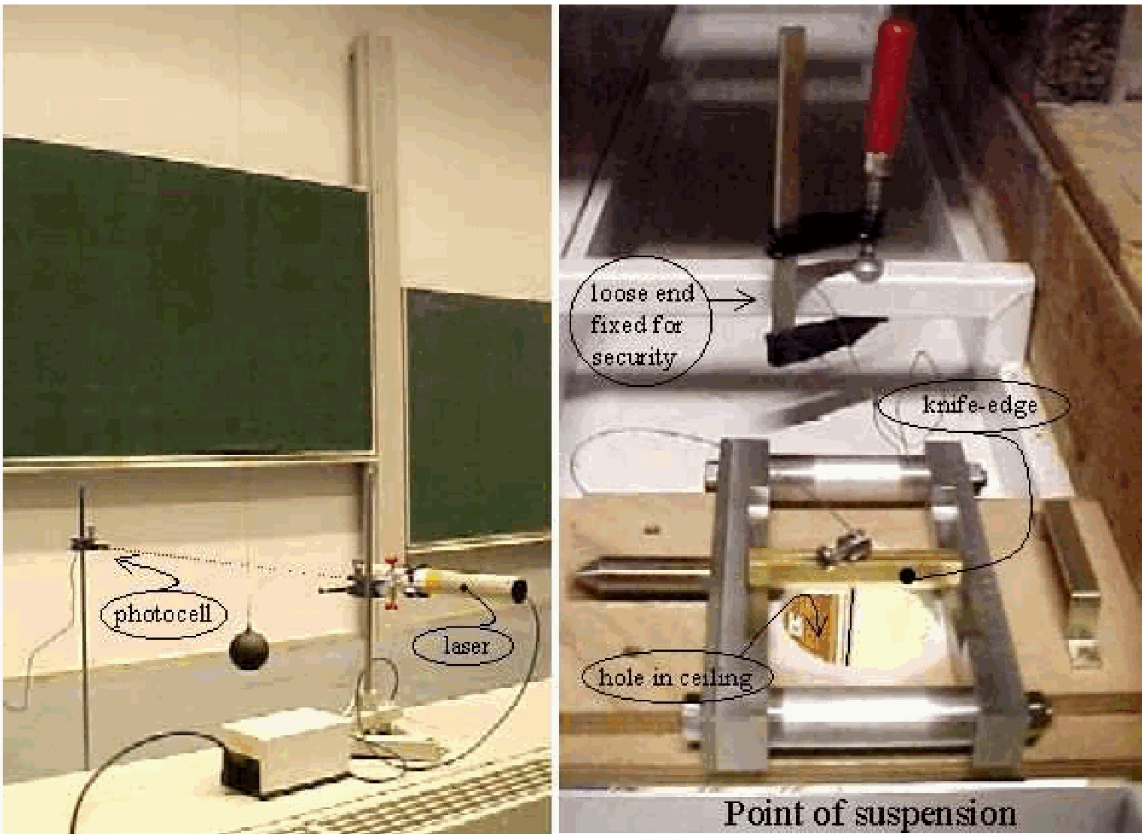


Figure 4.6: .

4.1.1.3.4 Equipment

- Cast iron sphere.
- Thread.
- Knife-edge suspension.
- Photogate (Laser and laser switch).
- Tape measure.
- Data-acquisition system and computer. (We use Science Workshop).
- Projector to project monitor-image.

4.1.1.3.5 Presentation

Set up the pendulum and photogate (see Diagram). The length of the pendulum is measured. The photocell is connected to the interface and the software is made such that on the monitor a table of period-time (T), and the calculated value of g, is presented.

The pendulum is given an very small amplitude and around ten measurements are registered. When the measurement is stopped, the software also presents the mean value of T and g and their standard deviation.

4.1.1.3.6 Explanation

If the motion of the pendulum is confined to small amplitude oscillations, the period of motion is given by $T = 2\pi\sqrt{\frac{l}{g}}$, and $g = \frac{4\pi^2 l}{T^2}$. We give our pendulum an amplitude of approx. 1 cm. Having a length of around 6.3 m this means that the angle the thread makes with the vertical is about $0 \cdot 1°$. This small-angle approximation is very accurate (see literature) compared to the accuracy with which we measure T and $/$.

We measured: $1 = 6.305$ m and $T = 5.0348$ s (std.dev.:0.0007), giving $g = 9.81(9)\text{ms}^{-2}$.

4.1.1.3.7 Remarks

- See also 'Mathematical pendulum (2) - Large angle'.
- The most troublesome is the measurement of $\%$: How accurate is a simple hardware store tape measure?
- The measurement of T is performed carefully, since in $g = \frac{4\pi^2 l}{T^2}T$ appears as T^2 and so in the error analysis this gives a weighing factor of 2 .
- Also the length of the pendulum compared to the size of the sphere is important to consider. When we neglect the mass of the thread compared to that of the cast iron sphere, but not neglecting the dimensions of the sphere, we should write: $T = 2\pi\sqrt{\frac{l_{sphere}}{mgl}}$. When the sphere is a point-mass, $I = m^P$ and we have again $T = 2\pi\sqrt{\frac{l}{g}}$. But when the sphere is not a point-mass, we have $I_{sphere} = \frac{2}{5}mR^2 + ml^2$ and $\frac{2}{5}R^2$ introduces an error compared to P. In our situation $l = 6.305$ m and $R = 9.3$ cm. This introduces an error of less than 0.0001 in g, so small compared to the standard deviation.

4.1.1.3.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 129-131
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 72-73 and 168
- Roest, R., Inleiding Mechanica, pag. 91-93
- Stewart, J, Calculus, pag. 262 and 266
- Young, H.D. and Freeman, R.A., University Physics, pag. 407-410

4.1.1.4 04 Chaotic Pendulum

4.1.1.4.1 Aim

To analyze the chaotic motion of a parametrically driven pendulum by explaining its motion in phase space by making a Poincaré plot.

4.1.1.4.2 Subjects

- 3A10 (Pendula)
- 3A95 (Non-Linear Systems)

4.1.1.4.3 Diagram

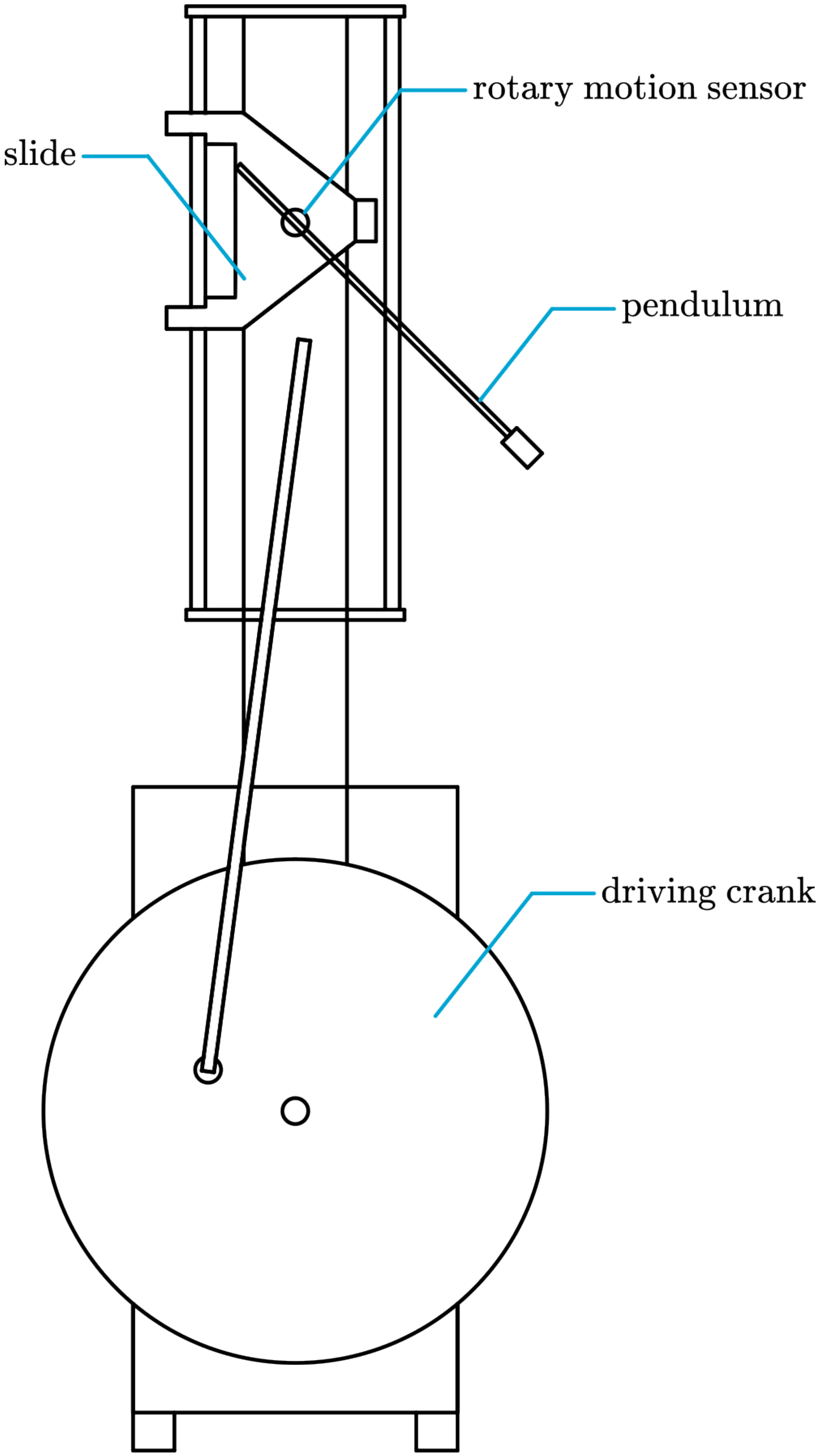


Figure 4.7: .

4.1.1.4.4 Equipment

- Parametrically driven pendulum
- Photogate
- Rotary motion sensor
- Data-acquisition system and computer. (We use Science Workshop).
- Projector to project monitor-image.

4.1.1.4.5 Presentation

The Pendulum is fixed on the shaft of the rotary motion sensor. The rotary motion sensor is fixed to the slide that is driven up and down by a crank mechanism (See Diagram and Figure 3 1).

The driven pendulum, see Figure 2, is placed on a spot that can be observed by all the students but which can be closed off during the lecture i self. Place it for example just outside the lecture room, so the door can be shut during the lecture, while keeping the monitor image visible to the students

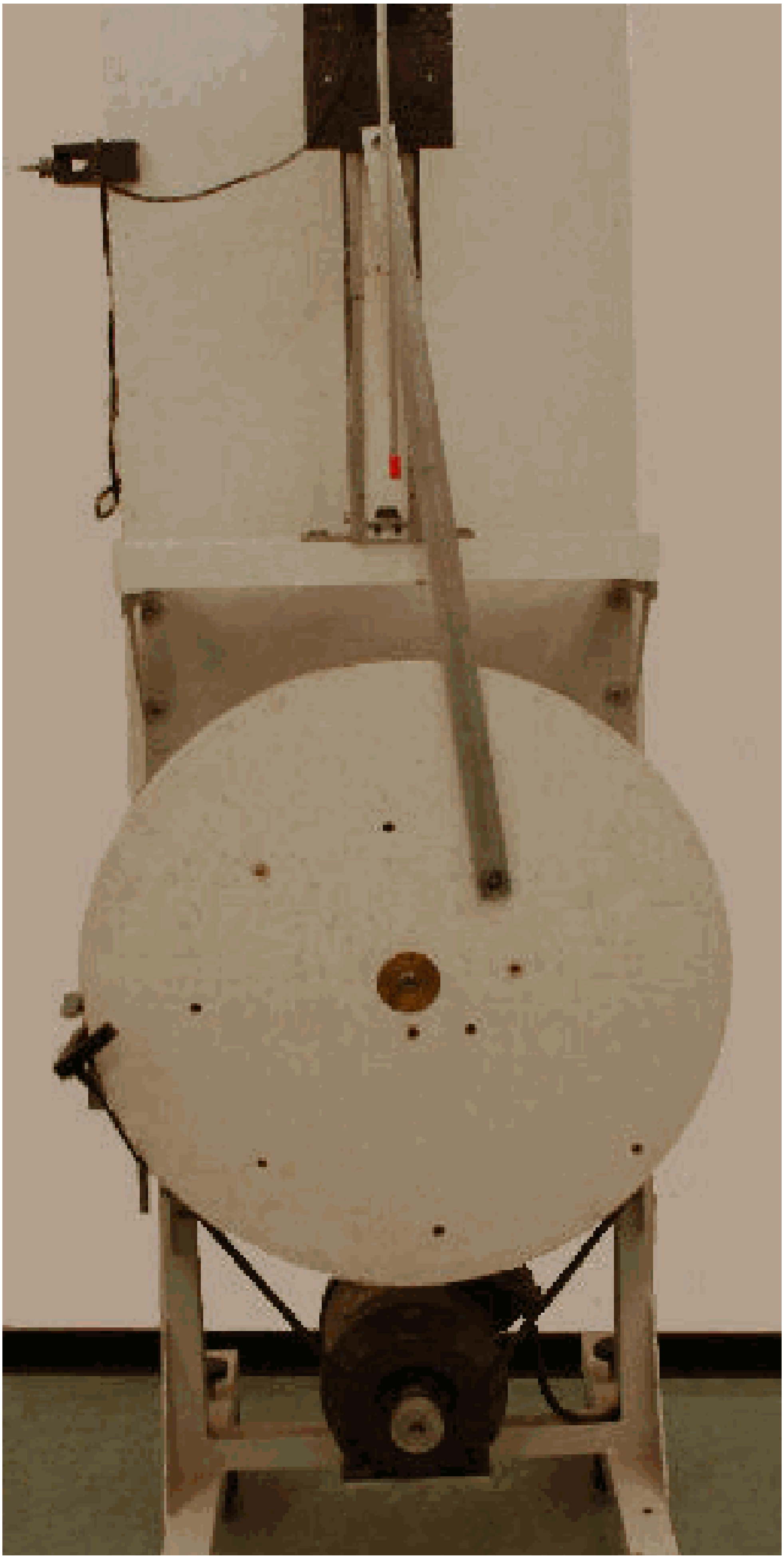


Figure 4.8: .

The software is set up to make a Poincaré plot of the angular position and angular velocity, and will be projected in the lecture room with use of the projector. The Poincaré plot will grow during the lecture and after a while the strange chaotic attractor will be displayed. In about 1 hour you will be able to see the contours of the attractor; after an other hour you will have a plot like in Figure 3.

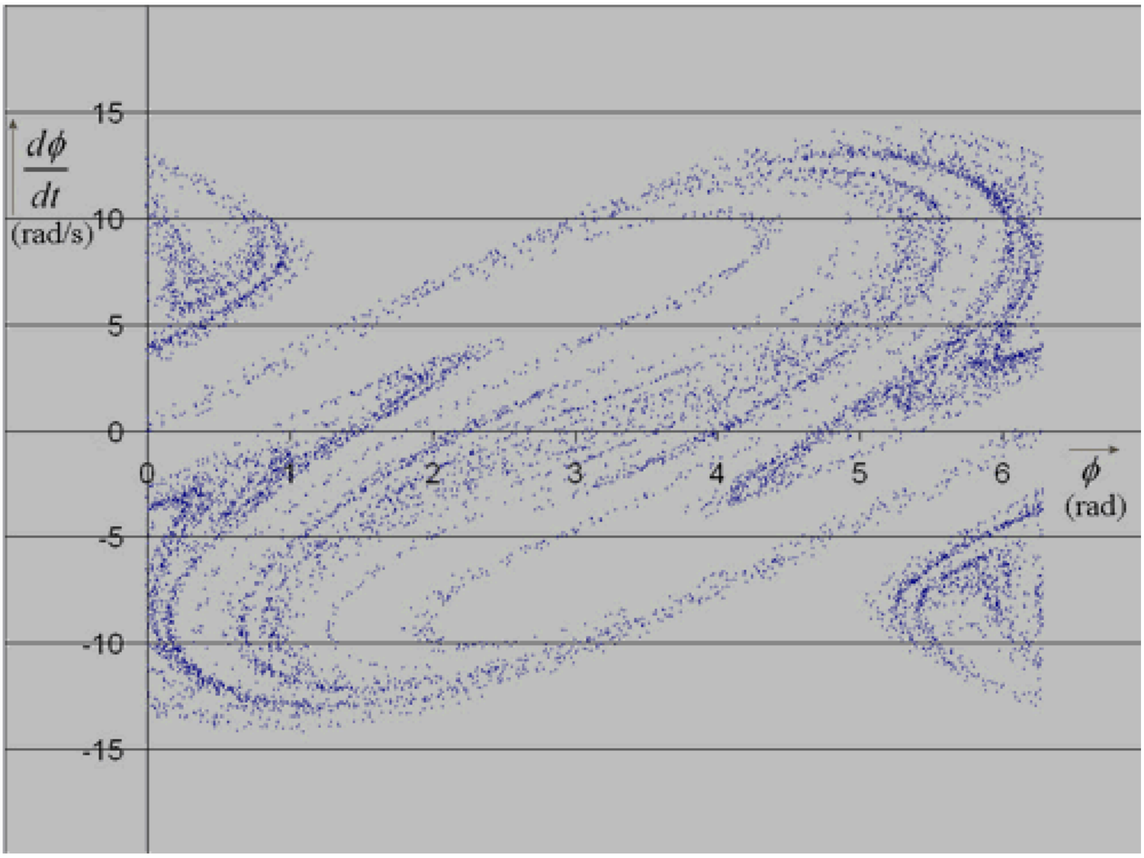


Figure 4.9: .

At the beginning of the lecture, having started the driven pendulum, you can introduce the driven pendulum and show its chaotic behavior. After this you can explain why we use a Poincaré plot to analyze the chaotic movement of the pendulum and that in a Poincaré plot not the time but space determines when to plot a point, by showing the students the spot where both angular position and angular frequency is measured en plotted against each other in the Poincaré plot.

4.1.1.4.6 Explanation

The equation of motion of a Chaotic pendulum is (see: SourcesXX):

$$\frac{d^2\text{��}}{dt^2} + \frac{k_2}{mL^2}\frac{d\text{��}}{dt} + \left[\omega^2 - \frac{A\Omega^2}{L}\cos(\Omega t)\right]\sin(\text{��}) = 0 \tag{4.1}$$

where:

- k_2 : damping constant
- m : mass of the pendulum
- $L = \frac{I}{m\ell} = \frac{(k^2+\ell^2)}{\ell}$: reduced length of the pendulum

where I is the moment of inertia of the pendulum with regard to its suspension point, ℓ is the distance between the point of suspension and the centre of mass, (see: McComb §6.2.8), and $k = \frac{\int r^2 dV}{\int dV} =$ (the radius of gyration of the pendulum, see: McComb §6.2.2)

- $\omega = \sqrt{\frac{g}{L}}$ (eigen frequency of pendulum at small amplitudes)
- A: amplitude of the nearly harmonic driving force
- Ω : angular driving frequency.

If there is no damping, $k_2 = 0$. If there is no driving force, $A = 0$. Then the equation of motion will be:

$$\frac{d^2��}{dt^2} + \omega^2 \sin(��) = 0 \tag{4.2}$$

When we substitute, $\omega = \sqrt{\frac{g}{L}}$ and $L = \frac{I}{m\ell}$, we will get the following equation of motion:

$$\frac{d^2��}{dt^2} + \frac{mg\ell}{I} \sin(��) = 0 \tag{4.3}$$

Solving this differential equation yields:

$$\frac{1}{2}��^2 - \frac{mg\ell}{I} \cos(��) = const.(McCombequation6.25). \tag{4.4}$$

The Parametrically driven pendulum is based on the article, *Unstable periodic orbits in the parametrically excited pendulum, of W. van der Water.*In this article some more friction terms have been added to the equation of motion of the chaotic pendulum, so that result of the simulation and the actual experiment are more like each other.

4.1.1.4.7 Remarks

- The pendulum is mounted on the Rotary motion sensor which is mounted on the slide and while provide use with the both the angular position and angular velocity (see Figure 4).

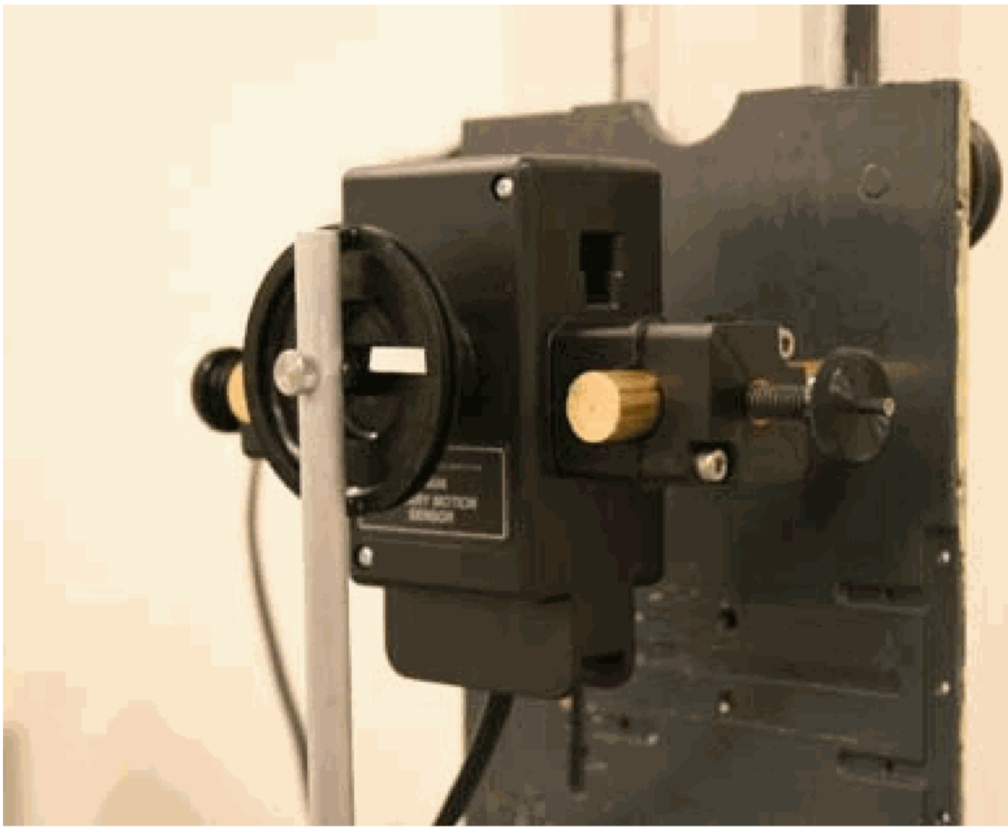


Figure 4.10: .

- The Photogate is placed on driving wheel and will give use the moment at which we will plot both the angular position and angular velocity of that moment in the Poincaré plot (see Figure 5).

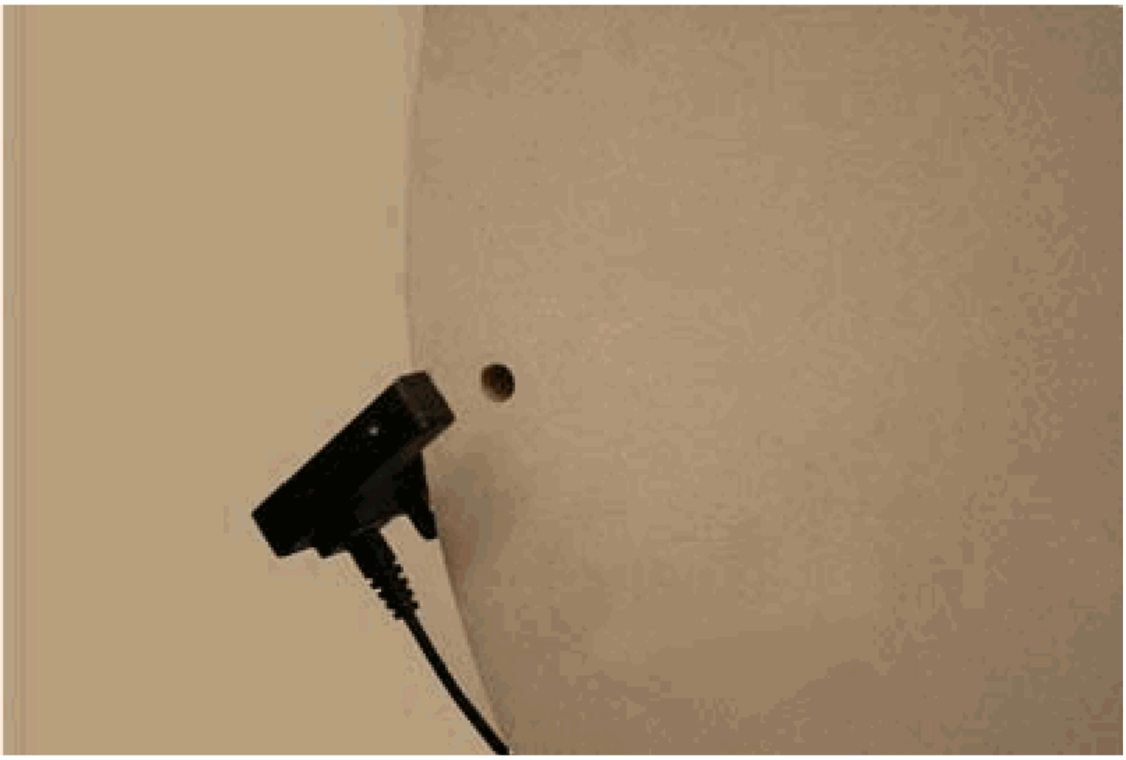


Figure 4.11: .

- Test if the driven pendulum keeps his chaotic movement for the period you want to use it, it sometimes ends in a harmonic movement after a while. When this happens try to adjust the driving frequency of the pendulum
- As extra you could ask the students to make a simulation of this pendulum using Maple or Mathlab.

Then you need to know the following parameters of the pendulum:

angular driving frequency $\approx 9\mathrm{rad/s}$

amplitude of the driving force ≈ 0.125 m

length of the pendulum ≈ 0.3 m

mass of the pendulum ≈ 0.03 kg

damping constant $\approx 1.7 \times 10^{-5}$ S

4.1.1.4.8 Sources

- Dynamics and Relativity, W.D. McComb, pag 125-128
- Unstable periodic orbits in the parametrically excited pendulum, W. van de Water; M. Hoppenbrouwers; F. Christiansen, Phys. Rev A 44(1991)6388698
- The Pendulum, A case study in physics, G.L.Baker J.A.Blackburn, pag. 121-149

4.1.2 3A15 Physical Pendula

4.1.2.1 01 Physical Pendulum (1) Compound Pendulum

4.1.2.1.1 Aim

To show and discuss the characteristics of a physical pendulum: reduced length, reversion pendulum and minimal period.

4.1.2.1.2 Subjects

- 3A15 (Physical Pendula)

4.1.2.1.3 Diagram

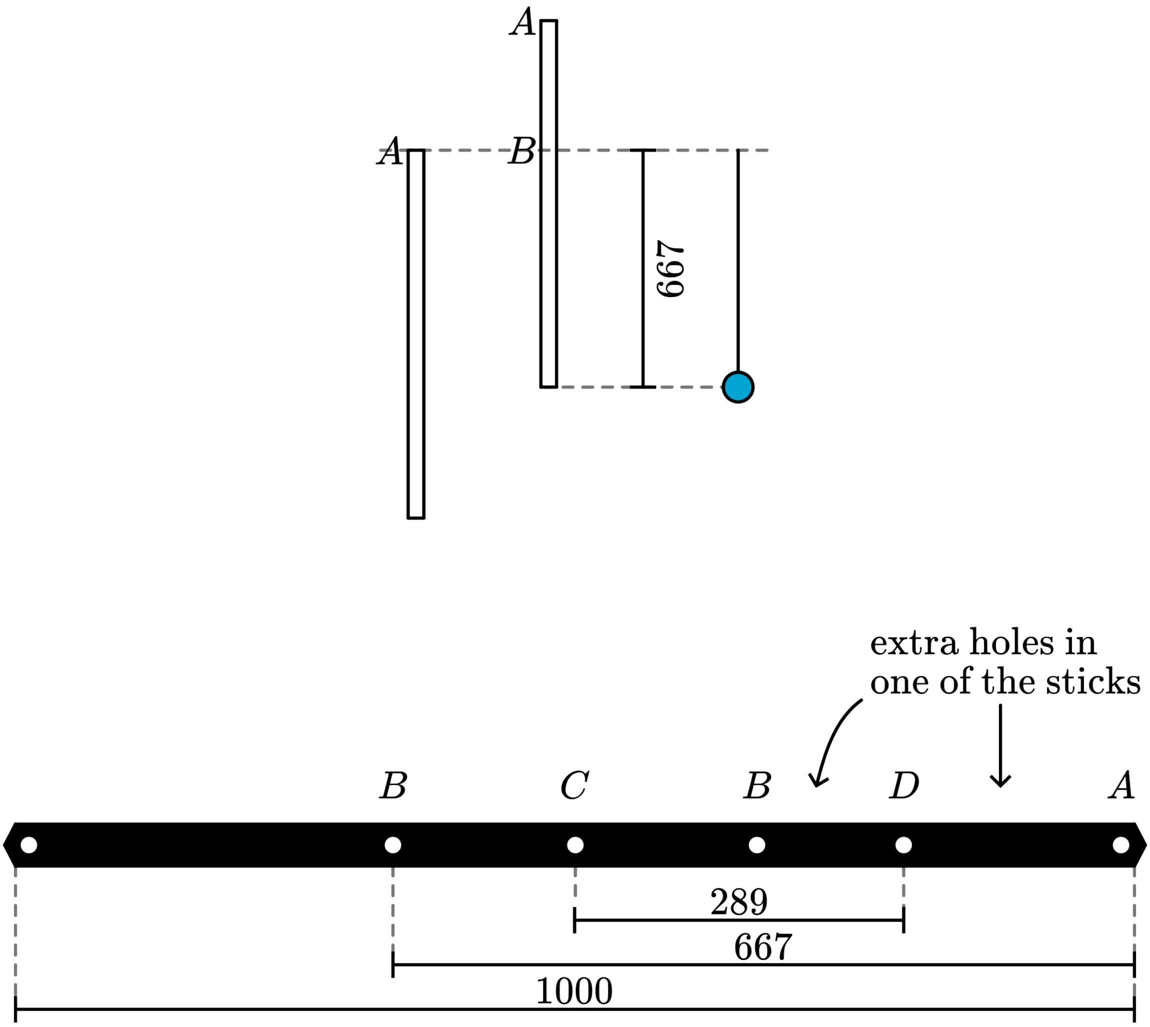


Figure 4.12: .

4.1.2.1.4 Equipment ‘

- 2 meter sticks; $I = 1$ m, with holes for reversed pendulum and minimum pendulum. (One of the sticks has extra holes at $s = 20$ cm and $s = 40$ cm (see PresentationXX 3.)
- 2 axes in a ball-bearing.
- 1 mathematical pendulum ($l = .667$ m).
- 1 meter stick for measurements.

4.1.2.1.5 Presentation

1. The physical pendulum is suspended on an axis at hole A. A mathematical pendulum is swinging and given such a length that its period equals that of the physical pendulum. Its length is measured and it shows 67 cm.
2. Now the physical pendulum is suspended on the axis at hole B. Its period shows to be the same as both foregoing pendulums. The length of the pendulum below B is measured and it shows that this length equals the length of the mathematical pendulum!
3. The pendulum is suspended at hole D. Now T is shorter than in the foregoing demonstrations. Evidently there is a minimum between A and B.

This can be demonstrated when both pendulums are suspended: one at D and the other in one of the extra holes on either side of D (between A and B). When both pendulums start together, after only a few oscillations it is clear that D is the faster pendulum.

4.1.2.1.6 Explanation

1. For a physical pendulum with mass m, oscillating around its suspension in point A, we can write for the period: $T = 2\pi\sqrt{\frac{I_A}{mgS}}$ (see Figure 2 I_A being the moment of inertia, and s being the distance between the centre l_M of mass and the axis of rotation).

When the physical pendulum is a long uniform stick of length l_F its moment of inertia is $I_c = \frac{1}{12}ml_F^2$ and when it oscillates around a point A a distance $s = \frac{1}{2}l_f$ away from C, then $I_A = \frac{1}{12}ml^2 + m\left(\frac{1}{2}l\right)^2$, so: $I_A = \frac{1}{3}ml_F^2$. The period of the pendulum becomes:

$$T_F = 2\pi\sqrt{\frac{\frac{1}{3}ml_F^2}{\frac{1}{2}mgl_F}} = 2\pi\sqrt{\frac{2}{3}\frac{l_F}{g}} \tag{4.5}$$

A mathematical pendulum of length l_M has a moment of inertia

$I_A = ml_M^2$ and so:

$$T_M = 2\pi\sqrt{\frac{ml_M^2}{mgl_M}} = 2\pi\sqrt{\frac{l_M}{g}} \tag{4.6}$$

When we want $T_F = T_M$, then we need that $l_M = \frac{2}{3}l_F$. This l_M is called the reduced length of the physical pendulum.

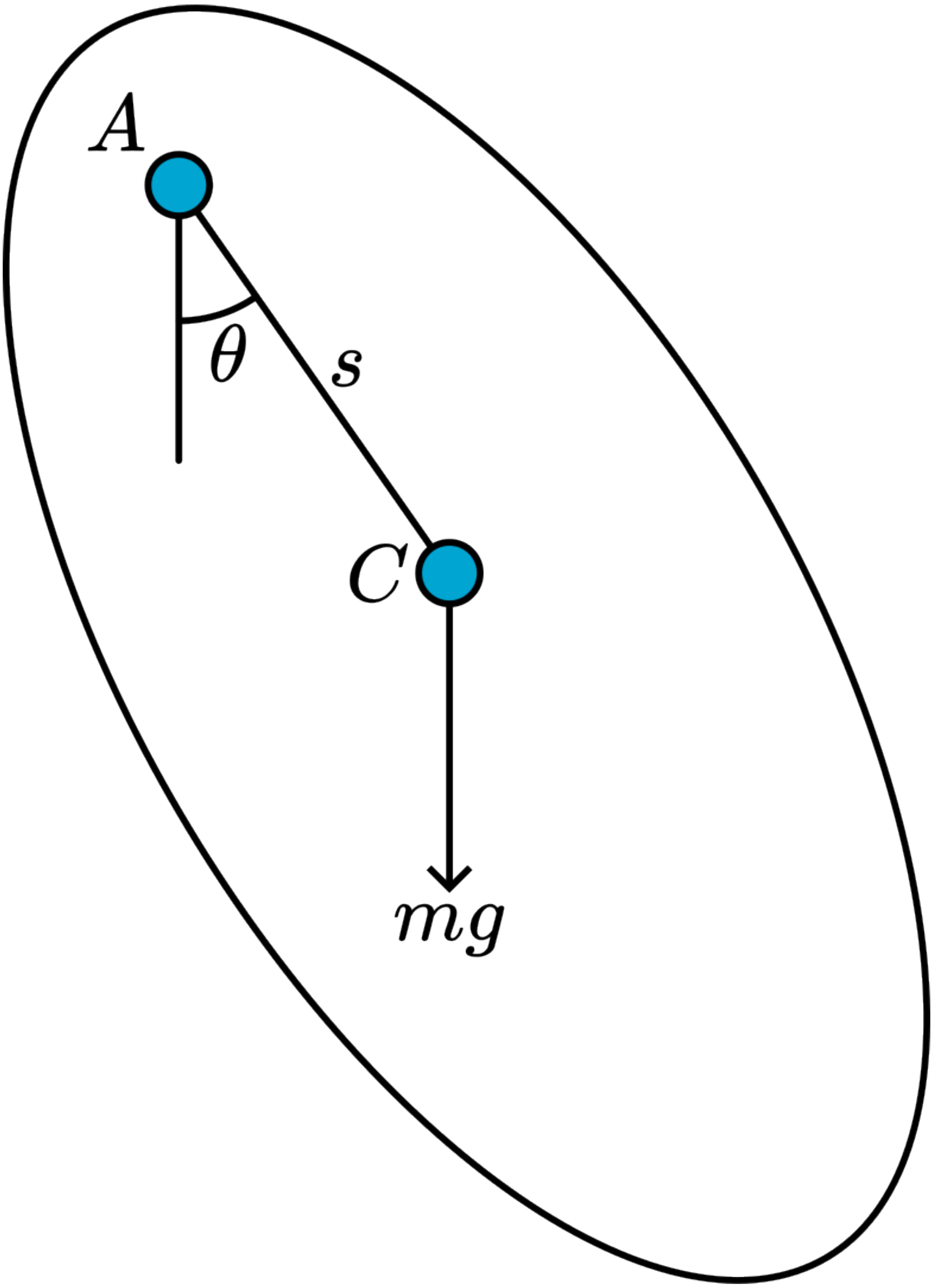


Figure 4.13: .

2. When the physical pendulum is suspended in a point B, such that its remaining length is l_M, then again the period is the same! (See Figure 3)

$T = 2\pi\sqrt{\frac{I_B}{mgs}}$

$I_B = \frac{1}{12}ml_F^2 + ms^2$ $s = l_M - \frac{1}{2}l_F$

and with $l_M = \frac{2}{3}l_F$, and $s = \frac{1}{6}l_F$, we find: $I_B = \frac{1}{12}ml_F^2 + \frac{1}{36}ml_F^2 = \frac{1}{9}ml_F^2$.

Then the period will be: $T = 2\pi\sqrt{\frac{\frac{1}{9}ml_F^2}{\frac{1}{6}mgl_F}} = 2\pi\sqrt{\frac{2}{3}\frac{l_F}{g}}$

So this pendulum has the same reduced length and the same period as the physical pendulum shown in the first presentation.

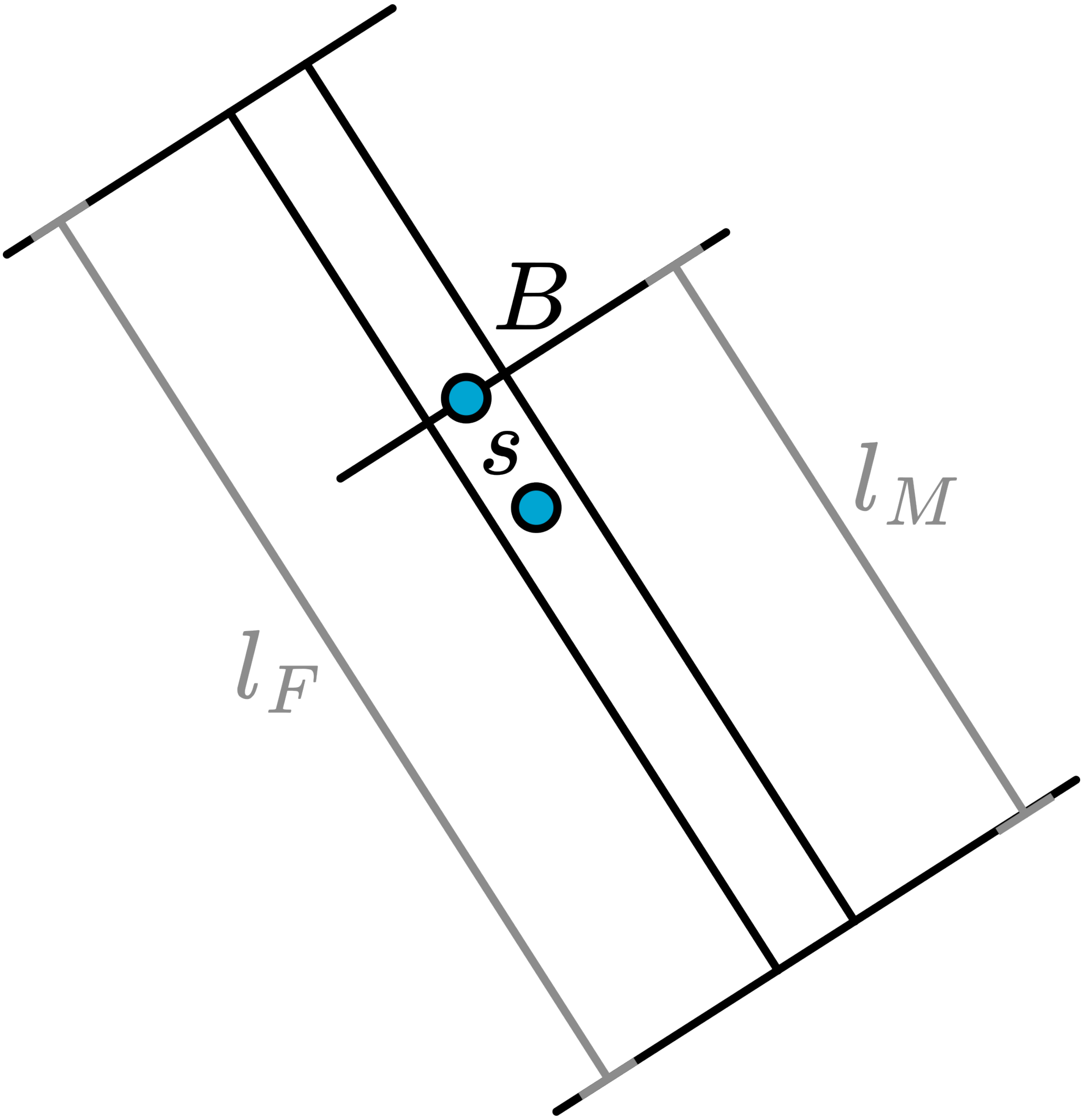


Figure 4.14: .

3. Between the suspension of A and B the presentation shows that a minimum period appears (suspension at D; see Diagram).

Now: $T = 2\pi\sqrt{\frac{I_D}{mgs}}$ (D being some point at s away from C.)

$I_d = I_c + ms^2$ and with $I_c = \frac{1}{12}ml_F^2$ we find:

$T = 2\pi\sqrt{\frac{\frac{1}{12}ml_F^2 + ms^2}{mgs}} = \sqrt{\frac{2\pi}{\sqrt{g}}\sqrt{\frac{l_F}{12s}} + 1}$

T being a minimum for $\frac{dT}{ds} = 0$, we find: $s = \frac{l_F}{\sqrt{12}}$.

The length of the stick (l_F) is 1 meter, so s equals $\frac{1}{\sqrt{12}} = 0.289$ meters.

4.1.2.1.7 Remarks

- In order to give the physical pendulum a length of 1 meter and yet have a hole at the ends of this stick, we have triangularly shaped the ends (see Figure 4).

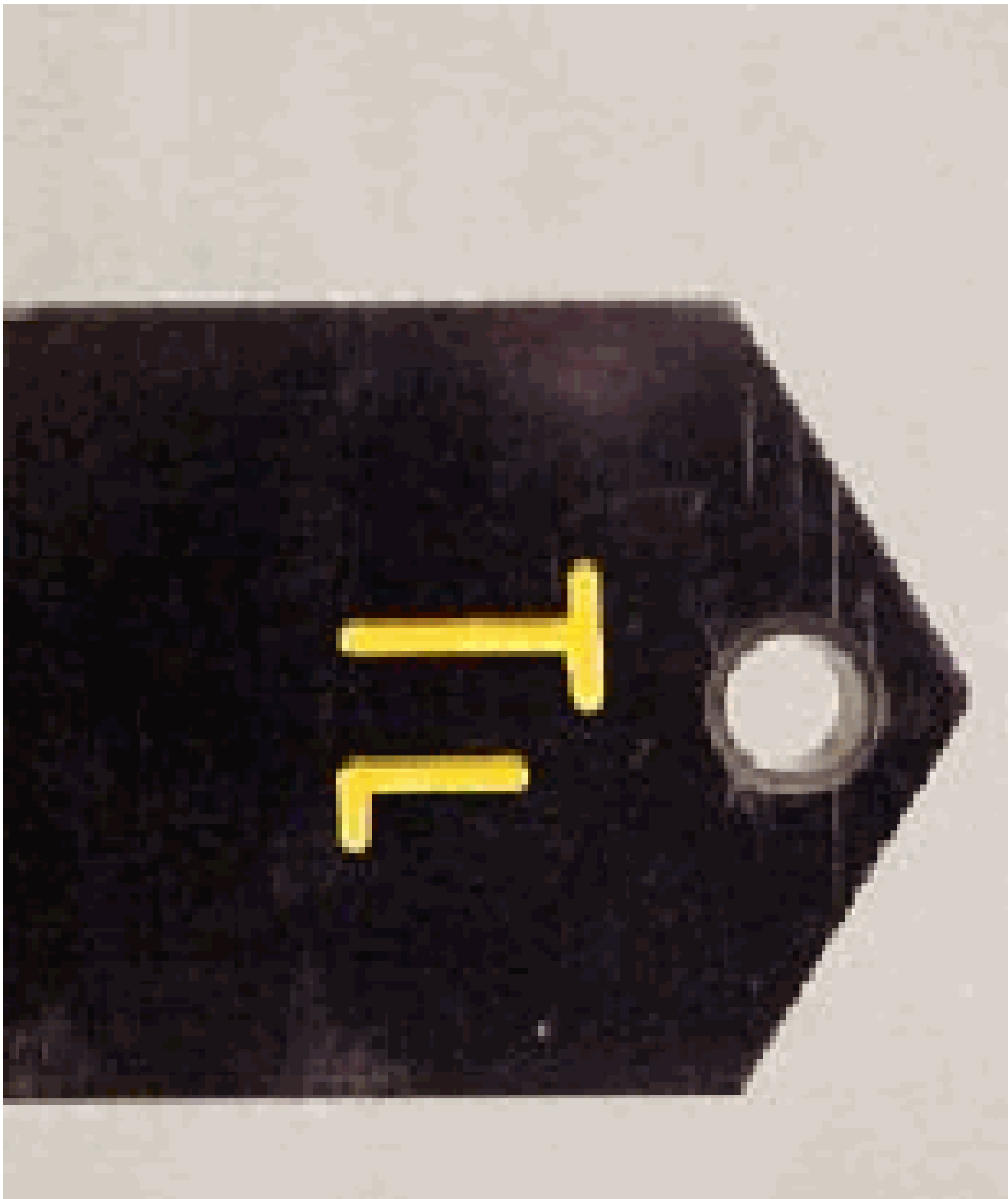


Figure 4.15: .

- The differences in T are small. With $I_F = 1$ meter, we find: $T_A (= T_B) = 1.64$ sec. And $T_D = 1.52$sec.

To obtain larger T s a suspension closer to C is needed.

Calculating: at $s = 12.5$ cm$(1/8 l_F), T = 1.78$sec.;

at $s = 8.3$ cm, $(1/12 l_F), T = 2.09$sec;

$s = 2.0$ cm, $T = 4.1$sec;

$s = 1.0$ cm, $T = 5.8$sec.

Of course at $s = 0, T =$ infinitive.

- $T = 2\pi\sqrt{\frac{I_A}{mgs}}$ shows that physical pendulums of the same mass have different periods due to their I/s-ratio. Comparing different pendulums can be done when comparing that ratio.

For a long uniform stick this reduces to comparing the I_F/s-ratio

4.1.2.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 154-156 and 161-162
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 277-278
- Roest, R., Inleiding Mechanica, pag. 168-169

4.1.2.2 02 Physical Pendulum (2)

4.1.2.2.1 Aim

To show the validity of the parallel axis theorem (Steiner's law).

4.1.2.2.2 Subjects

- 1Q10 (Momentum of Inertia)
- 3A15 (Physical Pendula)

4.1.2.2.3 Diagram

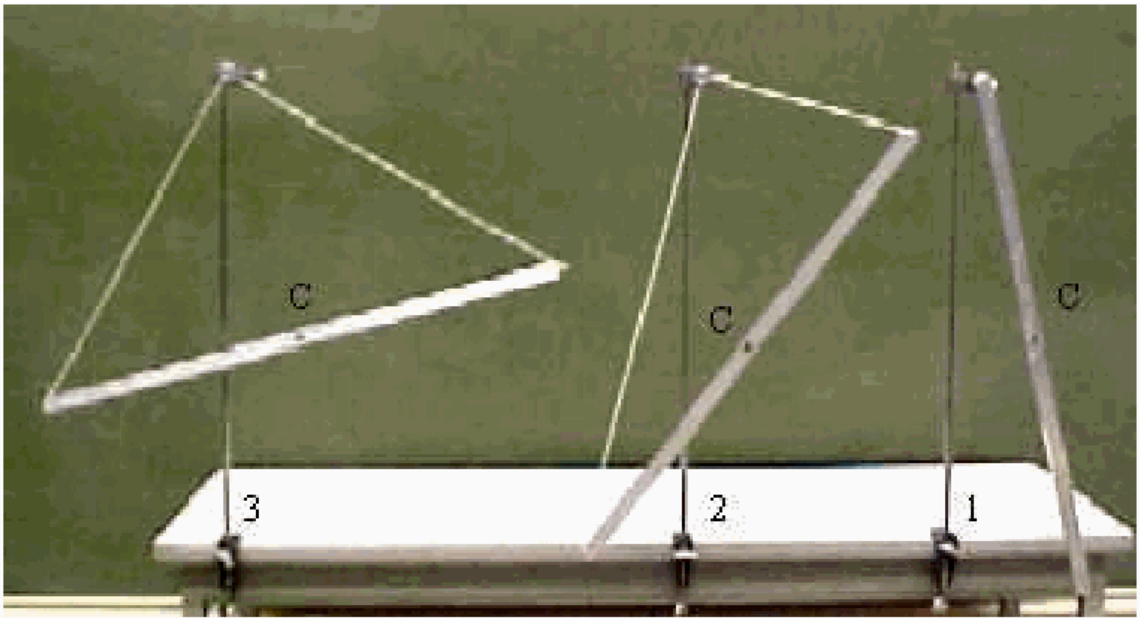


Figure 4.16: .

4.1.2.2.4 Equipment

- 4 sticks, one meter each, with holes at the ends.
- 1 meter stick for measurements.
- suspension wires for sticks (see Diagram).

4.1.2.2.5 Presentation

Pendulum 1 and 2 are swinging. It can be observed that they have the same period. Pendulum 1 and 3 are swinging. Again the same period is observed.

All three pendulums have the same period. Once started, they keep swinging in the same way together (observe the three centres of mass, C).

4.1.2.2.6 Explanation

For a physical pendulum the period T is given by: $T = \frac{2\pi}{\sqrt{g}}\sqrt{\frac{I_A}{ms}}$ (see "Physical pendulum (1)"

Also, $I_A = I_C + ms^2$ (Steiner), so T is constant as long as s is constant.

The suspension of the three pendulums is chosen such that the distance s is always the same because they are situated on a circle through C (see Figure 2). $s = 50$ cm.

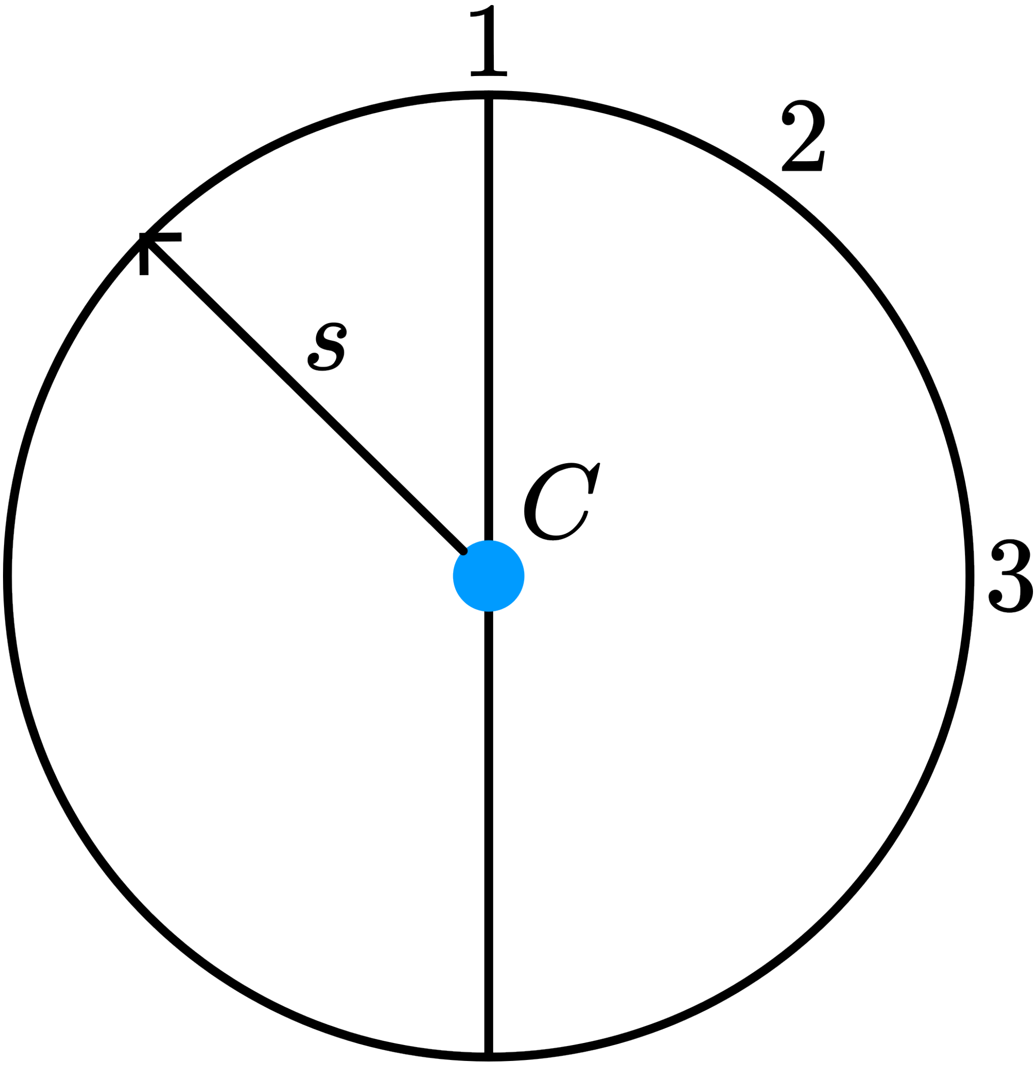


Figure 4.17: .

4.1.2.2.7 Remarks

We also have a suspension as shown in Figure 3. Now the suspension point is 0.167 m away from C and again T is the same because now the pendulum swings through the point of its reduced length (see demonstration “Physical pendulum (1)”).

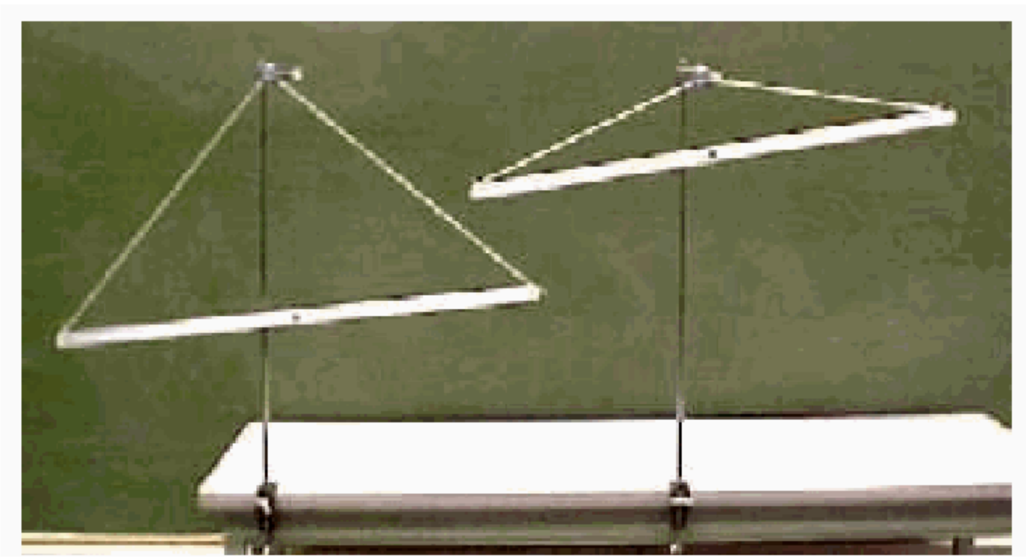


Figure 4.18: .

4.1.2.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 154-156
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 277-278

4.1.2.3 03 Physical Pendulum (3) Oscillating Ring

4.1.2.3.1 Aim

To show a particular example of a compound pendulum.

4.1.2.3.2 Subjects

- 3A15 (Physical Pendula)

4.1.2.3.3 Diagram

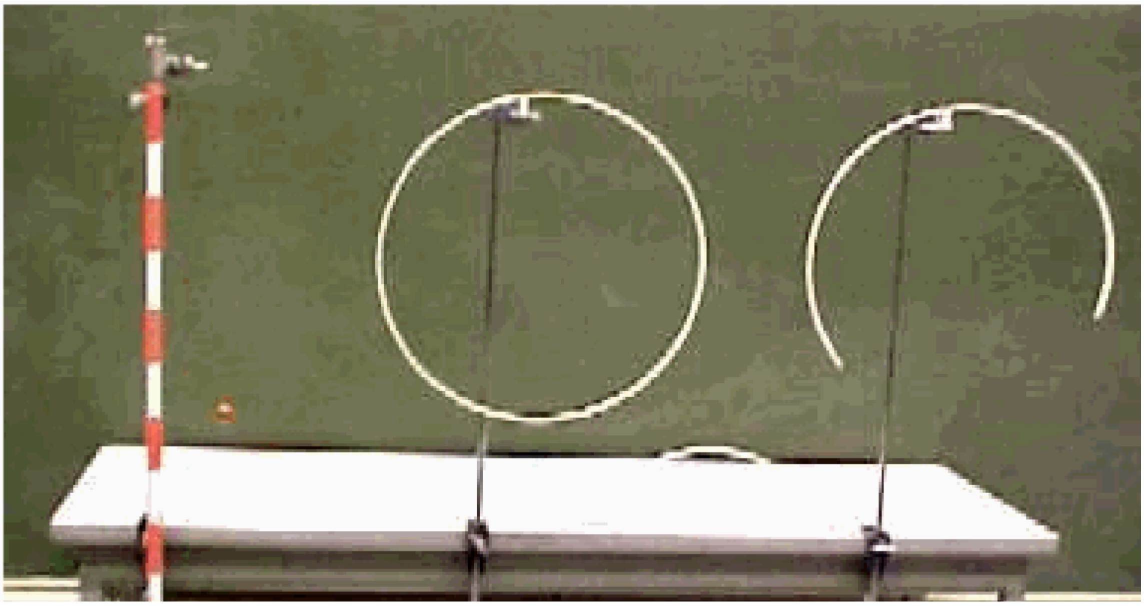


Figure 4.19: .

4.1.2.3.4 Equipment

- 2 large (steel) rings, $\phi = 600$ with knife-edge suspension. Th ese rings can be divided into 2/3 and 1/3.
- mathematical pendulum, I $= 600$
- meterstick

4.1.2.3.5 Presentation

One complete ring swings in its plane at the knife-edge on its periphery. A simple pendulum whose length is equal to the diameter of the ring is suspended beside it so the equality of periods can be observed.

A second 2/3-ring is made swinging. It can be observed that the ring has still the same period!

Again the same period is measured when 1/3-ring is swinging

4.1.2.3.6 Explanation

- For a physical pendulum, the period T is given by $T = \frac{2\pi}{\sqrt{g}}\sqrt{\frac{I_A}{ms}}$.

If the pendulum is a complete ring, then $s = R$ (see Figure 2), $I_A = I_C + mR^2$ and $I_c = mR^2$. Then $T = \frac{2\pi}{\sqrt{g}}\sqrt{2R}$, so $I_r = 2R$.

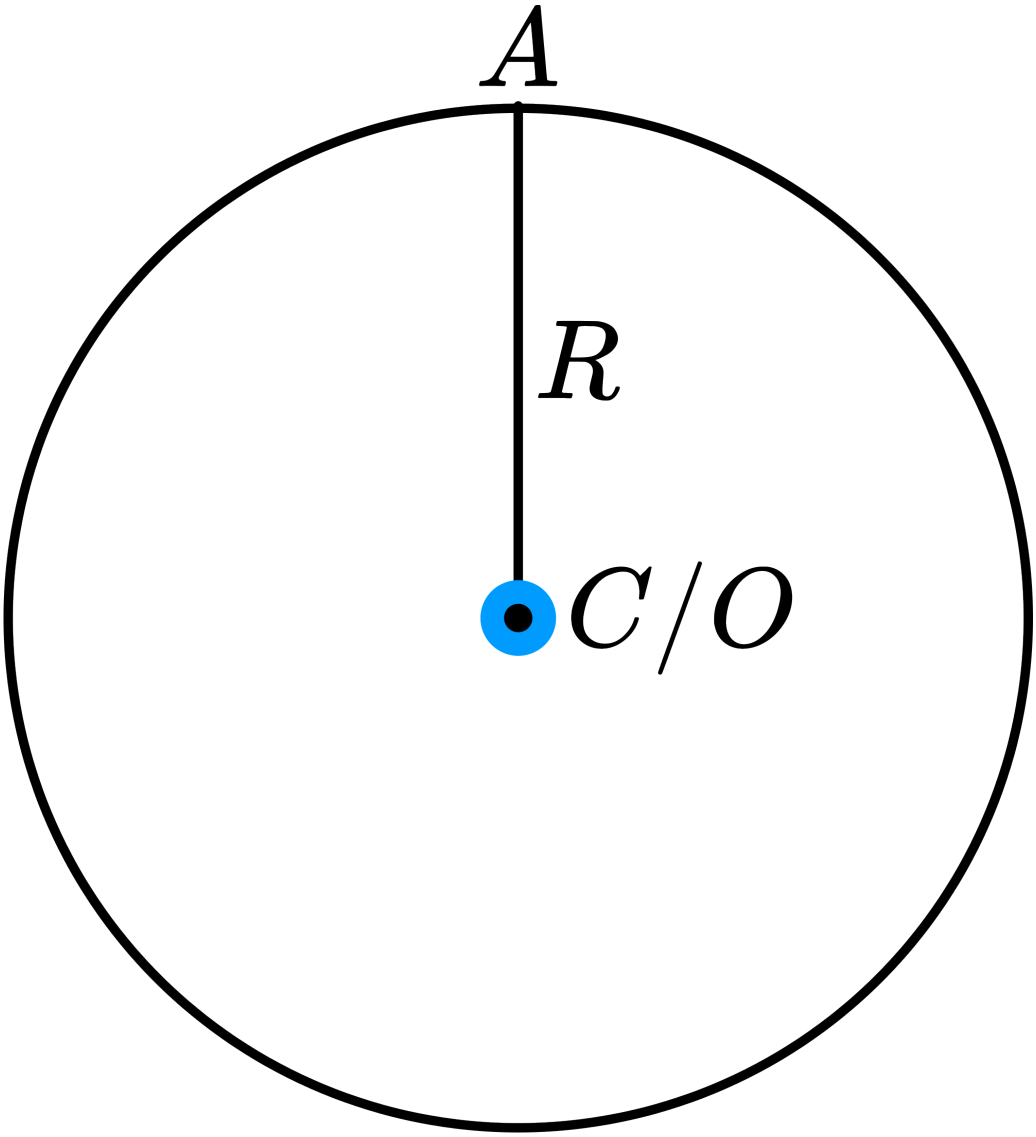


Figure 4.20: .

So a complete ring has the same period as a mathematical pendulum of length 2R.

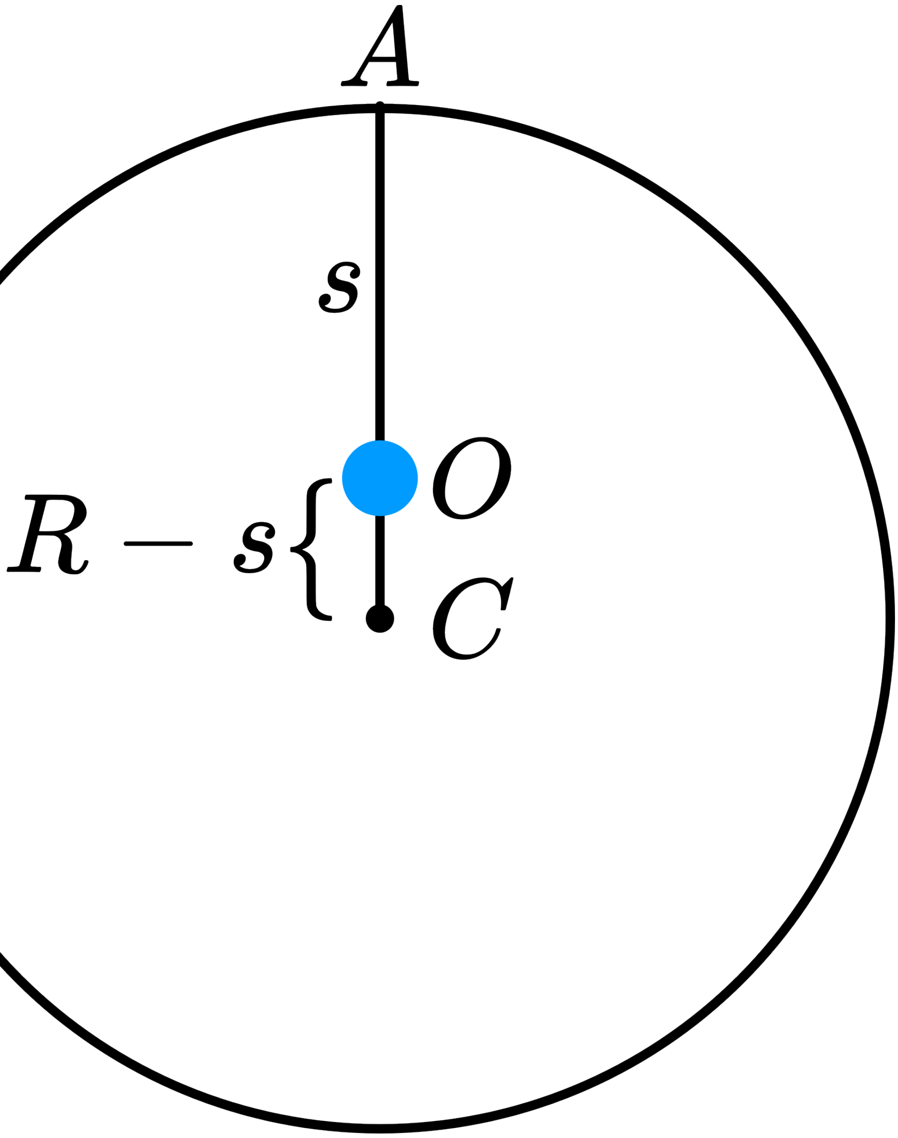


Figure 4.21: .

- If the pendulum is part of a complete ring, $I_O = mR^2$ (Figure 3). Also $I_O = I_C + m(R - s)^2$ (C is the center of mass) and $I_A = I_C + ms^2$. It follows that $I_A = 2mRs$ and $T = \frac{2\pi}{\sqrt{g}}\sqrt{2R}$. So again $I_r = 2R$.

4.1.2.3.7 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 126-127
- Roest, R., Inleiding Mechanica, pag. 169-170
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 88

4.1.3 3A40 Simple

4.1.3.1 01 Mathematical Pendulum (1) Simple Harmonic Motion

4.1.3.1.1 Aim

To show the relationship between position, velocity and acceleration of a simple pendulum.

4.1.3.1.2 Subjects

- 3A10 (Pendula)
- 3A40 (Simple Harmonic Motions)

4.1.3.1.3 Diagram

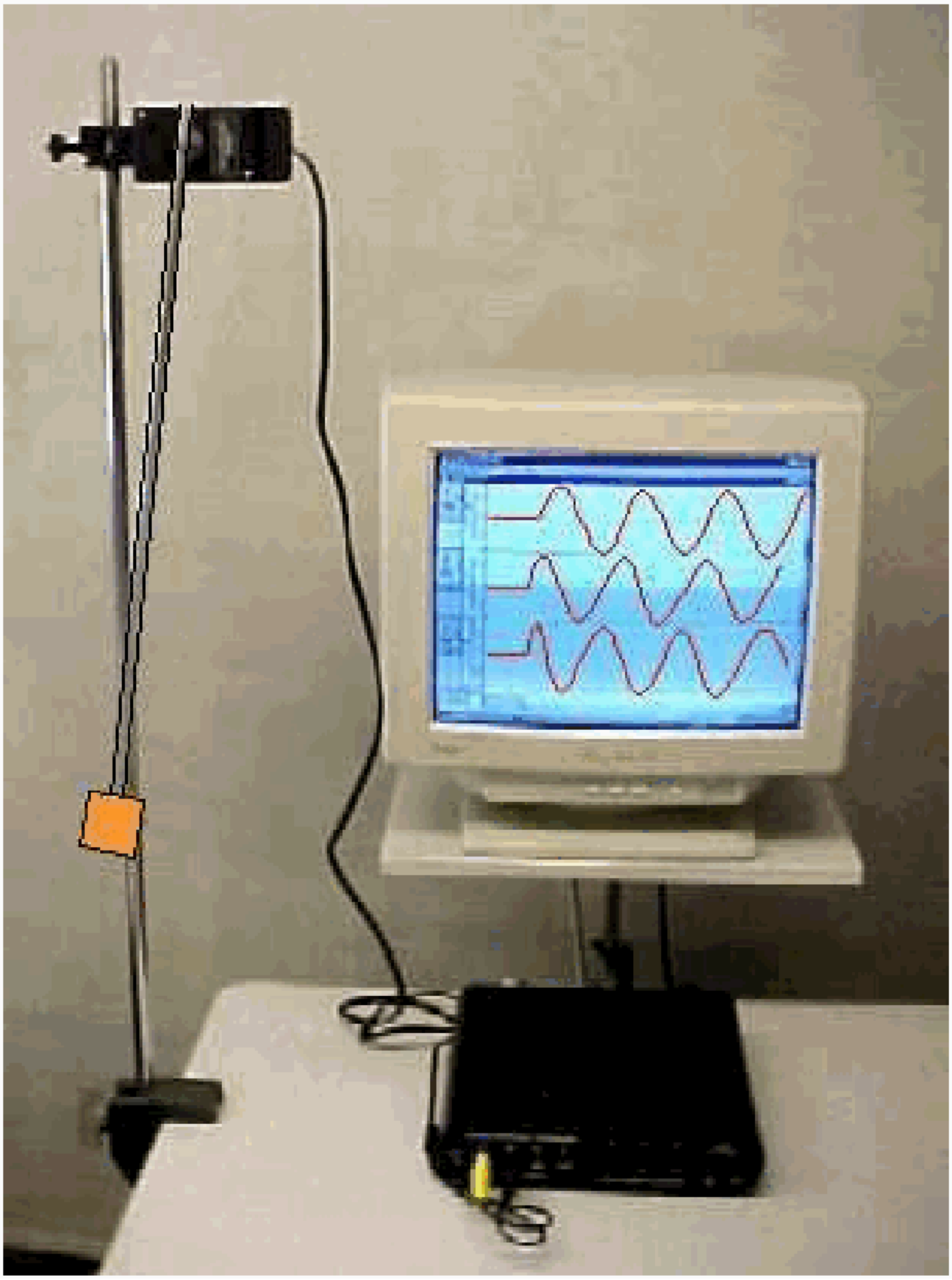


Figure 4.22: .

4.1.3.1.4 Equipment

- Simple pendulum: aluminum tube with brass mass.
- Rotary motion sensor (we use Pasco CI-6538).
- Data-acquisition system and computer with software (we use 'Science Workshop').
- Projector to project the monitorscreen.

4.1.3.1.5 Presentation

Set up the software to display graphically angular position, angular velocity and angular acceleration of the pendulum. When the pendulum is in its vertical position at rest, we start data collection. We give the pendulum a small amplitude and let it swing. When we have collected about four complete cycles, the data-acquisition is stopped.

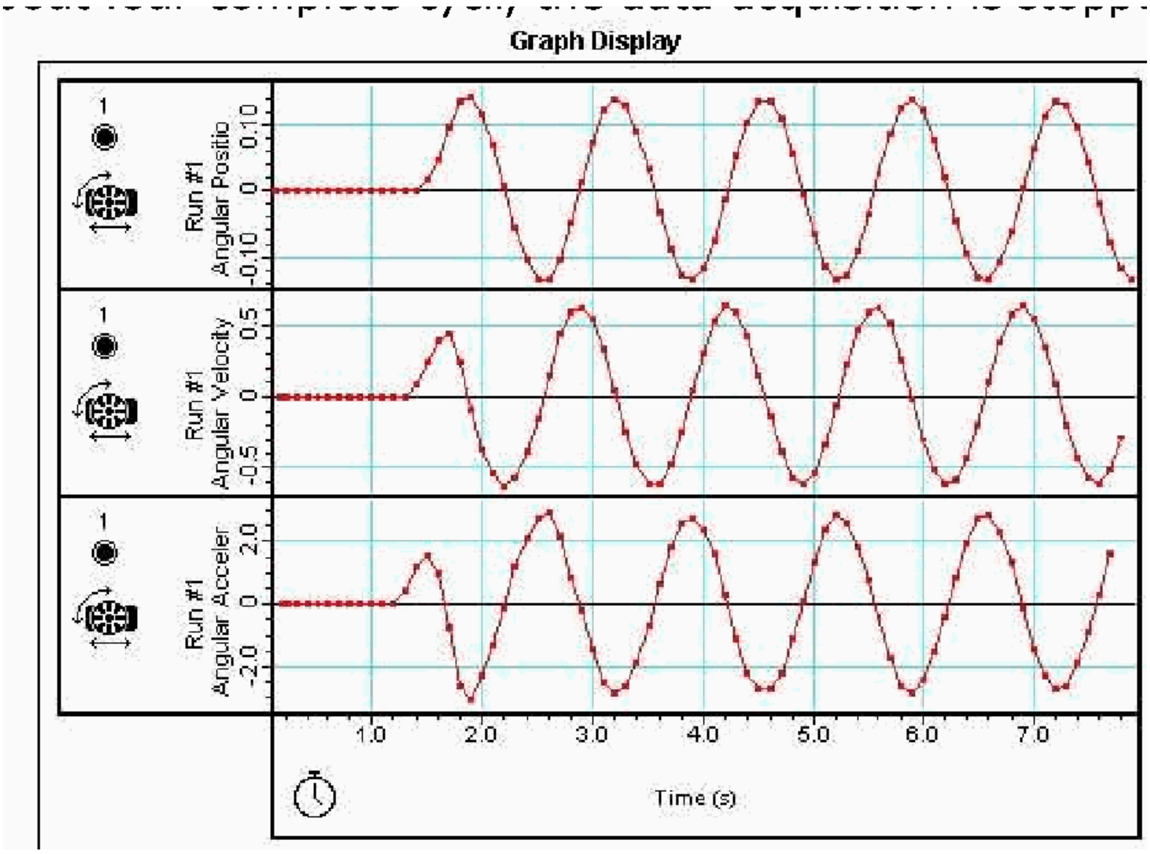


Figure 4.23: .

Already at first glance this registered graph shows its sine-shaped appearance. To have a more convincing conclusion the software can apply a mathematical curve-fit to the registered position-graph, to show that a sinusoidal equation "covers" the position-graph very good. So a sine-function describes the behavior (position-time) of this pendulum very good. A second run of the oscillations is registered, but now with a higher amplitude. Clearly can be observed now that the motion is no longer sinusoidal Trying a sine-fit will confirm this (read the chi2-value). Make a third run again with small amplitude and check the differential relationships between 'position', 'velocity' and 'acceleration': e.g.

- The points of zero-velocity correspond with maximum - and minimum position;
- The acceleration-graph is an inverse "copy" of the position-graph;
- ……….

4.1.3.1.6 Explanation

The equation that describes the motion of the mass m is given by $a_x = \frac{d^2s}{dt^2} = -g \sin\theta$.

This is not a simple harmonic motion since $\sin \theta$ is not proportional to s.

Only for small amplitude oscillations $\sin \theta \approx \theta = \frac{s}{l}$ and the equation of motion reduces to $\frac{d^2 s}{dt^2} = -\frac{g}{l} s$ This is the differential equation for simple harmonic motion, giving our observed sinusoidal graphs.

For further explanation see: SourcesXX.

4.1.3.1.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 48-52
- Young, H.D. and Freeman, R.A., University Physics, pag. 398-399

4.1.3.2 03 Simple Harmonic Motion (SHM) (1)

4.1.3.2.1 Aim

To show that a spring-mass system is a harmonic oscillator.

4.1.3.2.2 Subjects

- 3A40 (Simple Harmonic Motions)

4.1.3.2.3 Diagram

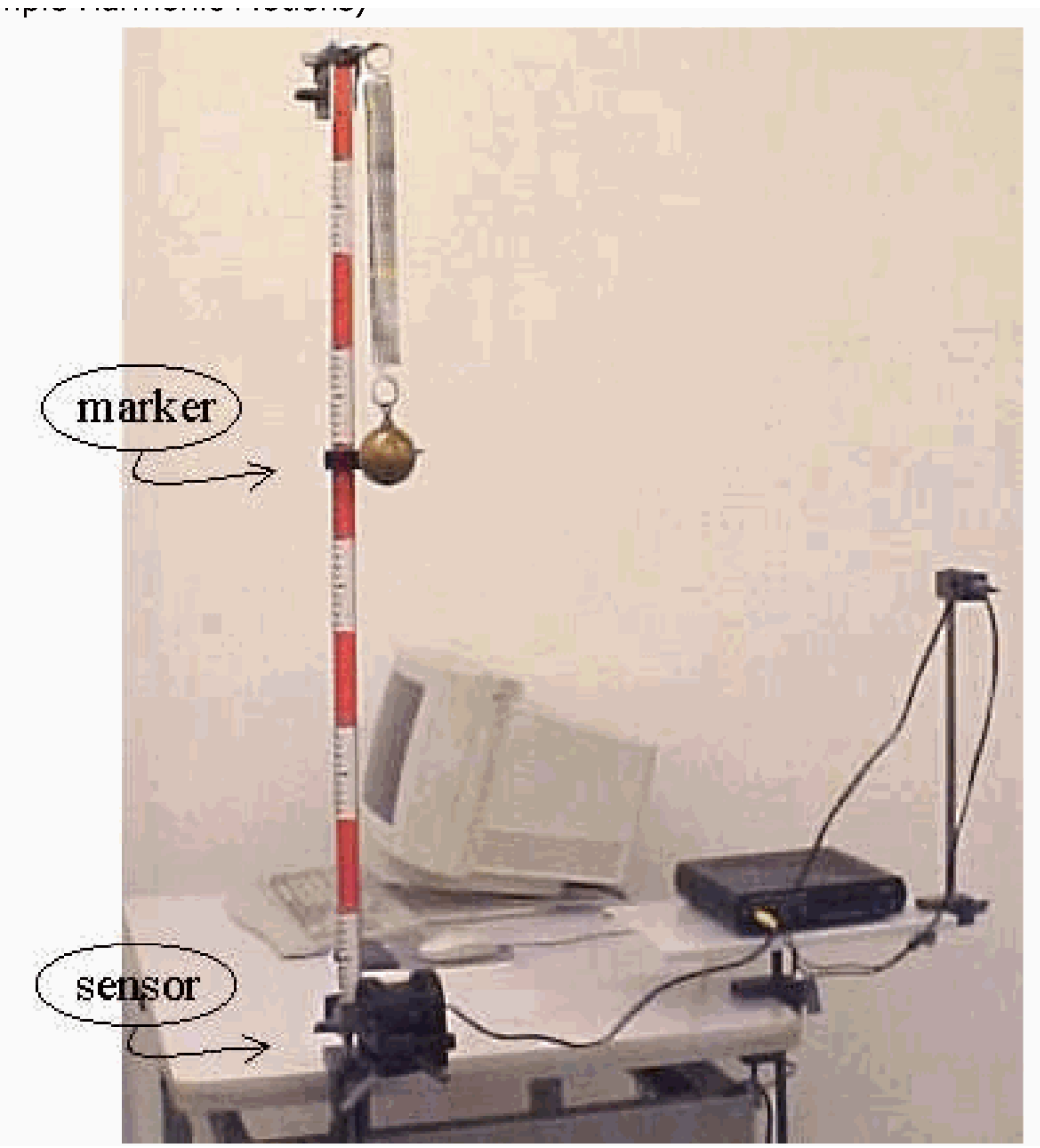


Figure 4.24: .

4.1.3.2.4 Equipment

- Spring ($k = 45$ N/m).
- Mass (1 kg).
- Demonstration ruler with sliding marker.
- Position sensor.
- Interface and software.
- Projector to project monitor screen.

4.1.3.2.5 Presentation

The spring is hung to a hook and loaded with a mass of 1 kg. When the mass is at rest the sliding marker is positioned at the centre of mass (CM) of the 1 kg mass (see Diagram). Then the mass is set in oscillatory motion and it can be observed that the mass oscillates around the original position of the CM. Finally, it will end at this position (due to damping). When the system still oscillates, it is brought to a stop. Taking the mass in your hand and positioing it above its rest position, makes it clear to the students that the force on the mass is directed towards the marker. The same is done by positioning the mass below the marker.

he data-acquisition system shows a (still empty) graph of position versus time. Shortly, the functioning of the data-acquisition system is explained to the students (For instance, when moving your hand above the position sensor, the distance to the sensor is monitored on the presented position graph).

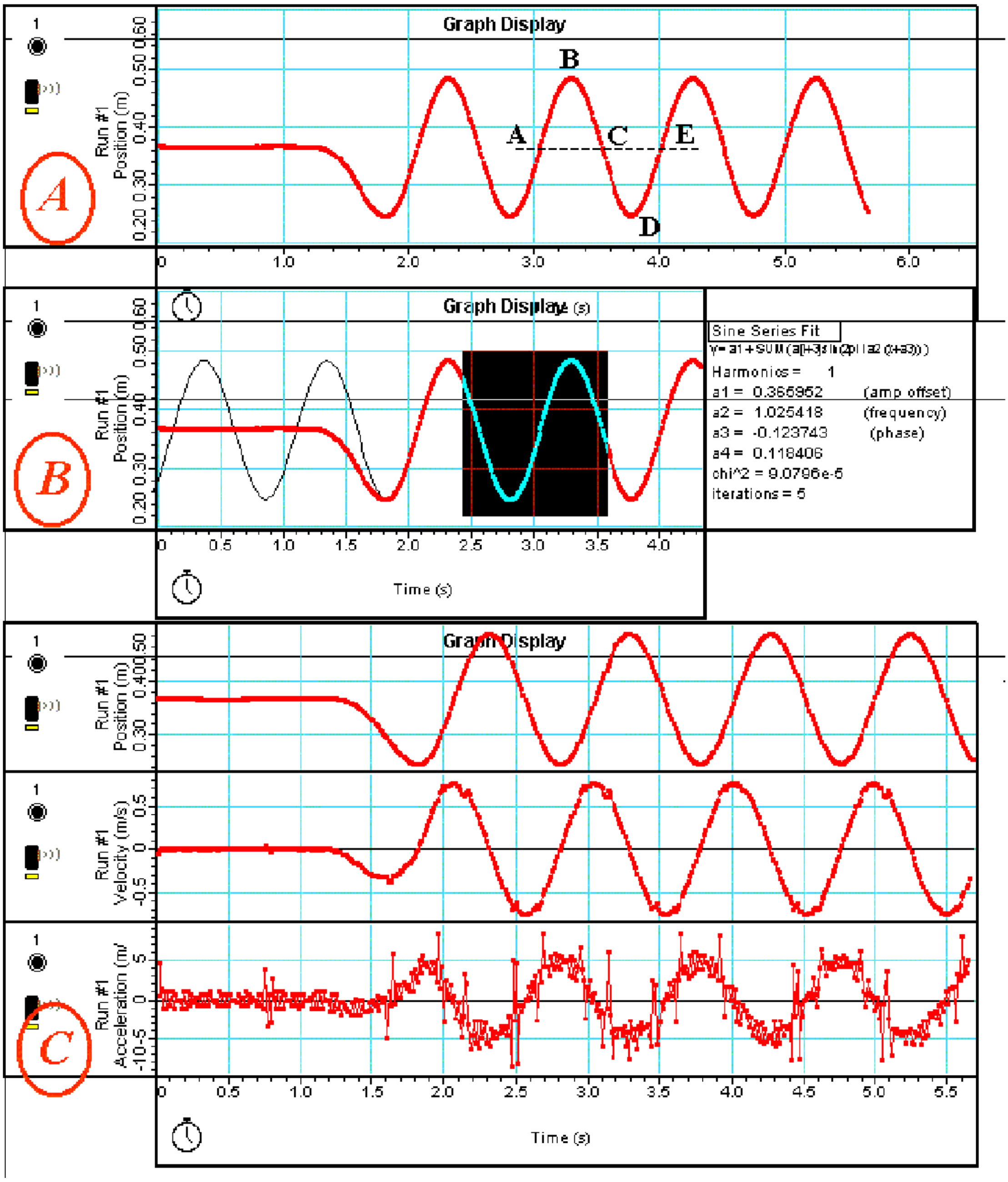


Figure 4.25: .

Data-recording is started and the spring-mass system is set in motion again. When about 5 cycles are registered, the data-recording is stopped and the resulting position graph can be studied (see Figure 2A)

1. When the mass rises above the marked rest position the first part (AB) of the curve shows that it slows down (because AB becomes more and more level). So during AB the force is downwardly directed. From B to C the graph shows that the mass accelerates (because BC becomes steeper all the time). So also during BC the force is directed downward. CDE can be described in a similar way: always the force is directed towards the rest-position.
2. The graph suggests very strongly that it has a sine-shape. So by means of the software we try a sine-fit (see Figure 2B). This fits very well (very low CHI2- value), confirming our "guess".
3. Applying the software we add the graphs of velocity and acceleration. The differential relationship between these three quantities can be verified now:

-The points of zero velocity correspond with maximum - and minimum position;

-The acceleration-graph is an inverse "copy" of the position-graph;

-.......

4.1.3.2.6 Explanation

1. An oscillating system in which the acceleration (or force) is always directed towards a fixed central point and increases linearly with displacement from that fixed point performs a so-called simple harmonic motion. A spring-mass system is such a system: When the (ideal) spring is displaced from its rest position, the restoring force (F) is proportional to this displacement $(F = -kx)$ and directed towards that rest position.
2. Applying Newton's second law, the dynamic equation of motion is $\frac{d^2x}{dt^2} = -\frac{k}{m}x$. Solution of this is $x(t) = A \sin \omega t$ The sine-fit in our demonstration confirms this.

4.1.3.2.7 Remarks

- Making the frequency of the position sensor lower will smoothen the calculated graphs of velocity and acceleration.

4.1.3.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 45-52
- Young, H.D. and Freeman, R.A., University Physics, pag. 394-397

4.1.3.3 03 Simple Harmonic Motion (SHM) (2)

4.1.3.3.1 Aim

To show the harmonic motion of a spring-mass system

4.1.3.3.2 Subjects

- 3A40 (Simple Harmonic Motions)

4.1.3.3.3 Diagram

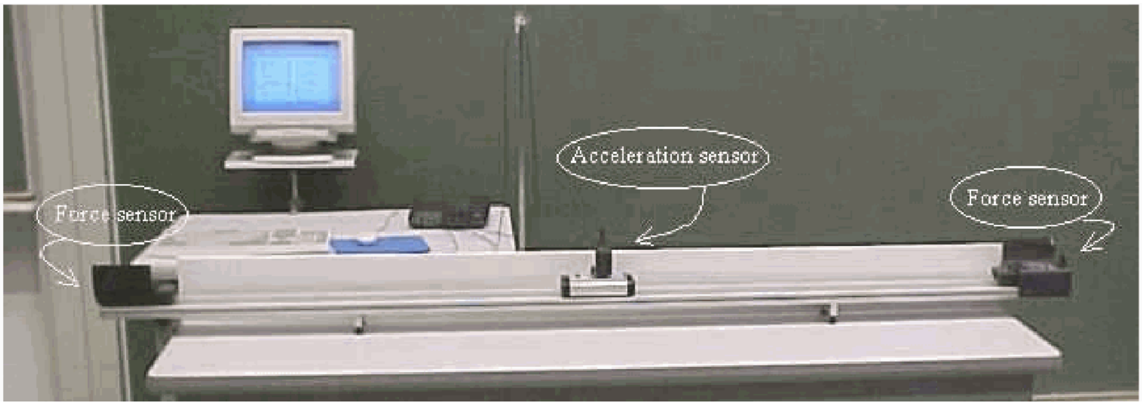


Figure 4.26: .

4.1.3.3.4 Equipment

- Track, 2.2 m.
- Cart.
- Mass equal to the cart.
- Two force-sensors, with mounting bracket.
- Acceleration sensor.
- Two springs.
- Data-acquisition system and software.
- Projector to project the monitorscreen.
- Mass, three times the mass of the cart.
- Stopwatch with large display.

4.1.3.3.5 Presentation

1. Set up the equipment as shown in the Diagram. On the monitorscreen four graphs are prepared: The springforces F_1 and F_2 and the resultant force on the cart $(F_1 - F_2)$ and the acceleration a of the cart (see Figure 21.

Collect data while the system is at rest. In the graphs F_1 and F_2 show a negative value and $(F_1 - F_2)$ and a are zero (see the green lines in Figure 2). Displace the cart from equilibrium and let it go. Collect data during about 4 complete swings of the system (the red curves in Figure 2). Make a sine curve-fit for the graph that displays the acceleration, to show that the motion is really harmonic.

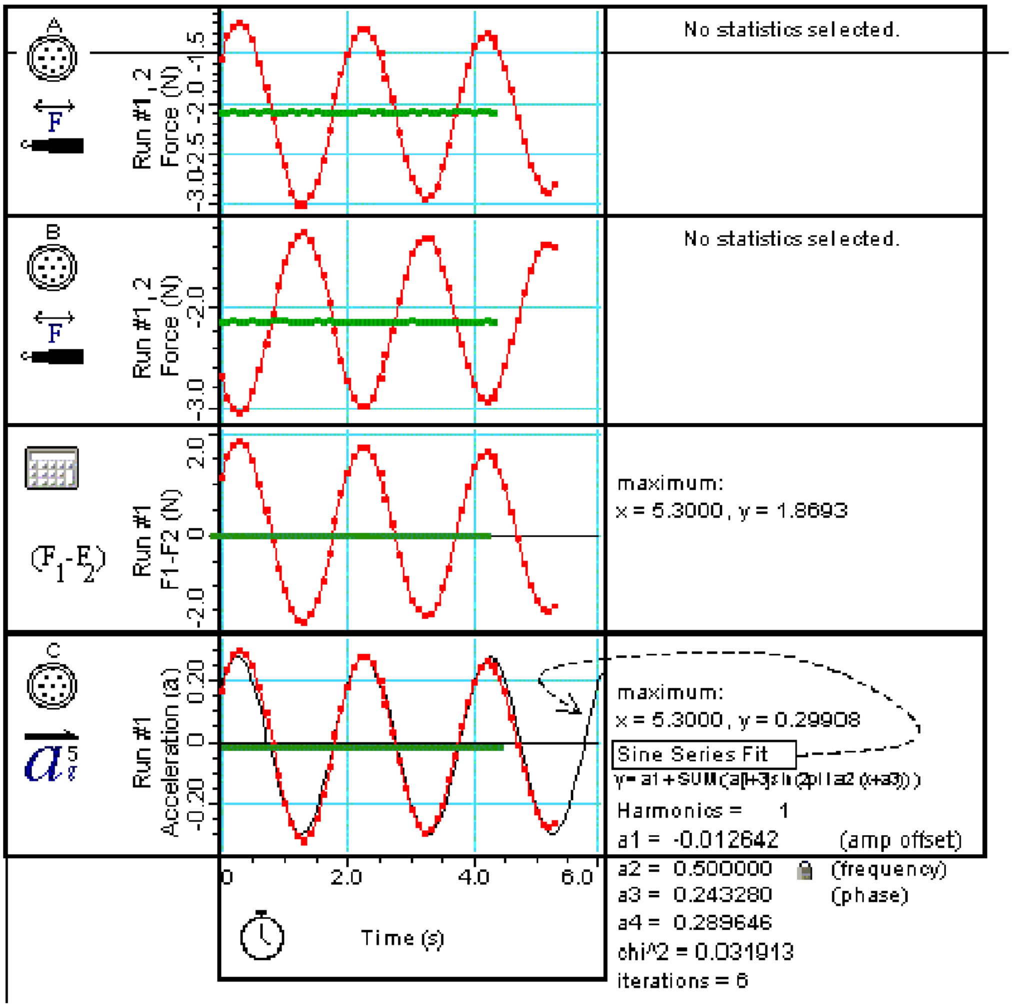


Figure 4.27: .

2. Set the cart in motion and clock how long it takes to run five periods. Add masses to the cart so that its total mass is four times its original mass. Make the students predict what will happen to the period. Set the cart in motion and clock again five periods to check if the prediction fits.

4.1.3.3.6 Explanation

1. A mass is in SHM as long as its acceleration (a) is always directed towards a fixed central point and increases linearly with displacement. The force on themass is a springforce ($F = -kx$). Applying Newton's second law we get $F = -kx = ma$ and hence $a = -\frac{k}{m}x$, so $a \propto -x$.
2. Analysis shows that for SHM of a spring-mass system $\omega = \sqrt{\frac{k}{m}}$. So increasing the mass fourfold means a reduction of ω by a factor 2.

4.1.3.3.7 Remarks

- The graphs of $F_1 - F_2$ and acceleration show directly the linear relationship between F and a. So in this demonstration Newton's second law is visible directly. The values of maximum $(F_1 - F_2)$ and maximum a, shown in the "statistics box" of the display (see Figure 2) give directly the value of $m : m = \frac{F_1 - F_2}{a}$.

4.1.3.3.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 47-52

4.1.3.4 05 Simple Harmonic Motion (SHM) (3)

4.1.3.4.1 Aim

To show simple harmonic motion of a spring-mass system and the relationship between the variables that determine the period.

4.1.3.4.2 Subjects

- 3A40 (Simple Harmonic Motions)

4.1.3.4.3 Diagram

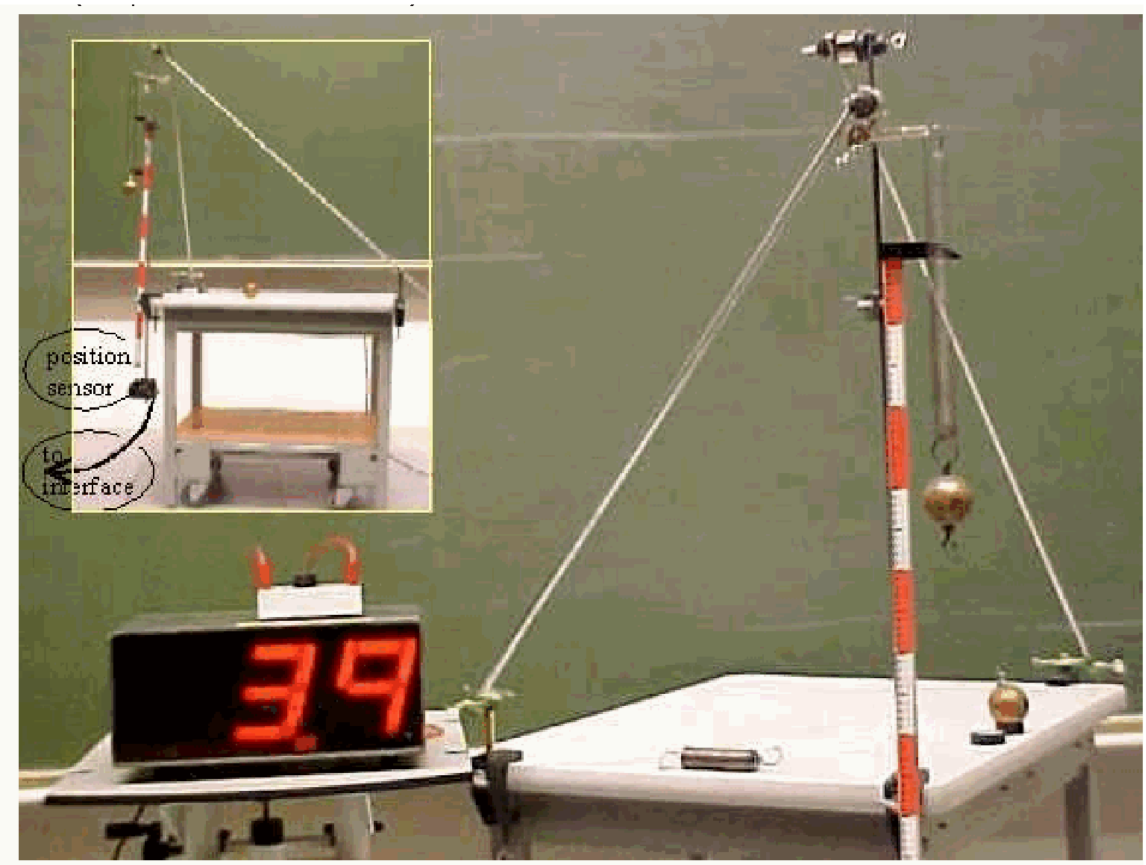


Figure 4.28: .

4.1.3.4.4 Equipment

- Two identical helical springs (we use k = 45 N/m).
- Two masses of 1 kg.
- Demonstration ruler with sliding markers.
- Large stopwatch.
- Position sensor.
- Interface and software.
- Projector to project monitor screen.
- Clamping material.

4.1.3.4.5 Presentation

- One spring is hung to a hook and loaded with 1 kg. The extension is observed and the spring constant k can be determined.
- The software is set up to display a graph of position-time. By hand the mass is displaced more vertically and released. Now the mass oscillates: a linear translational motion confined to the vertical direction. After some time data collection is started. We collect data during

around 10 seconds. It can be observed that the position-time graph has a sinusoidal shape. To verify this, we select a little more than one cycle displayed on the screen and then have the software make a sine-fit. A black-lined sine is drawn in the red-colored collected data and the fit is unmistakable correct (within certain limits, see Figure 2: $\mathrm{CHI}^2 = 0.002254$, the smaller this number, the better the agreement between collected data and the mathematical sine).

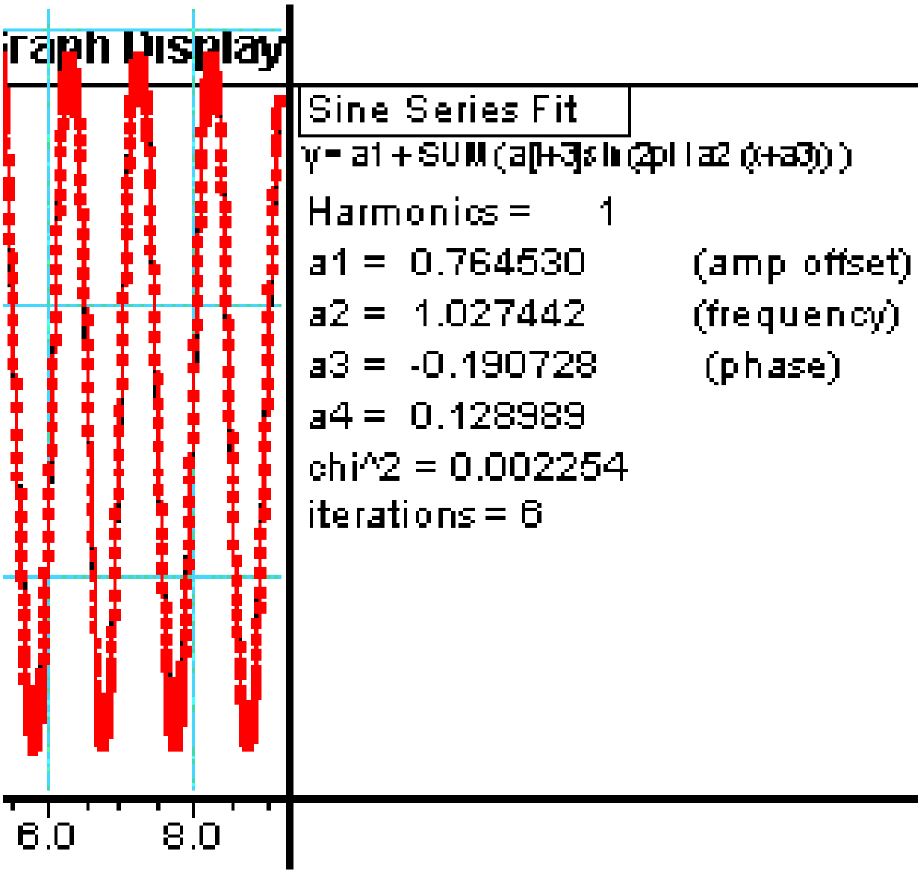


Figure 4.29: .

- The mass is set in oscillatory motion again. The stopwatch is started and the time needed for ten oscillations is measured. $\omega = \sqrt{\frac{k}{m}}$ can be verified.

  1. The mass hung to the spring is doubled. Let students predict what will happen to the period. Set the system in motion and again clock ten periods to check if the prediction fits.
  2. Two springs are connected in series. This combination is loaded with 1 kg and the spring constant of this combination can be determined. Also this series combination can be loaded with one or two kg and set in oscillatory motion and wchecked.
  3. The same can also be performed when the two identical springs are positioned parallel.

4.1.3.4.6 Explanation

1. A simple mass-spring system oscillates with a frequency $\omega = \sqrt{\frac{k}{m}}$. So doubling the mass will lower the frequency by a factor $\frac{1}{\sqrt{2}}$.
2. When two springs are connected in series, this combined spring will have a "new" spring constant of $k_3 = \frac{F}{x_1+x_2}$ (see Figure 3). F acts everywhere in the combined system, so $x_1 = F/k_1$ and $x_2 = F/k_2$. This yields $k_3 = \frac{k_1 k_2}{k_1+k_2}$.

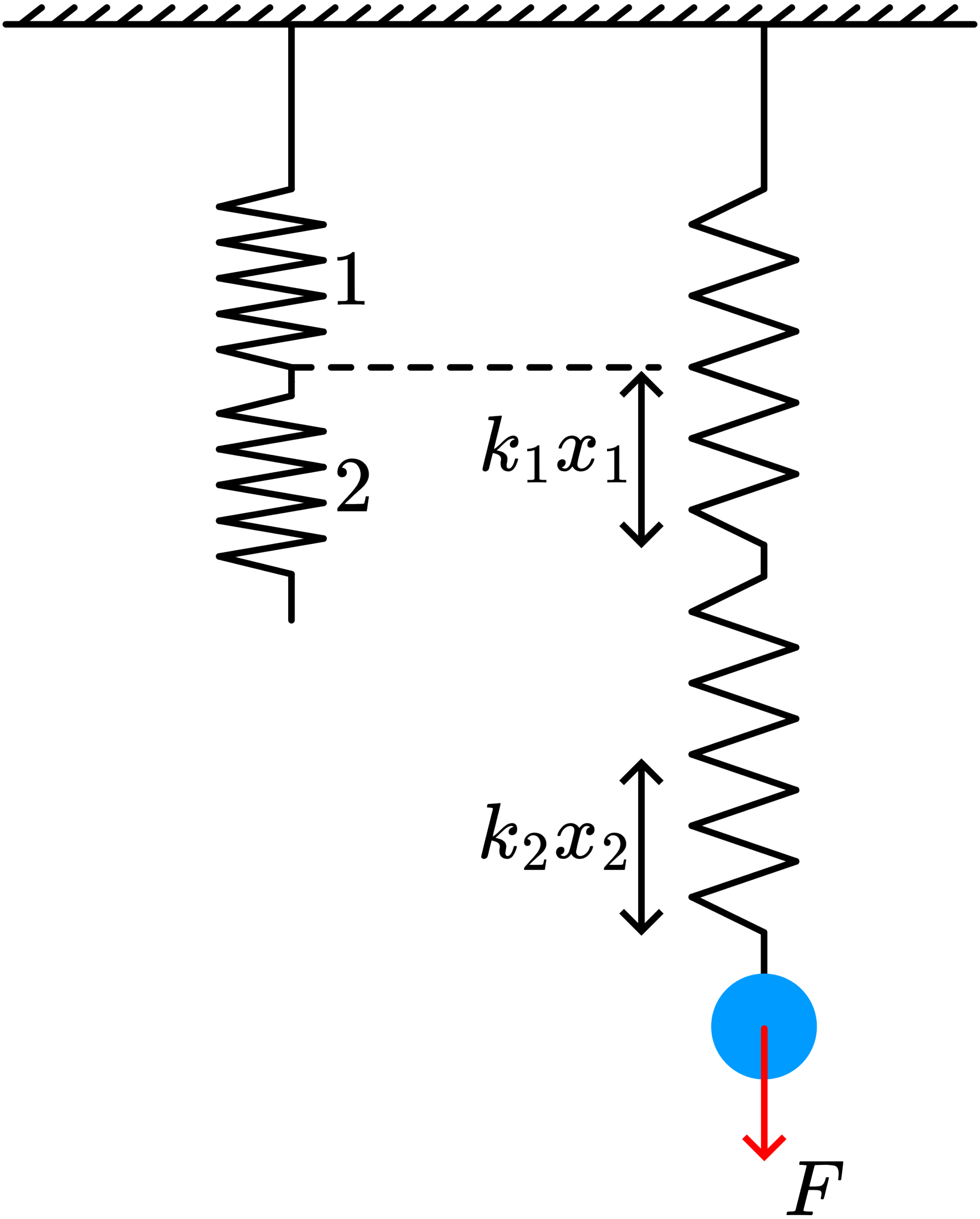


Figure 4.30: .

In our demonstration $k_1 = k_2 (= k)$, so $k_3 = 1/2k$. The frequency will change according to $\omega = \sqrt{\frac{k}{m}}$. So a system with two springs in series and two masses added to it will have half the frequency of one mass suspended to one spring.

3. When two springs are connected parallel: $k_1x_1 + k_2x_2 = F = k_3x$. $k_3 = F/x$ (see Figure 4), so $k_3 = \frac{k_1x_1+k_2x_2}{x}$.

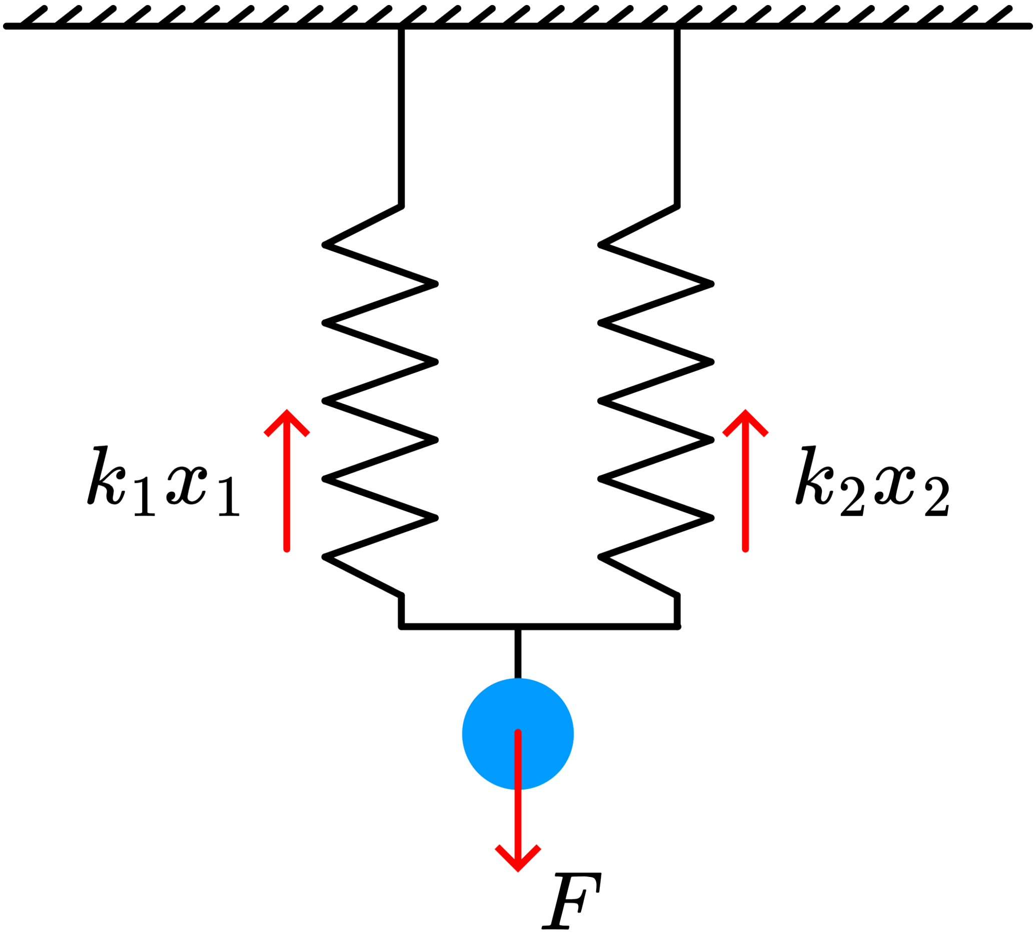


Figure 4.31: .

When the system is made in such a way that $x_1 = x_2$, then $x_1 = x_2 = x$ and $k_3 = k_1 + k_2$. So in our demonstration $k_3 = 2k$. So a system with two springs in parallel and two masses added to it will oscillate with the same frequency as when one mass is suspended to one spring. The measured ω s can be verified now.

4.1.3.4.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 48-52, 89 and 97-101
- McComb,W.D., Dynamics and Relativity, pag. 81-82

4.1.4 3A50 Damped

4.1.4.1 01 Damped Harmonic Motion

4.1.4.1.1 Aim

To show the effect of damping on amplitude and frequency of an oscillation.

4.1.4.1.2 Subjects

- 3A50 (Damped Oscillators)

4.1.4.1.3 Diagram

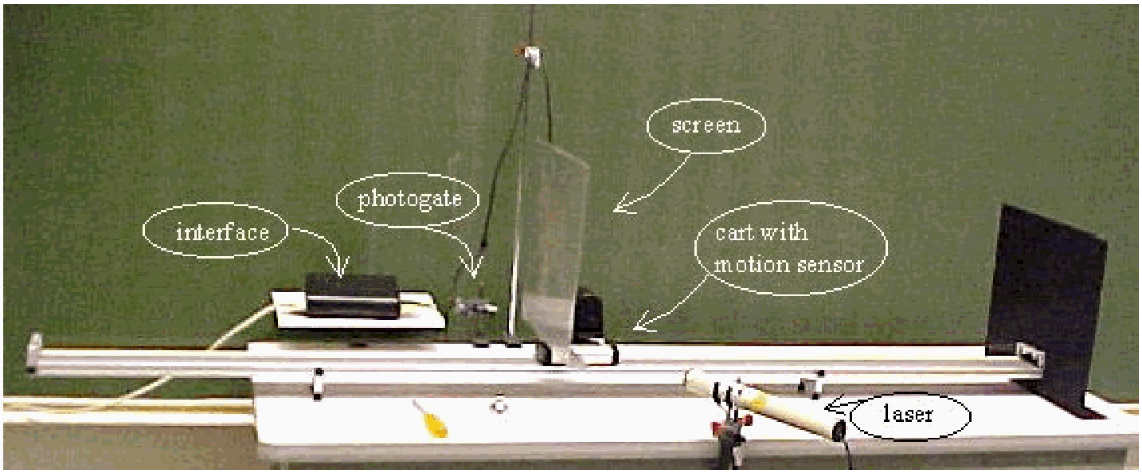


Figure 4.32: .

4.1.4.1.4 Equipment

- Track, 2.2 m.
- Cart.
- Motion sensor, mounted on cart.
- Reflecting screen.
- Two springs.
- Screen, (50×50 cm^2; $m = 0.5$ kg) with socket screw.
- Socket head to mount screen on cart.
- Mass $m = 0.5$ kg.
- Pair of scales with large display.
- Photo-gate and laser.
- Data-acquisition system and software.
- Beamer to project the monitor-screen.

4.1.4.1.5 Presentation

Mount the cart with motion sensor and the mass of .5 kg between the two springs that are attached to the end-stops of the track. Position the reflecting screen, needed for the motion sensor, at the end of the track. Place the photo-gate in such a position that the laser-beam just not touches the cart. The data-acquisition system is set so that collection of data starts as soon as the cart crosses the laser-beam. (See Diagram.) Prepare a graph to display position versus time (see Figure 2)

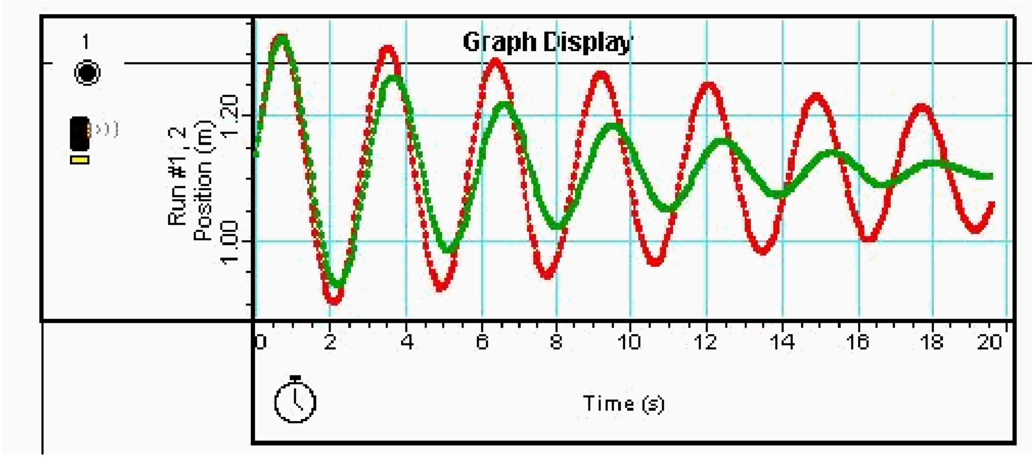


Figure 4.33: .

Give the cart a deflection, start the data-acquisition system and let the cart go. Data are collected during 20sec.

Remove the mass of .5 kg. Show by means of a pair of scales that the 50 × 50 cm^2 screen has also a mass of .5 kg. Mount the screen on the cart. Give the cart the same deflection as in the foregoing run, start the data-acquisition system and let the cart go. Again collect data during 20 sec.

The two graphs of position can be studied and discussed now (see Figure 2). Clearly can be observed that the screen on the cart introduces more damping to the oscillating system. Also can be seen that damping reduces the frequency of the oscillation.

4.1.4.1.6 Explanation

Damping happens due to resistance forces dissipating energy. Such forces can be described assuming that the magnitude of the resistance force is related to the speed of the body as $F = -bv^n$ (n is a number between 1 and 2; b is the damping coefficient).

For many situations n is given the extreme value of $n = 1$, making the resistance force equal to $F = -bv$. Then for such a damped oscillator the position of mass m can be expressed by $x = e^{-\alpha t} A \sin(\omega t + \phi), \alpha = \frac{b}{2m}$. Increasing b (mounting the 50 × 50 cm^2-screen on the cart) means increasing α and so $e^{-\alpha t}$ decreases faster with time.

The angular frequency of a damped system equals $\omega = \sqrt{\omega_0^2 - \frac{b^2}{4m^2}}, \omega_o$ being the frequency in the absence of damping. So increasing b means decreasing ω. Comparing the period of the oscillations of the green line in Figure 2 with those of the red line, shows this clearly.

4.1.4.1.7 Sources

- Alonso, M/Finn, E. J., Fundamentele Natuurkunde, part 1, Mechanica, pag. 297-299
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 99-101
- Roest, R., Inleiding Mechanica, pag. 266-274
- Young, H.D. and Freeman, R.A., University Physics, pag. 411-412

4.1.4.2 02 Damped Galvanometer

4.1.4.2.1 Aim

To show various modes of damping (under-, critical- and overdamping)

4.1.4.2.2 Subjects

- 3A50 (Damped Oscillators)
- 5K10 (Induced Currents and Forces)

4.1.4.2.3 Diagram

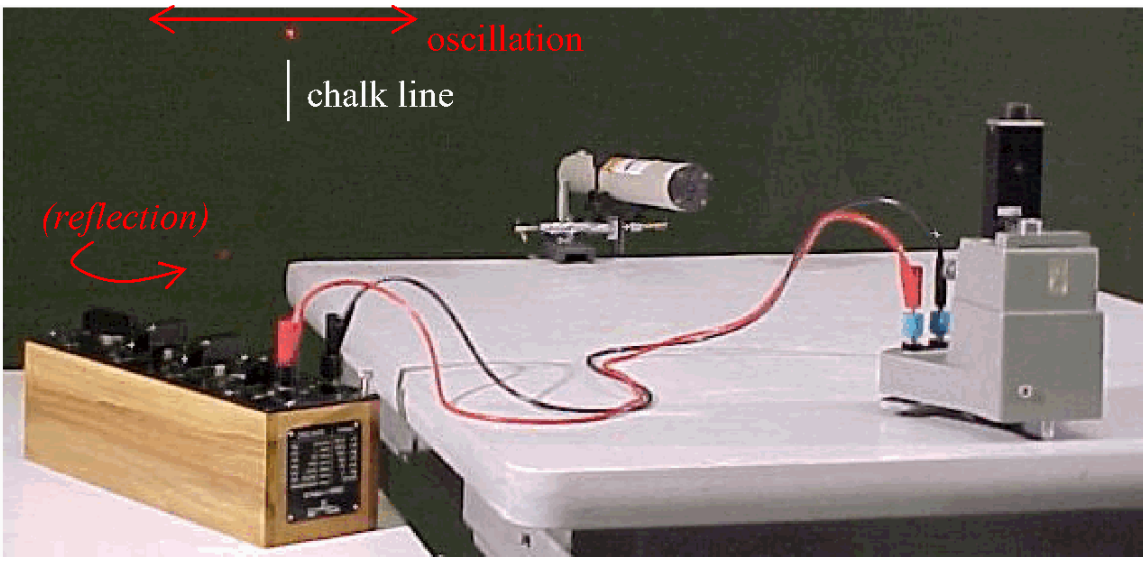


Figure 4.34: .

4.1.4.2.4 Equipment

- Lightspot galvanometer
- Resistance-box (10 kΩ)
- Laser
- Stopwatch
- (Torsionwire model, see Figure 3).

4.1.4.2.5 Presentation

Galvanometer and laser are positioned in such a way that, in the neutral position of the galvanometer, the reflected laser beam is projected on the blackboard behind the laser (see Figure 2). This neutral position is chalk-marked on the blackboard.

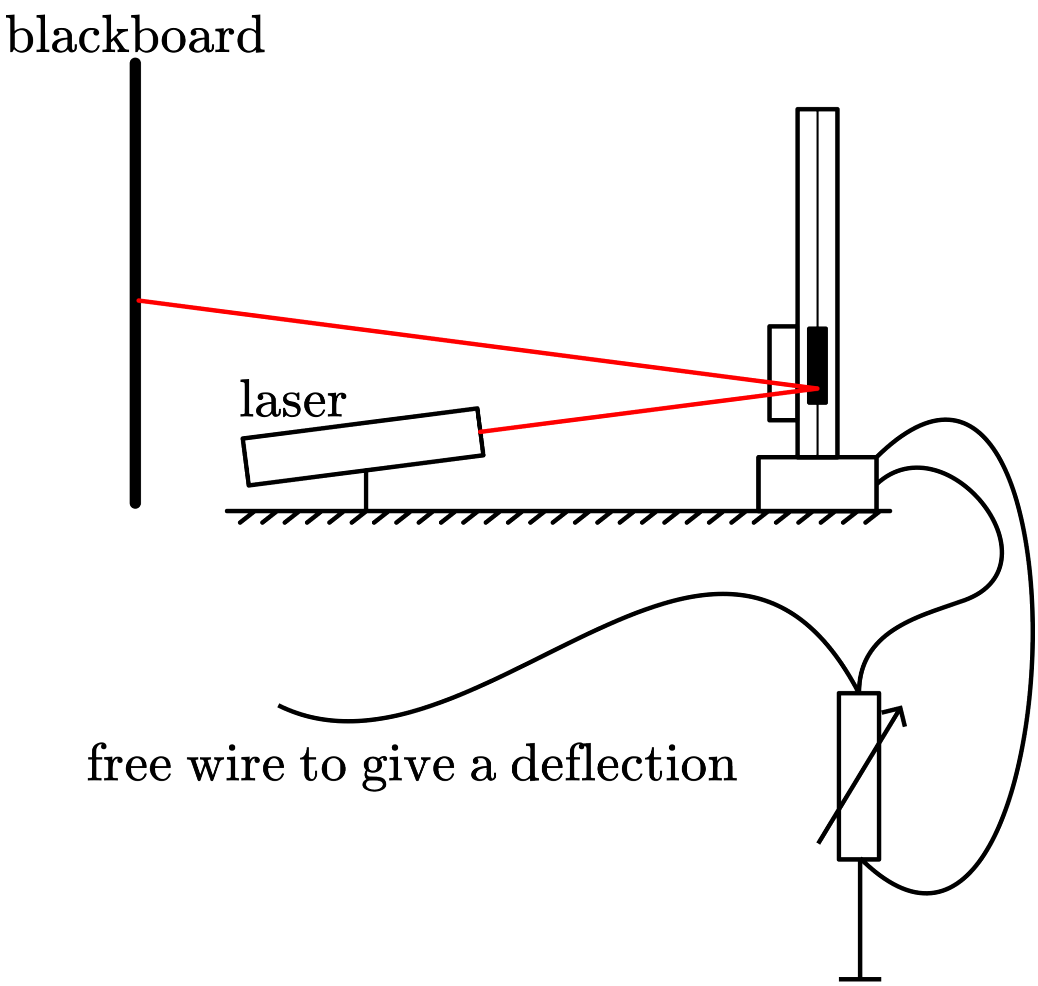


Figure 4.35: .

Now the suspension system of the galvanometer is given a deflection by just touching the leads to the galvanometer with your hands. (Charge on your body usually suffices to make the galvanometer deflect.) The movement of the lightspot on the blackboard shows the free oscillation of the galvanometer-mirror-suspension system. After some oscillations the system comes to rest again. The movement is a damped harmonic motion.

Now the resistance box is connected to the galvanometer (after it has been given a deflection again). The oscillation is observed and the difference in damping, compared to the first situation, is clear. The experiment is repeated with 10 kΩ, 6 kΩ and 1 kΩ. We have critical damping using 6 kΩ and 1 kΩ gives very clear overdamping. Overdamping can be made extreme when the leads are shorted (0Ω).

- Make the students notice that ‘critical damping’ means ‘reaching equilibrium (the chalk mark) in the shortest time’
- When using a stopwatch, it is possible to measure period-times, in order to show the influence of damping on the frequency of the oscillations.

4.1.4.2.6 Explanation

Textbooks give a lot of information about damped harmonic motion. Usually the description is about a simple one dimensional mass-spring system.

The galvanometer-system in our demonstration is a torsion pendulum in which a coil is suspended from a wire. The analysis of such a torsion pendulum can be done analog to that of a mass-spring system.

When the torsion pendulum is twisted an angle θ there will be a torque (τ) that tries to undo the twisting: $\tau = -\kappa\theta$. (κ is the torsion constant.) The equation of motion will be:

$I\ddot{\theta} = -\kappa\theta$ or

$I\ddot{\theta} + \kappa\theta = 0$.

The motion will be a harmonic oscillation with $\omega^2 = \kappa/I$ (/ is the rotational inertia). The coil of the galvanometer oscillates in a radial magnetic field and an emf will be induced. The coil is connected to a resistor and a current will flow. A Lorentz force results, giving a torque that counteracts the movement that produces the induction (Lenz's law) and so this torque will be a damping torque. This damping torque (τ_d) is directly proportional to the angular velocity (like the counter torque in an electric generator): $\tau_d = -r\dot{\theta}$, and now the dynamic equation of motion will be:

$I\ddot{\theta} + r\dot{\theta} + \kappa\theta = 0$ (there is no driving torque).

The demonstration shows a (co)sine-like motion that is multiplied by a factor that decreases in time.

A solution of this differential equation is:

$\theta = \Theta e^{-\alpha t} \cos \omega t,$

where $\Theta = \theta$ at $t = 0, \alpha = \frac{r}{2I}$, and $\omega^2 = \frac{\kappa}{I} - \left(\frac{r}{2I}\right)^2$.

$\alpha = \frac{r}{2I}$ is a measure of how quickly the oscillations decrease towards zero. The

larger r, the more quickly the oscillations die away. Three cases of damping are distinguished:

Overdamping when $r^2 >> 4I\kappa$,

Underdamping when $r^2 < 4I\kappa$ and

Critical damping when $r^2 = 4I\kappa$. Then equilibrium is reached in the shortest time. r is changed, when the value of the external resistance is changed, as seen in the Presentation.

$\omega^2 = \frac{\kappa}{I} - \left(\frac{r}{2I}\right)^2$ shows that ω has a lower value than in the undamped situation. ω

4.1.4.2.7 Remarks

- When the students have not seen a torsionwire system before, such a system is shortly explained to them using a large scale model (a piece of rope, having a rectangular sheet of metal and a small coil, taped to it. See Figure 3.)

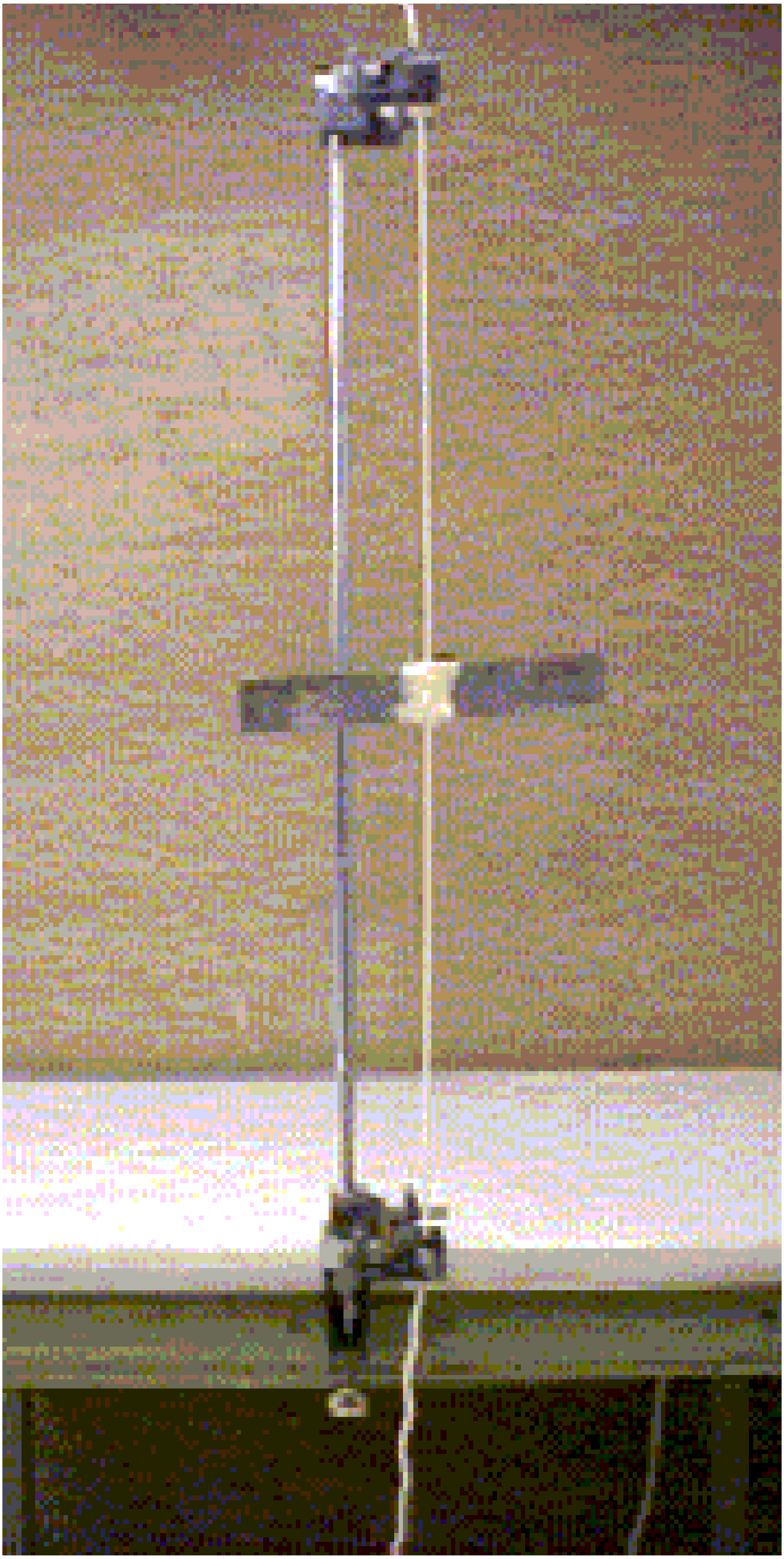


Figure 4.36: .

- The resistance-box is placed on a separate table, so that manipulating the box will not disturb the very sensitive galvanometer.
- There are three laser spots visible on the blackboard. The first is a reflection of the front glass of the housing of the galvanometer (a fixed spot). The second is the reflection of the mirror (that's the one we use in the demonstration). The third is a second reflection of the mirror (the first reflection of the mirror reflects partially on the inside of the front glass of the housing) and so shows a double deflection compared to the second spot.

4.1.4.2.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 264
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 99-101
- Roest, R., Inleiding Mechanica, pag. 269
- Young, H.D. and Freeman, R.A., University Physics, pag. 411
- Alonso, M/Finn, E. J., Fundamentele Natuurkunde, part 1, Mechanica, pag. 278
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 374-376

4.1.5 3A95 Nonlinear

4.1.5.1 3A95.01

4.1.5.1.1 Fakir

4.1.5.1.1.1 Aim
To show an example of non-linear behavior

4.1.5.1.1.2 Subjects
- 3A95 (Non-Linear Systems)

4.1.5.1.1.3 Diagram

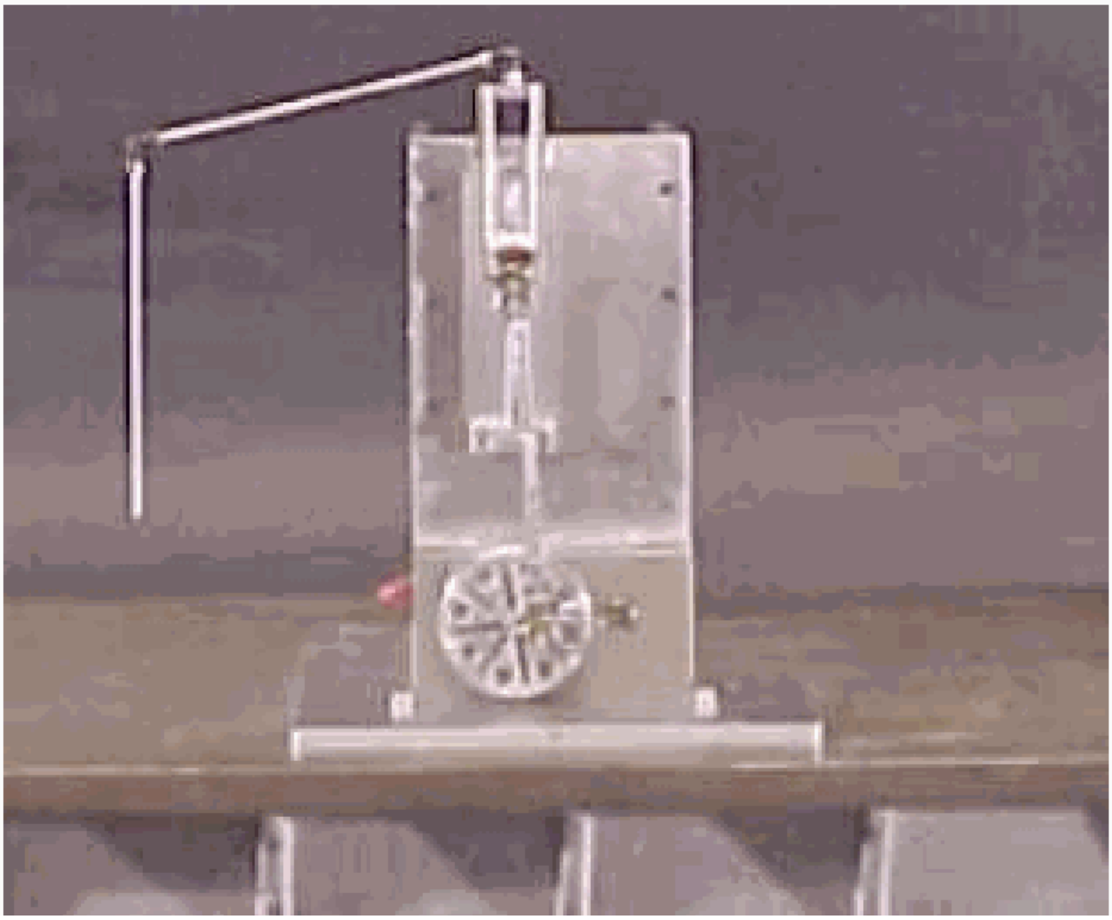


Figure 4.37: .

4.1.5.1.1.4 Equipment
- Driven upside-down pendulum,
- Adjustable dc powersupply (50 V/10 A),
- 1 aluminium rod ($\emptyset 3$ mm, $\mathrm{l} = 17$ cm),
- 2 aluminum rods ($\emptyset 3$ mm, $\mathrm{I} = 17$ cm), linked with a cardan- joint,
- (3 aluminum rods ($\emptyset 3$ mm, $\mathrm{I} = 17$ cm), linked with two cardan joints).

4.1.5.1.1.5 Presentation
On top of the driver shaft the single aluminum rod is fixed in a cardan joint. The eccentric is adjusted to obtain a drive-amplitude of about 1.5 cm. While loosely holding (by hand) the

aluminum rod vertically upright above its pivot, the voltage of the powersupply is increased to speed up the electric motor. When the frequency of rotation is high enough (> 20 Hz), the up and down dancing rod can be left by itself and suprisingly will not fall down!

You can push it off balance by almost $60°$ and still the rod will not fall. Leaving it, it will dance back up to the vertical again much in the same way as an ordinary downward hanging pendulum moves.

The single aluminum rod is removed from the cardanjoint and replaced by the linked two Al-rods. To get this pendulum balanced upright a higher frequency is needed. When the needed frequency cannot be reached, it is also possible to adjust the eccentric to a higher drive amplitude.

This double upside-down pendulum can be made as stable as the single one.

The same procedure is followed when using the triple pendulum.

Etc.

4.1.5.1.1.6 Explanation

A basic understanding arises when it is realised that the fast moving pivot drags the linkage downwards faster than it would fall normally by gravity alone. When the inverted pendulum is a small angle ϕ away from its vertical position, then a torque $\tau = 1/2\text{mg}/\phi$ acts on the pendulum and the pendulum accelerates away from the vertical. Newton's second law describes the movement: $Id^2\phi/dt^2 = 1/2\text{mg}/\phi$, I being the moment of inertia. When the pivot moves with $y = -R\sin\omega t$ (negative when going upwards), then the pivot's acceleration is: $R\omega^2$ sinut. Newton's second law becomes: $Id^2\phi/dt^2 = 1/2m/\phi(g + R\omega^2\sin\omega t)$. When $(g + R\omega^2\sin\omega t) < 0$, then the torque is of the restoring type. When $R\omega^2$ is large enough then this is the case during a large part of the downward movement of the pivot. So a restoring torque is possible.

This reduced analysis holds only for very small values of ϕ and even then it can be seen that during the largest part of the movement of the pivot, the torque has a positive sign and so the pendulum will fall down. A real understanding can only be obtained when nonlinearity is taken in account (see literature).

4.1.5.1.1.7 Remarks

- We don't demonstrate the triple pendulum very often, because it sometimes happens that the cardan joints cannot withstand the forces that occur when high ω values are used.

4.1.5.1.1.8 Sources

- Acheson, D.J. and Mullin, T., Nature, Vol.366, pag. 215
- Butikov, E.I., American Journal of Physics 69(7), july 2001, pag. 755-768
- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 134
- Stephenson, A., Memoirs and proceedings of Manch. Lit. and Phil. Soc., part 52(8), pag. 1-10

4.1.5.2 02 Chaotic Pendulum

4.1.5.2.1 Aim

To analyze the chaotic motion of a parametrically driven pendulum by explaining its motion in phase space by making a Poincaré plot.

4.1.5.2.2 Subjects

- 3A10 (Pendula) 3A95 (Non-Linear Systems)

4.1.5.2.3 Diagram

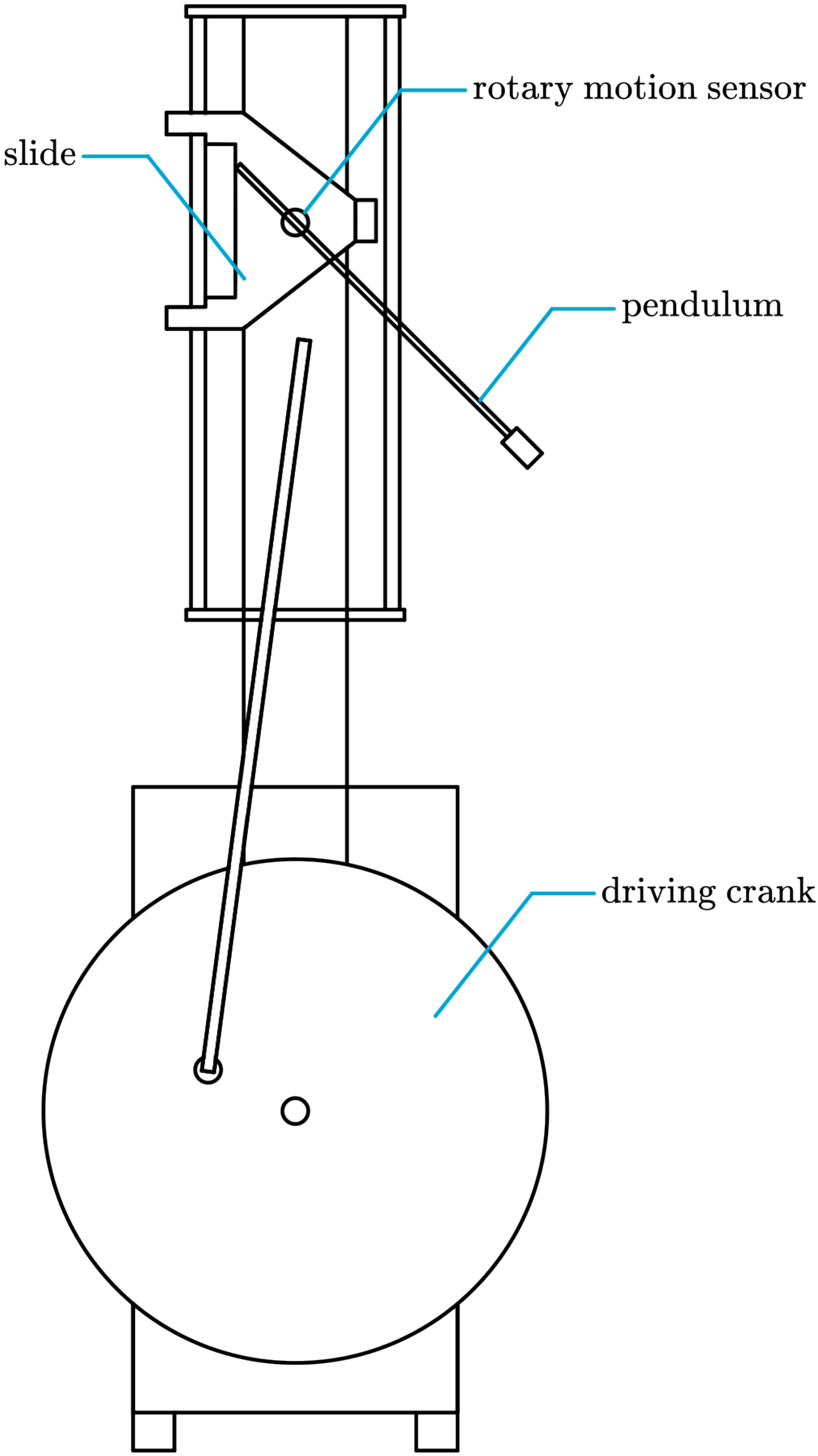


Figure 4.38: .

4.1.5.2.4 Equipment

- Parametrically driven pendulum
- Photogate
- Rotary motion sensor
- Data-acquisition system and computer. (We use Science Workshop).
- Projector to project monitor-image.

4.1.5.2.5 Presentation

The Pendulum is fixed on the shaft of the rotary motion sensor. The rotary motion sensor is fixed to the slide that is driven up and down by a crank mechanism (See Diagram and Figure 3 1).

The driven pendulum, see Figure 2, is placed on a spot that can be observed by all the students but which can be closed off during the lecture i self. Place it for example just outside the lecture room, so the door can be shut during the lecture, while keeping the monitor image visible to the students

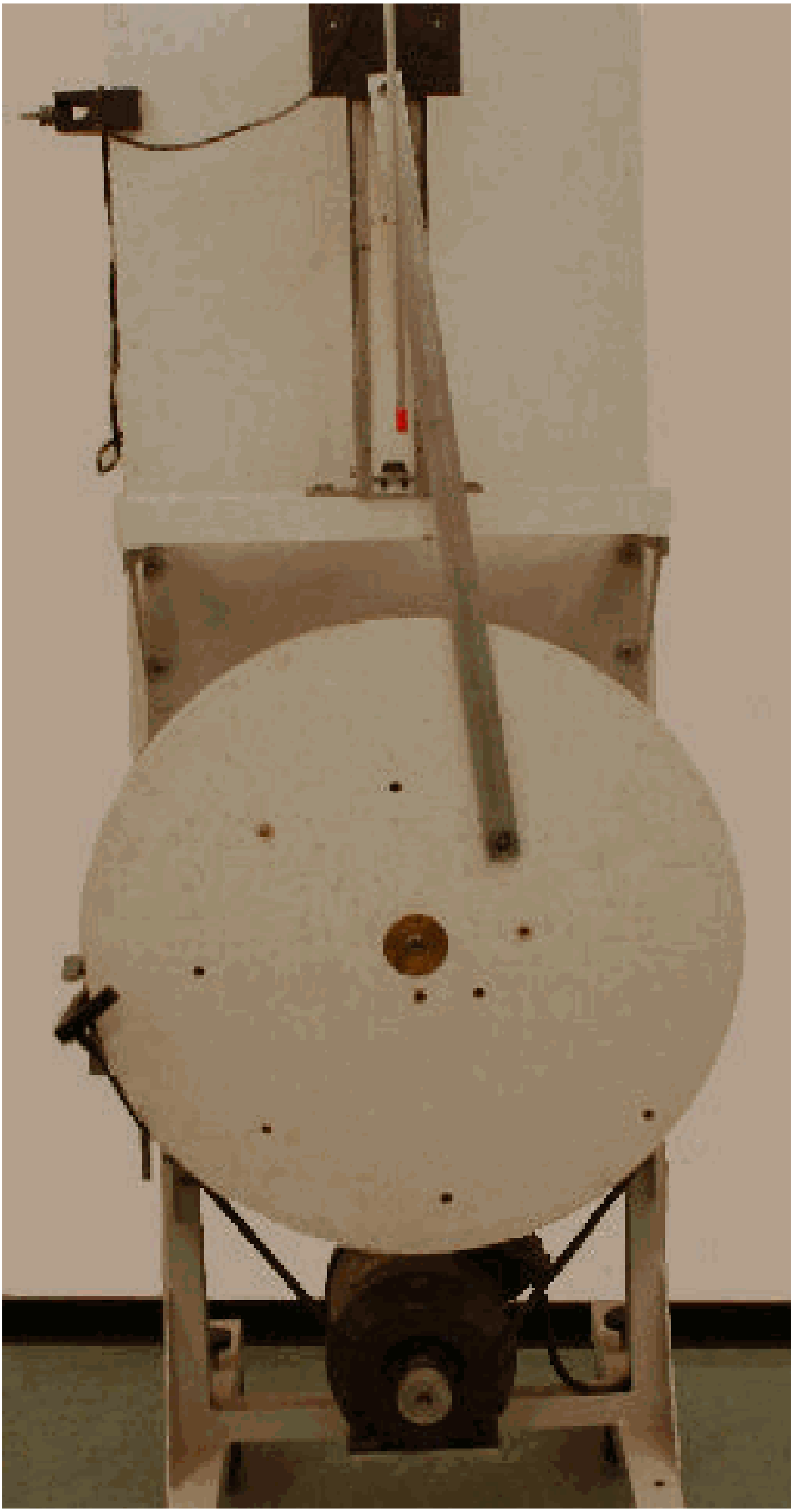


Figure 4.39: .

The software is set up to make a Poincaré plot of the angular position and angular velocity, and will be projected in the lecture room with use of the projector. The Poincaré plot will grow during the lecture and after a while the strange chaotic attractor will be displayed. In about 1 hour you will be able to see the contours of the attractor; after an other hour you will have a plot like in Figure 3.

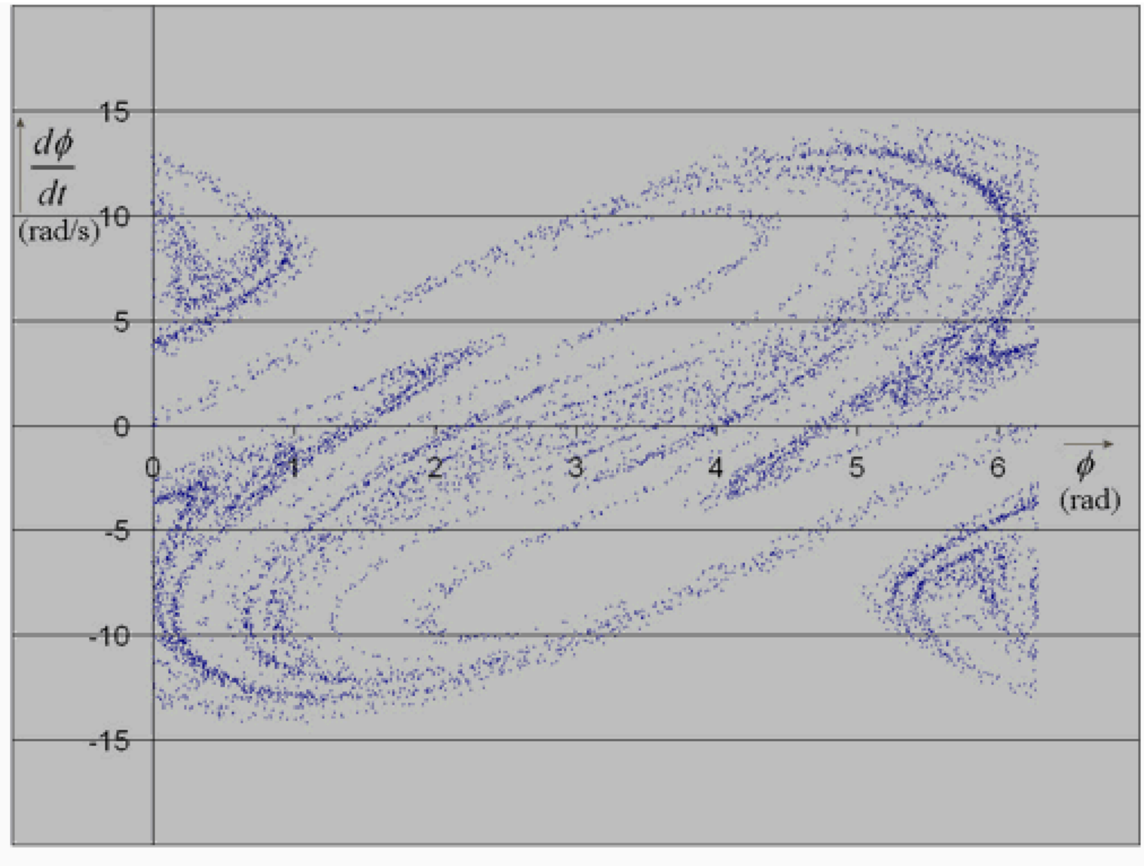


Figure 4.40: .

At the beginning of the lecture, having started the driven pendulum, you can introduce the driven pendulum and show its chaotic behavior. After this you can explain why we use a Poincaré plot to analyze the chaotic movement of the pendulum and that in a Poincaré plot not the time but space determines when to plot a point, by showing the students the spot where both angular position and angular frequency is measured en plotted against each other in the Poincaré plot.

4.1.5.2.6 Explanation

The equation of motion of a Chaotic pendulum is (see: SourcesXX):

$$\frac{d^2\text{��}}{dt^2} + \frac{k_2}{mL^2}\frac{d\text{��}}{dt} + \left[\omega^2 - \frac{A\Omega^2}{L}\cos(\Omega t)\right]\sin(\text{��}) = 0 \tag{4.7}$$

where:

- k_2 : damping constant
- m : mass of the pendulum
- $L = \frac{I}{m\ell} = \frac{(k^2+\ell^2)}{\ell}$: reduced length of the pendulum

where I is the moment of inertia of the pendulum with regard to its suspension point, ℓ is the distance between the point of suspension and the centre of mass, (see: McComb §6.2.8), and $k = \frac{\int r^2 dV}{\int dV}$ = (the radius of gyration of the pendulum, see: McComb §6.2.2)

- $\omega = \sqrt{\frac{g}{L}}$ (eigen frequency of pendulum at small amplitudes)
- A: amplitude of the nearly harmonic driving force
- Ω : angular driving frequency.

If there is no damping, $k_2 = 0$. If there is no driving force, $A = 0$. Then the equation of motion will be:

$$\frac{d^2��}{dt^2} + \omega^2 \sin(��) = 0 \tag{4.8}$$

When we substitute, $\omega = \sqrt{\frac{g}{L}}$ and $L = \frac{I}{m\ell}$, we will get the following equation of motion:

$$\frac{d^2��}{dt^2} + \frac{mg\ell}{I} \sin(��) = 0 \tag{4.9}$$

Solving this differential equation yields:

$$\frac{1}{2}��^2 - \frac{mg\ell}{I}\cos(��) = const.(McCombequation6.25). \tag{4.10}$$

The Parametrically driven pendulum is based on the article, *Unstable periodic orbits in the parametrically excited pendulum, of W. van der Water.*In this article some more friction terms have been added to the equation of motion of the chaotic pendulum, so that result of the simulation and the actual experiment are more like each other.

4.1.5.2.7 Remarks

- The pendulum is mounted on the Rotary motion sensor which is mounted on the slide and while provide use with the both the angular position and angular velocity (see Figure 4).

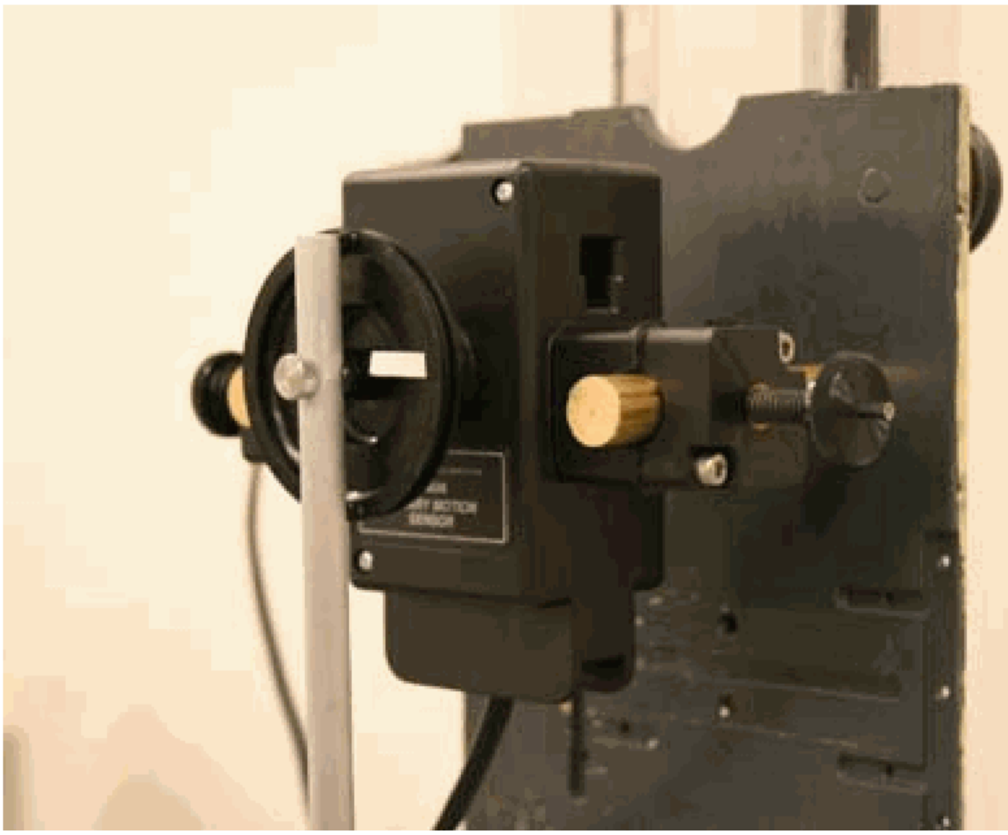


Figure 4.41: .

- The Photogate is placed on driving wheel and will give use the moment at which we will plot both the angular position and angular velocity of that moment in the Poincaré plot (see Figure 5).

Figure 4.42: .

- Test if the driven pendulum keeps his chaotic movement for the period you want to use it, it sometimes ends in a harmonic movement after a while. When this happens try to adjust the driving frequency of the pendulum
- As extra you could ask the students to make a simulation of this pendulum using Maple or Mathlab.

Then you need to know the following parameters of the pendulum:

angular driving frequency $\approx 9\text{rad/s}$

amplitude of the driving force ≈ 0.125 m

length of the pendulum ≈ 0.3 m

mass of the pendulum ≈ 0.03 kg

damping constant $\approx 1.7 \times 10^{-5}$ S

4.1.5.2.8 Sources

- Dynamics and Relativity, W.D. McComb, pag 125-128
- Unstable periodic orbits in the parametrically excited pendulum, W. van de Water; M. Hoppenbrouwers; F. Christiansen, Phys. Rev A 44(1991)6388698
- The Pendulum, A case study in physics, G.L.Baker J.A.Blackburn, pag. 121-149

4.2 3B Waves

4.2.1 3B10 Transverse

4.2.1.1 01 Reflections of Transverse Pulses (2)

4.2.1.1.1 Aim

To show how a transverse disturbance in a wave demonstrator reflects.

4.2.1.1.2 Subjects

- 3B10 (Transverse Pulses and Waves)

4.2.1.1.3 Diagram

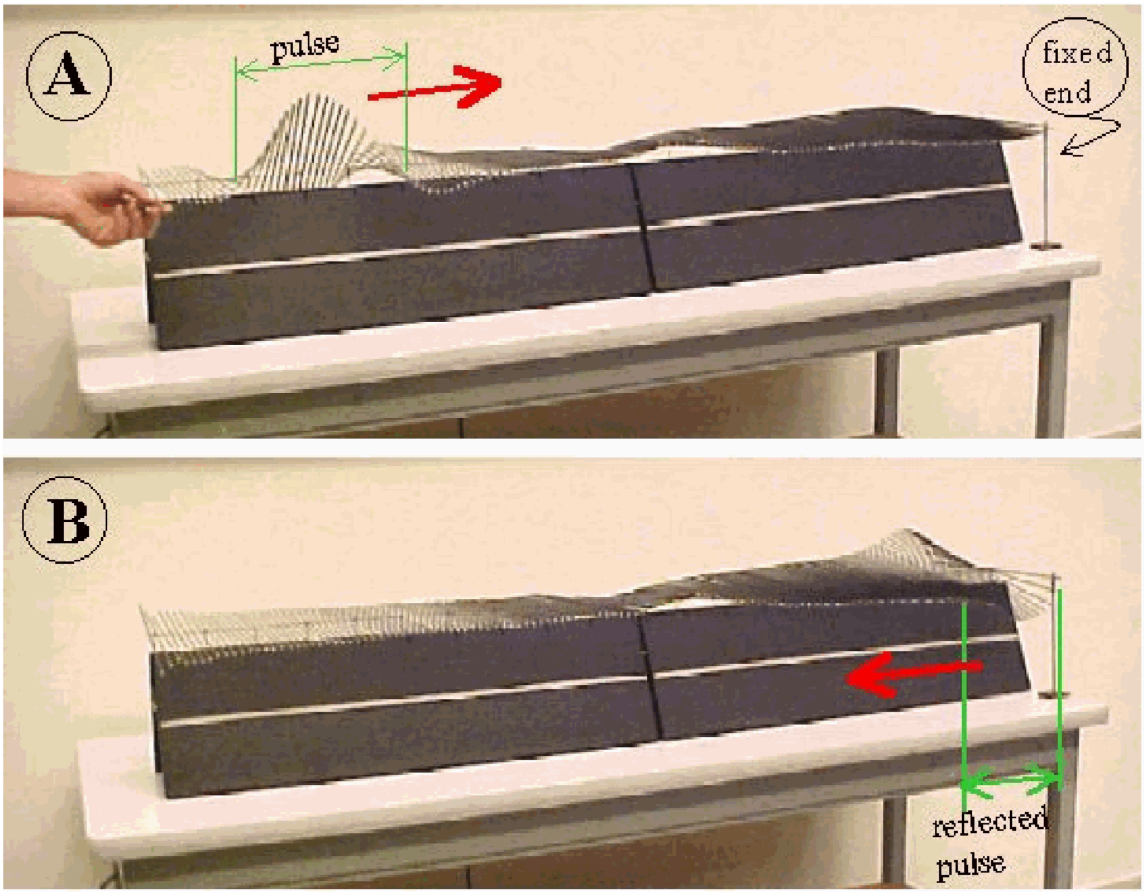


Figure 4.43: .

4.2.1.1.4 Equipment

- 2 1-meter sections of slow wave demonstrator.
- Terminal clip.

4.2.1.1.5 Presentation

Couple the two sections of wave demonstrator together.

-With the far end of the wave demonstrator free, start a single sharp crest traveling down the demonstrator. At the end there is total reflection and the crest reflects as a crest (a trough reflects as a trough). The phase is preserved.

-Now the terminal clip is clipped to the far end (see Diagram) and the experiment is repeated. The reflected wave is inverted relative to the initial wave.

4.2.1.1.6 Explanation

See the explanation in “Reflections (1)”.

Also applying the energy-concept can strengthen the insight in the shown phenomenon: In case of the free end there must be total reflection in the same way, since there is no mechanism by which energy can be extracted, not even temporarily.

When the end of the wave demonstrator is fixed, a convenient model to explain the phase change by 180° is that the end must be a node, so at any moment the sum of the arriving pulse and the reflected one must add to zero.

4.2.1.1.7 Remarks

- Before showing the demonstration it is advised to practice with it, because it needs some ‘skill’ to produce a sharp disturbance in the upward direction without overshoot in the downward direction. And such a disturbance is needed for a good demonstration. A good way to do this is that with one hand you produce the disturbance and the other hand you hold in the zero-deflection position as a reference you should not pass (see Figure 2).

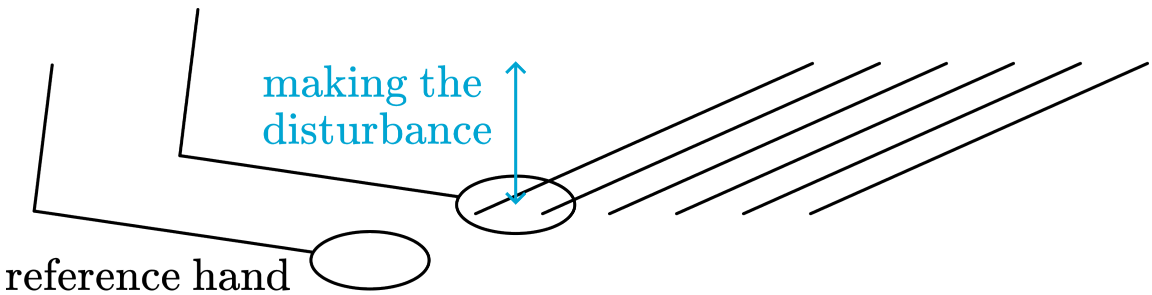


Figure 4.44: .

4.2.1.1.8 Sources

- PASCO scientific, Instruction Manual for the PASCO scientific Model SE-9600, 9601, 9602, and 9603.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 402-403.
- Jewett, J.W. and Serway, R.A., Physics for Scientists and Engineers with Modern Physics (seventh edition), pg 461-462.

4.2.1.2 02 Speed of a Single Pulse on Different Strings (2)

4.2.1.2.1 Aim

To show that a transverse pulse moves faster on a lighter rope.

4.2.1.2.2 Subjects

- 3B10 (Transverse Pulses and Waves)

4.2.1.2.3 Diagram

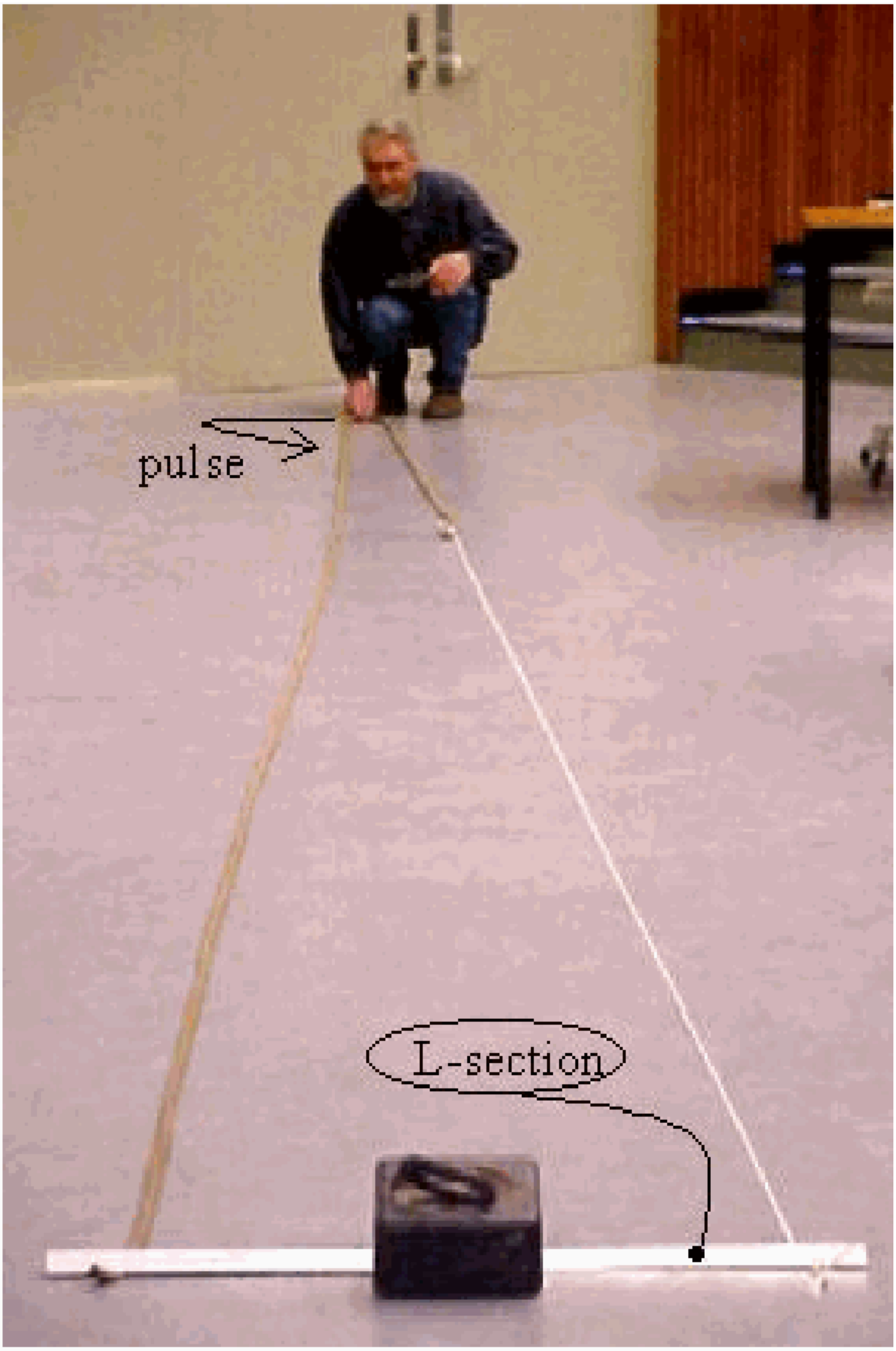


Figure 4.45: .

4.2.1.2.4 Equipment

- Heavy rubber hose ($l = 10$ m).
- Rope ($l = 10$ m).
- Aluminum L-section ($l = 1$ m).
- Heavy weight ($m = 25$ kg).
- Camera.
- Projector.

4.2.1.2.5 Safety

- In lifting and carrying the heavy weight, do so in the right way (use your legs when lifting the weight): Mind your back.

4.2.1.2.6 Presentation

The piece of rope is knotted to the rubber hose. The loose ends of rubber hose and rope are blocked by the L-section and heavy weight (see Diagram). The demonstration is set up in such a way that the instructor holds the rubber hose: One leg of the assembly is completely a rubber hose, the other leg: rubber hose tied to rope (piece of rope about 70% of the total length of the leg).

The instructor gives, by hand, the combined end a sharp horizontal transverse pulse. Along both legs a crest travels. Clearly can be seen that as soon as the crest passes from rubber hose to rope it travels much faster: It overtakes the slower moving crest in the other rubber leg and is on its way back and "home" long before the slow crest even arrives at the L-section.

(Careful observation makes it possible to see also that, at the knot, where the crest passes from the rubber hose into the rope, there is not only transmission but also reflection.)

4.2.1.2.7 Explanation

The velocity of a pulse along a rope is $v = \sqrt{\frac{T}{\mu}}$, T being the tension along the rope

and μ its mass per unit length. Both legs have the same tension, so the observed difference in the velocity of propagation is explained by the difference in μ. The lower μ the higher v.

In our situation we have:

$\mu_{hose} = 0.12[\text{ kg/m}]; \mu_{rope} = 0.0094[\text{ kg/m}]$.

Since $v \propto \sqrt{\frac{1}{\mu}}$, we find: $\frac{v_{hose}}{v_{rope}} = \sqrt{\frac{\mu_{rope}}{\mu_{hose}}} = \sqrt{\frac{0.0094}{0.12}} = 0.28$.

So, the speed of the pulse on the hose is 28% of the speed of the pulse on the rope. In demonstrating it is good enough to calculate roughly:

$\frac{v_{hose}}{v_{rope}} = \sqrt{\frac{\mu_{rope}}{\mu_{hose}}} = \sqrt{\frac{0.0094}{0.12}} \approx \sqrt{\frac{0.01}{0.12}} = \sqrt{\frac{1}{12}} \approx \frac{1}{3.5}$.

So the difference in speed of the pulses is around a factor 3 . This is more or less visible once you know this factor and the demonstration is observed a couple of times.

4.2.1.2.8 Remarks

- Practicing this demonstration before presenting it is necessary to feel the right tension needed to make a clearly visible single pulse that is really short.
- For good visibility of the traveling crest, observation along the legs is needed. That's why a camera is placed at the end. A picture is projected by the projector as the Diagram shows.

4.2.1.2.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 344-345.
- Young, H.D. and Freeman, R.A., University Physics, pag. 600-605.
- Jewett, J.W. and Serway, R.A., Physics for Scientists and Engineers with Modern Physics (seventh edition), pg 461-462.

4.2.1.3 03 Reflections of Transverse Pulses (1)

4.2.1.3.1 Aim

To show how a transverse disturbance in a rubber hose reflects.

4.2.1.3.2 Subjects

- 3B10 (Transverse Pulses and Waves)

4.2.1.3.3 Diagram

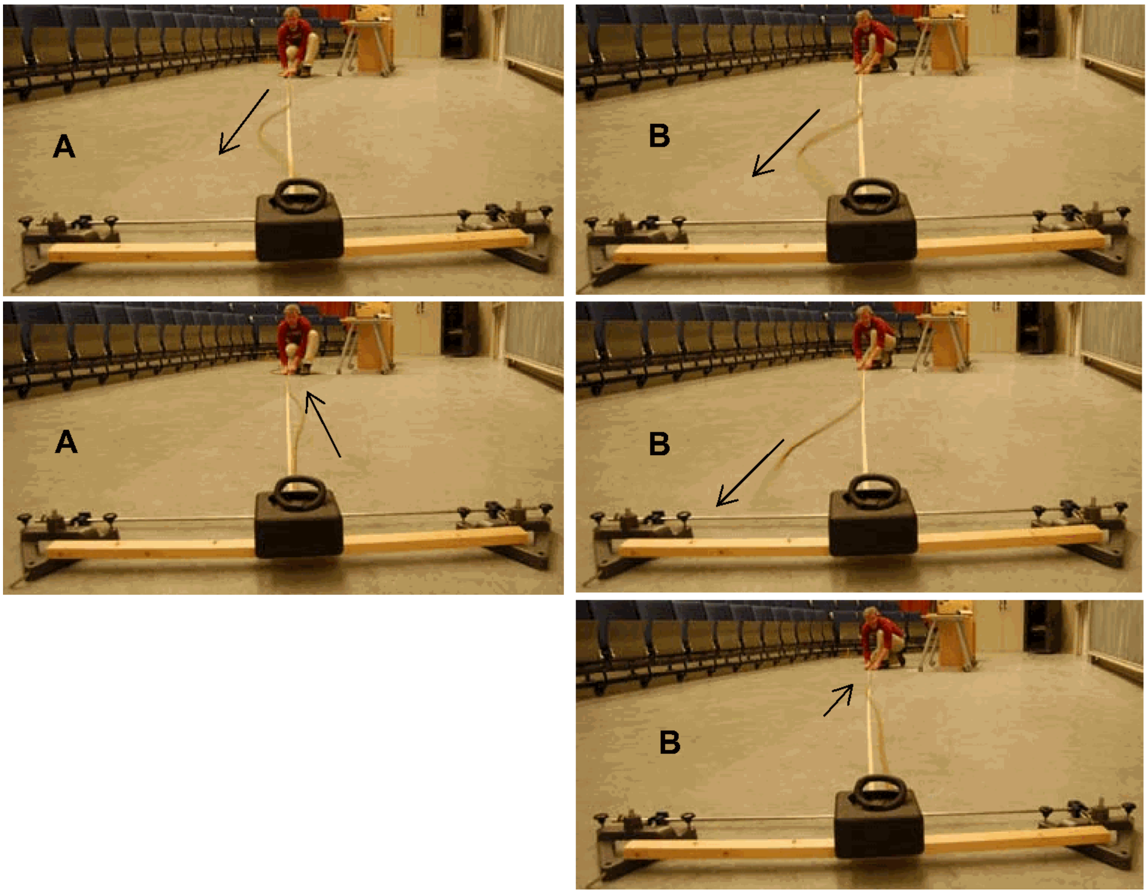


Figure 4.46: .

4.2.1.3.4 Equipment

- Heavy rubber hose ($l = 10$ m).
- Heavy weight ($m = 25$ kg; see the construction in Figure 2 and Figure 3).
- Tape
- Oil.
- Camera
- Projector

4.2.1.3.5 Presentation

Lay the long piece of hose in a straight line on the floor in front of the lecture room. On the floor, this straight line is marked by tape (see Diagram). -At one end the hose is fixed (see Figure 2).

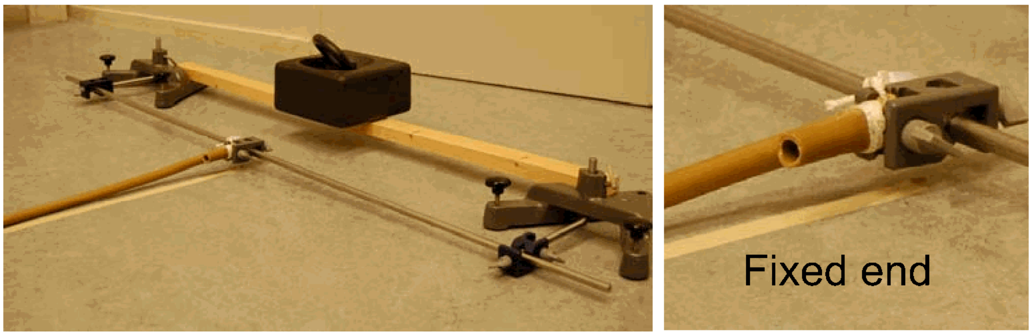


Figure 4.47: .

Reflections of transverse pulses (1)

Give, by hand, the free end of the hose a sharp horizontal displacement. A crest travels along the hose (see the pictures of Diagram A) and reflects at the fixed end as a trough.

-Next the hose is fixed as a loose end (see Figure 3).

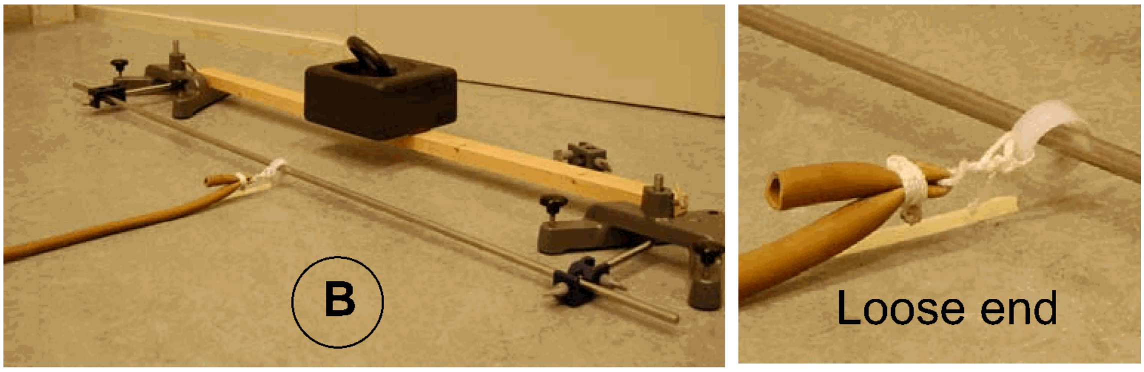


Figure 4.48: .

The end of the hose can now freely move sideways; it is a so-called “free end”. (We apply some oil on the metal shaft to reduce friction.) The demonstration is repeated and it can be observed that a crest traveling along the hose now returns as a crest (see the pictures of Diagram B).

4.2.1.3.6 Explanation

-When the hose has a fixed end, the arriving pulse exerts a force on the support. The reaction to this force, exerted by the support on the string, “kicks back” on the string (Newton’s third law; conservation of momentum) and sets up a reflected pulse in the reverse direction.

-When the hose has a free end, the free moving support exerts no transverse force. When the arriving pulse displaces the free end sideways, it even overshoots the arriving pulse. In the hose a force pulls it back to its rest position. This generates the reflected pulse, and so the direction of displacement is the same as for the initial pulse.

4.2.1.3.7 Remarks

- Practicing this demonstration before presenting it is necessary. In preparing the demonstration, experiment with the tension in the hose and the amplitude of the pulse given in order to get a satisfactory demonstration. Adapt your pulse amplitude also to the relative strong damping. Also observe in the pictures of the Diagram that the demonstrator holds one hand on the line to prevent overshoot when a pulse is given on to the hose (notice his left hand in the pictures).
- To observe the traveling crest, observation along the rubber hose is advised. That’s why we place a camera at the fixed end. The projector projects an image to the audience like the pictures in Diagram show.

- When lifting and carrying the heavy weight (25 kg!) do it in the right way! Mind your back!

4.2.1.3.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 126.
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 1, Schwindungen, Wellen, Schall, Ultraschall, pag. 82.
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 307-308.
- Giancoli, D.G., Physics for scientists and engineers with modern physics (third edition) , pag. 402-403.
- Young, H.D. and Freeman, R.A., University Physics, pag. 620-621.
- Jewett, J.W. and Serway, R.A., Physics for Scientists and Engineers with Modern Physics (seventh edition), pg 461-462.

4.2.1.4 04 Speed of a Single Pulse on Different Strings (1)

4.2.1.4.1 Aim

To show that a transverse pulse moves two times slower on a four times heavier rope.

4.2.1.4.2 Subjects

- 3B10 (Transverse Pulses and Waves)

4.2.1.4.3 Diagram

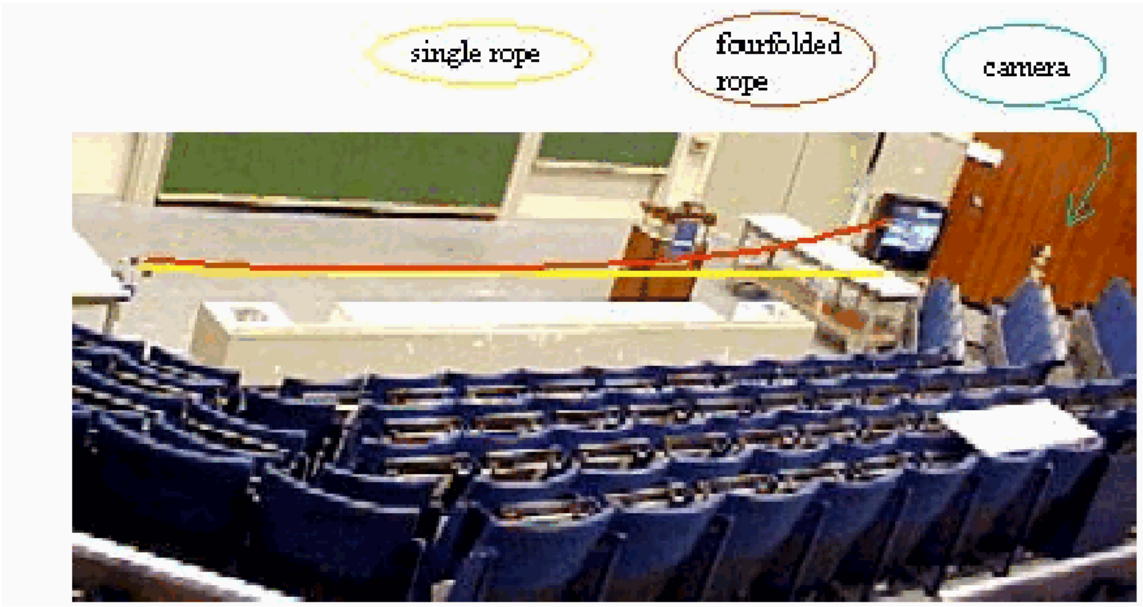


Figure 4.49: .

4.2.1.4.4 Equipment

- Piece of rope ($l = 8$ m).
- Piece of fourfolded rope ($\texttt{mid} = 8m$).
- Two pulleys.
- Two masses of 1 kg.
- Clamping material.
- Camera.
- Projector

4.2.1.4.5 Presentation

The demonstration is set up as shown in Diagram and Figure 2.

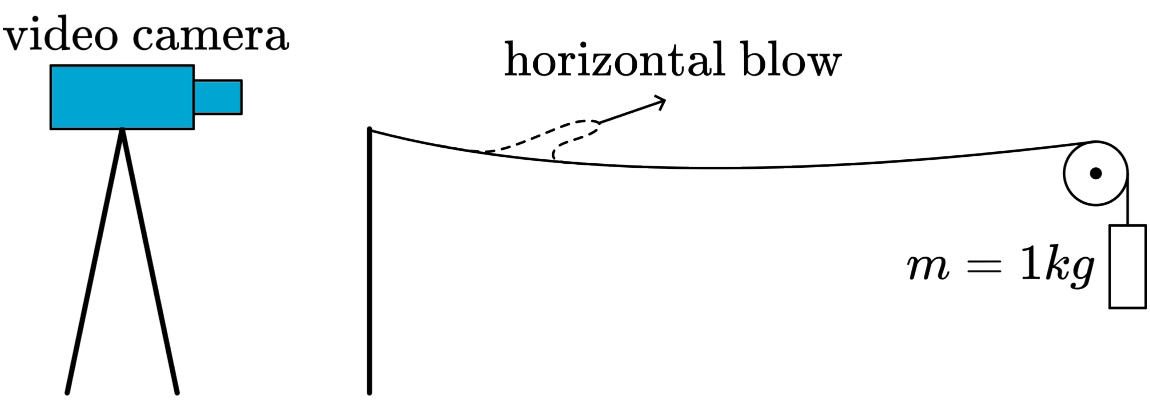


Figure 4.50: .

Using a ruler, the instructor gives a sharp blow on the four-folded piece of rope: A crest travels fast along the rope, continuously reflecting at its fixed ends. The same is done on the single rope. Here the crest travels much faster (also its crest-inversion at reflection is clearly visible).

When demonstrating the four-folded rope, you can use your voice as a stable timekeeper: just "pom-pom-pom-..." on the time it takes a crest to travel away from you to the end of the rope where the weight is hanging. You keep this rhythm when you demonstrate the single rope. It will be clearly visible that on that same rhythm the crest travels now away and back to you: it makes a complete run. This shows that on the single rope the crest travels twice as fast as on the four-folded one.

4.2.1.4.6 Explanation

The velocity of a wave along a rope is $v = \sqrt{\frac{T}{\mu}}$, T being the tension in the rope and μ its mass per unit length. Both parts have the same tension (both are loaded with 1 kg), so the difference in the velocity of propagation is explained by the difference in μ. μ being four times higher in the fourfolded rope makes ν two times lower.

4.2.1.4.7 Remarks

- As presented in the picture of the Diagram, to the audience it is hard for them to see the crest traveling along the rope. Observation along the rope presents a much better view. We use the camera in such a position to make the traveling crest clearly visible (see Figure 2 and Diagram).
- The "sharp blow" should be given horizontally.

4.2.1.4.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 344-345.
- Young, H.D. and Freeman, R.A., University Physics, pag. 600-605.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 392.
- Jewett, J.W. and Serway, R.A., Physics for Scientists and Engineers with Modern Physics (seventh edition), pg 461-462.

4.2.1.5 05 Transverse Traveling Wave (1)

4.2.1.5.1 Aim

To show a traveling wave and the inverse relationship between frequency and wavelength.

4.2.1.5.2 Subjects

- 3B10 (Transverse Pulses and Waves)

4.2.1.5.3 Diagram

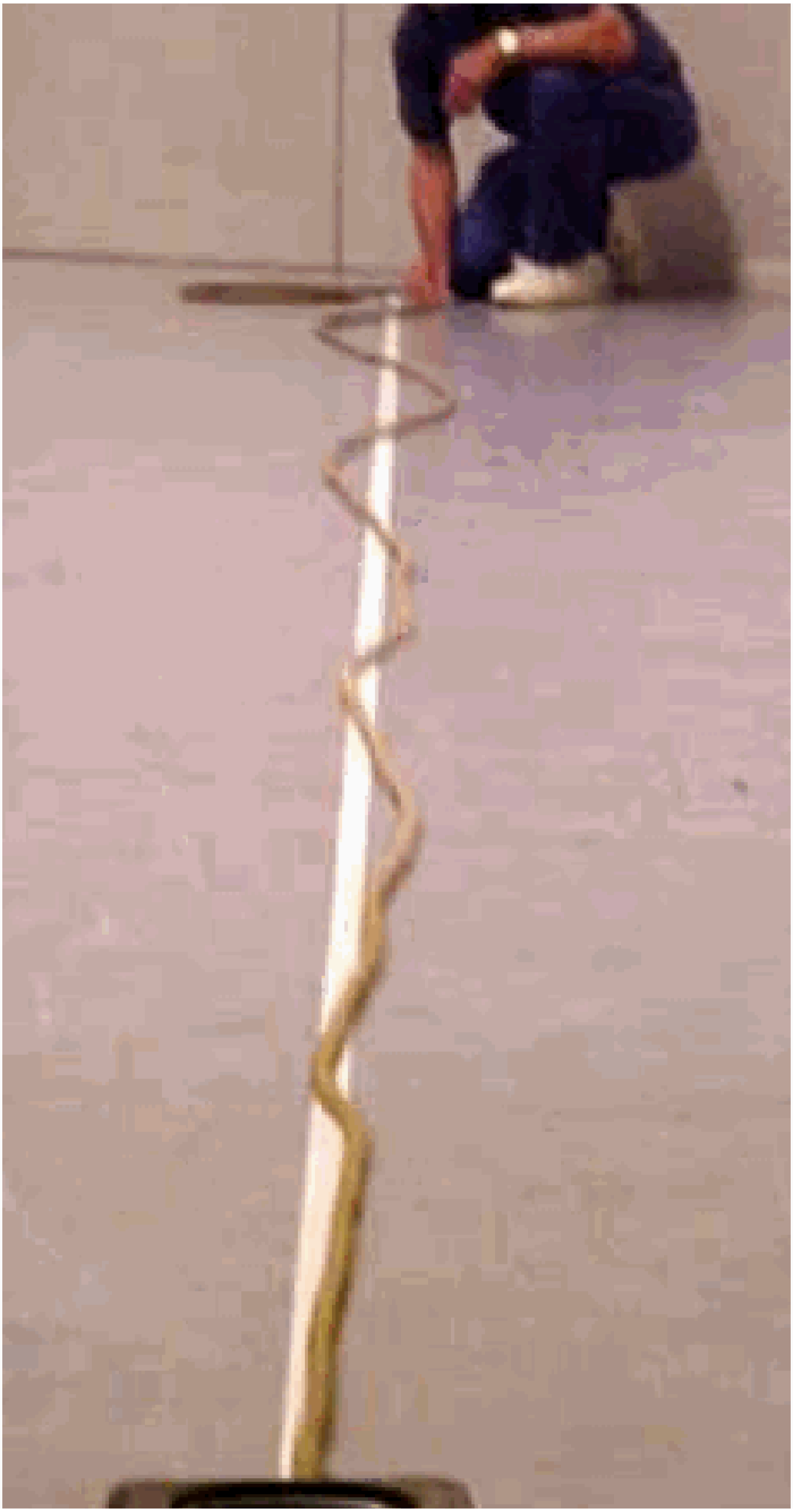


Figure 4.51: .

4.2.1.5.4 Equipment

- Heavy rubber hose ($l = 10$ m).
- Heavy weight ($m = 25$ kg).
- Tape.
- Camera.
- Projector.

4.2.1.5.5 Presentation

Lay the piece of hose in a straight line on the floor in front of the lecture room. On the floor, this straight line is marked by tape. At one end the hose is fixed by the heavy weight.

Now create a sine wave by shaking the free end of the hose vigorously in a horizontal direction. Give the hose that much tension and amplitude that the wave amplitude is damped to zero when it reaches the fixed end of the hose. Then you don't have to worry about reflections.

The traveling wave can be observed, and its name "traveling wave" will be clear. By shaking the end of the hose at different frequencies you can show the inverse relationship between frequency and wavelength.

4.2.1.5.6 Remarks

- To get a "nice" wave make sure that you drive the rubber hose at the same amount of amplitude at both sides of the taped line. Practicing before demonstrating is necessary.
- To get a good view of the traveling wave, a camera is placed at the fixed end, so that a picture can be projected by the Projector as shown in the Diagram.

4.2.1.5.7 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 126
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 1, Schwindungen, Wellen, Schall, Ultraschall, pag. 74
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 307-310

4.2.1.6 06 Transverse Traveling Wave (2)

4.2.1.6.1 Aim

To show a traveling wave and the inverse relationship between frequency and wavelength.

4.2.1.6.2 Subjects

- 3B10 (Transverse Pulses and Waves)

4.2.1.6.3 Diagram

Diagram

4.2.1.6.4 Equipment

- 2 1-meter sections of the slow wave motion demonstrator.
- dashpot filled with water

4.2.1.6.5 Presentation

Couple the two sections of the wave motion demonstrator together. Connect the end of the complete demonstrator to the dashpot. Give, by hand, the beginning of the wave demonstrator a sharp up and down disturbance, so that one or two sine-waves travel along the demonstrator. (The dashpot minimizes reflections at the far end.) It can be observed that the speed of the traveling wave is independent of the frequency. Also the inverse relationship between frequency and wavelength can be shown.

4.2.1.6.6 Sources

- PASCO scientific, Instruction Manual for the PASCO scientific Model SE-9600, 9601, 9602, and 9603

4.2.2 3B20 Longitudinal

4.2.2.1 01 Reflected Sound Pulses

4.2.2.1.1 Aim

To show how a pulse in a column of air (in a long tube) reflects.

4.2.2.1.2 Subjects

- 3B20 (Longitudinal Pulses and Waves)

4.2.2.1.3 Diagram

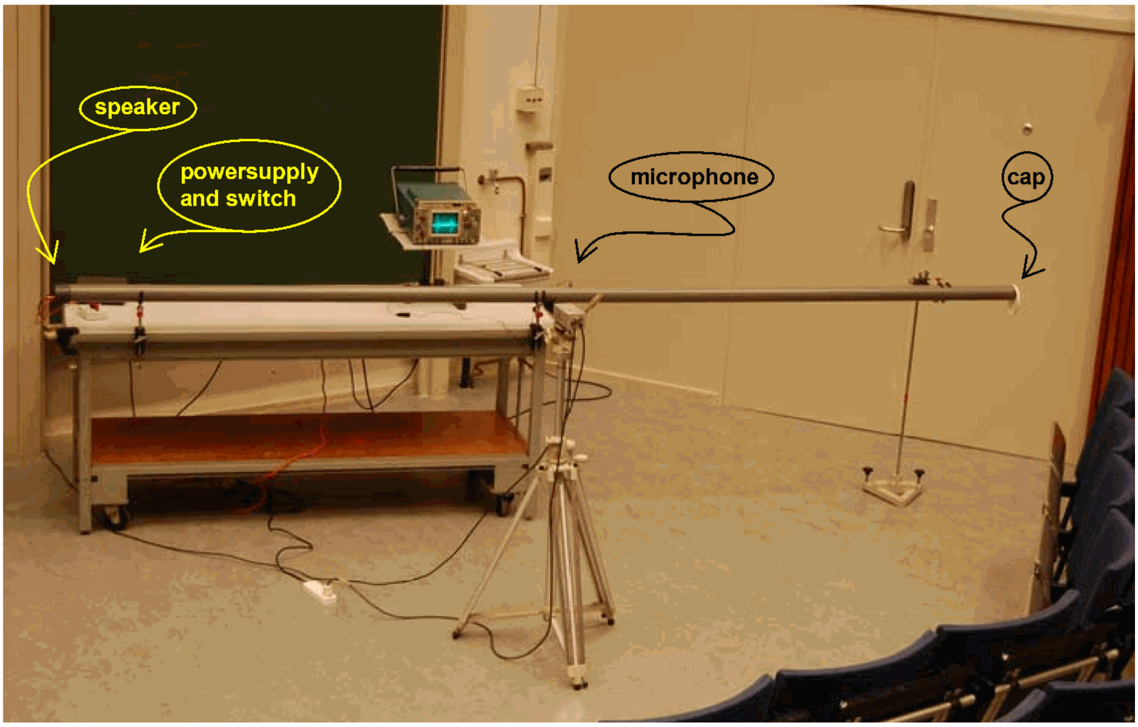


Figure 4.52: .

4.2.2.1.4 Equipment

- Pipe, pvc. $L = 4$ m; diam. $= 70$ mm; a small hole at 2 m.
- Miniature microphone, positioned in the small hole in the middle of the pipe.
- Slip on cap, needed to close the pipe (see right end of pipe in Diagram)
- Speaker at the left end of the pipe (see Diagram).
- DC power supply (needed is around 1 V/0.5 A) and switch.
- Storage oscilloscope.
- Video-camera and projector to project oscilloscope image.

4.2.2.1.5 Presentation

4.2.2.1.5.1 Preparation

The equipment is set up as shown in Diagram. The power supply is set at around 1 V dc and connected to the speaker by way of a switch. The oscilloscope is set at 2msec/DIV and prepared for storage mode, single sweep. Delay time is set such that a suitable display of pulses is obtained (see further on).

4.2.2.1.5.2 Presentation

Just to explain the operation of the set-up, the pipe is hit by hand and the oscilloscope displays the noise registered by the microphone and oscilloscope. Also the pulsing of the speaker is made audible to the students by switching the power supply to the speaker on and off a couple of times.

Next, the speaker is placed in front of the pipe and the cap is placed on the end of the pipe. The switch to the speaker is operated and after the pulse, the oscilloscope shows what is happening (see Figure 2). 'A' occurs after the sound pulse has left the speaker and has travelled halfway down the pipe. The second pulse (B) is the microphone's registration of the sound pulse after reflection at the end cap. This reflection mirrors the original pulse quite well.

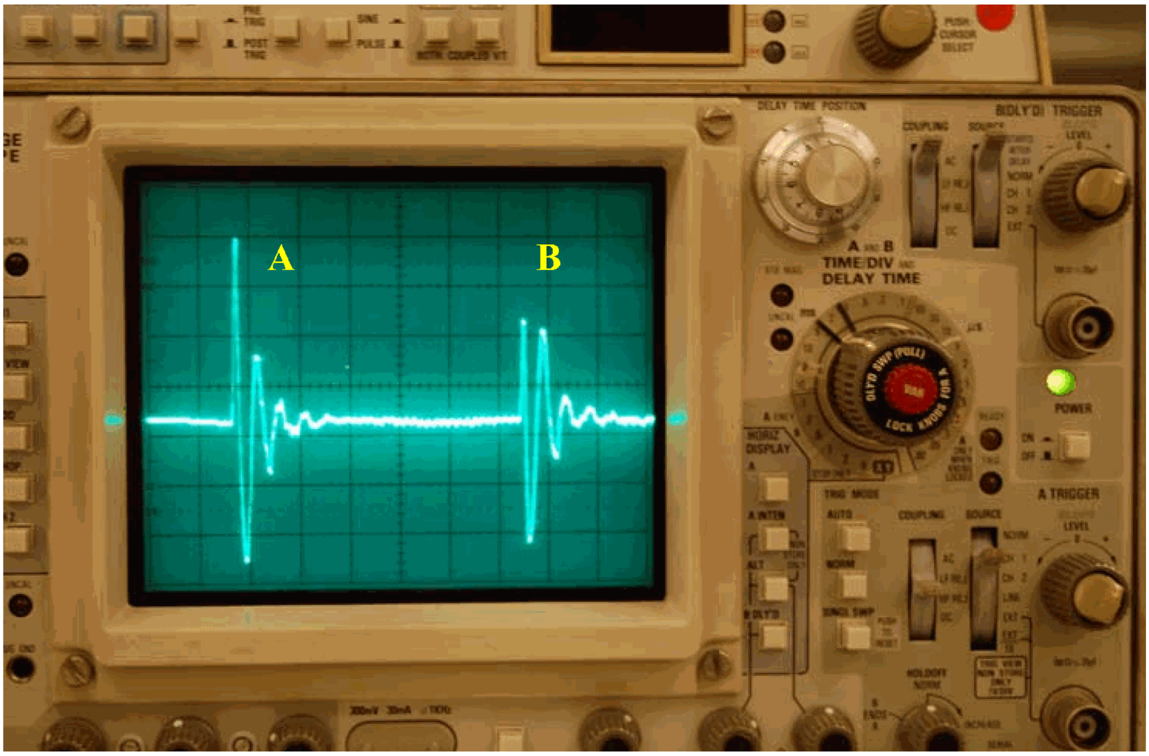


Figure 4.53: .

Two observations are made:

- The pulse travels 4 meters between pulse A and B. We observe around 6 divisions between pulse A and B; with 2msec/DIV at the horizontal time base, we get a pulse speed of: $v = 4\ \mathrm{m}/6 \times 2\mathrm{msec} = 333\ \mathrm{m/sec}$.
- The reflected pulse B has the same phase as pulse A.

The cap at the end of the pipe is removed and by operating the switch again a sound pulse is made traveling down the tube. The scope image registers what is happening now (see Figure 3).

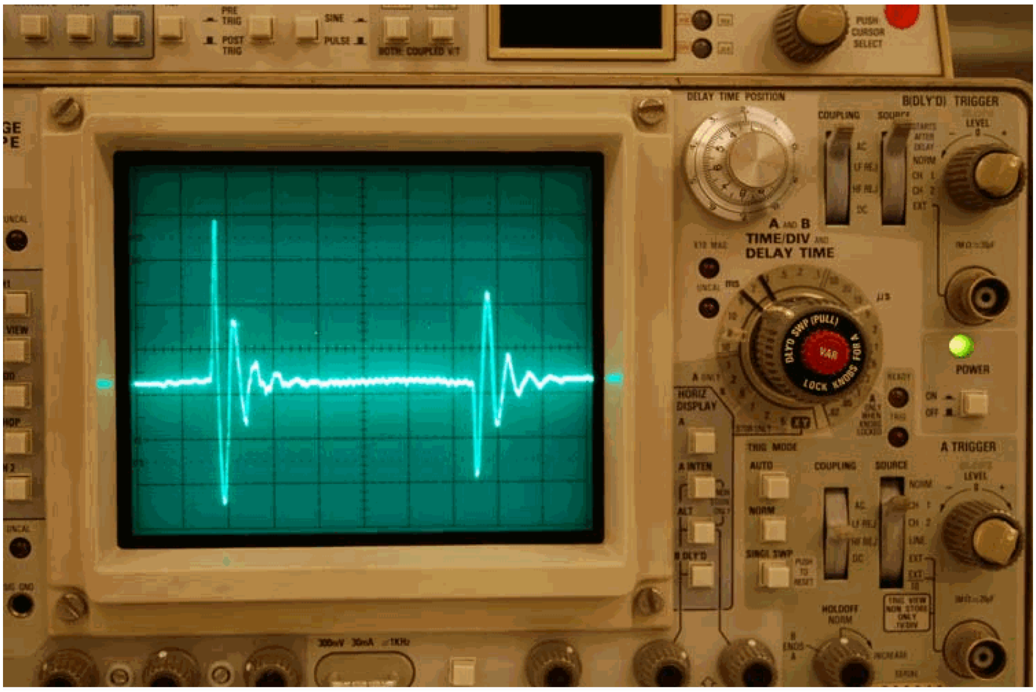


Figure 4.54: .

Again the reflected pulse mirrors the first pulse, but, as can be seen, its phase is inverted now!

A reference is made to the demonstrations Reflections of transverse pulses and Reflections of transverse pulses.

4.2.2.1.6 Explanation

One way to explain the mechanism of reflection is by means of a very simplified 1D-billiard ball model of the air column (see Figure 4 A and B): Five balls in a row represent the air column in the pipe; the separation between the balls indicates the pressure (the microphone has an output proportional to pressure-increase/decrease).

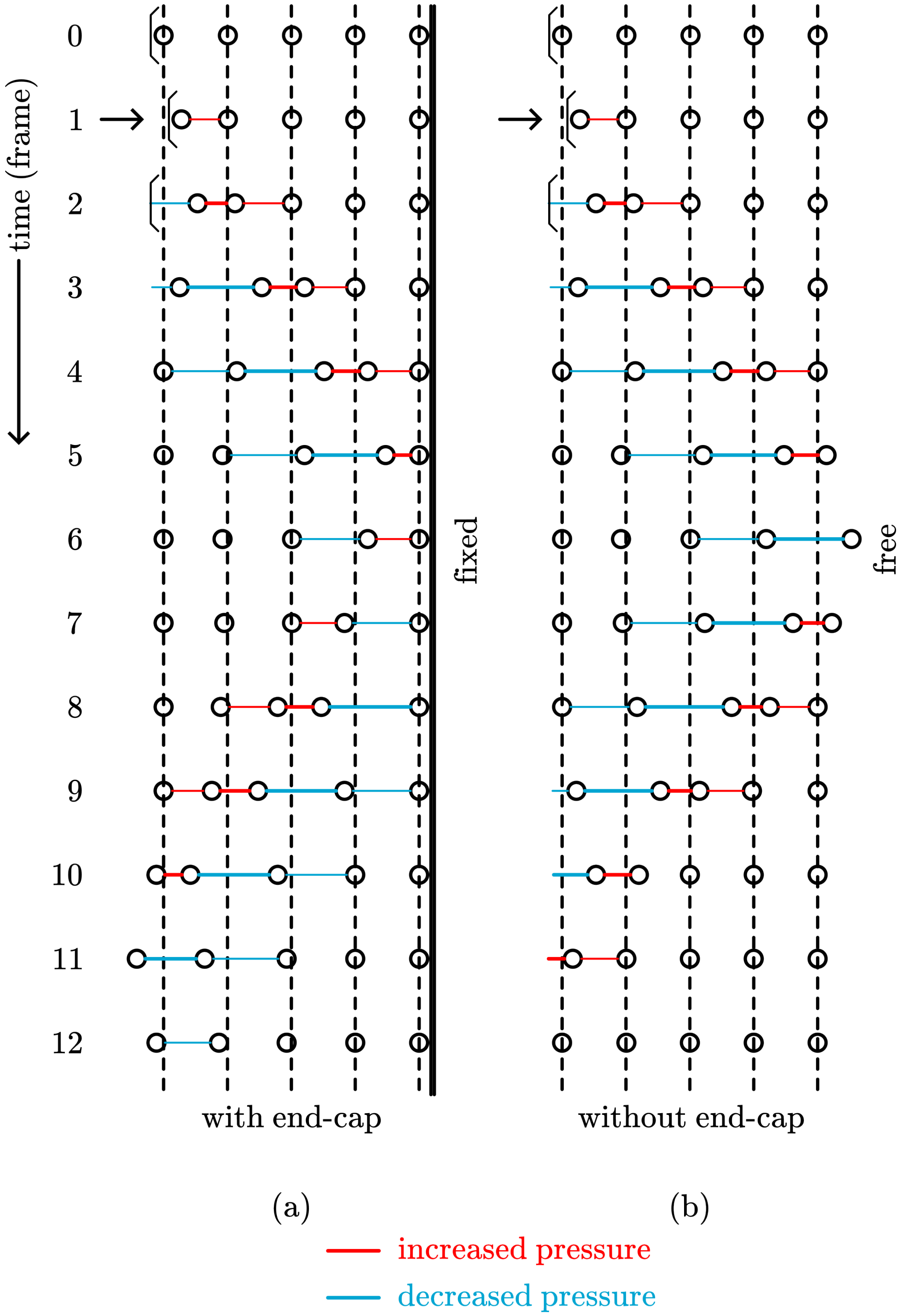


Figure 4.55: .

Figure 4A shows how a pulse fed to the speaker drives its cone to the right and the subsequent "frames" show how in the air column an increased pressure region (red) is followed by a decreasing pressure region (blue). The frames make also clear that after reflection the sequence of higher - and lower pressure remains the same. When the end cap is removed, the opening of the pipe is a free end (see Figure 4B). When the original pulse arrives at the last billiard ball, it will swing outward and a pressure drop is created at the end of the pipe, pulling billiard balls inside the pipe also outward (see frame 7,8,9 and 10). A pressure through displaces itself to the left and the lower pressure region is now ahead of the higher pressure region.

When comparing this demonstration of reflecting sound pulses with reflections of pulses on ropes (see the demonstrations Reflections of transverse pulses and Reflections of transverse pulses), confusion may rise. Most students will see the cap as a fixed end. But it should be realized that in this sound demonstration the microphone reacts to pressure! That is what we see on the display of the oscilloscope, and not displacement! When a sound pulse hits the cap, this closed end corresponds to a pressure antinode, that is, a point of maximum pressure variation (to air displacement the cap is a node). So, when compared with the observed reflections on the ends of ropes, the cap (being a point of maximum pressure variation) should be compared with a rope that has a free end (being a point of maximum rope displacement). In the same way the situation of an open pipe is a pressure node; the pressure at this end remains at atmospheric pressure. Compared with a rope this corresponds with a fixed end.

Summarized:

Air column (longitudinal pressure)	Rope (transverse displacement)	Pulse
Closed end	Free end	No inversion
Open end	Fixed end	Inversion

4.2.2.1.7 Remarks

- To compare longitudinal displacement of matter and longitudinal pressure differences see also the demonstration “Kundt’s tube”.

4.2.2.1.8 Sources

- Jewett, J.W. and Serway, R.A., Physics for Scientists and Engineers with Modern Physics, seventh edition, pg 512.
- Young, H.D. and Freeman, R.A., University Physics, pag. 631-632.

4.2.3 3B22 Standing

4.2.3.1 01 deBroglie Applied to Bohr

4.2.3.1.1 Aim

To introduce how matter waves can be associated to Bohr's model of an atom; a classical analogy.

4.2.3.1.2 Subjects

- 3B22 (Standing Waves)
- 7A50 (Wave Mechanics)
- 7B50 (Atomic Models)

4.2.3.1.3 Diagram

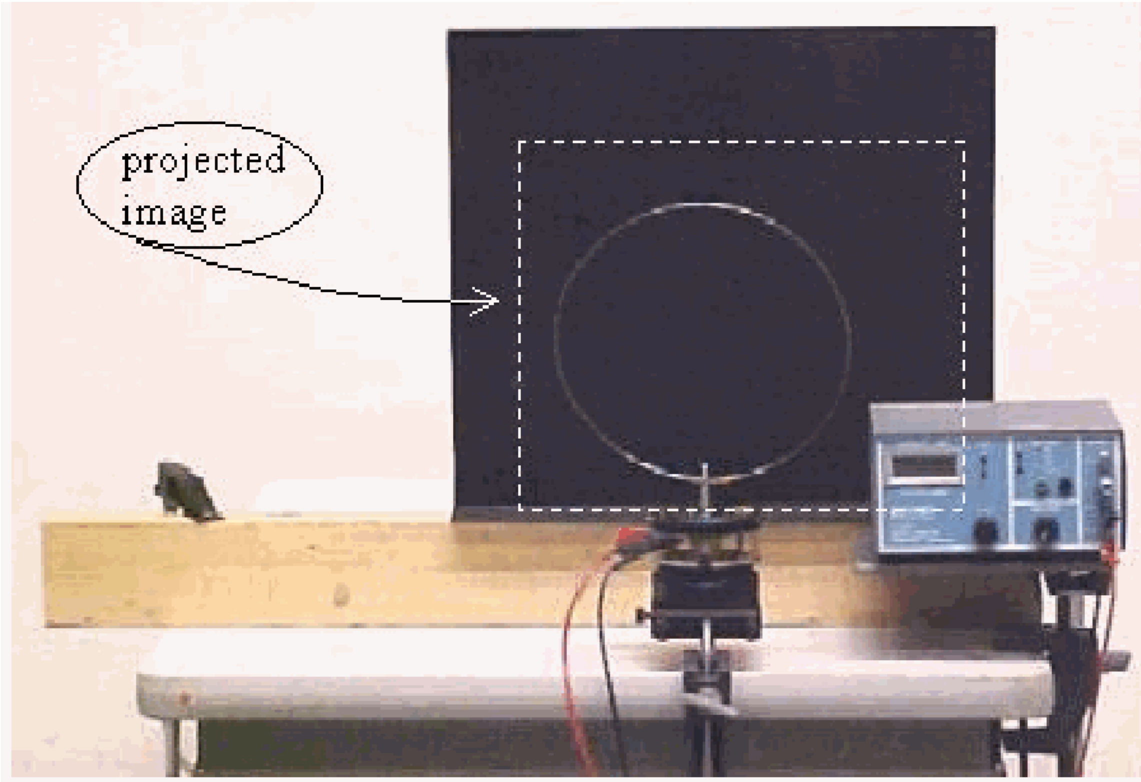


Figure 4.56: .

4.2.3.1.4 Equipment

- Wire loop of spring steel (round, 1mm), bend into a circular loop with a diameter of around 25 cm, and fixed to a banana plug (Pasco SF-9405).
- Mechanical wave driver (Pasco SF-9324), actually an adapted loudspeaker.
- Signal generator.
- Black screen.
- Camera and beamer to show the demonstration to a large audience.

4.2.3.1.5 Safety

- The loop is fixed to the wave driver. When the loop is agitated heavily it is possible that it loosens itself. Then a free end sweeps around dangerously. So fix the loop tightly.

4.2.3.1.6 Presentation

The wire loop is fitted to the mechanical wave driver shaft. The wave driver is connected to the signal generator. The image of wire loop and display of the frequency of the driving generator is projected (see Diagram).

Start at low frequency (around 5 Hz) and low amplitude, making the loop starting to vibrate. Increase the frequency to see various modes of standing waves in the circular loop. (At higher frequencies the amplitude of the signal generator has to increase to obtain visible amplitude in the oscillating wire loop.) We observe:

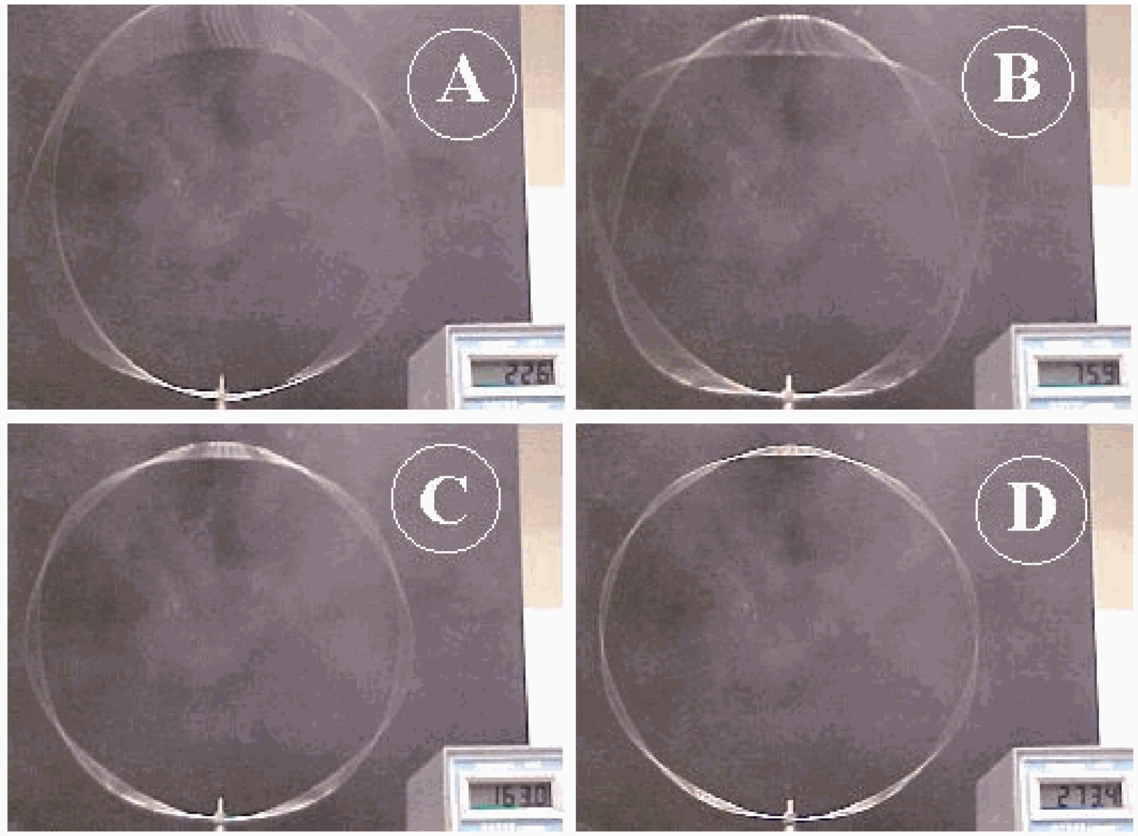


Figure 4.57: .

- 2 nodes and anti-nodes at 14 Hz;
- 3 nodes and anti-nodes at 23 Hz (very large amplitude) (see Figure 2A);
- 4 nodes and anti-nodes at 30 Hz;
- 5 nodes and anti-nodes at 76 Hz (see Figure 2B);
- 7 nodes and anti-nodes at 163 Hz (see Figure 2C);
- 9 nodes and anti-nodes at 273 Hz (see Figure 2D);

−11 nodes and anti-nodes at 398 Hz (this last one is not so good visible to a larger audience due to its low amplitude).

4.2.3.1.7 Explanation

According to Bohr electrons move in circles.

DeBroglie argued that the “electron wave” was a circular standing wave that closes in itself (in order to obtain constructive interference). So, for persisting waves: $2\pi r_n = n\lambda, n = 1, 2, 3, ...$. This is what we observe in our demonstration.

DeBroglie: $\lambda = h/mv$ and we get: $mvr_n = nh/2\pi$. In this way the ad hoc quantized orbits of Bohr are derived form deBroglie. This “shown” wave-particle duality is at the root of atomic structure.

(In discussing the analogy it should be remembered that the “electron wave” is not in reality a standing wave along a line, but it extends through all space.)

4.2.3.1.8 Remarks

- For the lower frequencies, $14 -$, $23 -$ and 30 Hz, the successive patterns (2,3 and 4 half wavelengths) are “logic” when we suppose that $1/2\lambda$ is obtained at around $6 -$, 7 Hz. For higher number of nodes/anti-nodes this logic order is apparently a different one.

4.2.3.1.9 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 971-972
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 573-574
- Meiners,H., Physics demonstration experiments, part 2, pag. 1185-1188

4.2.3.2 02 Handheld Standing Waves

4.2.3.2.1 Aim

To show the normal modes of a standing wave on a string (nodes and antinodes).

4.2.3.2.2 Subjects

- 3B22 (Standing Waves)

4.2.3.2.3 Diagram

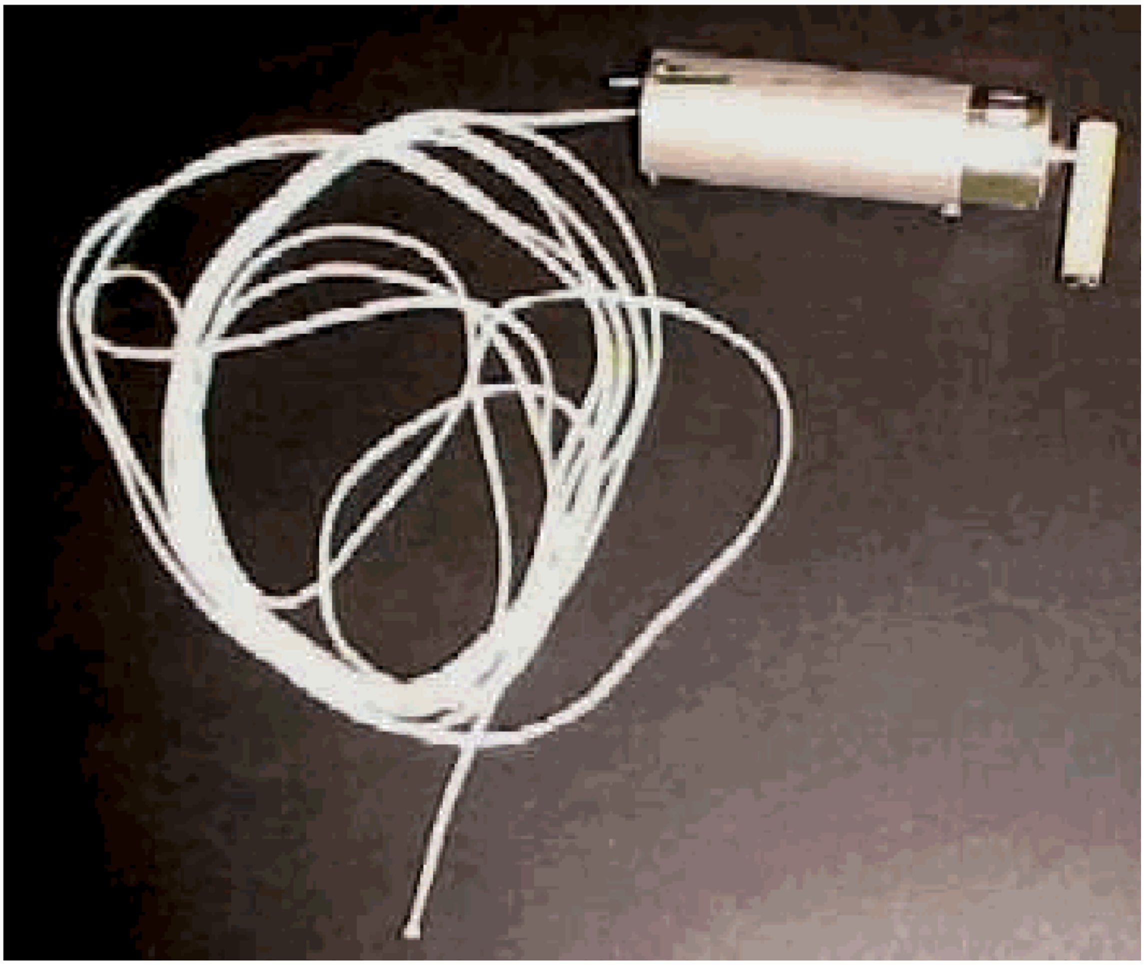


Figure 4.58: .

4.2.3.2.4 Equipment

- Standing-wave generator
- White string
- Black screen
- Small clamp

4.2.3.2.5 Presentation

The white string is fixed to the standing-wave generator (see the first topic in "Remarks" for a description of the standing-wave generator). Hold the standing-wave generator by the string close to the device.Slowly increase the amount of string by which the generator is suspended and you will see standing waves at specific lengths of the string(see Figure 2).

4.2.3.2.6 Explanation

The fundamental frequency of a vibrating string fixed at both ends is $f = n\left(\frac{1}{2l}\right)\sqrt{\frac{T}{\mu}}$.

T (the tension in the string) and μ are constant in this demonstration (μ is the mass per unit length of the string). So at a certain length l, we observe the first normal mode $(n = 1)$.

Doubling the length reduces the fundamental frequency of the string by a factor 2 . Since $f_{qenerator}$ is constant we observe now the normal mode of the second harmonic (first overtone; $n = 2$) of that fundamental frequency. And so on.

4.2.3.2.7 Remarks

- To make the generator vibrate, a dowel is fixed eccentrically to the shaft of the motor. We obtain lower frequencies by clipping a small clamp to the dowel (see Diagram). Shifting the clamp changes the frequency.
- Be sure that the clamp is fixed strong enough so it will not fly away when the device is vibrating.
- In order not become entangled in the string while demonstrating, the free end of the string hangs down across the shoulder of the demonstrator (see Figure 2)

Figure 4.59: .

4.2.3.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 336-338 and 344-345
- Young, H.D. and Freeman, R.A., University Physics, pag. 627-629
- The Physics Teacher, Vol. 38 sept. 2000

4.2.3.3 03 Kundt's Tube

4.2.3.3.1 Aim

To show standing acoustic waves.

4.2.3.3.2 Subjects

- 3B22 (Standing Waves)

4.2.3.3.3 Diagram

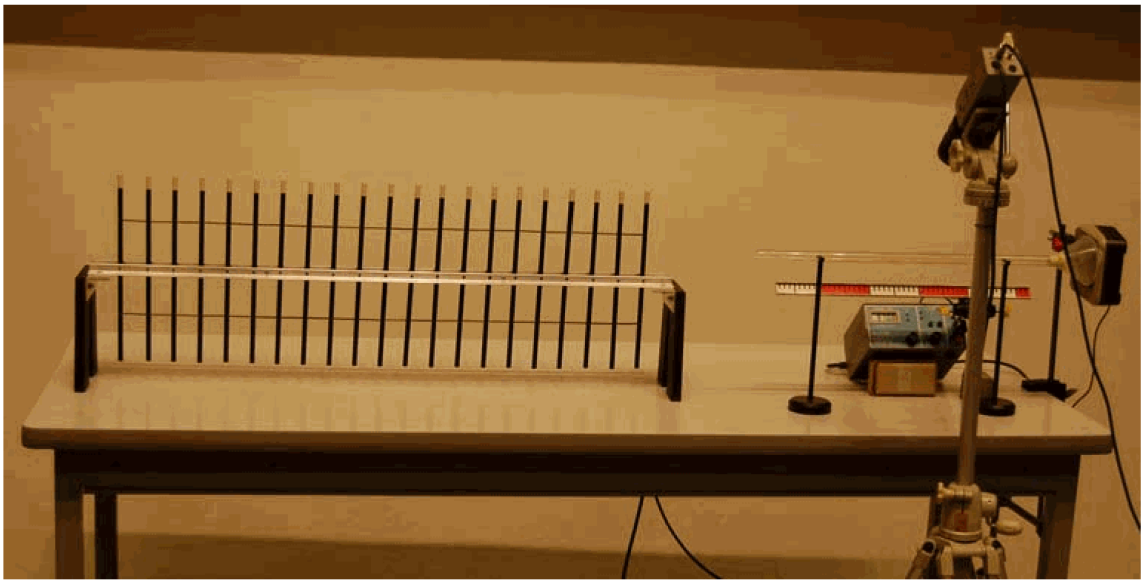


Figure 4.60: .

4.2.3.3.4 Equipment

- Longitudinal Wave Demonstrator.
- Glass tube (with moveable piston).
- Funnel, placed between glass tube and speaker.
- Cork dust; poured into the glass tube and evenly distributed into a thin layer.
- Loudspeaker.
- Signal generator.
- Meterstick.
- Camera.

4.2.3.3.5 Safety

- The demonstrator should use ear plugs to protect his ears. Instruct the audience to place their hands to their ears.

4.2.3.3.6 Presentation

4.2.3.3.6.1 Longitudinal Wave Demonstrator.

Ask the students to concentrate on the white ends of the sticks of the wave demonstrator. These white ends represent “air molecules”. The distance between the white ends is a measure for “air pressure”.

Apply, by hand, a short pulse into this wave demonstrator and see how a compression displaces itself horizontally, reflects from the free end, and returns. This is similar to a pulse on a rope which they have seen before, so stress the difference: Now the “particles” have a velocity in the same direction as the pulse travels while on the rope the particle velocity is transverse to the movement of the pulse.

Also stress the observation that particle velocity differs from the velocity of the pulse. Make, by hand a standing wave in the wave demonstrator, with around 3, 4 nodes in it (see Figure 2A). Pay attention to “particles” that are not moving at all and “particles” that are moving fast, and observe that in places without “particle”-movement the distance between the “particles” changes strongly (= strong change in pressure), and in places with strong “particle”-movement the distance between the “particles” is almost constant (= no change in pressure).

[In this demonstration we stress these two observations, because in textbooks you often see drawings of standing waves in tubes showing either the displacement of air and/or the pressure in air. To students this can be confusing when they relate these pictures to what they see in a demonstration.]

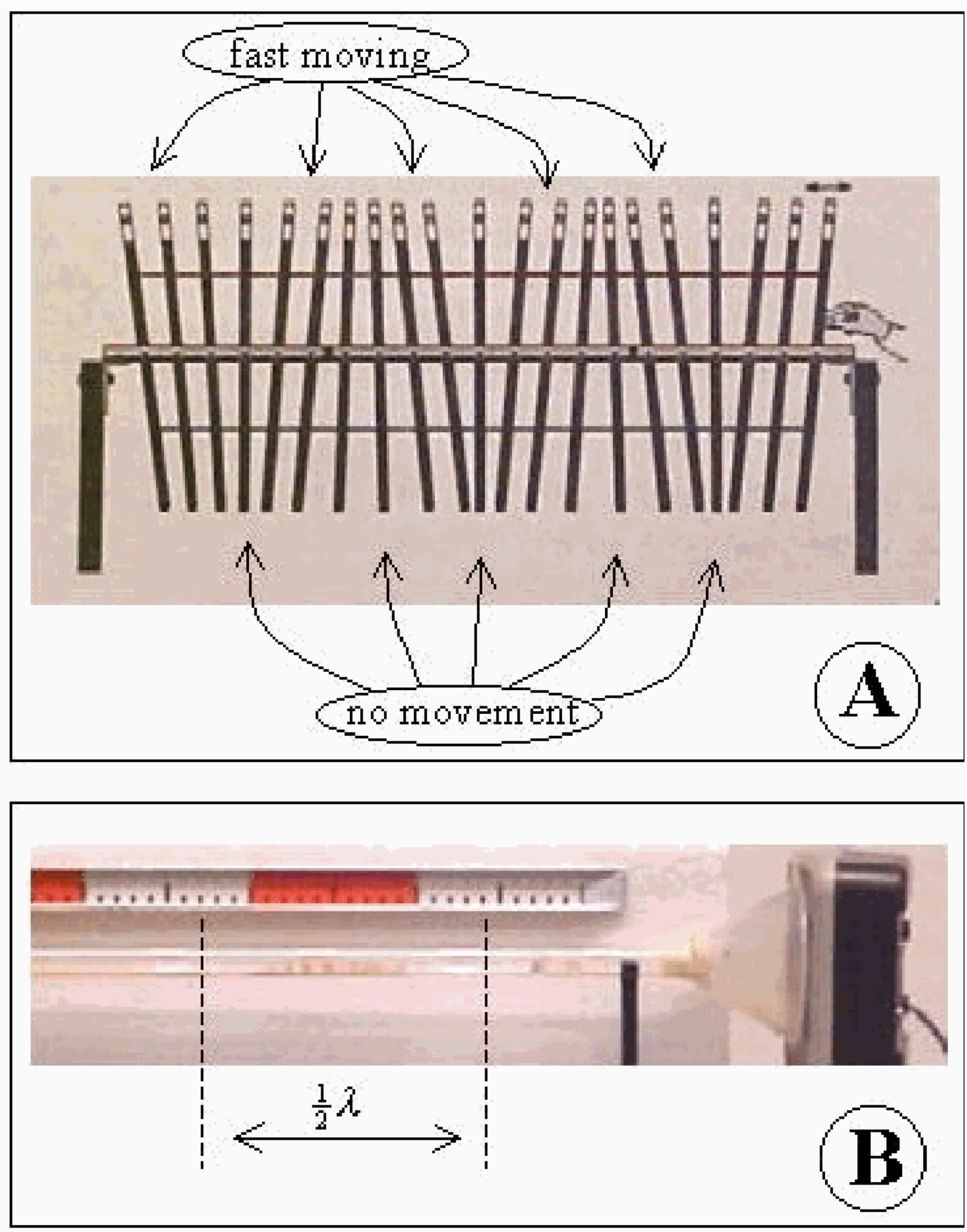


Figure 4.61: .

4.2.3.3.6.2 Open end tube.

The camera focuses on the glass tube, the ruler and the frequency-reading of the signal generator (see the position of the camera in Diagram). The signal generator is set to a high amplitude and a loud sound is heard. The frequency is increased until a standing wave is observed in the cork dust (we start around 500 Hz and go up to a couple of kHz). At a standing wave we see that at certain places dust is swept away (anti-nodes in terms of displacement) and at other places dust collects (nodes) (see Figure 3). At the open end of the tube cork dust is swept out of the tube. Clearly air is moving fast at that open end (anti-node).

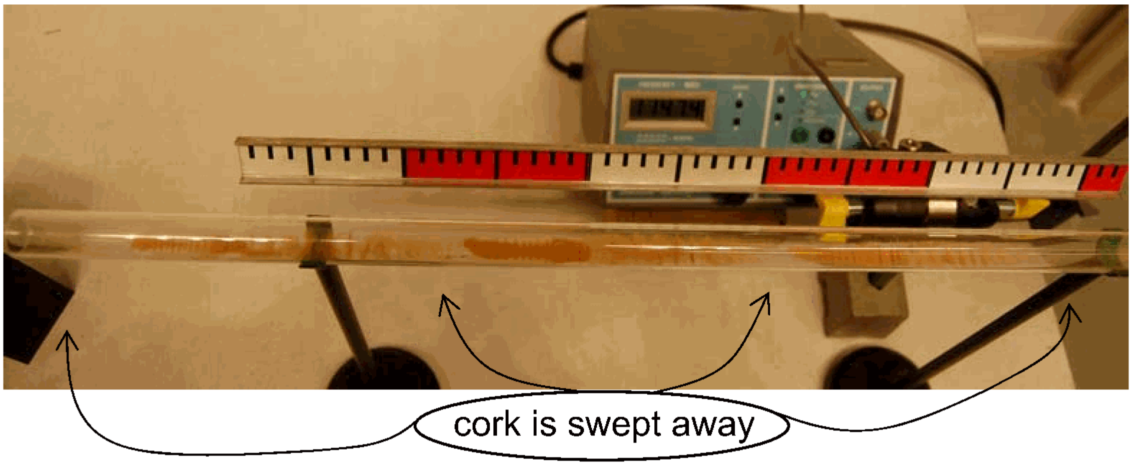


Figure 4.62: .

Closed end tube. The piston is shifted into the tube. The frequency of the signal generator is fixed at 1 kHz (this value enables easy calculations). The piston is displaced until again a standing cork dust pattern appears (see Figure 2B). We measure 17 cm distance between two anti-nodes (half λ). With $c = \lambda f$ we get $c = 340$ m/s.

4.2.3.3.7 Explanation

In Kundt's tube (1866) the cork dust is so light that moving air easily displaces it when a strong standing wave occurs. The cork is swept away at places where the air is in motion. The cork dust collects at places where the air is not moving. Referring to the Longitudinal Wave Demonstrator highlights what happens in Kundt's tube, e.q.:

- At a closed end the displacement of air is zero, while the pressure variations are maximum.
- At an open end there are no pressure variations while the displacement of air is maximum.
- At an open end the displacement of air goes beyond the length of the tube, so for nodes and anti-nodes the tube is a little "longer".

4.2.3.3.8 Remarks

- In the area where cork dust collects, small vertical "curtains" appear, separated by around 4-5mm (see Figure 4). Probably this is caused by higher harmonics? We are not sure and until now found nothing of this phenomenon in literature. When it is a higher harmonics it can be useful to try to perform the experiment with other particles, because then a different curtain-separation will occur? When you know more we like to hear from you.

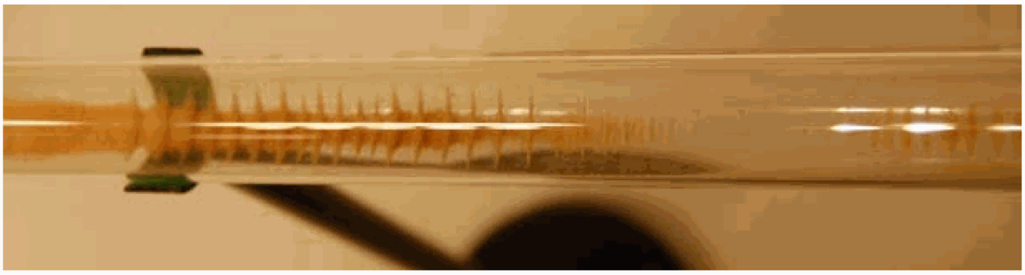


Figure 4.63: .

4.2.3.3.9 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, third edition, pag. 426-427.

4.2.3.4 04 Sonometer by Hand

4.2.3.4.1 Aim

To show the validity of the relationship between wavelength, string tension and linear density of the string.

4.2.3.4.2 Subjects

- 3B22 (Standing Waves)

4.2.3.4.3 Diagram

Diagram

4.2.3.4.4 Equipment

- 2 ropes ($l = 10$ m)
- rope, four strings wrapped together ($l = 10$ m)
- mass, $m = 0.5$ kg
- mass, $m = 2$ kg
- smooth bar

4.2.3.4.5 Presentation

One rope is hung across the bar and loaded with 0.5 kg. The demonstrator graps the other end, standing about 8 m away and swings the rope vertically to a standing wave of one half wavelength. When he doubles his speed one complete wave appears in the rope.

With his other hand he also takes the second rope that is loaded with 2 kg. First he makes one complete wavelength in the rope that is loaded with .5 kg. Then he starts moving the second hand in the same rhythm. A half wave will appear in this second rope (Figure 1).

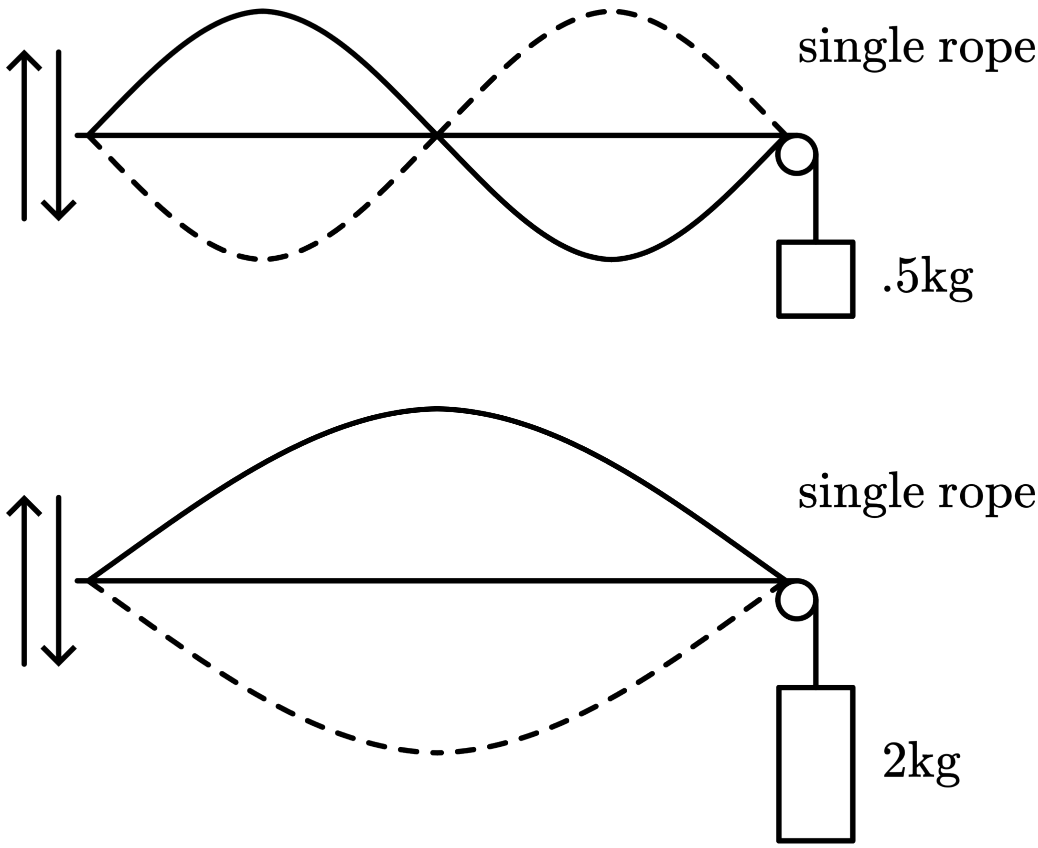


Figure 4.64: .

The demonstrator takes the rope that is four times as heavy and loads it with 2 kg. Slowly moving he makes a standing wave of one half wavelength. Doubling his speed, he makes a standing wave of one complete wavelength.

With his second hand he takes a single rope, also loaded with 2 kg and when this rope moves in the same rhythm as his first hand is doing for a complete wavelength, then a half wavelength appears in this second rope (Figure 2).

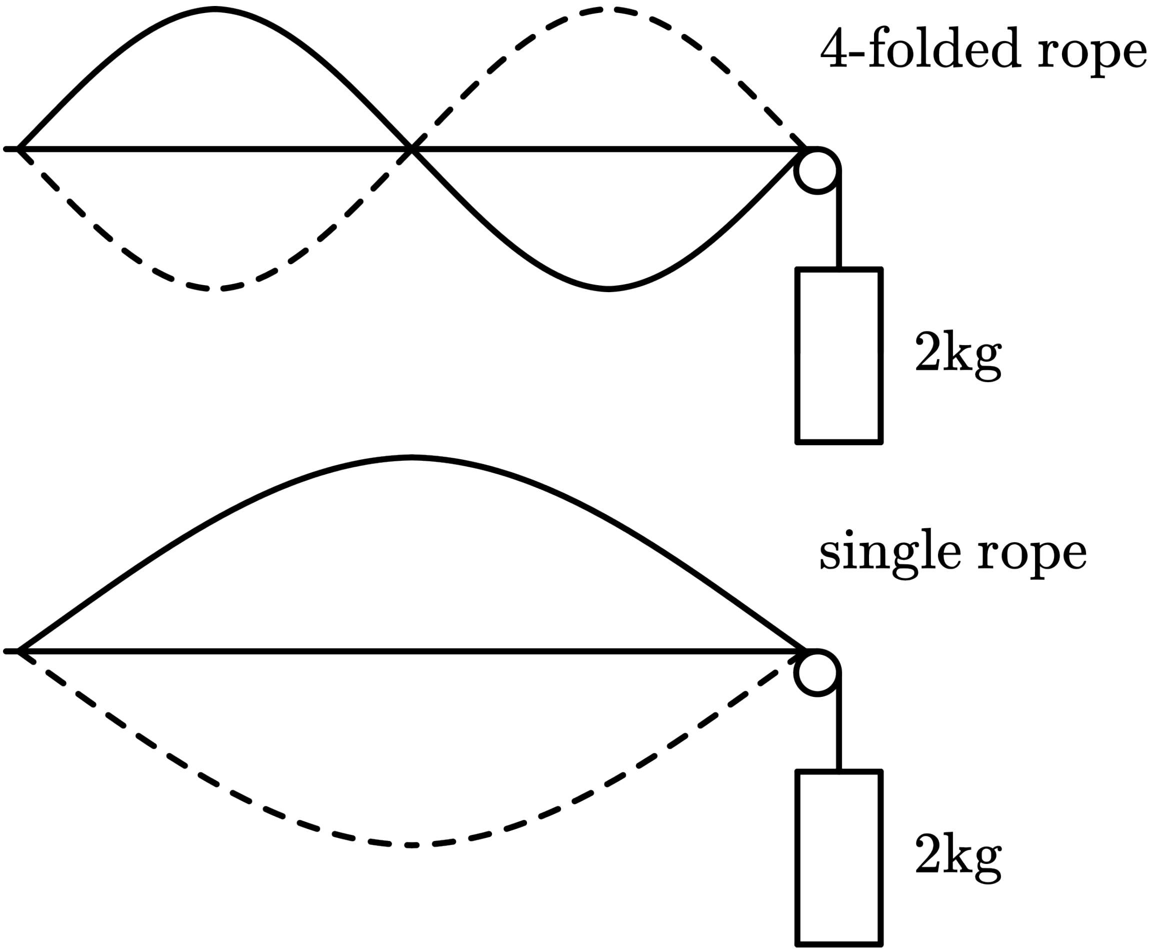


Figure 4.65: .

4.2.3.4.6 Explanation

For wave motion on a rope we can write $v = \frac{1}{\lambda}\sqrt{\frac{T}{\mu}}$ where,

$\nu =$ frequency of wave

$\lambda =$ wavelength

$T =$ rope tension

$\mu =$ linear density of rope

($v = \sqrt{\frac{T}{\mu}}$ = velocity of wave propagation)

The first demonstration shows that, at the same frequency, λ doubles when T is four-folded.

The second demonstration shows that, at the same frequency and tension, λ halves when μ is four-folded.

4.2.3.4.7 Remarks

- Before demonstrating, take enough time to practice.
- In our set-up it seems inevitable that a circular wave appears even when we strictly move our hands in a vertical plane. But this does not spoil the demonstration.

4.2.3.4.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 405-408
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 344-345

4.2.3.5 05 Plucking a String

4.2.3.5.1 Aim

To show the frequency-components in a plucked string and how they depend on the strings tension.

4.2.3.5.2 Subjects

- 3B22 (Standing Waves)
- 3C50 (Wave Analysis and Synthesis)

4.2.3.5.3 Diagram

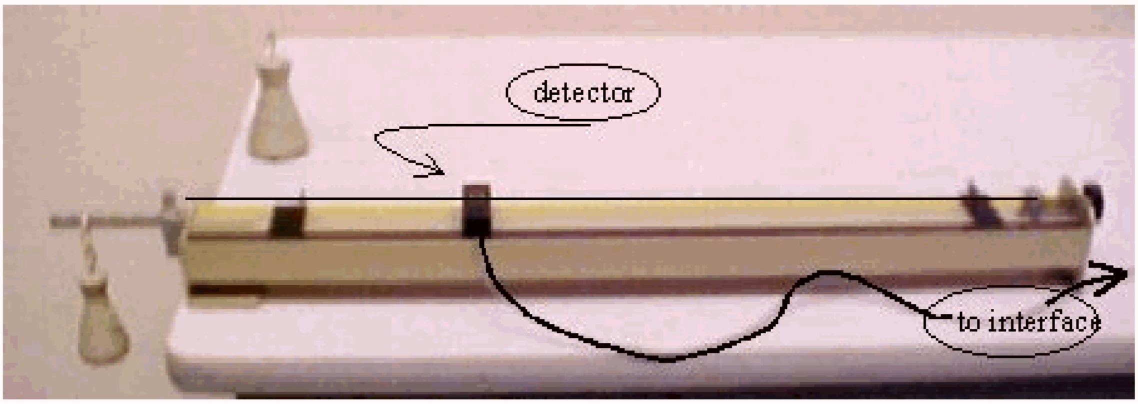


Figure 4.66: .

4.2.3.5.4 Equipment

- Sonometer with detector.
- Steel string, $\emptyset = 0.5$ mm$(\mu = 1.5 \times 10^{-3}$ kg/m$)$.
- Two masses (0.5 kg and 1 kg).
- Data-acquisition system.

4.2.3.5.5 Presentation

Set up the demonstration as shown in Diagram and connect the detector, that is placed near the string, to the interface. The software is set up to have an oscilloscope screen and an FFT display (frequency spectrum) as in Figure 2.

1. Load the string with . 5 kg (see Diagram, mass hanging at the end of the lever). Pluck, by hand/nail, the string (moving it in a vertical direction). We do this in two ways:

a. Pluck the string in its centre.

The scope display shows a more or less symmetric shape. The FFT display shows the frequency components in it. Using the crosshair cursor we read: 102 —, 289 —, 473 —, 663 Hz. Very roughly the relationship $1 : 3 : 5 : 7$ is visible in these frequencies.

b. Pluck the string close to its end.

The scope display shows a more or less sawtooth shape, and while it dampens becomes more or less sinusoidal. The FFT display shows the frequency components in it. The fundamental frequency is very high compared to the higher harmonics. (Using the crosshair cursor we read: 102 —, 190 —, 288 —, 385 —, 473 —, 570 —, 666 —, 755 —, 853 Hz, etc. Very roughly the relationship $1 : 2 : 3 : 4 : 5 : 6 : 7 : 8 : 9$ is visible in these frequencies.)

1. Loading the string with another force.

a. By hand.

When the string is plucked, we pull the weight. We see on the FFT-display shift the frequency components to higher frequencies.

***b. Load the string with* 1 kg.**

Again the string is plucked, first in its centre, and next close to its end. The observed frequencies are now:

2a: 140 —, 268 —, 405 —, 541 —, 677 —, 799 —, 939 Hz;

2b: 140 —, 405 —, 678 Hz (see Figure 2).

Compare these data with the results of the first part of our demonstration and show that the ratio's 140/102; 268/190; 405/288; 541/385; etc. are all very close to $\sqrt{2}$.

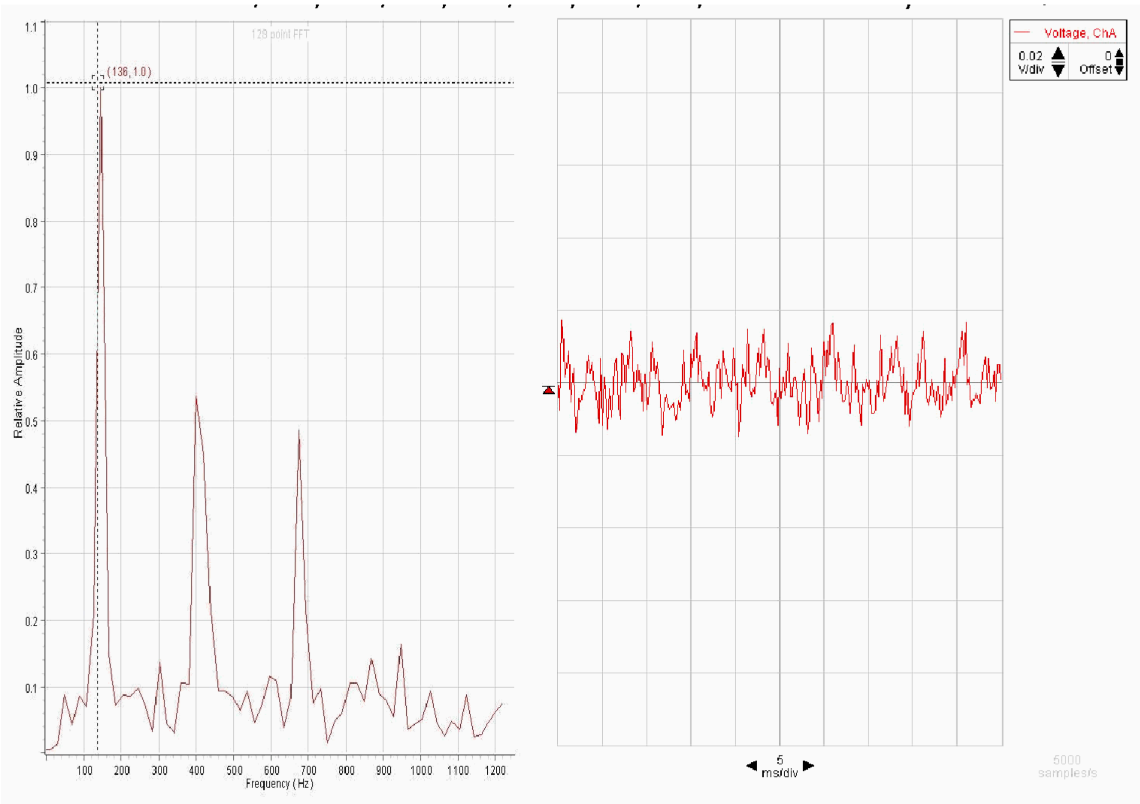


Figure 4.67: .

4.2.3.5.6 Simulation:

To support the results of our demonstration we show the simulation of a vibrating string. To do so we choose "Loaded String Simulation", a JAVA-Applet on the site https://www.falstad.com/ in which the string can be plucked at different points using the mouse. Adjusting the simulation speed top 'low' the vibrating string is shown in slow motion, clearly showing its frequency amplitude components (and its first three phasors). You can hear also the sound of the plucked string and observe the difference between a centre-pluck and an end-pluck.

4.2.3.5.7 Explanation

Grasping a string near its end to pluck it, makes the triangular shape in the oscillating string to be expected. The FFTdisplay distincts a fundamental frequency and a number of its harmonics. In general a triangular shape appears when to a fundamental frequency a second harmonic (first overtone), a third harmonic (second overtone), etc. is added. The demonstration verifies this.

Grasping the string in its centre to make it oscillating, a symmetric waveform is to be expected with uneven harmonics in it.

When the crosshair cursor is used in the FFT-display to read the observed frequencies it shows that doubling the string's tension means a factor $\sqrt{2}$ in increase in frequency.

A standing wave occurs when traveling waves/pulses after their reflections at the end of the string interfere positively, giving large standing amplitudes. The speed of pulses/waves traveling along the string is: $v = \sqrt{\frac{F}{\mu}}$, (see Speed of a single pulse on different strings (1). $v = f\lambda$ and so: $f = \frac{v}{\lambda} = \frac{1}{2L}\sqrt{\frac{F}{\mu}}$, $\angle$ being the length of the string. Our demonstration in doubling the string tension (F) verifies the square root of F in relation to f.

(When we fill up the formula $f = \frac{v}{\lambda} = \frac{1}{2L}\sqrt{\frac{F}{\mu}}$ with the data of our demonstration we calculate a fundamental frequency of 115 Hz (Demonstration yields 102 Hz).

That many frequencies occur in a plucked string can be explained by showing the solution on the one-dimensional wave equation. This equation, $\frac{\partial^2 f}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 f}{\partial t^2} = 0$,

can generally be solved by: $f(x,t) = f_1\left(t - \frac{x}{c}\right) + f_2\left(t + \frac{x}{c}\right)$ (d'Alembert solution), where f_1 and f_2 can be any function. So f_n can be any time-harmonic solution like $Ae^{-i\omega(t-x/c)} + Be^{-i\omega(t+x/c)} + Ce^{i\omega(t-x/c)} + De^{i\omega(t+x/c)}$, etc., in which ω can have many values.

For a string with fixed ends we get a number (n) of possible standing waves; n different modes of vibration: $\omega_n = n\omega_1, n = 1, 2, 3, \ldots\omega_1$ is called *fundamental frequency*, the others *harmonics or overtones.*

4.2.3.5.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 344-345 and 349-350
- Young, H.D. and Freeman, R.A., University Physics, pag. 627-630

4.2.3.6 06 Microwave Oven Standing Waves

4.2.3.6.1 Aim

To show a standing electromagnetic wave.

4.2.3.6.2 Subjects

- 3B22 (Standing Waves)
- 5N10 (Transmission Lines and Antennas)

4.2.3.6.3 Diagram

Figure 4.68: .

4.2.3.6.4 Equipment

- Microwave oven. The oven is adapted so it can operate with its door open.
- Piece of cardboard covered with marsh-mallows.
- Video-camera and projector to project an image of the marsh-mallows to the students.

4.2.3.6.5 Safety

- We operate the microwave oven with its door open, so keep enough distance away from it. One hazard is well known and documented: As the lens of the eye has no cooling blood flow, it is particularly prone to overheating when exposed to microwave radiation. This heating can in turn lead to a higher incidence of cataracts in later life.
- There is also a considerable electrical hazard around the magnetron tube, as it requires a high voltage power supply.

4.2.3.6.6 Presentation

Shortly the operation of the microwave oven is explained to the students. This is done by showing the cavity magnetron to them and explaining its operation (see Figure 2). See for instance: https://www.radartutorial.eu/08.transmitters/tx08.en.html

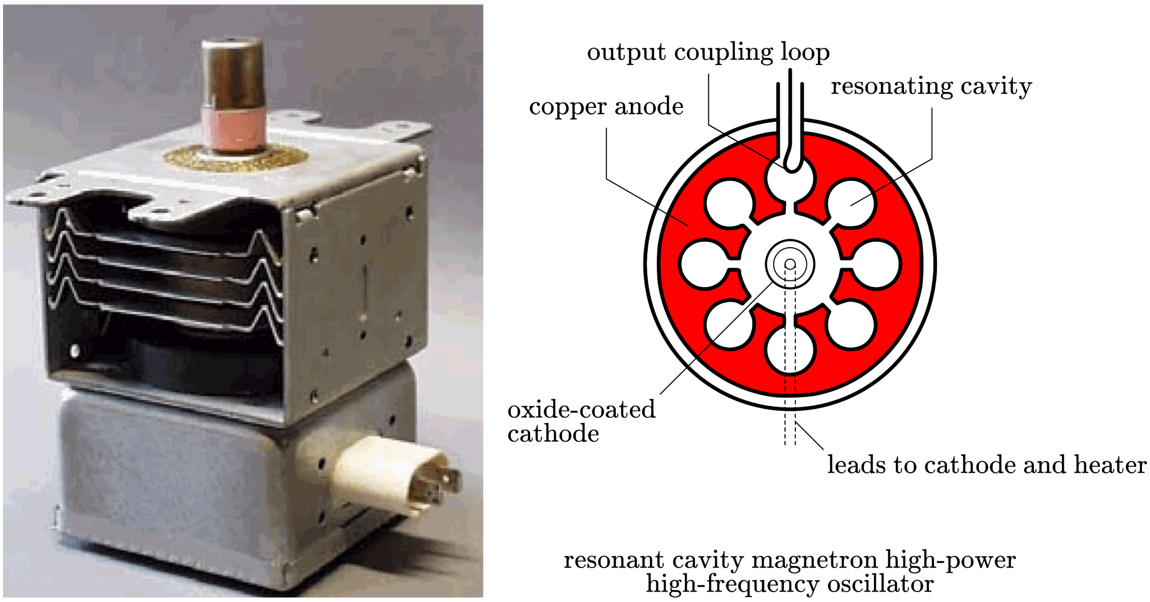


Figure 4.69: .

The oven is switched ON for around 2 minutes. After around 30 seconds it is observed that the marsh-mallows rise. After two minutes it is clearly observed that the rising occurs only at certain spots (see Figure 3).

Figure 4.70: .

We measure $d = 10$ cm.

4.2.3.6.7 Explanation

The rising of the marshmallows at certain spots only, shows that there is heating only at certain spots. This can be explained by assuming a standing em-wave in the cavity that the oven is.

4.2.3.6.7.1 Discussion:

Knowing that the magnetron-frequency is 2.45Ghz, makes that the wavelength in air of the em-wave equals 12.2 cm. Then possible standing waves are standing waves with $n(12.2)\mathrm{cm}[n = 1, 2, 3, \ldots]$, and we expect heating at multiples of half wavelength distances, so at $\mathrm{n}(6.1)\mathrm{cm}$. We measure heating hills at 10 cm separation (see Figure 3). This means that the standing wave has a wavelength of 20 cm. This can only mean that the frequency of the em-wave inside the oven is less than 2.45MHz. supposing it is half that frequency, then we expect standing waves with $\mathrm{n}(24.4)\mathrm{cm}$, and heating hills at 12.2 cm separation. That we measure 10 cm can be caused by the dielectric constant of marshmallows being > 1, causing a smaller wavelength inside the marshmallows.

4.2.3.6.8 Sources

- https://www.radartutorial.eu/08.transmitters/tx08.en.html

4.2.4 3B25 Impedance and Dispersion

4.2.4.1 01 Impedance Matching

4.2.4.1.1 Aim

To show the effect of impedance matching.

4.2.4.1.2 Subjects

- 3B25 (Impendance and Dispersion)

4.2.4.1.3 Diagram

Diagram

4.2.4.1.4 Equipment

- 1 section of slow wave demonstrator
- 1 section of fast wave demonstrator
- 1 tapered section of wave demonstrator
- 1 dashpot

4.2.4.1.5 Presentation

The slow wave demonstrator is coupled to the fast wave demonstrator. The dashpot is fixed to the end of the fast wave demonstrator. At the beginning of the slow wave demonstrator a sharp up and down disturbance is given by hand and a crest travels along the wave demonstrator. At the point of coupling, it can be observed that a significant portion of the crest is reflected and another part is transmitted to the fast wave demonstrator. If the tapered section is coupled between the slow and fast wave demonstrator, it can be shown that there is almost no reflection at the boundary.

4.2.4.1.6 Explanation

The tapered section serves as an impedance matching transformer.

4.2.4.1.7 Sources

- PASCO scientific, Instruction Manual for the PASCO scientific Model SE-9600, 9601, 9602, and 9603

4.2.5 3B40 Doppler

4.2.5.1 01 Doppler

4.2.5.1.1 Aim

To present the acoustic Doppler effect, using beats produced by a swinging speaker.

4.2.5.1.2 Subjects

- 3B40 (Doppler Effect)

4.2.5.1.3 Diagram

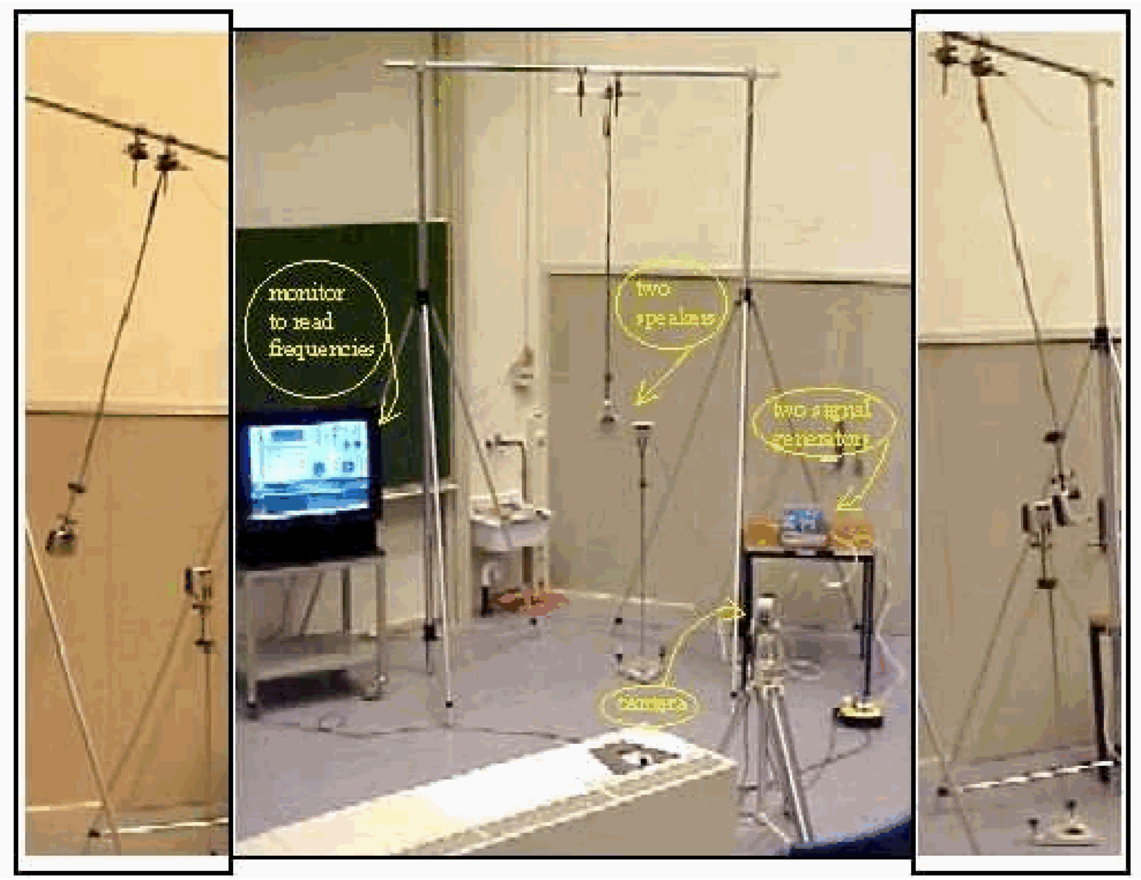


Figure 4.71: .

4.2.5.1.4 Equipment

- Two loudspeakers, one standing, the other swinging (see Diagram).
- Two signal generators, with high frequency stability.
- Two switches (see Figure 2).
- Camera.
- Monitor with large screen.

4.2.5.1.5 Presentation

The two speakers are mounted as shown in Diagram. One of the speakers is mounted as a pendulum with an arm of around 1.5 m. In the beginning the pendulum is not moving.

Both signal generators are set at 1000 Hz (all four digits are significant!). Switching from one generator to the other (see the switches in Figure 2), both amplitudes are set in such a way that both speakers produce the same loudness (switching from one to the other no difference is heard).

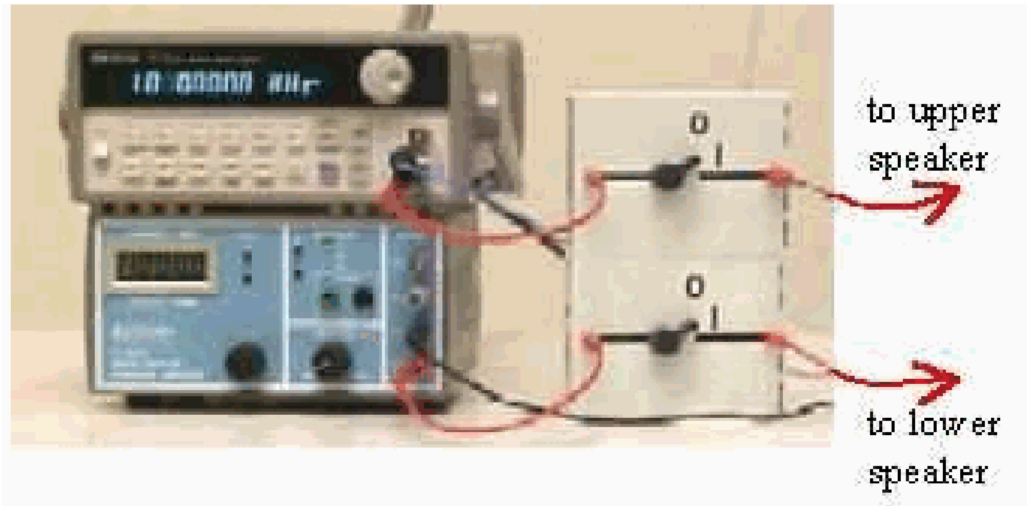


Figure 4.72: .

4.2.5.1.5.1 Beats

Then the phenomenon of beats is demonstrated, because this is used as a means of observing the Doppler effect:

One of the signal generators is set at 1001 Hz and a beat of 1 Hz is observed;

The signal generator is set at 999 Hz and again a beat of 1 Hz is heard;

The signal generator is set at 998 Hz and a beat of 2 Hz is heard;

The signal generator is set at 1002 Hz and again a beat of 2 Hz is heard; Etc.

Notice that it is not possible to distinguish between the two speakers which of the two has the higher (or lower) frequency, and whether the beat heard is caused by an increase or decrease in frequency of one of the generators.

4.2.5.1.5.2 Same frequency

Both generators are set again at 1000 Hz. The speaker mounted as a pendulum is given an amplitude of around 1 meter. Beats are heard by the audience when the speaker moves towards the audience and also when it moves away from the audience. Both beats are the same, so it is not possible to say that the frequency coming from the moving speaker is increasing or lowering in relation to its forward or backward motion. We can only observe that the sound coming from the moving speaker has changed by a couple of Hz.

4.2.5.1.5.3 Difference in frequency

The pendulum speaker is at rest. Its frequency is set at 1005 Hz. We hear a beat of 5 Hz. Then the pendulum is made swinging. The audience hears that the beat frequency increases when the speaker swings towards them and that the beats almost disappear when the speaker moves away from them.

While still swinging we change that frequency to 995 Hz and now almost no beats are heard when the pendulum swings towards the audience and a high beat frequency is heard when the pendulum moves backwards.

4.2.5.1.6 Explanation

4.2.5.1.6.1 Beats

The beat frequency is just the difference in frequency of the two waves: $f_1 - f_2$.

4.2.5.1.6.2 Doppler

The shift to f_R in the observed frequency, of a wave send with a frequency f_s as result of relative motion, is $f_R = f_s \frac{1}{1-\frac{v_s}{c}\cos\theta}$ (see Figure 3).

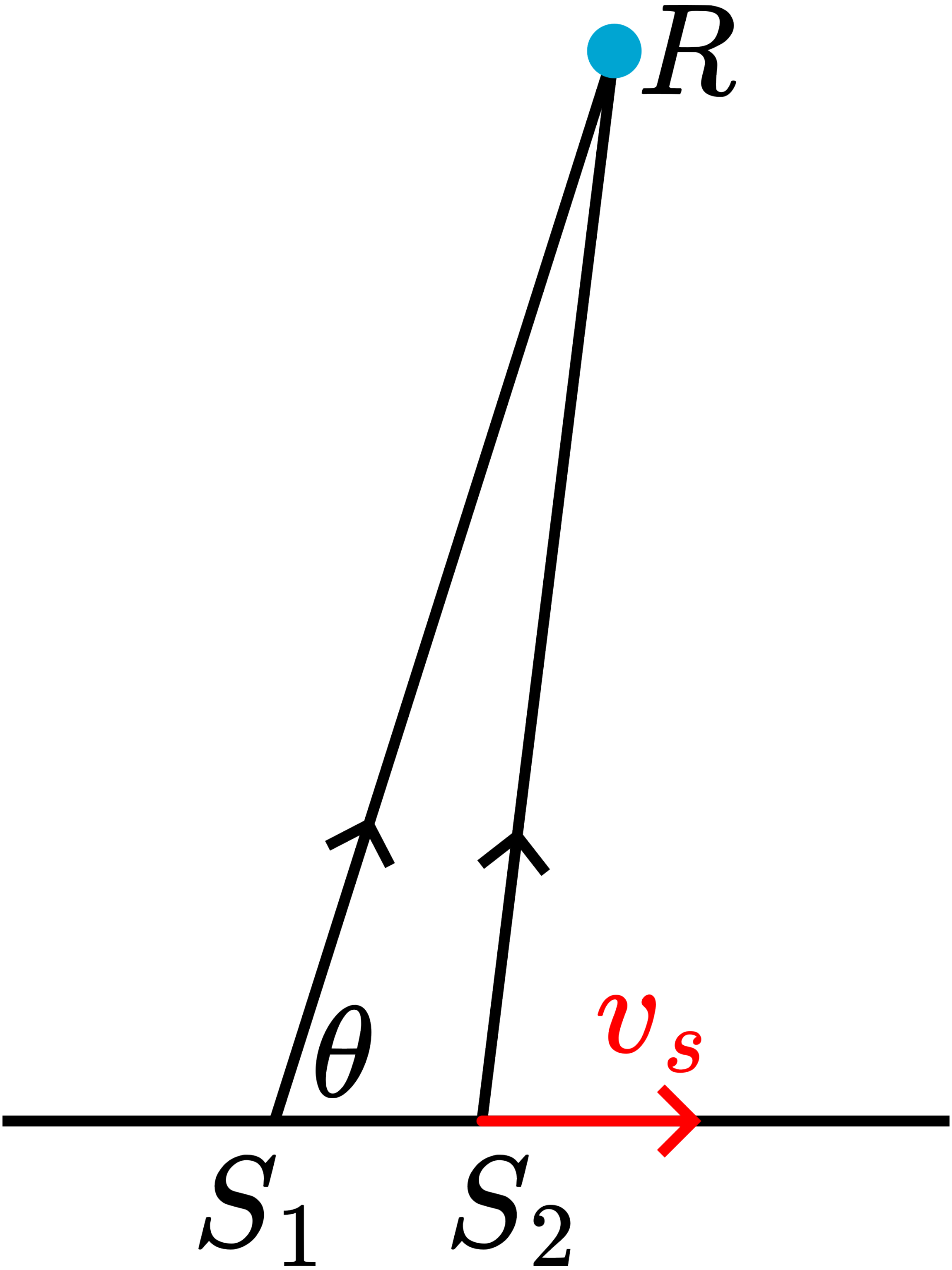


Figure 4.73: .

With $\theta = O$ (moving towards the audience) this reduces to: $f_R = f_s \frac{1}{1-\frac{v_s}{c}}$, showing an increase in frequency, and when moving away from the audience, $\theta = \pi$ the formula reduces to $f_R = f_s \frac{1}{1+\frac{v_s}{c}}$, showing a decrease in frequency.

4.2.5.1.6.3 Same frequency

The pendulum, having a length of around 1.5 m and given an amplitude of around 1 m, will have an average speed of around 2 m/sec. When the speed of sound cequals 340 m/sec, a frequency of 1000 Hz changes to 1005.92 Hz when it approaches the audience and to 994.15 Hz when it moves away from the audience. In beatfrequency this gives in both cases the value of around 5.9 Hz. So no difference is heard between the two movements.

4.2.5.1.6.4 Difference in frequency

When the swinging speaker has a frequency of 1005 Hz, it will be heard by an audience when it approaches them with 2 m/sec, as 1011 Hz (producing a beat of 11 Hz) and when it moves away from them as 999.1 Hz (producing a beat of .9 Hz, so a very slow beat is heard).

When the swinging speaker is set at 995 Hz the situation is just the opposite: slow beat when the speaker approaches the audience, and fast when it moves away.

So, observing the beatfrequency we can in this way observe that the frequency increases as the speaker approaches you and lowers when the speaker moves away

4.2.5.1.7 Remarks

- Contrary to the picture in Diagram we mount the two speakers above each other. The same is done with the two signal generators (see Figure 2). So, when the audience sees the two frequency displays of the two generators on the monitor screen, they know which frequency belongs to which speaker.
- Calculating the frequency by means of $f_R = f_s \frac{1}{1-\frac{v_s}{c}}$ or $f_R = f_s \frac{1}{1+\frac{V_s}{c}}$ can be done quicker by means of $f_R = f_s \frac{1}{1-\frac{v_s}{c}} = f_s \frac{1}{1+\frac{v_s}{c}}$ or

$$f_R = f_s \frac{1}{1+\frac{v_s}{c}} = f_s \left(1 - \frac{v_s}{c}\right), because v_s << c \tag{4.11}$$

4.2.5.1.8 Video Rhett Allain

Extra demo to illustrate the Doppler Effect.

(a)

(b)

Figure 319: :align: center - Scan the QR code or click here to go to the video.

4.2.5.1.9 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 430-435
- McComb,W.D., Dynamics and Relativity, pag. 99-101
- Meiners, Harry F., Physics demonstration experiments, part I, pag. 513-514

4.3 3C Acoustics

4.3.1 3C50 Wave Analysis and Synthesis

5. Thermodynamics

5.1 4A Thermal Properties of Matter

5.1.1 4A10 Thermometry

5.1.1.1 01 Constant Volume Gas Thermometer

5.1.1.1.1 Aim

To show how the ideal gas temperature scale is defined.

5.1.1.1.2 Subjects

- 4A10 (Thermometry)

5.1.1.1.3 Diagram

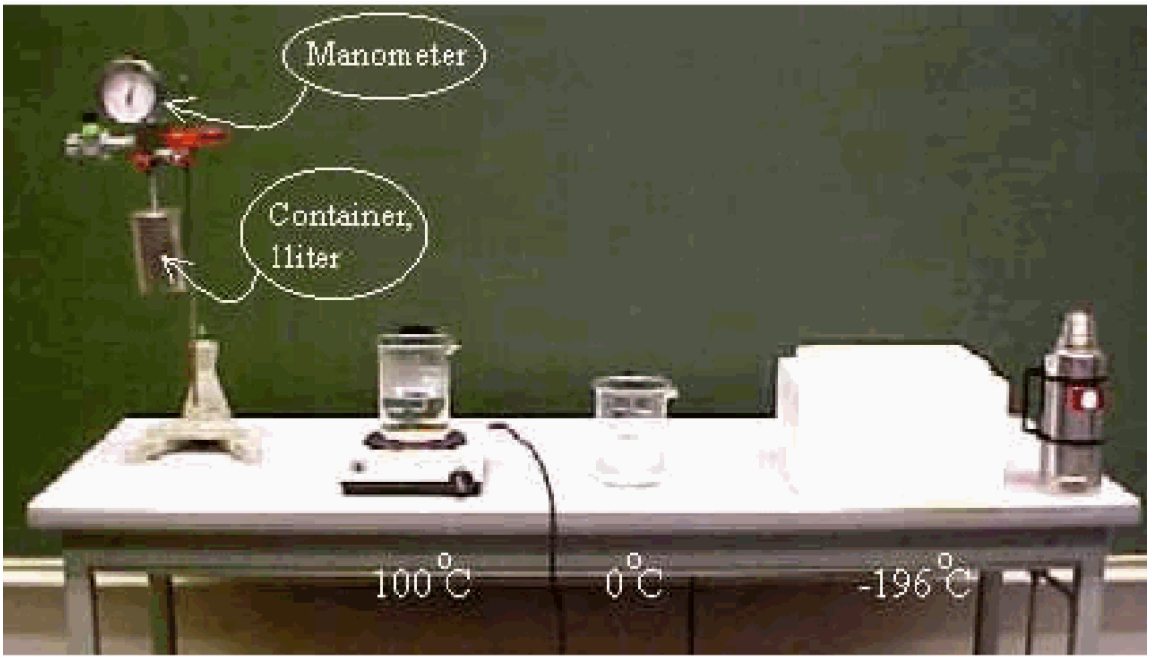


Figure 5.1: .

5.1.1.1.4 Equipment

- One liter container, filled with H_2 and a pressure-meter mounted to it.
- Clamping material.
- Glass beaker, 2 liter, filled with boiling water.
- Hot plate.
- Glass beaker, 2 liter, filled with ice-water.
- Polystyrene box that can be filled with liquid notrogen.
- Prepared pT-graph on overhead sheet (x-axis: $+100^{\circ}$C to -300°C; y-axis: 0 to 1.5 bar).

5.1.1.1.5 Presentation

First, the container is dipped into the beaker with ice-water. The pressure reduces and after settling, the pressure is read. Then the container is immersed into the glass beaker with boiling water. The pressure rises and settles after some time: the pressure is read.

Finally, the container is placed in the polystyrene box and then liquid nitrogen is poured into it. While the container cools down the liquid nitrogen boils vigorously, quieting when the boiling point of the liquid nitrogen is reached. Then the pressure is read. The three measured points are fitted in the graph on the overhead sheet and it can be observed that the three measured points show a linear relationship, intersecting the T-axis at around $-270°C$.

5.1.1.1.6 Explanation

The product of pressure and volume of a gas depends strongly on the temperature of that gas. So pressure or volume can be used as a thermometric quantity. In this demonstration pressure is used as such and V is kept constant (one liter). So we speak of a constant volume gas thermometer. $\mathrm{pV} = \mathrm{nRT}$, making $\mathrm{T} = (\mathrm{V}/\mathrm{RT})\mathrm{p}$, and so an appropriate temperature scale is defined as $\mathrm{T} = \mathrm{Ap}$. For calibration only one constant is needed now. So when we measure pressure at two temperatures and draw a straight line between them we can read from this graph the temperature corresponding to any other pressure $(T_2/T_1 = p_2/\mathrm{p}_1)$. Extrapolating this graph, we see that there is a hypothetical temperature $(-273, 15°\mathrm{C})$ at which the pressure would become zero. This extrapolated zero-pressure temperature is used as the basis for a temperature scale: p is directly proportional to this Kelvin temperature (see Figure 2)

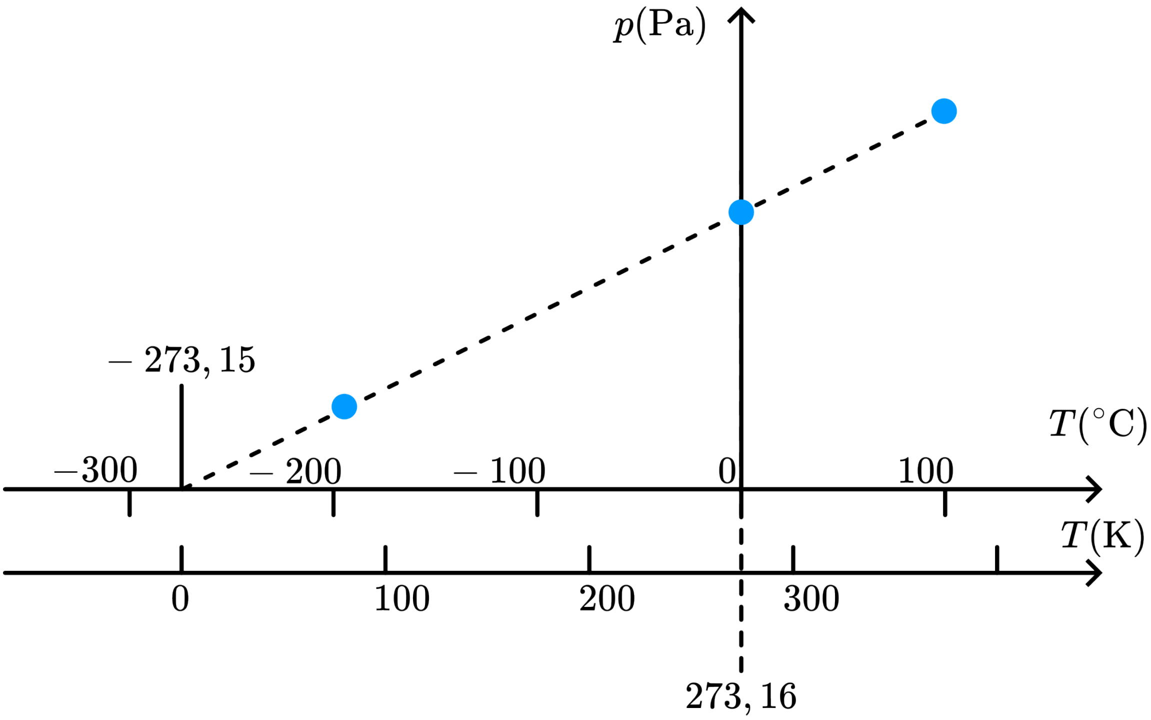


Figure 5.2: .

To complete the definition of T one point of the graph is specified. For this the triple point of water is chosen. This occurs at $0.01°\mathrm{C}$ and this point is defined as having the value 273.16 K (see Figure 2).

5.1.1.1.7 Remarks

- Instead of the beaker with ice-water we sometimes use the room temperature as a point of measurement. Then we start the measurement with this point and so we save time in doing the demonstration.

5.1.1.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 263-265 and 277
- Young, H.D. and Freeman, R.A., University Physics, pag. 463-464

5.1.1.2 02 Inverted Thermometer

5.1.1.2.1 Aim

To show that a liquid thermometer is based on the difference between expansion coefficients.

5.1.1.2.2 Subjects

- 4A10 (Thermometry)

5.1.1.2.3 Diagram

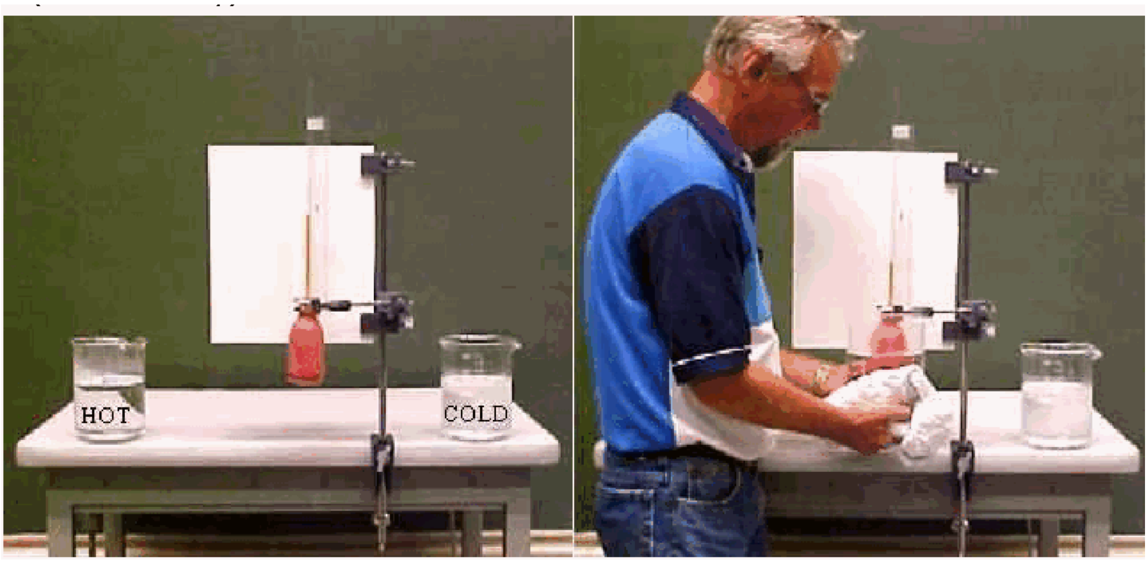


Figure 5.3: .

5.1.1.2.4 Equipment

- Bottle, 250 ml, polythene.
- Glass tube, $d = 5$ mm, $l = 40$ cm, tightly fitted to the bottle.
- mm-scale, stuck to glass tube.
- Red ink to color the water.
- Clamping material.
- Two glass beakers, 2 liter, one filled with hot water, the other with ice-water.
- Video camera and projector to project the image to a large audience.

5.1.1.2.5 Presentation

This thermometer is based on thermal expansion as basis of a scale of temperature. Students see the red colored water in the bottle that will be used for this purpose. To calibrate this thermometer we have a container with hot water and one with ice-water. The container with hot water is taken and held such that the bottle with red water dips in it. Immediately the level of the red water sinks dramatically. Students will be puzzled, because they expect a simple (almost dull) demonstration and now something contradicting their expectation happens. When the bottle with red liquid dips into the ice-water, the level of the thermometer rises.

5.1.1.2.6 Explanation

Liquid thermometers are based on the difference between the expansion coefficients of the liquid and the container holding the liquid. Usually the expansion coefficient of the liquid is higher than that of the material the container is made of, but when using polythene it is just the opposite (water: $0.21 \times 10^{-3} K^{-1}$; polythene: $0.54 \times 10^{-3} K^{-1}$). What we see is in fact a transition effect: The polythene bottle rises quickly in temperature, so the water level goes down, but when we take enough time the water will rise again because the red water heats up slowly. Also a glass container shows this transition effect, but so much less than when using polythene (expansion coefficient of glass: $0.024 \times 10^{-3} K^{-1}$).

5.1.1.2.7 Remarks

- The result shown to the students is not a real thermometric quantity, since there is not a thermal equilibrium during the demonstration.
- Fahrenheit encountered the thermometric effect of the glass containing the liquid when he accidentally applied different sorts of glass.

5.1.1.2.8 Video Rhett Allain

(a)

(b)

Figure 323: :align: center - Scan the QR code or click here to go to the video.

5.1.1.2.9 Sources

- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 262-263 and 272-273

5.2 4B Heat and the First Law

5.2.1 4B10 Heat Capacity and Specific Heat

5.2.1.1 01 Joule's Experiment

5.2.1.1.1 Aim

To show the conversion of mechanical energy into heat (and its proportionality with temperature).

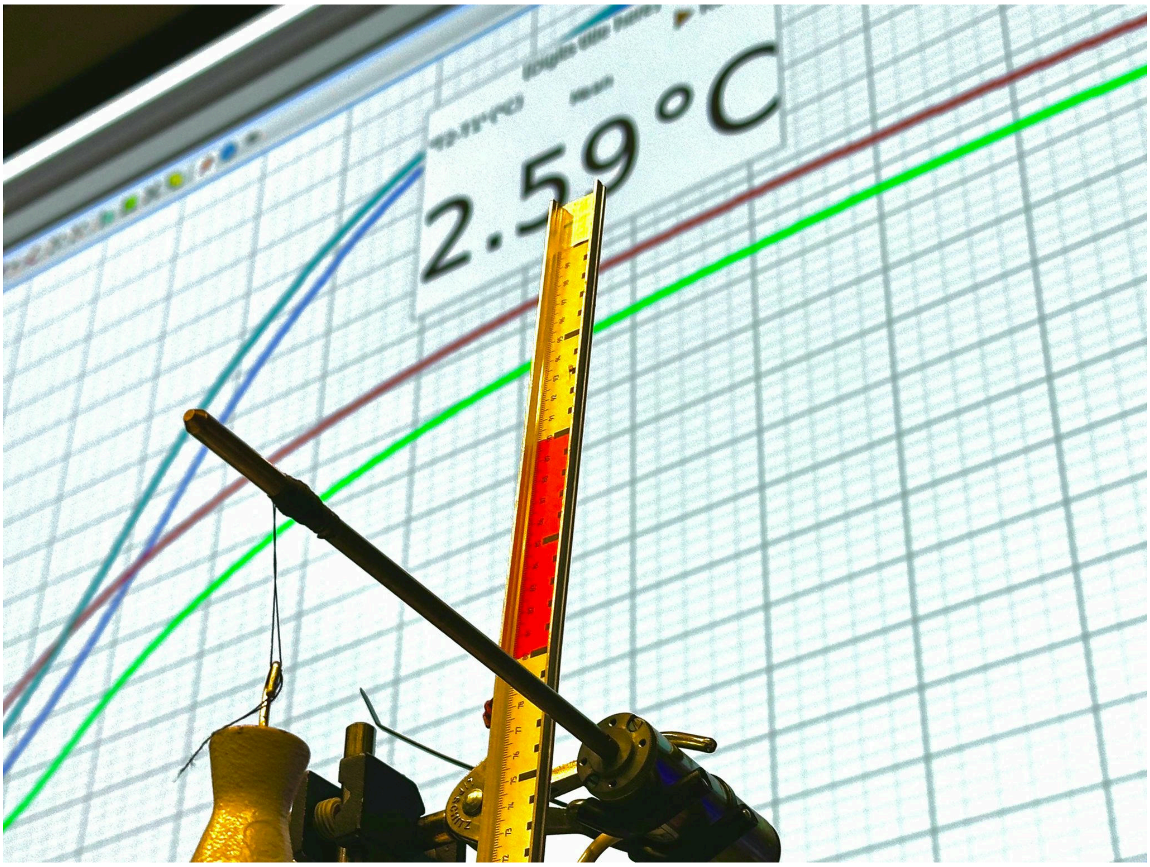


Figure 5.7: .

5.2.1.1.2 Subjects

- 4B10 (Heat Capacity and Specific Heat)
- 4B60 (Mechanical Equivalent of Heat)

5.2.1.1.3 Diagram

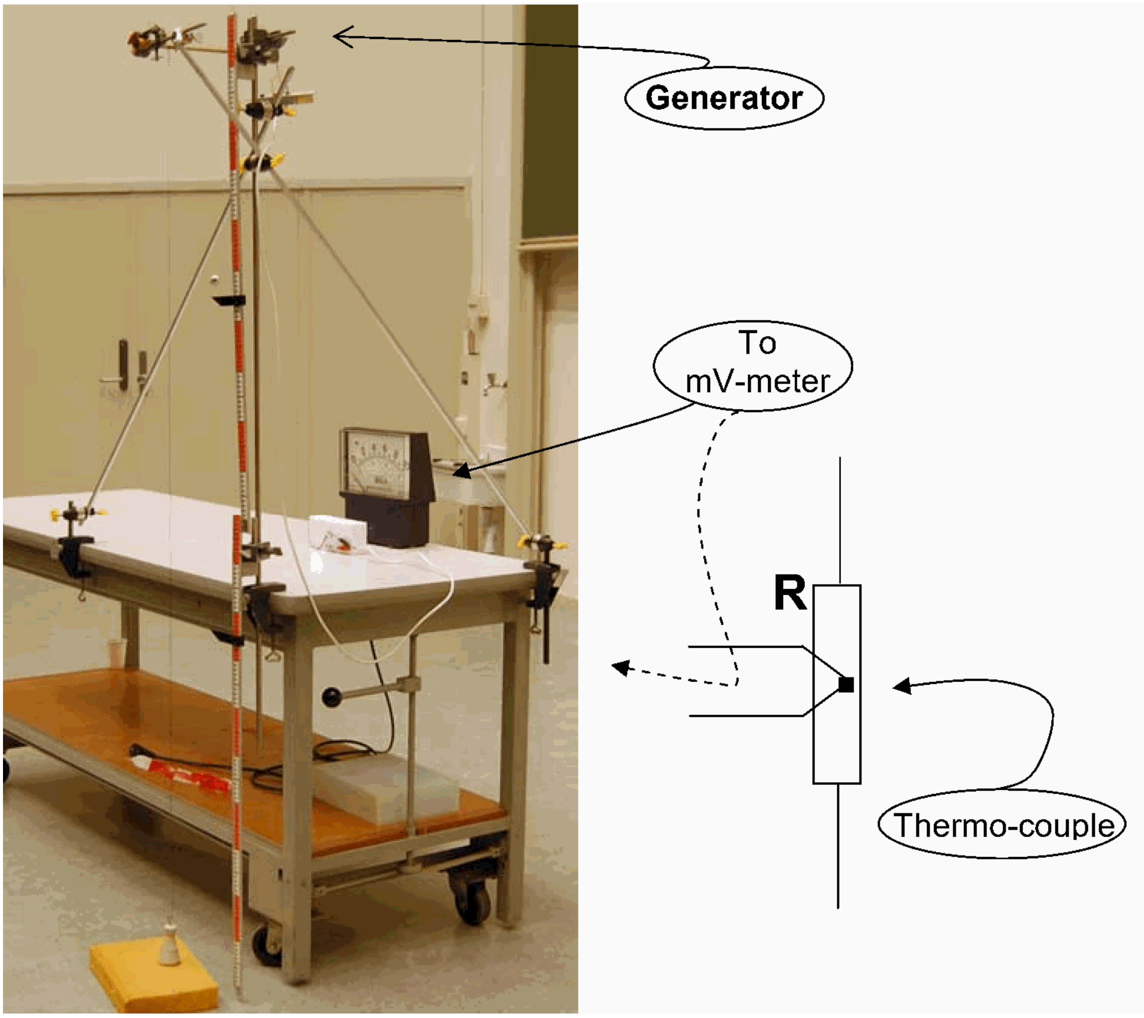


Figure 5.8: .

5.2.1.1.4 Equipment

- Electric motor used as generator.
- Resistor, with thermocouple attached to it.
- mV-meter.
- Mass of 0.5 kg, fixed to the axis of the generator by a strong piece of rope.
- Piece of foam rubber, to “catch” the falling mass.
- Two rulers, 1 m each.
- Two cursors on each ruler.

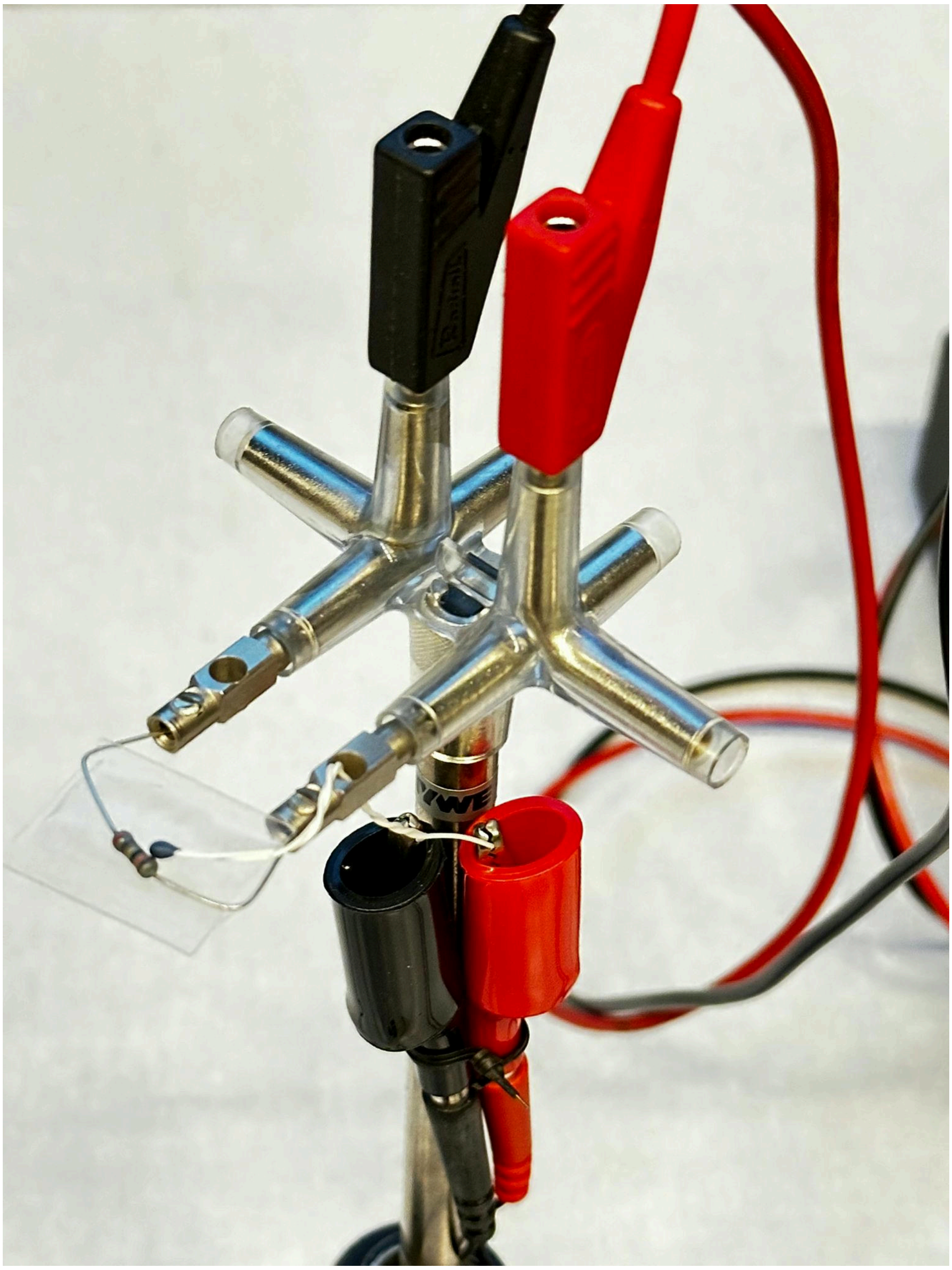


Figure 5.9: .

5.2.1.1.5 Presentation

Set up the equipment as shown in Diagram. Explain the set-up to the students and show that the thermocouple that is fixed on the resistor R, measures temperature, by touching the thermocouple with your fingers: the mV-meter shows a deflection. 1. Disconnect the generator from the resistance R. By turning the shaft with your hands the mass is lifted .75 m above the ground. Then let it go. It falls with a high speed on the ground (almost free fall).

2. By turning the shaft, the mass is lifted again . 75 m above the ground (position of cursor). The generator is connected to the resistance R. Let it go again. It falls slower towards the ground now. Almost immediately the mV-meter (temperature meter) shows a rise in temperature. Read its highest value before it shows the cooling down of the resistor.

3. Lift the mass to a height of 1.5 m above the ground and let it go. The measured temperature-rise will be double the value we measured in the first . 75 m-experiment. We conclude a linear relationship between mechanical work and temperature rise (or heat).

5.2.1.1.6 Explanation

Mechanical work is transformed into heat in the system (See Figure 4 1). Part of that heat is dissipated in the resistor.

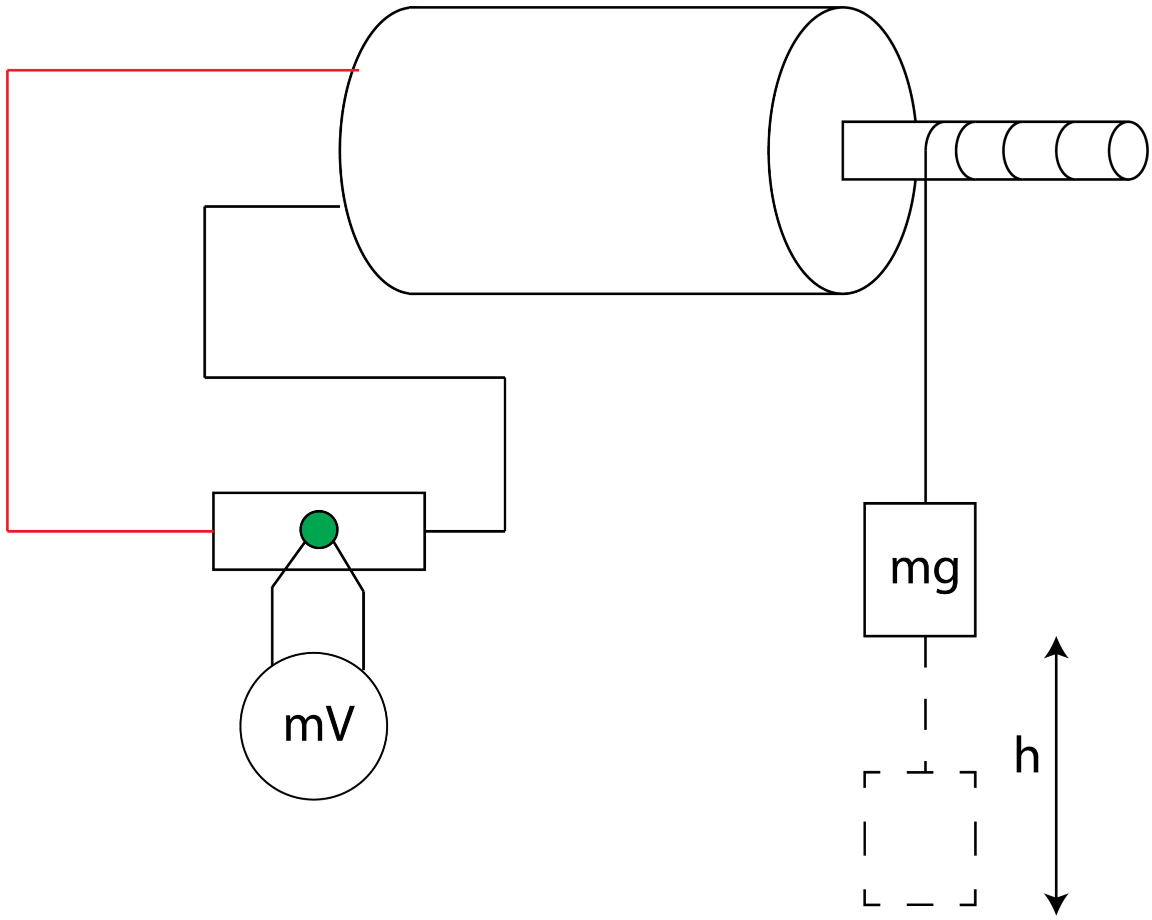


Figure 5.10: .

Doubling the mechanical energy shows that the temperature rise is doubling. So this experiment shows that the change in internal energy is directly proportional to the corresponding change in temperature.

5.2.1.1.7 Remarks

- The mass that drives the system has to go down relatively slow, otherwise the kinetic energy of this mass is too large compared to the energy that enters the system.
- The temperature rise of the system is measured in the resistor (part of the total system). Of course there are losses in all transformations involved. We suppose that the efficiencies are constant for different values of h, then $\Delta T \propto \Delta U$.
- When recording the thermocouple mV-reading we find a figure as shown in Figure 5

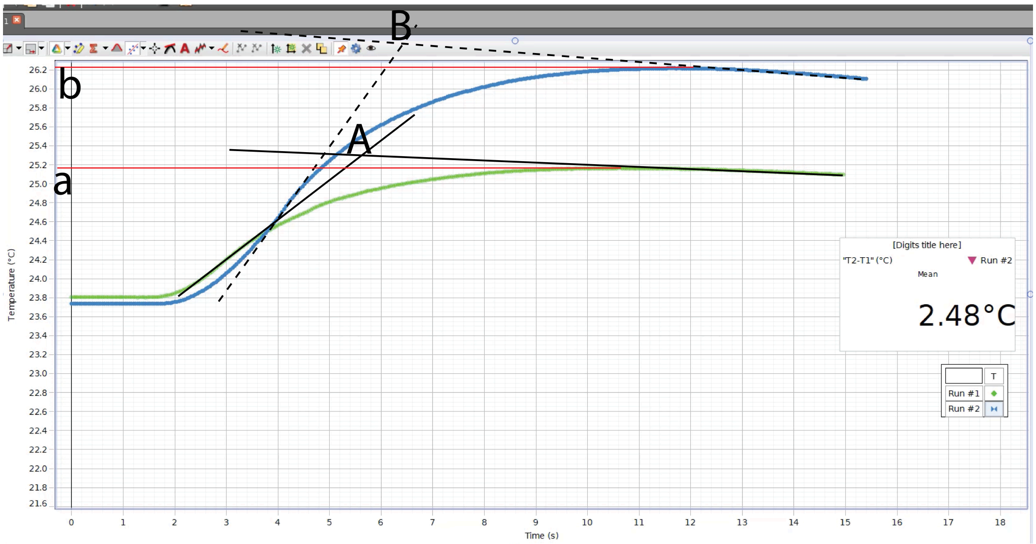


Figure 5.11: .

- The two slopes at the beginning of the temperature-rise show the difference in the amounts of heat of the two situations. The end-temperature reached for an ideally isolated resistor can be found by extrapolating the cooling down-lines to these slopes. It can be seen that the ratio between the temperature-readings A and B correspond more or less with the ratio of the highest temperatures (a and b) reached in the real experiment. (Good enough for a demonstration.)
- In the set-up a power supply and a two-way switch can be included in such a way that you can drive the generator as a motor to aid in lifting the weight and winding the rope around the axis.

5.2.1.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 260-262
- Young, H.D. and Freeman, R.A., University Physics, pag. 470-471

5.2.2 4B20 Convection

5.2.2.1 01 Cooling by Insulation

5.2.2.1.1 Aim

To show a counterintuitve demonstration on thermal insulation. We compare the heating up of an insulated - and bare copper wire.

5.2.2.1.2 Subjects

- 4B20 (Convection) 4B30 (Conduction) 4B40 (Radiation)

5.2.2.1.3 Diagram

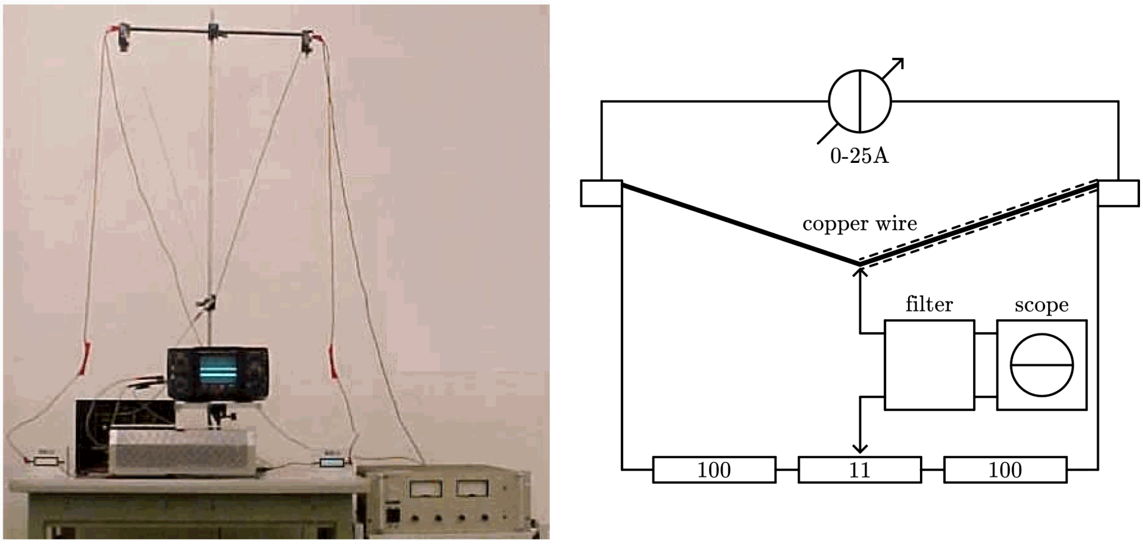


Figure 5.12: .

5.2.2.1.4 Equipment

- 1.5 m of copper wire, $d = 0.7$ mm (as used in house wiring) half of its length stripped of its insulation.
- Two resistors of 100Ω.
- Rheostat, 11Ω.
- Adjustable current source, 0 to 25 A.
- Oscilloscope.
- Lowpass LC-filter

5.2.2.1.5 Presentation

The presentation is set up as shown in the diagram. The circuit is a Wheatstone bridge. Central part is the copper wire, half of its insulation removed. The oscilloscope is used as the balance detector in the bridge (the second not used scope-channel provides the zero reference line). 5 A DC is made flowing through the bridge (flowing almost completely through the copper wire with its low resistance). In this situation the copper wire heats up only a little. Students can observe that the bridge can be balanced by means of the rheostat.

The current is increased to 25 A. The oscilloscope shows that the Wheatstone bridge becomes unbalanced: the line on the screen displaces itself slowly from its zero reference line (stable after about half a minute). This unbalance must be due to the temperature-difference between the insulated - and bare copper wire. Students are asked which of the two wires will have the highest temperature. (Our experience is that almost all the students intuitively guess that the insulated wire has the highest temperature.) Now the bridge is balanced by means of the rheostat. The new balance of the bridge shows clearly that the bare copper wire has increased most its resistance value, so this wire has a higher temperature than the insulated wire!

5.2.2.1.6 Explanation

See Figure 2A. T_1 is the temperature of the hotter surface and T_o the temperature of the colder surroundings.

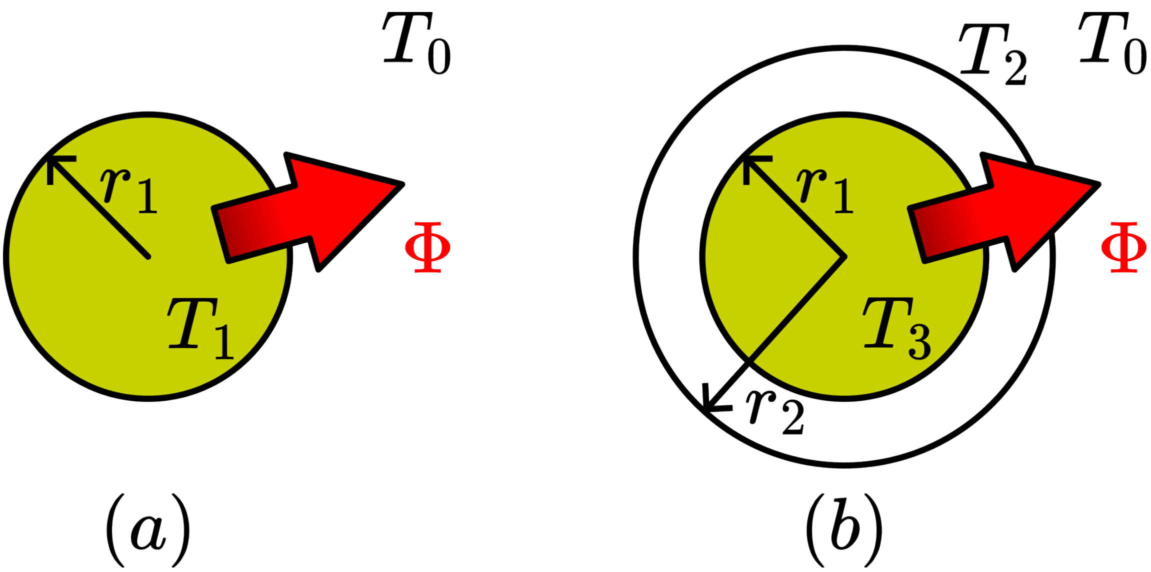


Figure 5.13: .

The rate of flow of heat (Φ) transferred through a surface (A) from T_1 to the surroundings with temperature T_o is given by $\Phi = \alpha A(T_1 - T_0)$ (α is the heat transfer coefficient accounting for convective and radiative heat transfer to the surroundings). This can also be written as $T_1 - T_0 = \Phi \frac{1}{\alpha A} \cdot \Phi = \alpha A(T_1 - T_0)$ is determined by the electric power dissipated in the wire. $\frac{1}{\alpha A} = R_{th}$ is the so called thermal resistance. The higher R_{th}, the higher the temperature of the wire (T_1) will be. In the situation of the bare copper wire $R_{th} = \frac{1}{\alpha 2\pi r_1 L}$ (L being the length of the wire).

In the situation of the insulated copper wire (see Figure 2B) R_{th} is made up of two thermal resistances in series: one resistance opposing the conduction through the insulation (R_{th1}) and the second opposing the transfer from the outer surface to the surrounding air (R_{th2}). The problem of conduction through a cilindrical wall is treated in many textbooks:

$R_{th1} = \frac{1}{2\pi L\lambda} \ln \frac{r_2}{r_1}$. The total thermal resistance of the insulated copper wire is then $\left(\frac{1}{2\pi L\lambda} \ln \frac{r_2}{r_1}\right) + \left(\frac{1}{\alpha 2\pi r_2 L}\right)$.

In our demonstration the heat flow per second (Φ) is the same for the bare and the insulated wire. Therefore, the wire with the highest thermal resistance will have the highest temperature.

So we compare R_{th} with $R_{th1} + R_{th2}$;so we compare $R_{th} = \frac{1}{\alpha 2\pi r_1 L}$ with $\left(\frac{1}{2\pi L\lambda} \ln \frac{r_2}{r_1}\right) + \left(\frac{1}{\alpha 2\pi r_2 L}\right)$; so we can compare $\frac{1}{\alpha r_1}$ with $\left(\frac{1}{\lambda} \ln \frac{r_2}{r_1}\right) + \left(\frac{1}{\alpha r_2}\right)$. With the values of $r_1 = 0.7\ \mathrm{mm}$; $r_2 = 1.4\ \mathrm{mm}$; $\alpha = 6\ \mathrm{W/m^2} K$ (surface in contact with air at rest); $\lambda = 0.2\ \mathrm{W/mK}$ (thermal conductivity of pvc) it is easily calculated that the bare copper wire has a higher thermal resistance to its surroundings than the insulated wire. The increase in surface in insulating the wire has more effect on lowering the thermal resistance then the insulation itself has in increasing it.

5.2.2.1.7 Remarks

- Students should understand Wheatstone's bridge before showing this demonstration.

- Do not exceed the current above 25 A because of excessive heating of wires.
- We use an oscilloscope as a balance-detector because then the increasing unbalance during heating up is clearly visible by a large group.
- As rheostat we use a large slide resistance. With this slide resistance it is clearly visible in which direction the Wheatstone bridge is unbalanced when the copper wire heats up.
- The circuit has a lot of noise induced into it, originating form the magnetic flux captured by the unavoidable large area of the wire loops in the circuit. This broadens the line on the screen of the oscilloscope. That's why we use a low-pass LC filter at the input of the oscilloscope (see Figure 3).

Figure 5.14: .

- Because we use dc in this demonstration, thermal emf's can be a nuisance. However we experienced that above currents of 1 A in the circuit their effects are negligible.

5.2.2.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 268-270

5.2.3 4B30 Conduction

5.2.3.1 01 Cooling by Insulation

5.2.3.1.1 Aim

To show a counterintuitve demonstration on thermal insulation. We compare the heating up of an insulated - and bare copper wire.

5.2.3.1.2 Subjects

- 4B20 (Convection) 4B30 (Conduction) 4B40 (Radiation)

5.2.3.1.3 Diagram

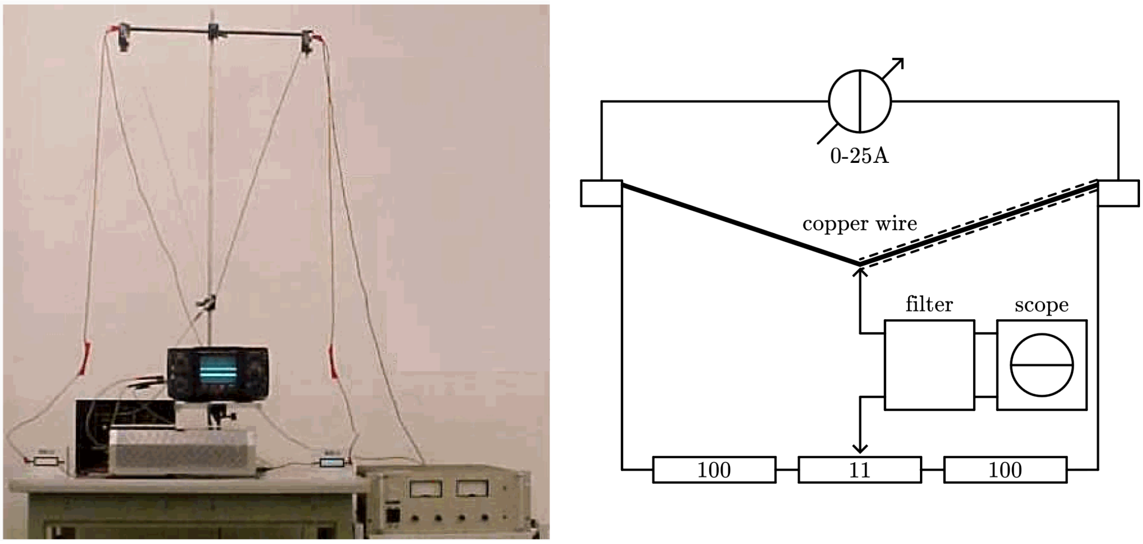


Figure 5.15: .

5.2.3.1.4 Equipment

- 1.5 m of copper wire, $d = 0.7$ mm (as used in house wiring) half of its length stripped of its insulation.
- Two resistors of 100Ω.
- Rheostat, 11Ω.
- Adjustable current source, 0 to 25 A.
- Oscilloscope.
- Lowpass LC-filter

5.2.3.1.5 Presentation

The presentation is set up as shown in the diagram. The circuit is a Wheatstone bridge. Central part is the copper wire, half of its insulation removed. The oscilloscope is used as the balance detector in the bridge (the second not used scope-channel provides the zero reference line). 5 A DC is made flowing through the bridge (flowing almost completely through the copper wire with its low resistance). In this situation the copper wire heats up only a little. Students can observe that the bridge can be balanced by means of the rheostat.

The current is increased to 25 A. The oscilloscope shows that the Wheatstone bridge becomes unbalanced: the line on the screen displaces itself slowly from its zero reference line (stable after about half a minute). This unbalance must be due to the temperature-difference between the insulated - and bare copper wire. Students are asked which of the two wires will have the highest temperature. (Our experience is that almost all the students intuitively guess that the insulated wire has the highest temperature.) Now the bridge is balanced by means of the rheostat. The new balance of the bridge shows clearly that the bare copper wire has increased most its resistance value, so this wire has a higher temperature than the insulated wire!

5.2.3.1.6 Explanation

See Figure 2A. T_1 is the temperature of the hotter surface and T_o the temperature of the colder surroundings.

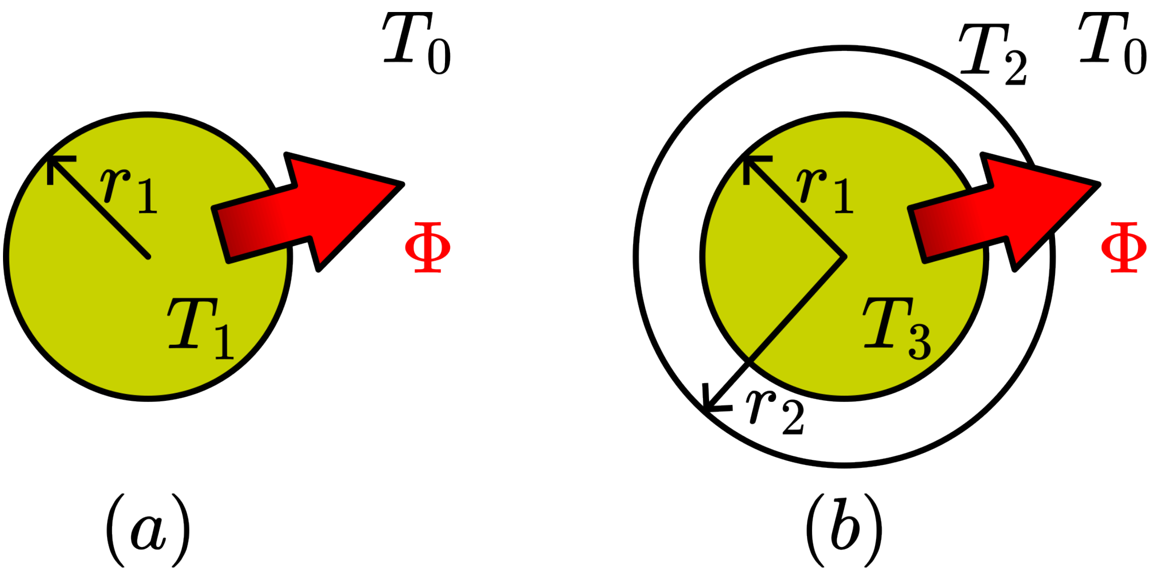


Figure 5.16: .

The rate of flow of heat (Φ) transferred through a surface (A) from T_1 to the surroundings with temperature T_o is given by $\Phi = \alpha A(T_1 - T_0)$ (α is the heat transfer coefficient accounting for convective and radiative heat transfer to the surroundings). This can also be written as $T_1 - T_0 = \Phi \frac{1}{\alpha A} \cdot \Phi = \alpha A(T_1 - T_0)$ is determined by the electric power dissipated in the wire. $\frac{1}{\alpha A} = R_{th}$ is the so called thermal resistance. The higher R_{th}, the higher the temperature of the wire (T_1) will be. In the situation of the bare copper wire $R_{th} = \frac{1}{\alpha 2\pi r_1 L}$ (L being the length of the wire).

In the situation of the insulated copper wire (see Figure 2B) R_{th} is made up of two thermal resistances in series: one resistance opposing the conduction through the insulation (R_{th1}) and the second opposing the transfer from the outer surface to the surrounding air (R_{th2}). The problem of conduction through a cilindrical wall is treated in many textbooks:

$R_{th1} = \frac{1}{2\pi L\lambda} \ln \frac{r_2}{r_1}$. The total thermal resistance of the insulated copper wire is then $\left(\frac{1}{2\pi L\lambda} \ln \frac{r_2}{r_1}\right) + \left(\frac{1}{\alpha 2\pi r_2 L}\right)$.

In our demonstration the heat flow per second (Φ) is the same for the bare and the insulated wire. Therefore, the wire with the highest thermal resistance will have the highest temperature.

So we compare R_{th} with $R_{th1} + R_{th2}$;so we compare $R_{th} = \frac{1}{\alpha 2\pi r_1 L}$ with $\left(\frac{1}{2\pi L\lambda} \ln \frac{r_2}{r_1}\right) + \left(\frac{1}{\alpha 2\pi r_2 L}\right)$; so we can compare $\frac{1}{\alpha r_1}$ with $\left(\frac{1}{\lambda} \ln \frac{r_2}{r_1}\right) + \left(\frac{1}{\alpha r_2}\right)$. With the values of $r_1 = 0.7\ \mathrm{mm}$; $r_2 = 1.4\ \mathrm{mm}$; $\alpha = 6\ \mathrm{W/m^2}K$ (surface in contact with air at rest); $\lambda = 0.2\ \mathrm{W/mK}$ (thermal conductivity of pvc) it is easily calculated that the bare copper wire has a higher thermal resistance to its surroundings than the insulated wire. The increase in surface in insulating the wire has more effect on lowering the thermal resistance then the insulation itself has in increasing it.

5.2.3.1.7 Remarks

- Students should understand Wheatstone's bridge before showing this demonstration.

- Do not exceed the current above 25 A because of excessive heating of wires.
- We use an oscilloscope as a balance-detector because then the increasing unbalance during heating up is clearly visible by a large group.
- As rheostat we use a large slide resistance. With this slide resistance it is clearly visible in which direction the Wheatstone bridge is unbalanced when the copper wire heats up.
- The circuit has a lot of noise induced into it, originating form the magnetic flux captured by the unavoidable large area of the wire loops in the circuit. This broadens the line on the screen of the oscilloscope. That's why we use a low-pass LC filter at the input of the oscilloscope (see Figure 3).

Figure 5.17: .

- Because we use dc in this demonstration, thermal emf's can be a nuisance. However we experienced that above currents of 1 A in the circuit their effects are negligible.

5.2.3.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 268-270

5.2.4 4B40 Radiation

5.2.4.1 02 Stefan-Boltzmann Law for Radiation

5.2.4.1.1 Aim

To show that the power radiated by an area is proportional to T4.

5.2.4.1.2 Subjects

- 4B40 (Radiation)

5.2.4.1.3 Diagram

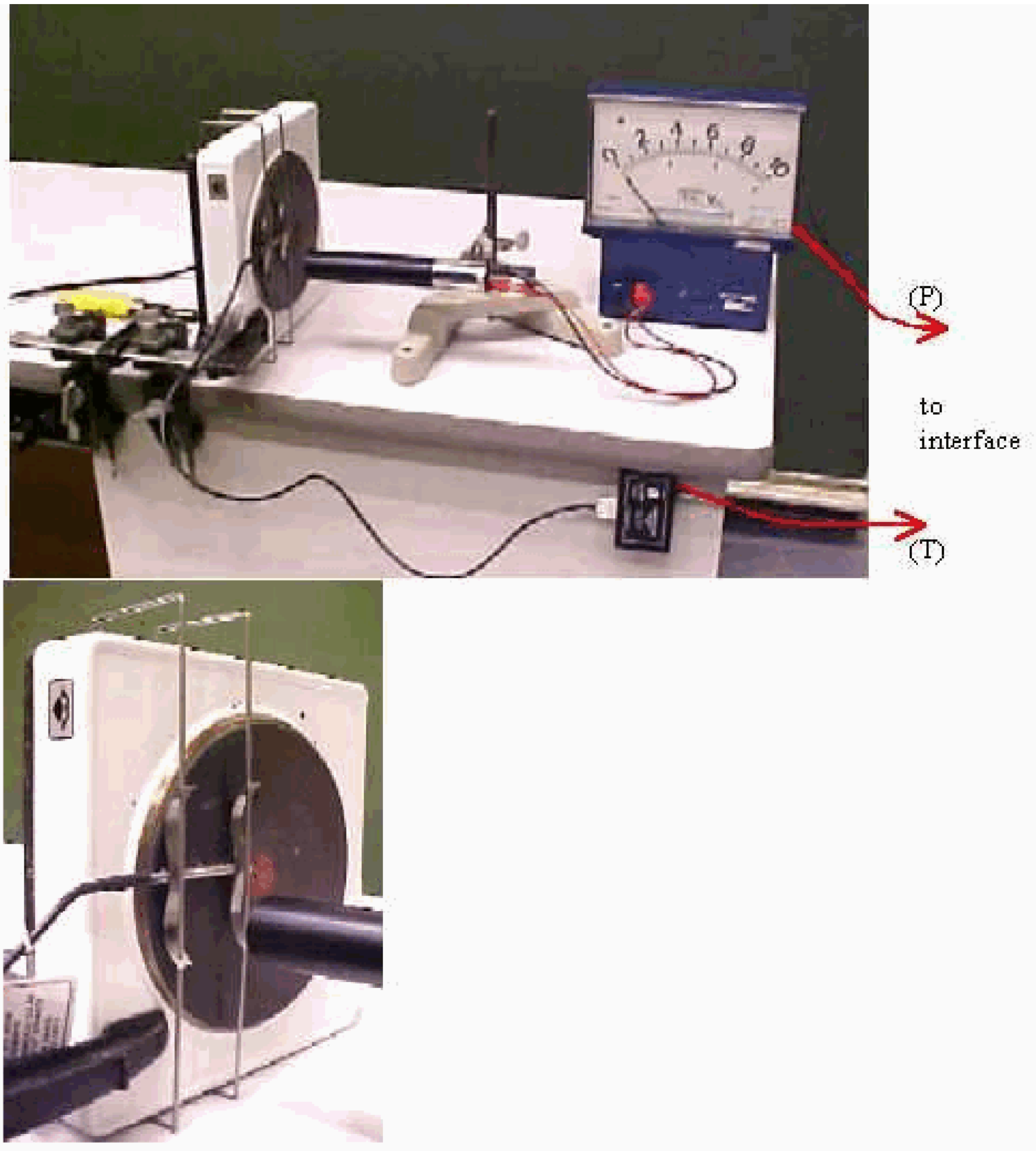


Figure 5.18: .

5.2.4.1.4 Equipment

- Electric hot plate.
- Radiation sensor (thermopile).
- Measuring amplifier.
- Temperature sensor.
- Heat-conducting compound.
- Interface and data-acquisition system (we use PASCO ScienceWorkshop).

- Projector to project monitor screen.

5.2.4.1.5 Presentation

5.2.4.1.5.1 Preparation.

The temperature sensor is pressed to the hot plate using the spring/clamp mechanism (see Diagram). There is heat-conducting compound between the temperature sensor and plate. The radiation sensor “looks” at an area close to the temperature ensor. The software of the data-acquisition system is prepared to measure, every second: radiation (P), as a voltage and temperature. Four graphs are displayed simultaneously on the monitorscreen: Radiation as a function of $T(K), T^3(\mathrm{~K}^3), T^4(\mathrm{~K}^4)$ and $T^5(\mathrm{~K}^5)$ respectively. Also a digital display reading temperature in $^{\circ}\mathrm{C}$ is added to the screen.

5.2.4.1.5.2 Presentation

The electric hot plate is switched on, ***on its lowest setting***. The digital temperature meter shows the rising temperature of the plate.

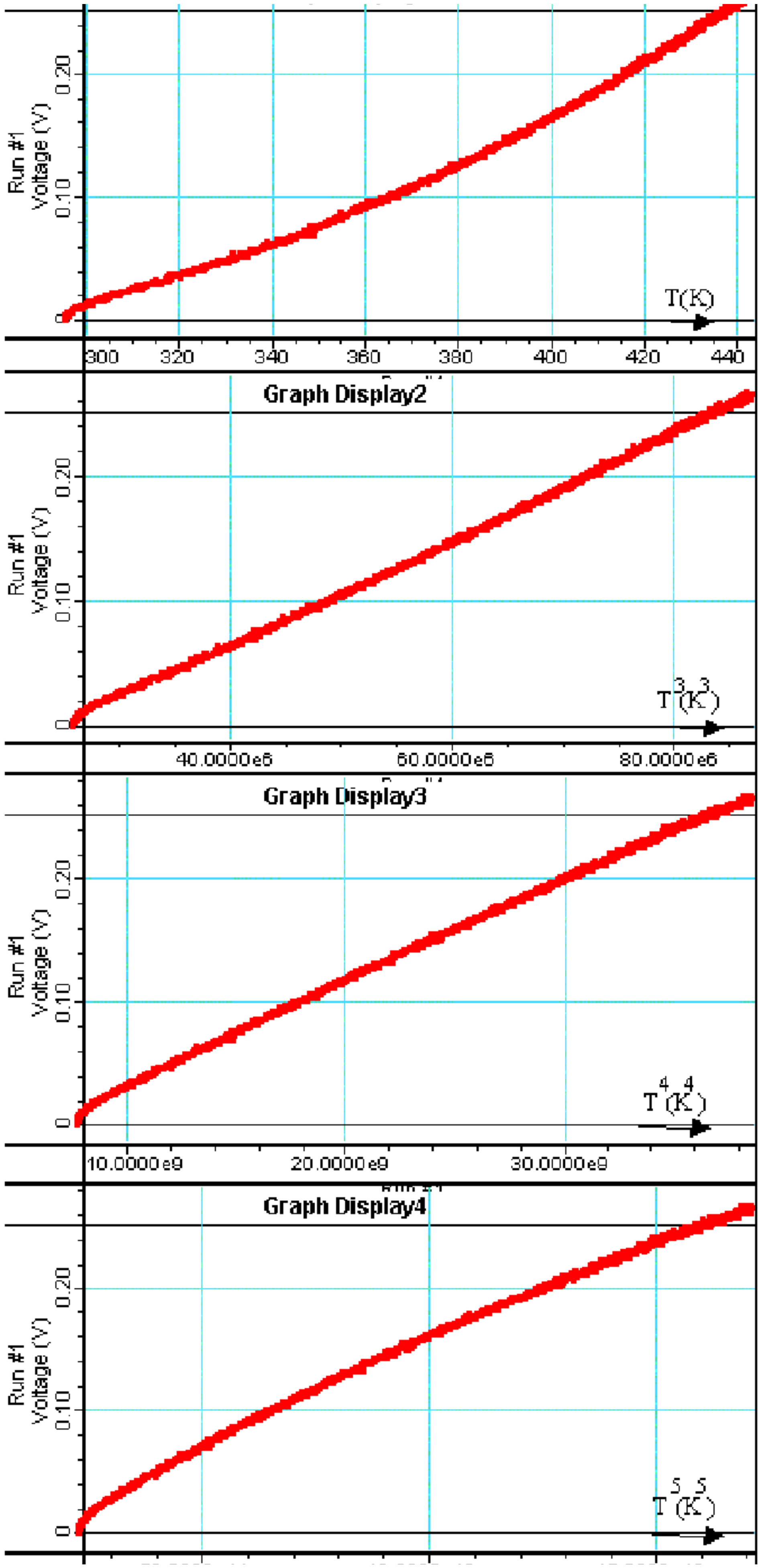

Run #1
Voltage (V)
0.20
0.10
0
T(K)
300
320
340
360
380
400
420
440
Graph Display2
Run #1
Voltage (V)
0.20
0.10
0
T3(K3)
40.0000e6
60.0000e6
80.0000e6
Graph Display3
Run #1
Voltage (V)
0.20
0.10
0
T4(K4)
10.0000e9
20.0000e9
30.0000e9
Graph Display4
Run #1
Voltage (V)
0.20
0.10
0
T5(K5)

Figure 5.19: .

As soon as the temperature of the plate reads about 30°C, the data-acquisition system is started to record temperature- and radiation measurements. Slowly temperature rises and the teacher can go on with his lecture. It takes about 30 minutes to reach a temperature of 150°C. So, near the end of the lecture the data-acquisition is stopped and the heating of the plate switched off. Studying the four graphs it is clear that the T^4-graph is the straightest line among the four (see Figure 2), so this is the best $P - T$ relationship. (T^3-graph "curves" upwards and T^5-graph "curves" downwards.)

5.2.4.1.6 Explanation

We can obtain the Stefan-Boltzmann radiation law by integrating Planck's radiation law over all λ.

5.2.4.1.7 Remarks

- Do not start measurements directly after switching on the hot plate. Heat capacity of the system makes that at the very beginning, temperatures in the system are not equally distributed. That's why we start measurements from 30°C on. (In Figure 2 you can see this "switching-on"-effect in the graph at the left-side of the vertical Voltage-axis.)

This is also the reason why the plate should heat up slowly, otherwise measured temperature and measured radiation are not related properly.

- The software also enables to apply a linear fit on the graphs recorded. This also shows that the T^4-graph has the closest approach to such a linear relationship (lowest chi').

5.2.4.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 270-272
- Young, H.D. and Freeman, R.A., University Physics, pag. 1256-1258

5.2.5 4B60 Mechanical Equivalent of Heat

5.2.5.1 02 Smashing

5.2.5.1.1 Aim

- To show an example of energy conversion.

5.2.5.1.2 Subjects

- 4B60 (Mechanical Equivalent of Heat)

5.2.5.1.3 Diagram

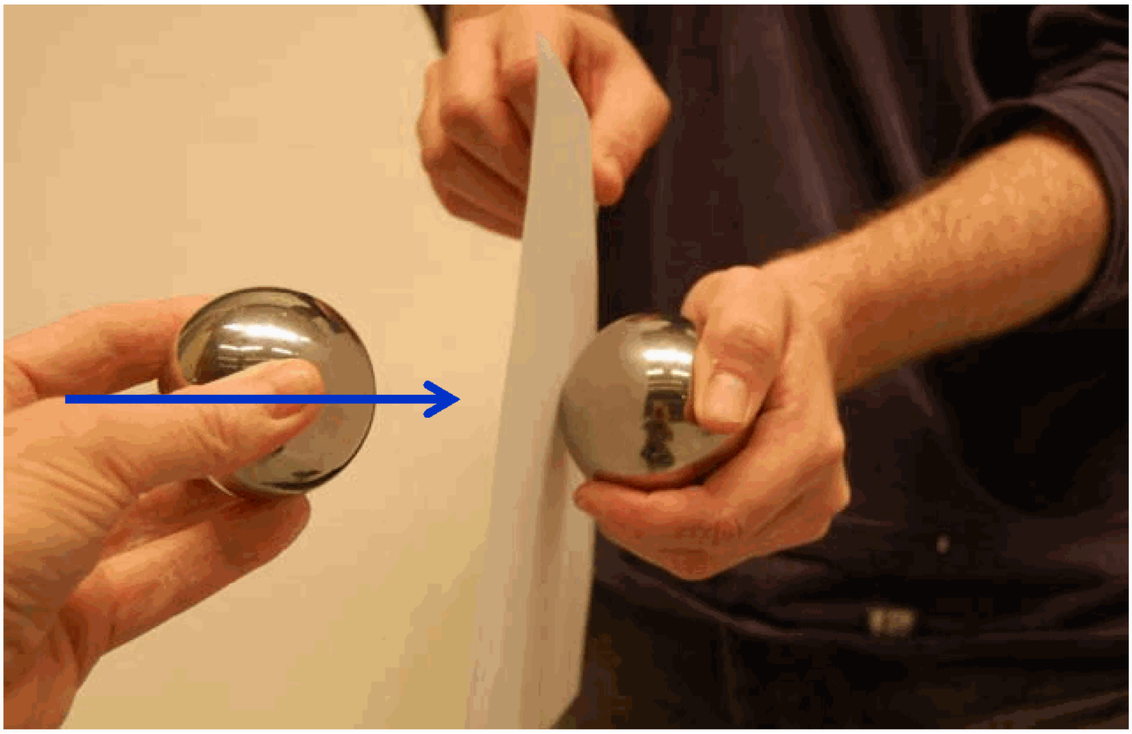


Figure 5.20: .

5.2.5.1.4 Equipment

- Two large chrome steel spheres (we use spheres with a diameter of 63 mm $(m \approx 1\ \text{kg})$.
- Sheet of paper $(80\ \text{g}/\text{m}^2)$.
- Document camera.

5.2.5.1.5 Presentation

The two 1 kg, chrome steel spheres are smashed together, while the sheet of paper is between them. At the point of contact a hole is burned in the piece of paper (see the enlarged Figure 2).

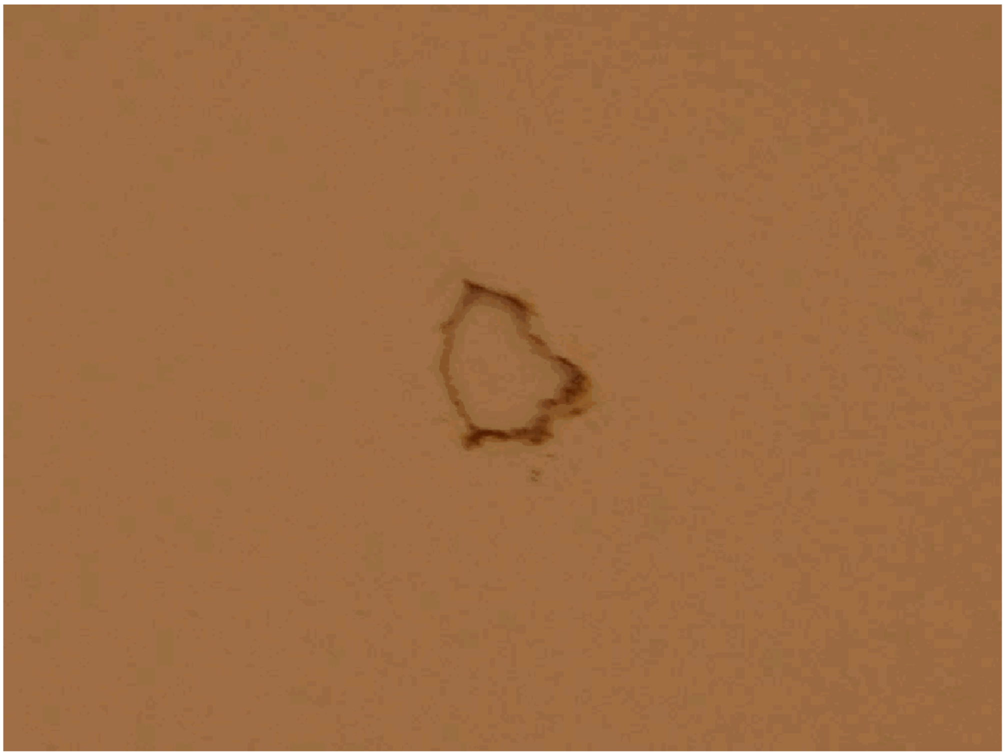


Figure 5.21: .

The demonstrator will smell the odour of burnt paper. Also a charred hole appears (see the brown rim in Figure 2). To convince the audience, this hole is shown to them using a document camera (is present in our lecture rooms).

5.2.5.1.6 Explanation

This demonstration just illustrates the conversion of mechanical energy into heat energy.

An easy calculation can give an estimate of the temperature rise:

Suppose just before hitting that the steel ball has a speed of 2 $\mathrm{m/sec}$. Then an amount of (kinetic) energy of $\frac{1}{2}mv^2 = \frac{1}{2} \cdot 1 \cdot 2^2 = 4$ J oules can be transformed into heat.

The point of contact between the two spheres is very small. Suppose it has an area of around 10 mm^2. Since the paper used is 80 $\mathrm{g/m}^2$, the considered piece of paper between the two spheres has a mass of 0.8 milligram.

Now the local temperature rise of the paper between the spheres can be calculated, knowing that the specific heat of paper (c) is around 2.5×10^{-3} J/K.kg : $\Delta T = \frac{Q}{mc}$, Q being the amount of heat that is induced without a loss by the transformation of the kinetic energy into heat. This leads to $\Delta T = \frac{4}{0.8 \times 10^{-6} 2.5 \times 10^{3}} = 2000$ Kelvin.

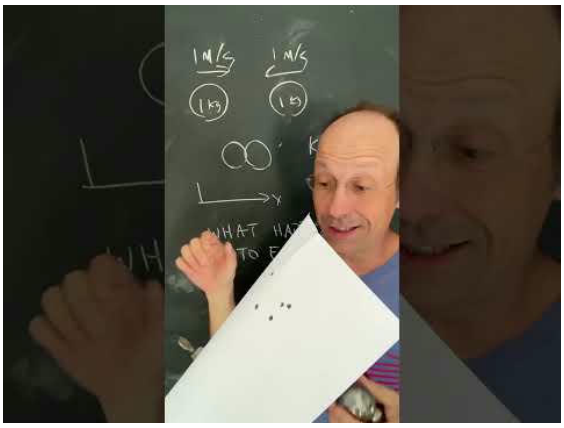
Paper inflames at around 232°C (“ 451 Fahrenheit”; Ray Bradbury), so the paper will certainly inflame (we suppose of course that all kinetic energy is transformed into heat into the paper with no losses).

This calculation is just an estimate. Supposing the area a little larger, for instance 1 cm^2, will lead to a temperature rise of “only” 200 Kelvin. And this is not enough to inflame the paper.

5.2.5.1.7 Remarks

- Give the spheres high speed! In practice we notice that the spheres need a high speed to produce the burning of the paper. When the speed is too low just a deformation of the paper can be observed. This experience shows that the estimation of temperature rise made in the Explanation is not too bad.

5.2.5.1.8 Video Rhett Allain



(a) (b)

Figure 339: :align: center - Scan the QR code or click here to go to the video.

5.2.5.1.9 Sources

- www.teachersource.com/.

5.2.5.2 03 Dropping Lead Shot

5.2.5.2.1 Aim

- To demonstrate the mechanical equivalent of heat.

5.2.5.2.2 Subjects

- 4B60 (Mechanical Equivalent of Heat)

5.2.5.2.3 Diagram

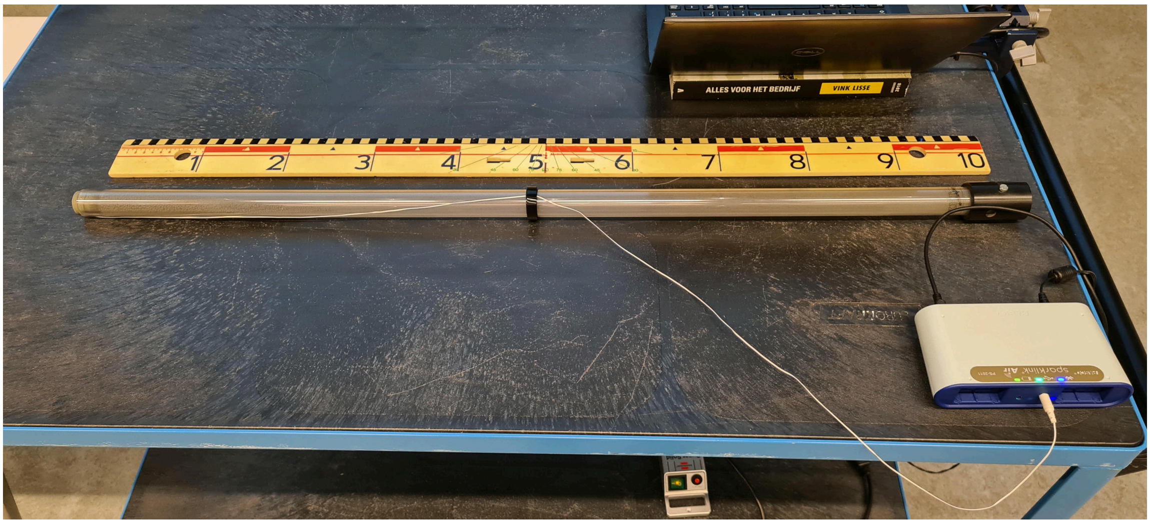


Figure 5.25: .

5.2.5.2.4 Equipment

- A 1 meter long perspex tube filled with 0.100 kg lead shot, and a thermistor mounted inside the tube.
- Data acquisition to display the temperature reading (PASCO).

5.2.5.2.5 Presentation

The tube is rotated several times over 180 degrees, such that the lead shot drops from one end of the tube to the other end (see the enlarged Figure 2).

Figure 5.26: .

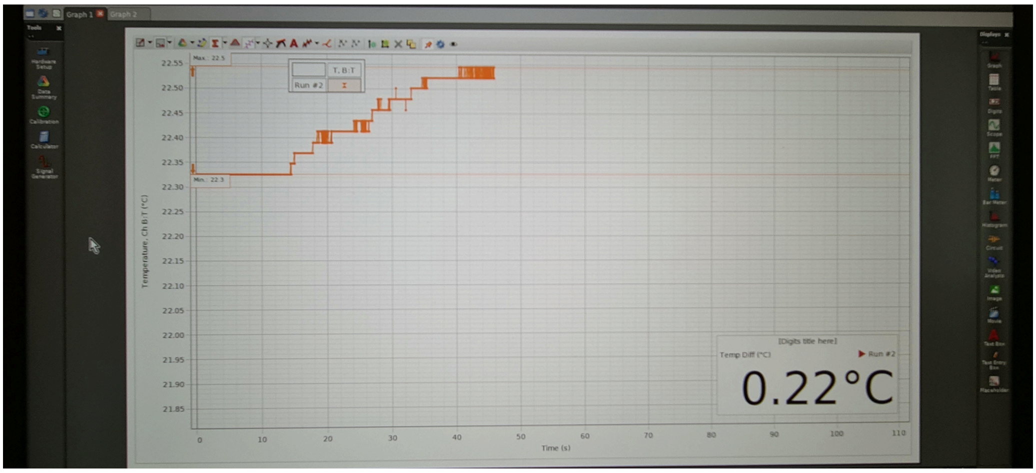


Figure 5.27: .

The temperature and the temperature rise is displayed real time (see the inset in the graph in Figure 3).

5.2.5.2.6 Explanation

This demonstration illustrates the conversion of mechanical energy into heat energy. The temperature rise of the lead shot is readily calculated as follows:

Given that the 1 meter tube is rotated 13 times means that the lead shot effectively drops over a height h of 13 meters. Assume that the conversion between potential energy $E_p = mgh$, kinetic energy E_k, and internal energy $U = m_{Pb}C_{p,Pb}\Delta T$ is perfect, the potential energy can be equated to the internal energy of the lead shot, i.e:

$m_{Pb}gh = m_{Pb}C_{p,Pb}\Delta T$

Solving for the temperature rise ΔT, and given that lead has a specific heat capacity of $C_{p,Pb} = 130\text{J} \cdot kg^{-1} \cdot K^{-1}$, the dropping height $h = 13m$, and the gravitational acceleration is $g = 9.81\text{m/s}^2$, we obtain:

$\Delta T = \frac{gh}{C_{p,Pb}} = \frac{9.81 \cdot 13}{130} \approx 1^{\circ}\text{C}$

The measured temperature rise is significantly lower and is approxmately $\Delta T \approx 0.26^{\circ}C$, which is probably due to the following factors:

- not only does the lead shot heat up, but also other materials, such as the alluminium plate onto which the thermistor is fixed (note that the mass of the lead shot drops out of the first expression)
- poor thermal conductivity between the lead shot and the thermistor
- the lead shot slides down the tube instead of falling from one end to the other end of the tube

Taking into account the heat capacity of the alluminium plate, the conservation of mechanical energy gives:

$m_{Pb}gh = m_{Pb}C_{p,Pb}\Delta T_{Pb} + m_{Al}C_{p,Al}\Delta T_{Al}$

and if we assume that the temperature rise of the alluminium plate with a mass of $m = 0.006\text{kg}$ and a specific heat capacity of $C_{p,Al} = 900\text{J} \cdot kg^{-1} \cdot K^{-1}$ and of the lead shot is the same (i.e. $\Delta T_{Pb} = \Delta T_{Al}$), we obtain for the temperature rise:

$\Delta T = \frac{m_{Pb}gh}{m_{Pb}C_{p,Pb} + m_{Al}C_{p,Al}}$

or:

$\Delta T = \frac{0.100 \cdot 9.81 \cdot 13}{0.100 \cdot 130 + 0.006 \cdot 900} \approx 0.69°\mathrm{C}$

This is a more accurate estimate of the actual temperature rise.

5.2.5.2.7 Remarks

- Ascertain that when the demonstration is performed, that after the final rotation the lead shot is at the end of the tube where the thermistor is mounted, such that the lead shot continues to give off its heat to the thermistor.

5.2.5.2.8 Sources

-

5.2.6 4B70 Adiabatic Processes

5.2.6.1 01 Clement's and Desormes' Experiment

5.2.6.1.1 Aim

- To show an adiabatic proces.
- To determine the ratio of the specific heats of a gas.

5.2.6.1.2 Subjects

- 4B70 (Adiabatic Processes)

5.2.6.1.3 Diagram

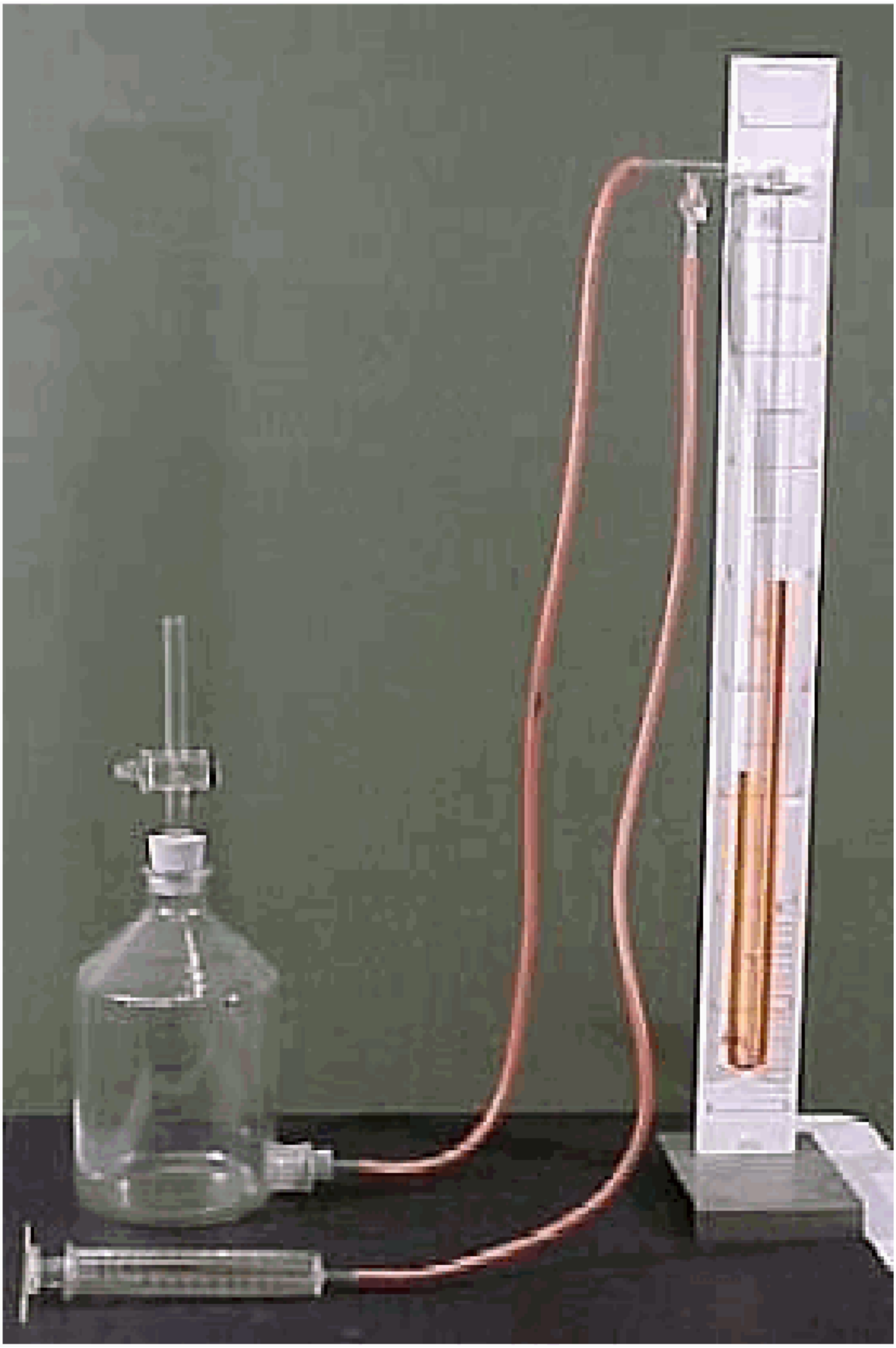


Figure 5.28: .

5.2.6.1.4 Equipment

- Large container (we use a 5 liter decantationbottle)

- valve with large opening, 10 mm
- syringe, 100ml
- U-tube manometer

5.2.6.1.5 Presentation

The valve of the container is closed. By means of the syringe an amount of air is pushed into the container. The manometer shows the raised pressure in the container (h_1). Now the valve of the container is opened for a short time (just long enough to have the pressure in- and outside the container to be equal; about is in our situation). After closing the valve, the manometer shows that the pressure inside the container rises and after some time reaches a fixed value (h_2).

The ratio of heat capacities, C_ρ/C_V can now be determined by $\gamma = \frac{Cp}{CV} = \frac{h_1}{h_1 - h_2}$

5.2.6.1.6 Explanation

The air in the container and syringe is at room temperature T_0 and pressure p_0. Pressing the syringe raises the pressure to p_1. The manometer reads h_1. (See Figure 2.)

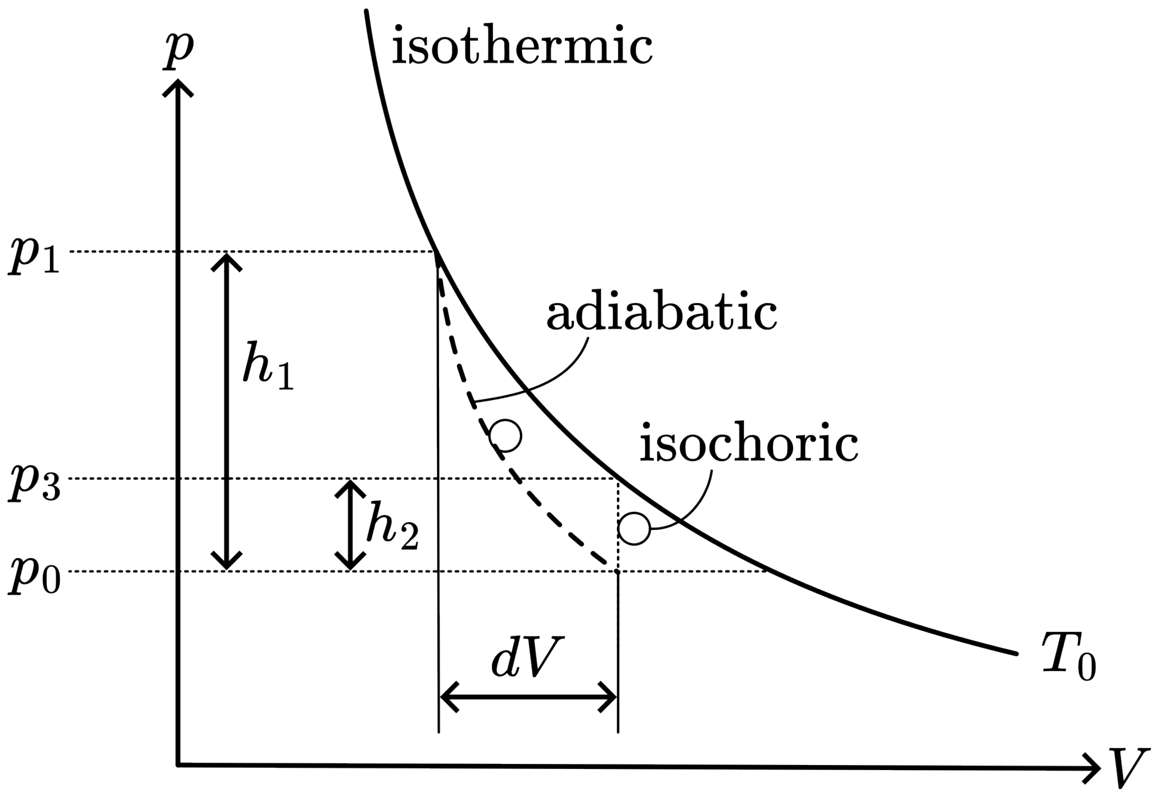


Figure 5.29: .

Opening the valve makes the air expand adiabatically to pressure p_0 and temperature falls to T_2. The valve is quickly closed and now the trapped air in the container raises isochorically in temperature to T_0 and pressure p_3. The manometer reads h_2. Consider the isothermic - and adiabatic process:

Isothermic: $pV = \text{const.}\ Vdp + pdV = O\left(\frac{dy}{dV}\right)_i = -\frac{p}{V}$

Adiabatic: $pV^r = \text{const.}$, $V^r dp + pV^{r-1} dV = 0$, $\left(\frac{dp}{dV}\right)_a = -\gamma\frac{p}{V}$

These two combined: $\left(\frac{dp}{dV}\right)_a = \gamma\left(\frac{dp}{dV}\right)_i$

Consider this for the same dV in both processes (see Figure 2) and we find:

$\frac{dp_a}{dp_i} = \gamma = \frac{h_1}{h_1 - h_2}$

5.2.6.1.7 Remarks

- It is easy to repeat the experiment a number of times.
- Instead of starting the experiment by pressing air into the container it can also be performed by sucking air out of it. (Figure 2 will be different, of course.)

5.2.6.1.8 Sources

- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. H.14
- Grimsehl, Lehrbuch der Physik, part 1, pag. 473-475
- Aulis, Handbuch der Physik, part 4, pag. 65

5.2.6.2 02 Fire-Pump

5.2.6.2.1 Aim

To show that fast compression is accompanied by a considerable raise in temperature.

5.2.6.2.2 Subjects

- 4B70 (Adiabatic Processes)

5.2.6.2.3 Diagram

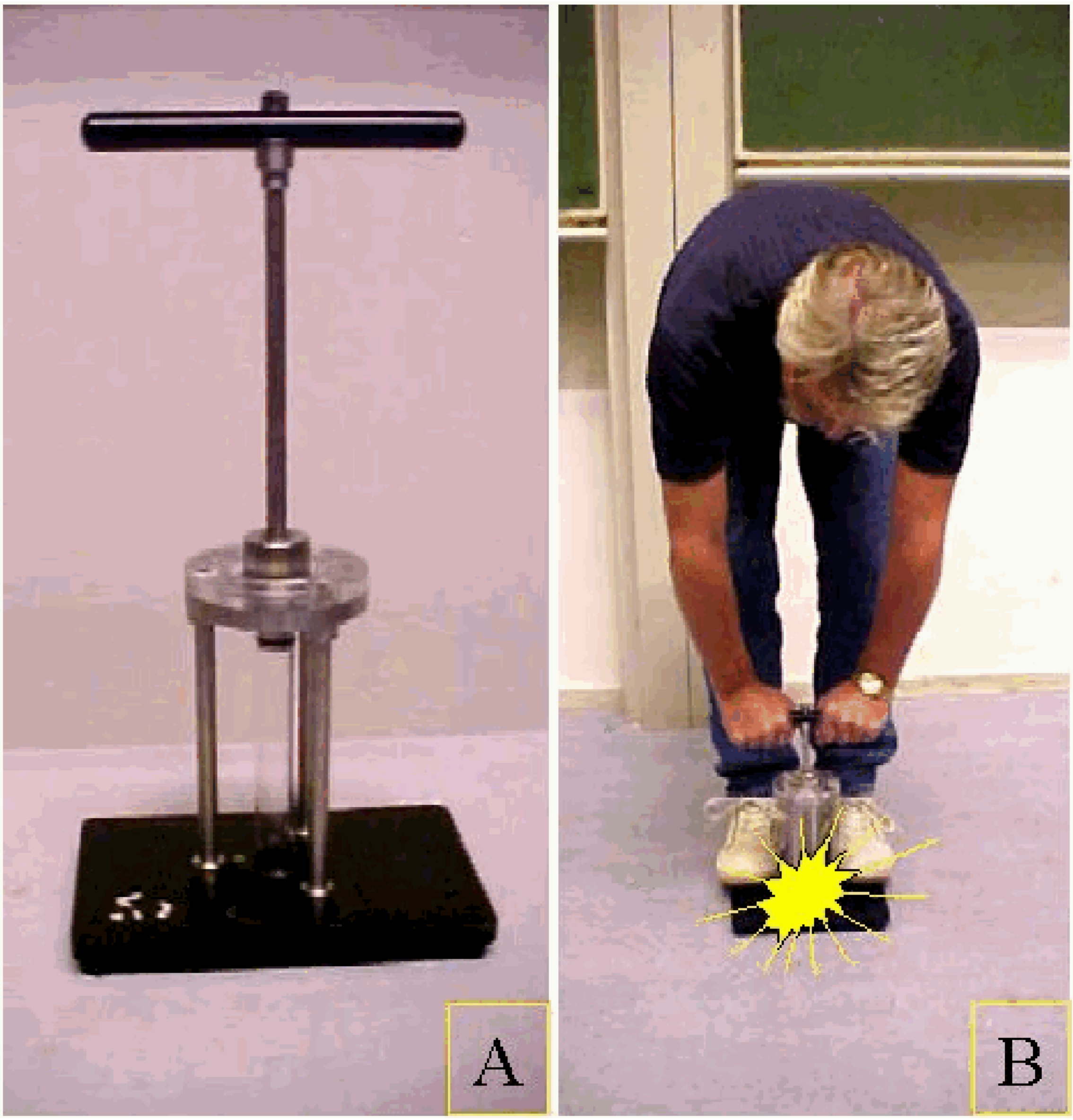


Figure 5.30: .

5.2.6.2.4 Equipment

- Closed tube, fitted with plunger.
- Pyroxyl wire.

5.2.6.2.5 Presentation

Small pieces of pyroxyl are put in the tube. The plunger is fitted into the tube and then pushed down rapidly. The pyroxyl lights and burns with a flash (see DiagramB). This points out to a steep increase in temperature.

5.2.6.2.6 Explanation

In general the process of the gas is polytropic, so: $pV^n =$ constant. In this demonstration the air in the closed tube is compressed rapidly, so during this action there is almost no heat exchanged with the surroundings. Such a process is performed adiabatically, and $n = \gamma$, giving $pV^\gamma =$ constant. Rewriting this in terms of temperature gives: $TV^{\gamma-1} =$ constant and so: $T_2 = \left(\frac{V_1}{V_2}\right)^{\gamma-1} T_1$.

When the compression ratio $\left(\frac{V_1}{V_2}\right)$ is around 6 and using air $(\gamma = 1.4)$ we have: $T_2 = 6^{0.4}$.

$T_1 = 2T_1$. So starting at room temperature ($T_1 = 300$ K), the air should heat up to around 600 K(327°C)!

5.2.6.2.7 Remarks

- Hold the tube firmly, so that when you press the plunger downwards forcefully the tube doesn't topple and break. We prevent toppling by standing on the foot of the construction.
- When the flash occurs you can feel also the rise in pressure

$$\left(p_2 = \left(\frac{V_1}{V_2}\right)^\gamma p_1 = 6^{1.4} = 12bar\right) \tag{5.1}$$

- We use pyroxyl wire, but you can also use small pieces of paper and/or the scrapings of a match. But do not use too much; more material means a higher heat capacity and as a consequence a lower temperature-rise of that material.

5.2.6.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 279-281.
- Meiners,H., Physics demonstration experiments, part 2, pag. 800.
- Wolfson, R., Essential University Physics, pag. 297-299.

5.3 4C Change of State

5.3.1 4C10 pVT Surfaces

5.3.1.1 4C10.01

5.3.1.1.1 Compressing a Gas

5.3.1.1.1.1 Aim
Showing how to consider the work done on a gas

5.3.1.1.1.2 Subjects
- 4C10 (PVT Surfaces)

5.3.1.1.1.3 Diagram

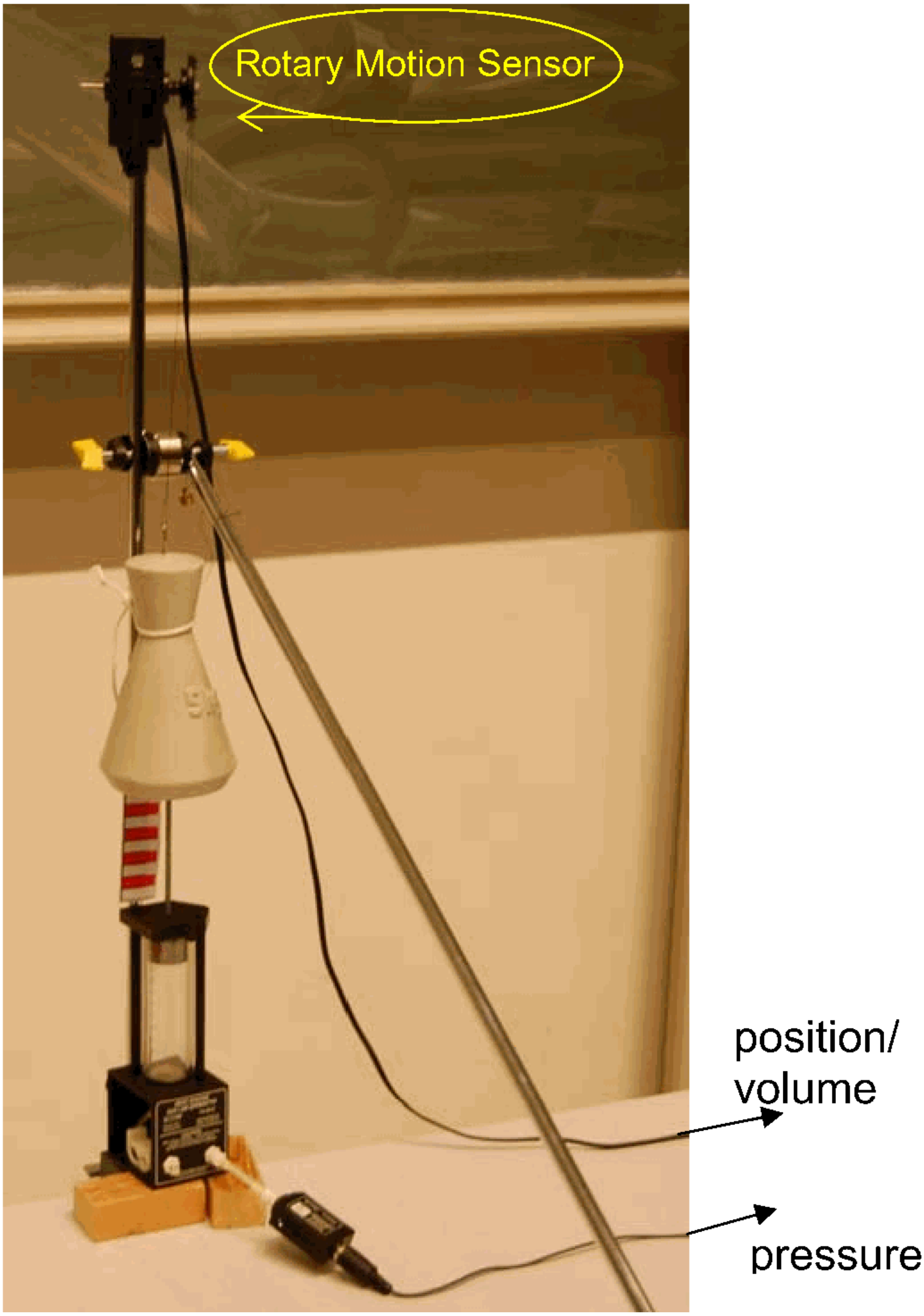


Figure 5.31: .

5.3.1.1.1.4 Equipment

- Cylinder with piston. Piston diameter $\emptyset = 32.5$ mm
- Pressure sensor.
- Position sensor.
- Mass, 5 kg.
- Blocks of wood.

- Ruler.
- Data-acquisition system.

5.3.1.1.1.5 Presentation

Preparation: Set up the equipment as shown in Diagram. The mass of 5 kg is large compared to the cylinder with piston. We take care that the set up is also stable when that mass is positioned on the platform of the piston shaft. (See the thread that holds and guides the mass when moving, and the slanting shaft that fixes the vertical shaft that holds the cylinder. Also the blocks of wood under the cylinder give extra support.). The pressure sensor is connected to the cylinder. A thin wire, connected to the top of the mass and wound around the pulley of the Rotary Motion Sensor, makes it possible to measure the volume of the cylinder. In the software of Science Workshop a graph is prepared, showing pressure as function of cylinder volume. Pressure can be displayed directly in the graph; displaying volume on the x-axis needs some calculation, using the piston area. (see Figure 2 1).

5.3.1.1.1.6 Presentation

5.3.1.1.1.7 Preparation:

Set up the equipment as shown in Diagram. The mass of 5 kg is large compared to the cylinder with piston. We take care that the set up is also stable when that mass is positioned on the platform of the piston shaft. (See the thread that holds and guides the mass when moving, and the slanting shaft that fixes the vertical shaft that holds the cylinder. Also the blocks of wood under the cylinder give extra support.).

The pressure sensor is connected to the cylinder. A thin wire, connected to the top of the mass and wound around the pulley of the Rotary Motion Sensor, makes it possible to measure the volume of the cylinder.

In the software of Science Workshop a graph is prepared, showing pressure as function of cylinder volume. Pressure can be displayed directly in the graph; displaying volume on the x-axis needs some calculation, using the piston area. (see Figure 2).

5.3.1.1.1.8 Presentation:

The piston is placed in its highest position. The pressure inside the cylinder is atmospheric (around $100 \mathrm{kPa}$) and the volume of the air chamber is 100ml. Be sure that the shut-off valve of the cylinder is closed.

The mass of 5 kg is placed on the platform. A thumbscrew turned into the cylinder housing holds the piston still in this starting position.

Ask the students what they expect to see on the displayed graph.

Then data-acquisition is started, slowly the thumbscrew is released and the piston slides downward, compressing the gas. When equilibrium is reached the data acquisition is stopped. The gas volume is compressed to around 70ml. On the ruler we can see that the mass has fallen around 3.5 cm. A graph as displayed in Figure 2 is the result of this demonstration.

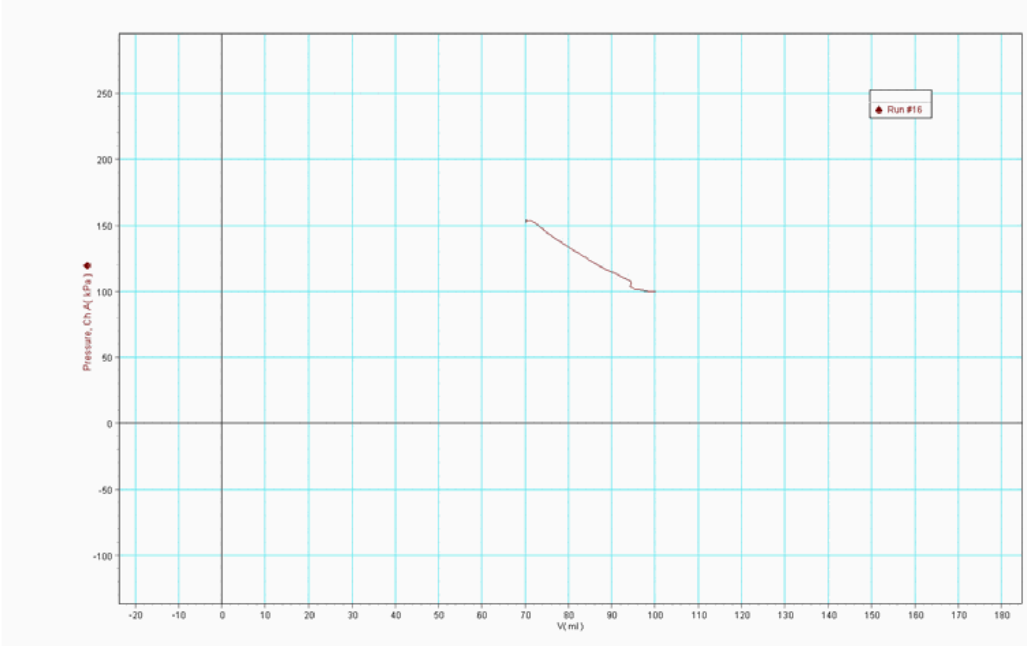


Figure 5.32: .

- At first sight, the graph looks almost like a straight line. Usually students expect a more curved line because that is what is presented to them in textbooks. We perform a power fit on these results, showing that when in such a way our results are extrapolated, the function resembles the pictures we see in textbooks.
- In the software we calculate the area under the measured PV curve, in order to know the work done on the gas in the cylinder. We find around 4J (see: Area in Figure 3). Then we calculate the work done by the mass: $\Delta U = mg\Delta h = 5 \times 10 \times 0.035 = 1.75]$! The difference is surprising; are we gaining in energy? Have we found a possible perpetuum mobile? Ask the students how they can explain this.

5.3.1.1.1.9 Explanation

What the software is calculating is the work done on the gas inside the cylinder. From outside not only the mass of 5 kg is standing on the piston, also the outside air with a pressure of 100kPa is “standing” on it. This is an isobaric part of the area under the graph, representing an amount of work of around $100\mathrm{kPa} \times 30\mathrm{ml} = 3$ J (see Figure 3). The remaining 1 J is delivered by the mass of 5 kg. (The remaining 0.75 J, to get 1.75 J, is lost elsewhere.)

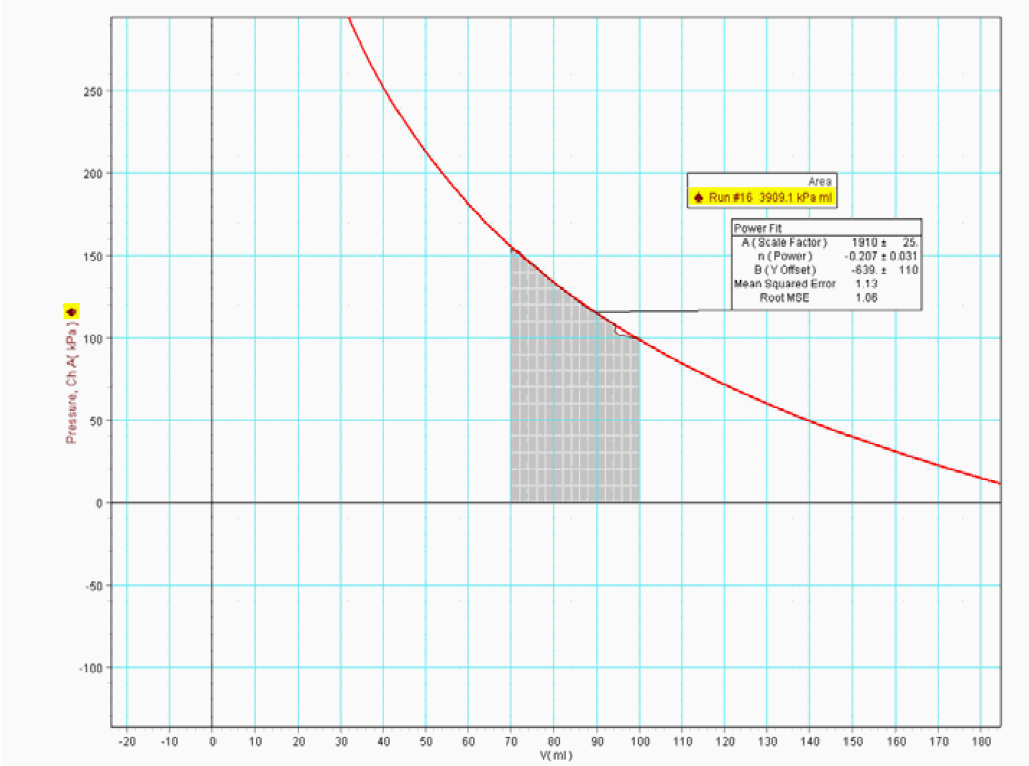


Figure 5.33: .

5.3.1.1.1.10 Remarks

- The process is more or less quasi-static because we release the thumbscrew, holding the piston, very slowly.

5.3.1.2 02 Work = int(PdV)

5.3.1.2.1 Aim

To show an example of work done to a gas in a cylinder.

5.3.1.2.2 Subjects

- 4C10 (pVT Surfaces)

5.3.1.2.3 Diagram

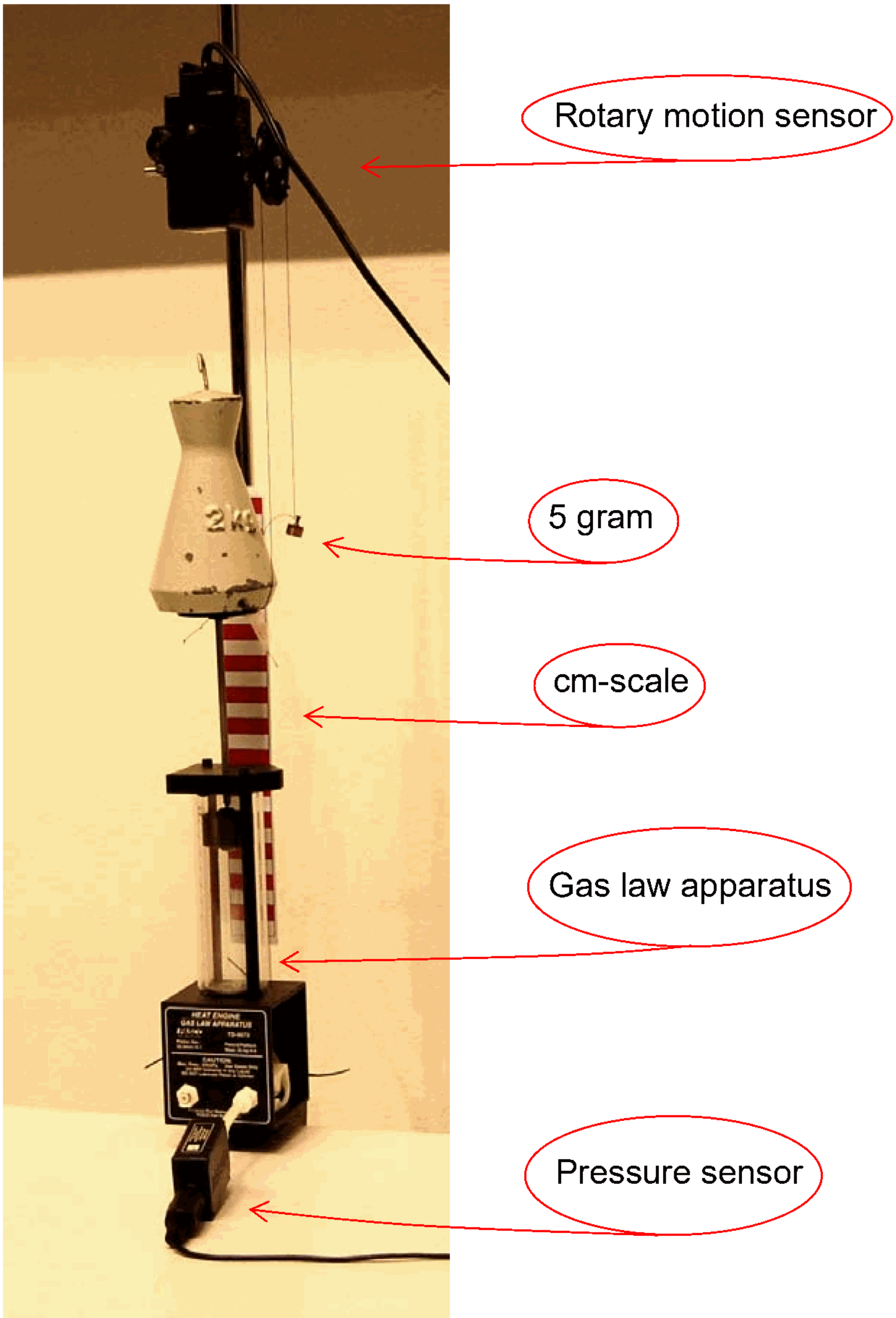


Figure 5.34: .

5.3.1.2.4 Equipment

- Gas Law Apparatus; $h_{cylinder} = 100$ mm; $V_{cylinder} = 85$ cm^3; $A_{piston} = 8.3$ cm^2=.
- Pressure sensor.
- Rotary motion sensor (Volume sensor).
- Mass, 2 kg.
- Piece of thread and small mass (we use a 5 gram mass).
- Data acquisition system and projector to project pV-diagram.
- Camera and monitor to show displacement of piston.

5.3.1.2.5 Presentation

5.3.1.2.5.1 Preparation:

The demonstration is set up as shown in Diagram. In order to use the Rotary Motion sensor as a sensor for the volume of the cylinder, a thread is stuck to the platform, swung twice around the large wheel of the Rotary Motion sensor and loaded with the mass of 5 grams (see Diagram). The software is set up to display a pV-diagram.

5.3.1.2.5.2 Presentation

The set up is explained to the students. The piston is lifted in its upper position $(83 \text{ mm}/; 100 \text{ mm})$ and fixed there. The cylinder is open to the surroundings, so the pressure in the cylinder is the ambient pressure.

The pV-graph is shown to the students. Ask them where in this graph a point will appear when we start measuring ($x = 83 \text{ m}/[\text{cm}^3]$ and $y = 100\text{kPa}$). Ask them also what we will see happening in the graph when we load the platform with 2 kg.

Then we close the cylinder and load the platform. The 2 kg mass goes downward (around 2 cm): the gas is compressed (smaller volume; higher pressure). The pV graph of the process appears (see Figure 2).

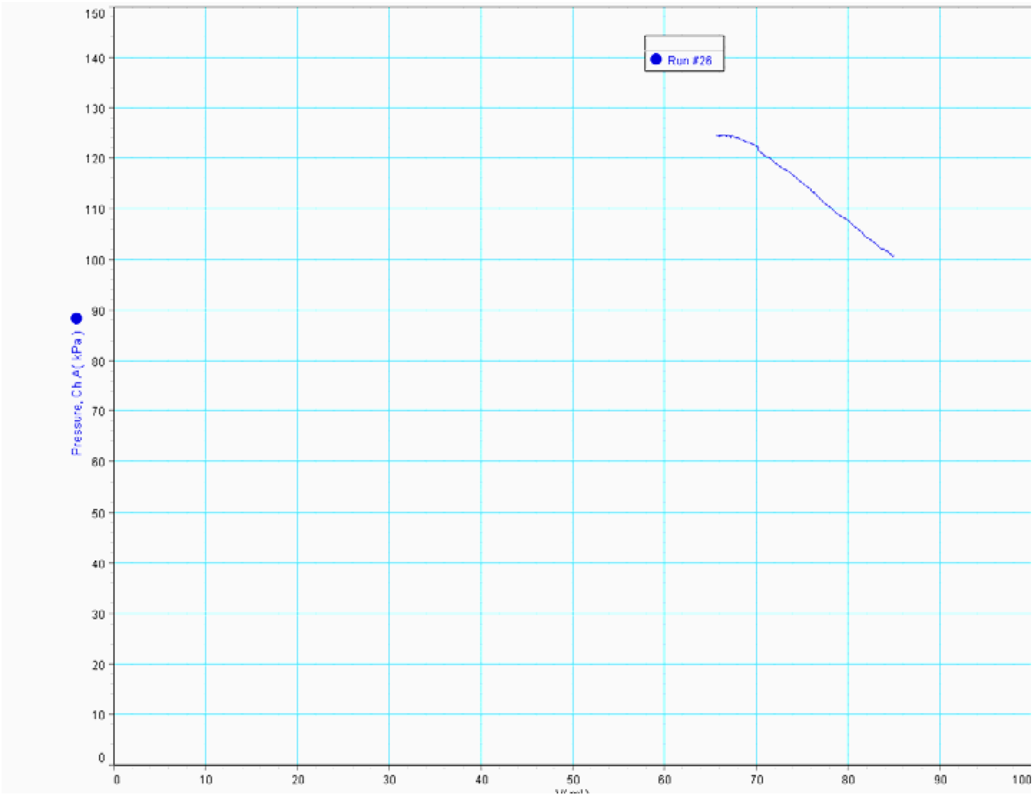


Figure 5.35: .

Then we ask to students how to calculate the work done on the gas in the cylinder. Two possibilities appear:

1. The mass of 2 kg is lowered 2 cm, so $\Delta E_p = mg\Delta h = 2 \times 10 \times 2.10^{-2} = 0.4$ J;
2. The area under the measured pV-graph. The software calculates it and it shows: $2097.3 \mathrm{kPa} \cdot \mathrm{ml}$ (see Figure 3). The peculiar unit is rewritten and the number is rounded to 2.1 J.

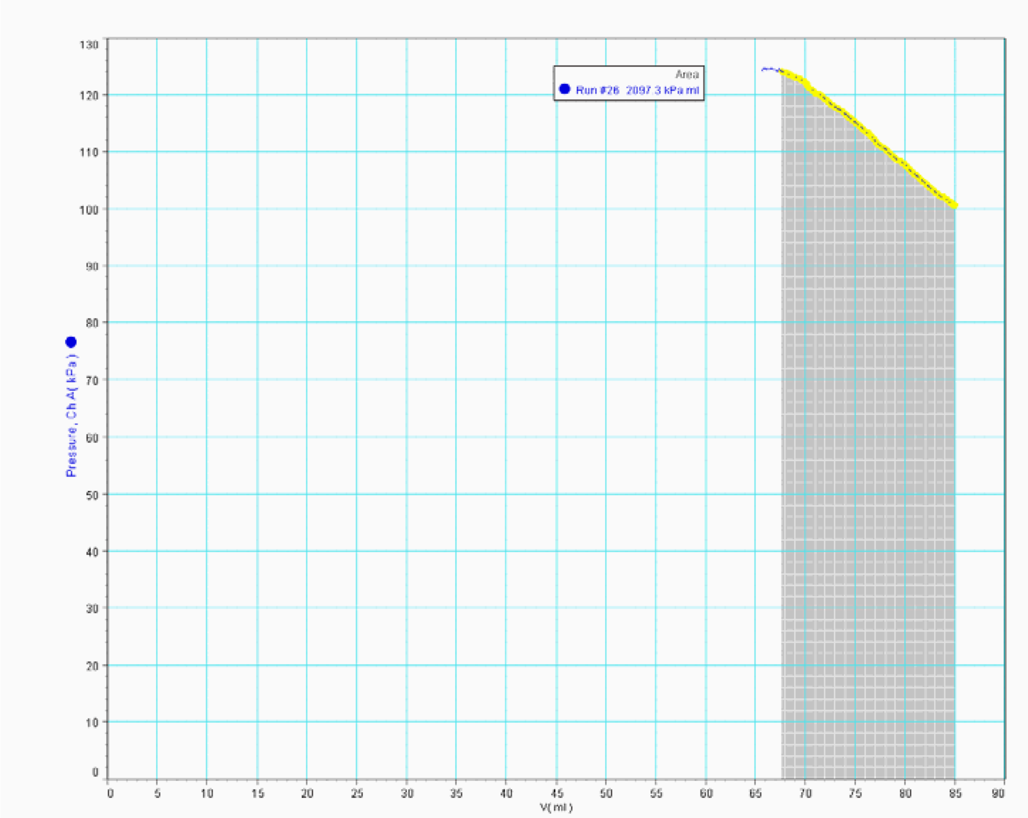


Figure 5.36: .

Students are confused seeing the difference between these two numbers (0.4 J) and (2.1 J). A very useful discussion follows.

5.3.1.2.6 Explanation

With a load of 2 kg on the piston having an area of 8.3 cm^2, we get a pressure of $\frac{2\times 10}{8.3\times 10^{-4}} = 0.241 \times 10^5$ Pa$\frac{2\times 10}{8.3\times 10^{-4}} = 0.241 \times 10^5$ Pa. So the pressure inside the cylinder rises from 1×10^5 Pa to 1.241×10^5 Pa. J ust calculation, using Boyle's law, $p_1 V_1 = p_2 V_2$ gives: $V_2 = 68.5$ cm^3. This is very close to what the pV-graph shows in its measurements of final pressure and final volume (read the values in Figure 3; do not look at the final 'horizontal' part of the graph, because that part is caused by leakage).

In calculating the work done on the gas in the cylinder it should be realized that also the outside atmosphere works on the piston by its atmospheric pressure. This is shown in Figure 4: The atmospheric pressure works with 1.8 J , the weight by an amount of 0.43 J (calculated by reducing the pV-diagram to a triangle). This 0.43 J is close to what was calculated by the potential mechanical energy of the work done by the weight.

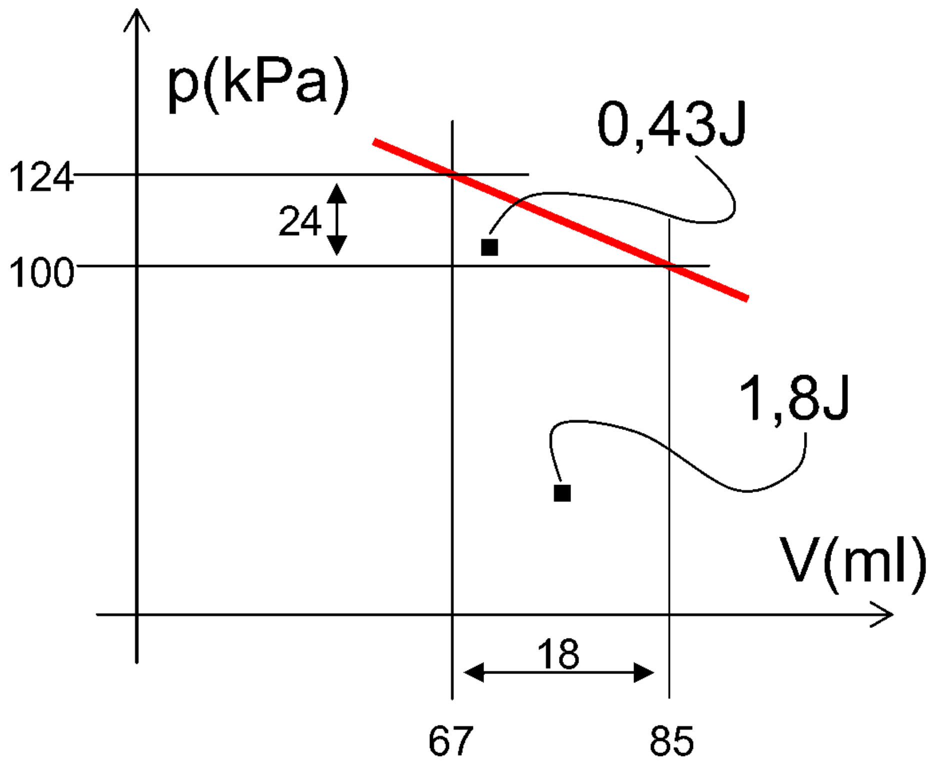


Figure 5.37: .

5.3.1.2.7 Remarks

- Take care that the mass of 2 kg does not fall from the relatively small platform.

5.3.2 4C30 Phase Changes Liquid Gas

5.3.2.1 01 Boiling to Freeze

5.3.2.1.1 Aim

To show that boiling evaporation requires a lot of heat.

5.3.2.1.2 Subjects

- 4C30 (Phase Changes: Liquid-Gas)

5.3.2.1.3 Diagram

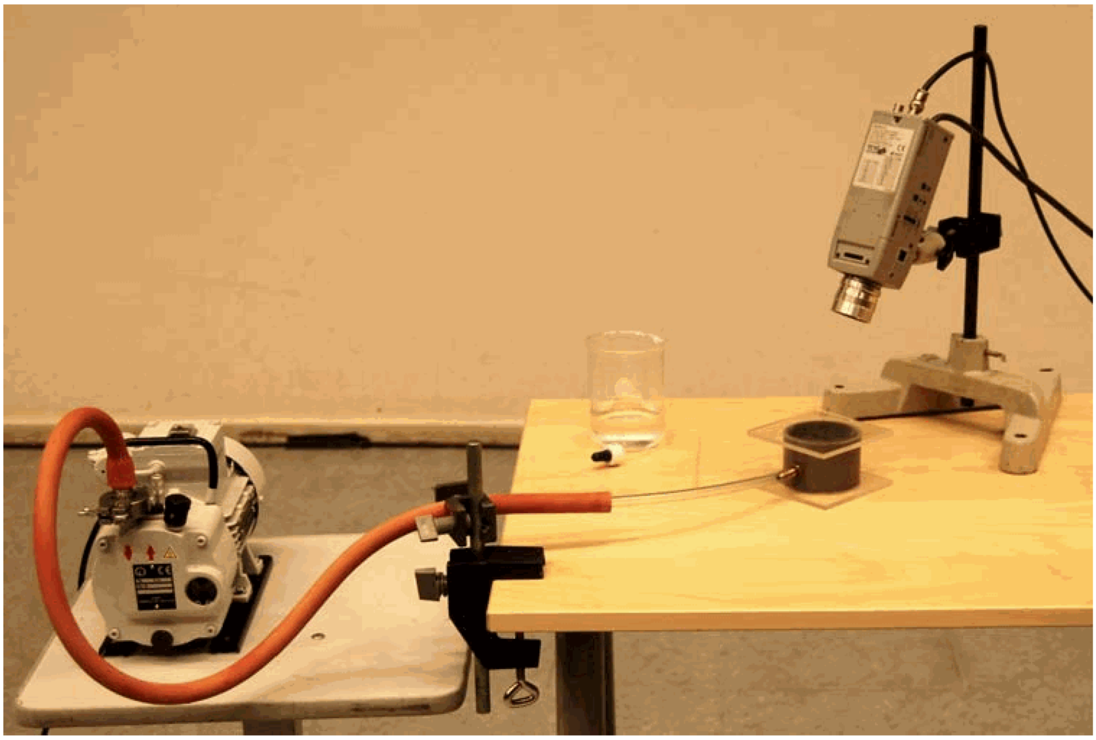


Figure 5.38: .

5.3.2.1.4 Equipment

- Vacuum pump
- PVC-cylinder with transparent end caps and a small table inside.
- Dripper.
- Camera and projector focused on the drop of water.

5.3.2.1.5 Safety

- In using the vacuum pump, never expose parts of the body to the created vacuum. There is a danger of injury. Never operate the pump with an open, and thus accessible, inlet. Do not open the vacuum system during operation of the pump.

5.3.2.1.6 Presentation

5.3.2.1.6.1 Preparation

The vacuum pump is connected to the cylinder. One rim of the cylinder is greased with vacuum grease, and then one of the square transparent end caps is pressed to the cylinder, creating the bottom of the assembly. The upper rim of the cylinder is also greased, after which the small table is placed inside the cylinder.

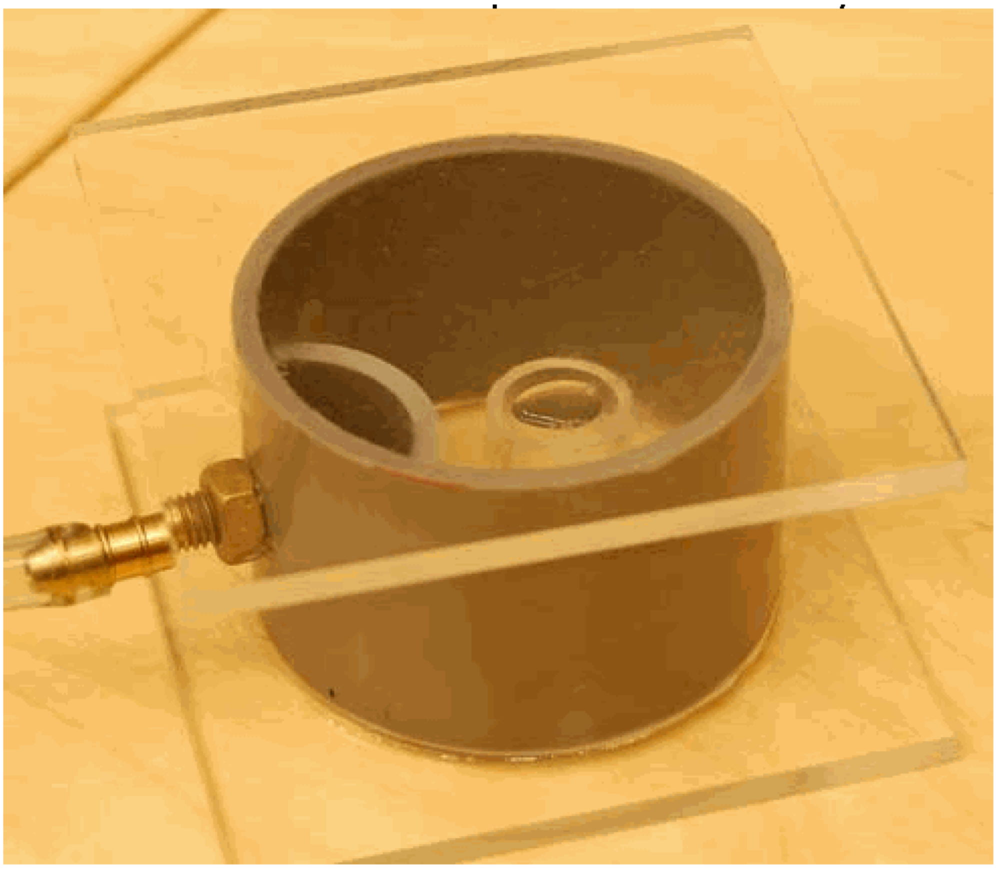


Figure 5.39: .

5.3.2.1.6.2 Preparation

Using a dripper, a large drop of water is deposited on the tabletop. The second transparent end cap is put on top of the cylinder and pressed down. The assembly is ready now (see Figure 2) and the camera is focused on the drop of water.

The pump is switched on, after which vigorous boiling can be immediately observed.

This stops, and a quiet drop of water is observed.

Then, after some time, suddenly the drop of water turns opaque (see Figure 3)

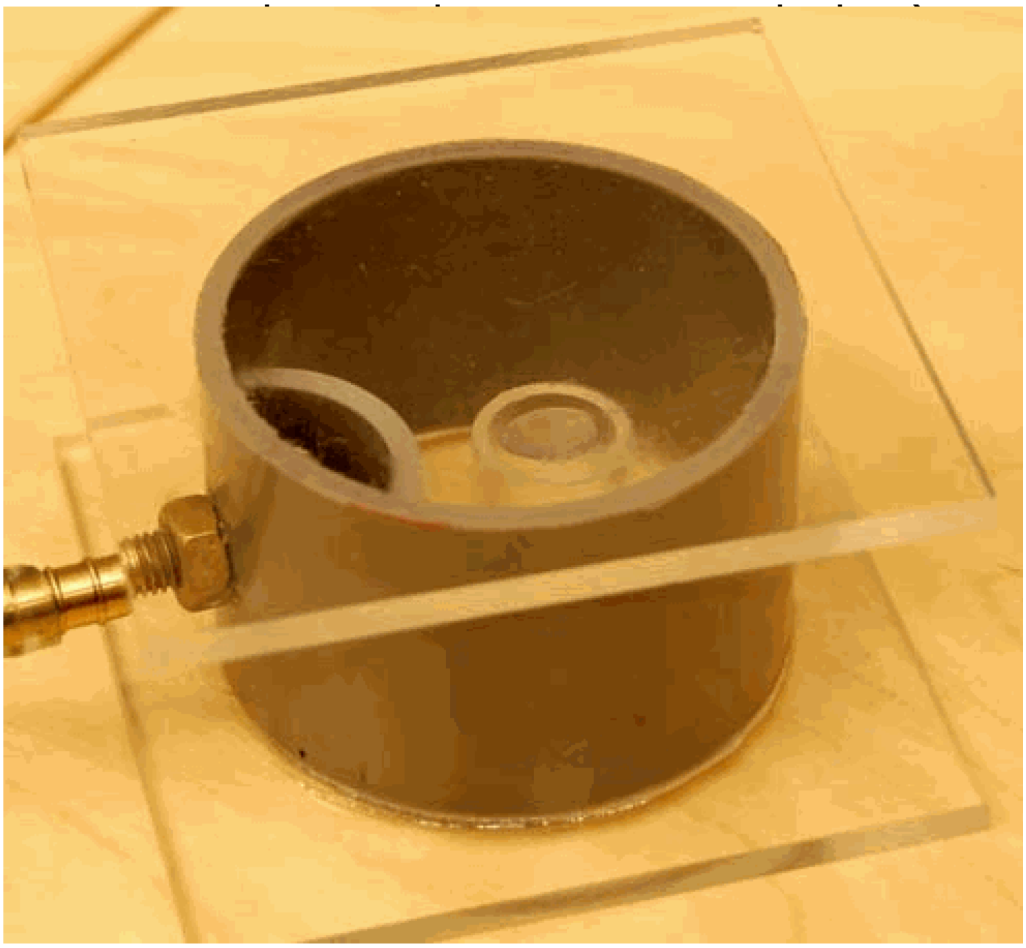


Figure 5.40: .

We stop the pump, remove the upper transparent cap, and shift the frozen drop across the table using a small stick. This shows the audience that the drop is solid.

5.3.2.1.7 Explanation

When the pump is switched on, the water starts boiling due to the low pressure. This boiling is vigorous due to the fast drop in pressure.

Then, after some time, this boiling stops because the decrease in pressure is now continuing at a slower rate. (The evaporation of water continues in this part of the demonstration but is not visible to us now.)

During the process of boiling and evaporation, the drop of water loses heat and its temperature decreases. Because the small tabletop is very clean, the drop of water even becomes supercooled; it reaches a temperature below its freezing point of 0°C, at which it suddenly freezes.

5.3.2.1.8 Video Rhett Allain

To further showcase the boiling of water at reduced pressure.

(a)

(b)

Figure 356: :align: center - Scan the QR code or click here to go to the video.

5.3.3 4C31 Cooling by Evaporation

5.3.3.1 01 Evaporating Ether

5.3.3.1.1 Aim

Showing that evaporation needs heat

5.3.3.1.2 Subjects

- 4C31 (Cooling by Evaporation)

5.3.3.1.3 Diagram

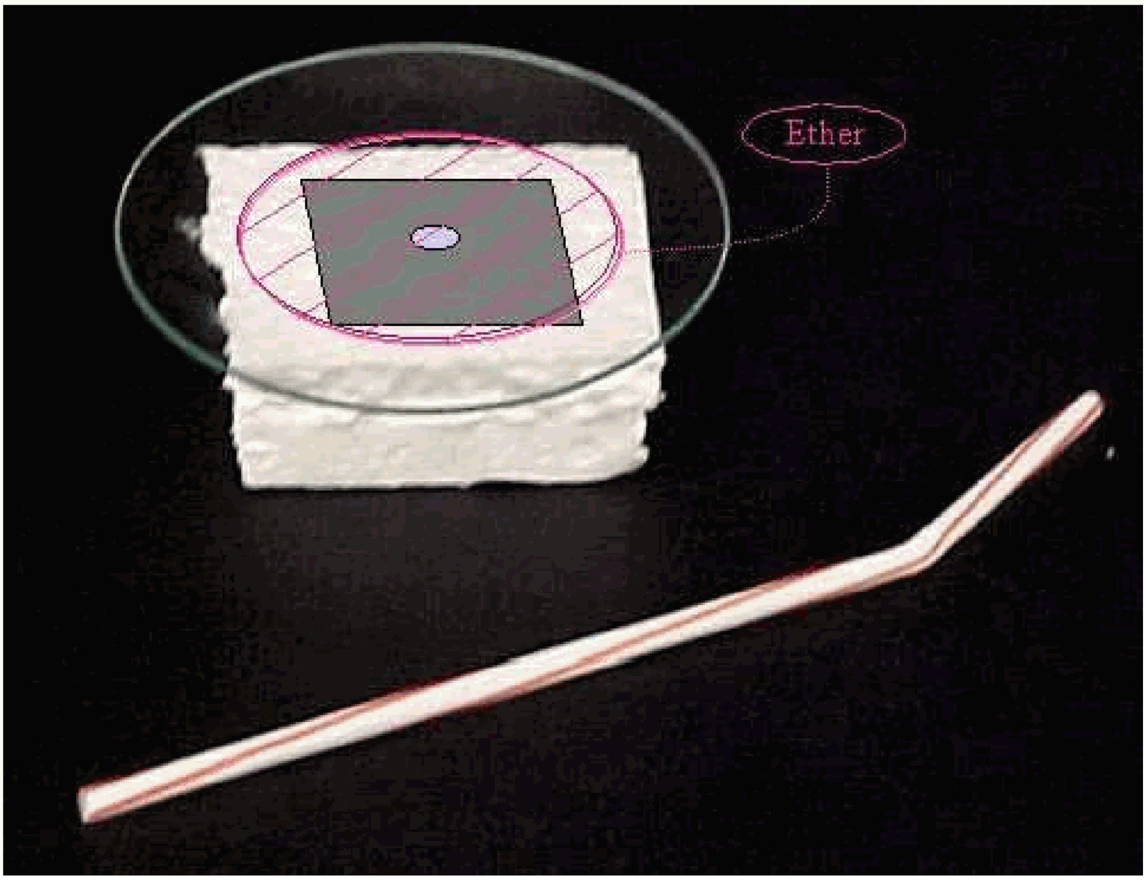


Figure 5.44: .

5.3.3.1.4 Equipment

- Petri disk, e.g. $d = 100$ mm.
- Styrofoam block (we use: $10 \times 6 \times 4\ \text{cm}^3$).
- Piece of black paper between petri disk and styrofoam block
- Blower, dry air spray-can or straw.
- Ether.
- Thermometer.
- Video camera and large screen projection.

5.3.3.1.5 Presentation

- A layer of ether is poured into the petri disk. The thermometer probe is placed in the ether. Blowing across the petri disk will cause the temperature of the ether to go down.
- A small drop of water is placed on top of the styrofoam block. The petri disk with the ether is placed on the drop of water. Blowing is started again and when this is continued long enough, the ether temperature drops below 0°C, freezing the drop of water. The petri disk is

lifted and the styrofoam block sticks to it. While blowing across the ether, water vapor in the air condenses on the petri disk. When all the ether is evaporated, this condensed water is frozen and can be seen as an ice/snow layer on the disk.

5.3.3.1.6 Explanation

Evaporation needs heat. This heat is taken from the surroundings, so also from the drop of water, and so lowering the temperature of the water and turning it into ice.

5.3.3.1.7 Remarks

- When using ether, no fire or sparks should be in the neighborhood!
- Take care not to blow the ether out of the petri disk. (The styrofoam is dissolved by it and when the ether mixes with the water, this mixture will not freeze anymore.)
- With a video-camera and -projector, the process of freezing can be shown on screen.

5.3.3.1.8 Sources

- Aulis, Handbuch der Physik, part 4, pag. 123
- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 5/6 vwo, pag. 31
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 276

5.3.4 4C33 Vapor Pressure

5.3.4.1 01 Dippy Bird

5.3.4.1.1 Aim

To show the pressure-volume behavior of a vapour.

5.3.4.1.2 Subjects

- 4C33 (Vapor Pressure) 4F30 (Heat Cycles)

5.3.4.1.3 Diagram

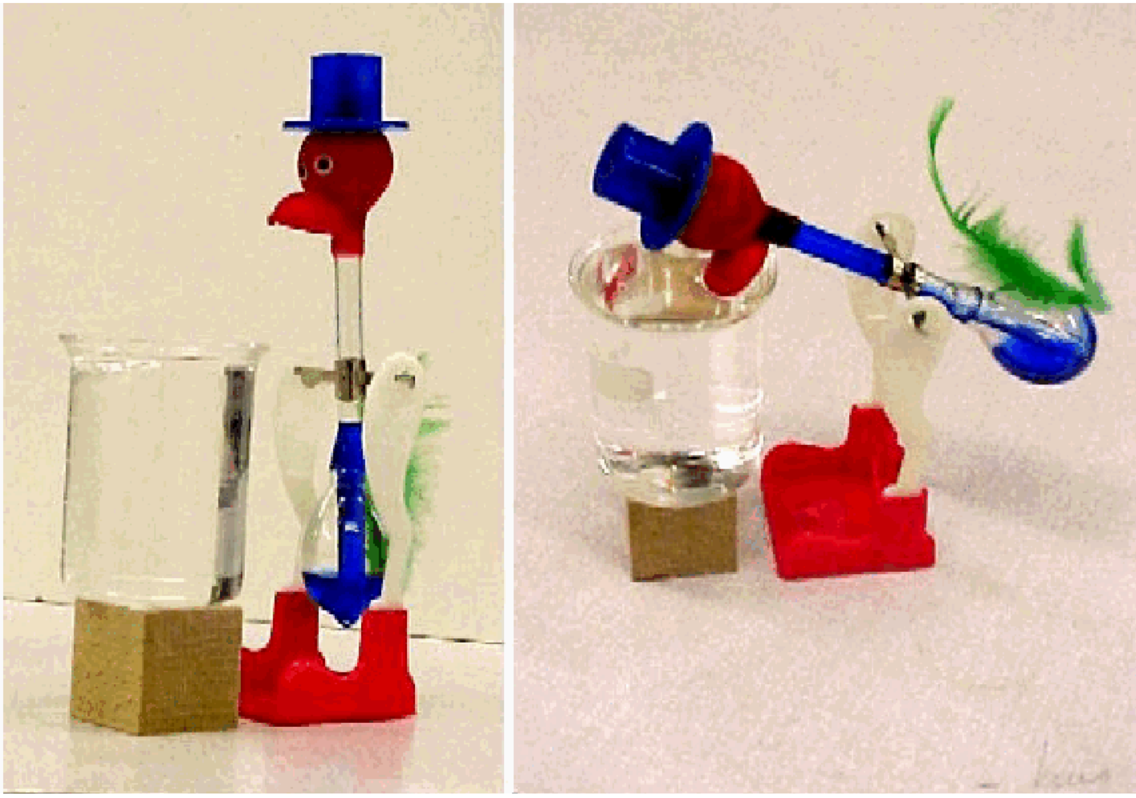


Figure 5.45: .

5.3.4.1.4 Equipment

- Dippy bird.
- Small beaker, filled with distilled water.
- (Second dippy bird and lamp; see at the end of ‘Explanation’.)

5.3.4.1.5 Safety

- Despite the drinking bird’s appearance and classification as a toy, some safety considerations apply. The liquid inside the dippy bird is dichloromethane. Dichloromethane can irritate the skin on contact, and the lungs if inhaled; it is a mutagen and teratogen, and potentially a carcinogen. The intact toy is leakage proof and completely safe, but if broken hazardous dichloromethane is released. Dichloromethane evaporates quickly; good ventilation after a spill will dilute and disperse the vapour.
- Always keep a beaker in front of the bird. The beaker stops the forward movement of the bird. When there is no beaker to stop the forward movement of the bird, the glass bird will fall down and the glass breaks.
- (Early models of the dippy bird were often filled with highly flammable substances. The fluid in later versions is nonflammable.)

5.3.4.1.6 Presentation

Set up the dippy bird and the beaker as shown in the Diagram. Fill the beaker with distilled water and dip the beak of the dippy bird in it. Then let the bird go. While the bird is swinging, the blue liquid rises from the belly through the central tube to the head. The bird topples, and dips its beak into the water again, the blue liquid runs down the straight tube and the bird rises again to its vertical, swinging position. This goes on and on, repeating its chain of events.

To the teacher it is very instructive to have the students explain what is happening. So just put the bird in your lecture room and let the students break their brains.

5.3.4.1.7 Explanation

Figure 2 shows the system. The bird is filled with a liquid (dichloromethane) having low latent heat of evaporation. Only this liquid and its vapour are inside the bird.

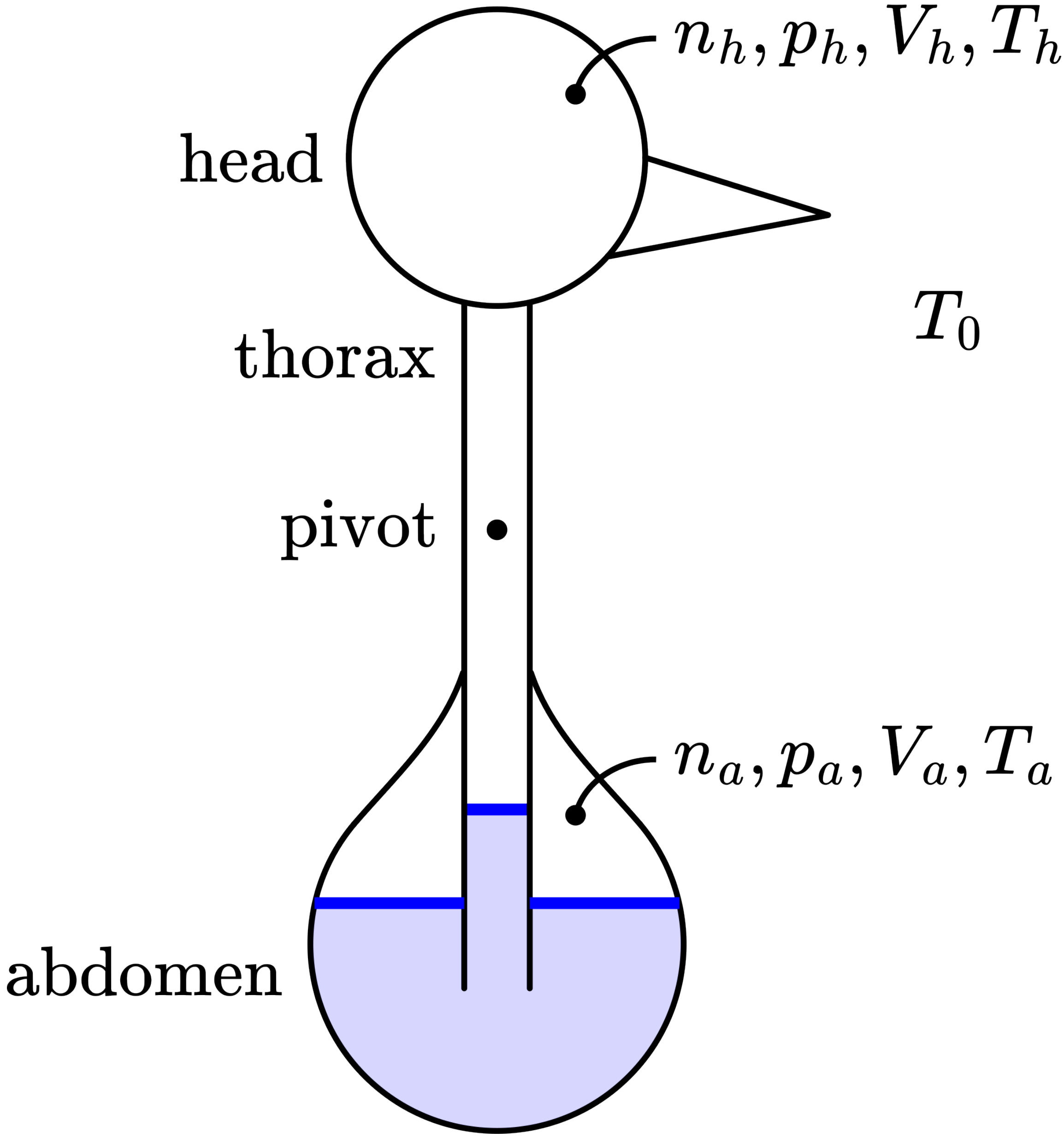


Figure 5.46: .

Initially the system is at equilibrium. There are two spaces to consider: the head with n_h moles of vapour and the abdomen with n_a moles of vapour.

Evaporation of water on the beak outside the head draws heat from inside it; the vapour inside the head partially condenses, reducing n_h and thus lowering p_h. Now the pressure p_{a} in the abdomen pushes fluid up the thorax, which reduces the volume V_h of the head. Consequently the volume V_a of the abdomen increases. This causes evaporation in the abdomen (increasing n_{a}), made possible by drawing heat from the surroundings.

The rising fluid raises the centre of mass above the pivot point, so the bird dips. The amount of fluid is set so that at full dip the lower end of the tube is exposed to the vapour. A bubble of vapour rises in the tube and fluid drains into the abdomen. The rising bubble transfers heat to the head. The centre of mass drops below the pivot point and the bird bobs up, oscillating back to its starting position.

Due to this fast swinging movement, there is good evaporation of the water on the beak, and the whole cycle described above repeats itself.

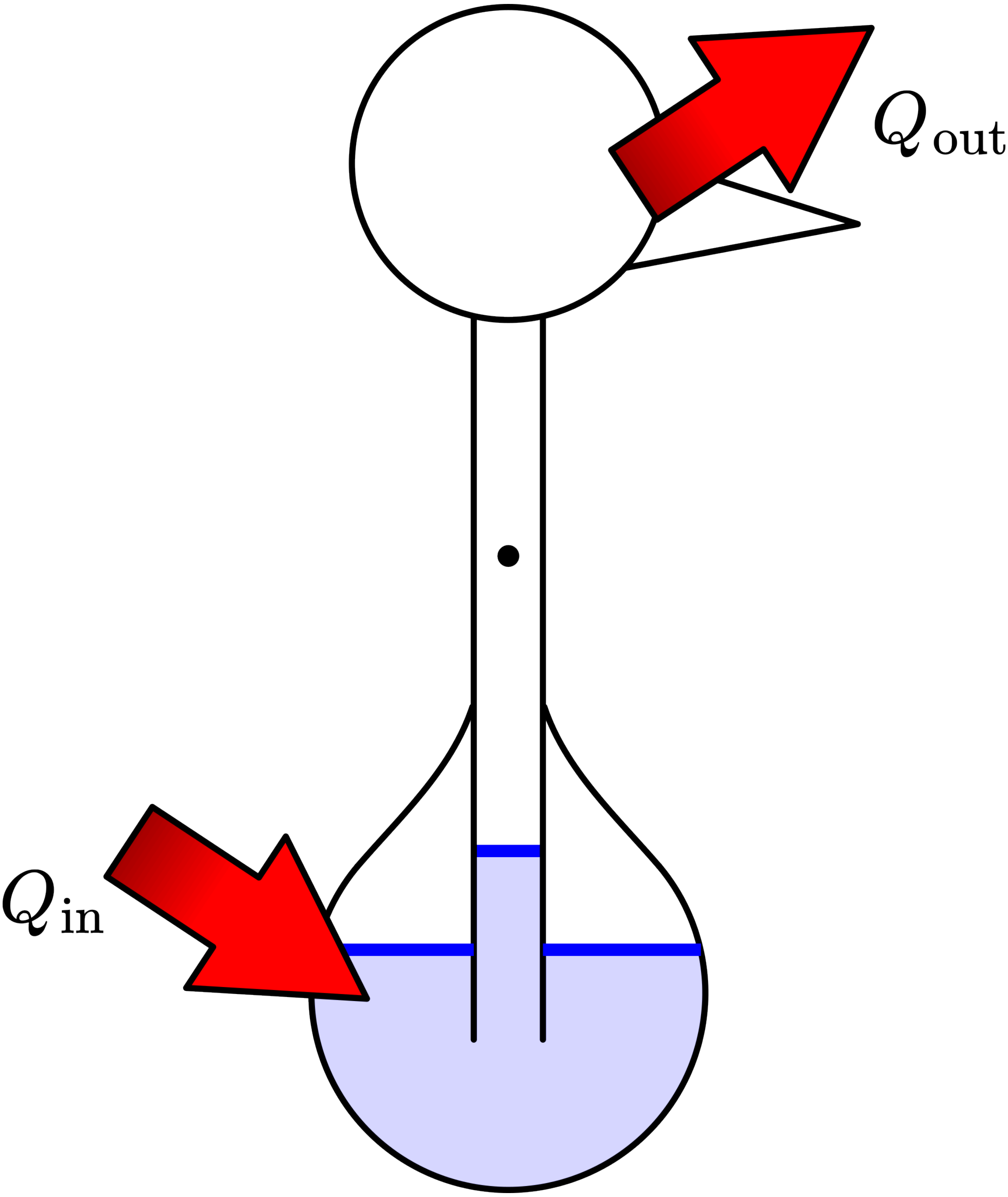


Figure 5.47: .

Figure 3 shows the behaviour of the dippy bird as a heat-engine. Heat flows into the bird at the abdomen and is discarded at the head/beak-side.

5.3.4.1.7.1 A second bird

Considering the dippy bird as a heat-engine (see Figure 3) induces the idea that it will work as well when, instead of cooling the head, you heat up the abdomen. We tried this by shining light on the dippy's bottom and indeed, the bird dipped! Demonstrating also this version of the dippy bird will once more make clear that the factor that makes heat-engines work is the temperature gradient.

5.3.4.1.8 Remarks

- We use distilled water instead of tap water, because in our city tap water is hard water and in due time the lime would thermally isolate the beak of the bird.
- When the bird dips his beak into the water, sometimes it is stuck there due to surface tension. This can be prevented by changing the set up such that it dips its beak less deep into the water.
- Take care not to make the head so wet that it drips down the tube: it will change the balance of the bird and it will also cool down the bottom too much. Both effects will stop the swinging of the dipping bird.
- The pivot of the bird is bent, to unbalance the bird always into the forward direction.
- As a heat engine the dippy bird can produce work, but this is very low, with a low efficiency (see Sources).

5.3.4.1.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 276-277.
- The Physics Teacher, R. Mentzer, pag. 126-127, Vol 31 (1993).
- The American Journal of Physics, J. Guemez e.o., pag. 1257-1263, Vol 71 (2003).
- The American Journal of Physics, R. Lorenz, pag. 677-682, Vol 74 (2006).

5.3.4.2 02 Boiling Water at Reduced Pressure

5.3.4.2.1 Aim

To show that at pressures below 105 Pa water boils below 100°C.

5.3.4.2.2 Subjects

- 4C33 (Vapor Pressure)

5.3.4.2.3 Diagram

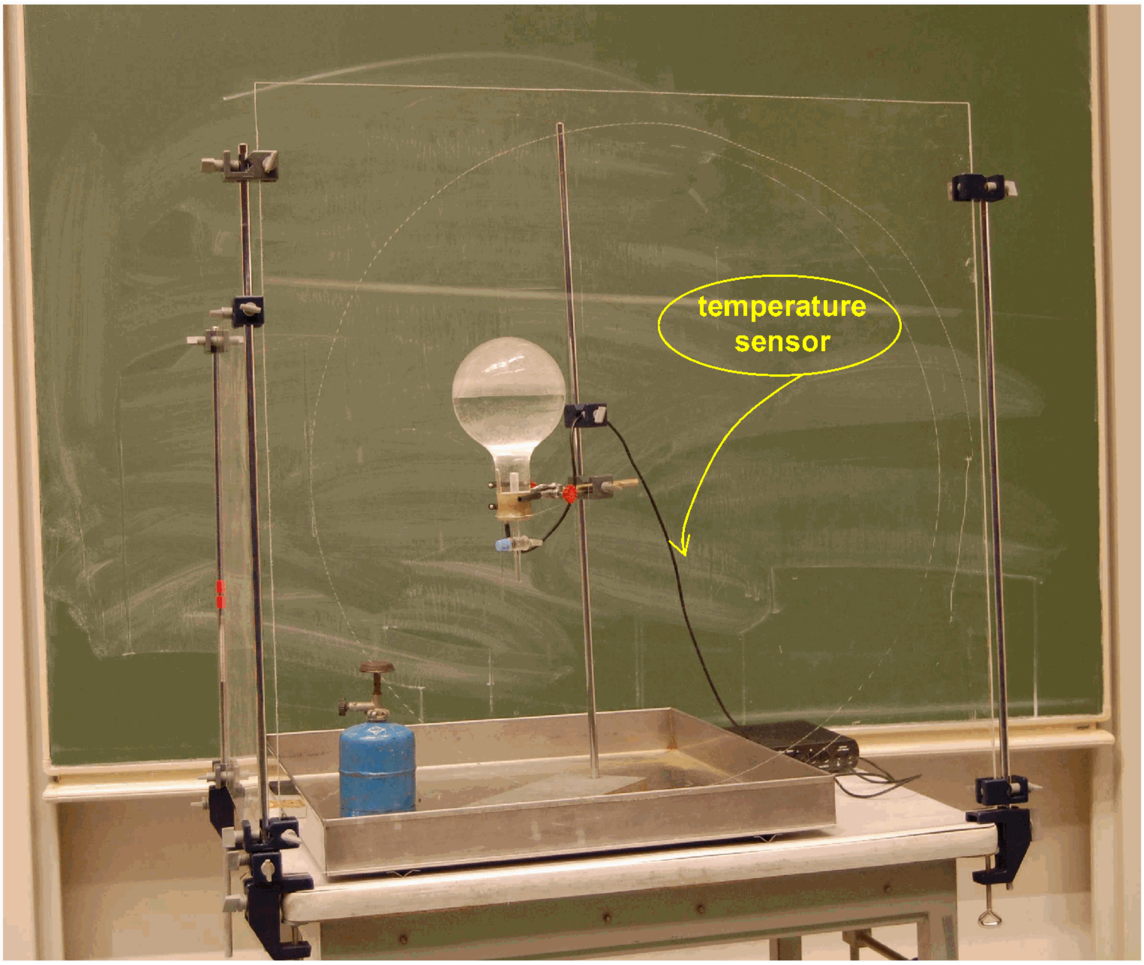


Figure 5.48: .

5.3.4.2.4 Equipment

- Large metal tray $(1 \times 1m^2)$.
- 2 I flask, with round bottom, half filled with water.
- Rubber stopper, with cock and temperature sensor with digital read-out.
- Support clamp.
- Gas flame.
- Protective gloves.
- Ice-water.
- Video-camera and projector to project an image of the flask.

5.3.4.2.5 Safety

- Perspex safety screens are placed between the audience and the flask, because implosion can occur. (See the two screens, that are placed on the table, in the Diagram above.)
- Don't use a flat bottomed flask. Such a flask is more likely to implode under the reduced pressure.

- Use protective gloves when turning the flask upside down.
- Always fix the clamp, that holds the flask, firmly!

5.3.4.2.6 Presentation

The 2 l flask is half filled with water. Open the cock. The water is made boiling by means of a gas flame.

Figure 5.49: .

Make it boil rigorously for about one minute to drive out air. Remove the flame and when you see that vapour no longer blows out of the cock, quickly close it. Then invert the flask (see photo in Diagram).

1. In the beginning the water trapped inside the flask keeps boiling.
2. After some time the water will stop boiling.

When cold water is poured over the outside of the flask, the water inside the flask starts boiling again. This can be repeated quite a number of times. When there is no longer success with pouring tap-water, ice-water can be tried.

The thermometer shows that the water inside the flask is boiling far below 100°C. When using ice-water you can even make the water in the flask boil when it has cooled down to 20°C !

5.3.4.2.7 Explanation

1. The moment the flask is closed by the rubber stopper, only water and water vapour are present inside the flask. The water-vapour will cool down faster than the water, due to the lower mass of the water-vapour. The resulting lower vapour pressure will make that the water continues to boil in order to saturate the vapour at the saturation pressure that corresponds to the water temperature.
2. When the temperature becomes lower the process of cooling becomes slower and water temperature and vapour temperature are closer to each other. There is no boiling any longer.

When water is poured over the flask, the vapour temperature quickly lowers. The water temperature inside the flask barely lowers. So, the vapour pressure is lower than the saturation pressure and the water starts boiling again.

Supposing that pouring water can reduce the vapour temperature to (for example) 30°C, the process can be repeated until the water inside the flask is cooled to that temperature. Pouring ice-water can reduce the vapour temperature even further, thereby prolonging the described situation.

5.3.4.2.8 Remarks

- Stress in your explanation that the change in pressure due to temperature change is so much stronger than in the situation with an ideal gas.
- In preparing the flask, fill it with heated water in order to reach 100°C quicker.

5.3.4.2.9 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 217.
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 4, Wärmelehre, Thermodynamik, Wetterkunde, pag. 125.

5.4 4D Kinetic Theory

5.4.1 4D10 Brownian Motion

5.4.1.1 01 Brownian motion

5.4.1.1.1 Aim

To show the random zigzag motion of small particles in a liquid.

5.4.1.1.2 Subjects

- 4D10 (Brownian Motion)

5.4.1.1.3 Diagram

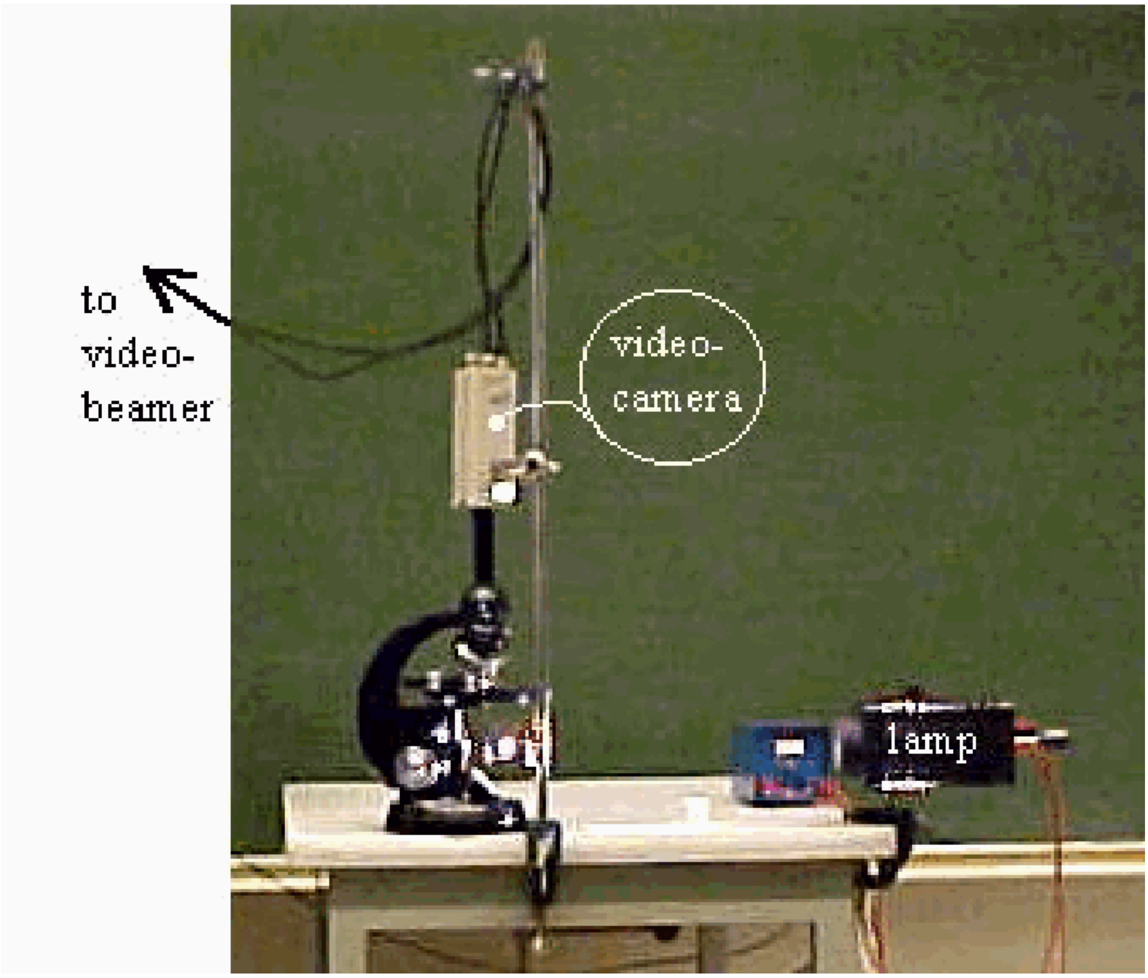


Figure 5.50: .

5.4.1.1.4 Equipment

- Microscope.
- Microscope slide on which a shallow "well" is made $\left(1 \times 1 \mathrm{~cm}^2\right)$ by means of thin adhesive tape.
- Thin cover glass (we use 0.1 mm).
- Solution op polystyrene latex particles, normally used as calibration particles in microscopic analysis (we use a solution with mean particle size $1.036 \mu \mathrm{m}$).
- Video projector.

5.4.1.1.5 Presentation

To show Brownian motion we use a solution of polystyrene latex particles in distilled water (see Equipment). A small drop of this solution is placed in the “well” on the microscope slide. The “well” is covered by the thin cover glass (see Figure 2).

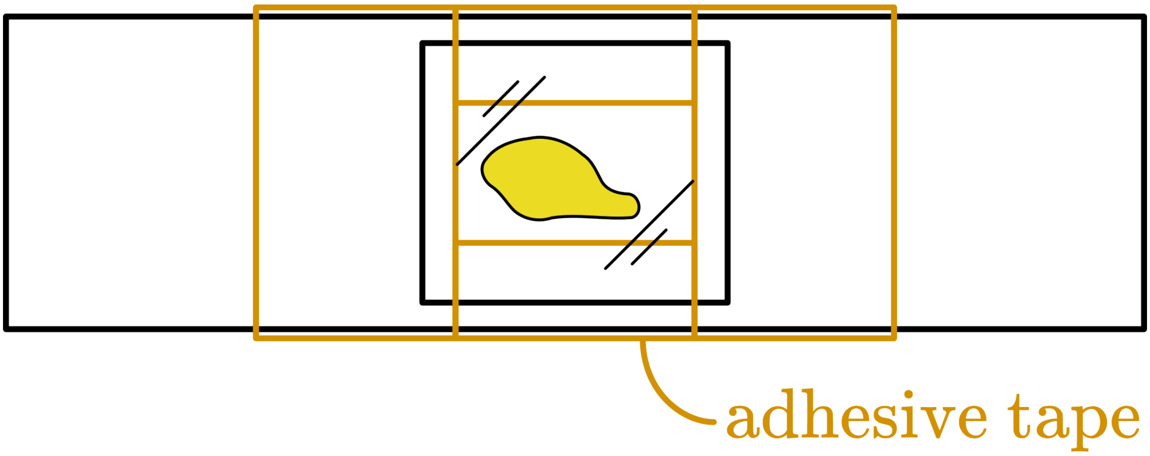


Figure 5.51: .

This combination is placed on the stage in the clutch mechanism of the microscope. The eyepiece of the microscope is removed and the video-camera (without lens) is placed on the tube (see Diagram). Using a 40x objective will make individual particles clearly visible when the sub-stage illumination is switched on. The zigzag movement of the particles can be observed now.

5.4.1.1.6 Explanation

This demonstration of these irregular motions by Robert Brown (1828) provides evidence for the basic hypotheses of the kinetic theory of gasses. These hypotheses postulate the microscopic particle nature of gasses to explain its macroscopic properties.

The random zigzag movement can be explained as being the result of the bombardment of the many molecules of the liquid (which are too small to be visible themselves). To “prove” this, a simulation can be shown. ISSUE: simulation needed.

5.4.1.1.7 Remarks

- The drop in the “well” should not touch the walls of the well, because otherwise leakage of liquid is inevitable and this will show as a strong flow in your liquid. So really get a drop something like in Figure 2.
- We get the best image when we focus not on the surface of the liquid but at a certain depth.

5.4.1.1.8 Sources

- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 247.

5.4.2 4D30 Kinetic Motion

5.4.2.1 01 Radiometer of Crooks

5.4.2.1.1 Aim

To show the effect of pressure due to molecular recoil.

5.4.2.1.2 Subjects

- 4D30 (Kinetic Motion)

5.4.2.1.3 Diagram

Figure 5.52: .

5.4.2.1.4 Equipment

- Crooks' radiometer.
- Incandescent lamp, 100 W.

5.4.2.1.5 Presentation

The radiometer is placed in the light beam of the incandescent lamp. The vanes of the radiometer will start rotating. Adjust the distance between the radiometer and lamp so the sense of rotation can be well observed: the black sides turn away from the light beam.

5.4.2.1.6 Explanation

The radiometer has been evacuated to a pressure of approximately 1 Pa. Since the black sides of the vanes absorb more energy than the mirrored sides, the black sides become hotter. By conduction, the air in contact with the black sides becomes hotter than that in contact with the mirrored sides and so the air molecules close to the black sides have a higher impulse than those close to the mirrored sides. When colliding with the vanes the change in impulse is higher on the black sides and so the force exerted on the black sides is higher.

(The mean free path of the gas molecules at the pressure of 1 Pa is about the size of the radiometer bulb, which allows for a particular efficient transfer of momentum between the gas molecules and the vanes.)

5.4.2.1.7 Remarks

- You can make the radiometer run backward when it is placed in the presence of a cold object.
- An incorrect explanation often given for the rotation of the vanes is based on the different pressure of light photons on the black and mirrored sides. But this would require the vanes to rotate in the direction opposite to that actually observed. (See also the demonstration: Radiation pressure?.)

5.4.2.1.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 117
- Jewett Jr., John W., Physics Begins With Another M... : Mysteries, Magic, Myth, and Modern Physics, pag. 271-72
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 242

5.4.2.2 D30 Rain of balls

5.4.2.2.1 Aim

To show by means of a large scale model the results of the interaction between gasmolecules and a wall.

5.4.2.2.2 Subjects

- 4D30 (Kinetic Motion)

5.4.2.2.3 Diagram

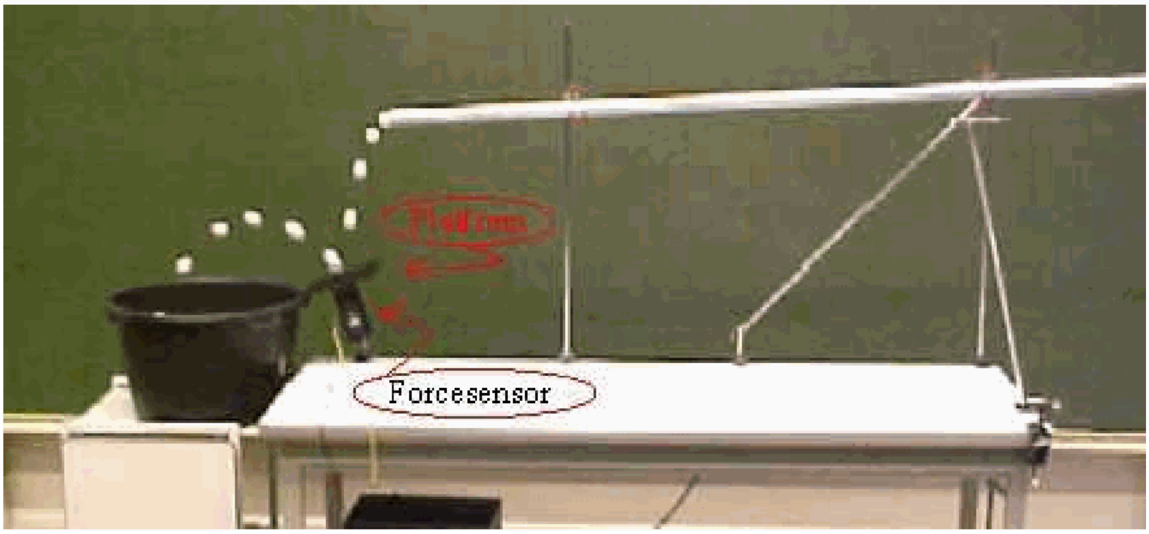


Figure 5.53: .

5.4.2.2.4 Equipment

- 50 ping-pong balls.
- Pipe, $l = 2$ m; internal diameter 40 mm, with a pin through its end.
- Large container to catch the rain of ping-pong balls.
- Force sensor.
- Platform. This is an acrylic sheet, $22 \times 22 \times .2$ cm, mounted to the forcesensor.
- Data-acquisition system with interface.
- Projector to project an image of the monitorscreen.

5.4.2.2.5 Presentation

5.4.2.2.5.1 Preparation.

The pipe is filled with ping-pong balls and clamped slightly slanting just to enable the balls to roll by themselves. The force-sensor with the acrylic platform is fixed to the table and stands oblique, that much that when a ping-pong ball falls on it, this ball jumps into the large container (see Diagram). The software of the data-acquisition system displays the force on the platform in a time-graph and average force on a digital display. Use the tare-button on the force-sensor to “zero” it.

5.4.2.2.5.2 Presentation

First drop, by hand, one ball on the platform and monitor the force-time graph. Use this graph to explain to your students how the demonstration set-up functions and what the readings of the graph and meter tell us.

- The force diagram shows a strong oscillation of the platform. Using the zoom function of the software, it can be shown that at the beginning there is a strong positive impulse: F - Δt-area. (The subsequent oscillation averages to zero.)

Reset the software to a recording mode and then pull the pin out of the end of the pipe: A train of balls falls onto the platform. All students' attention might be attracted to the falling balls, so draw their attention also to the ongoing registration of the graph and digital meter. After the rain of balls is over, the results can be discussed. Especially worthwhile are the high force readings of the individual balls (up to 14 N! See Figure 2) in contrast to the low average force on the digital scale (0.08 N).

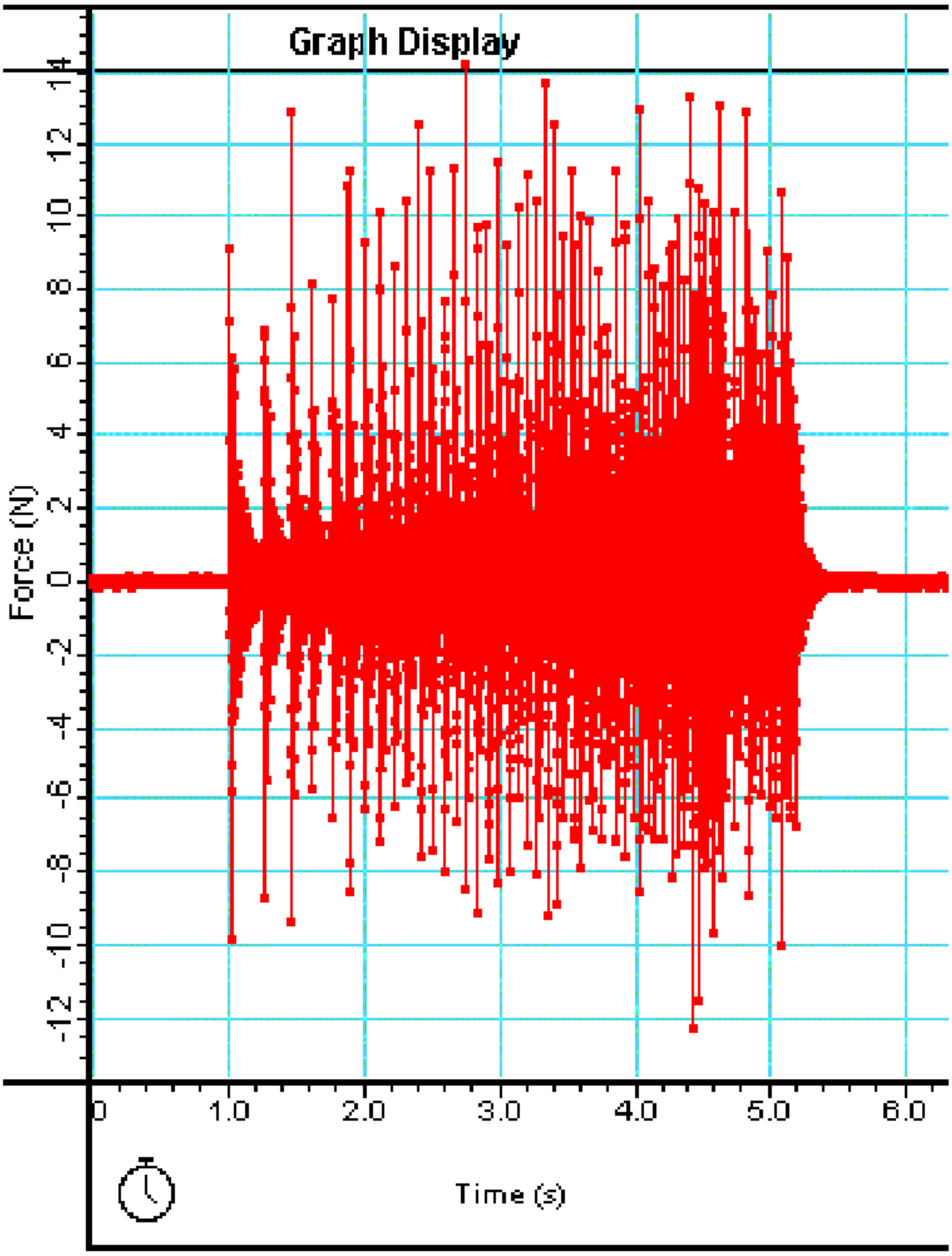


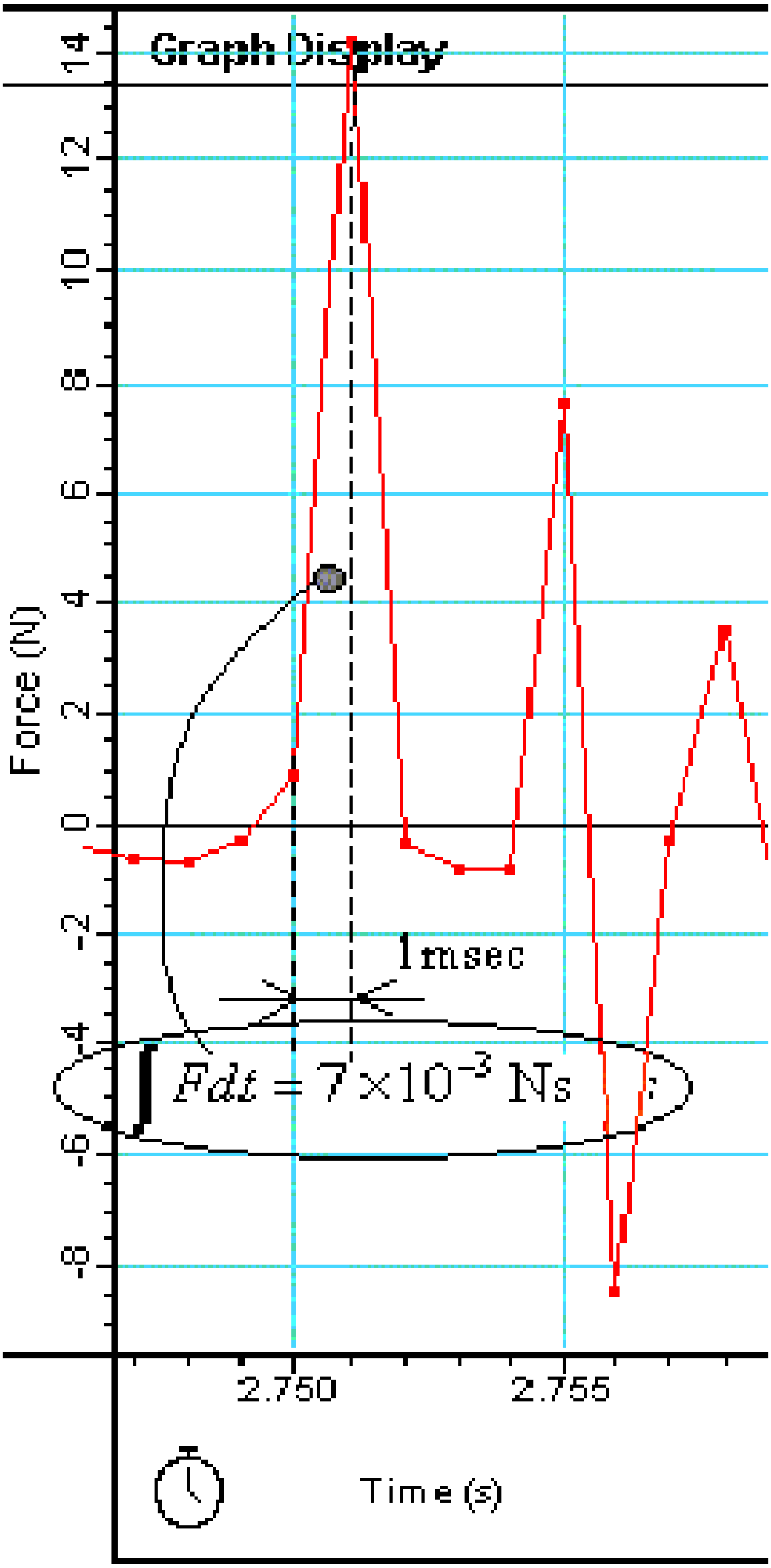
Figure 5.54: .

5.4.2.2.6 Explanation

The force exerted by an individual ping-pong ball equals $\vec{F} = \frac{\Delta \vec{p}}{\Delta t}$. F can be that high since Δt (the time the ball touches the platform) is very small. The kinetic theory of gasses shows that the force on the wall of a container filled with a gas is proportional to the average scalar product of momentum and velocity of the gas molecules $F = \frac{1}{3} \frac{NA}{V} (\vec{p} \cdot \vec{v})$.This demonstration shows the proportionality with $\vec{p}$.

5.4.2.2.6.1 Force due to one collision

When we examine the force-time graph it can be seen that the rise time of F during the collision is in the order of 1msec (see the registration in Figure 3).



Graph Display
14
12
10
8
6
4
2
0
-2
-4
-6
-8
Force (N)
1 msec
$\int Fdt = 7\times10^{-3}$ Ns
2.750
2.755
Time (s)

Figure 5.55: .

The ping-pong ball has a mass of 2.5×10^{-3} kg and falls a height of around 0.5 m, so at the collision with the platform it has a speed of around 3 m/s. So, the momentum at collision is 7.5×10^{-3}kgm/s. The impulse $\int F dt = \Delta p$. So, in this case $\int F dt$ should read 15×10^{3} Ns. Using the function "integrate" of the software over the corresponding impulse-area will produce that result. Since the collision is not perpendicular and not completely elastic, the registered $\int F dt$ will be lower than 15×10^{-3}Ns.

5.4.2.2.6.2 Average force

In our macroscopic world we experience the average force. After a collision with a pingpong ball the platform shows a damped free oscillation. Such a free oscillation averages to $\mathrm{F} = 0$. The force-time graph shows 5015×10^{-3}-collisions in about 4 seconds time average to around 0.19 N. Selecting the area between of 4 seconds the software shows this as the mean y-value.

5.4.2.2.7 Remarks

- The platform that is hit by the ping-pong balls is not an ideal rigid wall as meant when you treat the details of the kinetic theory of gasses. As the registered graph shows, the platform vibrates strongly (in many modes) after a hit. However, when we average the registered forces of these vibrations (so average the whole registered graph of a hit except the "real hit" at the beginning) we find 'zero' as a result.

5.4.2.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 247-250
- PASCO scientific, Instruction Manual and Experiment Guide, pag. CI-6537

5.5 4F Entropy and the Second Law

5.5.1 4F10 Entropy

5.5.1.1 01 Falling down or falling up

5.5.1.1.1 Aim

To show that falling down can be explained: it's entropy!

5.5.1.1.2 Subjects

- 4F10 (Entropy)

5.5.1.1.3 Diagram

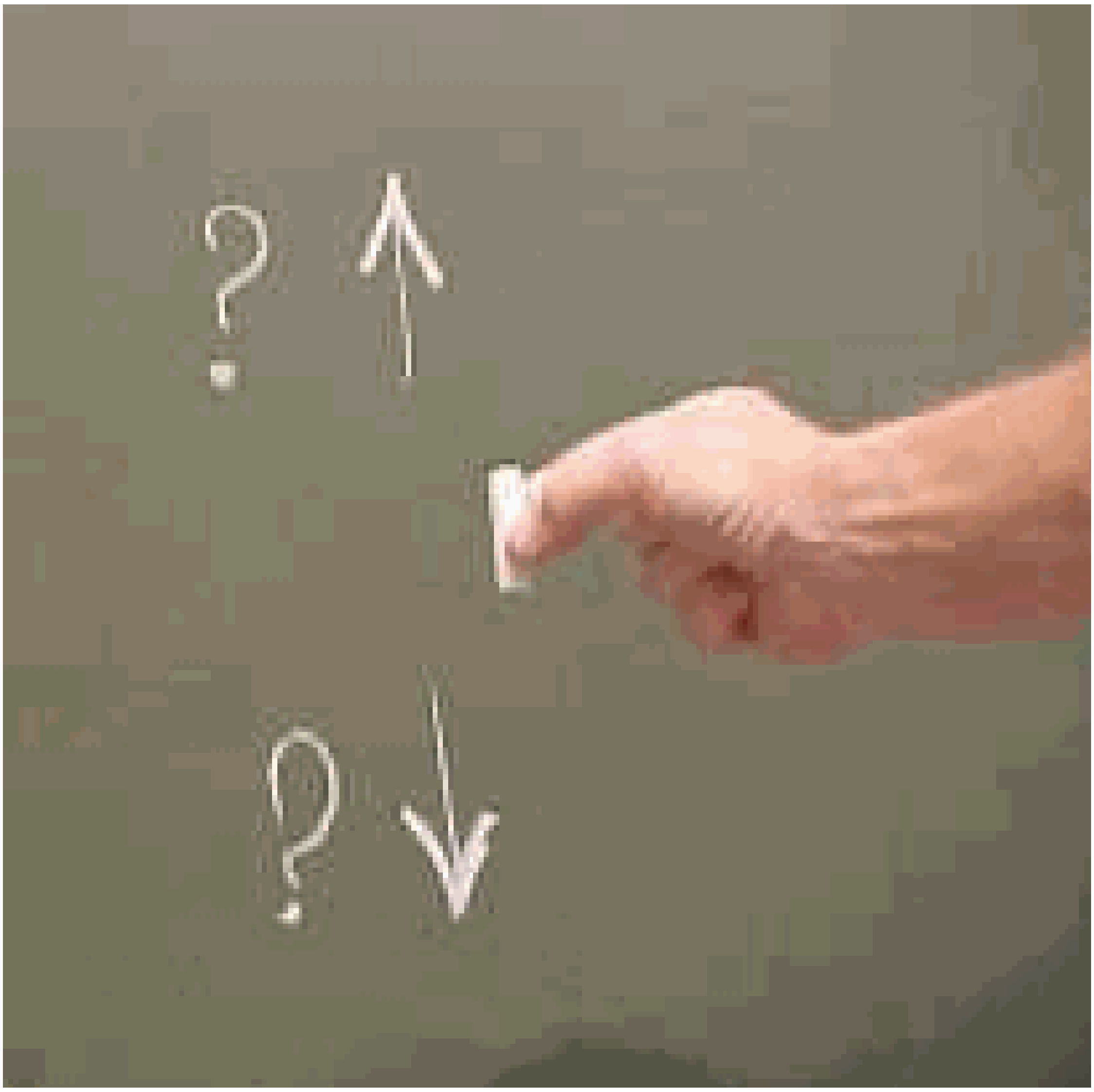


Figure 5.56: .

5.5.1.1.4 Equipment

- Piece of chalk

5.5.1.1.5 Presentation

Hold a piece of chalk and ask the students what will happen when you let it go. To them it goes without saying that it will fall downwards. But in physics nothing is taken for granted.

Physics gives us the equation of motion $m\frac{d^2y}{dt^2} = -mg$, and this produces two

solutions: One positive and the other negative. How to choose between these two? Why should one solution be more true to reality than the other? Usually mathematics gives us the right solution, so why should one solution be more worthwhile than the other?

5.5.1.1.6 Explanation

The instrument to choose with, is: Entropy !

During the movement of the chalk, either up or down, there is conservation of energy (first law of thermodynamics): $dU = dQ - dW$

Considering the falling chalk also as an isolated system means: $dU = 0$, and so: $dQ = dW$. Then we can also write: $\frac{dQ}{T} = \frac{dW}{T}$, and since $dW = F.dy$ and $\frac{dQ}{T} = dS$ (being the expression of the change in entropy of the system considered), we have: $dS = \frac{1}{T}Fdy$, giving: $dS = \frac{1}{T}(-mg)dy$ and: $\Delta S = -\frac{mg}{T}h$.

When h is positive, then the change in entropy, ΔS, is negative, showing the impossibility of this process; the entropy of an isolated system never decreases (second law of thermodynamics).

The piece of chalk cannot fall upwards due to the second law of thermodynamics!

5.5.1.1.7 Remarks

- Together with this demonstration we show the demo Fakir in order to show to the students that something not expected (falling upwards) can be reality (the upside-down pendulum).

5.5.1.1.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 494 and 532-533

5.5.1.2 02 Irreversible process

5.5.1.2.1 Aim

To show that the likelihood of the occurrence of a reverse process can be so small as to be completely negligible.

5.5.1.2.2 Subjects

- 4F10 (Entropy)

5.5.1.2.3 Diagram

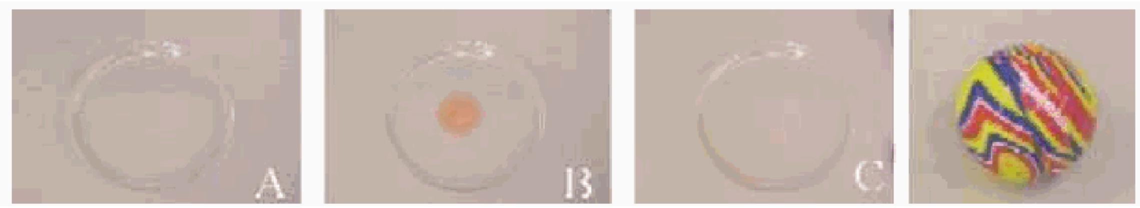


Figure 5.57: .

5.5.1.2.4 Equipment

- Glass basin; $\emptyset = 15$ cm
- Drop of ink.
- Overhead projector.
- (tennis) Ball.

5.5.1.2.5 Presentation

The glass basin is filled with a layer of water. This is projected (DiagramA). Then a drop of ink is carefully placed on the surface of the water. The drop slowly spreads itself in the water (DiagramB).

During the explanation (see Explanation) the continuing spreading of the drop can be observed by the students and at the end of the lecture they see the almost homogeneous distribution of the ink drop in the water (DiagramC).

Seeing the continuing spreading of the ink drop, we can also say that the homogeneous distribution of the ink drop is the most probable state of the fluid in the glass basin.

5.5.1.2.6 Explanation

The irreversibility of this mixing process is well known to the students; it corresponds to their own experiences. New is the concept of probability linked to this process. To illustrate this a tennis ball is given to one student in the middle of a complete row of students sitting in the lecture hall and they are asked to pass this ball in that row, unseen to other students, arbitrary from left to right. After some time you ask the other students to tell where the ball is: is it on the left side of the lecture hall or on the right side? After short discussion their answer will be that the probability for either side is 50%. Then the same question is posed in case we suppose that two balls are in the row: What is the chance that both balls are on one side? 25%, that will be their answer. The general rule is that the chance of finding all balls on one side is $(.5)^n$, n being the number of balls involved. So with 4 balls that chance is $(.5)^4 = 1/16$. The table shows the 16 possible states. With 10 balls the chance is 0.00098 (around .1%) and with 100 balls: 7.9×10^{-31}, showing that the chance decreases very rapidly with the number n.

A drop of ink (a sphere of "water" with a diameter of 1 mm) contains around 2.5×10^{15} molecules. So the chance to find all these molecules on one side of the basin equals $(.5)^{2.5\times10E15}$.

This is such an extremely small number, that it will never happen during any physically meaningful period of time.

Finding the ink drop just as “a drop” has a chance that is even lower.

So that will never happen.

Possible states of 4 balls A, B, C and D							Total
4 left	$ABCD/-$						1
3 left; 1 right	ABC/D	ABD/C	ACD/B	BCD/A			4
2 left; 2 right	AB/CD	AC/BD	AD/BC	BC/AD	BD/AC	CD/AB	6
1 left; 3 right	A/BCD	B/ACD	C/ABD	D/ABC			4
4 right	$-/ABCD$						1

In the table above we see that the situation with 2 balls left and 2 balls right is the most probable state. This is also the most homogeneous distribution of the 4 balls. And this corresponds to the homogeneous distribution of the fluids in the glass basin; so this is the most probable state.

5.5.1.2.7 Sources

- PSSC, College Physics, pag. 394-396
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 535-537

5.5.1.3 03 Violation of the entropy law

5.5.1.3.1 Aim

To show an apparent violation of the second law of thermodynamics

5.5.1.3.2 Subjects

- 4F10 (Entropy)

5.5.1.3.3 Diagram

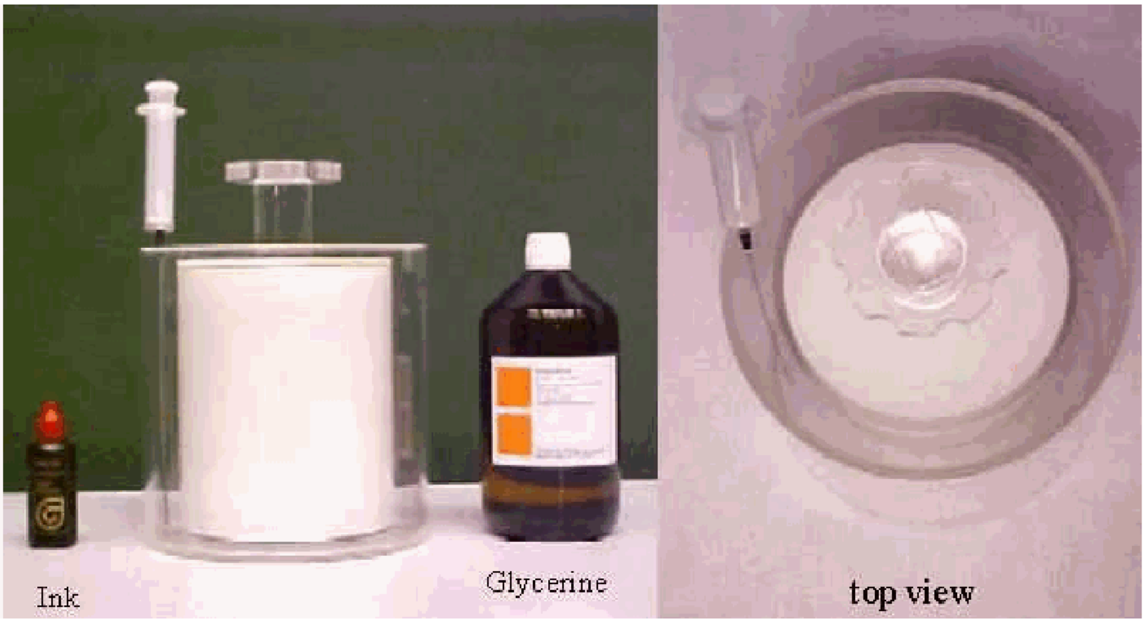


Figure 5.58: .

5.5.1.3.4 Equipment

- Petri dish.
- Transparent oil (e.g. sunflower oil).
- Transparent cylinder, containing a second, white cylinder inside that can turn around the common axis.
- Glycerine.
- Syringe with long needle.
- Red ink.

5.5.1.3.5 Presentation

As an introduction a Petri dish is placed on the overhead projector. The dish contains a layer of (transparent) oil. By means of the syringe a large drop of dark ink is spouted into the oil (see Figure 2 a). Using a flat spatula one rotation is made in the fluid. The drop of dark ink breaks into smaller drops (Figure 2b).

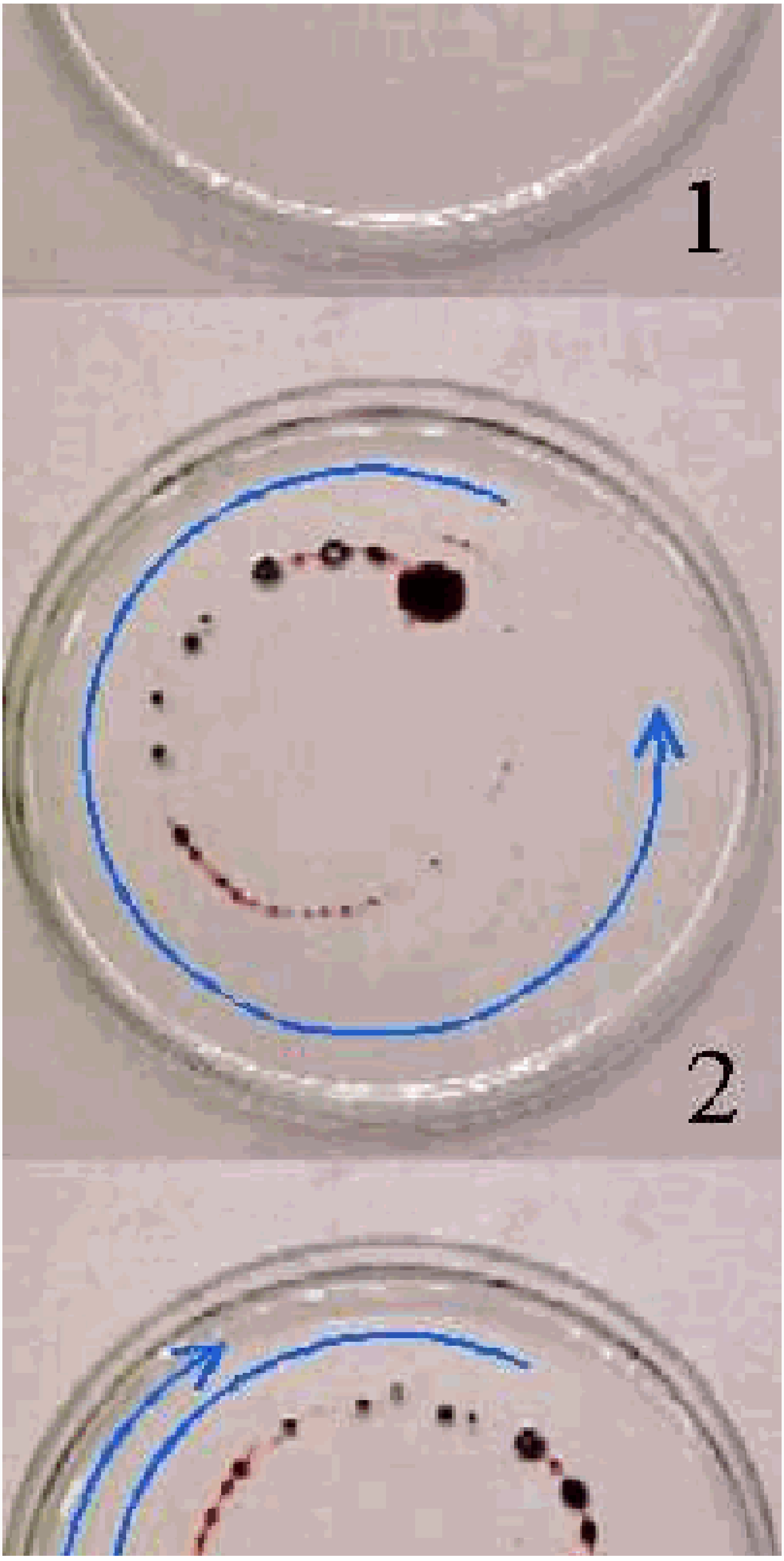

1
2

Figure 5.59: .

Now it is suggested to the students to turn the spatula in the liquid into the opposite direction, in order to repair the original drop of ink. This action is performed, but the result is that still more destruction is done to the inkdrops (Figure 2c).

Next the experiment with the plastic cylinder (see Diagram) is done:

The space between the two concentric cylinders is filled with glycerine and a column of ink is introduced into the glycerine using the syringe with a long needle.Then the inner cylinder is rotated one turn and it appears that the ink is mixed with the glycerine. But when a reverse turn is made, the column of ink reforms!

The experiment can be repeated, even making more turns: the column reforms when the same number of reverse turns is made.

5.5.1.3.6 Explanation

There is no violation of the entropy law at work in this demonstration. The spreading out of the ink does not represent any increase in entropy or disorder. An enlarged top view of the space between the two cylinders (see Figure 3) shows that molecules on the inner edge of the liquid rotate through angles different from those in the middle or outer edge. There is only a laminar displacement; no mixing occurs. And so the original vertical line is restored when the rotation is reversed.

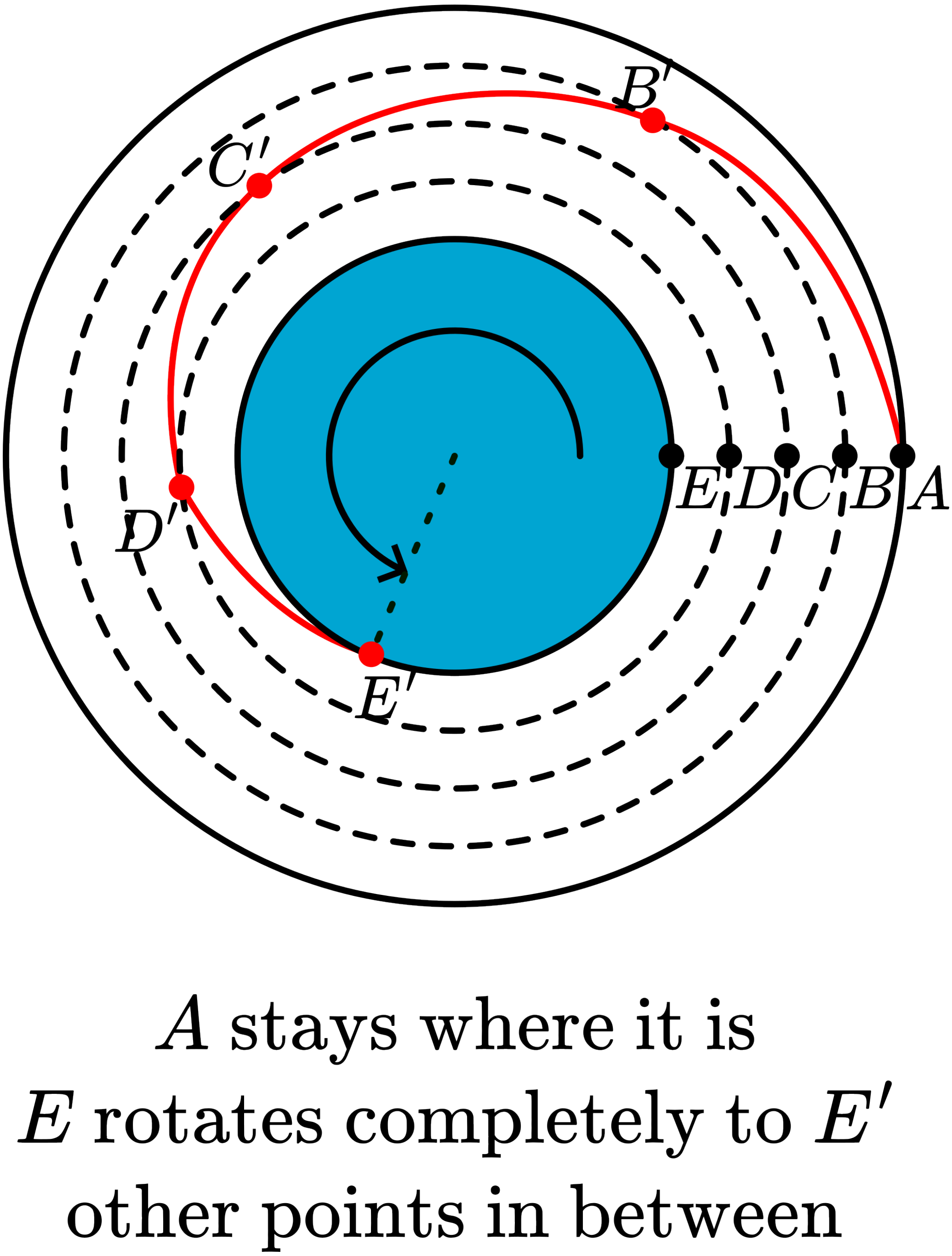


Figure 5.60: .

5.5.1.3.7 Remarks

- When the glycerine is too fluid it is advised to refrigerate the system before using it.
- The inner cylinder is constructed heavy enough to prevent it will float in the glycerine.

5.5.1.3.8 Sources

- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 124-125
- Freier, George D. and Anderson, Frances J., A demonstration handbook for physics, pag. H31
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 290

5.5.2 4F30 Heat Cycles

5.5.2.1 01 Dippy Bird

5.5.2.1.1 Aim

To show the pressure-volume behaviour of a vapour.

5.5.2.1.2 Subjects

- 4C33 (Vapor Pressure) 4F30 (Heat Cycles)

5.5.2.1.3 Diagram

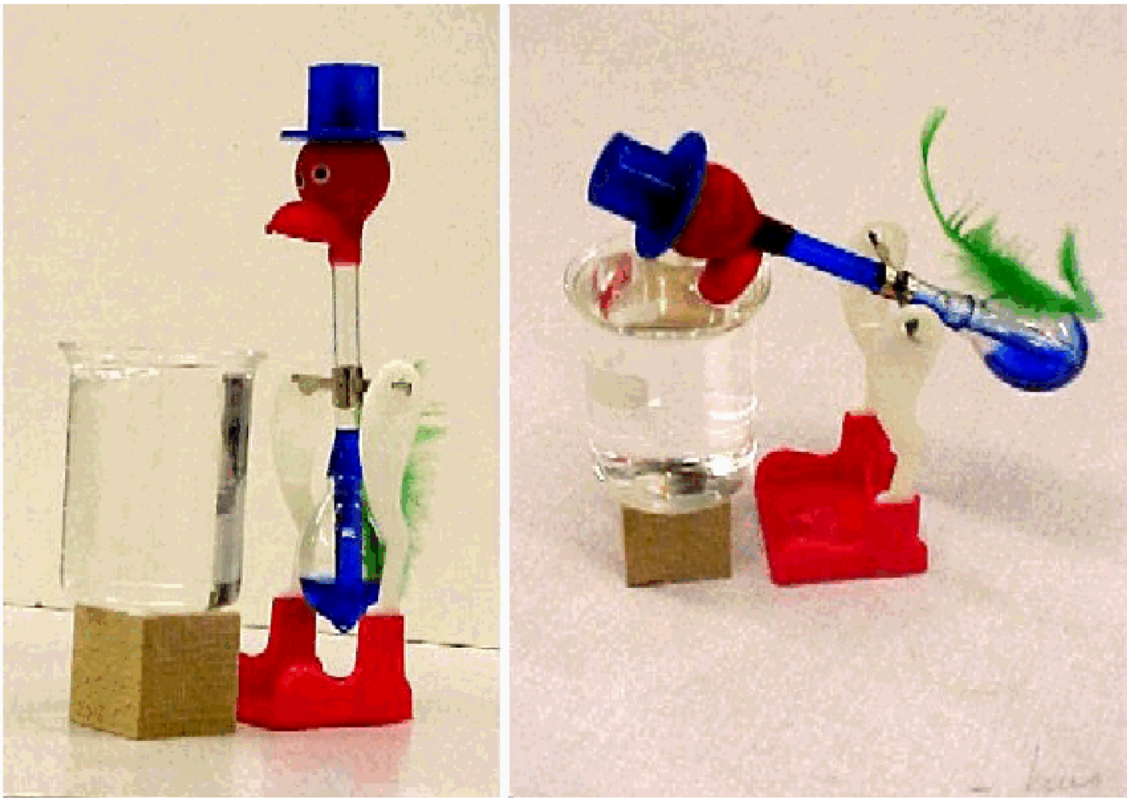


Figure 5.61: .

5.5.2.1.4 Equipment

- Dippy bird.
- Small beaker, filled with distilled water.
- (Second dippy bird and lamp; see at the end of 'Explanation'.)

5.5.2.1.5 Safety

- Despite the drinking bird's appearance and classification as a toy, some safety considerations apply. The liquid inside the dippy bird is dichloromethane. Dichloromethane can irritate the skin on contact, and the lungs if inhaled; it is a mutagen and teratogen, and potentially a carcinogen. The intact toy is leakage proof and completely safe, but if broken hazardous dichloromethane is released. Dichloromethane evaporates quickly; good ventilation after a spill will dilute and disperse the vapour.
- Always keep a beaker in front of the bird. The beaker stops the forward movement of the bird. When there is no beaker to stop the forward movement of the bird, the glass bird will fall down and the glass breaks.
- (Early models of the dippy bird were often filled with highly flammable substances. The fluid in later versions is nonflammable.)

5.5.2.1.6 Presentation

Set up the dippy bird and the beaker as shown in the Diagram. Fill the beaker with distilled water and dip the beak of the dippy bird in it. Then let the bird go. While the bird is swinging, the blue liquid rises from the belly through the central tube to the head. The bird topples, and dips its beak into the water again, the blue liquid runs down the straight tube and the bird rises again to its vertical, swinging position. This goes on and on, repeating its chain of events.

To the teacher it is very instructive to have the students explain what is happening. So just put the bird in your lecture room and let the students break their brains.

5.5.2.1.7 Explanation

Figure 2 shows the system. The bird is filled with a liquid (dichloromethane) having low latent heat of evaporation. Only this liquid and its vapour are inside the bird.

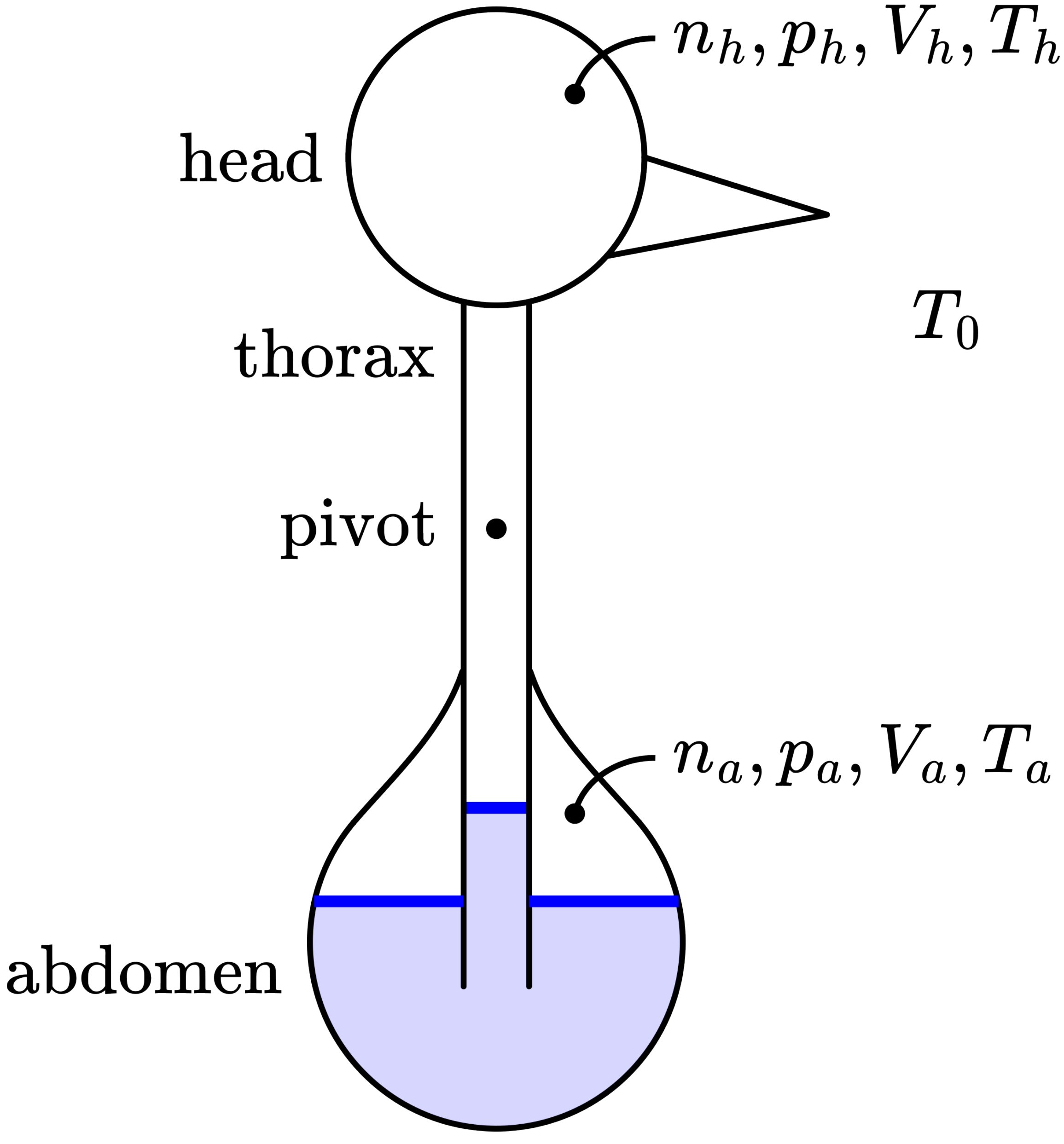


Figure 5.62: .

Initially the system is at equilibrium. There are two spaces to consider: the head with n_h moles of vapour and the abdomen with n_a moles of vapour.

Evaporation of water on the beak outside the head draws heat from inside it; the vapour inside the head partially condenses, reducing n_h and thus lowering p_h. Now the pressure p_a in the abdomen pushes fluid up the thorax, which reduces the volume V_h of the head. Consequently the volume V_a of the abdomen increases. This causes evaporation in the abdomen (increasing n_a), made possible by drawing heat from the surroundings.

The rising fluid raises the centre of mass above the pivot point, so the bird dips. The amount of fluid is set so that at full dip the lower end of the tube is exposed to the vapour. A bubble of vapour rises in the tube and fluid drains into the abdomen. The rising bubble transfers heat to the head. The centre of mass drops below the pivot point and the bird bobs up, oscillating back to its starting position.

Due to this fast swinging movement, there is good evaporation of the water on the beak, and the whole cycle described above repeats itself.

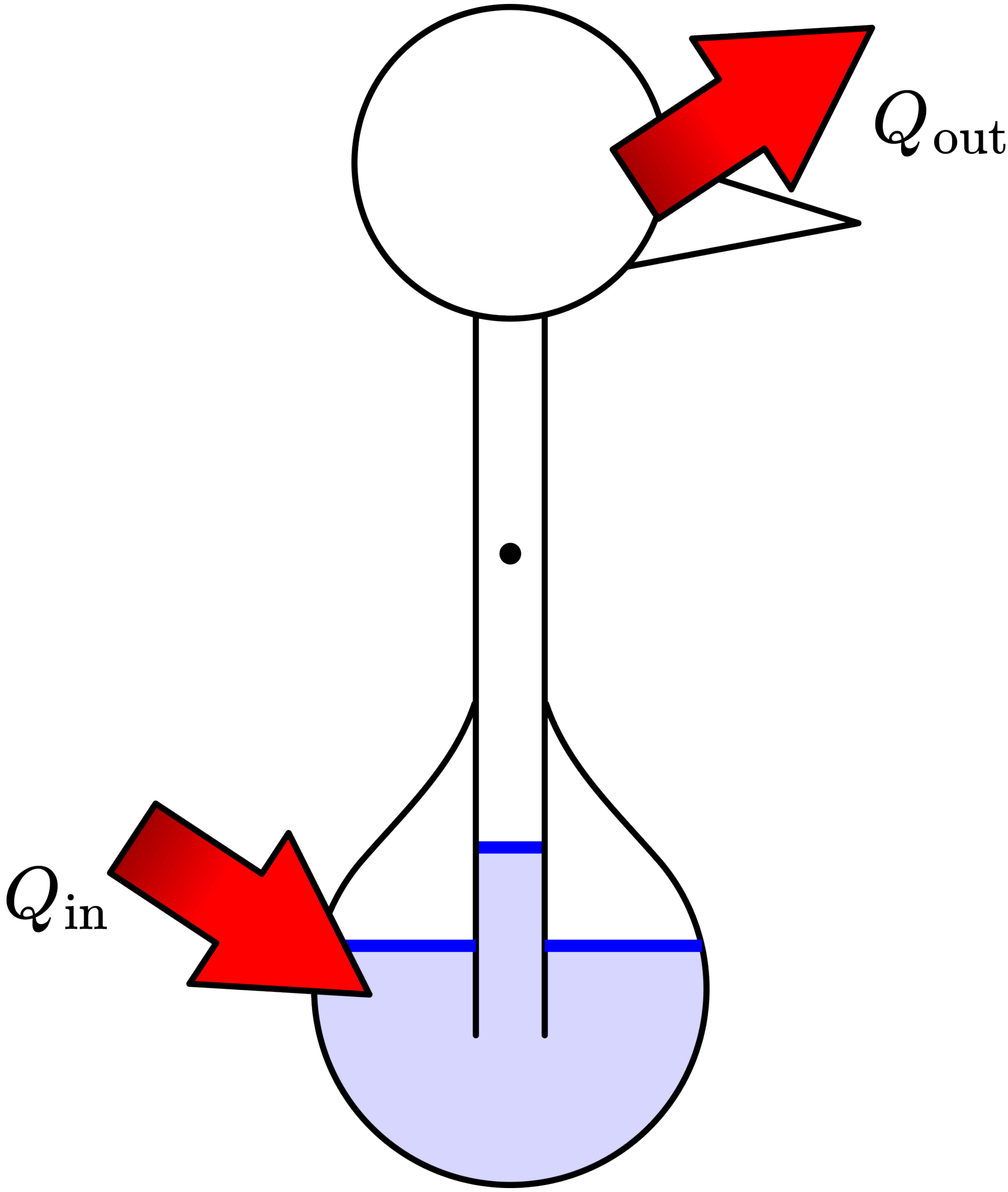


Figure 5.63: .

Figure 3 shows the behaviour of the dippy bird as a heat-engine. Heat flows into the bird at the abdomen and is discarded at the head/beak-side.

5.5.2.1.7.1 A second bird

Considering the dippy bird as a heat-engine (see Figure 3) induces the idea that it will work as well when, instead of cooling the head, you heat up the abdomen. We tried this by shining light on the dippy's bottom and indeed, the bird dipped! Demonstrating also this version of the dippy bird will once more make clear that the factor that makes heat-engines work is the temperature gradient.

5.5.2.1.8 Remarks

- We use distilled water instead of tap water, because in our city tap water is hard water and in due time the lime would thermally isolate the beak of the bird.
- When the bird dips his beak into the water, sometimes it is stuck there due to surface tension. This can be prevented by changing the set up such that it dips its beak less deep into the water.
- Take care not to make the head so wet that it drips down the tube: it will change the balance of the bird and it will also cool down the bottom too much. Both effects will stop the swinging of the dipping bird.
- The pivot of the bird is bent, to unbalance the bird always into the forward direction.
- As a heat engine the dippy bird can produce work, but this is very low, with a low efficiency (see Sources).

5.5.2.1.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 276-277.
- The Physics Teacher, R. Mentzer, pag. 126-127, Vol 31 (1993).
- The American Journal of Physics, J. Guemez e.o., pag. 1257-1263, Vol 71 (2003).
- The American Journal of Physics, R. Lorenz, pag. 677-682, Vol 74 (2006).

5.5.2.2 02 Stirling engine

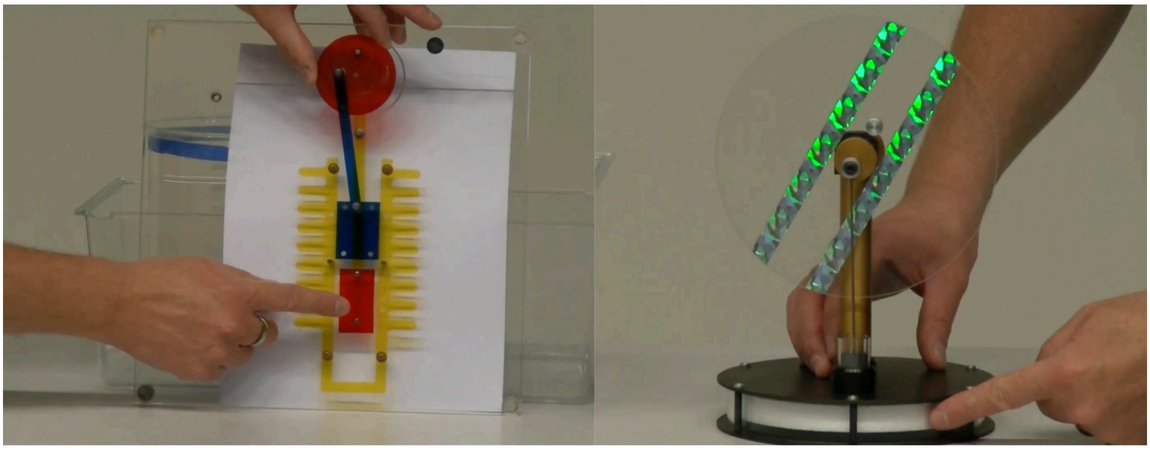
5.5.2.2.1 Aim

To show that a Stirling engine functions when there is a TD.

5.5.2.2.2 Subjects

- 4F30 (Heat Cycles)

5.5.2.2.3 Diagram



(a) (b)

Figure 5.64: .

5.5.2.2.4 Equipment

- 2 Beakers, 2 l.
- Stirling engine, low TD.
- OHP-model of Stirling engine.
- Digital thermometer.

5.5.2.2.5 Presentation

A beaker is filled, almost to the rim with hot tap water (about 50°C). The Stirling engine is placed on top of it (see Diagram A) and after some time the instructor gently spins the flywheel. Try anti-clockwise spin, because then the students will observe that the engine by itself wants to spin clockwise, and so it will do. During the lecture the engine continues spinning.

After some time, halfway your lecture, the instructor places the still running engine on the beaker filled with ice. Very soon the engine slows down and will stop. Some time later the instructor gently tries to spin the flywheel again in a clockwise direction, but to his surprise (?) the engine starts running now in the anti-clockwise direction. During the rest of the lecture-time the engine keeps on running this way.

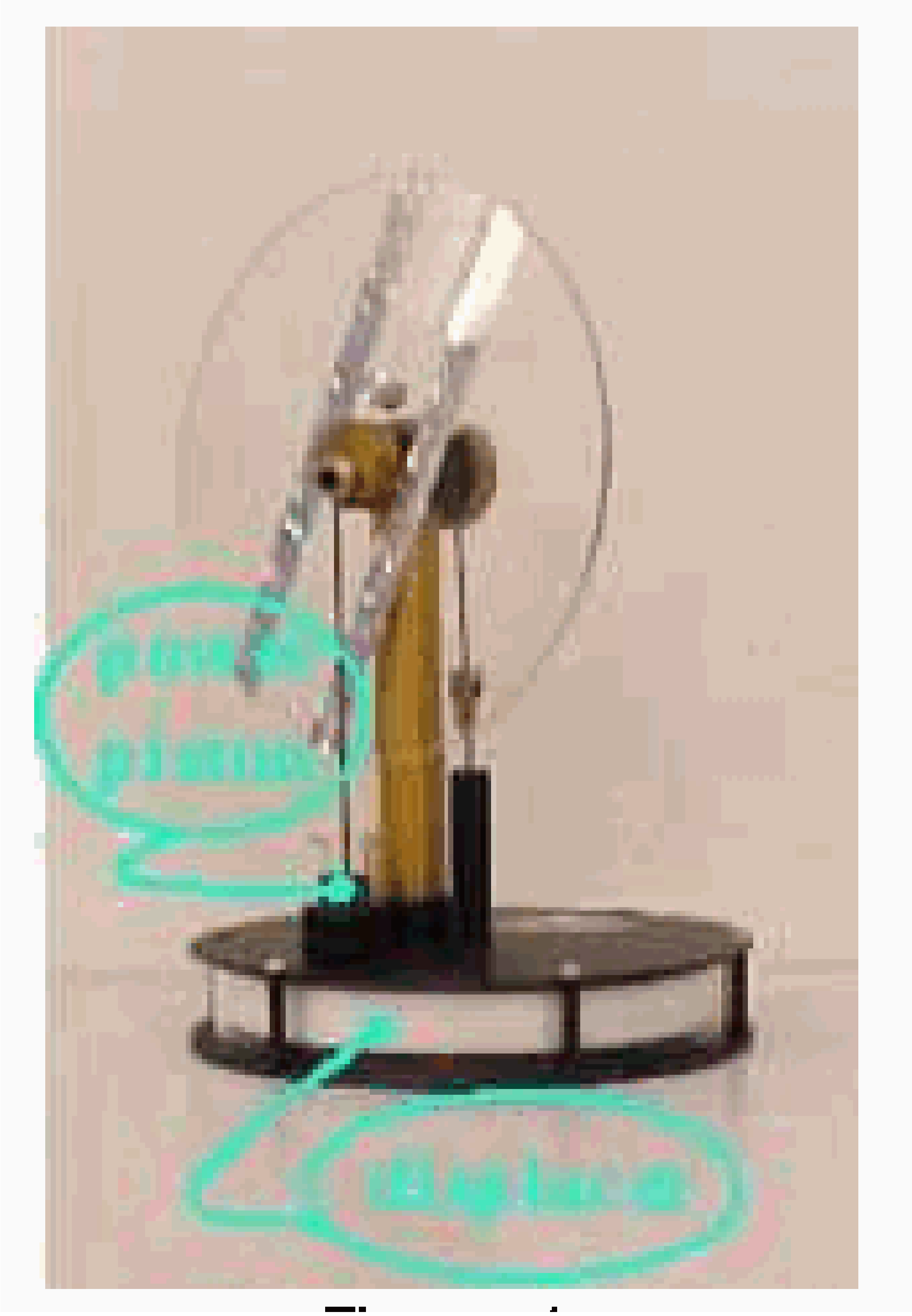


Figure 5.65: .

While studying the engine, the "hot"-side, the "cold"-side, the power piston and the displacer are observed (see Figure 2) and the similarity with the OHP-model is shown (see Diagram B; yes, upside-down!). The OHP-model is used to explain the principle of operation.

5.5.2.2.6 Explanation

Out of the Presentation it is clear that a temperature difference is needed to make the engine run and that the position of "hot" and "cold" determines the direction of rotation.

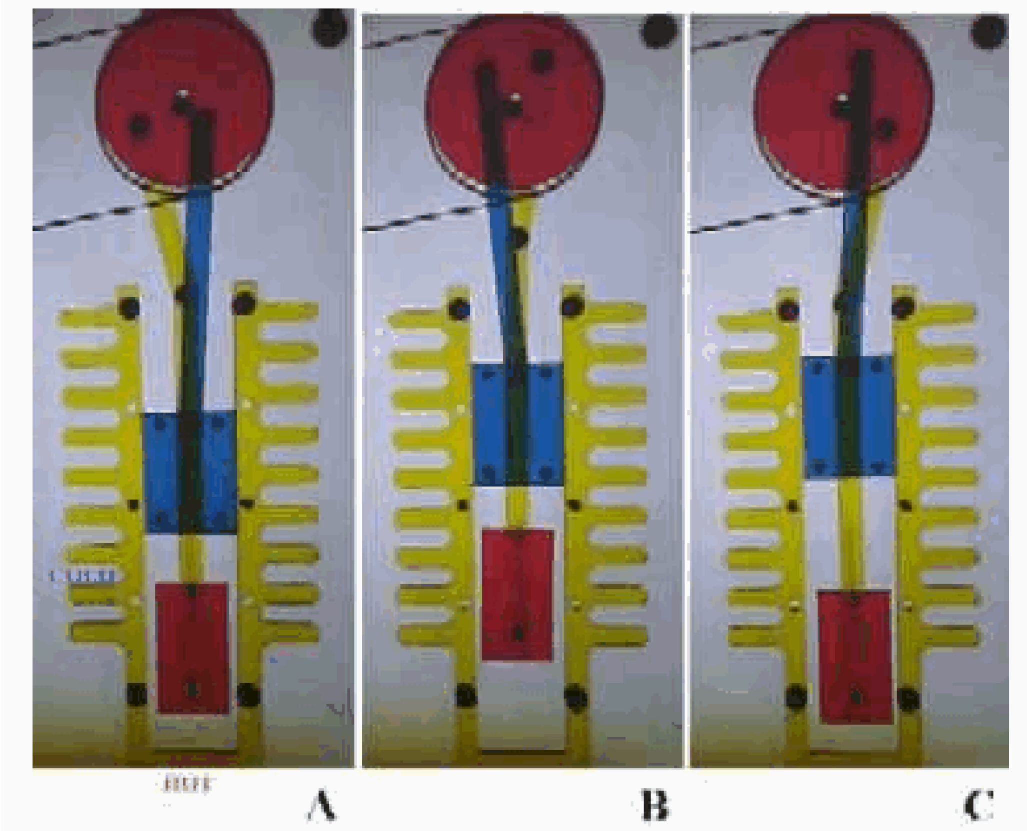


Figure 5.66: .

See Figure 3A. As the displacer moves away from the warmer side, air flows around the displacer to the warmer side and is heated.

Figure 3B. When the air is heated, it expands, which increases the pressure. This increase in pressure pushes up the power piston.

Figure2C. The energy stored in the flywheel moves the displacer to the warm side of the engine and the air once again flows around the displacer to the cold side of the engine. Figure 3A. When the air is cooled the pressure drops and this will pull down the power piston, the displacer moves back to the cold side, the air is displaced to the warm side, and the cycle starts all over again.

The displacer only moves the air back and forth from the warm side to the cold side of the engine.

When the "hot"-side and the "cold"-side change position it is easy to show with the OHPmodel that now the engine has to spin into the other direction to get the right sequence of: -Air is displaced to the warm side -The air is heated and there is expansion, pushing up the power piston -Air is displaced to the cool side -Air is cooled, contracts and pulls the power piston down -Air is displaced to the hot side -Etc.

5.5.2.2.7 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 281-282
- PASCO scientific, Instruction Manual and Experiment Guide, pag. SE-8575 and SE8576
- Wisman, W.H., Inleiding thermodynamica, pag. 115-117

6. Electromagnetism

6.1 5A Electrostatics

6.1.1 5A10 Producing Static Charge

6.1.1.1 01 E-Field in Material (Electric Soap Bubbles)

6.1.1.1.1 Aim

To discuss with students the phenomenon shown. It seems easy at first thought but yet appears rather complicated when shown to them.

6.1.1.1.2 Subjects

5A10 (Producing Static Charge) 5A40 (Induced Charge)

6.1.1.1.3 Diagram

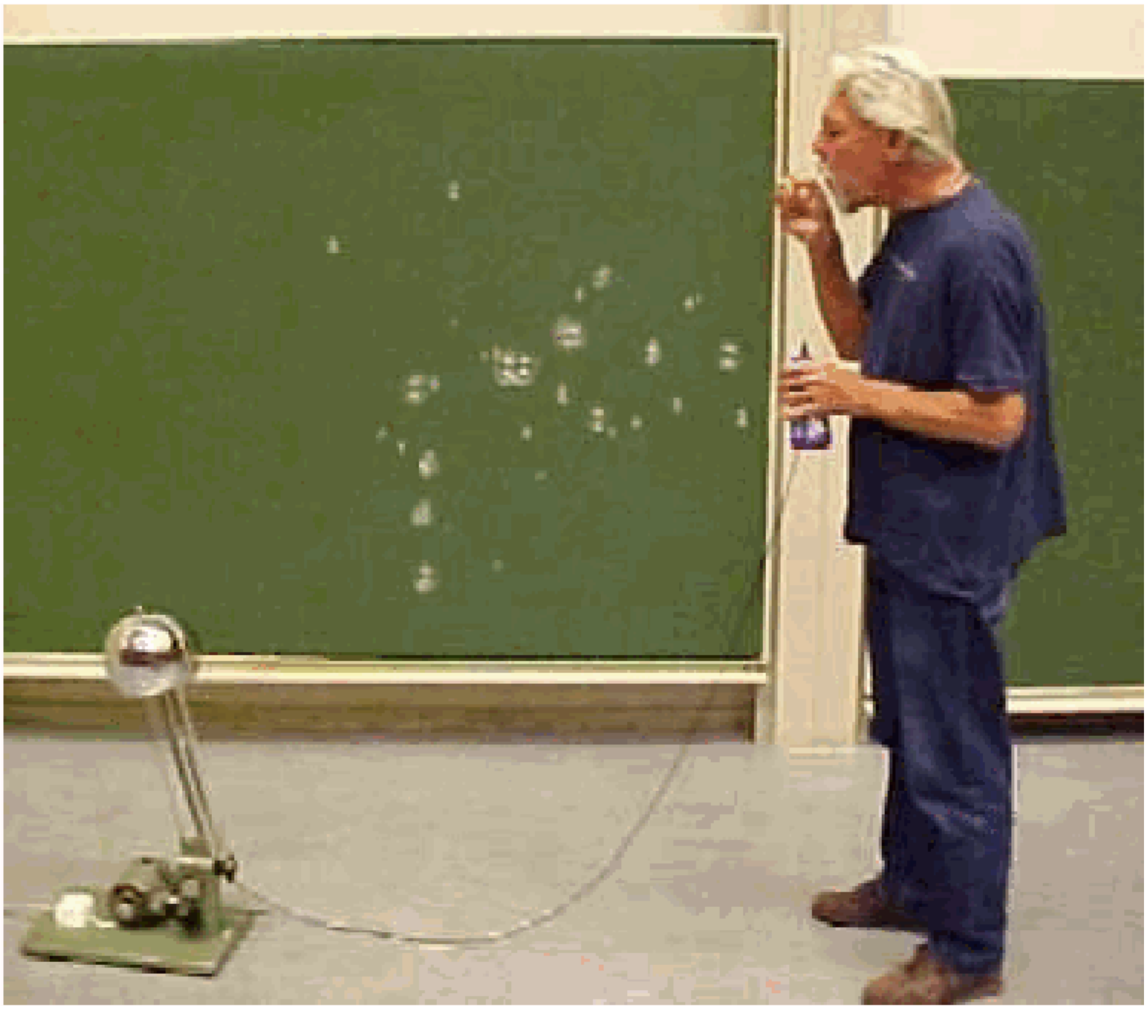


Figure 6.1: .

6.1.1.1.4 Equipment

- Van de Graaff generator.
- Soap solution.
- Grounded wire.
- Teacher, blowing soap bubbles.

6.1.1.1.5 Presentation

The teacher asks the students to reflect about what will happen to neutral soap bubbles that come in the neighborhood of a running Van de Graaff generator. After their ideas are discussed, and some predictions made, the Van de Graaff generator is switched on. The ground lead is plunged into the soap solution and at a distance of around 1.5-2 meters soap bubbles are blown into the direction of the generator.

The bubbles are clearly attracted towards the dome of the generator; they are accelerated (when coming close to the dome even their shape changes, see Figure 2). The first bubble hits the dome and explodes (occasionally it remains intact and bounces).

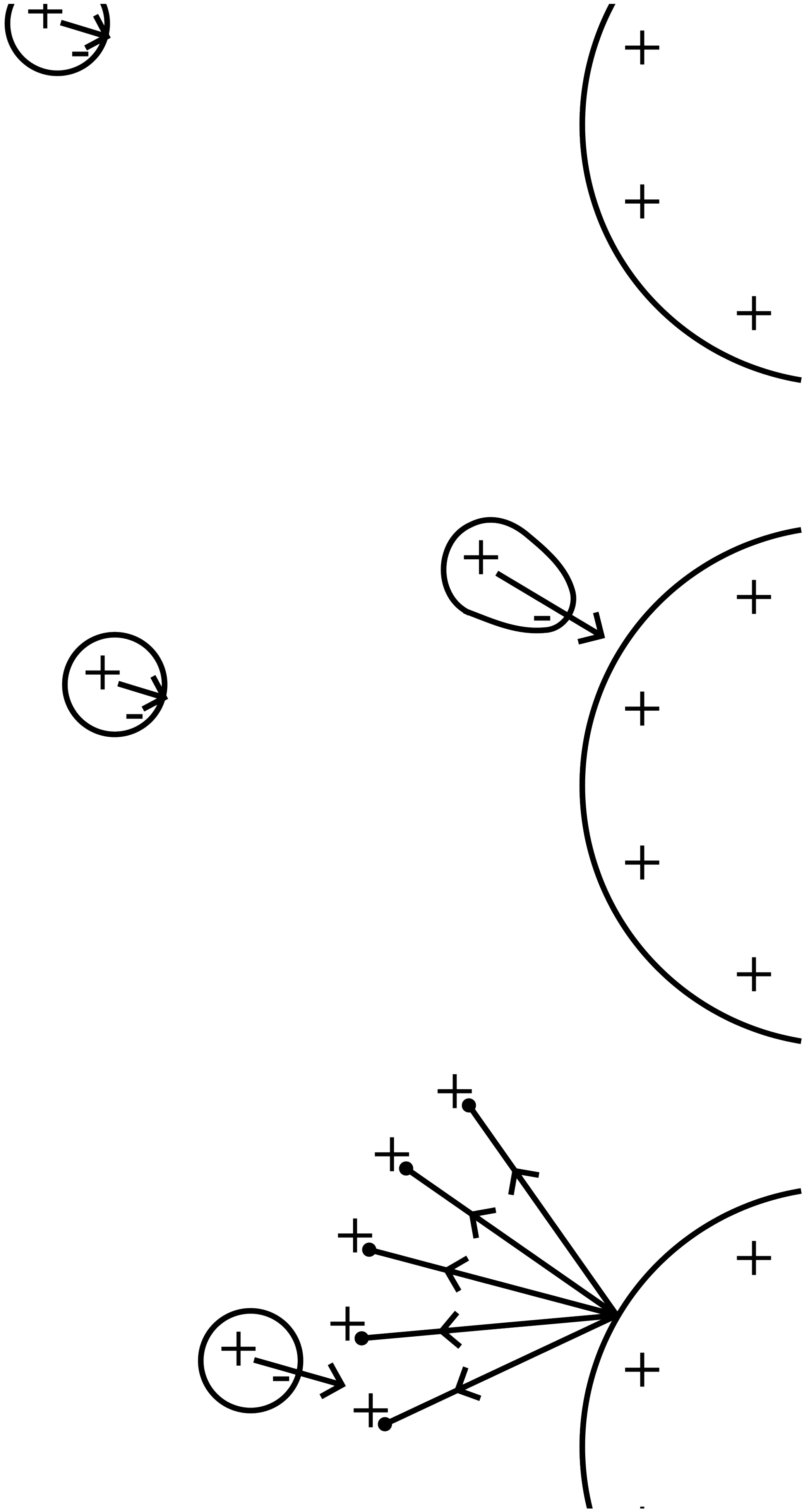


Figure 6.2: .

The other bubbles that are still on their way towards the dome are now pushed away from it. Also the next series of blown bubbles are all repelled. When you want again to see attraction, you first have to clean the dome.

6.1.1.1.6 Explanation

The blown bubbles are neutral and they are polarized in the E-field of the dome. Since this field is divergent, a polarized bubble is attracted and accelerated. On contact, the bubble obtains the charge of the dome and when the bubble survives it will be repelled from it (bounces). But when the bubble breaks it will break up as a very fine spray of very fine droplets all having the same charge as the dome and moving fast because of their very small size. This charged spray charges the other bubbles, that are still approaching, and these bubbles becoming charged by the spray they will be repelled now as well.

6.1.1.1.7 Remarks

- That a very fine spray occurs can be observed in a separate, individual experiment in which you make a drop of water fall on the charged dome and in your face you feel a refreshing fine haze (see Figure 3).

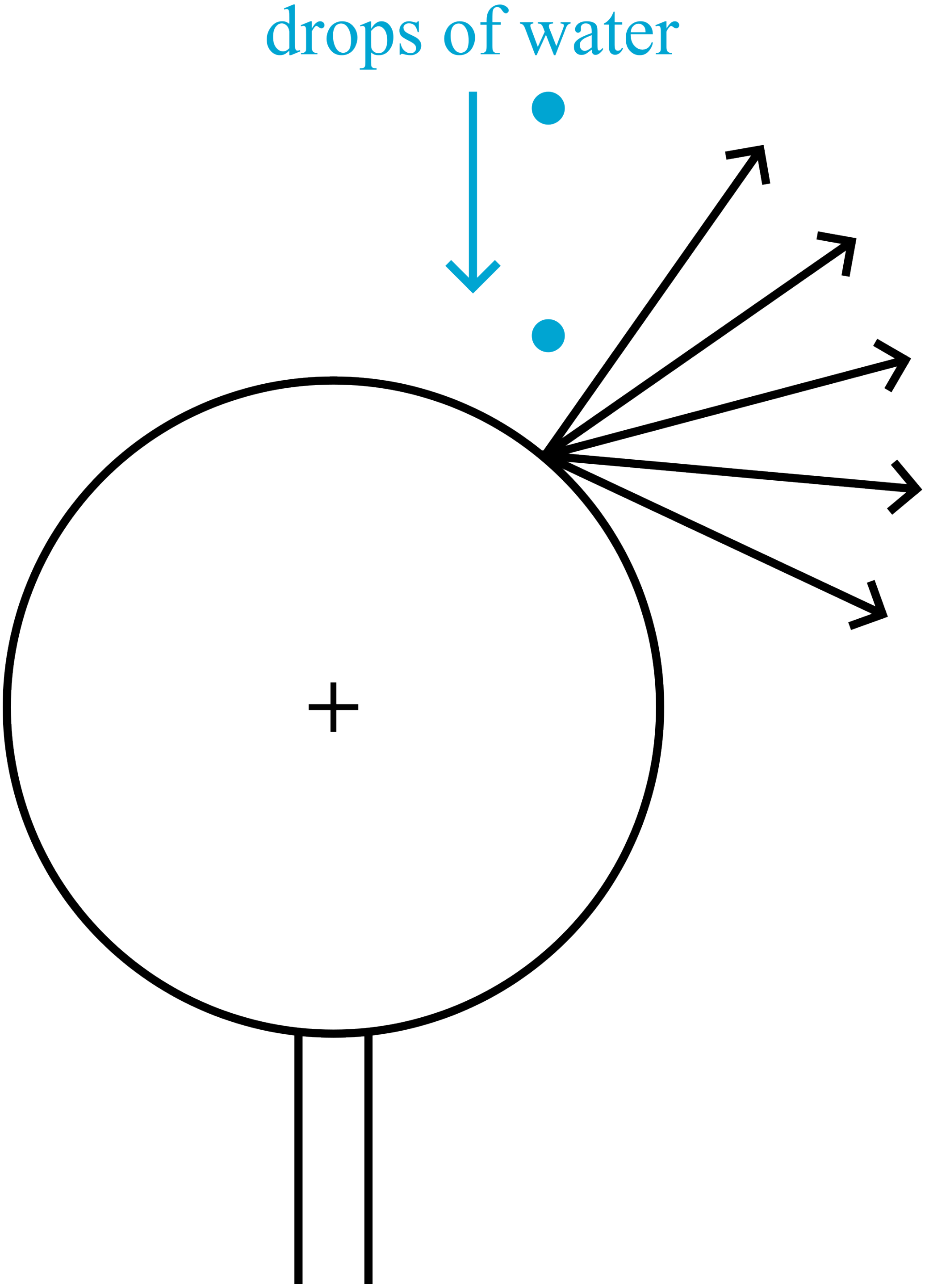


Figure 6.3: .

6.1.2 5A20 Coulomb's Law

6.1.2.1 01 Coulomb's Law (2)

6.1.2.1.1 Aim

To show the inverse square distance dependence of the electrostatic force between point charges.

6.1.2.1.2 Subjects

- 5A20 (Coulomb's Law)

6.1.2.1.3 Diagram

Figure 6.4: .

6.1.2.1.4 Equipment

- 2 Graphite-coated ping-pong balls, hanging from a pair of one meter long threads.
- Support (see Diagram).
- Glass rod (see Diagram).
- Red tape, to shift the thread length from L to $0,5$ L (see Diagram PresentationXX).
- Van de Graaff generator.
- Lamp, for shadow projection.
- Overhead sheet with the $(n - \frac{r_1}{r_2}$) table (see Explanation).

6.1.2.1.5 Presentation

The balls are hanging and touch each other. The shadow of the ping-pong balls is projected on the blackboard.

By means of the Van de Graaff generator the two balls are charged and immediately they separate by electrostatic repulsion. While the shadows of the two balls are dancing around towards their equilibrium, the method of the demonstration is explained to the students and to them it is shown that when we suppose the power in Coulomb's law (1785) is really −2 , the determined distance-ratio should be $2^{1/3} = 1.259$ (see Explanation). When the two balls have come to rest, the centres of the shadows of the balls are chalk-marked on the blackboard.

Now the two threads are sandwiched at the halfway point by means of a sliding piece of tape. (This tape is fixed to the threads already before you start the experiment; see Figure 2.)

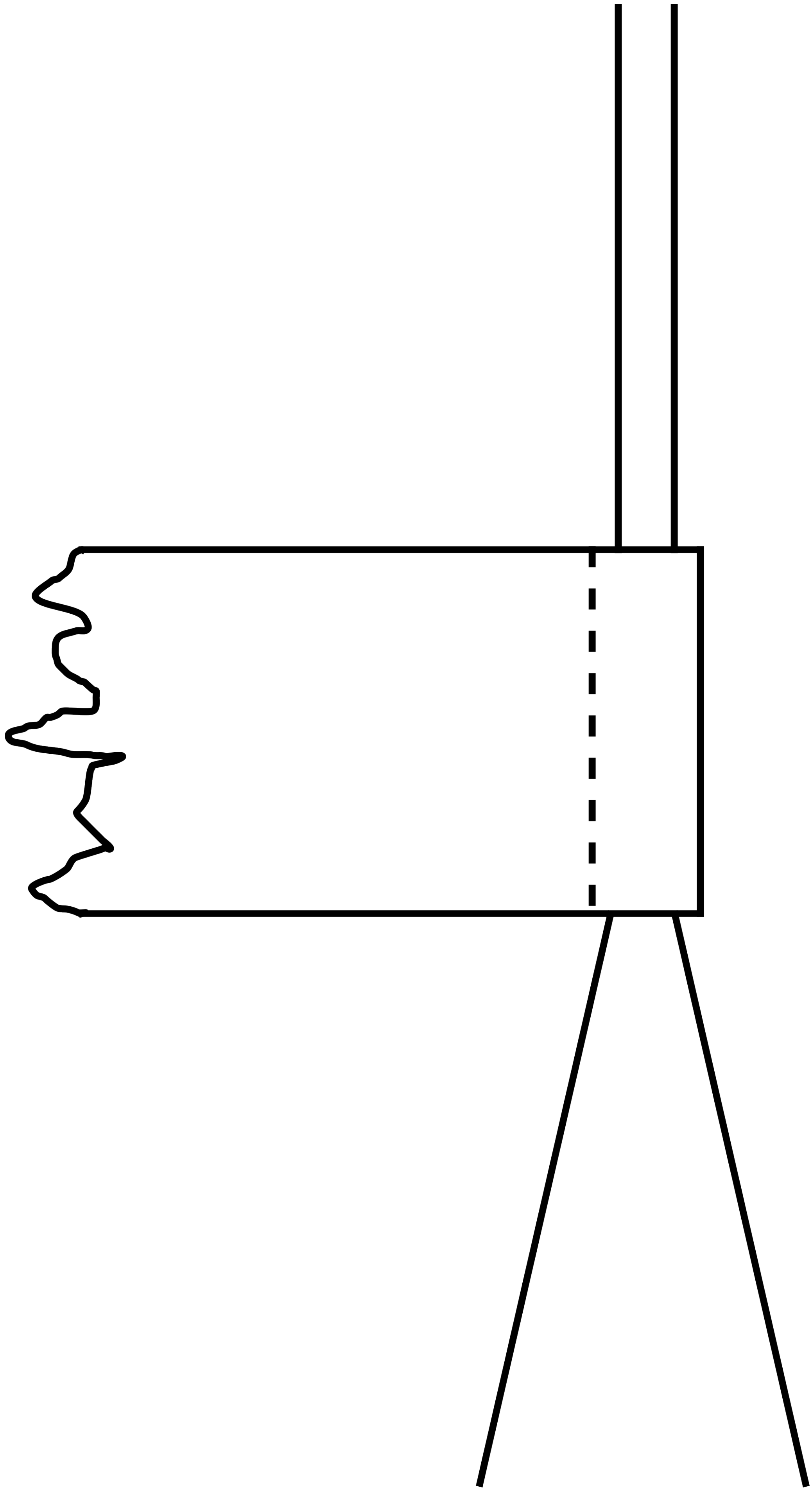


Figure 6.5: .

Clearly can be seen that the two shadows are closer to each other now. Again the centres of the ball-shadows are chalk-marked.

On the blackboard the two separations are measured. (In a trial, we measured 78and 62 cm respectively.) The ratio is calculated ($78/62 = 1.258$). This value is very close to the value 1.259 mentioned before and so the power in Coulomb's law being- 2 is supported by this demonstration.

This demonstration gives the opportunity to stress to the students that Coulomb's law is empirical and in that way very fundamental to the theory of electromagnetism.

That's why it is very fundamental that measurements around Coulomb's law are still performed, trying to determine n with increasing accuracy (nowadays –1971- it stands to be accurate to 1 part in 10^{16}; between 1,99999999999999994 and 2,00000000000000058)

6.1.2.1.6 Explanation

Figure 3 shows that in the equilibrium position: $F_{coulomb} = mg \tan \phi$.

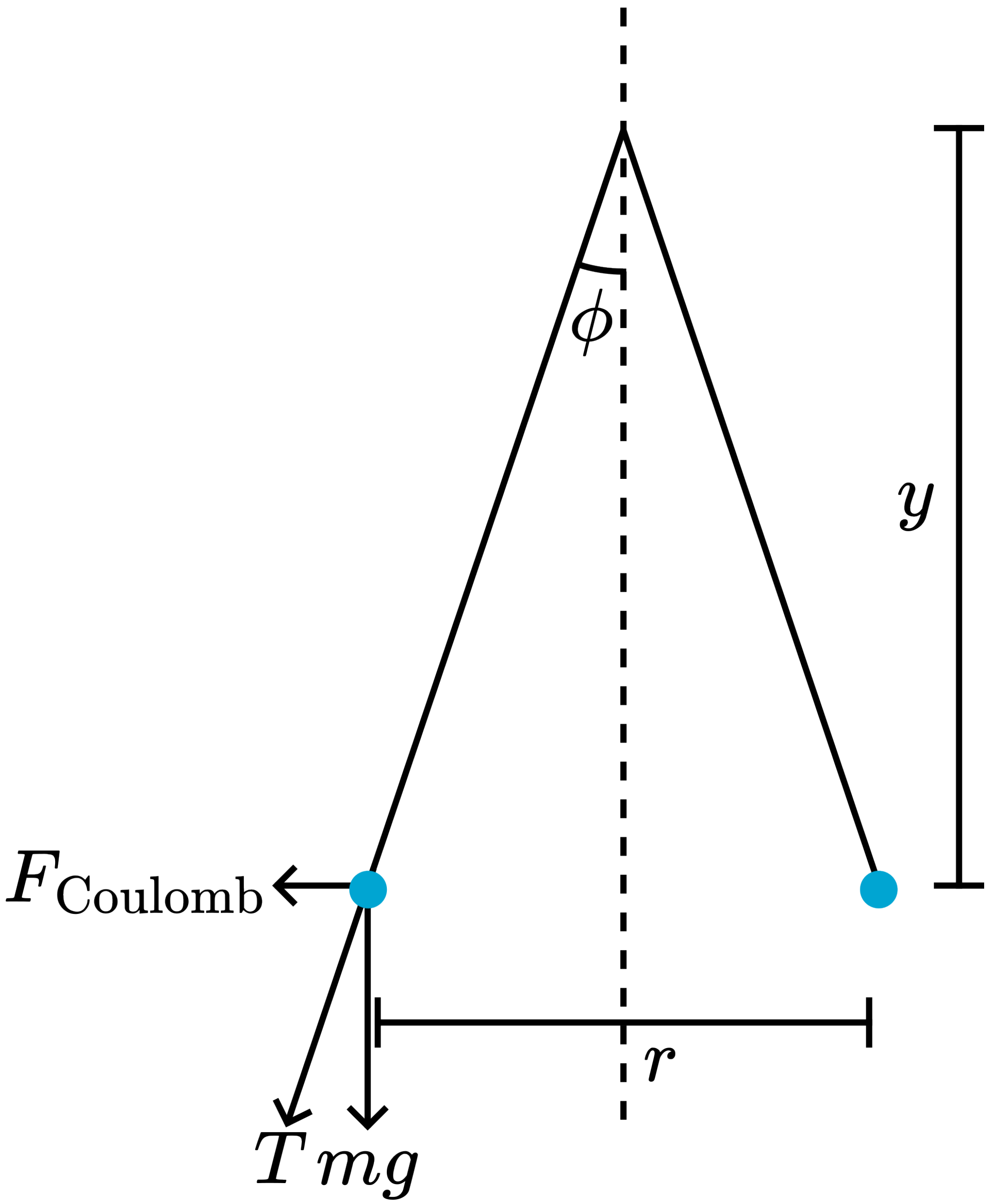


Figure 6.6: .

Since $\tan\phi = r/2y$, $F_{Coulomb} = \frac{mgr}{2y}$

Supposing $F_{Coulomb} = k\frac{q^2}{r^n}$, our equilibrium equation is $\frac{kq^2}{r^n} = \frac{mgr}{2y}$.

k, q, m, and g are constants, so $\frac{r^{n+1}}{y}$ has a constant value ($\frac{r^{n+1}}{y} = \frac{2ykq^2}{mg}$)

The first measurement gives us $\frac{r_1^{n+1}}{y_1}$, the second $\frac{r_2^{n+1}}{y_2}$. So, $\frac{r_1^{n+1}}{y_1} = \frac{r_2^{n+1}}{y_2}$.

Since in our demonstration $y_1 = 2y_2$, we find $\frac{r_1^{n+1}}{r_2^{n+1}} = \frac{y_1}{y_2} = 2$, and so: $\frac{r_1}{r_2} = 2^{\frac{1}{n+1}}$

For different values of n we calculate for $\frac{r_1}{r_2}$:

n	$\frac{r_1}{r_2}$
..	....
1	$1,414..$
1.5	1.319..
2	$1,259..$
2.5	1.219..
3	1.189..
..	....

In this way measuring r_1 and r_2 will give us the value for n.

The mentioned measurement in the Presentation with $r_1 = 78$ cm and $r_2 = 62$ cm presents the ratio $\frac{r_1}{r_2} = 1,258..$ the table above shows that this produces a value for n very close to 2 .

6.1.2.1.7 Remarks

- Measuring r_1 and r_2 must be done with some care. For instance when you measure r_2 being 63 cm instead of 62 cm you find $n = 2.2(5)$ instead of $n = 2.0(2)$.
- When charge leaks away during the demonstration the measured r_2 will be too low making $\frac{r_1}{r_2}$ higher and n will appear as a higher value. (So usually this will happen.)
- At 3/4 from the upper side of the support a horizontal bar is placed (see Diagram). This makes that when the balls move when they deflect, they remain in the same vertical plane. Without this bar the balls will start to rotate, making a useful shadow projection impossible. *Nowadays we use a thin double thread instead of a metal bar;* **a metal bar that close to the balls disturbs the E-field more than a thin thread.** *The balls hang between the double, horizontal threads.*

6.1.2.1.8 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 146-147
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 443 and 467
- Young, H.D. and Freeman, R.A., University Physics, pag. 674-679
- Buijze W. en Roest R., Inleiding electriciteit en Magnetisme, pag. 11, eerste zin.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 549-551 and 586!

6.1.2.1.9 Supplement

Historical results

$$E(r) - \frac{1}{r^{2+\varepsilon}} \tag{6.1}$$

- Henry Cavendish (1770):

  $| \varepsilon | \leq 0.02$
- James Clark Maxwell(1879):

  $| \varepsilon | \leq 5 \cdot 10^{-5}$
- E.R. Williams, J.E. Faller and H.A. Hill (1971):

  $| \varepsilon | \leq (2.7 \pm 3.1) \cdot 10^{-16}$

6.1.2.2 02 E-Field in Material (Electric Soap Bubbles)

6.1.2.2.1 Aim

To discuss with students the phenomenon shown. It seems easy at first thought but yet appears rather complicated when shown to them.

6.1.2.2.2 Subjects

5A10 (Producing Static Charge) 5A40 (Induced Charge)

6.1.2.2.3 Diagram

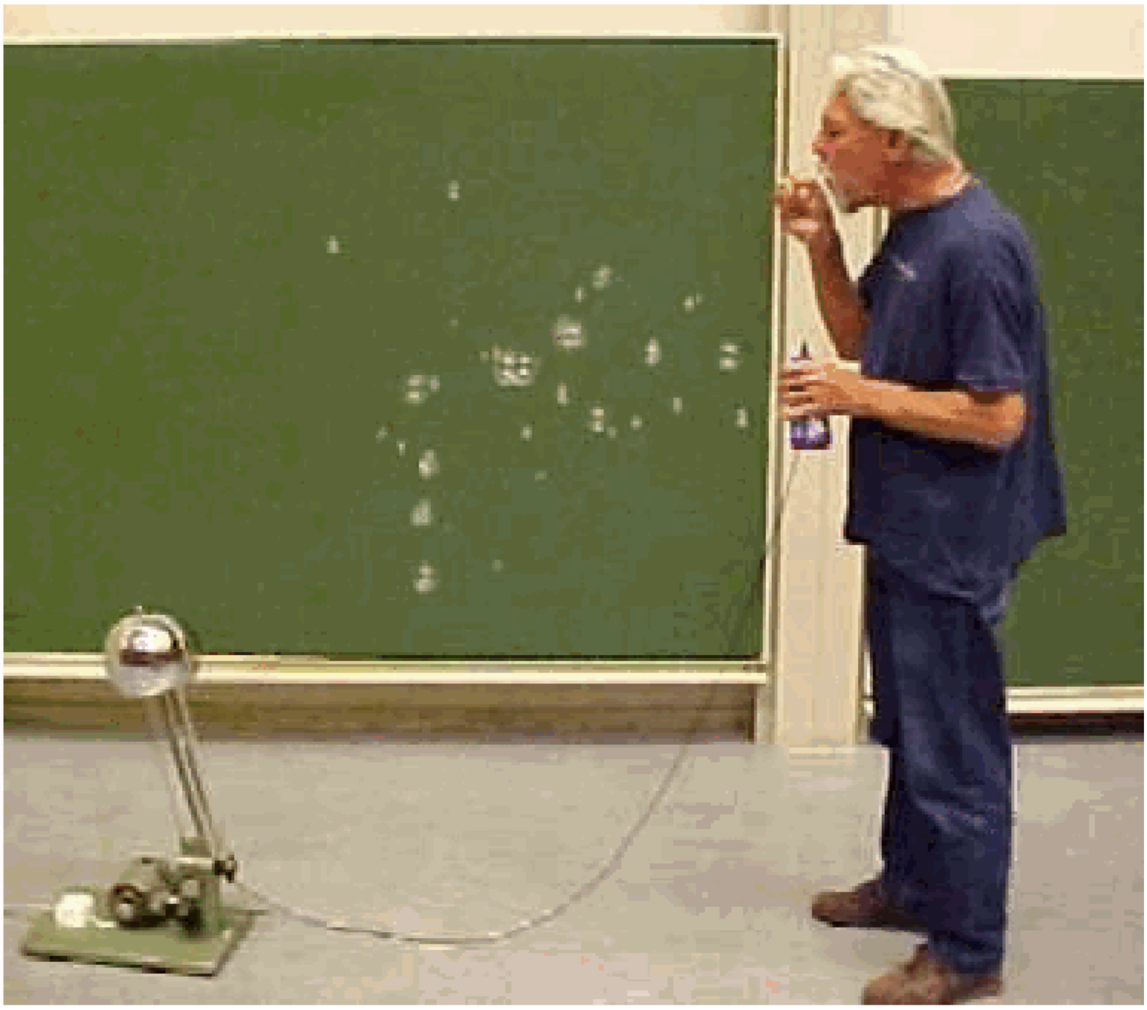


Figure 6.7: .

6.1.2.2.4 Equipment

- Van de Graaff generator.
- Soap solution.
- Grounded wire.
- Teacher, blowing soap bubbles.

6.1.2.2.5 Presentation

The teacher asks the students to reflect about what will happen to neutral soap bubbles that come in the neighborhood of a running Van de Graaff generator. After their ideas are discussed, and some predictions made, the Van de Graaff generator is switched on. The ground lead is plunged into the soap solution and at a distance of around 1.5-2 meters soap bubbles are blown into the direction of the generator.
The bubbles are clearly attracted towards the dome of the generator; they are accelerated (when

coming close to the dome even their shape changes, see Figure 2). The first bubble hits the dome and explodes (occasionally it remains intact and bounces).

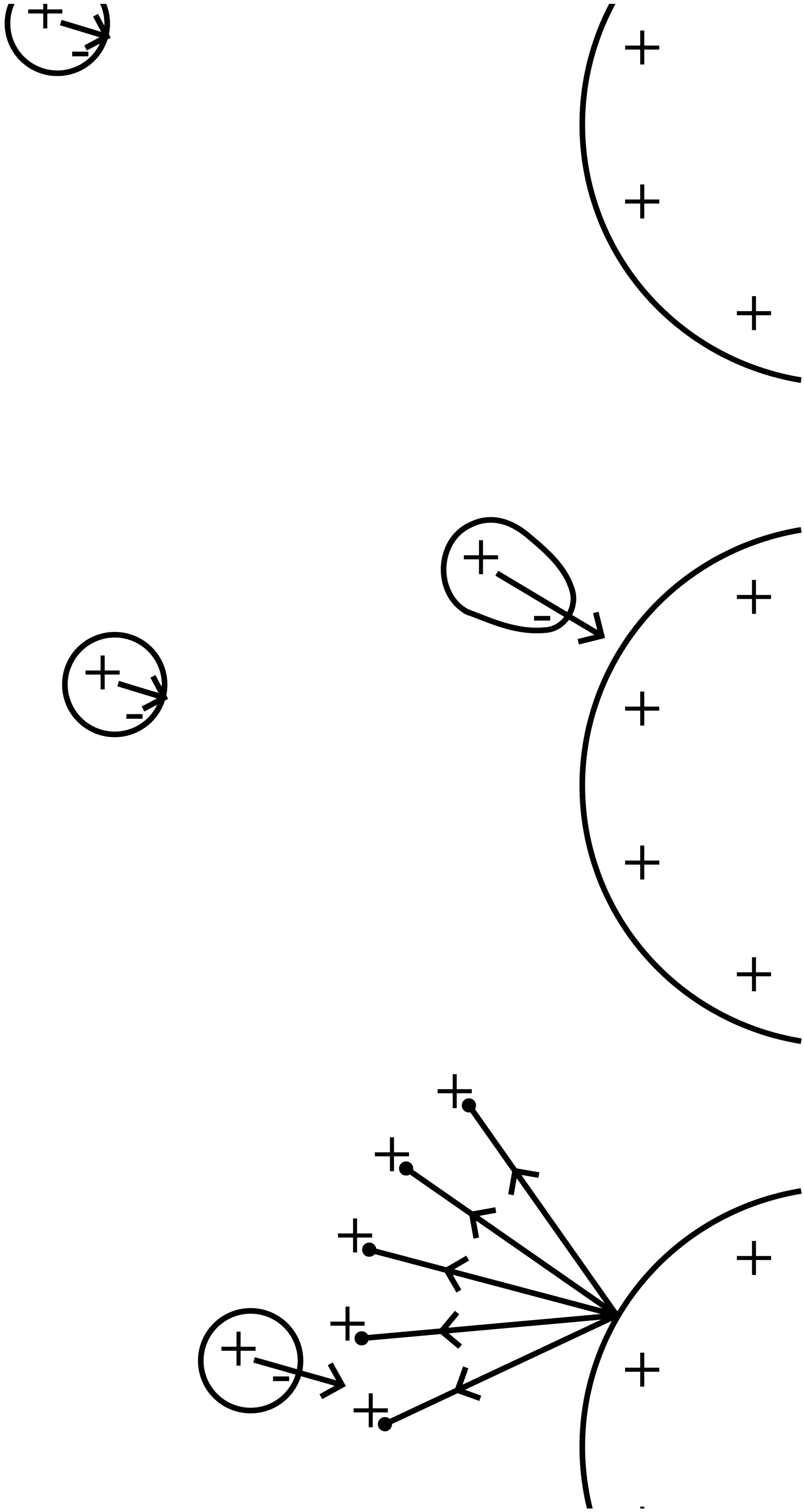


Figure 6.8: .

The other bubbles that are still on their way towards the dome are now pushed away from it. Also the next series of blown bubbles are all repelled. When you want again to see attraction, you first have to clean the dome.

6.1.2.2.6 Explanation

The blown bubbles are neutral and they are polarized in the E-field of the dome. Since this field is divergent, a polarized bubble is attracted and accelerated. On contact, the bubble obtains the charge of the dome and when the bubble survives it will be repelled from it (bounces). But when the bubble breaks it will break up as a very fine spray of very fine droplets all having the same charge as the dome and moving fast because of their very small size. This charged spray charges the other bubbles, that are still approaching, and these bubbles becoming charged by the spray they will be repelled now as well.

6.1.2.2.7 Remarks

- That a very fine spray occurs can be observed in a separate, individual experiment in which you make a drop of water fall on the charged dome and in your face you feel a refreshing fine haze (see Figure 3).

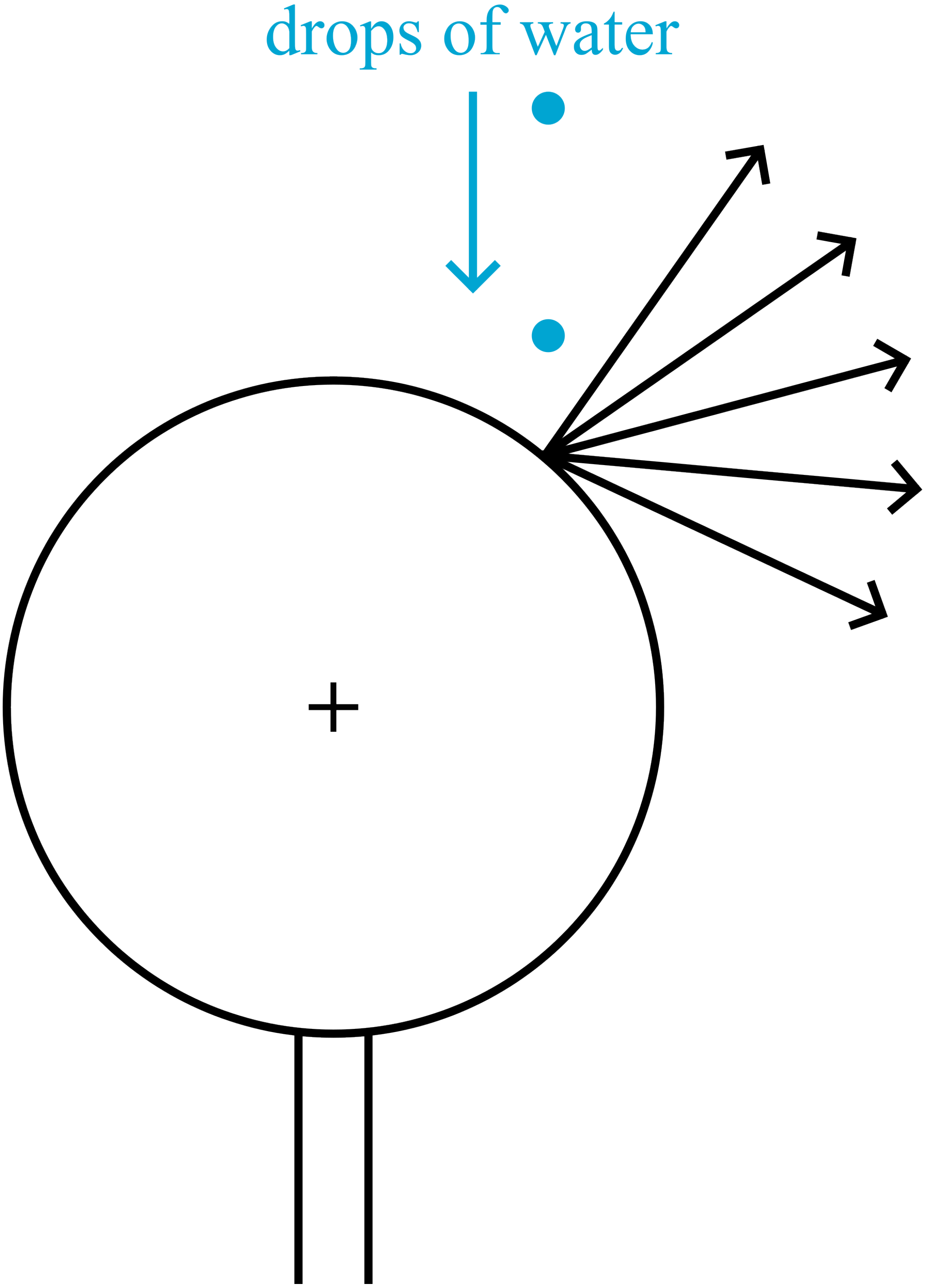


Figure 6.9: .

6.1.3 5A40 Induced Charge

6.1.3.1 01 Charging by Induction

6.1.3.1.1 Aim

Trying to apply the theory of attraction and repulsion in the phenomenon of attracting different pieces of scrap by a charged body.

6.1.3.1.2 Subjects

- 5A40 (Induced Charge)

6.1.3.1.3 Diagram

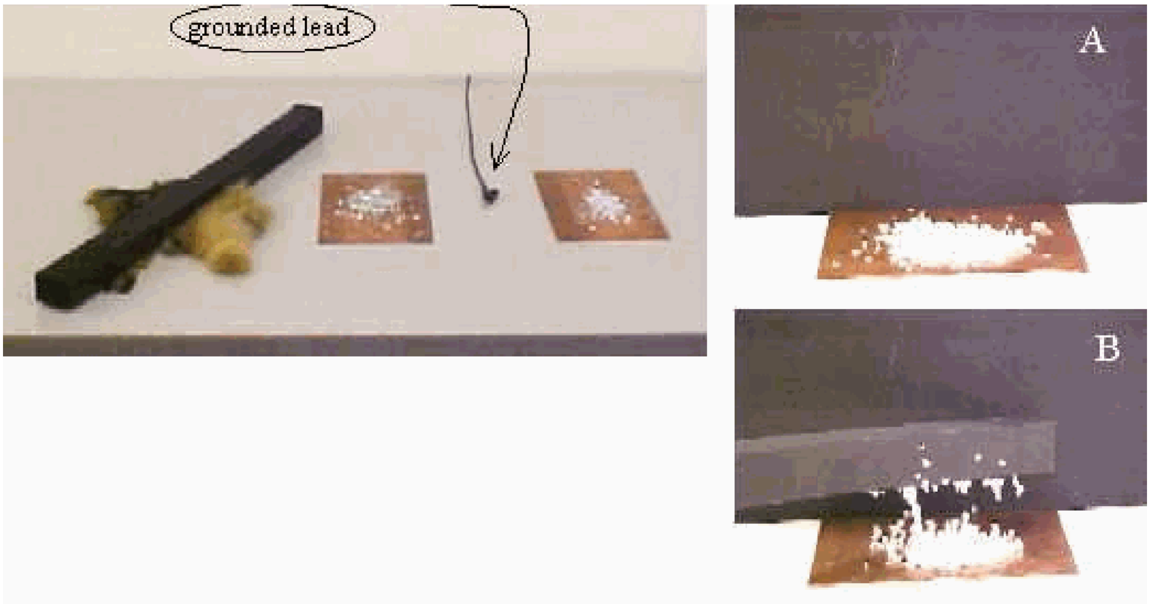


Figure 6.10: .

6.1.3.1.4 Equipment

- Rubber stick.
- Cat fur.
- Copper plate with scraps of aluminum foil.
- Copper plate with scraps of (toilet)paper. (A piece of paper scrap is in weight equal to a piece of aluminum scrap.)
- A lead connected to ground. .

6.1.3.1.5 Presentation

Shortly, the copper plates with scraps are grounded. Then we rub the rubber stick with the cat fur. Then slowly the rubber stick is approaching the scraps of paper. Many of the scraps of paper are attracted (not all). Most of the attracted scraps stick to the rubber stick, some are ordering themselves in lines (see Diagram, figure A and B) and a few of them fly away.

Again the rubber stick is rubbed with the cat fur. Now the rubbed stick approaches the scraps of aluminum. Many of them are attracted (not all) and most of them fly away with high speeds when touching the rubber. Also will some of them stick to the rubber.

6.1.3.1.6 Explanation

The scraps of paper and aluminum are neutral in the beginning. Rubbing the stick charges it negatively and on approaching the paper scraps it induces a polarization in them. The scraps of paper, being insulators are polarized locally. The stick, being charged negatively, redistributes the charge in the neutral “paper-molecules” so that closest to the stick the “paper-molecules” have a net positive charge and on the other side an equally large positive charge (A double overhead sheet can help to explain this: see the demonstration “Polarizing a dielectric” in this database). This results in the piece of scrap being positive on one side and negative on the other. The stick attracts the positive side and repels the negative side of the paper scrap. Applying Coulomb’s law shows that due to the r^{-2} relationship the attraction is stronger than the repulsion and the piece of scrap is attracted (see Figure 2A).

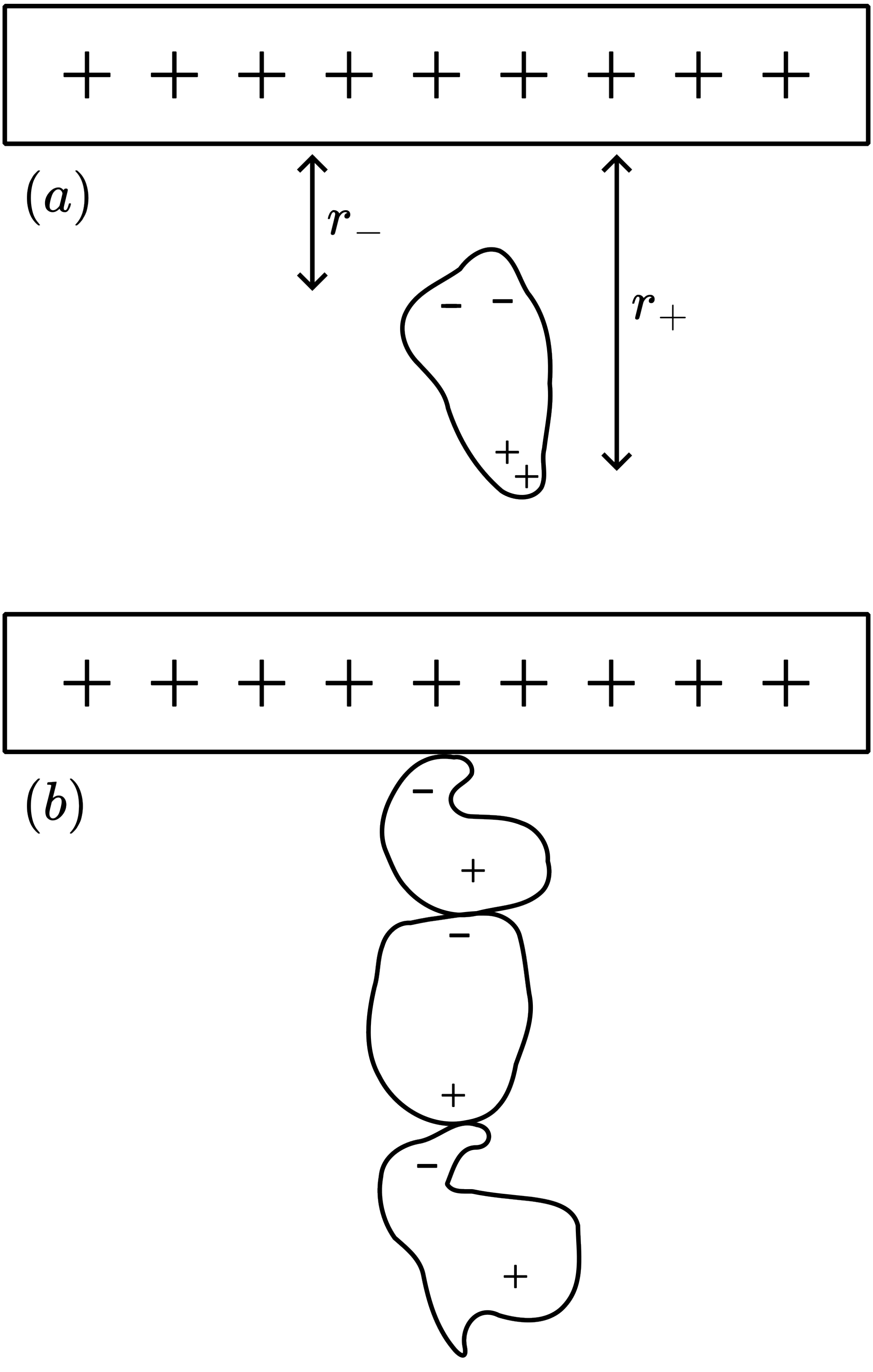


Figure 6.11: .

In case of the aluminum scraps a similar mechanism is at work, but now the free electrons in the aluminum do the job of charge distribution. The negatively charged rubber stick repels the free electrons in the piece of aluminum scrap to the far side and so the piece of scrap becomes polarized. Again Coulomb's law shows that the resulting force is attracting. When the aluminum scraps hit the rubber stick they are generally launched away from the stick: There must be a strong repulsive force at contact; charges have to be equal now.

This can be explained in supposing that free electrons move from the surface of the rubber stick into the aluminum scrap (that is still positive on that side just before contact to the rubber rod) and locally the rubber is neutralized. The piece of scrap, having gained electrons now has a net negative charge and, being close to a surrounding of negative charge, is strongly repelled (see Figure 3).

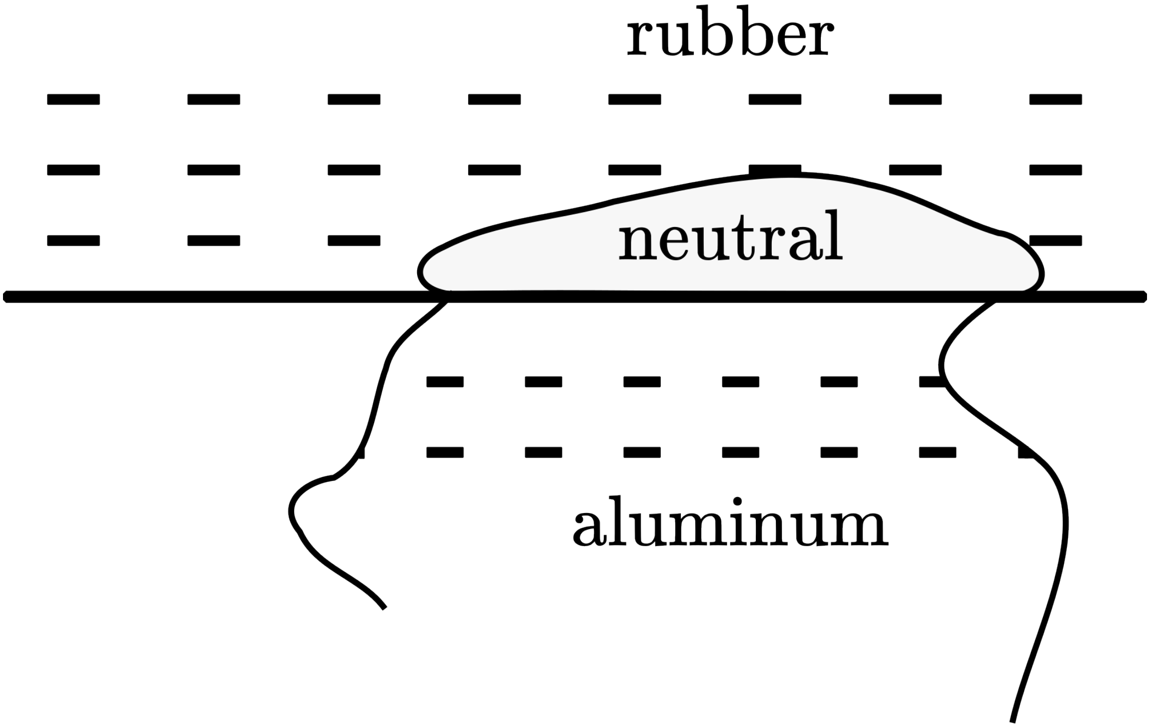


Figure 6.12: .

That some of the aluminium scraps stick to the rubber can be due to two causes: - The neutral area in the rubber stick is wider, and so the attraction of the negative piece of scrap to the neutral (polarized) area of the stick wins over the repelling forces; - The free electrons of the rubber are not going into the piece of aluminium scrap (on contact no tunnelling occurs) and so the polarized piece of aluminium sticks to the negative rubber like most of the paper scraps did.

That also some of the paper scraps fly away on touching the rubber stick means that in some cases some of the electrons in the rubber probably can move onto/into the paper scraps as well and repulsion results. But the demonstration also shows that these repulsions are weaker than in the case of aluminum scraps. (In this case of rubber and paper the neutral region is made in both materials.)

6.1.3.1.7 Remarks

- Often the rubber stick is charged "too good" and sparks jump from the stick to the scraps. The induction-story does not apply any longer. When in class this situation happens we apply a less good tribo-electric material: a pvc tube rubbed with a silk cloth. Take in mind that when you tell the story the pvc tube is negatively charged.

6.1.3.2 02 Polarizing a dielectric

6.1.3.2.1 Aim

To show how the voltage of a capacitor changes when changing -the spacing and -the dielectric between the parallel plates. This is done with constant charge and with constant voltage.

6.1.3.2.2 Subjects

- 5A40 (Induced Charge) 5C20 (Dielectric)

6.1.3.2.3 Diagram

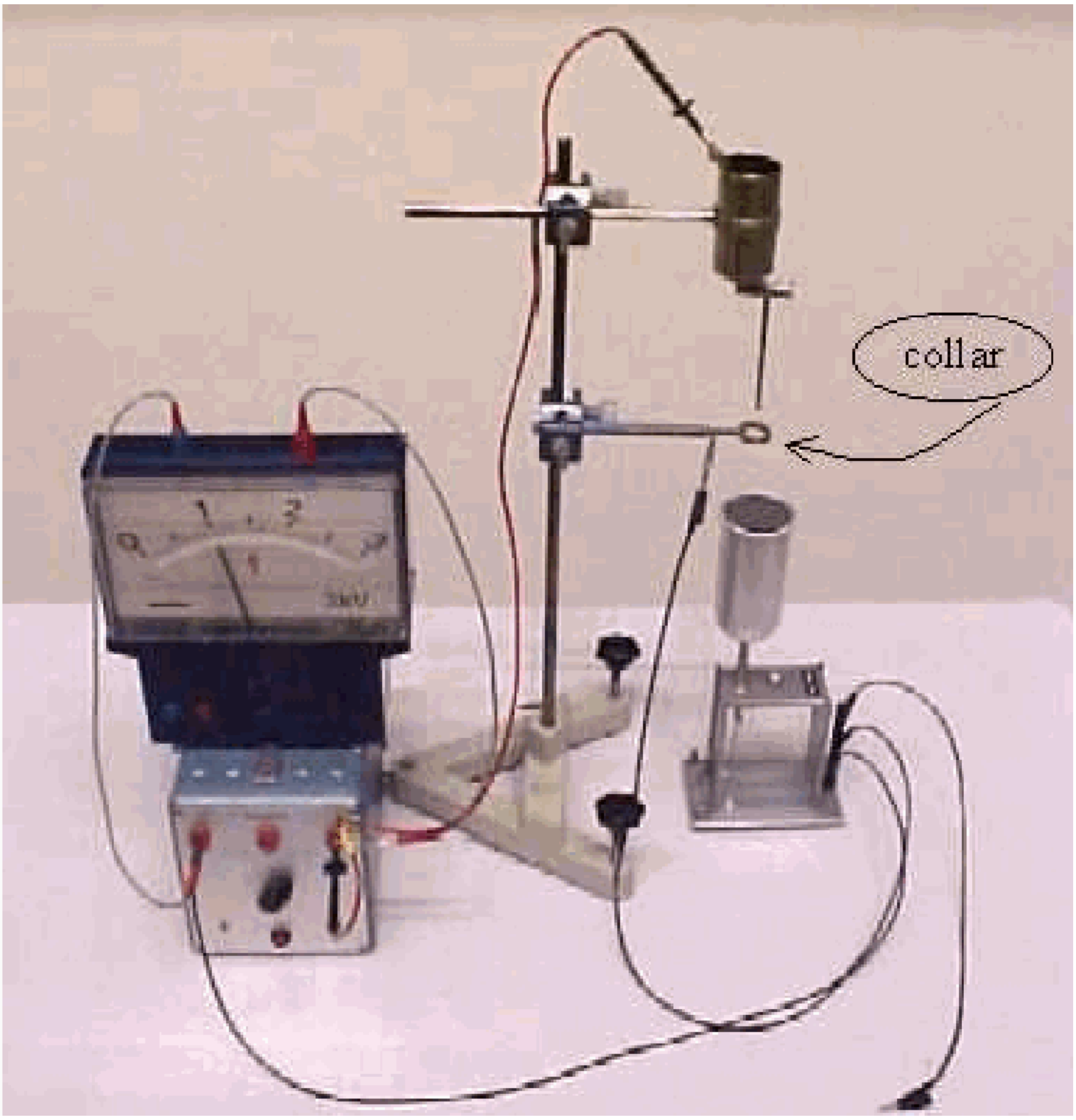


Figure 6.13: .

6.1.3.2.4 Equipment

An assembly of overheadsheets:

- Overheadsheet with capacitor drawn on it.
- Overheadsheet with six rows of six negative charges (green colored).
- Overheadsheet with six rows of six positive charges (red colored).

The overheadsheet with the capacitor plates drawn on it is actually a sleeve, in which the two sheets with the opposite charges just fit and can be shifted.

6.1.3.2.5 Presentation

The assembly of overheadsheets is projected: The two sheets with the opposite charges are placed between the capacitor plates such that the plus - and minus signs cover each other (the molecules are no dipoles) (See Diagram A and Figure 2).

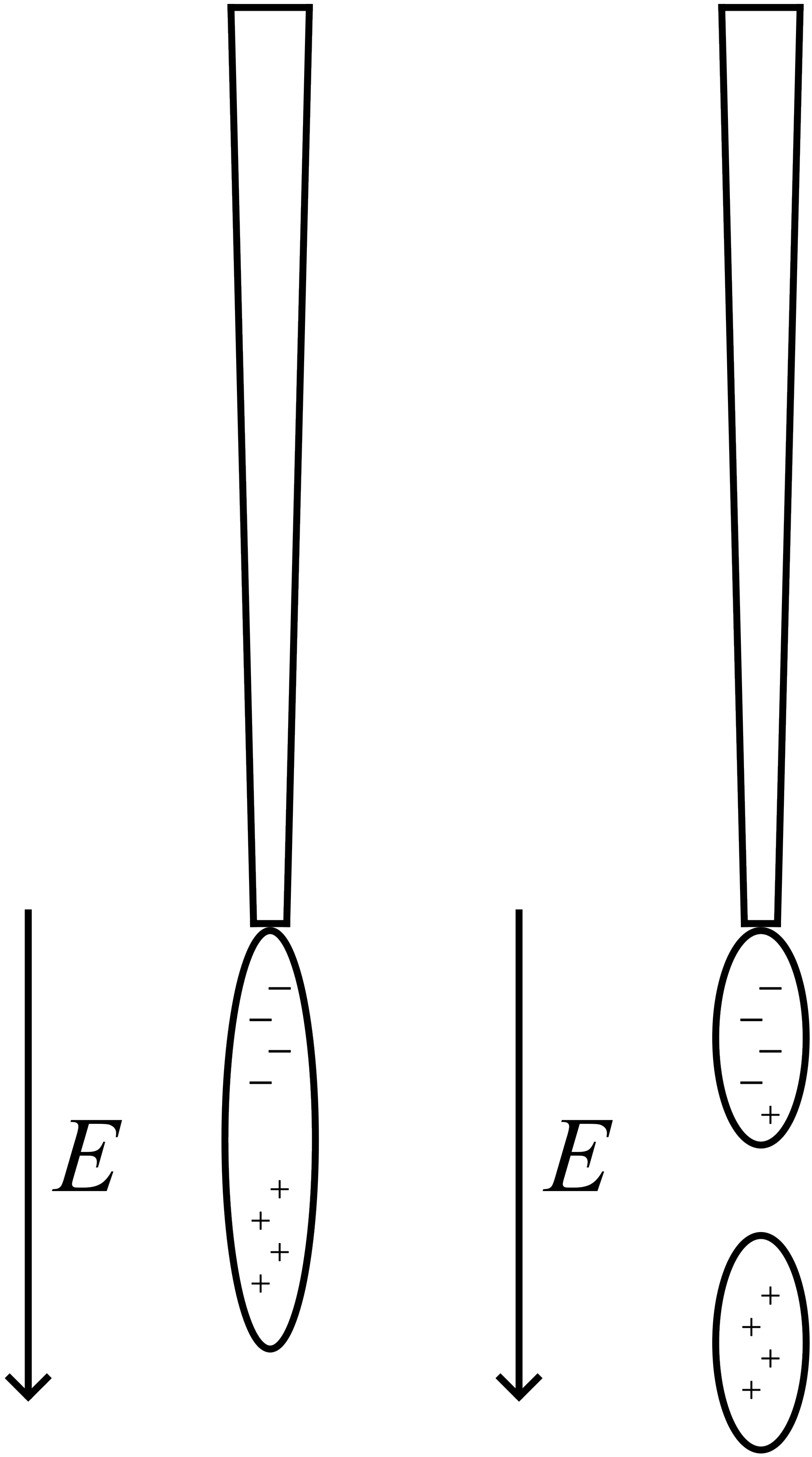


Figure 6.14: .

Using a non-permanent marker we apply (write) a clear PLUS- and MINUS-sign to the capacitor plates and by hand the two sheets with the charges are shifted a little, thus showing that the “molecular charges” are separated a little (see Diagram B). The net effect is clearly visible: There is a net negative charge on the outer edge of the material facing the positive plate and a net positive charge on the opposite side.

We can also draw the vectors to indicate the original electric field (E_0) and the induced, opposing field (E_{ind}), showing that now $E_{Dielectric} = E_0 - E_{ind}$.

6.1.3.2.6 Explanation

When an outside electric field is applied to the material (for instance by placing it between the plates of a capacitor) there is some separation of charge induced in the molecules. In the demonstration this is shown by slightly displacing the “negative” overhead sheet towards the positive plate (opposite to the direction of E_0).

6.1.3.2.7 Remarks

- The model is static; there is no thermal motion.

6.1.3.2.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 624-625

6.1.3.3 03 E-Field in Material (Electric Soap Bubbles)

6.1.3.3.1 Aim

To discuss with students the phenomenon shown. It seems easy at first thought but yet appears rather complicated when shown to them.

6.1.3.3.2 Subjects

5A10 (Producing Static Charge) 5A40 (Induced Charge)

6.1.3.3.3 Diagram

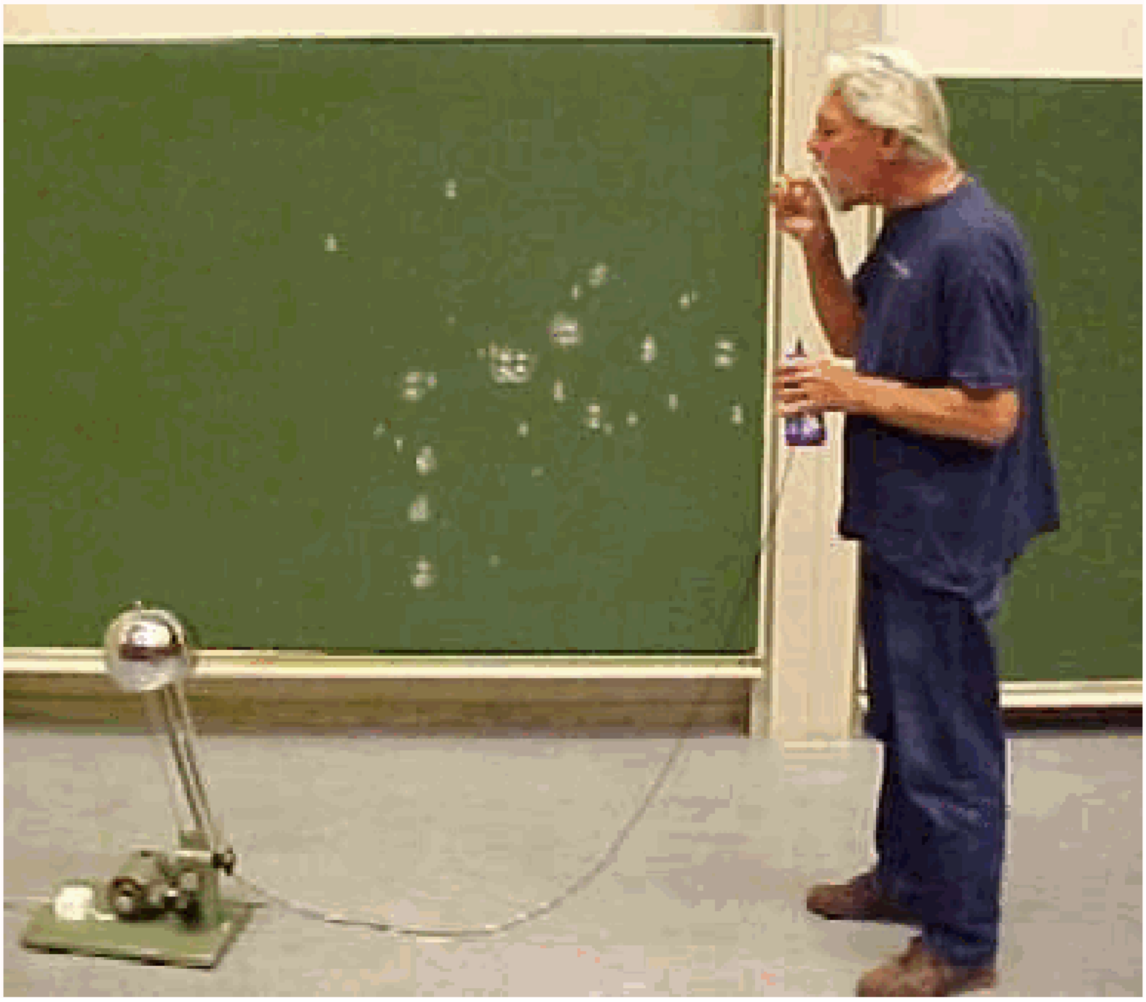


Figure 6.15: .

6.1.3.3.4 Equipment

- Van de Graaff generator.
- Soap solution.
- Grounded wire.
- Teacher, blowing soap bubbles.

6.1.3.3.5 Presentation

The teacher asks the students to reflect about what will happen to neutral soap bubbles that come in the neighborhood of a running Van de Graaff generator. After their ideas are discussed, and some predictions made, the Van de Graaff generator is switched on. The ground lead is plunged into the soap solution and at a distance of around 1.5-2 meters soap bubbles are blown into the direction of the generator.
The bubbles are clearly attracted towards the dome of the generator; they are accelerated (when

coming close to the dome even their shape changes, see Figure 2). The first bubble hits the dome and explodes (occasionally it remains intact and bounces).

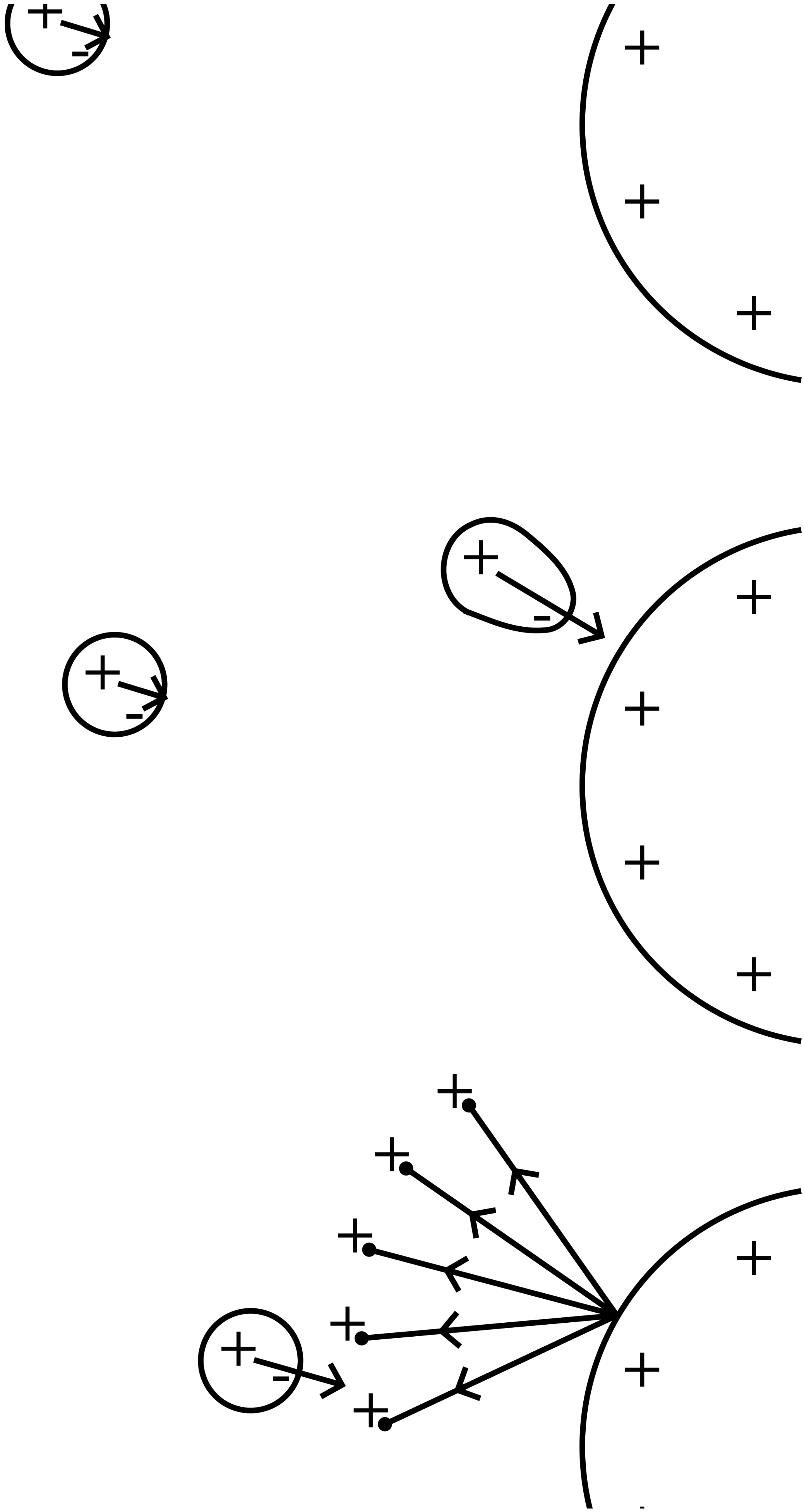


Figure 6.16: .

The other bubbles that are still on their way towards the dome are now pushed away from it. Also the next series of blown bubbles are all repelled. When you want again to see attraction, you first have to clean the dome.

6.1.3.3.6 Explanation

The blown bubbles are neutral and they are polarized in the E-field of the dome. Since this field is divergent, a polarized bubble is attracted and accelerated. On contact, the bubble obtains the charge of the dome and when the bubble survives it will be repelled from it (bounces). But when the bubble breaks it will break up as a very fine spray of very fine droplets all having the same charge as the dome and moving fast because of their very small size. This charged spray charges the other bubbles, that are still approaching, and these bubbles becoming charged by the spray they will be repelled now as well.

6.1.3.3.7 Remarks

- That a very fine spray occurs can be observed in a separate, individual experiment in which you make a drop of water fall on the charged dome and in your face you feel a refreshing fine haze (see Figure 3).

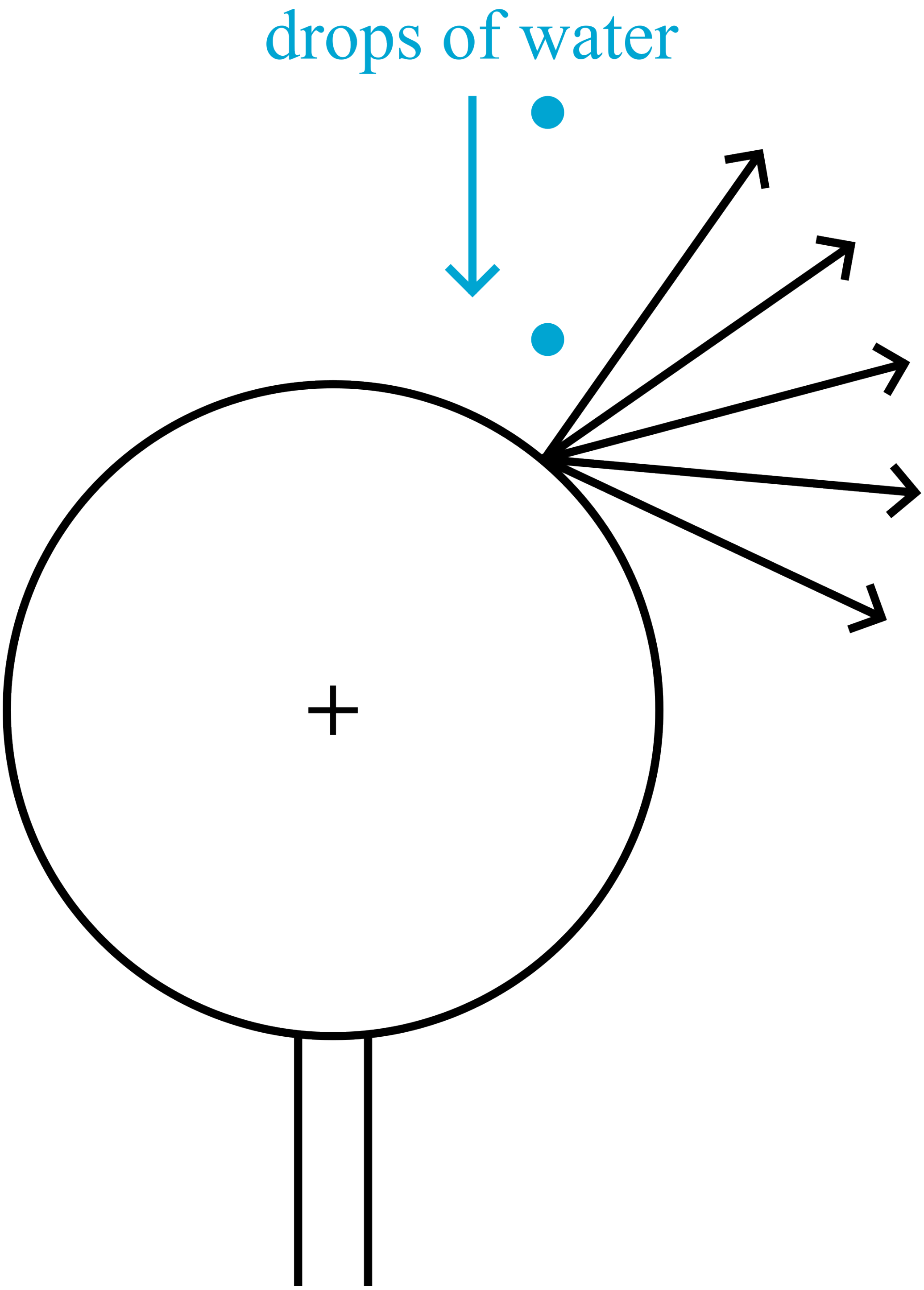


Figure 6.17: .

6.1.3.4 04 Water Dropper (almost Kelvin water dropper)

6.1.3.4.1 Aim

To show the principle of operation of a Van der Graaff generator.

6.1.3.4.2 Subjects

- 5A40 (Induced Charge) 5A50 (Electrostatic Machines)

6.1.3.4.3 Diagram

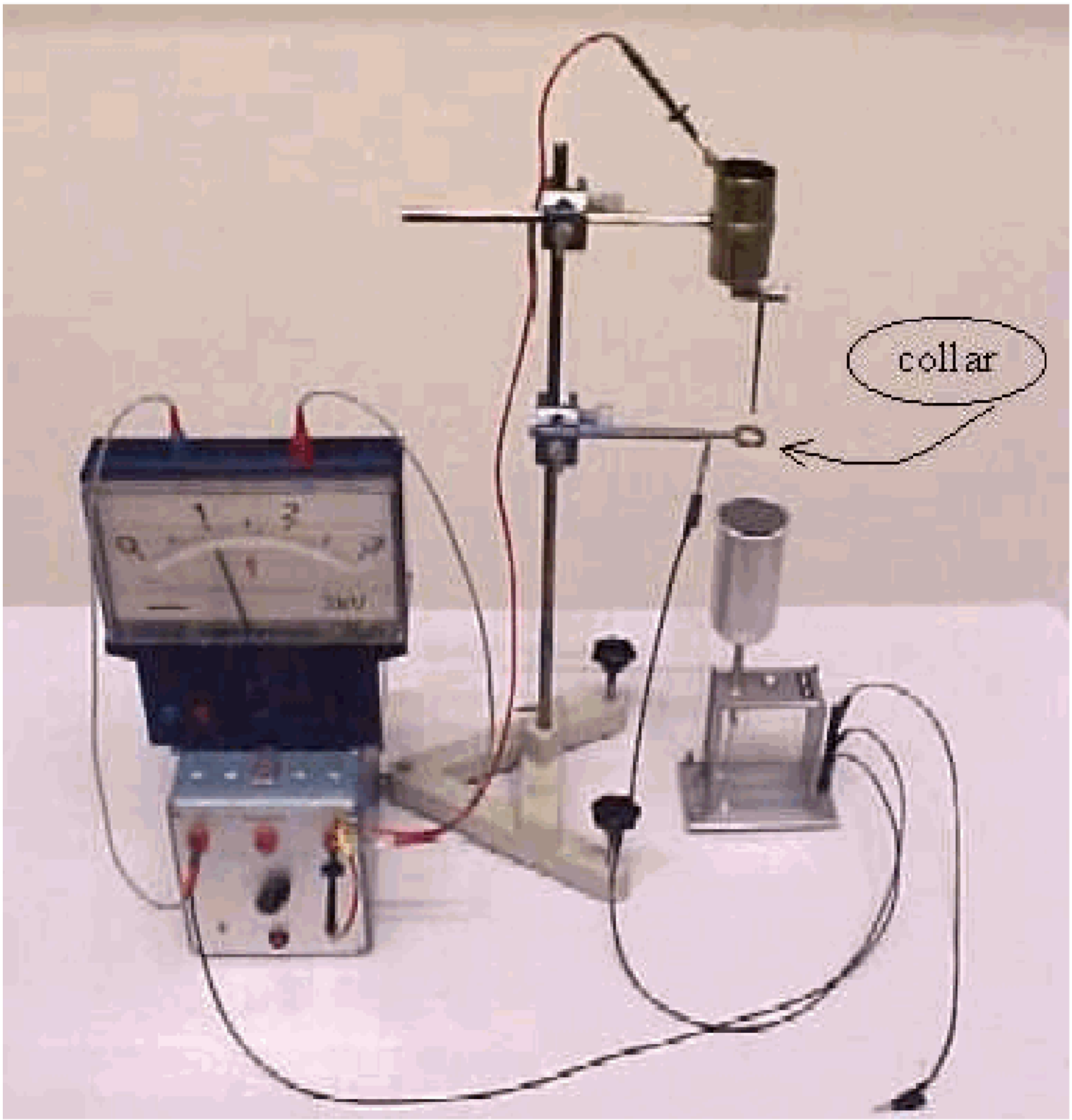


Figure 6.18: .

6.1.3.4.4 Equipment

- Electroscope.
- Metal beaker on top of electroscope.
- Metal collar, fitted on a bar of pvc.
- Metal container with pinchcock, allowing water to drip. (The holding bar is partly made of perspex for isolation.)
- Power supply (about 1kV).
- Camera.

- Electrostatic Voltmeter (see Remarks and Figure 3).

6.1.3.4.5 Presentation

Set up the equipment as shown in the Diagram (the metal collar is in the beginning turned away from the dropper; the +1kV lead is not yet connected). The power supply is adjusted to a voltage of about 1kV. Touching momentarily the electroscope with the +1kV lead shows that this voltage gives a small deflection (in our case 3 divisions). Discharge the electroscope.

Now the upper container is filled with water and placed about 10 cm above the beaker on the electroscope. The +1kV lead is connected to it. The pinchcock is opened and drops of water fall into the beaker on the electroscope. When the upper container is connected to the power supply, the electroscope will build up the small deflection (of 3 divisions) we had before.

Now the metal collar, connected to ground, is placed around the falling drops of water. The effect is that the deflection of the electroscope increases and very soon runs off scale!

When now the collar is moved away from the falling drops of water, the electroscope will slowly return to the lower deflection it had before.

6.1.3.4.6 Explanation

In the first part of the demonstration an electric field (1kV over 10 cm, so $E = 10\text{kV/m}$) exists between the upper water container and the electroscope.

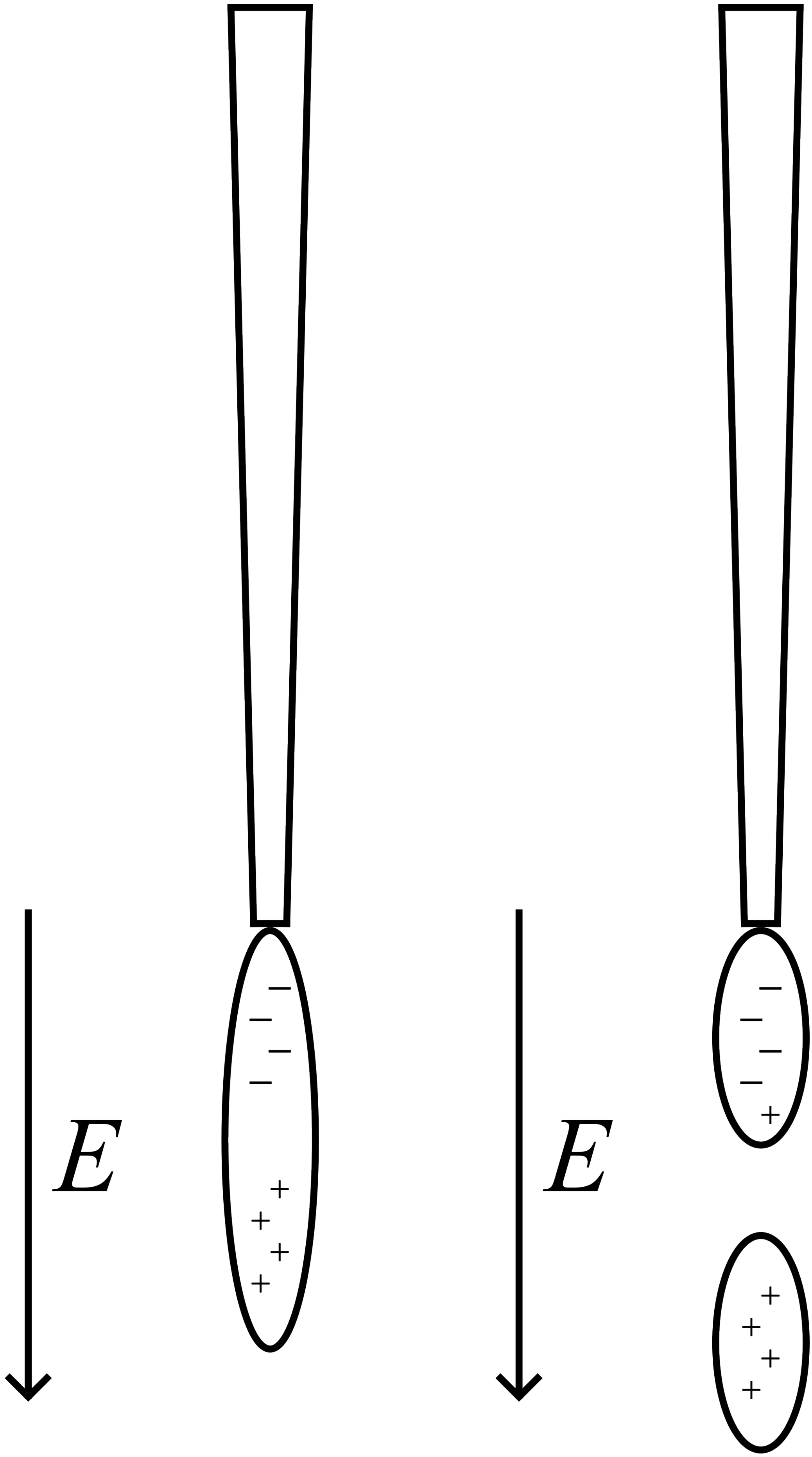


Figure 6.19: .

Due to this field, the drops of water will be charged when they break loose from the metal dropper (see Figure 2). When the drops fall into the beaker on the electroscope this charge accumulates (on the outside of the beaker) and the deflection of the electroscope increases. This continues until the potential of the beaker is the same as the potential of the upper water container, because now there is no longer an electric field to charge the drops of water.

When the grounded metal collar is placed around the stream of falling drops, there will be an electric field again between the collar and the upper water container and again the drops of water will be charged, and again the deflection of the electroscope increases. As long as drops of water fall, the charge on the electroscope increases!

When now the collar is removed, the electric field between the beaker and container changes direction. So, a drop of water will be charged opposite to the charge it got in the first part of the demonstration, lowering the deflection of the electroscope until the electric field between beaker and container is zero again.

6.1.3.4.7 Remarks

- By means of a camera the (reading of the) electroscope is projected on a monitor or large screen.
- The electroscope can be replaced by an electrostatic Voltmeter (see Figure 3). Then the students can see directly that the voltage of the metal beaker can reach a voltage much higher than the voltage of the container from where the drops are falling.

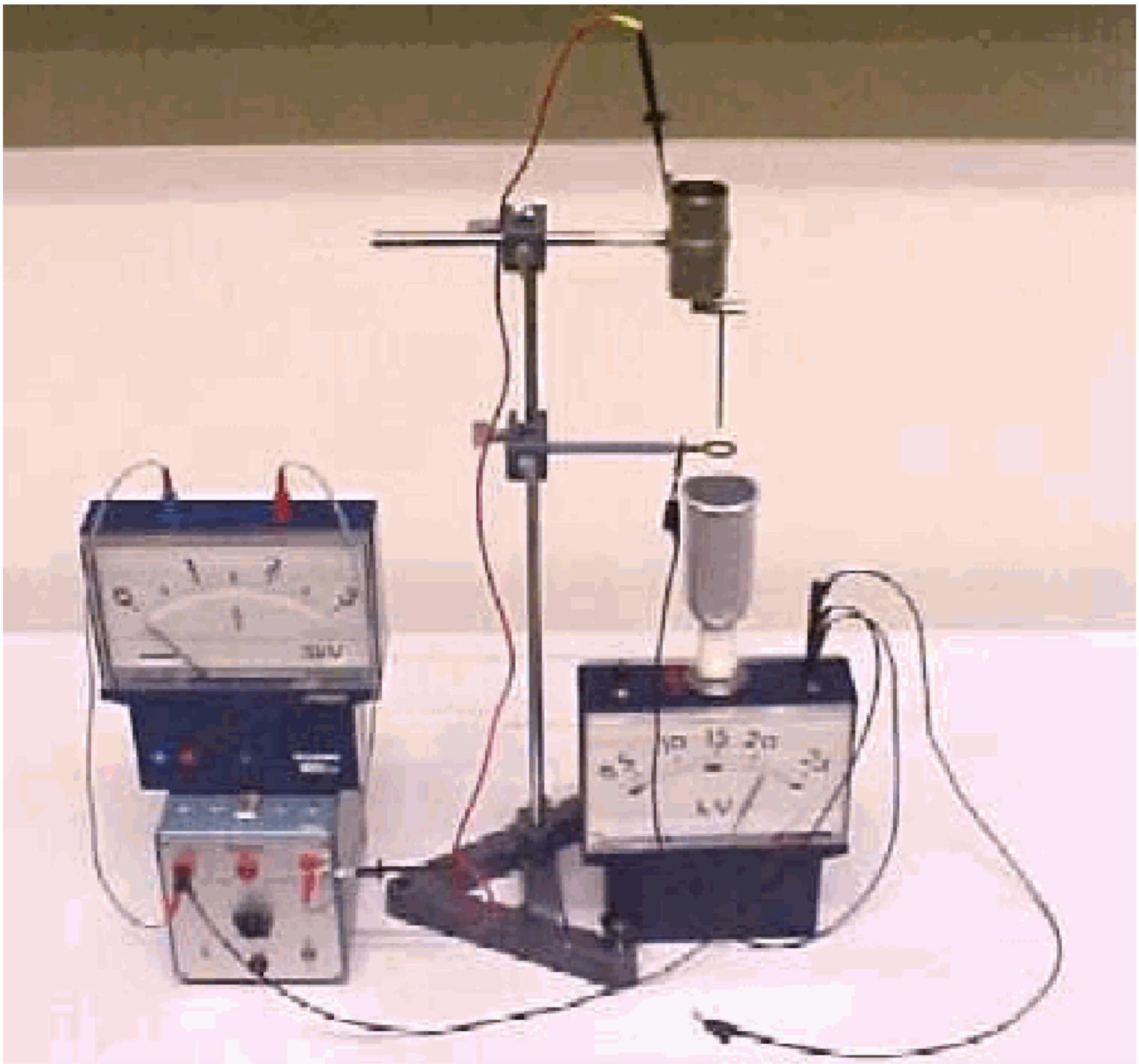


Figure 6.20: .

6.1.4 5A50 Electrostatic Machines

6.1.4.1 01 Water Dropper (almost Kelvin water dropper)

6.1.4.1.1 Aim

To show the principle of operation of a Van der Graaff generator.

6.1.4.1.2 Subjects

- 5A40 (Induced Charge) 5A50 (Electrostatic Machines)

6.1.4.1.3 Diagram

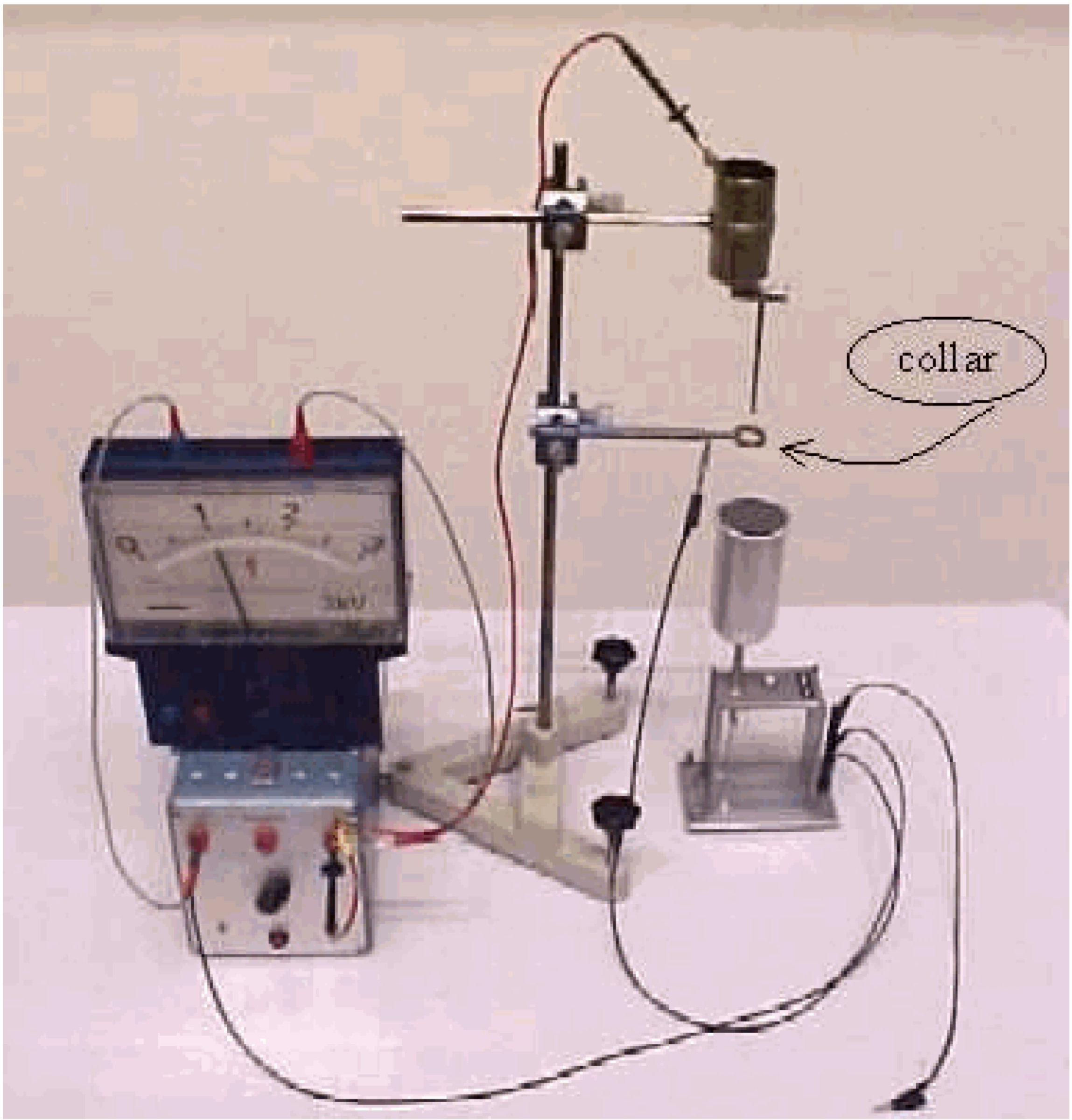


Figure 6.21: .

6.1.4.1.4 Equipment

- Electroscope.
- Metal beaker on top of electroscope.
- Metal collar, fitted on a bar of pvc.
- Metal container with pinchcock, allowing water to drip. (The holding bar is partly made of perspex for isolation.)
- Power supply (about 1kV).

- Camera.
- Electrostatic Voltmeter (see Remarks and Figure 3).

6.1.4.1.5 Presentation

Set up the equipment as shown in the Diagram (the metal collar is in the beginning turned away from the dropper; the $+1\text{kV}$ lead is not yet connected). The power supply is adjusted to a voltage of about 1kV. Touching momentarily the electroscope with the $+1\text{kV}$ lead shows that this voltage gives a small deflection (in our case 3 divisions). Discharge the electroscope.

Now the upper container is filled with water and placed about 10 cm above the beaker on the electroscope. The $+1\text{kV}$ lead is connected to it. The pinchcock is opened and drops of water fall into the beaker on the electroscope. When the upper container is connected to the power supply, the electroscope will build up the small deflection (of 3 divisions) we had before.

Now the metal collar, connected to ground, is placed around the falling drops of water. The effect is that the deflection of the electroscope increases and very soon runs off scale!

When now the collar is moved away from the falling drops of water, the electroscope will slowly return to the lower deflection it had before.

6.1.4.1.6 Explanation

In the first part of the demonstration an electric field (1kV over 10 cm, so $\text{E} = 10\text{kV/m}$) exists between the upper water container and the electroscope.

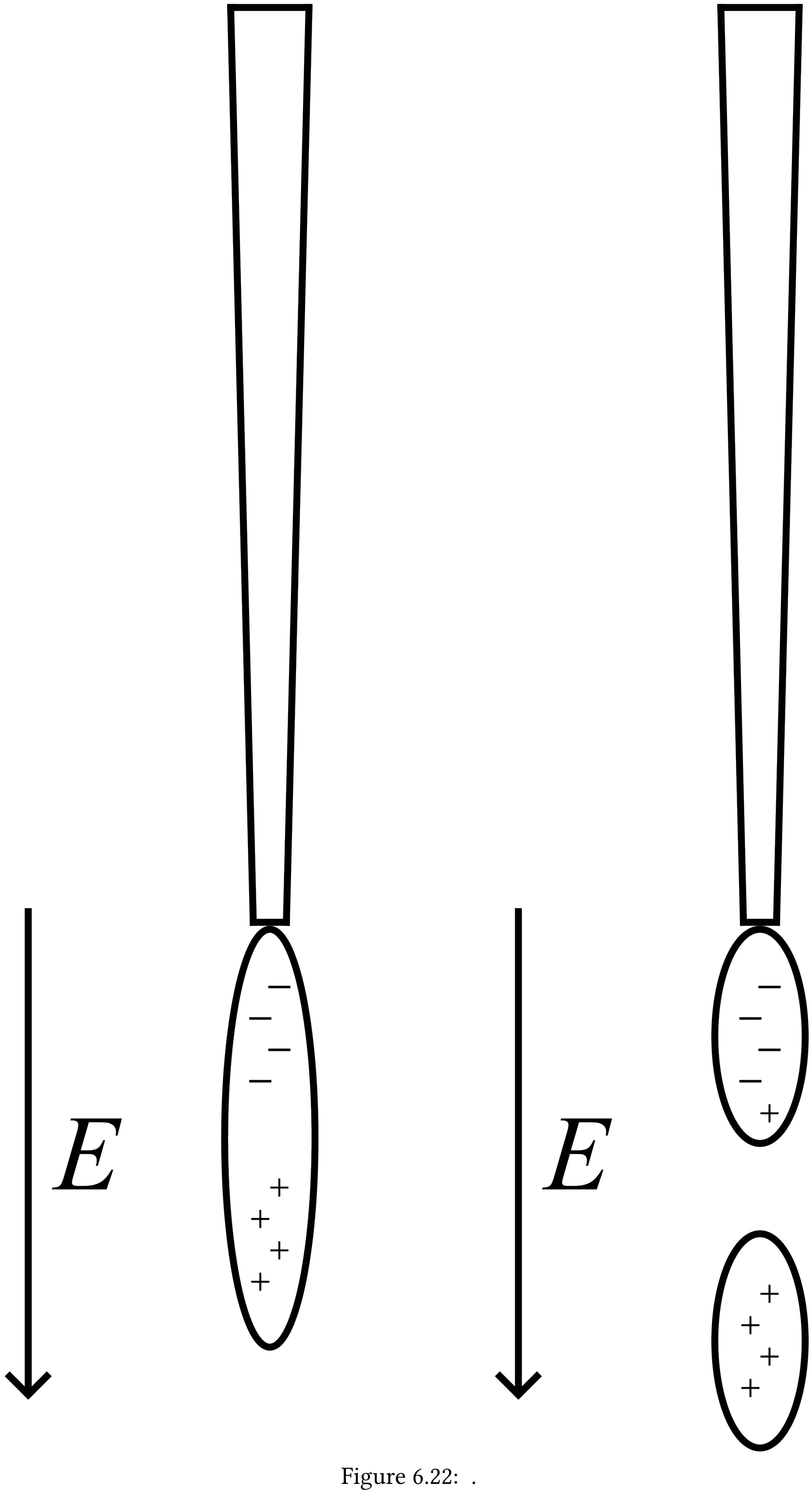


Figure 6.22: .

Due to this field, the drops of water will be charged when they break loose from the metal dropper (see Figure 2). When the drops fall into the beaker on the electroscope this charge accumulates (on the outside of the beaker) and the deflection of the electroscope increases. This continues until the potential of the beaker is the same as the potential of the upper water container, because now there is no longer an electric field to charge the drops of water.

When the grounded metal collar is placed around the stream of falling drops, there will be an electric field again between the collar and the upper water container and again the drops of water will be charged, and again the deflection of the electroscope increases. As long as drops of water fall, the charge on the electroscope increases!

When now the collar is removed, the electric field between the beaker and container changes direction. So, a drop of water will be charged opposite to the charge it got in the first part of the demonstration, lowering the deflection of the electroscope until the electric field between beaker and container is zero again.

6.1.4.1.7 Remarks

- By means of a camera the (reading of the) electroscope is projected on a monitor or large screen.
- The electroscope can be replaced by an electrostatic Voltmeter (see Figure 3). Then the students can see directly that the voltage of the metal beaker can reach a voltage much higher than the voltage of the container from where the drops are falling.

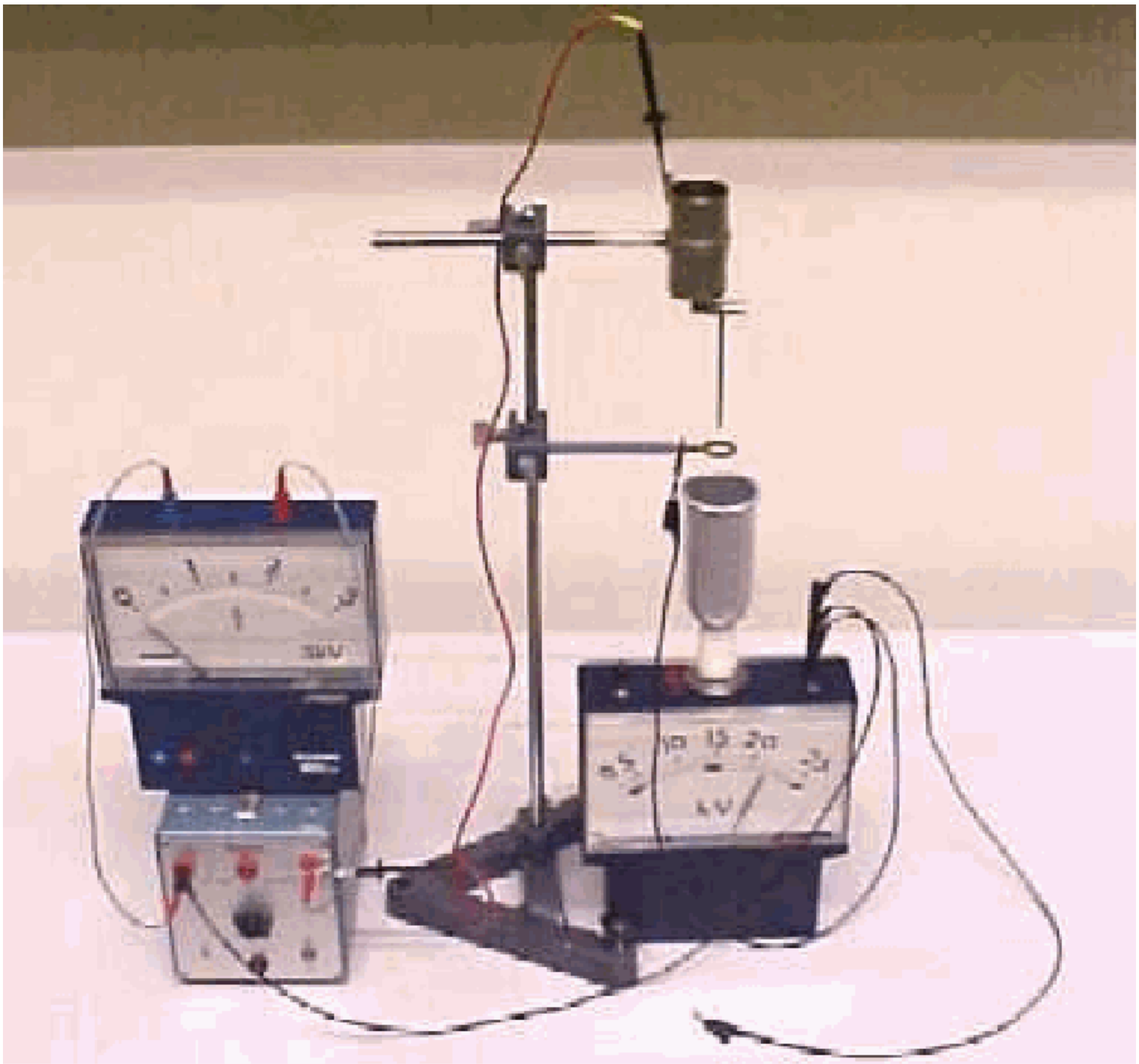


Figure 6.23: .

6.2 5B Electric Fields and Potential

6.2.1 5B10 Electric Fields

6.2.1.1 01 Charge and Field; inside and-or outside?

6.2.1.1.1 Aim

To show that on a conductor the charge resides on the outside and that inside a charged conductor there is no field.

6.2.1.1.2 Subjects

- 5B10 (Electric Fields) 5B20 (Gauss' Law)

6.2.1.1.3 Diagram

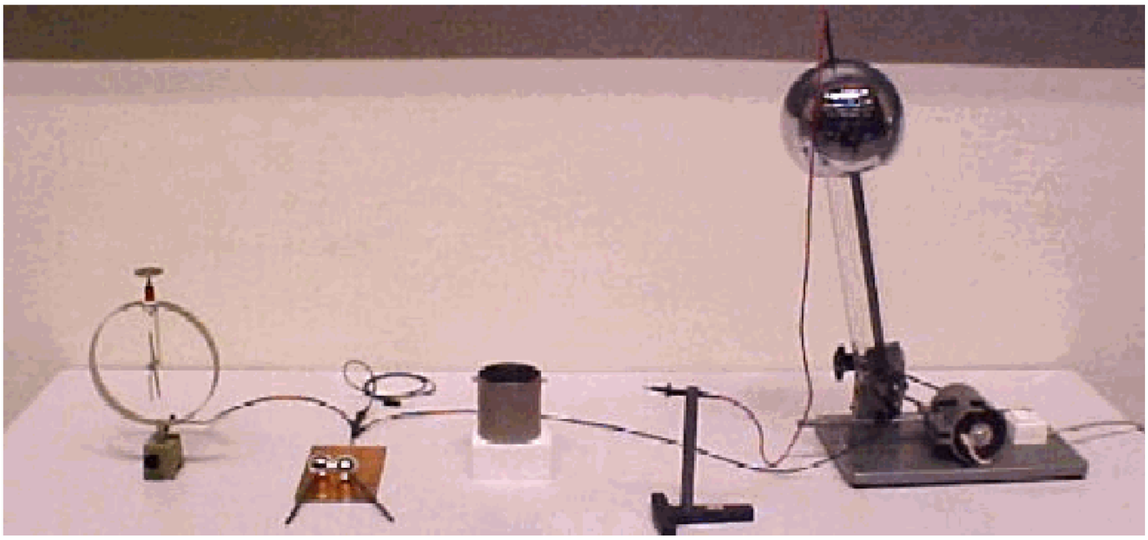


Figure 6.24: .

6.2.1.1.4 Equipment

- Metal pan on isolating piece of foam.
- Two small conducting spheres.
- Van de Graaff generator (see Safety).
- Electroscope.
- Grounded wire and grounded metal plate.

6.2.1.1.5 Safety

- In general working with a Van de Graaff generator is not considered as harmful. The Van de Graaff generator shown in the Diagram can produce voltages approaching 270kV ($R_{sphere} = 9$ cm and supposing breakdown in air occurs at $E = 3 \times 10^6$ V/m), and yet at worst it delivers a brief sting. This device has a limited amount of stored energy, so the current produced is low and usually for a short time. During the discharge, this machine applies high voltage to the body for only a millionth of a second or less. In order to produce heart fibrillation, an electric power supply must produce a significant current in the heart muscle continuing for many milliseconds, and must deposit a total energy in the range of at least milli-joules or higher.
- A critical remark added to this is the next letter that appeared in "Physics Today", March 2010;

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  page 10 Physics students often try the fun experiment of holding a high-voltage
pole while standing on an electrically isolating mat. The experiment is believed
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to be harmless, since no current is flowing. But the question can be raised,
however, as to what happens to our skin. Air is an excellent supplier of charge,
and it can be assumed that if our skin is at the same (positive) potential as the
high-voltage generator, electrons will be attracted to the surface of our body. If
the voltage supply is at tens of kilovolts, the energy with which electrons
impinge on our skin can be as high as tens of kiloelectron volts. I wonder if
anyone has ever studied the incidence of skin cancer in students who played with
such an experiment for prolonged periods or, for that matter, in birds that rest
on high-voltage cables. To be on the safe side, the experiment should be tested
only briefly, if at all. (walter.margulis@acreo.se).
```

So, the message is: stay careful when working with a Van de Graaff generator.

6.2.1.1.6 Presentation

6.2.1.1.6.1 Demo 1a

Charge is brought on the outside of the pan by means shortly touching it with the wire that is connected to the Van der Graaff generator.

The demonstrator takes one of the small conducting spheres and touches with that sphere the inside of the pan (the audience can clearly hear that the inside is touched). The sphere is then made touching the electroscope that will show no deflection. Repeating the action will have no effect on the electroscope. Then the demonstrator repeats this action, but now he touches the outside of the pan with the metal sphere. Now the electroscope shows a deflection, which increases when he repeats his action.

6.2.1.1.6.2 Demo 1b

The same demonstration is performed but now the metal pan is charged by touching the inside of the metal pan with the lead coming from the Van de Graaff generator. The result of this demo is exactly the same as in Demo 1a.

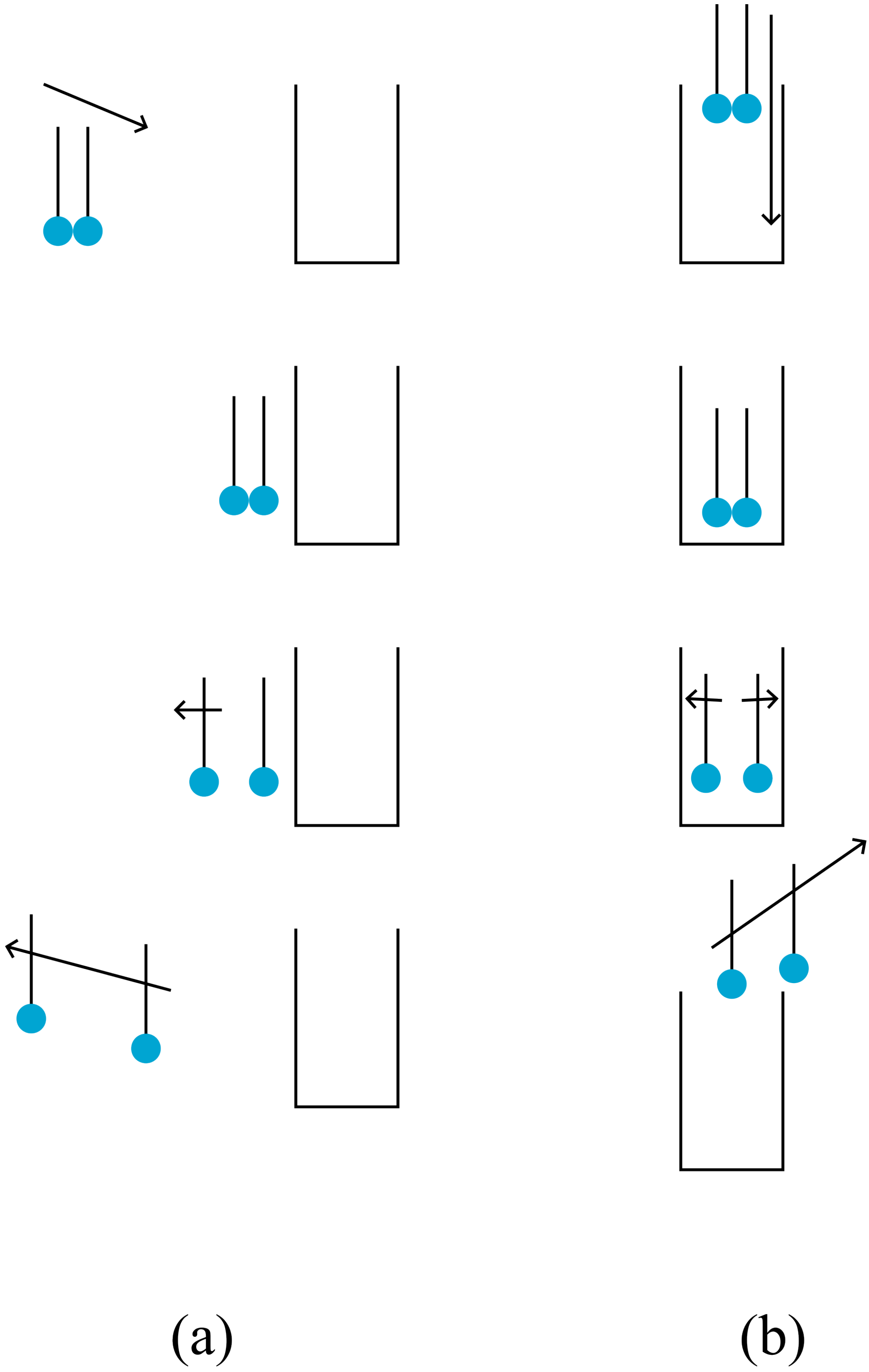

Figure 6.25: .

6.2.1.1.6.3 Demo 2

The demonstrator holds the two metal spheres that are touching each other and lowers them into the pan. He takes care that the spheres do not to touch the inside of the pan. Inside the pan he separates the two spheres (see Figure 2B), lifts them out of the pan and with one of the spheres he touches the electroscope. The electroscope does not react. Also when he touches the electroscope with the other sphere nothing will happen.

He repeats the demonstration, but now he brings the two touching spheres close to the outside of the charged metal pan and there he separates the two spheres (see Figure 2A). Again he touches with one sphere the electroscope and now the electroscope shows a deflection. Next, he touches the electroscope with the other metal sphere and the deflection of the electroscope becomes less.

6.2.1.1.7 Explanation

The first demonstration shows clearly that charge is always on the outside of the metal pan. Theoretically this can be explained when you apply Gauss's law (see the demonstration Charge is on the outside

The second demonstration shows clearly that outside the pan there is an electric field that acts on the charges in the two neutral conducting spheres. These charges are separated from each other. And when, still in the field, the two spheres are separated, these charges are isolated. One sphere is positively charged now and the other negatively.

In the same way the demonstration shows that inside the metal pan there is no electric field.

6.2.1.1.8 Remarks

- Sometimes students experience Gauss's law as the cause of phenomena. That's why it is useful to stress that it is just the other way round: Nature behaves in such a way that there is no field inside the metal pan. This phenomenon is described best in the way Gauss formulated it.
- Every time a new demonstration is done, discharge all components and yourself! To perform discharging, the grounded wire and grounded metal plate are used.
- Take care that when the balls are close to the metal pan no sparks occur, because then the assembly of the two spheres is no longer neutral.
- When in the electric field demonstration the two balls are not deep enough in the metal pan they will become charged a little when separated, showing that there exists a weak electric field near the opening of the metal pan.

6.2.1.1.9 Sources

Wolfson, Richard, Essential University Physics, pag, 359-360

6.2.1.2 02 Charge is on the Outside

6.2.1.2.1 Aim

To show that charge is on the outside of a conductor as an application of Gauss's law.

6.2.1.2.2 Subjects

- 5B10 (Electric Fields) 5B20 (Gauss' Law)

6.2.1.2.3 Diagram

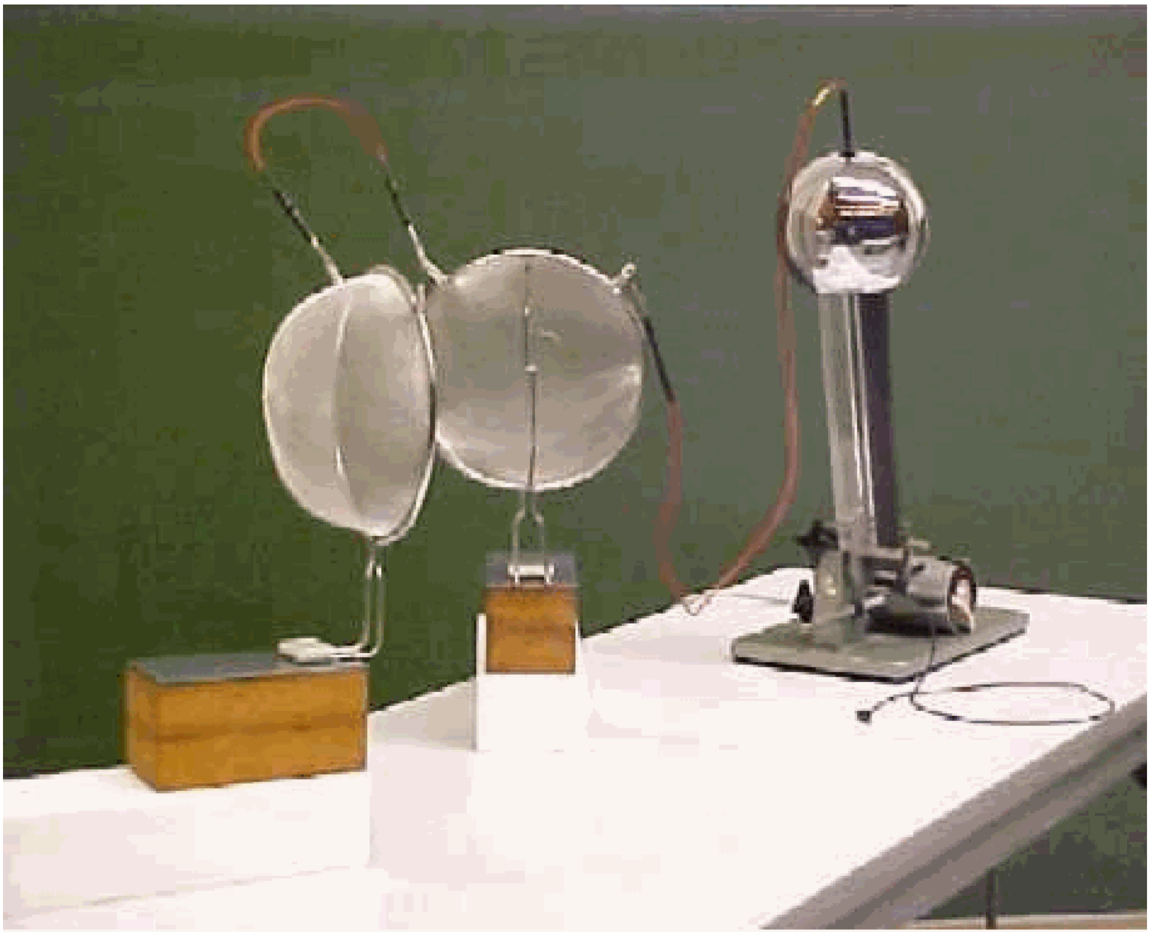

Figure 6.26: .

6.2.1.2.4 Equipment

- Two large metal sieves, one mounted with an electroscope. They are mounted on heavy wooden blocks.
- Two large blocks of styrofoam.
- Van de Graaff generator.
- Camera.

6.2.1.2.5 Presentation

The two metal hemispheres (sieves) are placed on the styrofoam blocks and placed in such a way that they make a complete metal sphere. The two metal hemispheres are electrically connected and together they are connected to a Van de Graaff generator. The camera is sharply focussed on the electroscope so that it is clearly visible through the metal sieve.

The students are asked to predict what will happen to the electroscope when the metal sphere is charged.

The Van de Graaff generator is switched on and charges the closed metal sphere. The electroscope inside shows no deflection (see Figure 2).

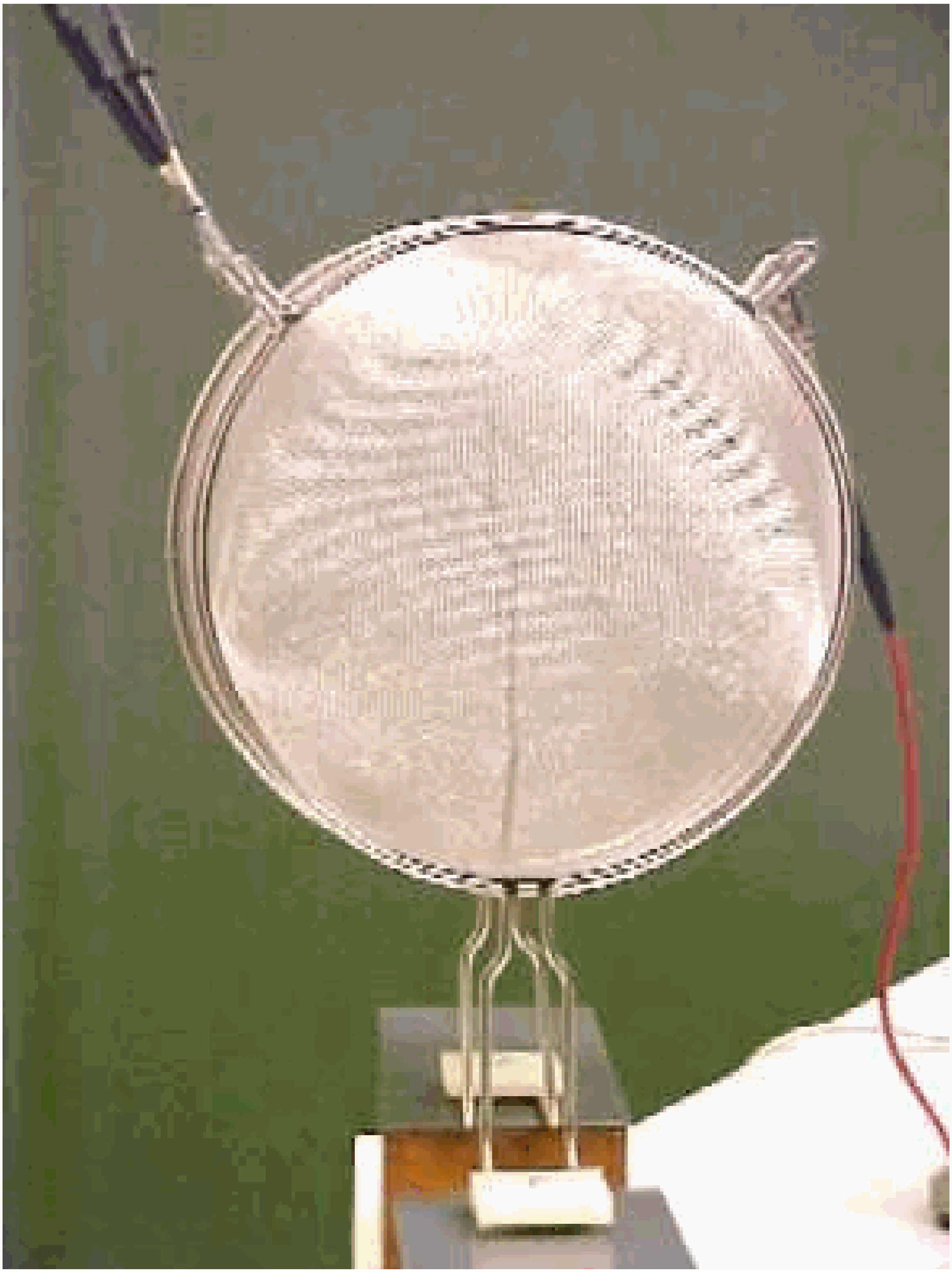

Figure 6.27: .

Now students are asked to predict what will happen to the electroscope when the charged metal sphere is separated into two halves.

The sphere is opened by pulling one sieve away (pulling the styrofoam block) and immediately the electroscope shows a deflection (see Figure 3). Closing the metal sphere again makes the deflection of the electroscope zero again.

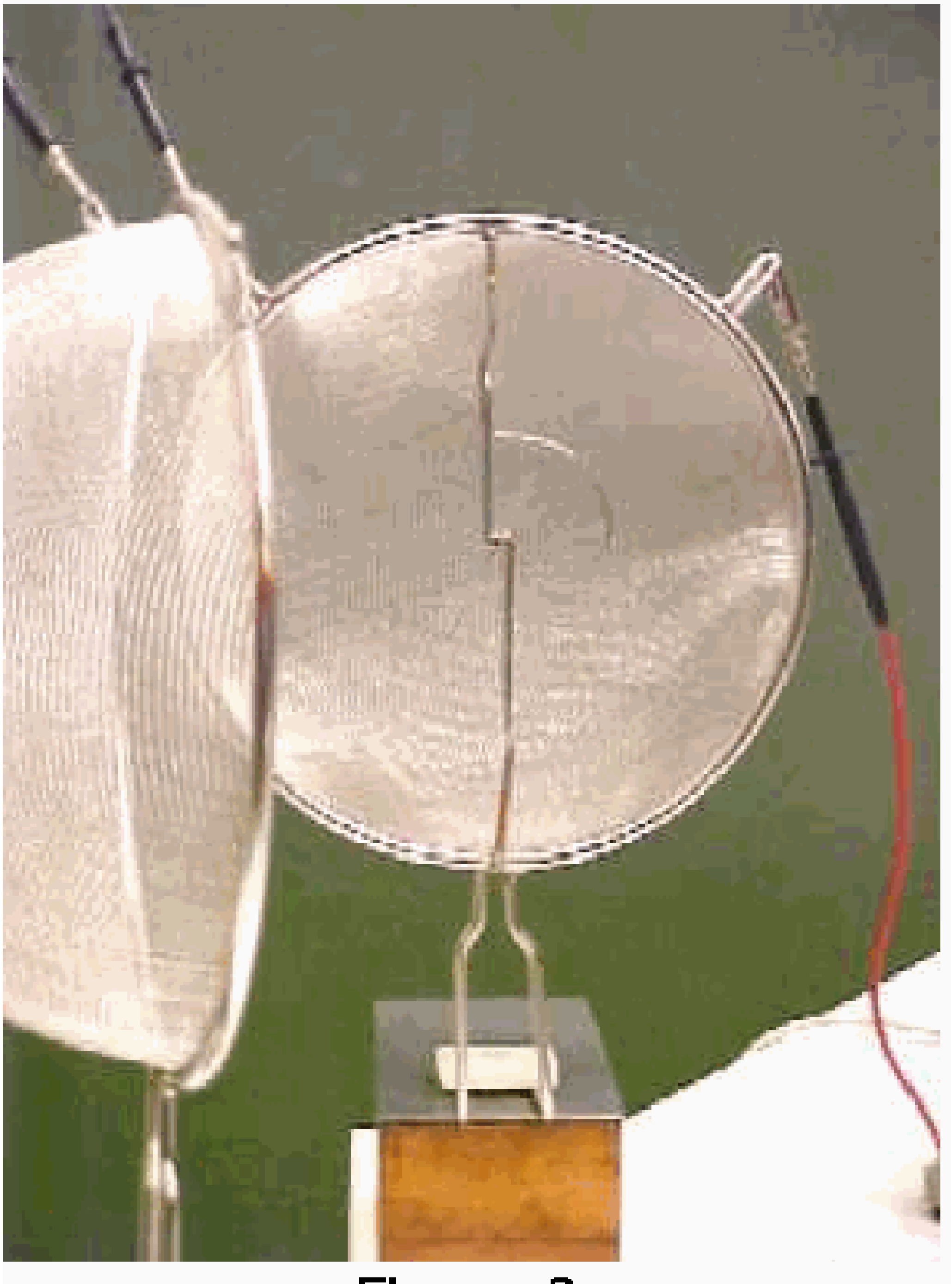

Figure 6.28: .

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6.2.1.2.6 Explanation

The electric field inside any conductor is zero even if it carries a net charge (otherwise the free charges inside the conductor would move until the net force on each were zero, and hence E were zero).

The net charge must reside on the outer surface. Gauss's law shows this: When we choose a Gaussian surface close to the surface of the conductor but still inside it, the electric field inside is zero at all points. Hence there can be no net charge on the inside. The electroscope on the inside of the hemisphere, being a charge detector, shows this.

When the two halves are separated, the electroscope becomes an outer surface and so it will carry charge. The electroscope, being this outer surface, shows this by its deflection.

6.2.1.2.7 Remarks

- Manipulate the two sieves only by touching the styrofoam blocks. The heavy wooden blocks are no good isolators.

6.2.1.2.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 584-585

6.2.2 5B20 Gauss's Law

6.2.2.1 01 Gauss' Law

6.2.2.1.1 Aim

In order to introduce Gauss's law, the analogy between the velocity field of a fluid flow and the electric field is used.

6.2.2.1.2 Subjects

- 5B20 (Gauss' Law)

6.2.2.1.3 Diagram

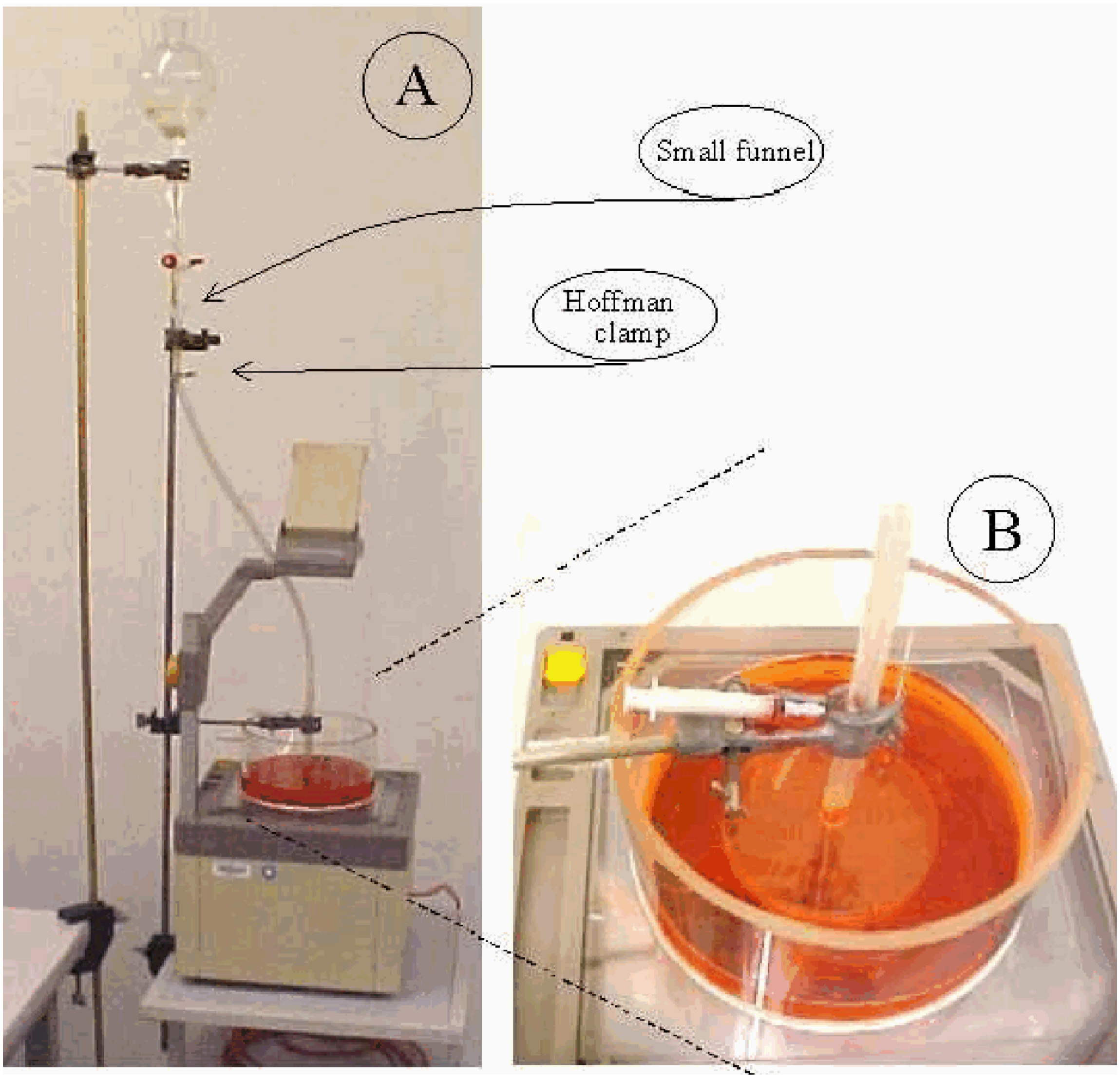

Figure 6.29: .

6.2.2.1.4 Equipment

- Two circular clear acrylic plates, separated by 0.5 mm
- Glass tray in which the assembly of circular plates fits easily (see Diagram).
- Syringe (2 mL), with small needle and filled with ink.
- Separating funnel (1 L).
- Overhead projector.

6.2.2.1.5 Presentation

The assembly of the clear acrylic plates is placed in the glass tray and positioned on the overhead projector. A flexible tubing of around 50 cm is connected to the central connector in the upper circular plate. The glass tray is filled with water until the assembly of circular plates is submerged. Using Hoffman clamps, the flexible tubing is filled with water. The needle of the syringe is stuck into the flexible tubing just above the connection to the plates (see DiagramB).

Slowly the Hoffman clamp is opened just a little so that a slow fluid flow occurs between the plates. The 1 liter-separating funnel is made dripping in order to keep the level in the flexible tubing constant and, in that way, the flow constant. Then the ink marker is injected into the fluid stream and the spreading of the fluid between the circular plates can be observed.

Placing radial distance marks on the circular acrylic plates, the velocity of the fluid can be determined directly by measuring the crossing times of the leading surface of the ink marker. The feature of the decrease in velocity as a function of radial distance is strikingly obvious and in agreement with $1/r$ dependence.

When this result is solidified, the demonstration is followed by a theoretical exercise of applying the same analysis to a fluid source that is allowed to expand outward uniformly in three dimensions. This will lead to a $1/r^2$ dependence (see Explanation).

Once the analogy between $E = Q/4\pi\varepsilon_0 t^2$ and $v = f/4\pi t^2$ is established, students are asked to identify the electric quantities that are analogues to the velocity, v, and the fluid flow f. These quantities are the electric field E, and Q/ε_0, respectively. Since both electric field and velocity are linear quantities an equivalent of the continuity principle $f = vA$ must also exist for electric fields. Given the analogies, students will find this electric continuity principle as $Q/\varepsilon_0 = EA$: Gauss's law! (The term EA has then rightfully the meaning of "electric flux")

6.2.2.1.6 Explanation

The continuity-relation between the volume rate of flow, $f(f = \Delta V/\Delta t)$, the fluid velocity, v, and the cross-sectional area, A, is $f = vA =$ constant. Challenging the students to consider the flow in this system they find, once the area A is identified as $2\pi rd$ (and so $2\pi rdv =$ constant), the $1/r$ dependence of the velocity field in this essentially two-dimensional system.

In case of three-dimensional flow the area A considered equals $4\pi r^2$ giving $4\pi r^2 v =$ constant leading to the $1/r^2$ dependence.

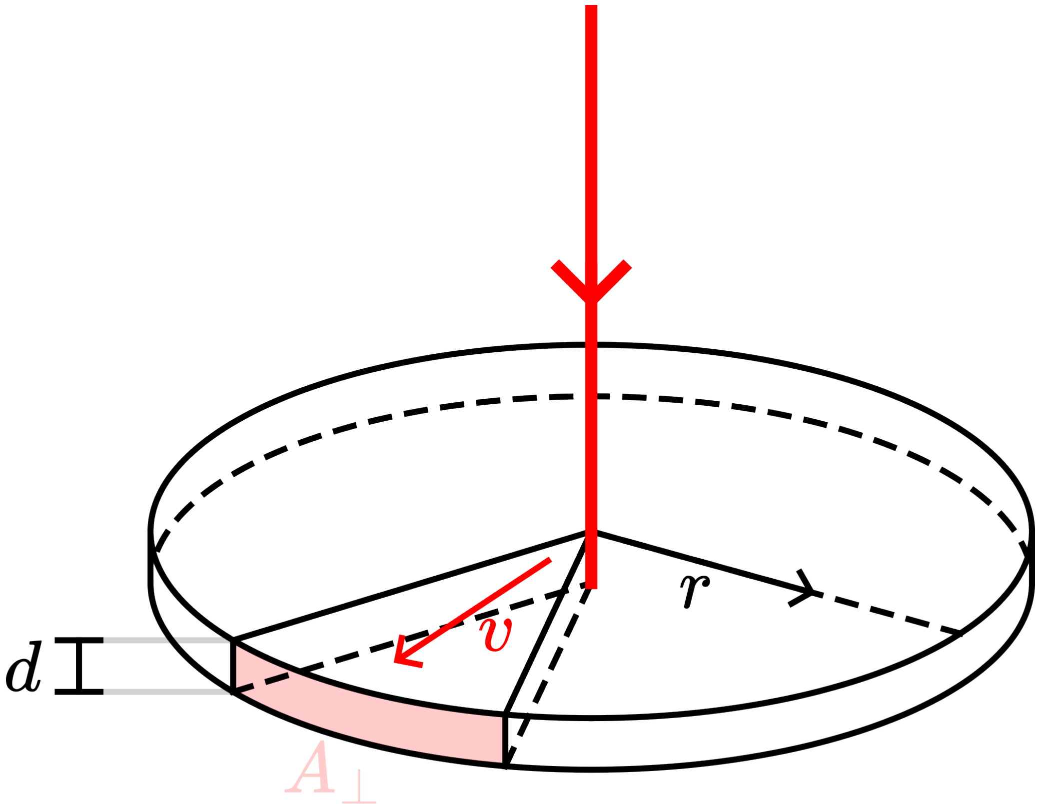

Figure 6.30: .

6.2.2.1.7 Remarks

- Comparing electric flux and fluid flux offers insight, but do not get them confused: An electric flux is not a flow of any substance! Flux can be defined for any vector field.
- The support for the separating funnel is not fixed to the overhead projector but to a separate table (see Diagram). This is done on purpose, because otherwise adjusting the dripping of the funnel makes the assembly shaking and that will disturb the observed fluid flow.
- Instead of an overhead projector also a camera can be used to show the fluid flow.
- Filling the flexible tubing of 50 cm is done by using two Hoffman clamps (see Figure 3).
- Take care that no air bubbles are in the fluid between the two circular plates. (We use a piece of overhead-sheet to wipe away bubbles.)

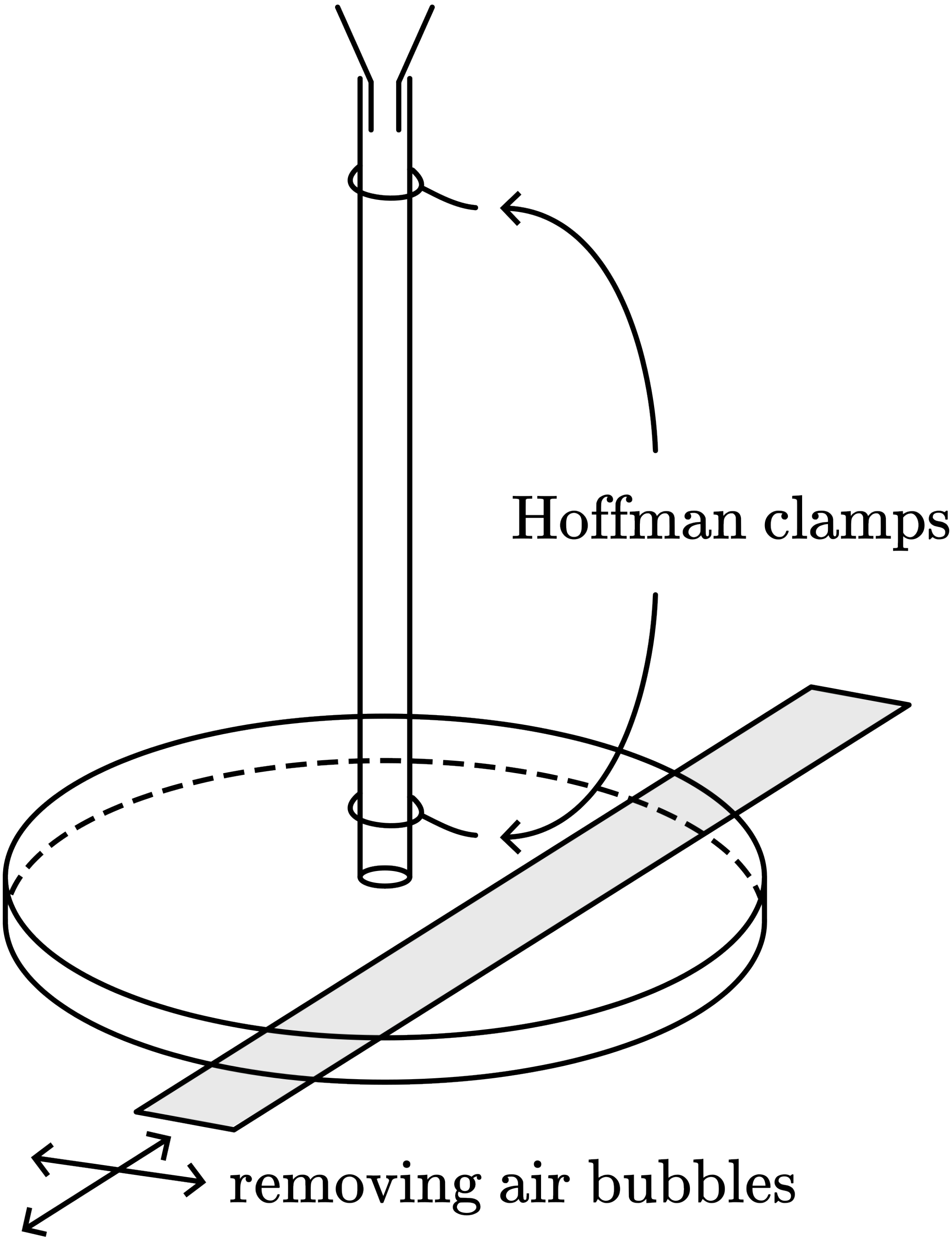

Figure 6.31: .

6.2.2.1.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 578 (upper part)
- American Journal of Physics, pag. Vol. 72, 1272-1275

6.2.2.2 02 Charge is on the Outside

6.2.2.2.1 Aim

To show that charge is on the outside of a conductor as an application of Gauss's law.

6.2.2.2.2 Subjects

- 5B10 (Electric Fields) 5B20 (Gauss' Law)

6.2.2.2.3 Diagram

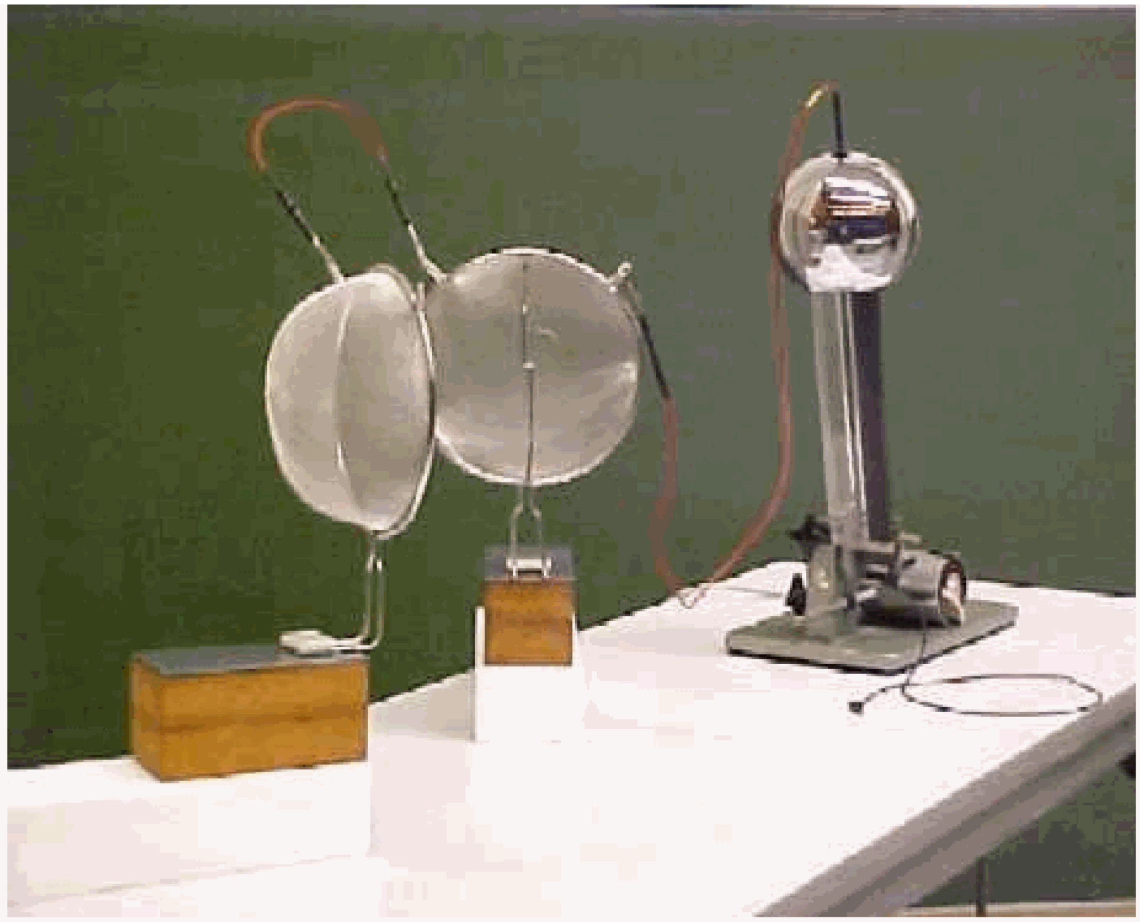

Figure 6.32: .

6.2.2.2.4 Equipment

- Two large metal sieves, one mounted with an electroscope. They are mounted on heavy wooden blocks.
- Two large blocks of styrofoam.
- Van de Graaff generator.
- Camera.

6.2.2.2.5 Presentation

The two metal hemispheres (sieves) are placed on the styrofoam blocks and placed in such a way that they make a complete metal sphere. The two metal hemispheres are electrically connected and together they are connected to a Van de Graaff generator. The camera is sharply focussed on the electroscope so that it is clearly visible through the metal sieve.

The students are asked to predict what will happen to the electroscope when the metal sphere is charged.

The Van de Graaff generator is switched on and charges the closed metal sphere. The electroscope inside shows no deflection (see Figure 2).

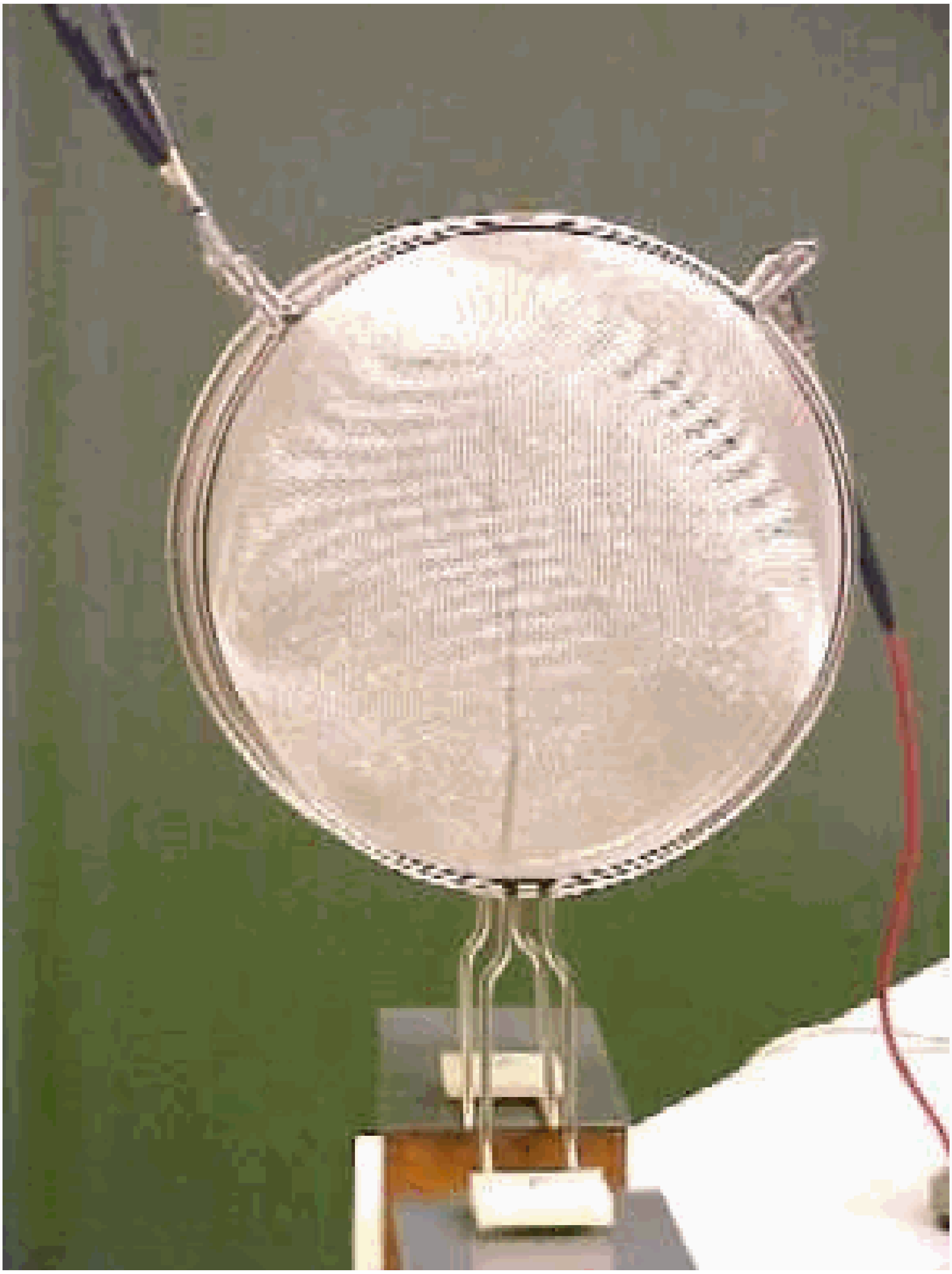

Figure 6.33: .

Now students are asked to predict what will happen to the electroscope when the charged metal sphere is separated into two halves.

The sphere is opened by pulling one sieve away (pulling the styrofoam block) and immediately the electroscope shows a deflection (see Figure 3). Closing the metal sphere again makes the deflection of the electroscope zero again.

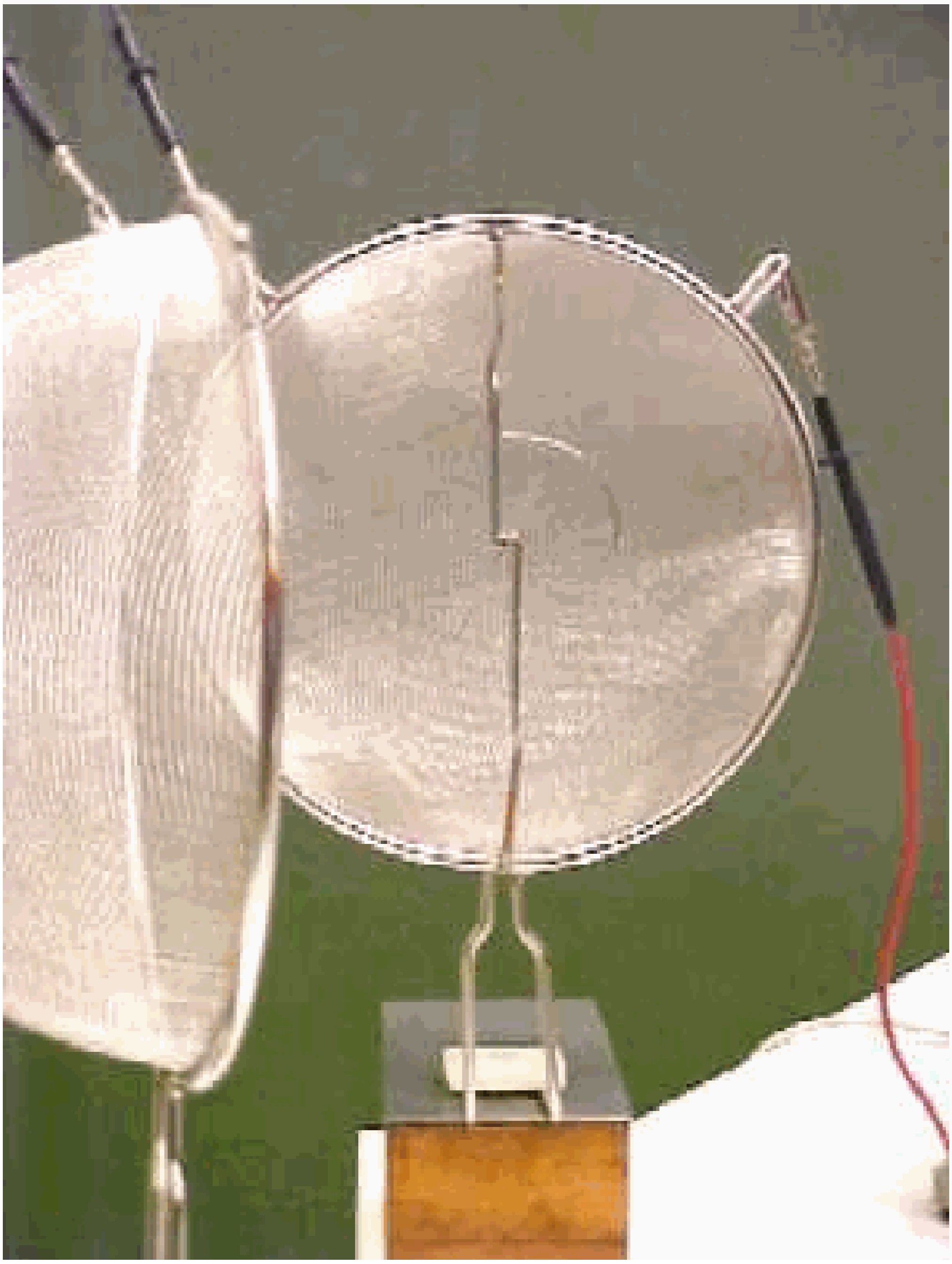

Figure 6.34: .

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6.2.2.2.6 Explanation

The electric field inside any conductor is zero even if it carries a net charge (otherwise the free charges inside the conductor would move until the net force on each were zero, and hence E were zero).

The net charge must reside on the outer surface. Gauss's law shows this: When we choose a Gaussian surface close to the surface of the conductor but still inside it, the electric field inside is zero at all points. Hence there can be no net charge on the inside. The electroscope on the inside of the hemisphere, being a charge detector, shows this.

When the two halves are separated, the electroscope becomes an outer surface and so it will carry charge. The electroscope, being this outer surface, shows this by its deflection.

6.2.2.2.7 Remarks

- Manipulate the two sieves only by touching the styrofoam blocks. The heavy wooden blocks are no good isolators.

6.2.2.2.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 584-585

6.2.2.3 03 Charge and Field; inside and-or outside?

6.2.2.3.1 Aim

To show that on a conductor the charge resides on the outside and that inside a charged conductor there is no field.

6.2.2.3.2 Subjects

- 5B10 (Electric Fields) 5B20 (Gauss' Law)

6.2.2.3.3 Diagram

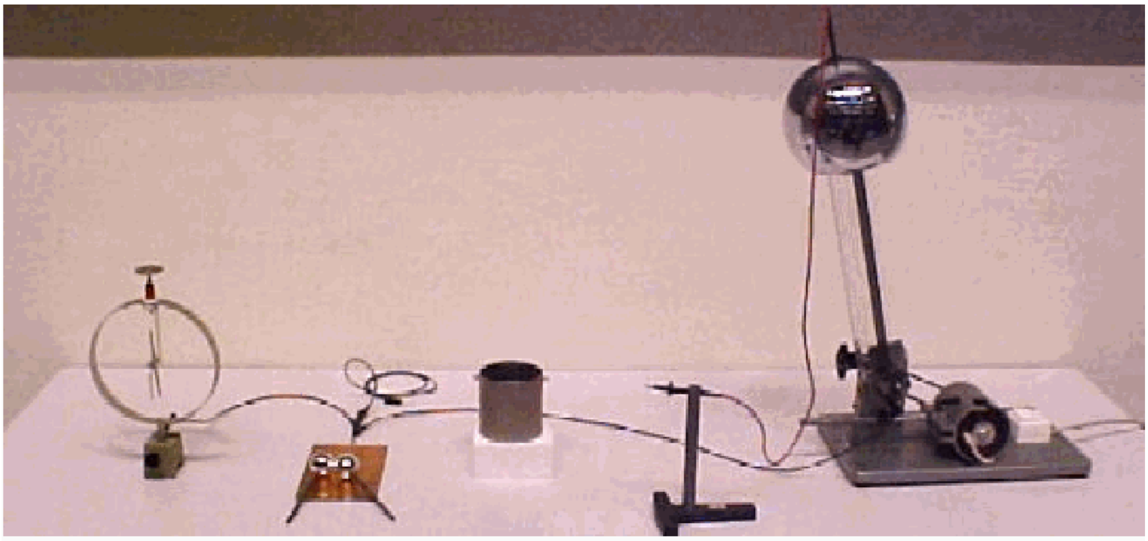

Figure 6.35: .

6.2.2.3.4 Equipment

- Metal pan on isolating piece of foam.
- Two small conducting spheres.
- Van de Graaff generator (see Safety).
- Electroscope.
- Grounded wire and grounded metal plate.

6.2.2.3.5 Safety

- In general working with a Van de Graaff generator is not considered as harmful. The Van de Graaff generator shown in the Diagram can produce voltages approaching 270kV ($R_{sphere} = 9$ cm and supposing breakdown in air occurs at $E = 3 \times 10^6$ V/m), and yet at worst it delivers a brief sting. This device has a limited amount of stored energy, so the current produced is low and usually for a short time. During the discharge, this machine applies high voltage to the body for only a millionth of a second or less. In order to produce heart fibrillation, an electric power supply must produce a significant current in the heart muscle continuing for many milliseconds, and must deposit a total energy in the range of at least milli-joules or higher.
- A critical remark added to this is the next letter that appeared in "Physics Today", March 2010;

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  page 10 Physics students often try the fun experiment of holding a high-voltage
pole while standing on an electrically isolating mat. The experiment is believed
to be harmless, since no current is flowing. But the question can be raised,
however, as to what happens to our skin. Air is an excellent supplier of charge,
and it can be assumed that if our skin is at the same (positive) potential as the
high-voltage generator, electrons will be attracted to the surface of our body. If
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the voltage supply is at tens of kilovolts, the energy with which electrons
impinge on our skin can be as high as tens of kiloelectron volts. I wonder if
anyone has ever studied the incidence of skin cancer in students who played with
such an experiment for prolonged periods or, for that matter, in birds that rest
on high-voltage cables. To be on the safe side, the experiment should be tested
only briefly, if at all. (walter.margulis@acreo.se).
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So, the message is: stay careful when working with a Van de Graaff generator.

6.2.2.3.6 Presentation

6.2.2.3.6.1 Demo 1a

Charge is brought on the outside of the pan by means shortly touching it with the wire that is connected to the Van der Graaff generator.

The demonstrator takes one of the small conducting spheres and touches with that sphere the inside of the pan (the audience can clearly hear that the inside is touched). The sphere is then made touching the electroscope that will show no deflection. Repeating the action will have no effect on the electroscope. Then the demonstrator repeats this action, but now he touches the outside of the pan with the metal sphere. Now the electroscope shows a deflection, which increases when he repeats his action.

6.2.2.3.6.2 Demo 1b

The same demonstration is performed but now the metal pan is charged by touching the inside of the metal pan with the lead coming from the Van de Graaff generator. The result of this demo is exactly the same as in Demo 1a.

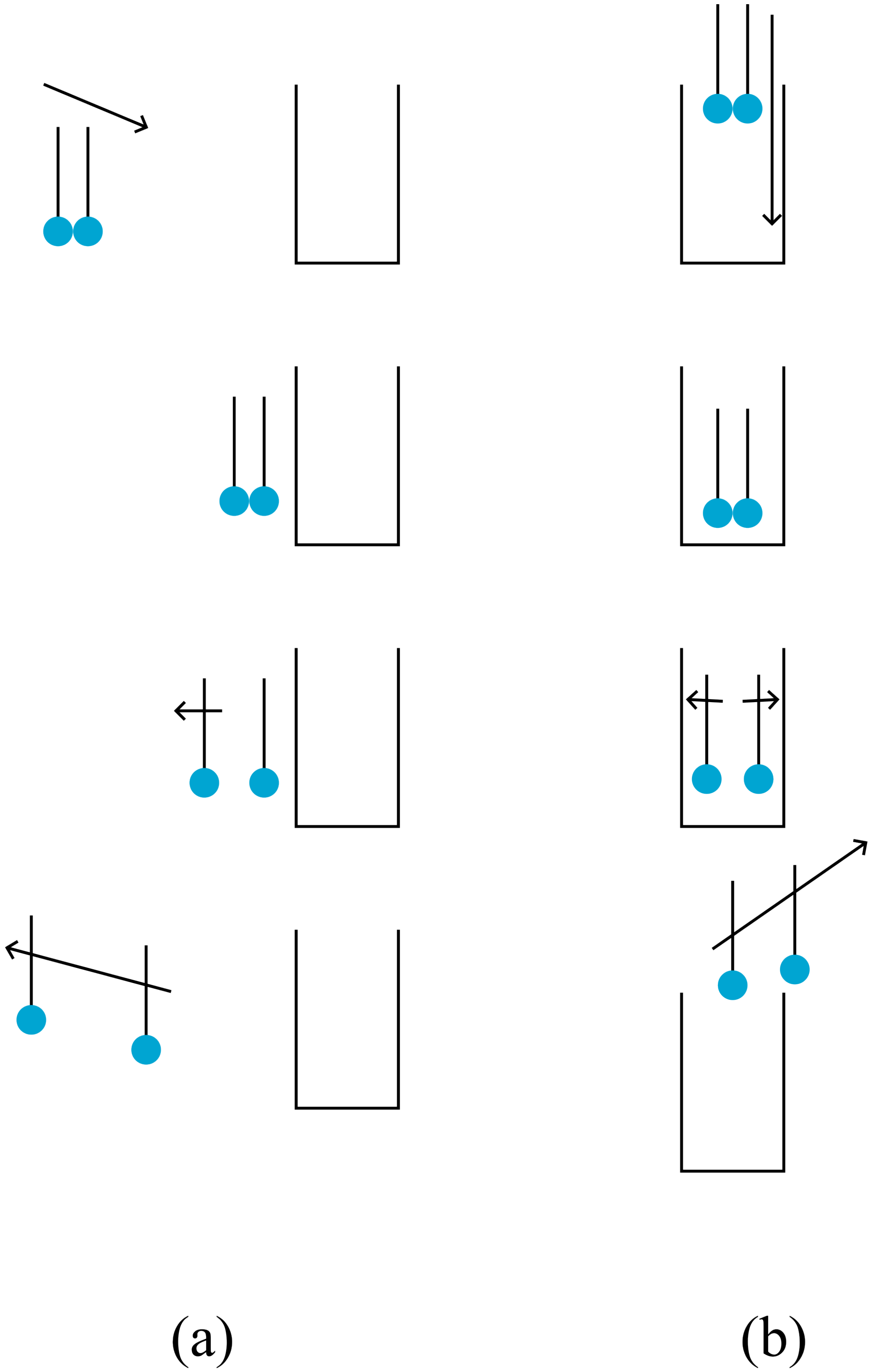


Figure 6.36: .

6.2.2.3.6.3 Demo 2

The demonstrator holds the two metal spheres that are touching each other and lowers them into the pan. He takes care that the spheres do not to touch the inside of the pan. Inside the pan he separates the two spheres (see Figure 2B), lifts them out of the pan and with one of the spheres he touches the electroscope. The electroscope does not react. Also when he touches the electroscope with the other sphere nothing will happen.

He repeats the demonstration, but now he brings the two touching spheres close to the outside of the charged metal pan and there he separates the two spheres (see Figure 2A). Again he touches with one sphere the electroscope and now the electroscope shows a deflection. Next, he touches the electroscope with the other metal sphere and the deflection of the electroscope becomes less.

6.2.2.3.7 Explanation

The first demonstration shows clearly that charge is always on the outside of the metal pan. Theoretically this can be explained when you apply Gauss's law (see the demonstration Charge is on the outside.

The second demonstration shows clearly that outside the pan there is an electric field that acts on the charges in the two neutral conducting spheres. These charges are separated from each other. And when, still in the field, the two spheres are separated, these charges are isolated. One sphere is positively charged now and the other negatively.

In the same way the demonstration shows that inside the metal pan there is no electric field.

6.2.2.3.8 Remarks

- Sometimes students experience Gauss's law as the cause of phenomena. That's why it is useful to stress that it is just the other way round: Nature behaves in such a way that there is no field inside the metal pan. This phenomenon is described best in the way Gauss formulated it.
- Every time a new demonstration is done, discharge all components and yourself! To perform discharging, the grounded wire and grounded metal plate are used.
- Take care that when the balls are close to the metal pan no sparks occur, because then the assembly of the two spheres is no longer neutral.
- When in the electric field demonstration the two balls are not deep enough in the metal pan they will become charged a little when separated, showing that there exists a weak electric field near the opening of the metal pan.

6.2.2.3.9 Sources

Wolfson, Richard, Essential University Physics, pag, 359-360

6.3 5C Capacitance

6.3.1 5C10 Capacitors

6.3.1.1 5C10.20

6.3.1.1.1 Capacitor (1) Spacing between the Plates

Capacitor: spacing and dielectric

6.3.1.1.1.1 Aim

To show how the voltage of a capacitor changes when changing -the spacing and -the dielectric between the parallel plates. This is done with constant charge and with constant voltage.

6.3.1.1.1.2 Subjects

- 5C10 (Capacitors) 5C20 (Dielectric)

6.3.1.1.1.3 Diagram

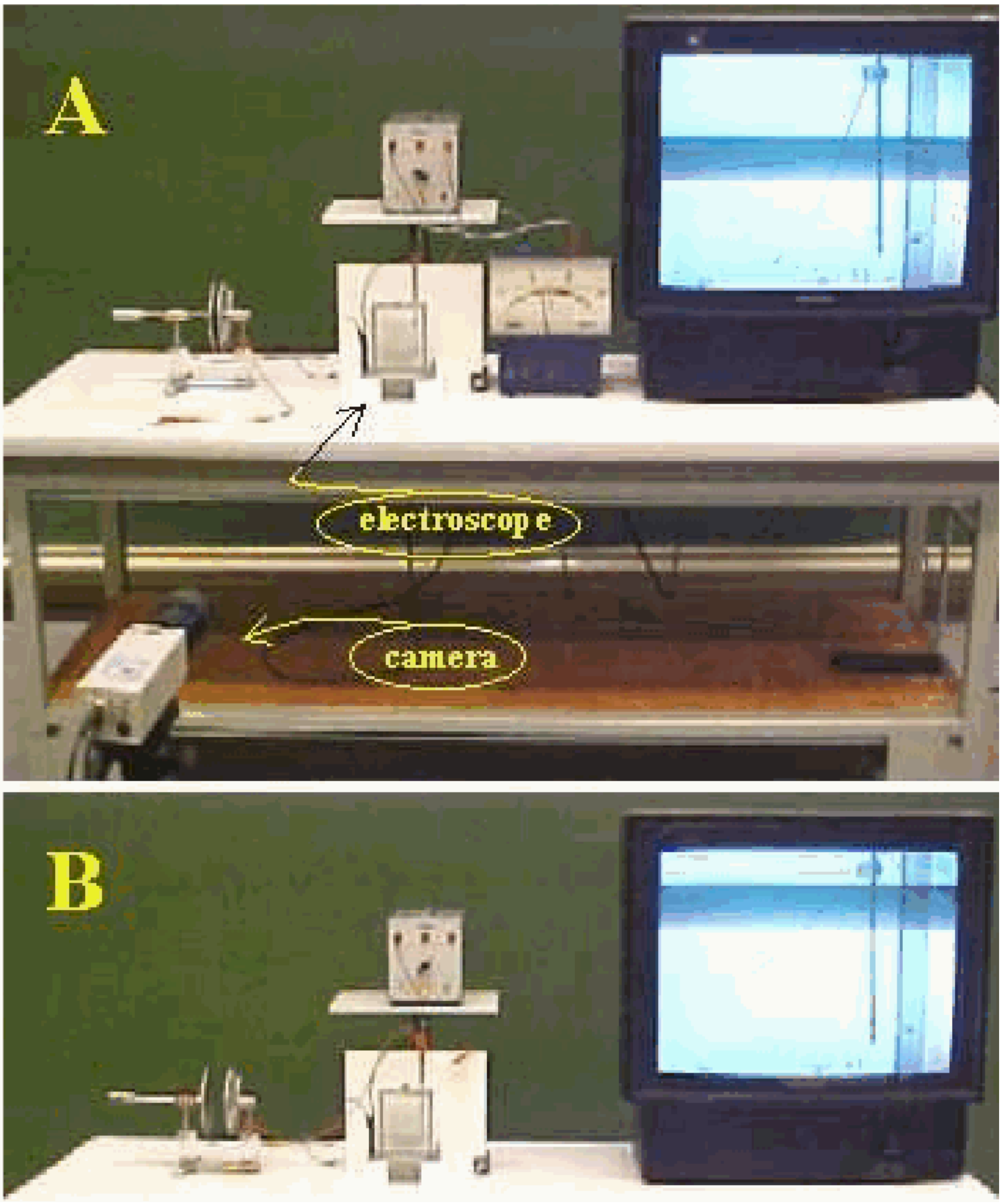


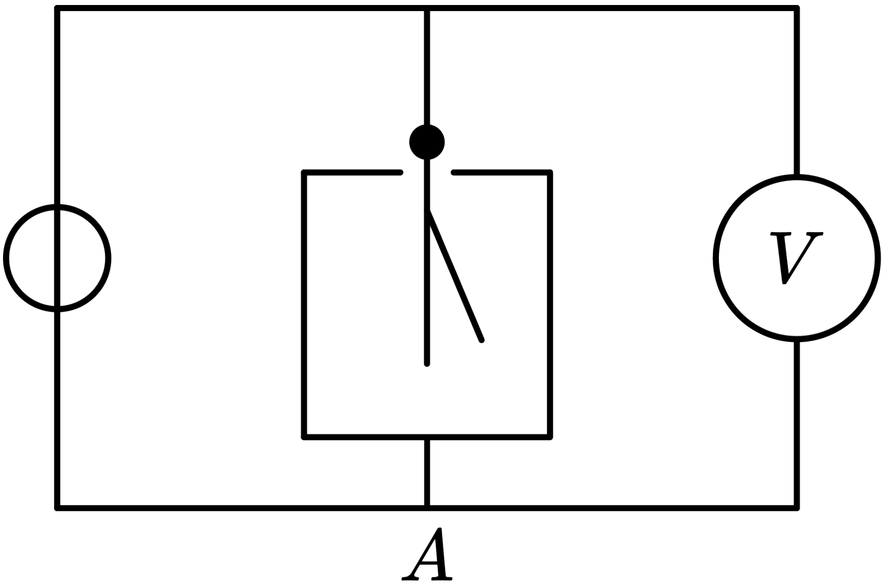
Figure 6.37: .

6.3.1.1.1.4 Equipment

- Parallel plate capacitor.
- Electroscope (watched by camera and displayed on monitor).
- Power supply, 0-6kV.
- Demonstration kV-meter.
- Glass plate, thickness 20mm.
- Perspex container, 50×30×3 cm3, half filled with water. Capacitor: spacing and dielectric

6.3.1.1.1.5 Presentation

The students are told that in this demonstration we will measure the voltage across a charged capacitor. Measuring this voltage is done by an electroscope. A “normal” moving coil meter cannot be used for this measurement, since such an instrument discharges the capacitor immediately (if needed you can show this: charge the capacitor with the power supply, apply the kV-meter and measure … nothing). So, the first thing to do in this demonstration is to show that the electroscope can be used as a voltmeter. The demonstration is set up as shown in Figure1A (DiagramA).



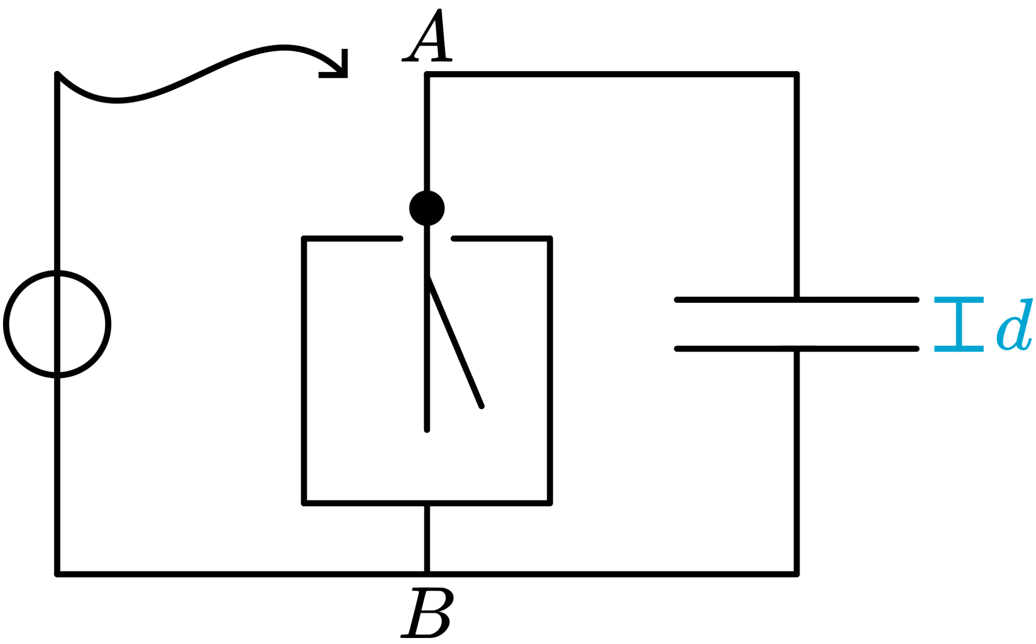


Figure 6.38: .

Just show that when when you change the voltage of the power supply, the kV-meter and the electroscope move synchronously. It is easy to conclude that the electroscope can be used as a voltmeter. Next, the circuit is build as shown in Figure1B. The distance d between the plates is set at a minimum. The capacitor is charged by touching the circuit at A, for a short moment, by the power supply. The electroscope shows a medium deflection. Ask the students what will happen with the deflection of the electroscope when the distance between the capacitor plates is increased. When they have answered this question, do the demonstration and they will see that the voltage increases. (To most students this is counterintuitive.) Capacitor: spacing and dielectric

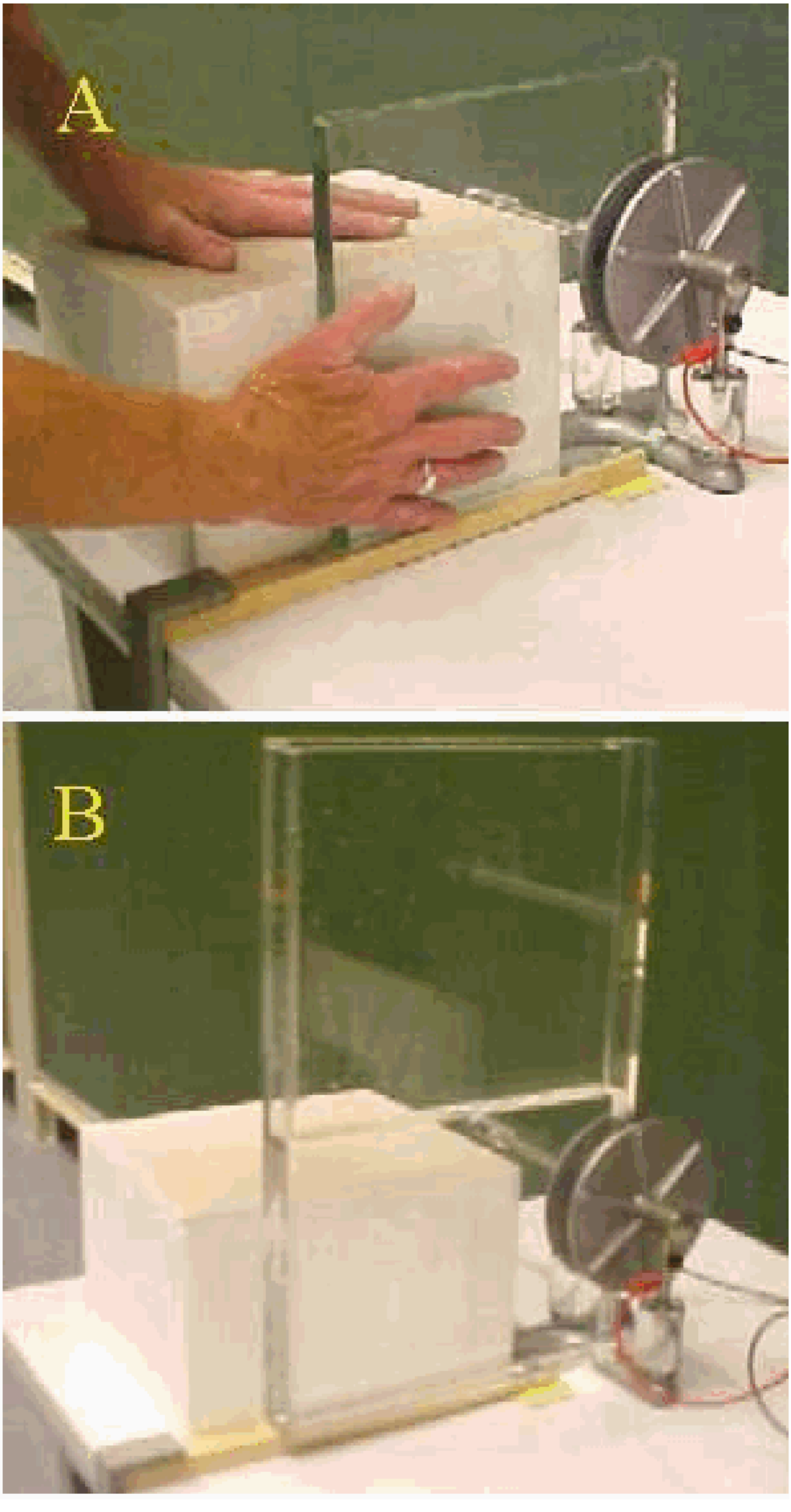

A
B

Figure 6.39: .

In the last part of the demonstration the influence of different dielectrics is shown. The capacitor is placed in front of an improvised guiding construction (see Figure2A). The capacitor is given a separation d, just a little bit larger than the thickness of the glass plate. The capacitor is charged by means of the power supply; the electroscope shows a medium deflection. Ask the students what will happen when the glass plate is shifted between the capacitor plates. When they have given their answers shift the plate between the plates and they will see that the voltage lowers. The same demonstration can be performed by shifting the container with water between the capacitor plates (see Figure2B). Capacitor: spacing and dielectric

6.3.1.1.1.6 Explanation

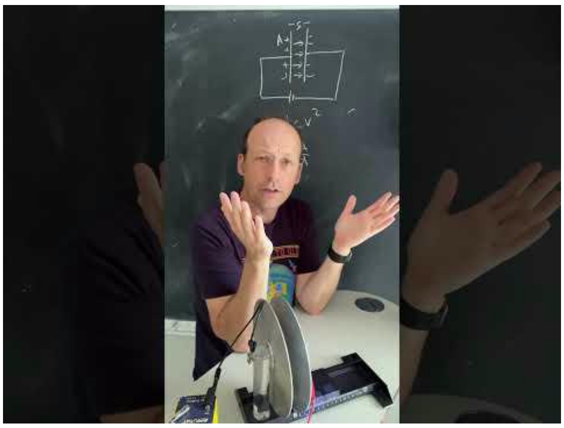
When charging, Q has a certain, constant value. When the seperation d increases, C decreases (ACde=) and since Q is constant this will cause V to increase (Q=CV). The influence of the dielectric on C is shown in ACde=, so when the glass plate is shifted between the plates, C increases. Since the amount of charge is constant, V has to become a lower value (Q=CV).

6.3.1.1.1.7 Remarks

- In order to easily set the distance d between the plates of the capacitor at a minimum, three small pieces of thin felt are stuck on the inside of one of the plates.
- In the explanation of the demonstration it is supposed that the charge on the capacitor is constant. This is true only if the capacitance of the electroscope is small compared to that of the parallel plate capacitor.

6.3.1.1.1.8 Video Rhett Allain

(a)



(b)

Figure 419: :align: center - Scan the QR code or click here to go to the video.

6.3.1.1.1.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 455-458

6.3.2 5C20 Dielectric

6.3.2.1 01 Polarizing a dielectric

6.3.2.1.1 Aim

To show how the voltage of a capacitor changes when changing -the spacing and -the dielectric between the parallel plates. This is done with constant charge and with constant voltage.

6.3.2.1.2 Subjects

- 5A40 (Induced Charge) 5C20 (Dielectric)

6.3.2.1.3 Diagram

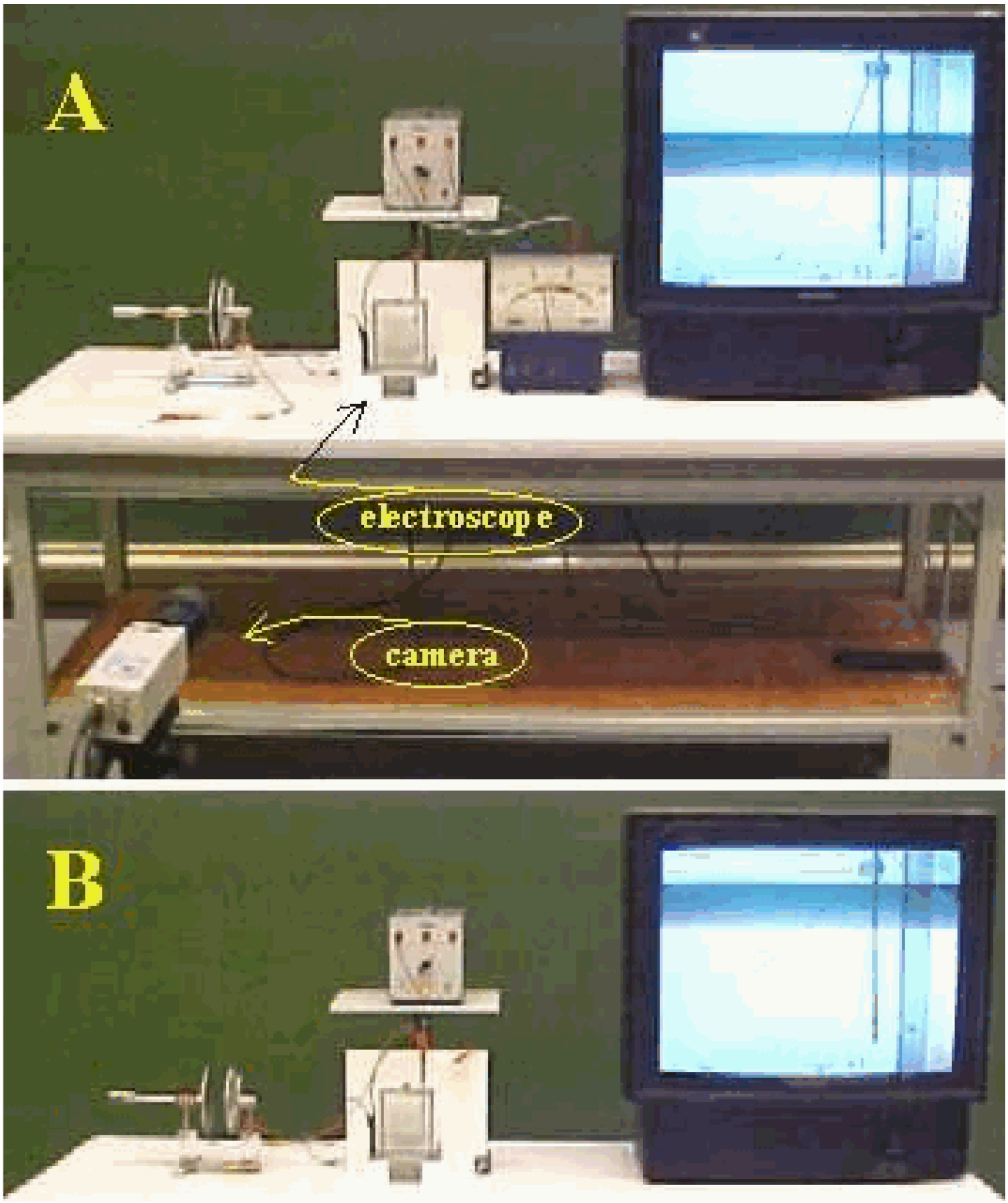


Figure 6.43: .

6.3.2.1.4 Equipment

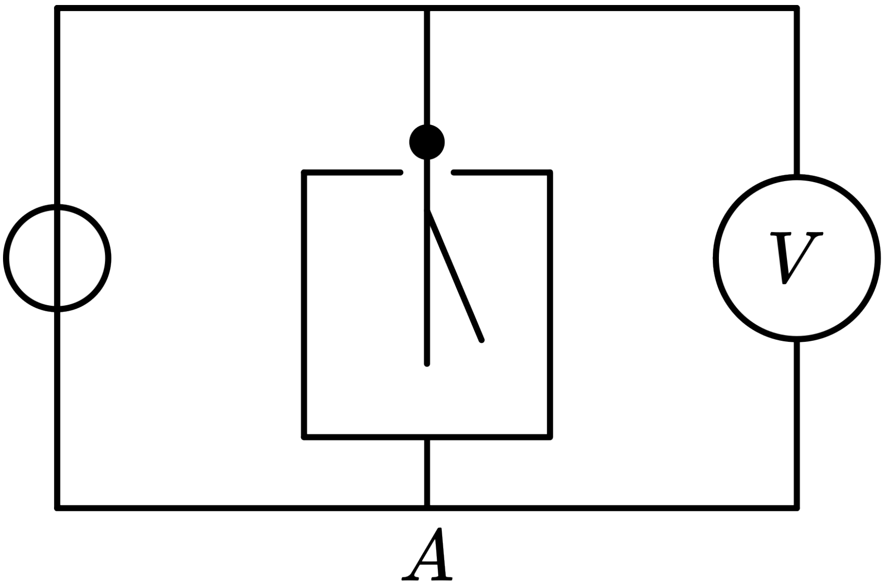
An assembly of overheadsheets:

- Overheadsheet with capacitor drawn on it.
- Overheadsheet with six rows of six negative charges (green colored).
- Overheadsheet with six rows of six positive charges (red colored).

The overheadsheet with the capacitor plates drawn on it is actually a sleeve, in which the two sheets with the opposite charges just fit and can be shifted.

6.3.2.1.5 Presentation

The assembly of overheadsheets is projected: The two sheets with the opposite charges are placed between the capacitor plates such that the plus - and minus signs cover each other (the molecules are no dipoles) (See Diagram A and Figure 2).



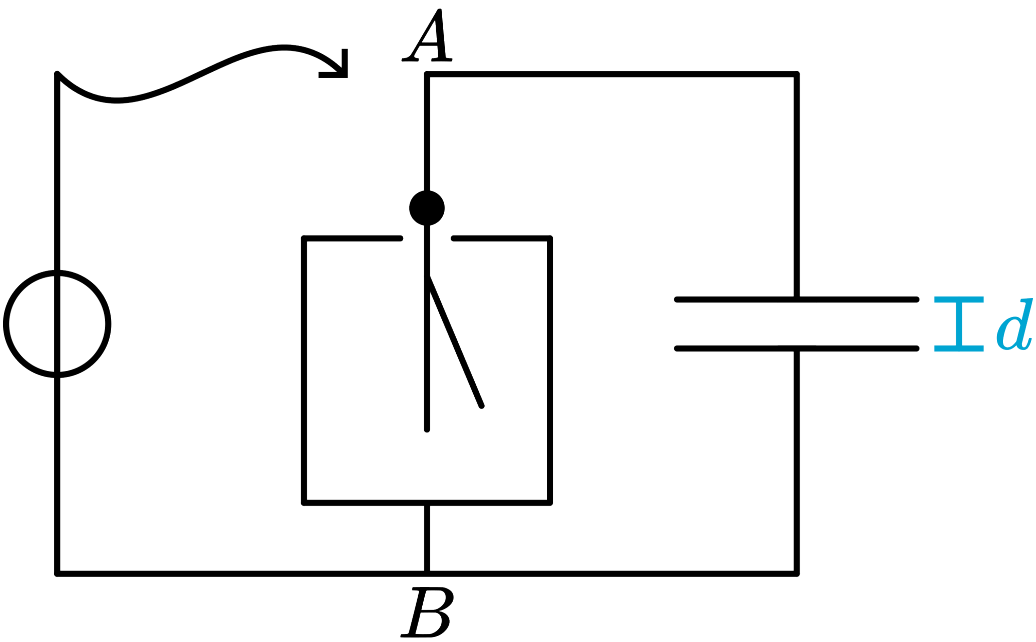


Figure 6.44: .

Using a non-permanent marker we apply (write) a clear PLUS- and MINUS-sign to the capacitor plates and by hand the two sheets with the charges are shifted a little, thus showing that the "molecular charges" are separated a little (see Diagram B). The net effect is clearly visible: There is a net negative charge on the outer edge of the material facing the positive plate and a net positive charge on the opposite side.

We can also draw the vectors to indicate the original electric field (E_0) and the induced, opposing field (E_{ind}), showing that now $E_{Dielectric} = E_0 - E_{ind}$.

6.3.2.1.6 Explanation

When an outside electric field is applied to the material (for instance by placing it between the plates of a capacitor) there is some separation of charge induced in the molecules. In the demonstration this is shown by slightly displacing the “negative” overhead sheet towards the positive plate (opposite to the direction of E_0).

6.3.2.1.7 Remarks

- The model is static; there is no thermal motion.

6.3.2.1.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 624-625

6.3.2.2 02 Capacitor (2) Different Dielectrics

6.3.2.2.1 Aim

To show how the voltage of a charged capacitor changes when changing the dielectric.

6.3.2.2.2 Subjects

- 5C20 (Dielectric) 5C30 (Energy stored in a capacitor)

6.3.2.2.3 Diagram

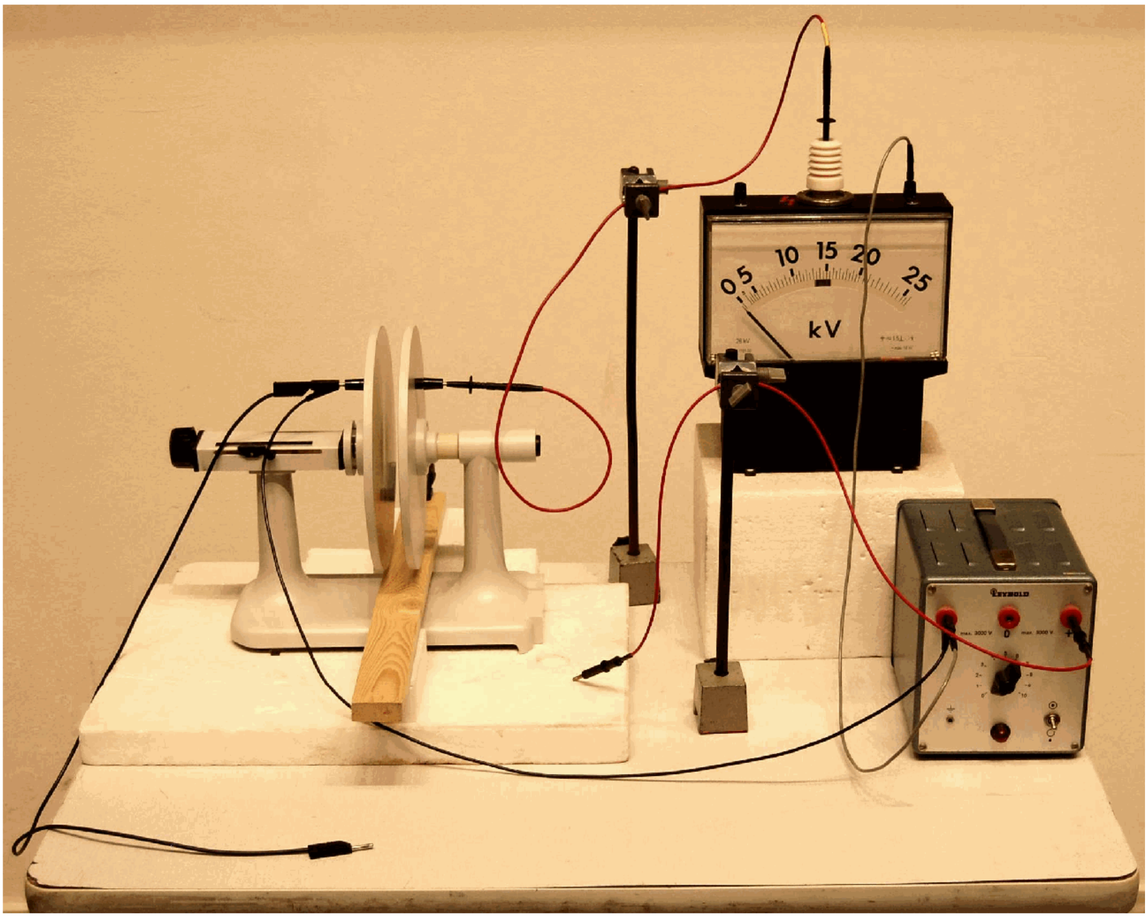


Figure 6.45: .

6.3.2.2.4 Equipment

- Parallel plate capacitor.
- Piece of isolating foam between the plate capacitor and table.
- Electrostatic voltmeter, 0 — 25kV.
- Glass plate, thickness 20 mm.
- Perspex container, $50 \times 30 \times 3$ cm^3, filled with demineralized water.
- Wooden bar as a guiding construction (very well visible in Figure 3).
- Power supply, 0 — 6kV (see Safety). For the demonstration it is better to use a 25kV power supply, set at 15kV
- Use connection leads with Teflon isolation.
- Electric heater (to prevent that moisture spoils the demonstration).

6.3.2.2.5 Safety

- The 6kV power supply has passive current limitation, ensuring that no dangerous contact voltage can occur*. Nevertheless be careful, because when you accidentally touch the high, you probably make a spastic movement, and you may hurt yourself (or somebody else).

*In accordance with IEC 61010-1 (Safety requirements for electrical equipment), a part is not deemed to be live (i.e. carrying a dangerous contact voltage) when, at voltages greater than extra-low voltage (> 60 V DC), the current through an induction-free resistance of 2kOhm is not greater than 2 mA for DC, additionally, the charge for voltages up to 15kV is less than 45μC, and the stored energy does not exceed 350 mJ for voltages over 15kV.

6.3.2.2.6 Presentation

The setup of the demonstration is explained to the students. The plates are set at such a separation that d just a little bit larger than the thickness of the glass-plate. The power supply is set at 15kV.

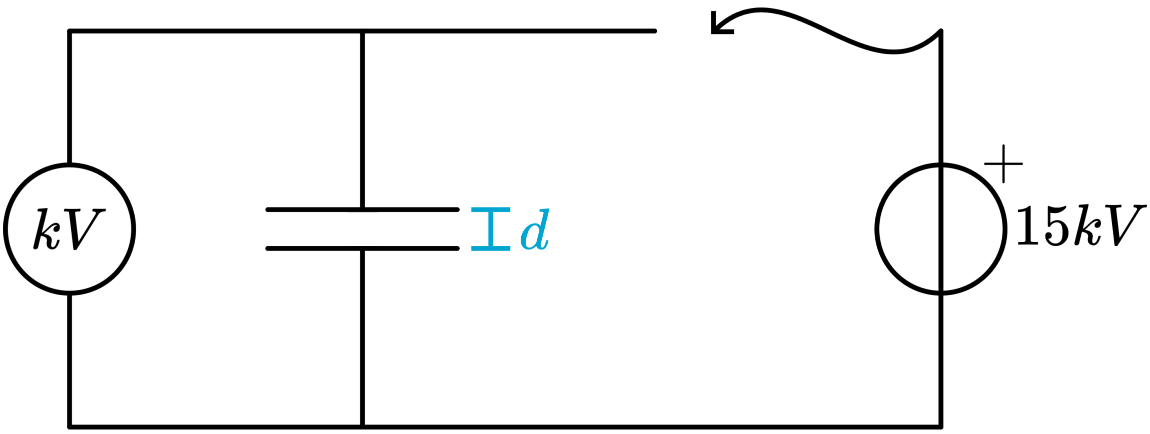


Figure 6.46: .

The capacitor is charged by shortly touching the capacitor with the free lead of the 15kV power supply (see Figure 2). After this charging of the capacitor, the voltmeter reads 15kV.

The students are asked what will happen to the voltage of a charged capacitor when the glass plate is shifted between the plates (see Figure 3). After their answers shift the glass between the capacitor plates. They will see that the voltage lowers. Shift carefully all the time, with the glass plate sliding along the grounded plate of the capacitor, so the glass plate does not touch the high voltage positive plate!

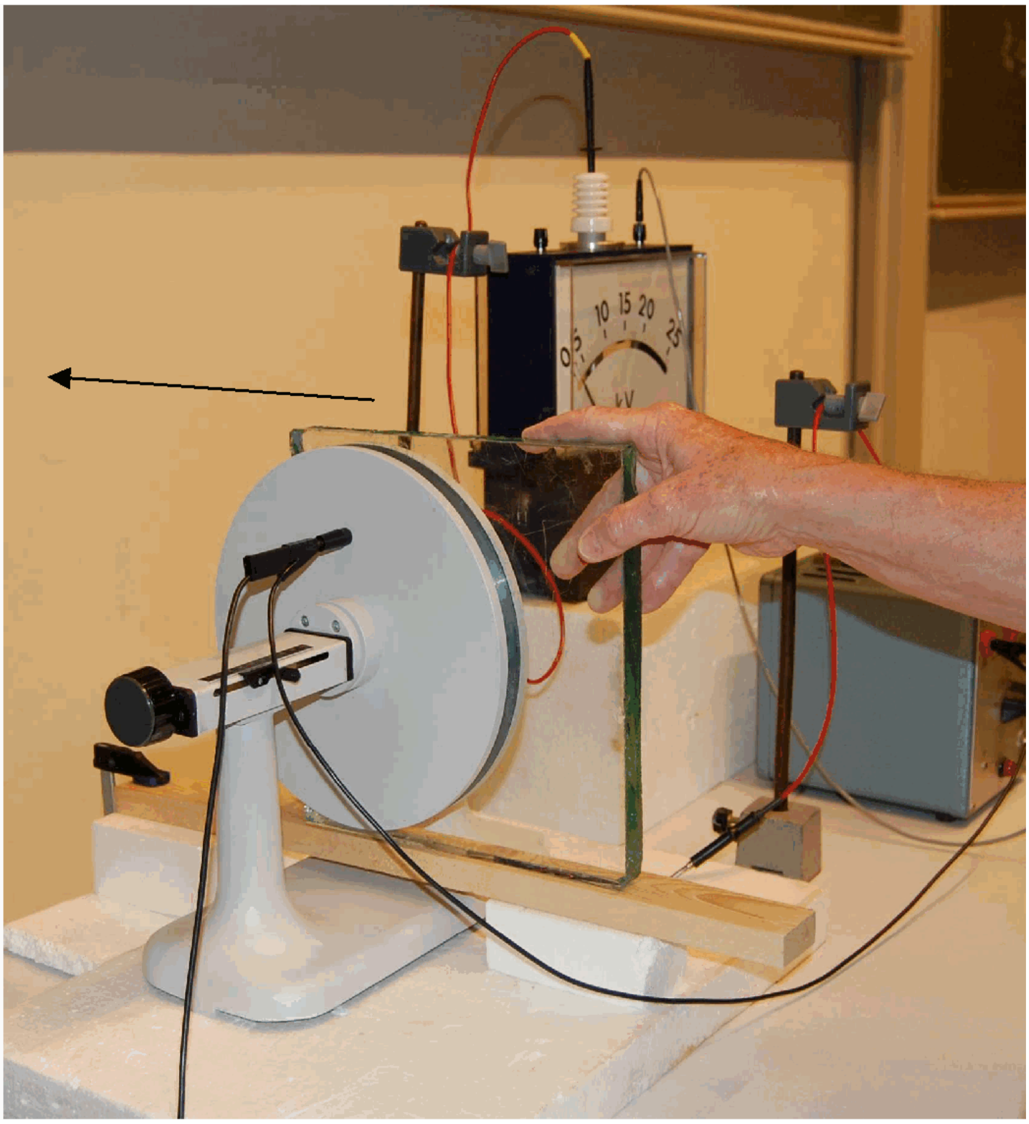


Figure 6.47: .

Removing the glass plate will increase the voltage again to its original value of 15kV. The same experiment is performed with the container filled with water (see Figure 4).

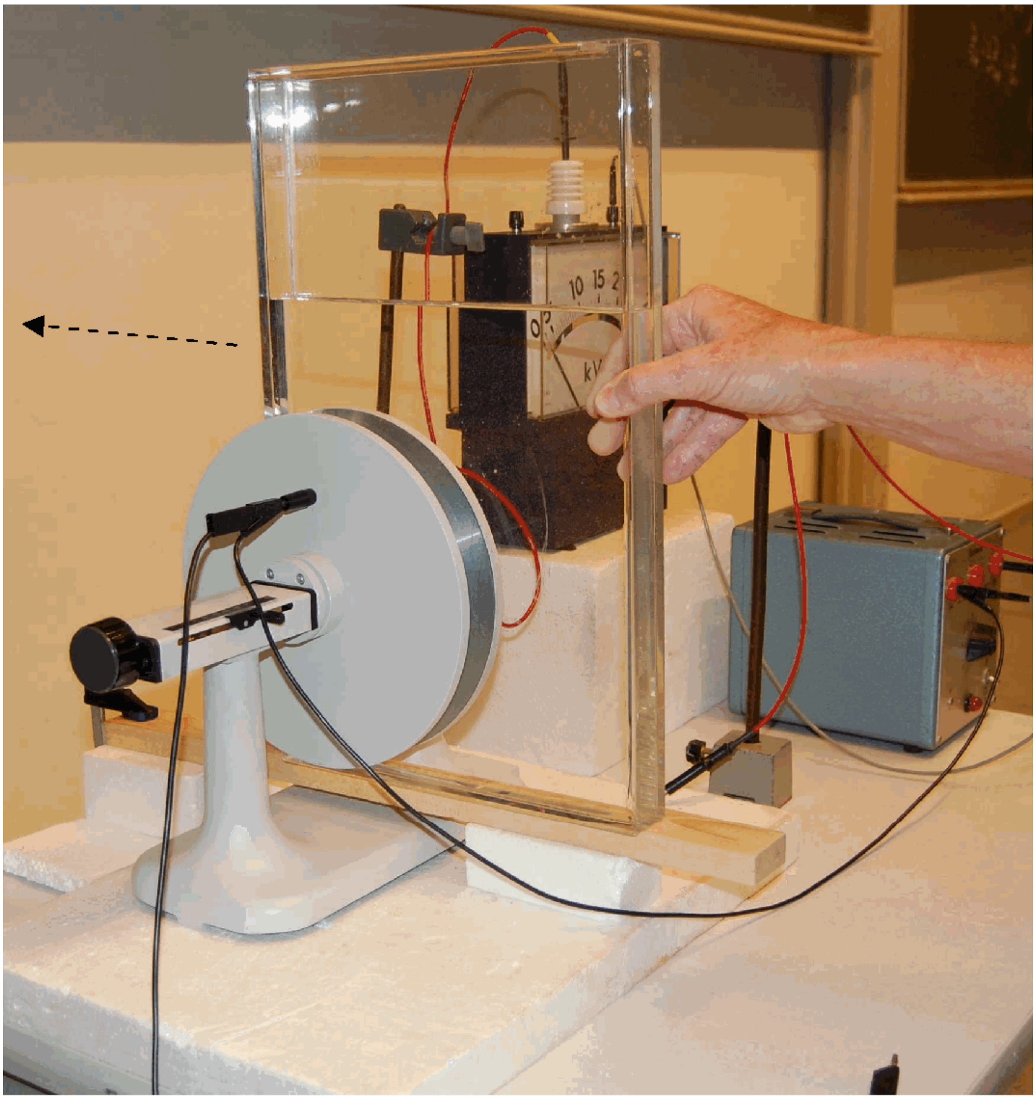


Figure 6.48: .

6.3.2.2.7 Explanation

6.3.2.2.7.1 Explanation 1:

The demonstration shows that the voltage lowers when a dielectric is shifted between the capacitor plates. Voltage is the energy per unit charge, so we can say that the potential energy of the capacitor lowers. Where is this energy gone? It was needed to polarize the dielectric! The "lost" energy is now in the polarized dipoles of the dielectric.

In the same way the energy stored in the capacitor becomes higher when the dielectric is removed. Also the demonstrator has to pull now because there is an attracting force between the induced charge on the dielectric and the plates. So he adds energy to the capacitor.

6.3.2.2.7.2 Explanation 2:

When the dielectric is between the plates, C increases ($C = \varepsilon \frac{A}{d}$) because ε becomes higher, and since Q is constant this will cause V to decrease $(Q = CV)$.

(This explanation is just mathematics and no physics.)

Especially when water is the dielectric the voltage should lower dramatically, since ε_r of water is around 80 !

6.3.2.2.8 Remarks

- In the explanation of the demonstration it is supposed that the charge on the capacitor is constant. This is true only if the capacitance of the electrostatic voltmeter is small compared to that of the parallel plate capacitor. Capacitor (2) Different dielectrics

6.3.2.2.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 455-458.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 621-625.

6.3.3 5C30 Energy Stored in a Capacitor

6.3.3.1 01 Capacitor (2) Different Dielectrics

6.3.3.1.1 Aim

To show how the voltage of a charged capacitor changes when changing the dielectric.

6.3.3.1.2 Subjects

- 5C20 (Dielectric) 5C30 (Energy stored in a capacitor)

6.3.3.1.3 Diagram

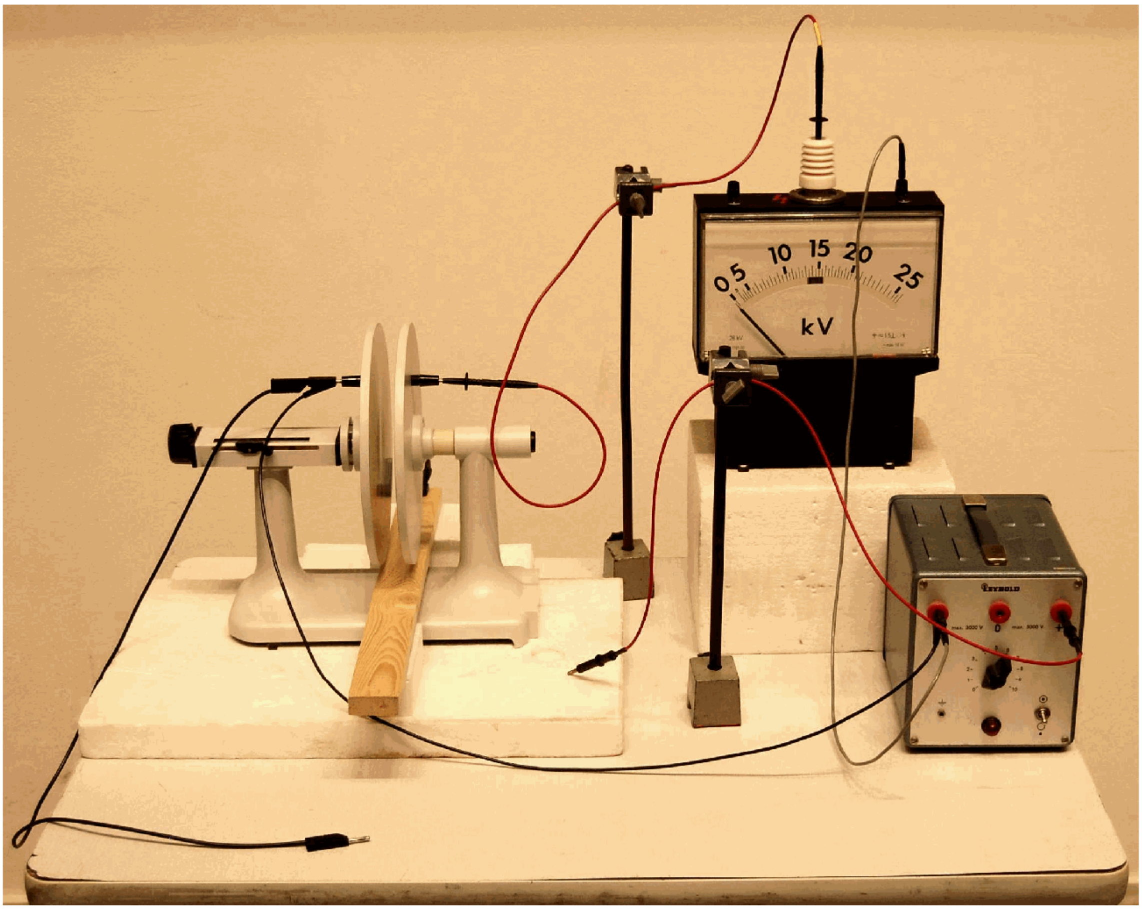


Figure 6.49: .

6.3.3.1.4 Equipment

- Parallel plate capacitor.
- Piece of isolating foam between the plate capacitor and table.
- Electrostatic voltmeter, $0-25$kV.
- Glass plate, thickness 20 mm.
- Perspex container, $50 \times 30 \times 3$ cm^3, filled with demineralized water.
- Wooden bar as a guiding construction (very well visible in Figure 3).
- Power supply, $0-6$kV (see Safety). For the demonstration it is better to use a 25kV power supply, set at 15kV
- Use connection leads with Teflon isolation.
- Electric heater (to prevent that moisture spoils the demonstration).

6.3.3.1.5 Safety

- The 6kV power supply has passive current limitation, ensuring that no dangerous contact voltage can occur*. Nevertheless be careful, because when you accidentally touch the high, you probably make a spastic movement, and you may hurt yourself (or somebody else).

*In accordance with IEC 61010-1 (Safety requirements for electrical equipment), a part is not deemed to be live (i.e. carrying a dangerous contact voltage) when, at voltages greater than extra-low voltage (> 60 V DC), the current through an induction-free resistance of 2kOhm is not greater than 2 mA for DC, additionally, the charge for voltages up to 15kV is less than 45μC, and the stored energy does not exceed 350 mJ for voltages over 15kV.

6.3.3.1.6 Presentation

The setup of the demonstration is explained to the students. The plates are set at such a separation that d just a little bit larger than the thickness of the glass-plate. The power supply is set at 15kV.

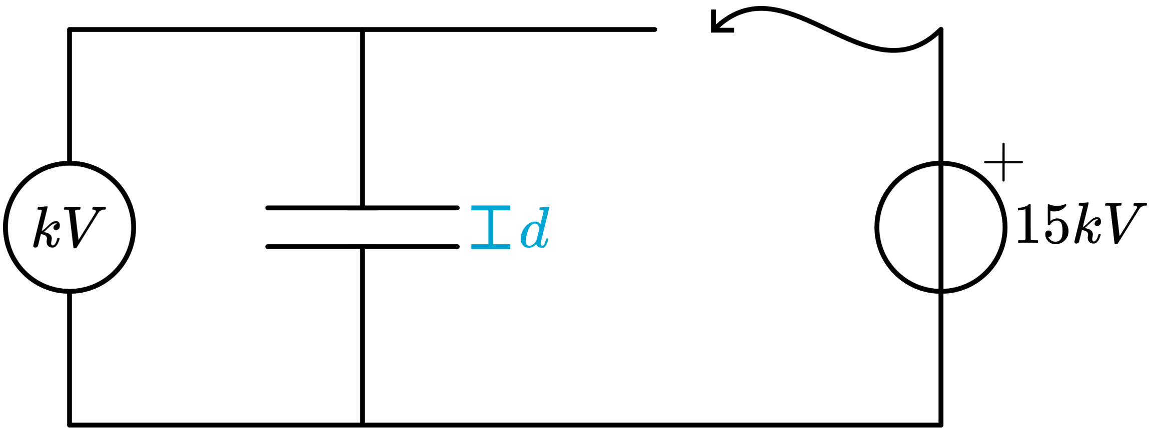


Figure 6.50: .

The capacitor is charged by shortly touching the capacitor with the free lead of the 15kV power supply (see Figure 2). After this charging of the capacitor, the voltmeter reads 15kV.

The students are asked what will happen to the voltage of a charged capacitor when the glass plate is shifted between the plates (see Figure 3). After their answers shift the glass between the capacitor plates. They will see that the voltage lowers. Shift carefully all the time, with the glass plate sliding along the grounded plate of the capacitor, so the glass plate does not touch the high voltage positive plate!

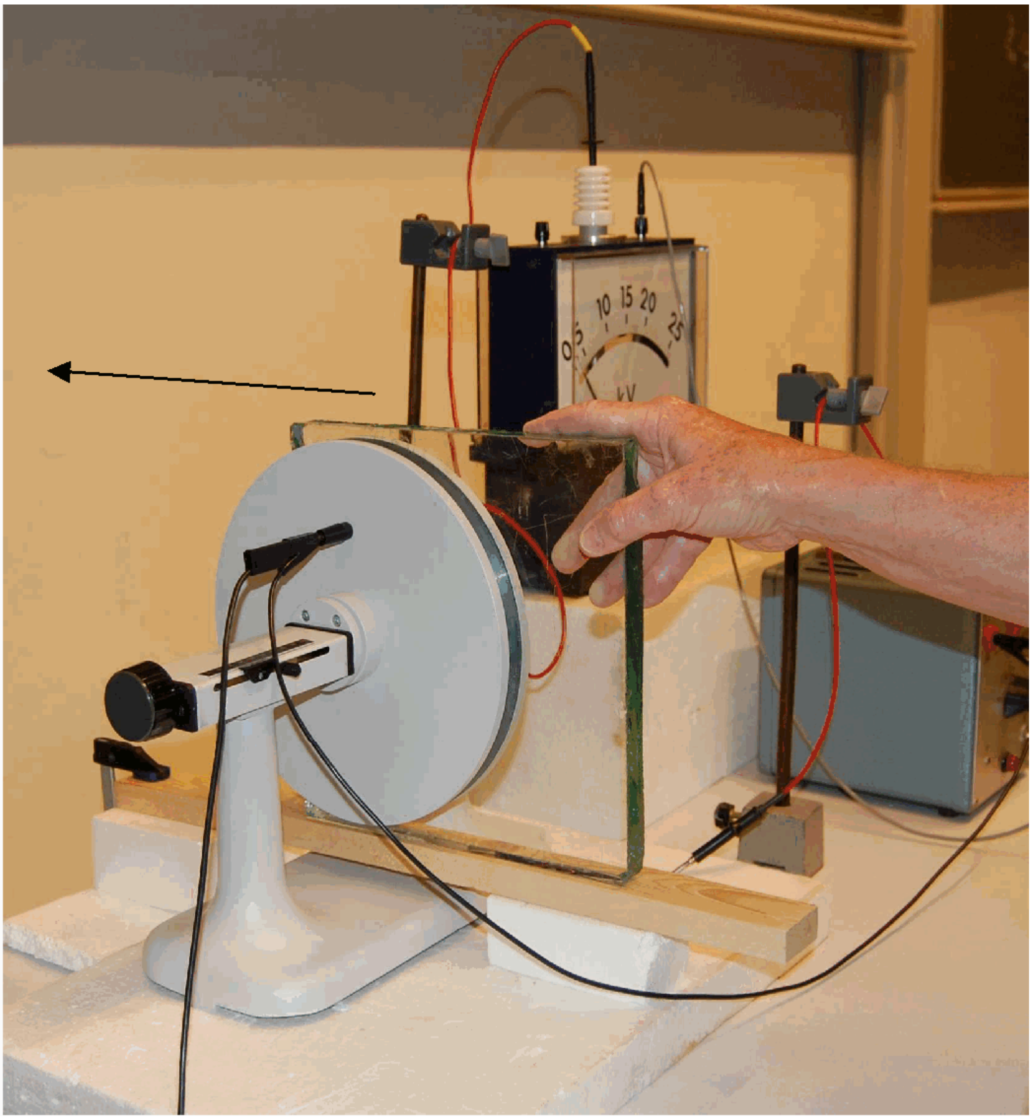


Figure 6.51: .

Removing the glass plate will increase the voltage again to its original value of 15kV. The same experiment is performed with the container filled with water (see Figure 4).

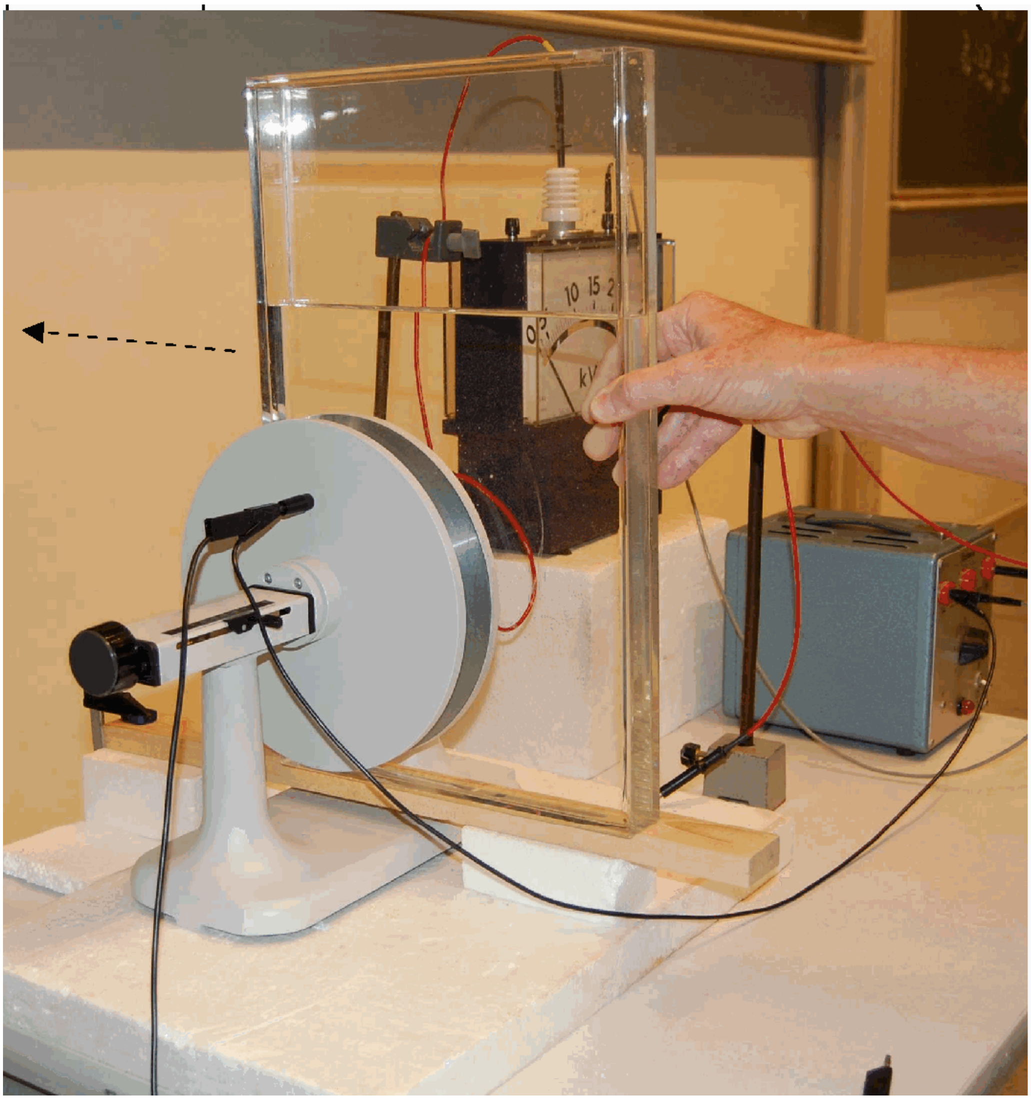


Figure 6.52: .

6.3.3.1.7 Explanation

6.3.3.1.7.1 Explanation 1:

The demonstration shows that the voltage lowers when a dielectric is shifted between the capacitor plates. Voltage is the energy per unit charge, so we can say that the potential energy of the capacitor lowers. Where is this energy gone? It was needed to polarize the dielectric! The "lost" energy is now in the polarized dipoles of the dielectric.

In the same way the energy stored in the capacitor becomes higher when the dielectric is removed. Also the demonstrator has to pull now because there is an attracting force between the induced charge on the dielectric and the plates. So he adds energy to the capacitor.

6.3.3.1.7.2 Explanation 2:

When the dielectric is between the plates, C increases ($C = \varepsilon \frac{A}{d}$) because ε becomes higher, and since Q is constant this will cause V to decrease $(Q = CV)$.

(This explanation is just mathematics and no physics.)

Especially when water is the dielectric the voltage should lower dramatically, since ε_r of water is around 80 !

6.3.3.1.8 Remarks

- In the explanation of the demonstration it is supposed that the charge on the capacitor is constant. This is true only if the capacitance of the electrostatic voltmeter is small compared to that of the parallel plate capacitor. Capacitor (2) Different dielectrics

6.3.3.1.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 455-458.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 621-625.

6.4 5D Resistance

6.4.1 5D20 Resistivity and Temperature

6.4.1.1 01 Positive Temperature Coefficient

6.4.1.1.1 Aim

To show how the resistance of copper wire depends on temperature.

6.4.1.1.2 Subjects

- 5D20 (Resistivity and Temperature)

6.4.1.1.3 Diagram

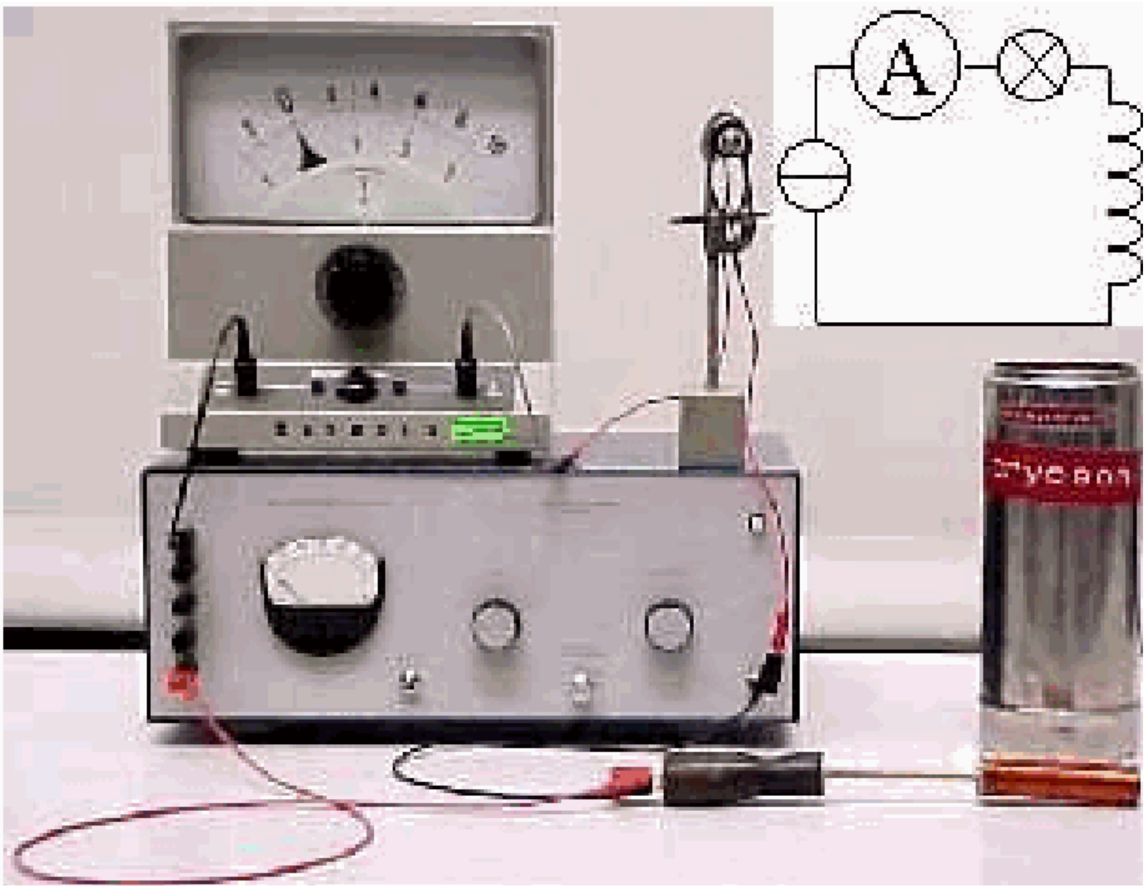


Figure 6.53: .

6.4.1.1.4 Equipment

- Coil with handgrip
- Lamp (we use 6 V/2.5 A)
- Power supply
- Dewar with liquid nitrogen
- Current meter with large display

6.4.1.1.5 Presentation

The power supply is used as a current source, limited at 2.5 A. Increase the voltage of the power supply until the lamp just glows (reduce the light in the lecture hall). Then the coil is dipped into liquid nitrogen and slowly the lamp will glow brighter and brighter. The increase in current can also be observed at the current meter.

When the coil is lifted out of the liquid nitrogen, the current reduces slowly and the glowing of the lamp becomes more faint.

6.4.1.1.6 Explanation

Copper has a resistance temperature coefficient (α) of $4.3 \times 10^{-3}\ \mathrm{K}^{-1}$. This resistance temperature coefficient indicates the relative change in resistance per Kelvin:

$\alpha = \frac{\Delta R}{R} \frac{1}{\Delta T}$. When the coil is dipped into the liquid nitrogen, it experiences a temperature drop of about $200\ \mathrm{K}$ (boiling point at $77\ \mathrm{K}$). This means that the relative change in resistance $\left(\frac{\Delta R}{R}\right)$. equals about 80% ! (Actually, the relative change in resistance is lower, because α is not a constant.)

6.4.1.1.7 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 226

6.4.1.2 02 Negative Temperature Coefficient

6.4.1.2.1 Aim

To show how the resistance of a semiconductor (P-Ge) depends on temperature.

6.4.1.2.2 Subjects

- 5D20 (Resistivity and Temperature)

6.4.1.2.3 Diagram

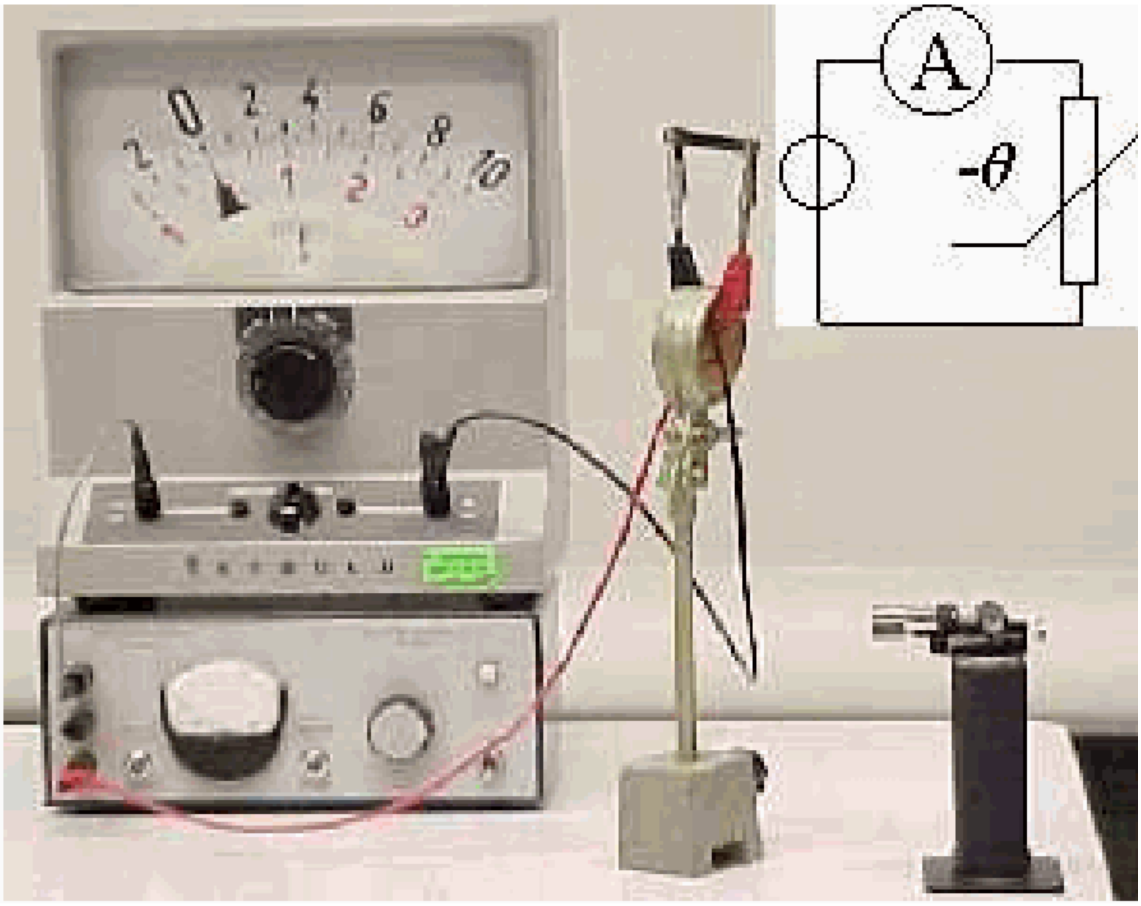


Figure 6.54: .

6.4.1.2.4 Equipment

- Bar of P-Ge
- Power supply
- Current meter with large display
- Gas flame

6.4.1.2.5 Presentation

Set the Ammeter at a 1 A-scale. The voltage of the power supply is raised until a current of about 0.05 A flows in the circuit. The bar of $P - Ge$ is heated by the gas flame and soon the current rises to a much higher value. After a short time of heating the gas flame can be removed and the current continues to rise, faster and faster, only limited by the power supply.

6.4.1.2.6 Explanation

The resistance of a semiconductor drops with temperature because at a higher temperature there are more free charge-carriers in it.

The current flowing in the material heats it up: $P_{el} = \frac{V^2}{R}$ The heat leaving the piece of material is proportional to $\Delta T : P_{out} \propto \Delta T$ (Newton cooling). When $P_{out} = P_{el}$ there will be thermal equilibrium and the temperature is constant. Reaching such an equilibrium takes some time.

In this demonstration R lowers due to a rise in temperature and so P_{el}, rises due to a rise in temperature. When this rise is faster than the rise of P_{out} an ever faster rising of ΔT (like an avalanche) will result.

6.5 5F DC Circuits

6.5.1 5F15 Power and Energy

6.5.1.1 01 Fuse-Wires Parallel

6.5.1.1.1 Aim

To show how in a parallel-circuit the total electric power distributes itself over the separate components.

6.5.1.1.2 Subjects

- 5F15 (Power and Energy) 5F20 (Circuit Analysis)

6.5.1.1.3 Diagram

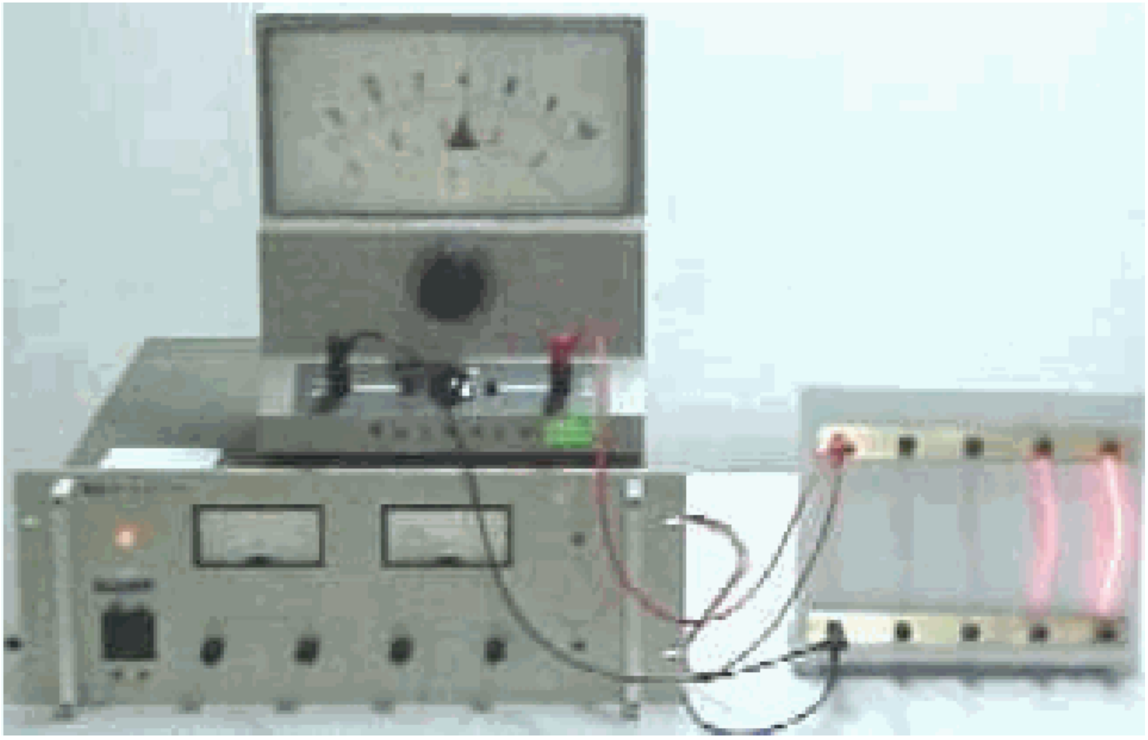


Figure 6.55: .

6.5.1.1.4 Equipment

- Piece of thin NiCr-wire.
- Board with 4 different nickel-chromium wires
  1. $d = .2$ mm,
  2. $d = .4$ mm,
  3. 2 twisted $d = .4$ mm,
  4. 3 twisted $d = .4$ mm.
- Two brass strips.
- Power supply (with our nickel-chromium wires we need at least 50 A).
- Voltmeter.

6.5.1.1.5 Presentation

First take the thin fusible NiCr wire. Make a current flow through it. Slowly increase that current and show how the wire starts glowing and finally melts/breaks.

Set up the demonstration as shown in Figure 2 and Diagram.

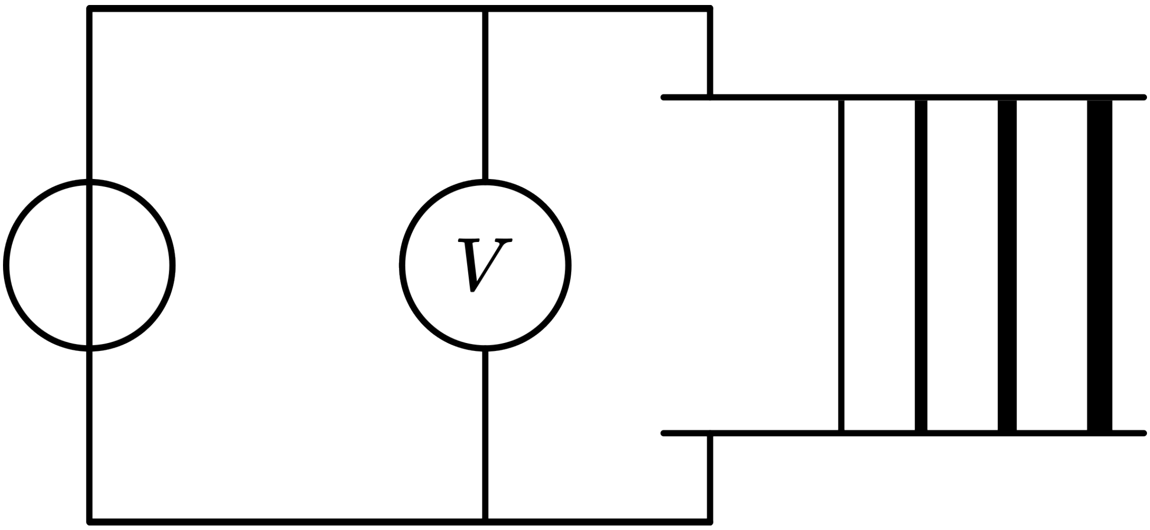


Figure 6.56: .

Two brass strips connect the nickel-chromium wires in parallel. Indicate the difference in diameter of the four wires to the students. Ask the students which wire will burn out first, as the voltage between the brass strips increases. (Most students will guess the wrong answer. Guessing possibilities: None of them melts; all melt together at the same time; the thinnest melts first; the thickest melts first; ...) Slowly increase the voltage. Soon the glowing of the wires indicates that the thickest wire will burn out first. The thinner the wire the more voltage is needed to burn it out.

6.5.1.1.6 Explanation

In a parallel-circuit the voltage (V) is common to the components. Comparing the power on the components should be done by using $P_{electrical} = \frac{V^2}{R_{component}}$. Since V is common to all parallel components the difference in P is determined by R : The lower R, the higher P_{el}. But it is also true that the thicker R, the larger its cooling surface. This counteracts the heating up of the thicker wire. Since $P_{el} = \frac{V^2}{R}$ and $R = \rho \frac{l}{A} = \rho \frac{l}{\frac{\pi d^2}{4}}$, $P_{el} \propto d^2$.

The power that leaves the wire to its surroundings is proportional to the surface of that wire and the ΔT to its surroundings (Newton cooling). The cooling surface S equals πdl (see Figure 3).

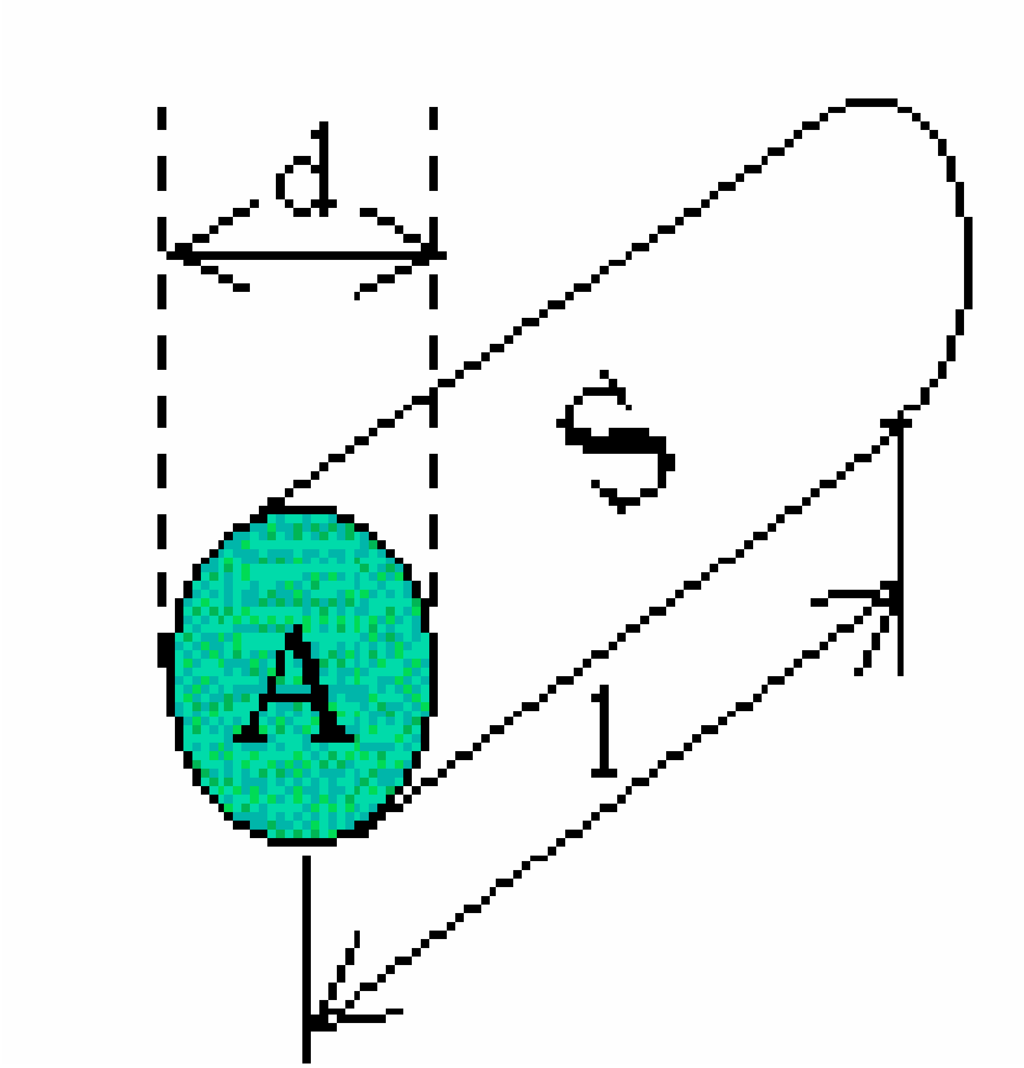


Figure 6.57: .

So $P_{out} \propto d\Delta T$. Comparing P_{el} and P_{out} shows that a thicker wire needs a higher ΔT to reach $P_{el.} = P_{out}$.

6.5.1.1.7 Remarks

- The wires on the board are bend outward a little. When they heat up they become longer and bend more outward. When you do not bend them outward they might bend inward when heating up, scorching the board.

6.5.1.1.8 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 320
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 417

6.5.2 5F20 Circuit Analysis

6.5.2.1 01 Fuse-Wires Parallel

6.5.2.1.1 Aim

To show how in a parallel-circuit the total electric power distributes itself over the separate components.

6.5.2.1.2 Subjects

- 5F15 (Power and Energy) 5F20 (Circuit Analysis)

6.5.2.1.3 Diagram

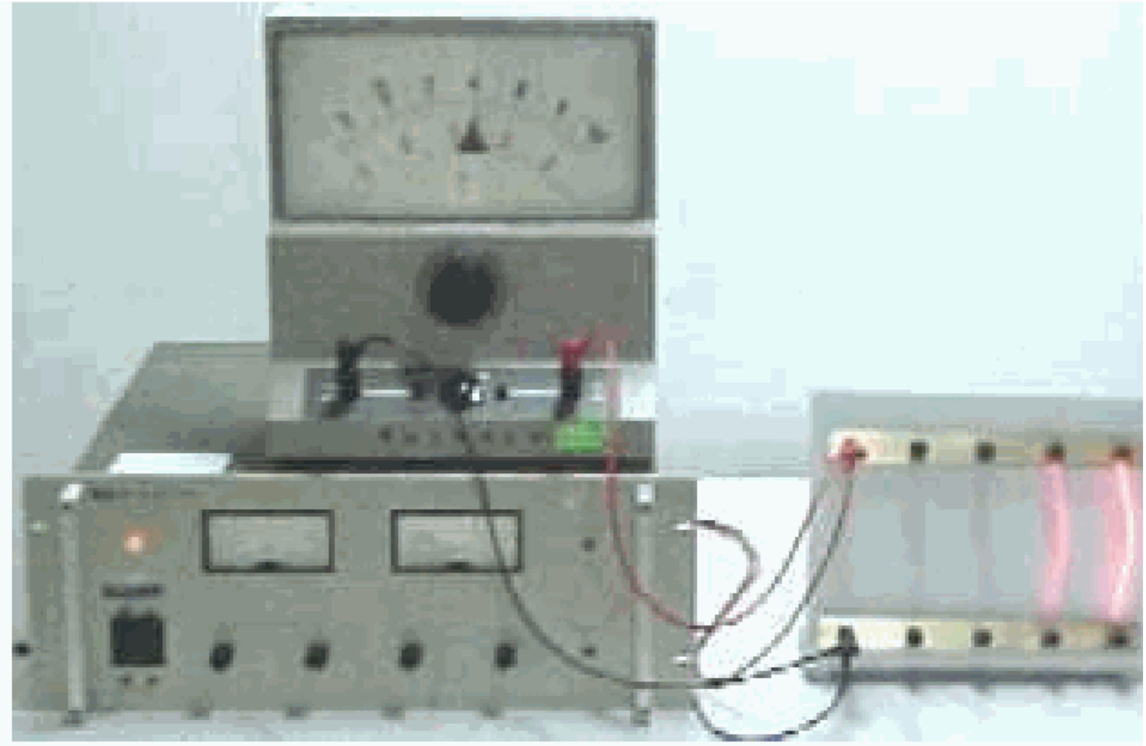


Figure 6.58: .

6.5.2.1.4 Equipment

- Piece of thin NiCr-wire.
- Board with 4 different nickel-chromium wires
    1. $d = .2$ mm,
    2. $d = .4$ mm,
    3. 2 twisted $d = .4$ mm,
    4. 3 twisted $d = .4$ mm.
- Two brass strips.
- Power supply (with our nickel-chromium wires we need at least 50 A).
- Voltmeter.

6.5.2.1.5 Presentation

First take the thin fusible NiCr wire. Make a current flow through it. Slowly increase that current and show how the wire starts glowing and finally melts/breaks.

Set up the demonstration as shown in Figure 2 and Diagram.

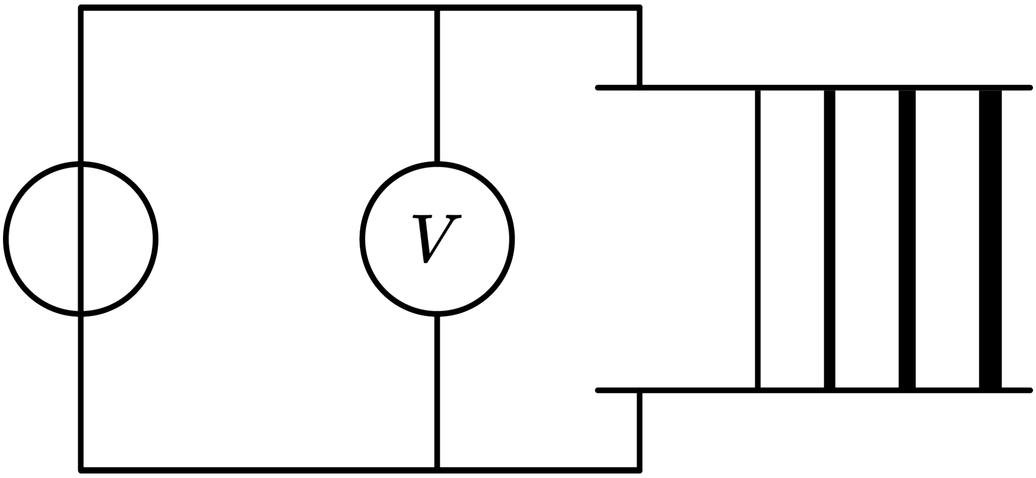


Figure 6.59: .

Two brass strips connect the nickel-chromium wires in parallel. Indicate the difference in diameter of the four wires to the students. Ask the students which wire will burn out first, as the voltage between the brass strips increases. (Most students will guess the wrong answer. Guessing possibilities: None of them melts; all melt together at the same time; the thinnest melts first; the thickest melts first; ...) Slowly increase the voltage. Soon the glowing of the wires indicates that the thickest wire will burn out first. The thinner the wire the more voltage is needed to burn it out.

6.5.2.1.6 Explanation

In a parallel-circuit the voltage (V) is common to the components. Comparing the power on the components should be done by using $P_{electrical} = \frac{V^2}{R_{component}}$. Since V is common to all parallel components the difference in P is determined by R : The lower R, the higher P_{el}. But it is also true that the thicker R, the larger its cooling surface. This counteracts the heating up of the thicker wire. Since $P_{el} = \frac{V^2}{R}$ and $R = \rho\frac{l}{A} = \rho\frac{l}{\frac{\pi d^2}{4}}$, $P_{el} \propto d^2$.

The power that leaves the wire to its surroundings is proportional to the surface of that wire and the ΔT to its surroundings (Newton cooling). The cooling surface S equals πdl (see Figure 3).

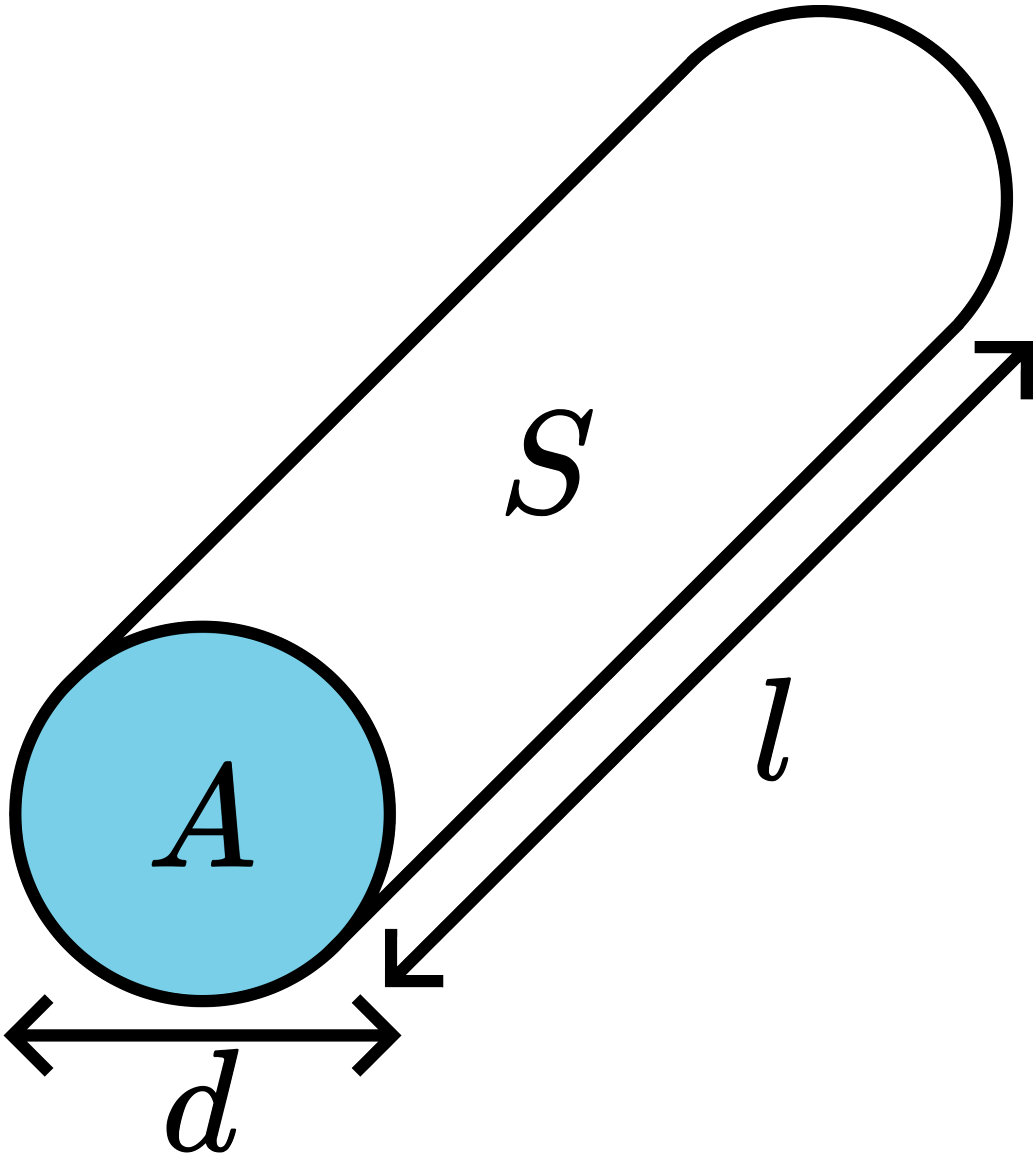


Figure 6.60: .

So $P_{out} \propto d\Delta T$. Comparing P_{el} and P_{out} shows that a thicker wire needs a higher ΔT to reach $P_{el.} = P_{out}$.

6.5.2.1.7 Remarks

- The wires on the board are bend outward a little. When they heat up they become longer and bend more outward. When you do not bend them outward they might bend inward when heating up, scorching the board.

6.5.2.1.8 Sources

- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 320
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 417

6.6 5G Magnetic Materials

6.6.1 5G20 Magnet Domains and Magnetization

6.6.1.1 01 Barkhausen Effect (1)

6.6.1.1.1 Aim

- To make the turning of the magnetic domains audible.
- To show hysteresis.

6.6.1.1.2 Subjects

- 5G20 (Magnet Domains and Magnetization) 5G40 (Hysteresis)

6.6.1.1.3 Diagram

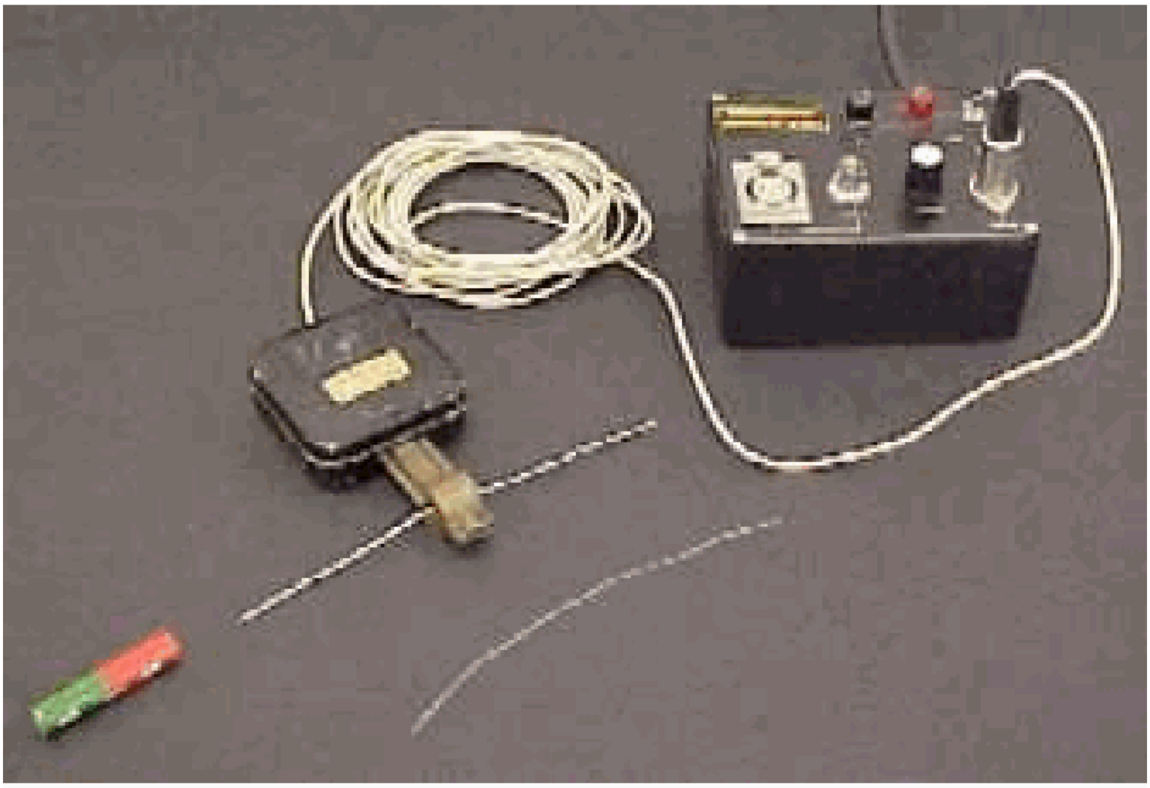


Figure 6.61: .

6.6.1.1.4 Equipment

- Solenoid, $n = 3000$.
- Pre-amplifier.
- Speaker.
- (Oscilloscope.)
- Steel wire (paperclip).
- Iron wire (soft iron).
- Bar magnet.

6.6.1.1.5 Presentation

6.6.1.1.5.1 Preparation:

The output of the pre-amplifier is connected to the audio system of the lecture-hall. Set the pre-amplifier and audio system at an appropriate level.

6.6.1.1.5.2 Presentation

- The iron wire is placed inside the solenoid, keeping it in place by hand. Then, with the other hand, one pole of a bar magnet slowly approaches the iron wire. At a certain distance a "groaning" sound is heard in the speaker. When the pole moves away from the iron wire, the "groaning" is heard again, but weaker this time. When next we approach the wire with the magnet with the other pole, again a loud rasping sound is heard.
- Then, the steel wire is placed inside the coil.

Repeating the experiment, again the rasping sound is heard. Moving the magnetic pole away from the wire, no sound is heard. Also, when the same pole approaches the steel wire again, no sound is heard. Only when the other magnetic pole approaches the steel wire, the rasping sound is heard again.

6.6.1.1.6 Explanation

When a bar magnet is moving towards a soft iron core, the elementary magnets align themselves intermittently in the direction of the magnetizing field. As each group of magnets turn over, a feeble emf is induced in the solenoid. When the bar magnet moves away from the soft-iron core, not all elementary magnets return to their original orientation (hysteresis) and so a lower emf is induced in the solenoid. This effect of hysteresis is much stronger in the steel wire (paperclip).

6.6.1.1.7 Remarks

- The induced emf can also be made visible by using an oscilloscope.

6.6.1.1.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 222.
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 6, Elektrizitätslehre I, pag. 178.
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 285.
- Griffith, D. J., Introduction to Electrodynamics, pag. 278-281.

6.6.1.2 02 Barkhausen Effect (2)

6.6.1.2.1 Aim

To show the ferromagnetic behaviour of a cubic lattice.

6.6.1.2.2 Subjects

- 5G20 (Magnet Domains and Magnetization) 5G40 (Hysteresis)

6.6.1.2.3 Diagram

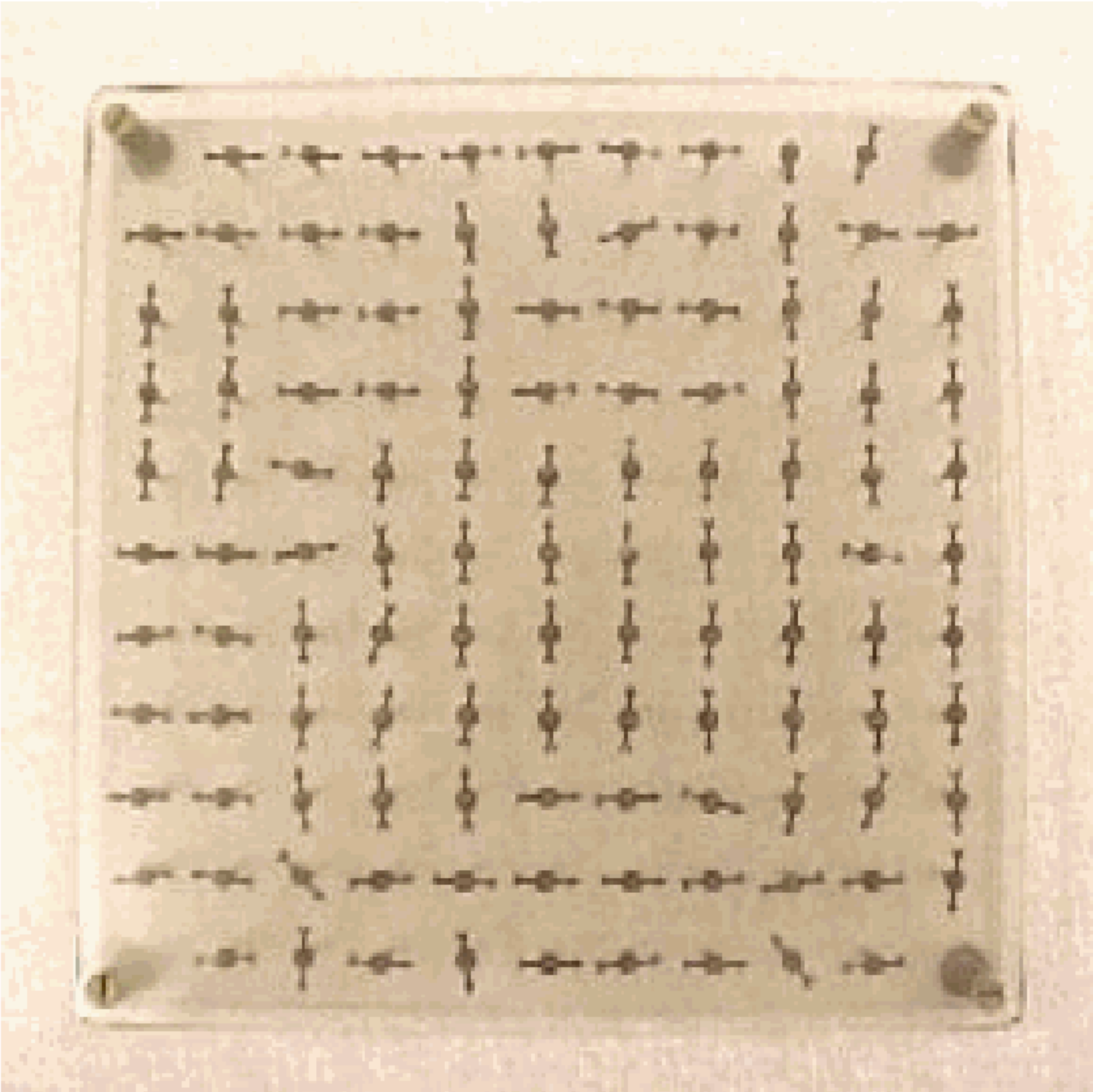


Figure 6.62: .

6.6.1.2.4 Equipment

- Cubic lattice with compass-needles (see Diagram).
- Bar magnet.
- Overhead projector.

6.6.1.2.5 Presentation

The model is placed on the overhead projector and projected. The individual compass-needles are aligned in groups, but in total there is no net direction. Slowly the bar magnet approaches the model. Every now and then a group of needles suddenly change their orientation and align themselves with the external magnetic field. When the bar magnet is close near the model, all needles are aligned in the same direction.

Slowly the bar magnet is moved away. Some of the needles change their direction with a step of 90 , but most of the needles keep their orientation. Only when you approach the model with the other pole of the bar magnet, then they redirect themselves.

Observing the number of needles aligned with the external field gives a good impression of the hysteresis loop. (Counting the number of individual compass needles enables you to draw a hysteresis loop.)

6.6.1.2.6 Explanation

The model behaves like ferromagnetic material. It has a cubic (better: flat square) structure with magnetic domains.

When the material (model) is magnetized to saturation and the external field is reduced to zero, a large magnetization remains. This behaviour is characteristic of permanent magnets. To reduce the magnetization to zero requires a magnetic field in the reverse direction.

6.6.1.2.7 Remarks

- You can have random orientation again by shaking the model.

6.6.1.2.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 222
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 6, Elektrizitätslehre I, pag. 178
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 285
- Griffith, D. J., Introduction to Electrodynamics, pag. 278-281.

6.6.2 5G40 Hysteresis

6.6.2.1 01 Barkhausen Effect (1)

6.6.2.1.1 Aim

- To make the turning of the magnetic domains audible.
- To show hysteresis.

6.6.2.1.2 Subjects

- 5G20 (Magnet Domains and Magnetization) 5G40 (Hysteresis)

6.6.2.1.3 Diagram

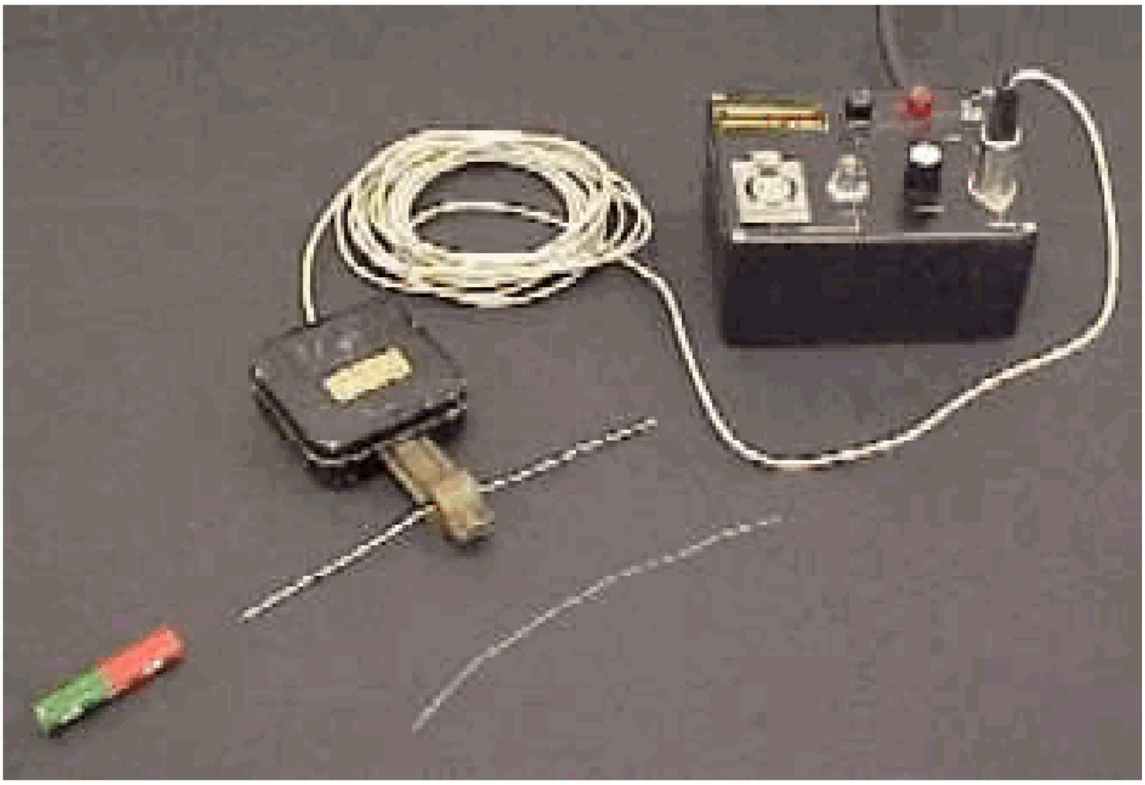


Figure 6.63: .

6.6.2.1.4 Equipment

- Solenoid, $n = 3000$.
- Pre-amplifier.
- Speaker.
- (Oscilloscope.)
- Steel wire (paperclip).
- Iron wire (soft iron).
- Bar magnet.

6.6.2.1.5 Presentation

6.6.2.1.5.1 Preparation:

The output of the pre-amplifier is connected to the audio system of the lecture-hall. Set the pre-amplifier and audio system at an appropriate level.

6.6.2.1.5.2 Presentation

- The iron wire is placed inside the solenoid, keeping it in place by hand. Then, with the other hand, one pole of a bar magnet slowly approaches the iron wire. At a certain distance a "groaning" sound is heard in the speaker. When the pole moves away from the iron wire, the "groaning" is heard again, but weaker this time. When next we approach the wire with the magnet with the other pole, again a loud rasping sound is heard.
- Then, the steel wire is placed inside the coil.

Repeating the experiment, again the rasping sound is heard. Moving the magnetic pole away from the wire, no sound is heard. Also, when the same pole approaches the steel wire again, no sound is heard. Only when the other magnetic pole approaches the steel wire, the rasping sound is heard again.

6.6.2.1.6 Explanation

When a bar magnet is moving towards a soft iron core, the elementary magnets align themselves intermittently in the direction of the magnetizing field. As each group of magnets turn over, a feeble emf is induced in the solenoid. When the bar magnet moves away from the soft-iron core, not all elementary magnets return to their original orientation (hysteresis) and so a lower emf is induced in the solenoid. This effect of hysteresis is much stronger in the steel wire (paperclip).

6.6.2.1.7 Remarks

- The induced emf can also be made visible by using an oscilloscope.

6.6.2.1.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 222.
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 6, Elektrizitätslehre I, pag. 178.
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 285.
- Griffith, D. J., Introduction to Electrodynamics, pag. 278-281.

6.6.2.2 02 Barkhausen Effect (2)

6.6.2.2.1 Aim

To show the ferromagnetic behaviour of a cubic lattice.

6.6.2.2.2 Subjects

- 5G20 (Magnet Domains and Magnetization) 5G40 (Hysteresis)

6.6.2.2.3 Diagram

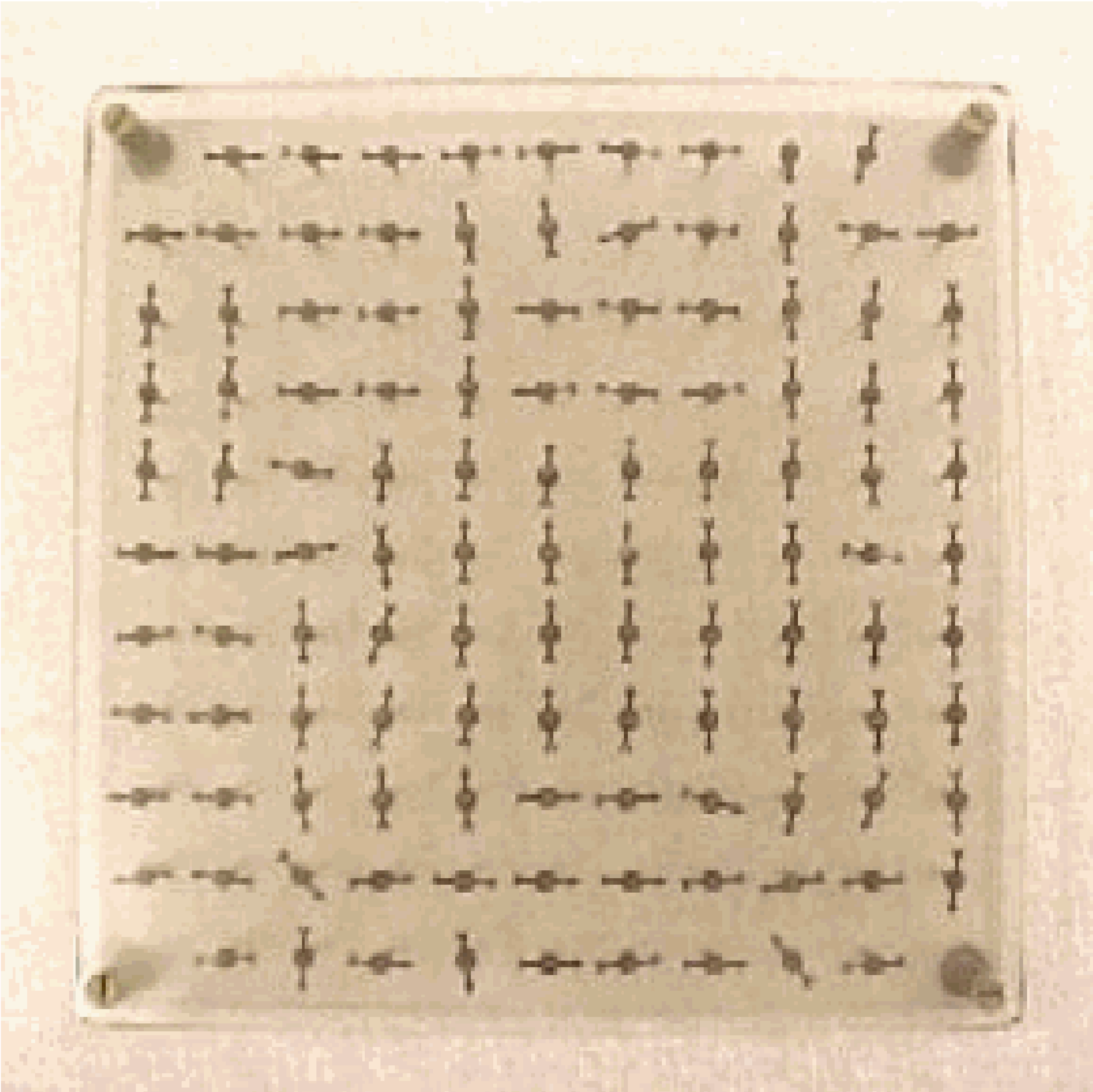


Figure 6.64: .

6.6.2.2.4 Equipment

- Cubic lattice with compass-needles (see Diagram).
- Bar magnet.
- Overhead projector.

6.6.2.2.5 Presentation

The model is placed on the overhead projector and projected. The individual compass-needles are aligned in groups, but in total there is no net direction. Slowly the bar magnet approaches the model. Every now and then a group of needles suddenly change their orientation and align themselves with the external magnetic field. When the bar magnet is close near the model, all needles are aligned in the same direction.

Slowly the bar magnet is moved away. Some of the needles change their direction with a step of 90 , but most of the needles keep their orientation. Only when you approach the model with the other pole of the bar magnet, then they redirect themselves.

Observing the number of needles aligned with the external field gives a good impression of the hysteresis loop. (Counting the number of individual compass needles enables you to draw a hysteresis loop.)

6.6.2.2.6 Explanation

The model behaves like ferromagnetic material. It has a cubic (better: flat square) structure with magnetic domains.

When the material (model) is magnetized to saturation and the external field is reduced to zero, a large magnetization remains. This behaviour is characteristic of permanent magnets. To reduce the magnetization to zero requires a magnetic field in the reverse direction.

6.6.2.2.7 Remarks

- You can have random orientation again by shaking the model.

6.6.2.2.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 222
- Friedrich, Artur, Handbuch der experimentellen Schulphysik, part 6, Elektrizitätslehre I, pag. 178
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 285
- Griffith, D. J., Introduction to Electrodynamics, pag. 278-281.

6.7 5H Magnetic Fields and Forces

6.7.1 5H10 Magnetic Fields

6.7.1.1 01 Magnetic Fields

6.7.1.1.1 Aim

To show the distance-dependence of magnetic fields in three situations: of a straight wire carrying a current; of a “monopole” and of a dipole.

6.7.1.1.2 Subjects

- 5H10 (Magnetic Fields)

6.7.1.1.3 Diagram

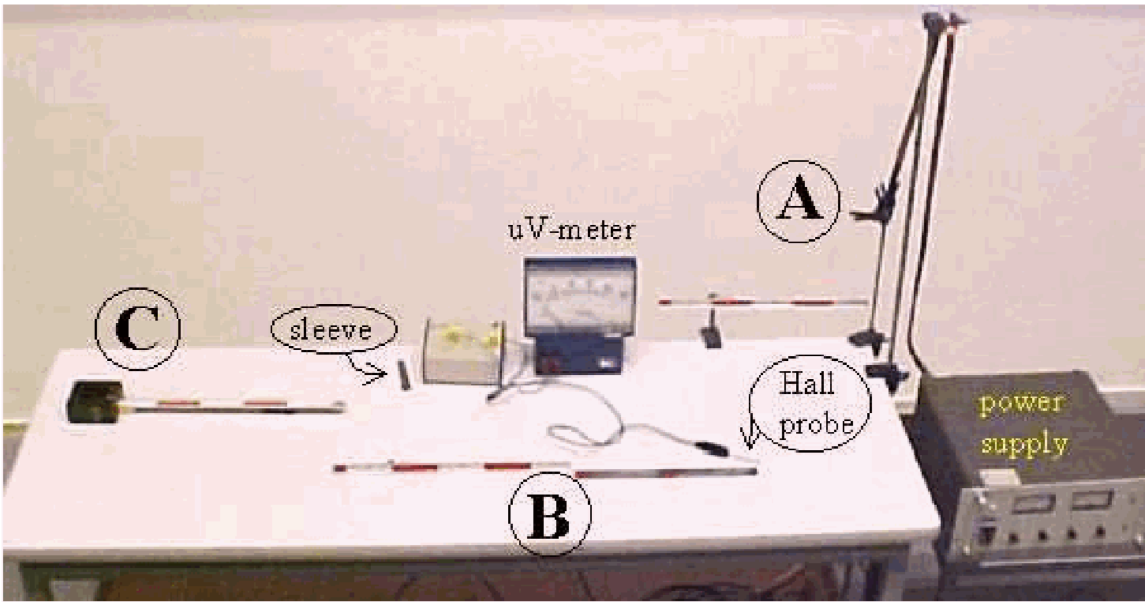


Figure 6.65: .

6.7.1.1.4 Equipment

- Brass rod, diameter 8 mm.
- Power supply, 100 A DC.
- Thick leads to conduct 100 A.
- Two bar magnets.
- Horseshoe magnet.
- Hall probe (tangential).
- Hall-probe power supply.
- Sleeve of metal to zero the Hall probe.
- UV-meter.
- Three short rulers, 30 cm.

6.7.1.1.5 Presentation

A Hall probe is used to measure the B-field. The reading is in u V (indicating the Hall-emf). In the demonstration we use the $0 - 10$ scale of the UV-meter in $0 - 10$ arbitrary B-field units.

6.7.1.1.5.1 Presentation A (see Diagram A)

In the brass rod a current of 100 A is flowing, supplied by the power supply. The Hall probe measures the B-field at 1 cm distance from the center of the brass rod. The measurement is done again at 2 — and 4 cm. We measure respectively 4,2 and 1 unit of magnetic field. This shows clearly the R^1 dependence of the magnetic field in this situation.

6.7.1.1.5.2 Presentation B (see Diagram B)

We create a monopole by placing two long magnets head to tail. In that way, the North- and South pole are far away from each other. So, in the neighborhood of the North pole the influence of the South pole can be neglected.

First we need to detect where this monopole is situated. The magnet bar is placed on an overhead projector and covered with a plexiglass sheet. Scattering iron filings on the sheet will show the shape of the magnetic field by the orientation of the filings. It is observed that the field lines "originate" from a point about 1 cm inside the bar magnet (see Figure 2).

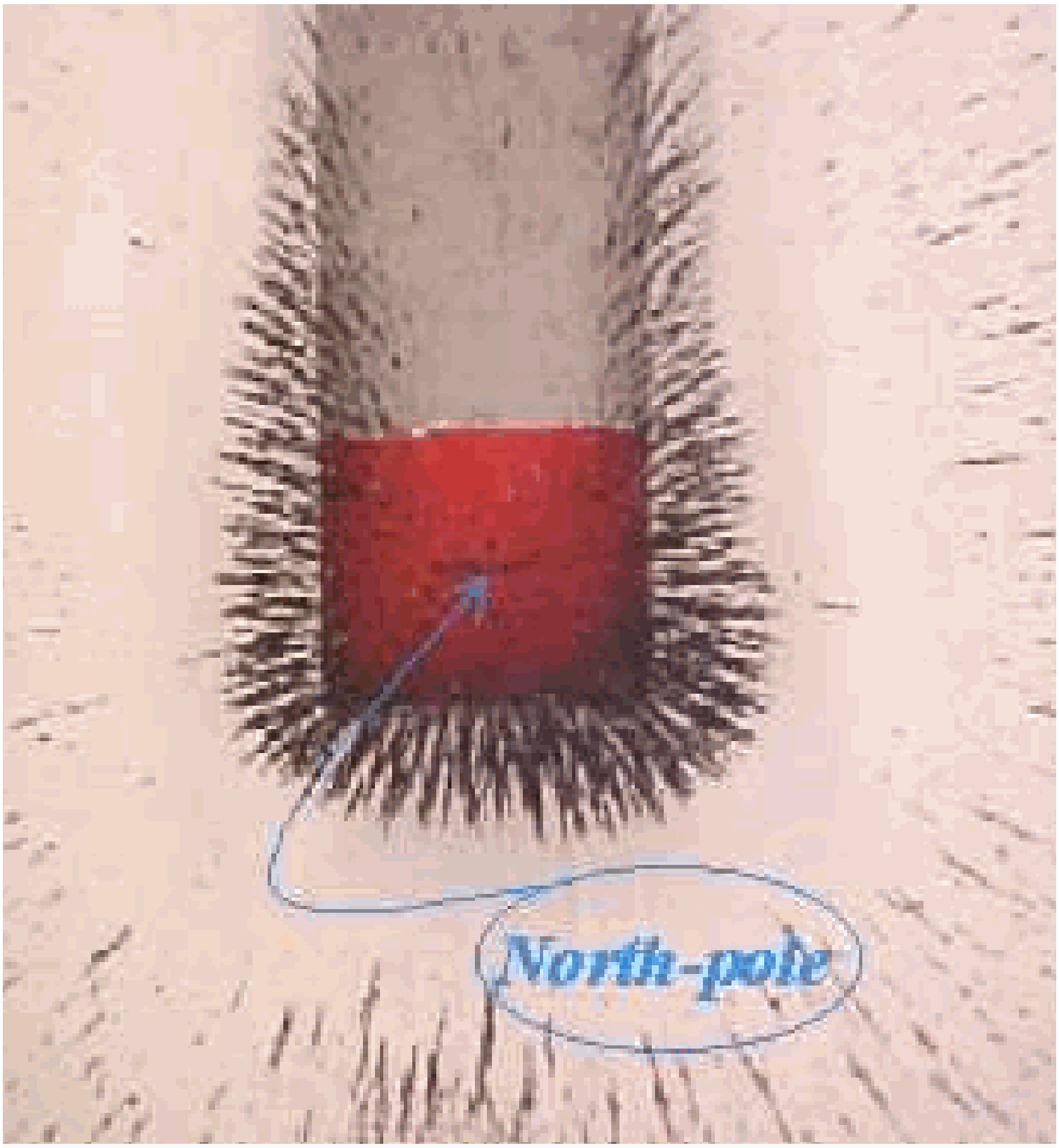


Figure 6.66: .

Then the magnetic field is measured. The Hall probe is shifted towards the monopole until a deflection of 8 units. The distance away from the monopole is read on the ruler. Then the distance is doubled, and the meter indicates: 2 units. These two measurements illustrate the R^2 dependence of the magnetic field in this situation.

6.7.1.1.5.3 Presentation C (see Diagram C)

As a dipole we use a strong horseshoe magnet. First we indicate from where we measure the distances and which orientation we will use (see Figure 3). We start perpendicular to the magnet. The probe is shifted until we measure 8 units on the meter. The distance from the dipole is measured on the ruler. Then we ask the students what will be read from the meter when the distance is doubled.

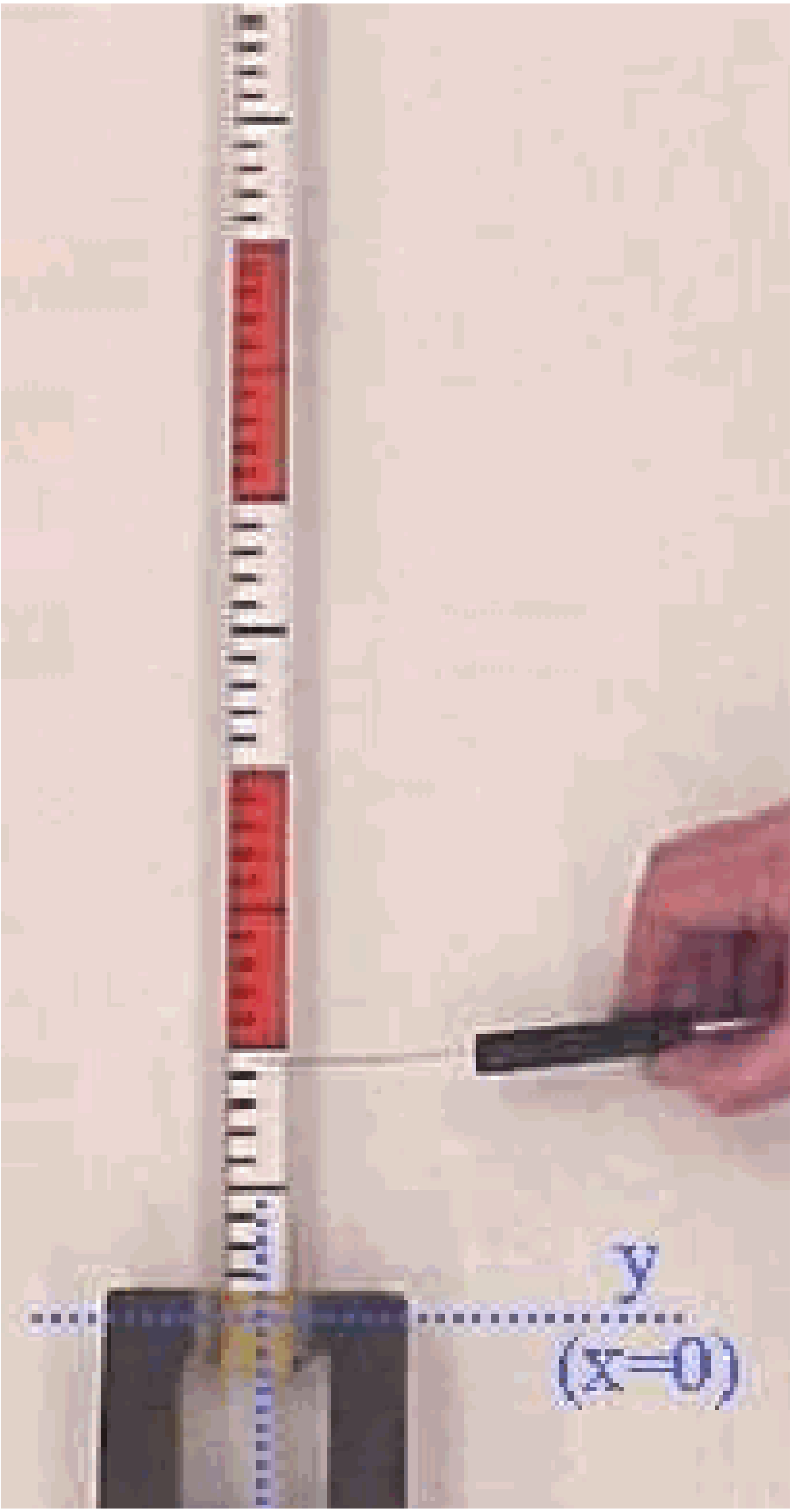

y
(x=0)

Figure 6.67: .

When we measure we come to 1 unit, illustrating the R^{-3} dependence of the B-field in case of a dipole.

The same procedure is followed when R is in the direction of the dipole (this is along the y-axis, see Figure 3). The same dependence will be found.

Also any other orientation can be measured with the same result.

6.7.1.1.6 Explanation

Textbooks explain the three situations presented.

6.7.1.1.6.1 Presentation A

In this presentation applying the Biot-Savart law gives the field near a long straight wire: $B = \frac{\mu_0 I}{2\pi R} = 2.10^{-7} \frac{I}{R}$. The factor 10^{-7} explains why such a high current is needed in this presentation (for $I = 100$ A and $R = 1$ cm, we find $B = 2$mT).

6.7.1.1.6.2 Presentation B

For a magnetic monopole $B = \frac{\Phi_m}{4\pi R^2}$, Φ_{m} is the total magnetic flux from the pole.

6.7.1.1.6.3 Presentation C

For a magnetic dipole: $B = \frac{\mu}{2\pi} \frac{\vec{m}}{R^3}$, m being the magnetic dipole moment.

6.7.1.1.7 Remarks

- In all three demonstrations more points can be measured, but since it is “only” a demonstration a limited amount of situations suffices to stress your point.
- In the explanation the R-dependence of the magnetic field can also intuitively be compared to the already known situation of the E-field of a point-charge (presentation B) and the E-field of a dipole (presentation C).

6.7.1.1.8 Sources

- Buijze W. en Roest R., Inleiding electriciteit en Magnetisme, pag. 109-111
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 719-720
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 484-485

6.7.2 5H20 Forces on Magnets

6.7.2.1 01 Force between Magnets (1)

6.7.2.1.1 Aim

To show how the force between two magnets depends on the distance between these two magnets. (An investigation.)

6.7.2.1.2 Subjects

- 5H20 (Forces on Magnets)

6.7.2.1.3 Diagram

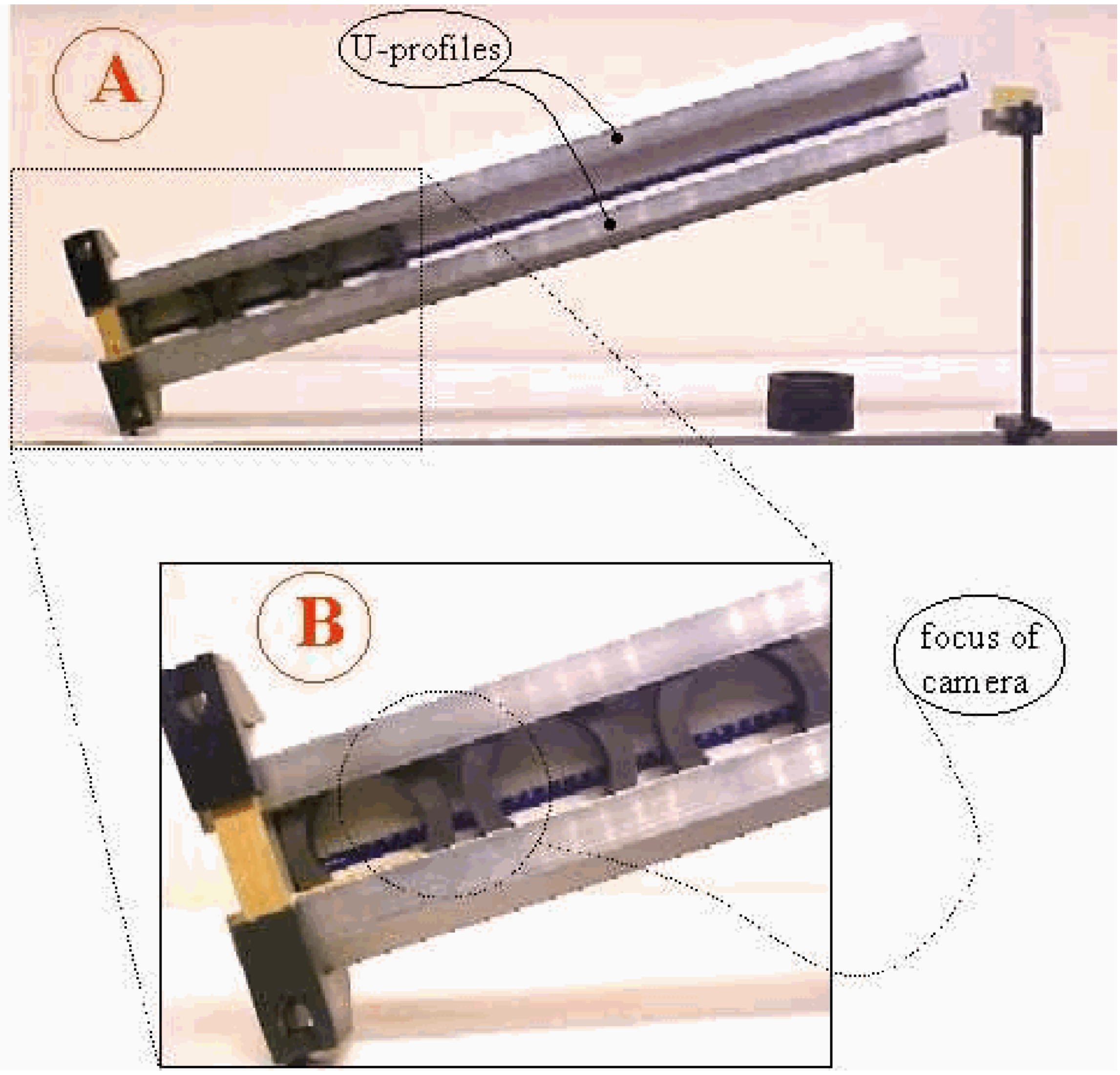


Figure 6.68: .

6.7.2.1.4 Equipment

- 6 Hardferrite magnets, $100 \times 70 \times 20$ mm^3 (ring).
- Smooth shelf.
- 2 Aluminum U-sections, $30 \times 30 \times 30 \times 2$ mm^3, clamped to shelf.
- Clamping material.
- Paper ruler, stuck to shelf.
- Camera and projector focussed on the first two magnets (see DiagramB).

6.7.2.1.5 Presentation

The U-sections and shelf are set up as shown in Diagram. The magnets can roll freely in the U-profiles. The first magnet is placed in the shelf, stopped by a clamp (see Diagram). Then the second magnet is placed in the U-section. It rolls towards the first magnet, then stops due to repulsion. The set up is bumped gently by hand, in order to reduce the influence of friction on the setting of the distance between the repelling magnets. Then the separation s, between the magnets can be read (the audience can do so thanks to the projection by the projector) and the center to center distance (d) is determined by adding 100 mm to s (see Figure 2).

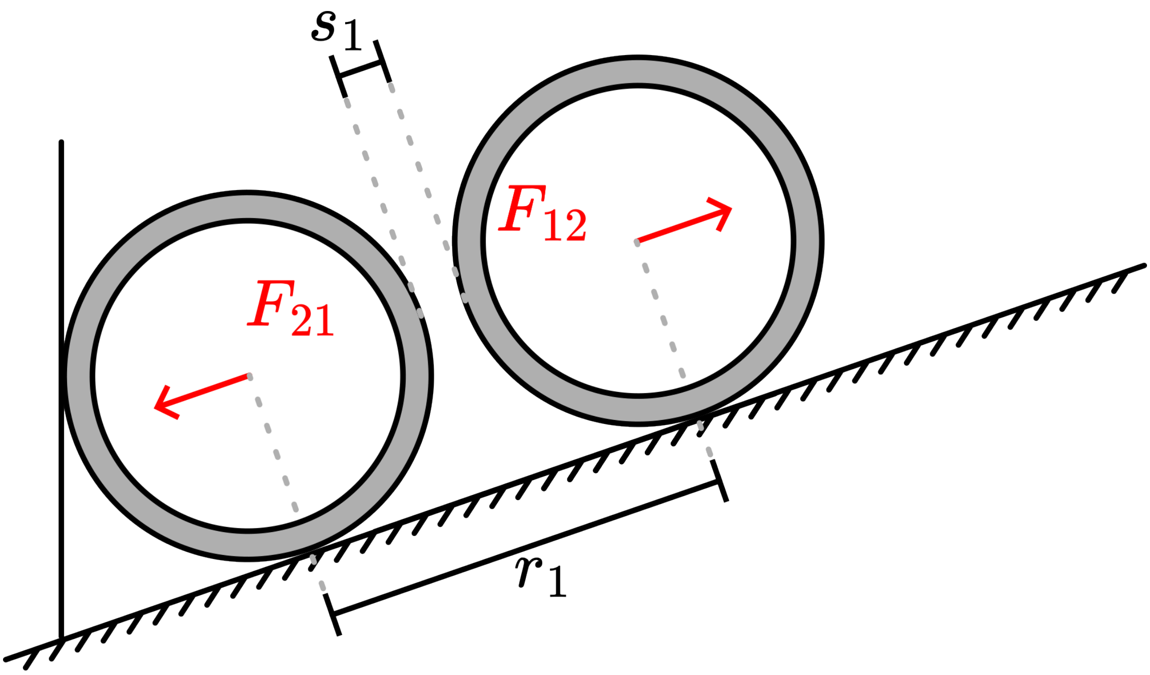


Figure 6.69: .

	Number of magnets	s (mm)	r (mm)
1	2	3.3	13.3
2	3	2.2	12.2
3	4	1.4	11.4
4	5	1.2	11.2
5	6	1.0	11.0

Table 6.70: Measurements

The third magnet is placed. It rolls towards the second magnet until it stops. Again the set up is bumped gently by hand until the three magnets have set themselves due to magnetic forces alone. The separation between the two first magnets has become smaller. Again this distance is read. A fourth magnet is added and the procedure repeated. Also a fifth - and sixth magnet follow. Table 1 shows a typical result of our measurements.

6.7.2.1.6 Explanation

Supposing that the force between magnetic (mono)poles is like Coulomb's law for electric charges, then we can write: $F_{poles} = k\frac{p_1 p_2}{r^n}$ (p_1 and p_2 are the "magnetic pole strength" of pole 1 and pole 2).

Between real magnets, being dipoles, the force between them will be of a higher power then the foregoing "Coulomb's law for magnets" indicates. So, we write: $F_{magnets} = c\frac{R_1 R_2}{r^m}$.

The first measurement (with two magnets) gives: $F_1 r_1^m = cR_1 R_2$.

The second measurement (with three magnets) gives: $F_2 r_2^m = cR_1 R_2$.

Since $F_2 = 2F_1$ (see Figure 3), we find: $\frac{r_1}{r_2} = \sqrt[m]{2}$

So measuring r_1 and r_2, we can determine m!

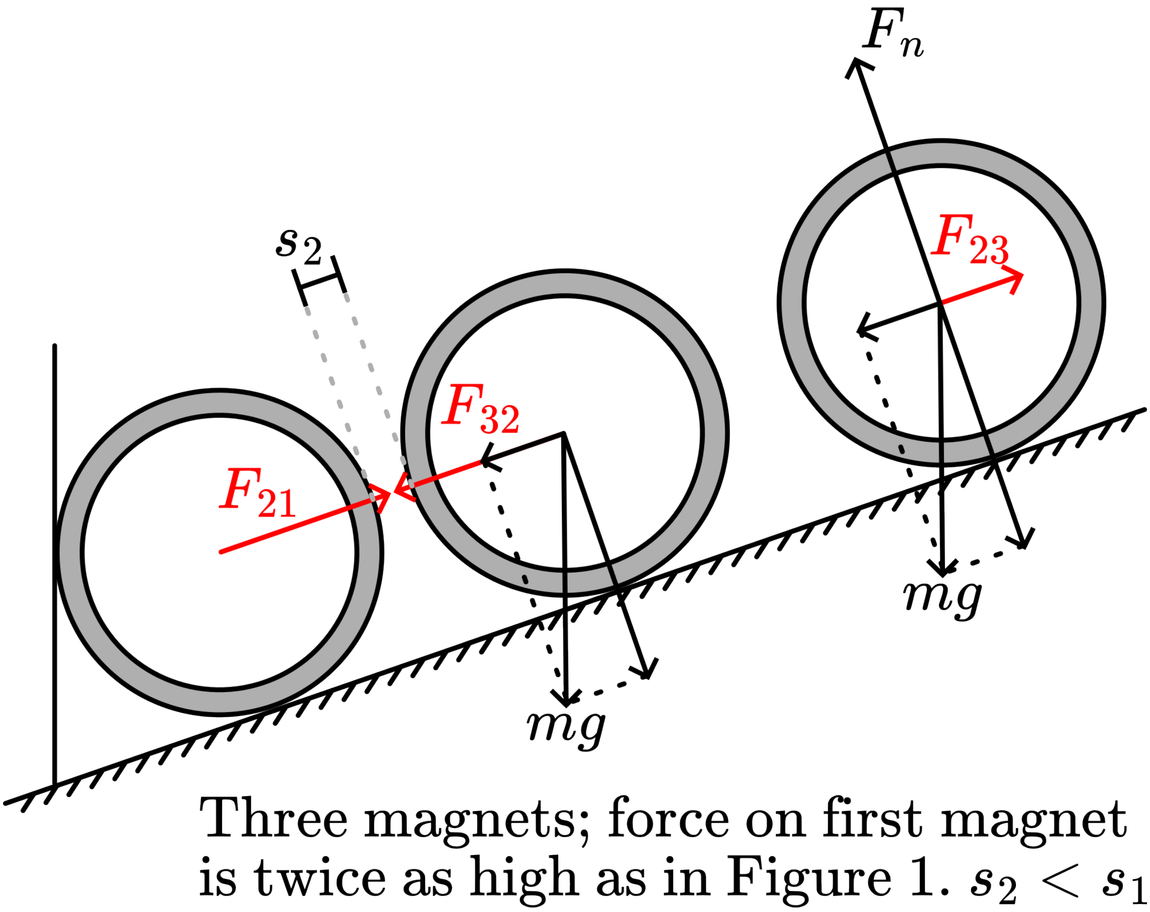


Figure 6.71: .

The result in Table 1 making $F_2 = 2F_1$, gives us $13.3/12.2 = 1.09$, making $m = 7\left(2^{1/7} = 1.10\right)$.

The next measurement, with four magnets in total, making $F_3 = 3F_1$, gives us $13.3/11.4 = 1.17$, making $m = 7\left(3^{1/7} = 1.17\right)$.

Next measurement, with five magnets in total, making $F_4 = 4F_1$, gives us: $13.3/11.2 = 1.19$, making $m = 8\left(4^{1/8} = 1.19\right)$.

Our last measurement with six magnets, making $F_5 = 5F_1$, gives us: $13,3/11.0 = 1.21$, making $m = 8\ \left(5^{1/8} = 1.22\right)$.

This demonstration shows that r has a high power $(m = 7, 8)$, and, as the results slightly suggest, that this power increases as r increases.

The Explanation in the next demonstration in this database (Force between magnets) shows that when dipoles are far enough away from each other that the theoretical m-value $= 4$. In our demonstration with ring magnets so close to each other, this is not the situation.

A second objection can be that these ring magnets cannot be considered as simple dipoles.

6.7.2.1.7 Remarks

- As an extra result we can also easily compare $F_2 (= 2F_1)$ and $F_4 (= 4F_1)$. Comparing these numbers gives: $12.2/11.2 = 1.09$, so again: $m = 7$.
- When all magnets are placed the increasing separation between them suggests that comparing these mutual separations will give the same result as we collected in Table 1 while looking at the changing separation between the first two magnets only. This other method can be used only when all magnets have the same strength (which usually is not so).

6.7.2.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 474-475 and 484-486

6.7.2.2 02 Force between Magnets (2)

6.7.2.2.1 Aim

To show how the force between two magnets depends on the distance between these magnets.

6.7.2.2.2 Subjects

- 5H20 (Forces on Magnets)

6.7.2.2.3 Diagram

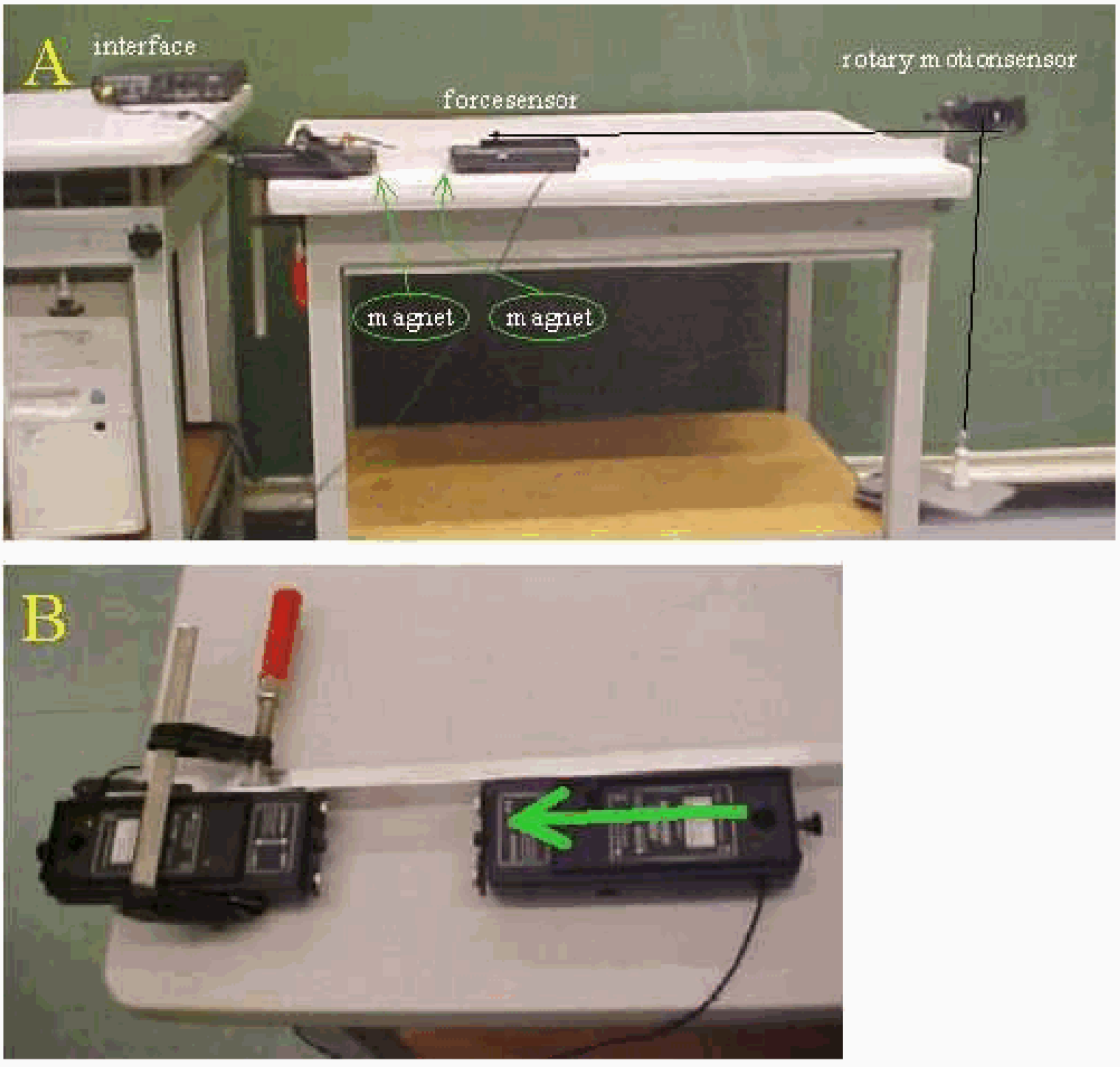


Figure 6.72: .

6.7.2.2.4 Equipment

- 2 Force sensors.
- Magnets fixed to both force sensors, opposing each other.
- Aluminum L-section to guide moving force sensor.
- Rotary motion sensor.
- String.
- Mass, . 2 kg.
- Clamps.
- Data-acquisition system and software.
- Projector, to project monitor screen to large group of students.

6.7.2.2.5 Presentation

The demonstration is set up as shown in DiagramA. One force sensor is firmly clamped. Make sure the table stands firmly on the ground. We connect the moving force sensor to the interface. The software is set in such a way that a graph of force versus displacement can be registered. Tare the moving force sensor.

Start data-acquisition and, by hand, displace the free force sensor quietly towards the clamped one. Take care to hold the moving force sensor along the guiding section. A graph as shown in red in Figure 2A will be registered.

Clearly can be seen that the force increases rapidly when the magnets approach each other. The curve-fit-option in the software it is tried (power fit). Choosing the region 5 — to 7.8 cm a power fit with power 4 is a good option (see Figure 2A, the black line).

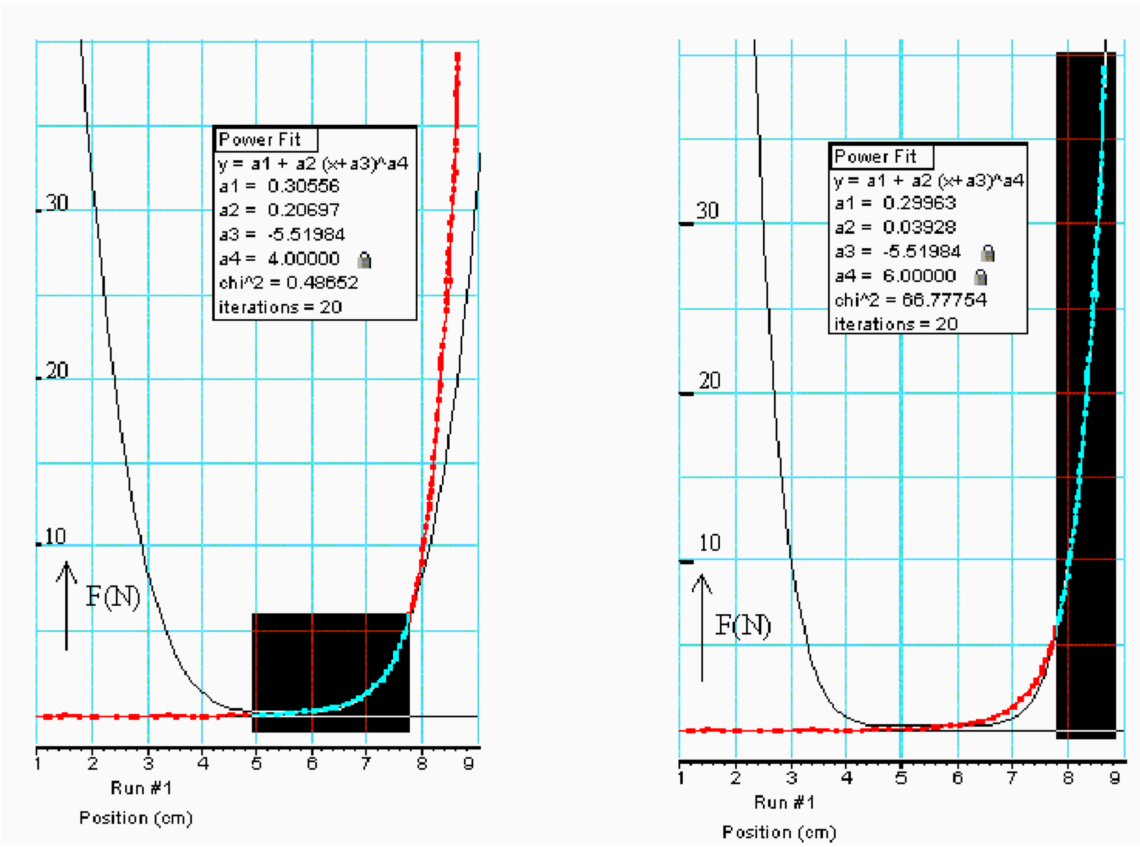


Figure 6.73: .

But it can be seen at the same time that for the region from 7.8 cm to “touching magnets”, the power in the formula needs a higher number. Selecting this region and applying $a_3 = -5.51984$ (line of symmetry in the graph as found in the former selection) we find, by trial and error (trying to make chi^ 2 as low as possible), a power of 6 being more or less a good one (see Figure 2B).

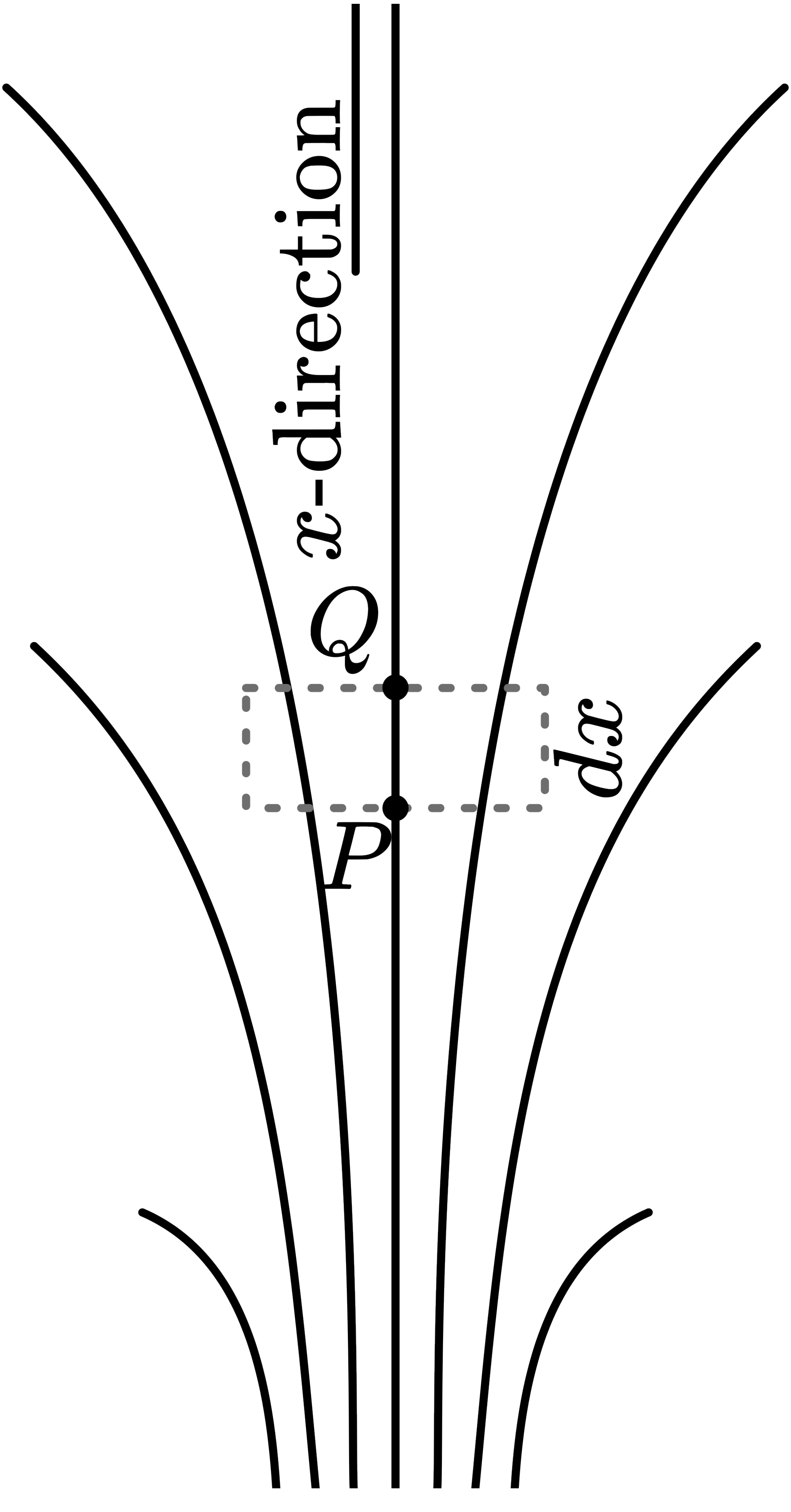
6.7.2.2.6 Explanation

The magnets that approach each other are dipoles. It are disc magnets, about 5 mm thick. Such a magnet is a magnetic dipole. We analyse our demonstration by first looking at the magnetic field produced by one magnetic dipole and next look what will happen when a second dipole is placed in that field.

Many textbooks show that the magnetic field strength (H) of a dipole depends on the distance (r) as $H \propto r^{-3}$ (provided that $r \gg l$; (2/ usually being the distance between the “poles”).

When a second dipole is placed in such a field it experiences a net force, since the field is not uniform and the opposing forces on its North- and Southpole will not cancel.

Figure 3B can be used to explain this: If at P the magnetic field strength is H_x, then at Q, for a dipole of length dx, it will have the magnitude $H_x + dH_{x,}$ or $H_x + \frac{dH_x}{dx} dx$.



x-direction
Q
P
dx

Figure 6.74: .

The forces on both poles are opposite:

$F_p \propto H_x$

$F_Q \propto -\left(H_x + \frac{dH_x}{dx} dx\right)$

The resultant force on dipole PQ:

$F_{dipole} \propto \frac{dH_x}{dx}$, so and applying $H \propto r^{-3}$ we get $F \propto r^{-4}$. The result of Figure 2A verifies this.

When the magnets are very close, the expression $r \gg l$ is no longer valid ($/ = 2.5$ mm) and the expression $H \propto r^{-3}$ for the field of the dipole will be different and so the expression for the force between the dipoles will be a different one.

6.7.2.2.7 Remarks

- Quite some force is needed to push the opposing magnets towards each other. So clamp everything tightly otherwise the magnets might "shoot away" abruptly.

6.7.2.2.8 Sources

- Duffin, W.J., Electricity and magnetism, pag. 153 and 78-83
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 484-486 and 441-443

6.7.3 5H30 Force on Moving Charges

6.7.3.1 02 Force on Electrons in a Magnetic Field (2)

6.7.3.1.1 Aim

- To show the effect of a magnetic field on a beam of electrons.
- To show the idea of a magnetic bottle.

6.7.3.1.2 Subjects

- 5H30 (Force on Moving Charges)

6.7.3.1.3 Diagram

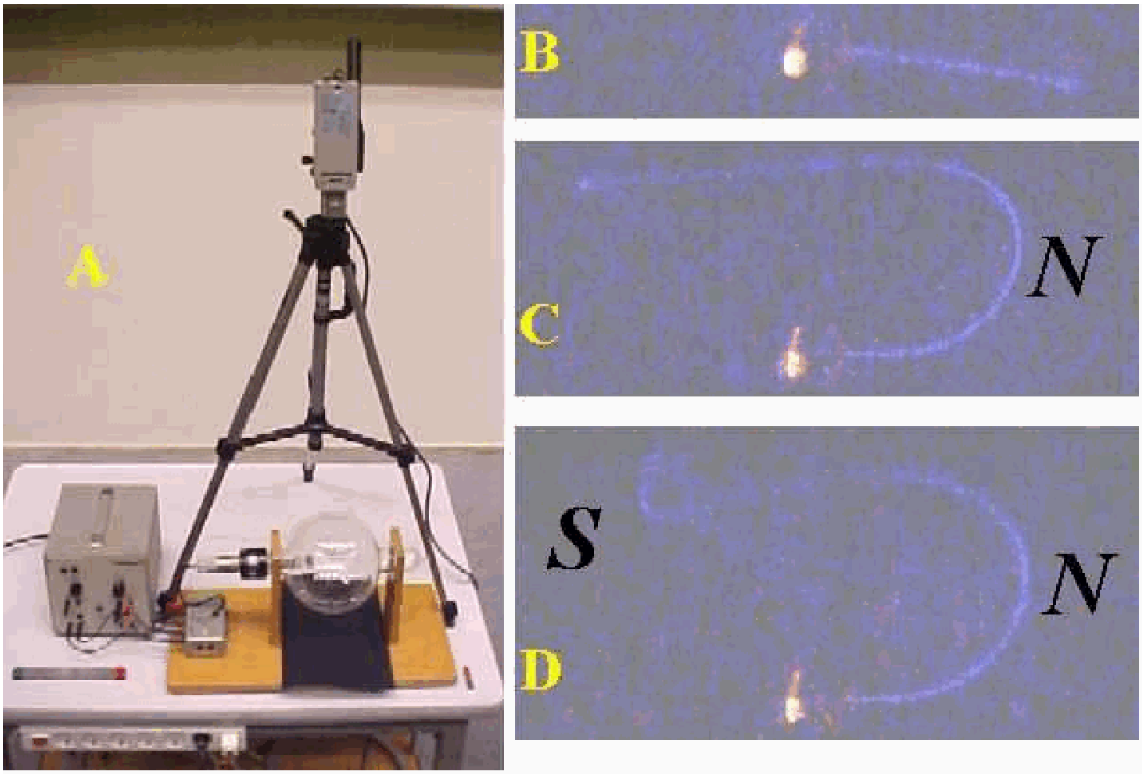


Figure 6.75: .

6.7.3.1.4 Equipment

- Fine beam tube, hydrogen filled (1 Pa).
- Power supply; 6.3 V filament; 0 — 300 V anode.
- Several bar magnets.
- Camera.
- Projector to project camera-image.

6.7.3.1.5 Presentation

Set up the demonstration as shown in DiagramA. The fine beam tube is positioned in such a way that its electrode system will emit an electron beam horizontally (this position makes it easy to manipulate the bar magnets). Power is switched on, the filament heats up. The room is darkened. The anode voltage is increased until a clearly visible rectilinear beam is seen (see DiagramB).

- The electron beam is approached head on by the N-pole of a bar magnet. A spiralling of the beam is observed.

Repeat this demonstration but now approaching the beam with a S-pole. Again a spiralling beam is observed.

- When the N-pole of the bar magnet approaches more sideways the beam can be turned backward making only one half loop of its spiral(DiagramC). Do the same demonstration also with a S-pole approaching the electron beam.
- Holding a second bar magnet on the other side of the tube, the electron beam can be trapped between the two bar magnets. This “succeeds” when the second bar magnet has an opposite pole approaching the tube: The beam is reversing its direction again (DiagramD) and also a blue glow (indicating the presence of moving electrons) between the magnetic poles then suddenly “switches on”: This indicates the action of a “magnetic bottle” (this blue glow is not visible in the picture of DiagramD). To show the difference also try to trap the electrons using two N-poles (or two S-poles) turned towards the tube: no trapping succeeds.

6.7.3.1.6 Explanation

The force (F) on a moving (v) electron (charge e^-) in a magnetic field (B) is expressed as $F = -e\vec{v} \times \vec{B}$. The force is always perpendicular to $\vec{v}$. So, a magnetic field only changes the direction of $\vec{v}$, not its magnitude. The drawings in the Figures explain the trajectories of the electrons in our demonstrations.

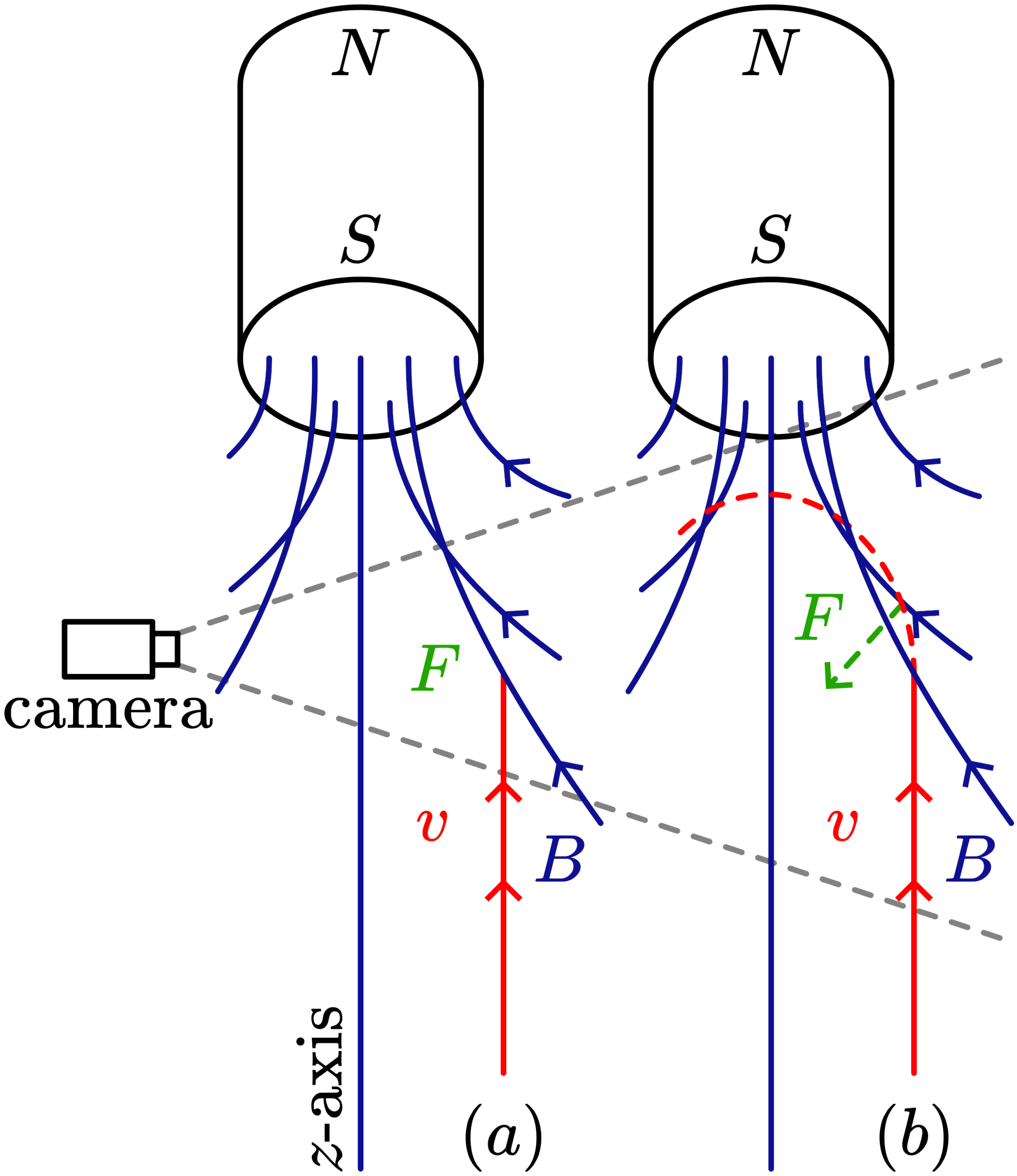


Figure 6.76: .

In Figure 2A the force (F) is pointing into the picture and so the electron beam is curving away from us (the camera sees the beam turning to the left). While curving away from us, the electron approaches the S-pole: the force on the electron will now point inward, making that, while the electron curves away from us, it also turns to the left (see Figure 2B). The more it approaches the S-pole, the more the trajectory will become circular. Summarizing: the path of the approaching electron will be a spiral.. The magnetic field lines act as a trap to the approaching electron. The higher the speed, the deeper it will spiral into the trap. Also when the electron approaches initially closer to the z-axis, it will go deeper into the trap, because close to the z-axis B and v are almost parallel, making F almost zero.

Due to the diverging field, the force F remains pointing downward and finally the electron will spiral away from the S-pole again.

Positioning a second pole on the other side of the tube makes it possible to have a similar trap on the other side. When we use an opposite pole on the other side, the electrons cannot escape from the region between these poles (see in Figure 3A the direction of F). The electrons experience at all points a force towards the centre between the poles.

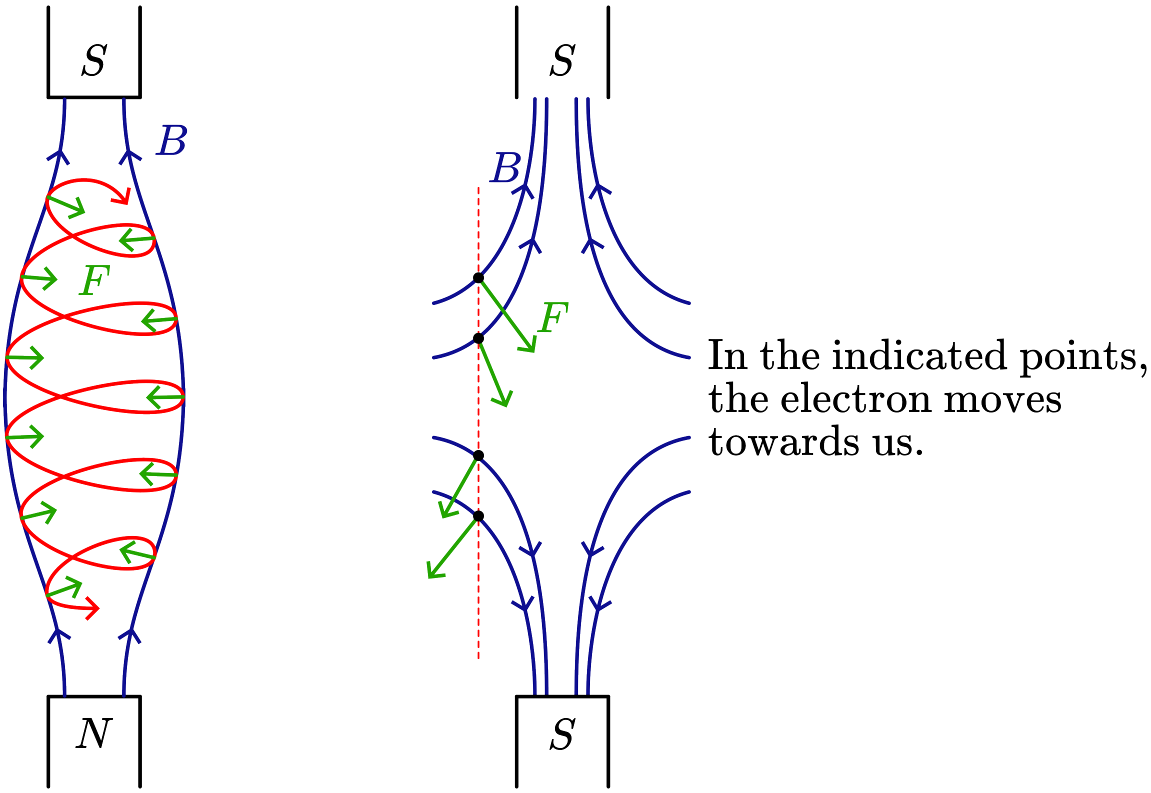


Figure 6.77: .

The vertical component of this force makes the electrons oscillate from one pole to the other continuously (the horizontal component causes the circular movement in the spiralled path).

When the second magnetic pole should be a same magnetic pole (S-pole in this Explanation), the electrons escape from the region between the poles (see in Figure 3B the different directions of F).

6.7.3.1.7 Remarks

- When, in the beginning of the demonstration, the N-pole is replaced by a S-pole the trap also functions. The electron beam spirals into the other direction when a different pole is used. Due to the configuration of our electron tube it is not possible to show a satisfactory trapping when approaching the electron beam head on by a S-pole.

6.7.3.1.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 5/6 vwo, pag. 212
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 497-498
- Young, H.D. and Freeman, R.A., University Physics, pag. 873-876
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 692-694

6.7.4 5H40 Force on Current Wires

6.7.4.1 01 Force Effect of Current

6.7.4.1.1 Aim

To show that when a current is flowing in a wire, parts of the wire exert forces on one another.

6.7.4.1.2 Subjects

- 5H40 (Force on Current Wires)

6.7.4.1.3 Diagram

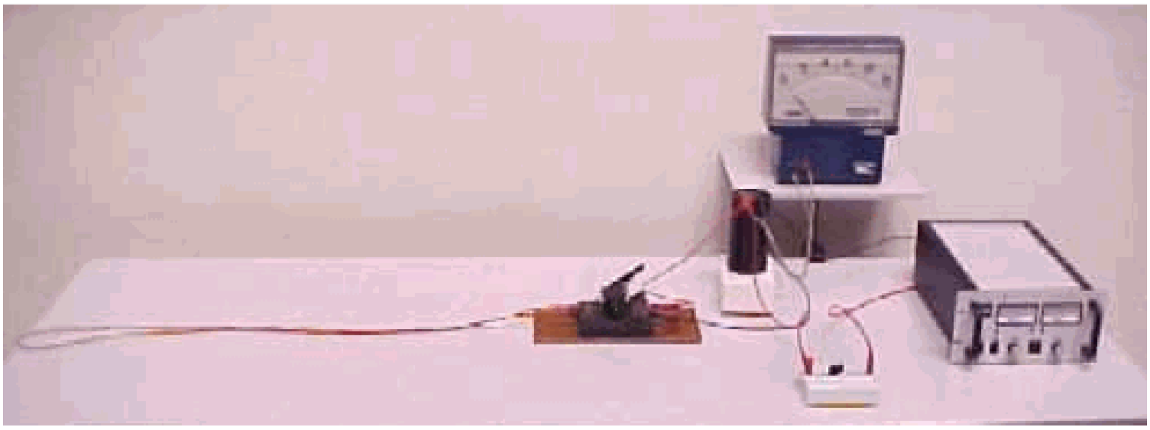


Figure 6.78: .

6.7.4.1.4 Equipment

- Power supply, we use 1.2kV/.2 A.
- Capacitor, we use 2200 uF/500 Vdc.
- High current switch.
- Unipolar switch.
- V-meter, large scale.
- Wire, 2 m.
- Power supply, 100 A.

6.7.4.1.5 Presentation

First connect the 2 m-wire to the 100A powersupply. Position the wire-parts close together (see Figure 2A). Switch on the powersupply and see how the wire-parts move away from each other.

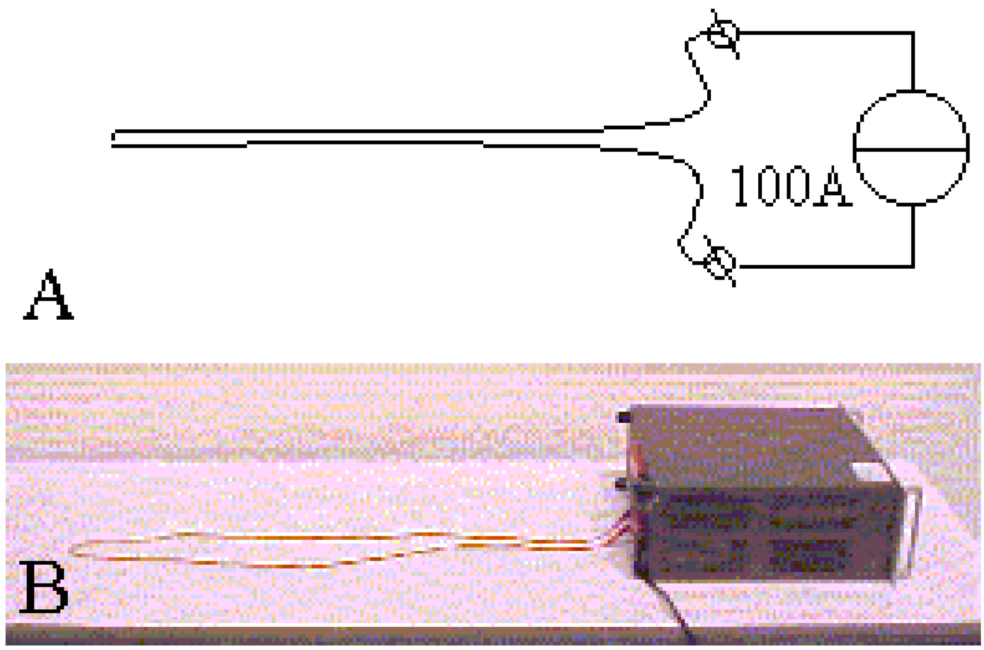


Figure 6.79: .

To make this effect stronger, we use the demonstration as shown in Diagram and Figure 3A. First the capacitor is charged to 500 V. Then switch S_1 is opened and the high current switch is closed. The wire-parts fly away from each other (Figure 3B).

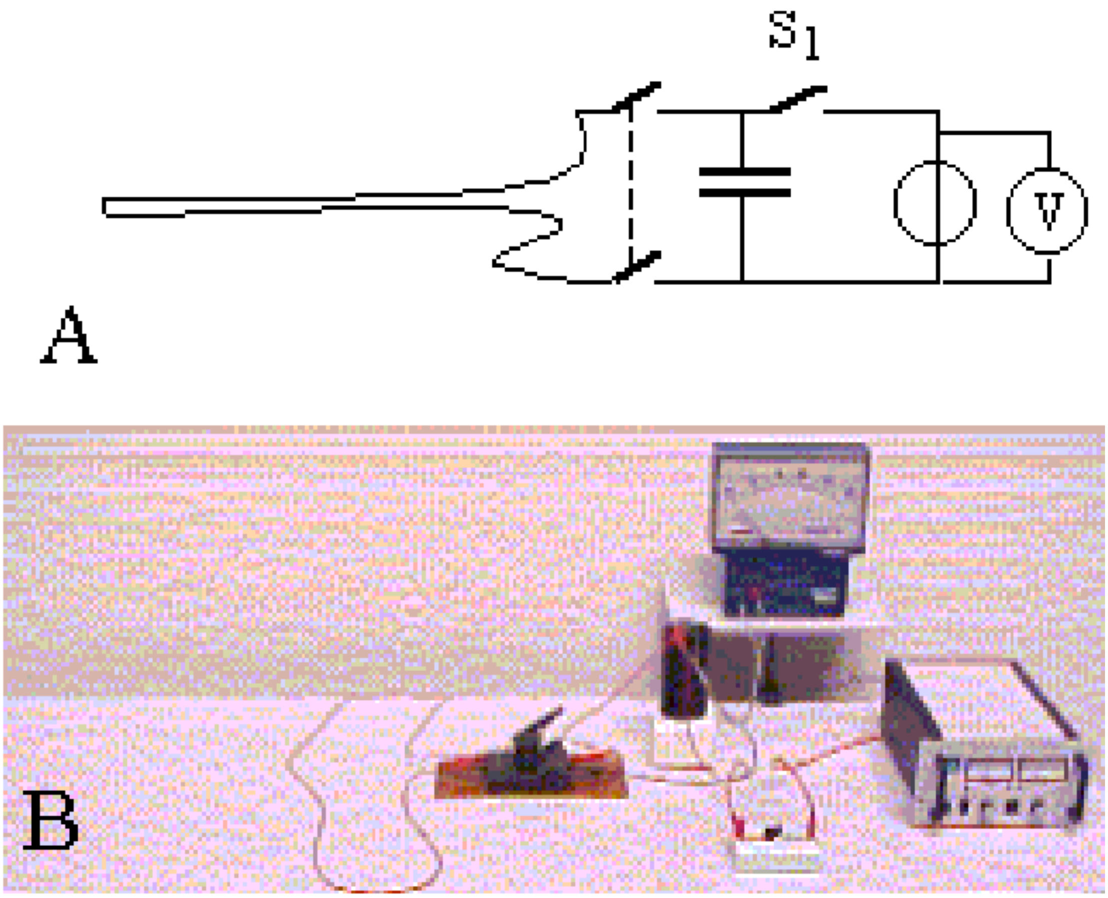


Figure 6.80: .

Ask the students what shape the wire loop would take if such a high current should flow continuously.

6.7.4.1.6 Explanation

The first part of the demonstration shows that opposing currents exert a repelling force on each other. Moreover, the demonstration shows how small this force effect of current is.

On this force effect the definition of the Ampere as the unit of electric current is based $\frac{\Delta F}{\Delta l} = 2 \times 10^{-7} \frac{I_1 I_2}{r}$. This demonstration, using $\mathrm{I}_1 = \mathrm{I}_2 = 100$ A and $\Delta l = 1$ m has to deal with a force of only $2 \cdot 10^{-3}$ N. No wonder the displacement of the wire is small.

In the second part of the demonstration the current is much higher. Supposing the wire and contacts having a resistance of 0.5Ω, a current of 1000 A is flowing in the beginning of the discharge. Then the force on the wireloop is . 2 N. This hundredfold higher force exists only a short time. Not only F diminishes due to the increasing distance, but also due to the reducing discharge current (the circuit has a RC-time of about 1msec). Due to its impulse the wire-parts continue to move after the discharge (Figure 3B).

If current should flow continuously the wire would take the shape of a perfect circle.

6.7.4.1.7 Remarks

- Mind that when using the 100 A power supply that the 100A is not interrupted abruptly, because when this happens the high induced voltages can damage the power supply.

6.7.4.1.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 220
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 407 and 411

6.7.4.2 02 Lorentz Force (1)

6.7.4.2.1 Aim

To show that a current in a magnetic field experiences a force.

6.7.4.2.2 Subjects

- 5H40 (Force on Current Wires)

6.7.4.2.3 Diagram

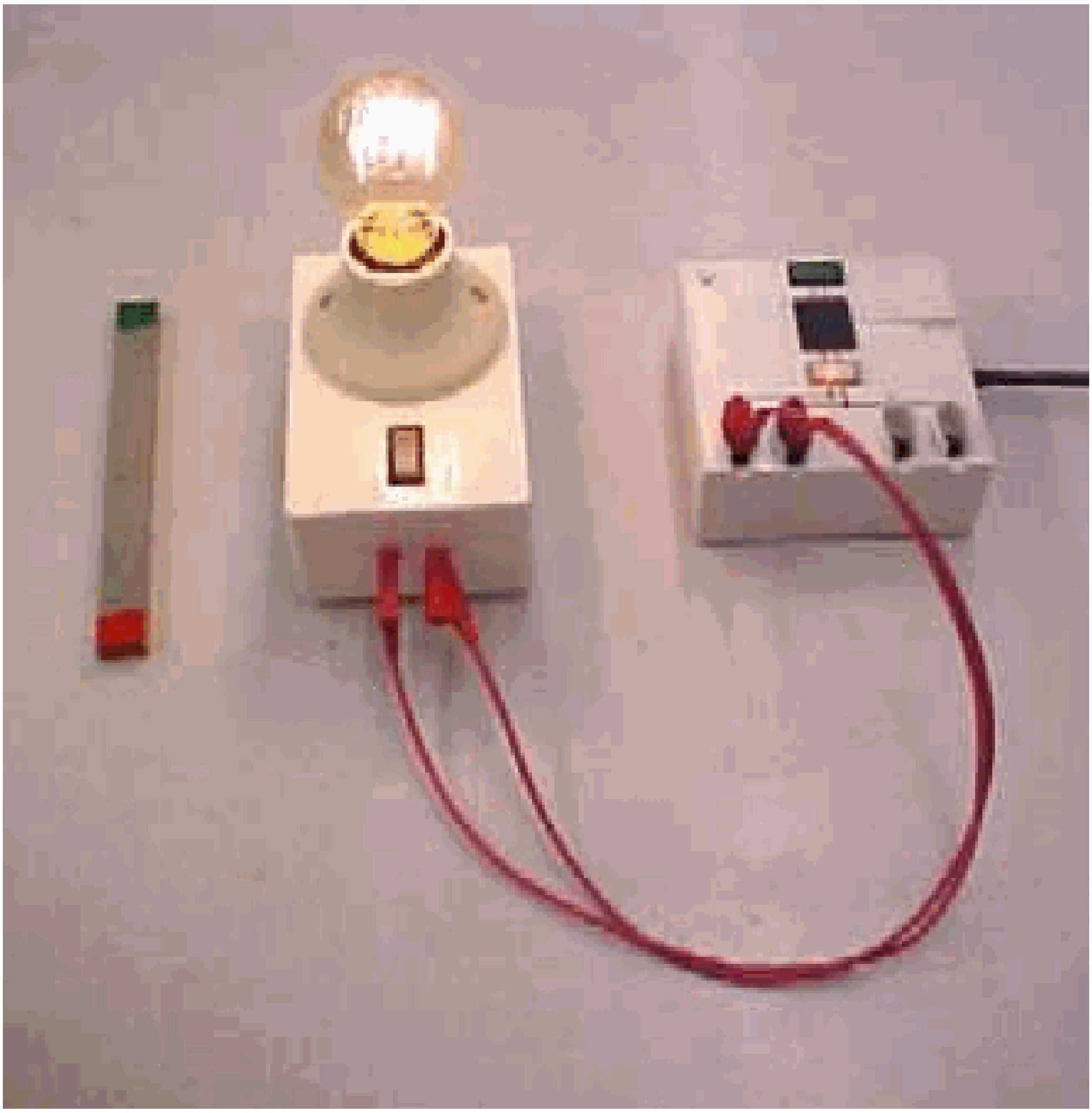


Figure 6.81: .

6.7.4.2.4 Equipment

- Spiral filament lamp.
- Safety connector to mains (220 V/50 Hz).
- Bar magnet.

6.7.4.2.5 Presentation

The lamp is connected to the mains and the filament is glowing. The filament can be seen clearly.

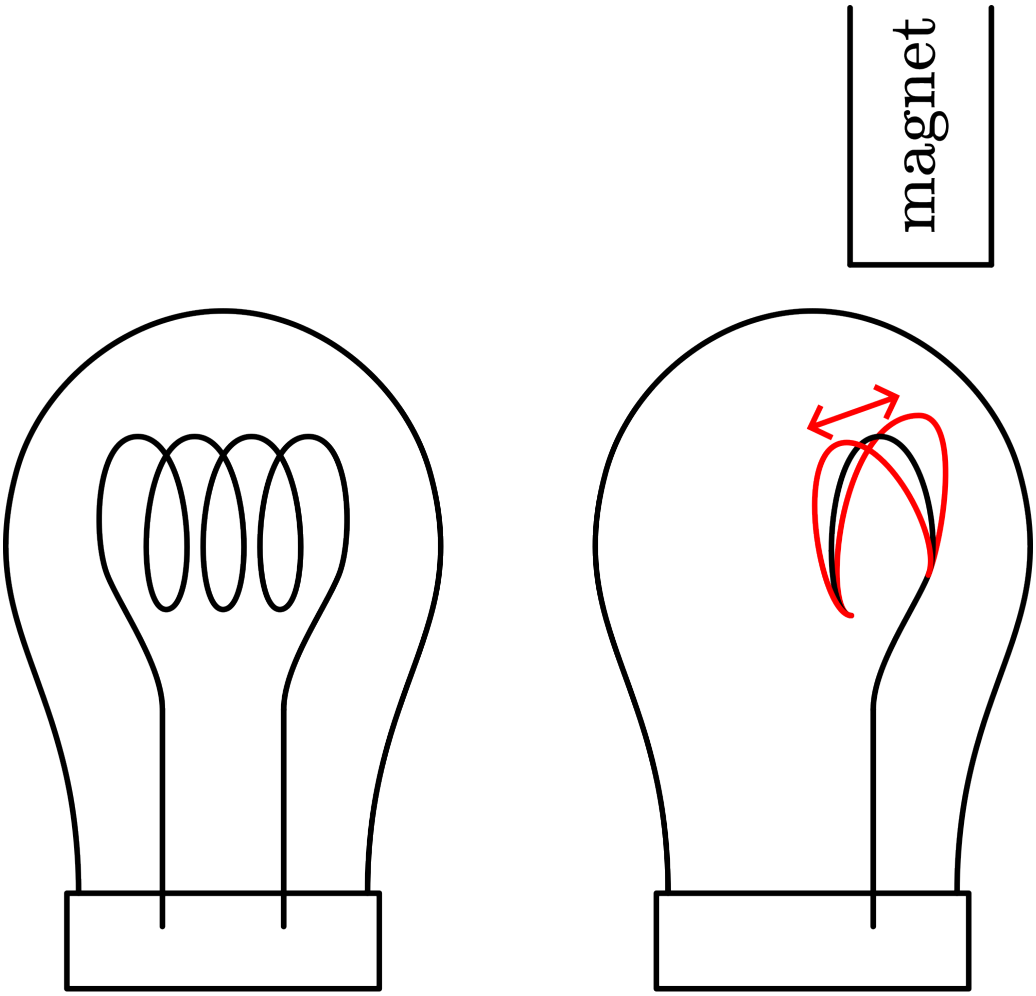


Figure 6.82: .

The bar magnet approaches the lamp and the individual turns of the spiral filament show themselves as broadened bands (see Figure 2). The filament performs a fast reciprocating motion

6.7.4.2.6 Explanation

The reciprocating motion of the filament indicates that a force is acting and that it is acting to and fro."To and fro" is caused by the constantly changing direction of the current (50 Hz).

6.7.4.2.7 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 200 and 210
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 486-487

6.7.4.3 5H40.03 Lorentz Force (2)

6.7.4.3.1 Aim

To show the force on a current carrying wire in a magnetic field.

6.7.4.3.2 Subjects

- 5H40 (Force on Current Wires)

6.7.4.3.3 Diagram

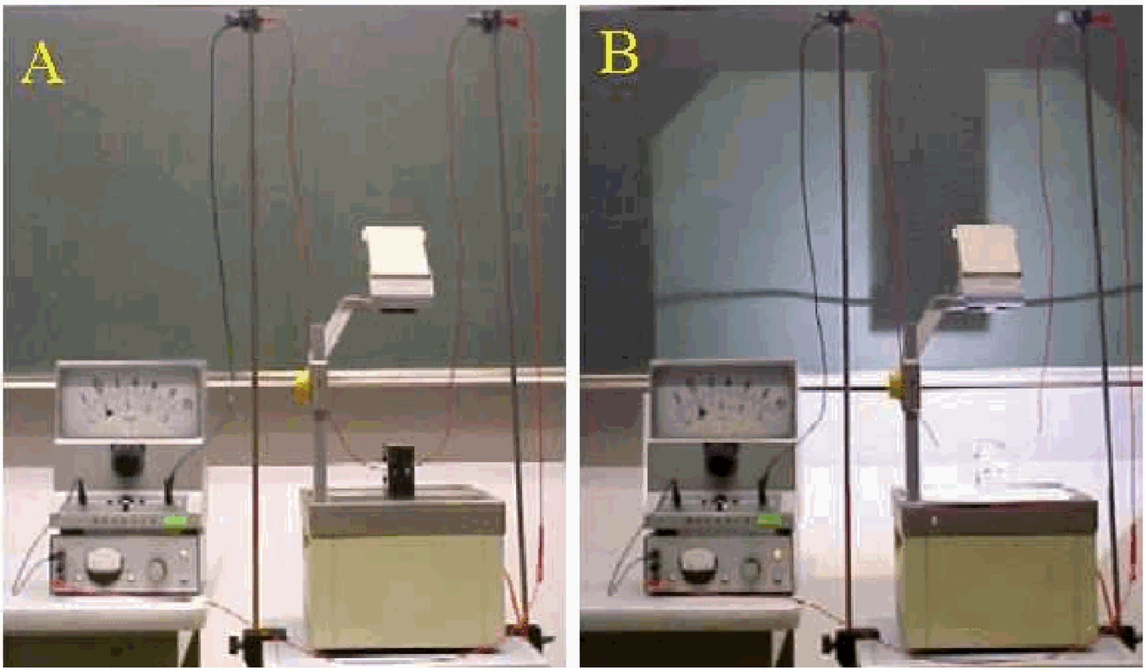


Figure 6.83: .

6.7.4.3.4 Equipment

- Conducting wire ($\mathrm{I} = 2$ m).
- A-meter ($0 - 1$ A).
- Current source ($0 - 1$ A).
- Strong horseshoe magnet (we use $\mathrm{B} = 0.5$ T).
- Overhead projector

6.7.4.3.5 Presentation

The wire is loosely hung over the overhead projector, so it can swing (see Diagram A). The picture of the wire is sharply projected on the blackboard (see Diagram B).

By hand, the wire is given a deflection in order to show that for such a deflection only a small force is needed. The larger the deflection, the larger the force. (For small deflections, the deflection is proportional to the force.) Now the horseshoe magnet is placed on the overhead projector. The wire is in the middle of the gap between the North- and the South pole. Mark this position of the wire on the blackboard. Slowly raise the current and observe that the wire deflects. The relationship between the direction of current, direction of magnetic field and direction of force is observed. Reverse the current and see that the force is directed towards the other side now. Also the horseshoe magnet can be turned.

Raising the current in steps and marking the position of the wire on the blackboard, it can be observed (roughly) that the Lorentz force is proportional to the current.

6.7.4.3.6 Explanation

Applying Biot-Savart's law it can be shown that the force on a current element $\Delta\vec{l}$ in a magnetic field of flux density $\vec{B}$ is given by $\vec{F} = I\Delta\vec{l} \times \vec{B}$. In our case, having $\vec{B}$ perpendicular to $\Delta\vec{l}$ and considering that the wire-element in the field is straight, then $F = IlB$. Our demonstration verifies $F \propto I$.

6.7.4.3.7 Remarks

- Verifying $F \propto I$ supposes that only the displacement of the wire between the magnetic poles is considered. Only in this region the magnetic field is uniform and $\vec{B}$ can be considered constant.
- The demonstration can also be used to estimate the value of the fluxdensity B. In $F = I/B_f$ I and /are known (see Figure 2).

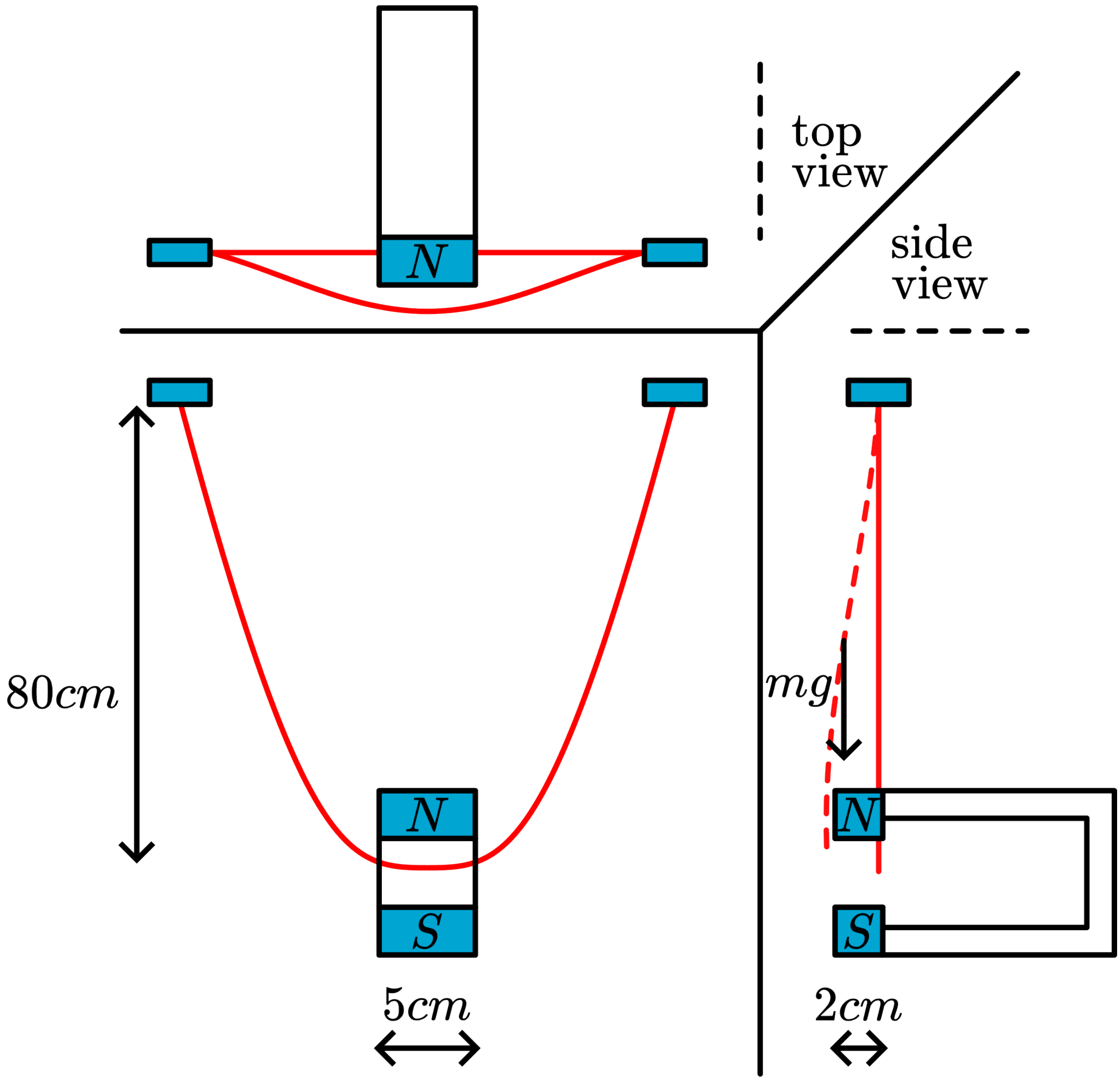
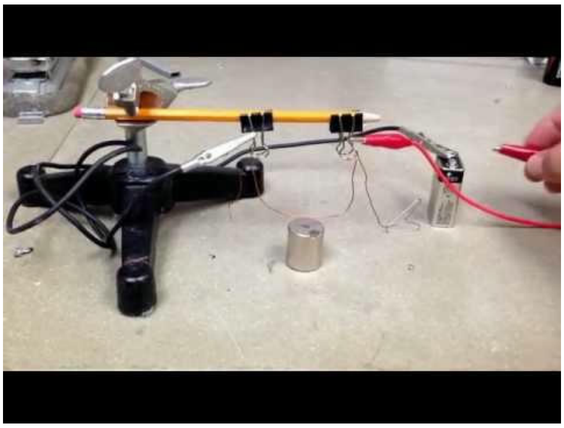


Figure 6.84: .

I is given such a value that it deflects the full width of the gap between the poles (2 cm). (In our case the current needed for that is .5A.) The force needed for such a deflection can be estimated when we know the mass of the suspended wire. (In our case: m = .032 kg, so F $= (1/40) \cdot (.032) \cdot (10) =$ 8mN. Then B will be .3(2)T).

6.7.4.3.8 Video Rhett Allain

(a)



(b)

Figure 461: :align: center - Scan the QR code or click here to go to the video.

6.7.4.3.9 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 486-487
- Young, H.D. and Freeman, R.A., University Physics, pag. 880-881

6.7.4.4 04 Parallel Wires

6.7.4.4.1 Aim

To show that parallel wires attract or repel depending on the current direction.

6.7.4.4.2 Subjects

- 5H40 (Force on Current Wires)

6.7.4.4.3 Diagram

Figure 6.88: .

6.7.4.4.4 Equipment

- Two long wires, 1.5 m each
- Power supply (we use 20 A.)
- Amp-meter
- White screen

6.7.4.4.5 Presentation

The two long wires are suspended from one clamp, close to the rigid white screen. One of the wires is also clamped at the lower end of the white screen and stretched. The second wire is hanging freely in such a way that at the lower end it is about 2 cm seperated from the fixed wire (see Diagram and Figure 2A).

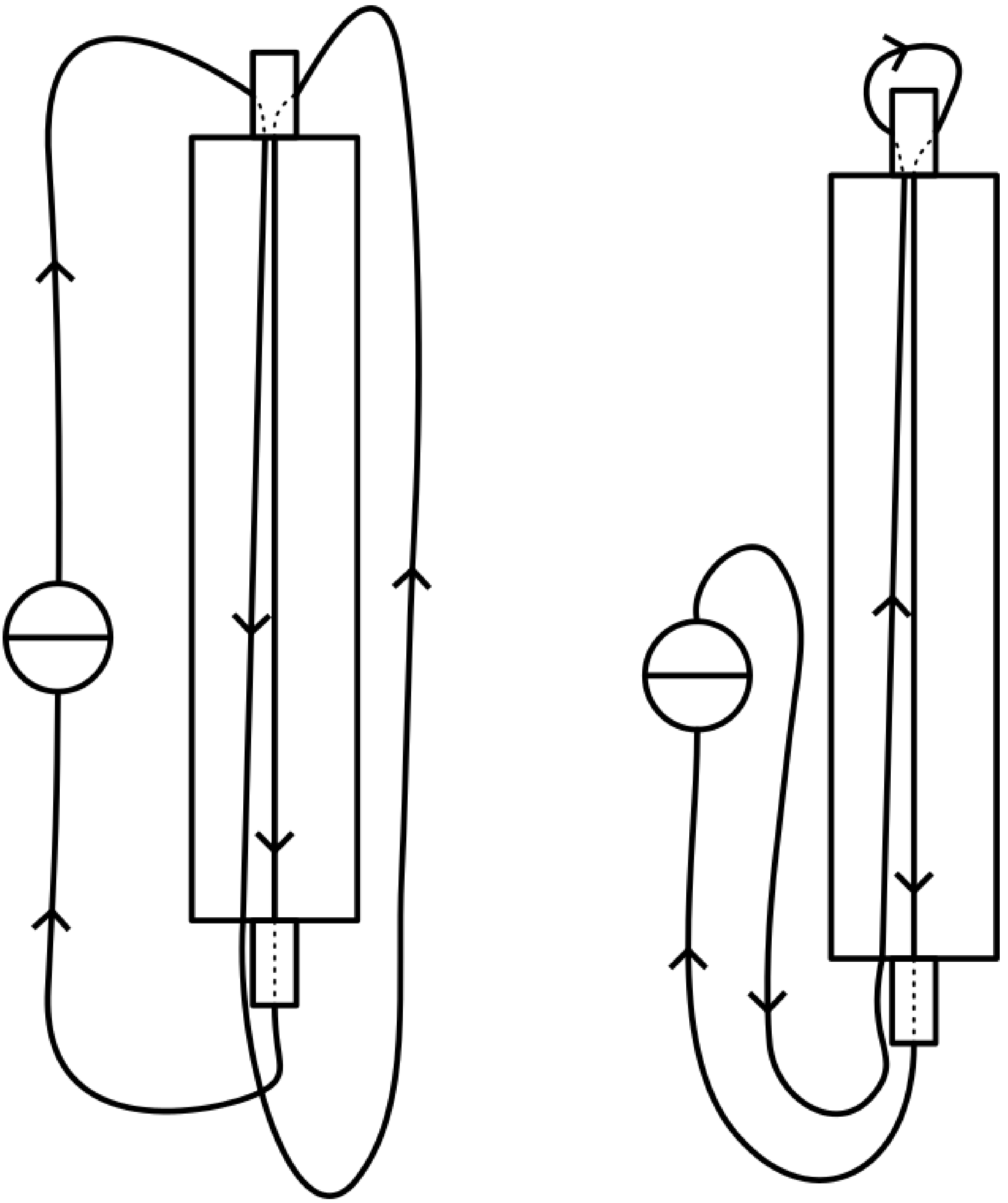


Figure 6.89: .

Parallel wires

The wiring is set up in such a way that both wires conduct the current in the same direction (Figure 2A). When switching on the current we see that the “loose” wire moves closer to the fixed wire.

Then the wiring is changed so that the two wires conduct the current in opposite directions (Figure 2B). Switching on the current now shows that the “loose” wire is moving away from the fixed wire.

6.7.4.4.6 Explanation

The magnetic induction around a current-carrying wire equals: $B(r) = \frac{\mu_0 I_1}{2\pi r}$ and is directed circularly around that wire (corkscrew). The force on a current in a magnetic field equals $F = I_2 l B(r)$ and is directed perpendicular to I_2 and $B.v_0$ being $4\pi.10^{-7}\text{Hm}^{-}$

^{1} leads to $F = 2.10^{-7}\frac{I_1 I_2 l}{r}$.

Applying the rigth-hand rule shows the direction of this force between current $I_1(B)$ and I_2 (see Figure 3).

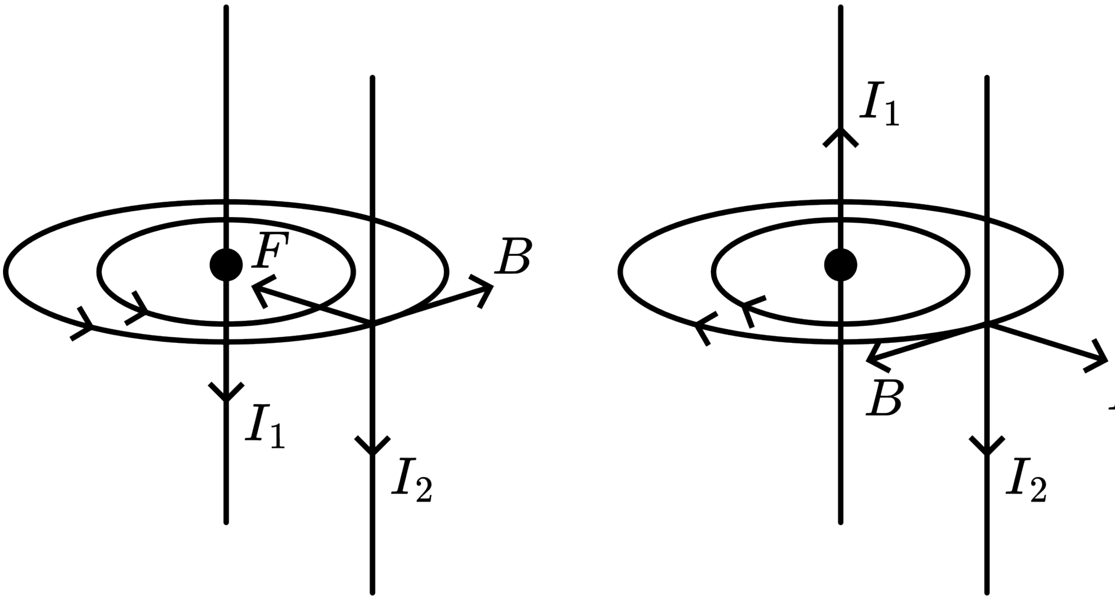


Figure 6.90: .

Calculating F for every 1 cm length of wire we find:

- at the top where the wires are separated about 3 mm : F $= 27.10^{-5}$ N/cm
- at the bottom where the wires are separated about 2 cm : F $= 4.10^{-5}$ N/cm
- and for the total length of wire: $F = 23\text{mN}$.

So, in this demonstration the force on the wires is very small.

6.7.4.4.7 Remarks

- When the effect in this demonstration is not visible enough, a video-camera with projection can be used.
- A higher current is advisable for this demonstration; the current shows itself squared in F.
- This demonstration can be used in combination with the current-balance demonstration.

6.7.4.4.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 223

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 409-410 and 486-487

6.7.5 5H50 Torques on Coils

6.7.5.1 01 Current Loop in Magnetic Field

6.7.5.1.1 Aim

To show torques and forces on a current loop in a magnetic field.

6.7.5.1.2 Subjects

- 5H50 (Torques on Coils)

6.7.5.1.3 Diagram

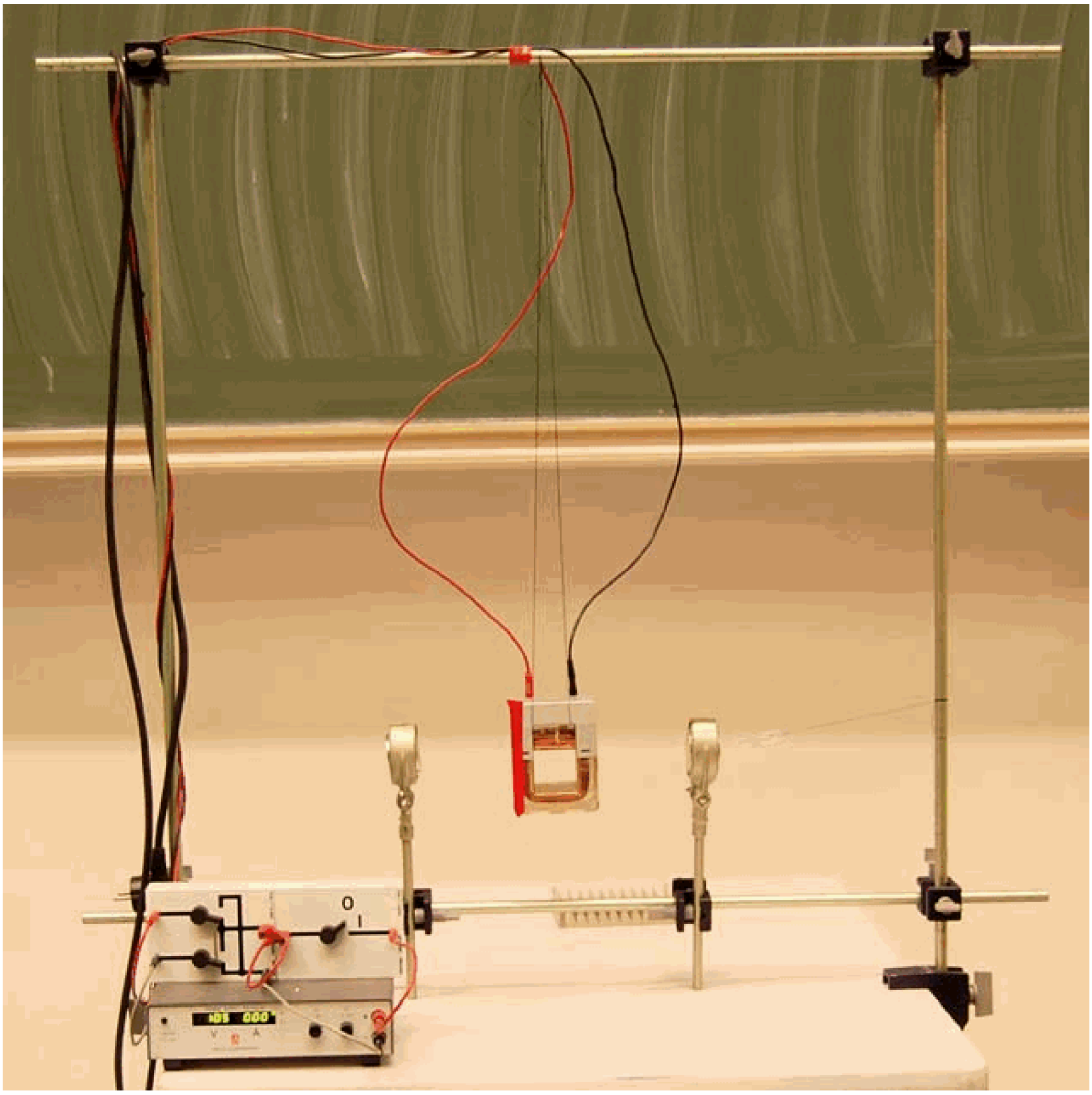


Figure 6.91: .

6.7.5.1.4 Equipment

- Two Neodymium magnets fixed in clamps.
- Coil ($n = 500$; $I_{max} = 2.5$ A) with a piece of red tape at one side. The coil is suspended by thin thread, so it can rotate easily (see Diagram).
- Power supply, 30 V/10 A.
- Switch and Two-way switch.
- Array of compass-needles.
- Paperclip (to show the presence of a magnetic field).

- Camera and screen to show the demo to a large audience.

6.7.5.1.5 Safety

- The Neodymium magnets are very strong. If these magnets are not handled carefully, there is risk of serious injury. The magnets are fixed in clamps and stored with a thick piece of sheet between them.

-Carefully slide them apart when you use them, to prevent your fingers becoming trapped between them.

-Keep them several meters away from magnetic information carriers.

-Never operate the magnets in explosive environments, since they generate sparks!

6.7.5.1.6 Presentation

Using the array of compass needles we show that there is a uniform magnetic field between the permanent magnets (see Figure 2).

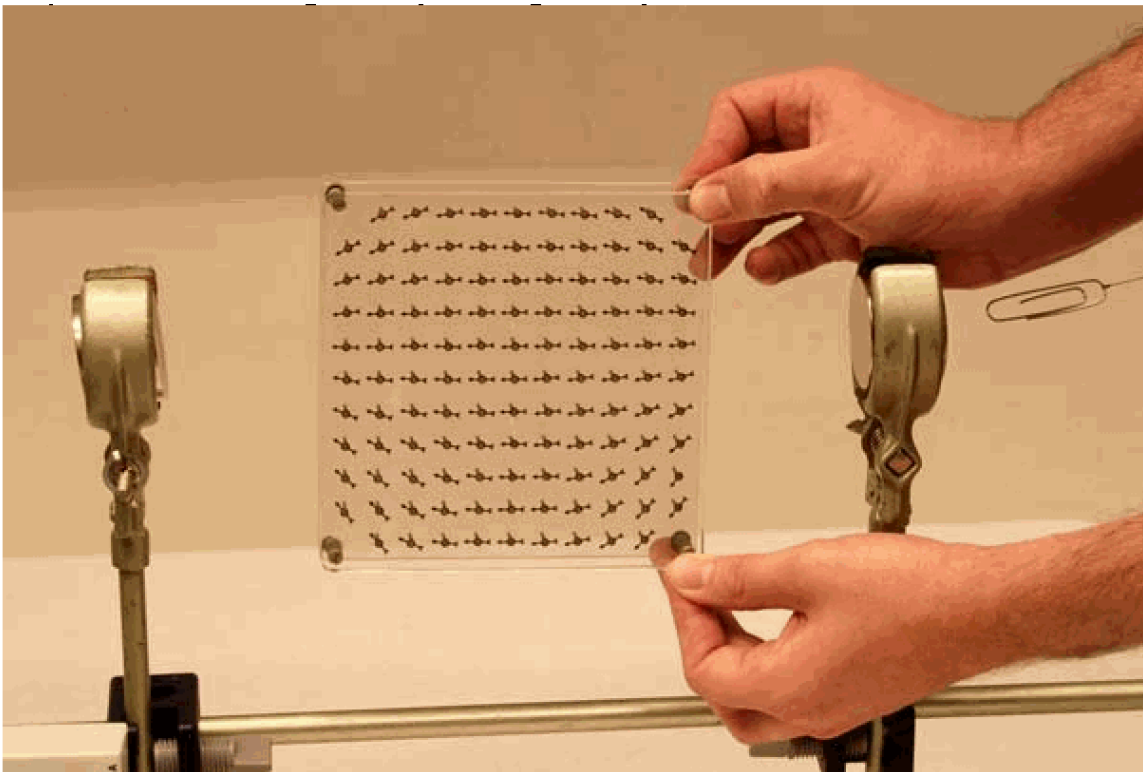


Figure 6.92: .

Close to the magnets the field is strongly divergent/convergent (see Figure 3).

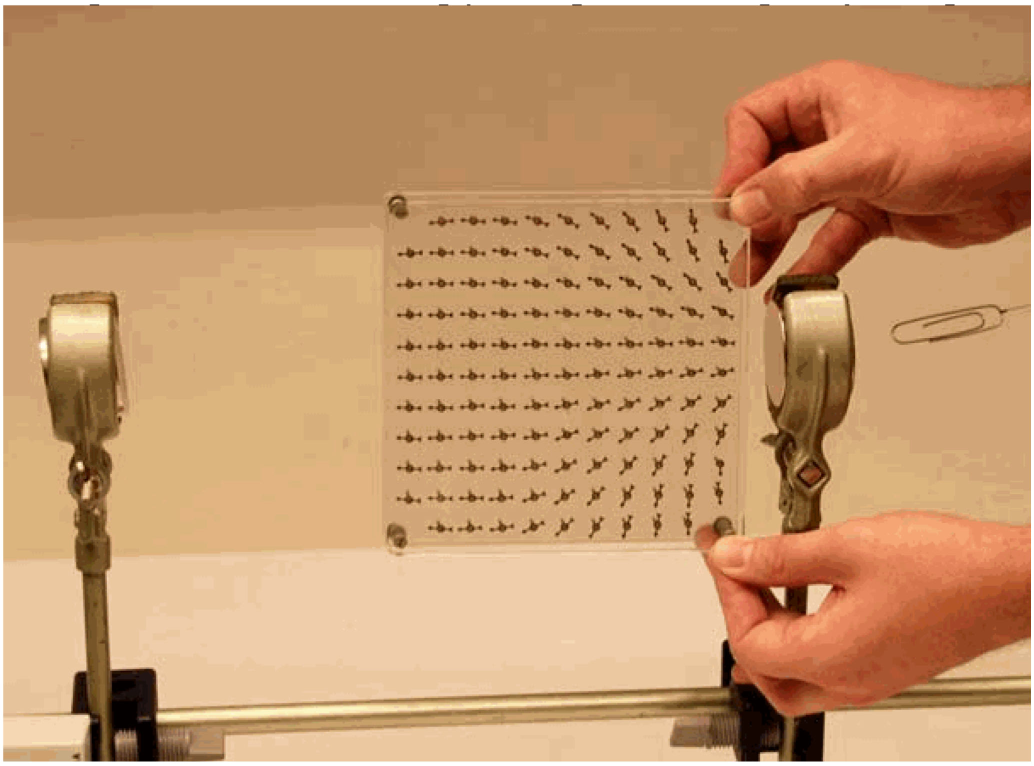


Figure 6.93: .

Then the coil is suspended between the two magnets (see Diagram). Connecting the power supply to the coil shows that the coil makes a rotation and lines up with the magnetic field (see Figure 4). There it remains at rest.

Conclusion is that in a homogeneous magnetic field a current carrying coil (a dipole) experiences a torque that lines up that dipole with the field. And in that uniform field there is no net force.

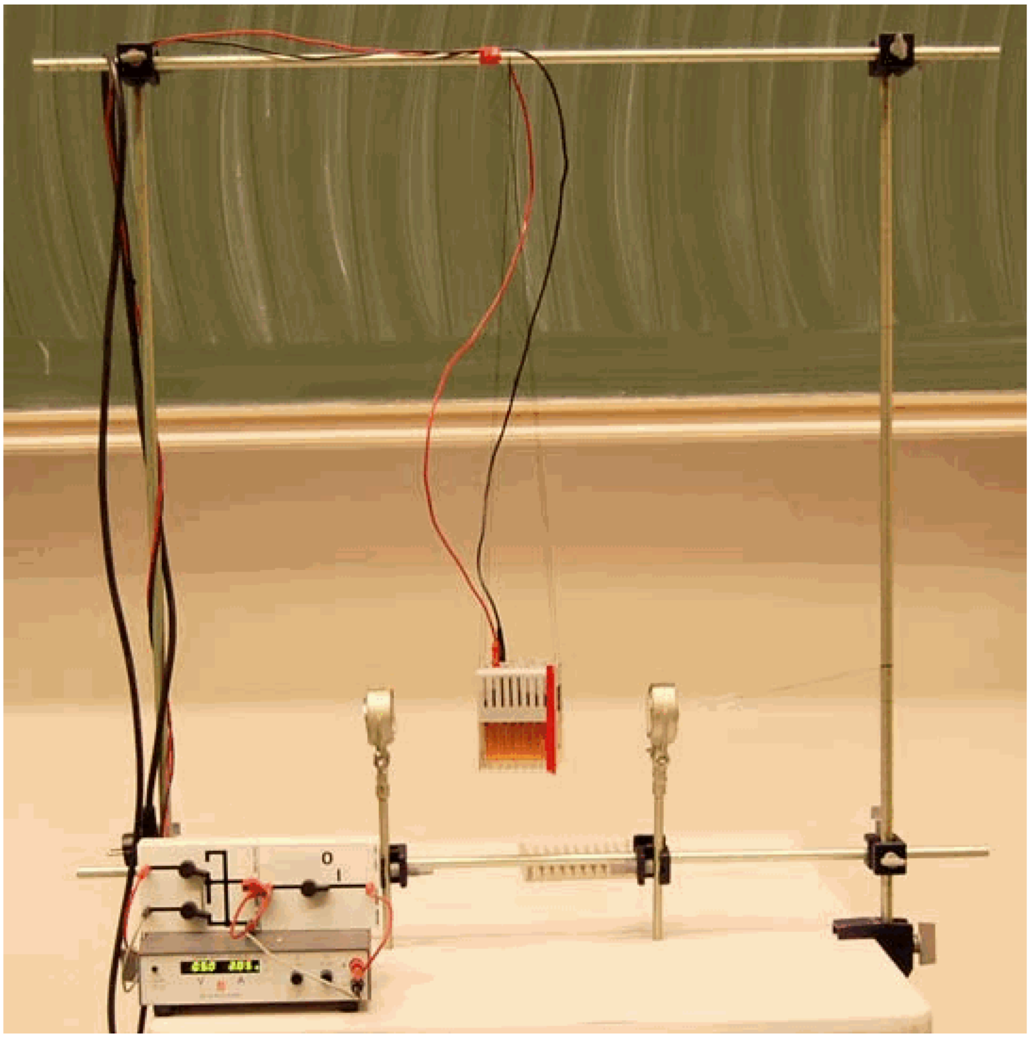


Figure 6.94: .

Then the coil is displaced a little from its central position: It attracts itself towards one of the magnets and sticks there (see Figure 5).

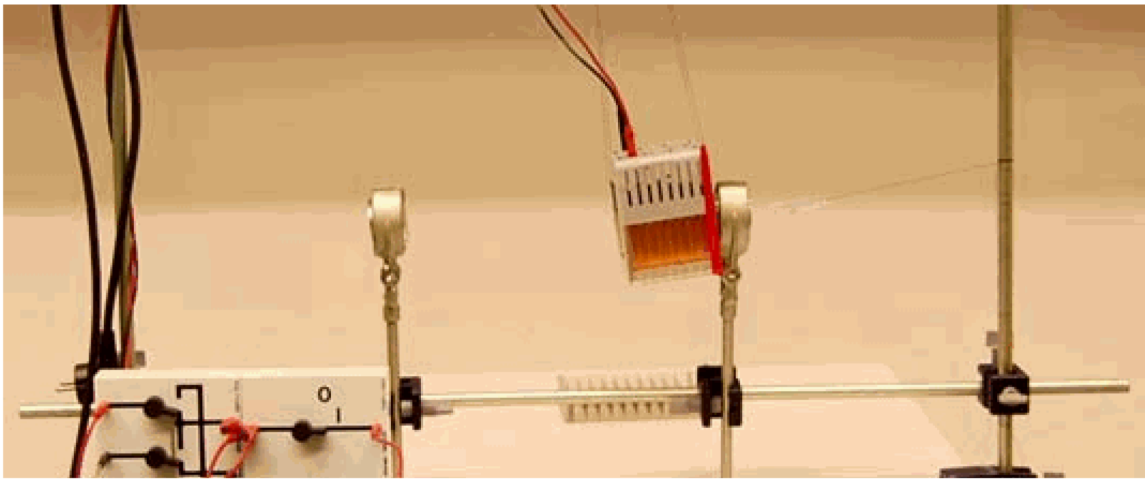


Figure 6.95: .

Conclusion is that in a non-uniform field there is a net force on a current loop (dipole).

6.7.5.1.7 Explanation

There are Lorentz-forces on all sides of the coil. The forces on the bottom- and topside of the coil cancel (they only tend to stretch the coil). The two forces on the sides are also equal and opposite but they do generate a torque $\vec{N}.\vec{N} = \vec{m} \times \vec{B}$ ($\vec{B}$ is the magnetic field and $\vec{A}$, $\vec{A}$ being the area of the current loop).

When the field is non-uniform, there is a radial component of B and there will be a net force towards the magnet (see Figure 6).

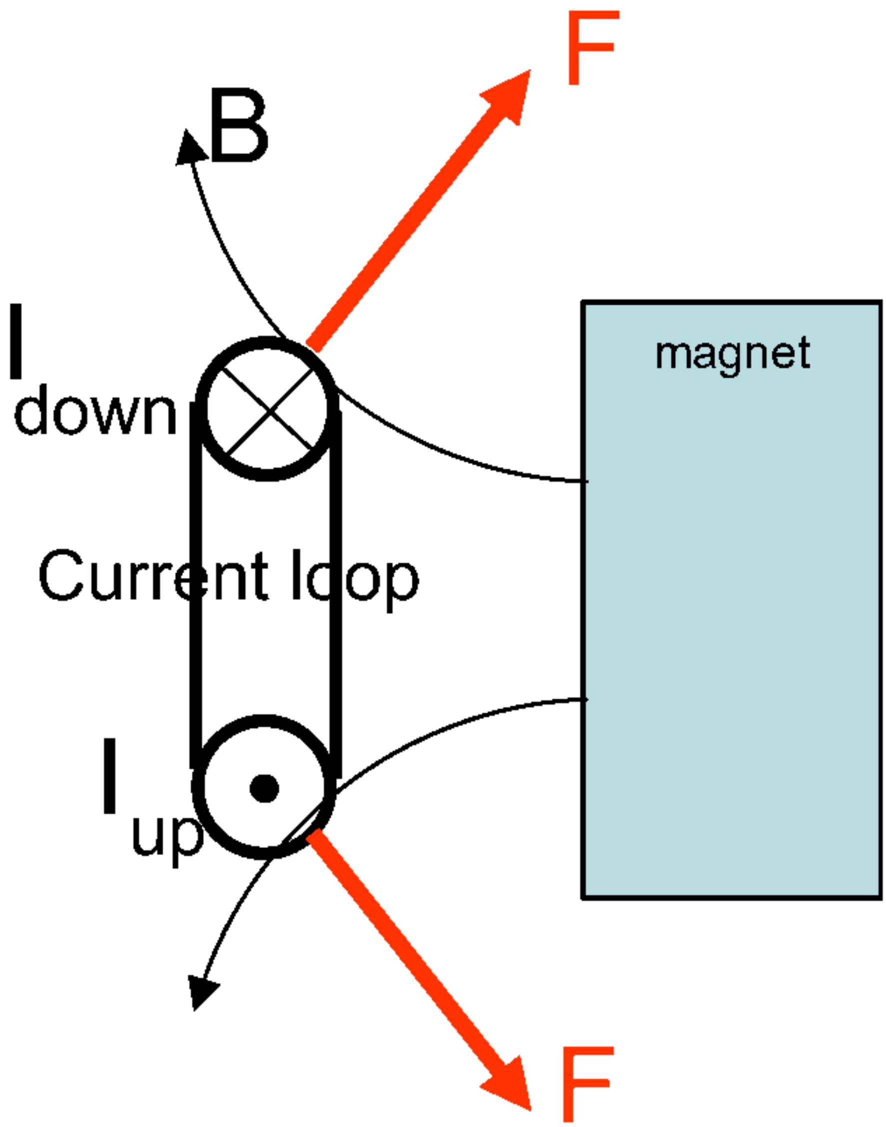


Figure 6.96: .

6.7.5.1.8 Remarks

- The lining up of a current loop in a uniform field is an example of what dipoles do in a material. So it can be used as an example to present para-magnetism.

6.7.5.1.9 Sources

- Griffiths, D.J., Introduction to Electrodynamics pag.255-258.

6.8 5J Inductance

6.8.1 5J10 Self Inductance

6.8.1.1 01 Self-Inductance in AC Circuit

6.8.1.1.1 Aim

To show how alternating current depends on the value of self-inductance.

6.8.1.1.2 Subjects

- 5J10 (Self Inductance) 5L20 (LCR Circuits – AC)

6.8.1.1.3 Diagram

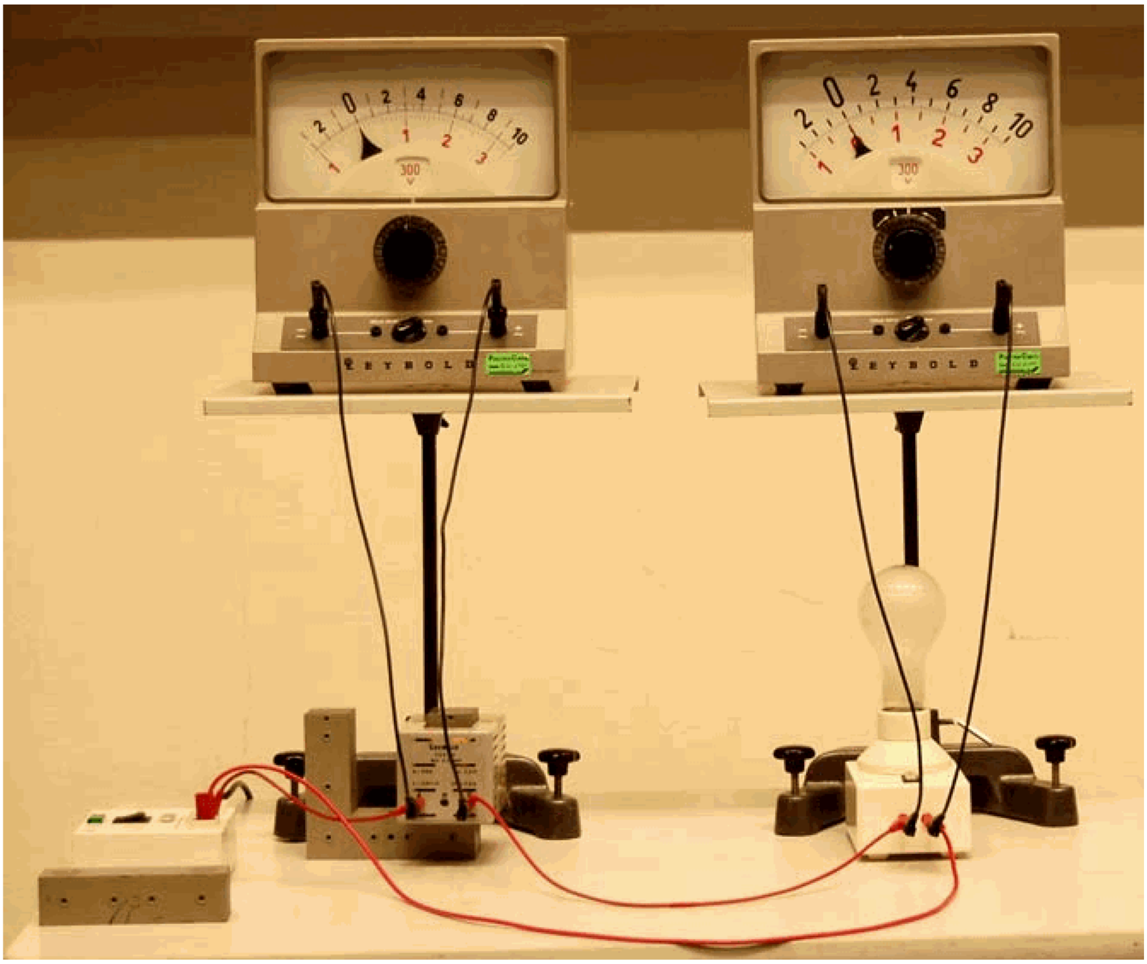


Figure 6.97: .

6.8.1.1.4 Equipment

- Lamp, 220 V/200 W.
- Coil, $n = 500$; $R = 2.5\Omega$.
- U-core with bar.
- 2 Demonstration meters.
- Safety connection box .
- Measuring junction box (See Figure 5).
- Net-adapter for mobile telephone (or other appliance).

6.8.1.1.5 Safety

- It's a circuit connected to mains voltage (220 V/50 Hz). That's why we use a safety connection box. This box shows a green light when the mains is disconnected and a red light when the mains is connected. Self-inductance in AC-circuit

6.8.1.1.6 Presentation

The circuit is build as shown in Figure 2 and in Diagram. First we show the circuit setup to the students and then connect the two Voltmeters.

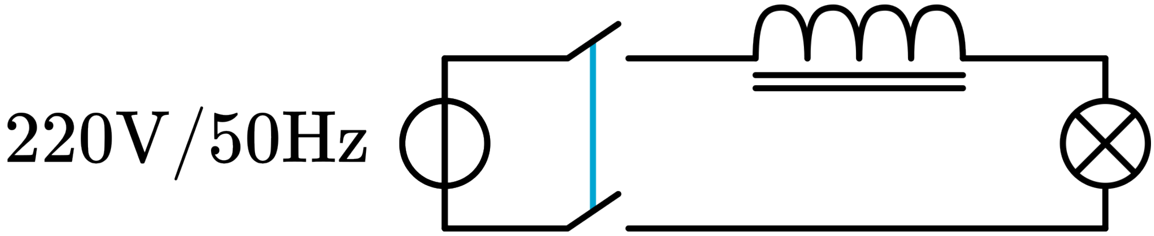


Figure 6.98: .

1. Connecting the 220 V to the circuit makes the lamp glows strongly (see Figure 3A). The Voltmeter connected to the lamp reads almost 220 V : All voltage appears across the lamp; just a very little voltage is read across the coil.

Conclusion is that only a very small emf of self-inductance is generated in the coil.

1. The bar is partly shifted on to the U-core. As soon as the bar touches the second leg of the U-core the lamp dims (see figure $2B$). the Voltmeter across the lamp shows a lower voltage now and at the same time we observe an increase in voltage across the coil.

Conclusion is that there is now a higher emf of self-inductance that opposes the 220 V.

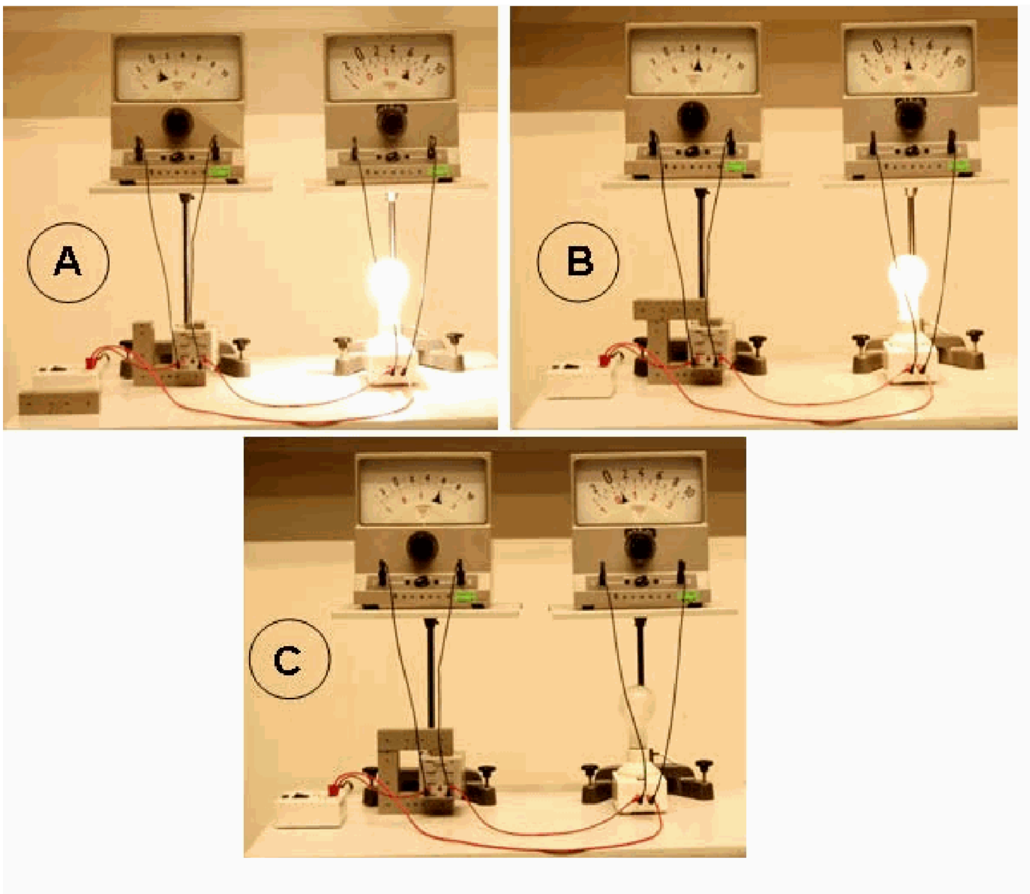


Figure 6.99: .

3. When the bar is shifted completely on to the U-core, the lamp only glows very faintly. The voltage read across it is very low. The voltage across the coil is almost 220 V now!

Conclusion is that the emf of self-inductance generated in the coil is almost 220 V now.

Shifting the bar back and forth across the U-core makes the lamp dim less or more.
3. Finally we disconnect the lamp. Now only the self-inductance is connected to the 220 V (see Figure 4).

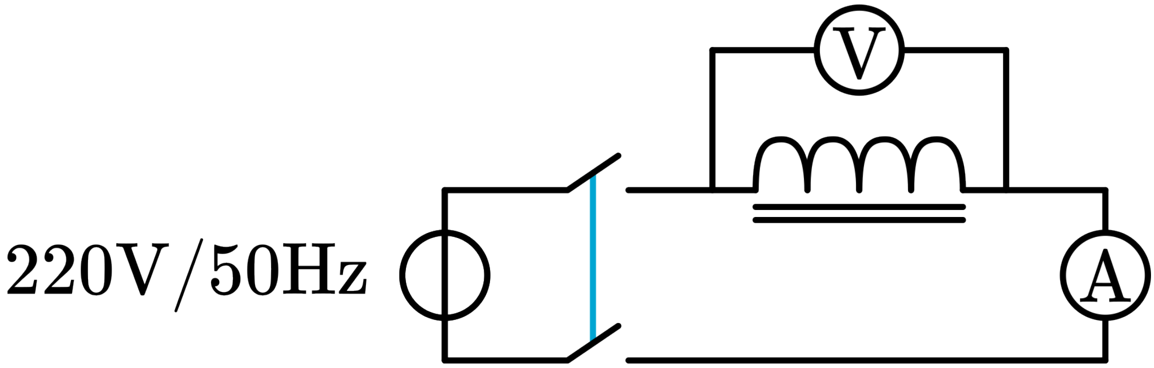


Figure 6.100: .

Now the effect of self-inductance is most clear: the voltmeter reads 220 V across the coil, and only a small current is flowing (we measure 0.4 A). When there would be no self-inductance, the current would be 220 V$/2.5\Omega = 88$ A !

Conclusion is that the emf of self-inductance really opposes the applied voltage. 5. The same demonstration is performed with a commercial net-adapter (used as charger for a mobile telephone; see Figure 5). Here also only the primary coil of the adapter is connected to the mains. We read a current of only 0.3 mA!

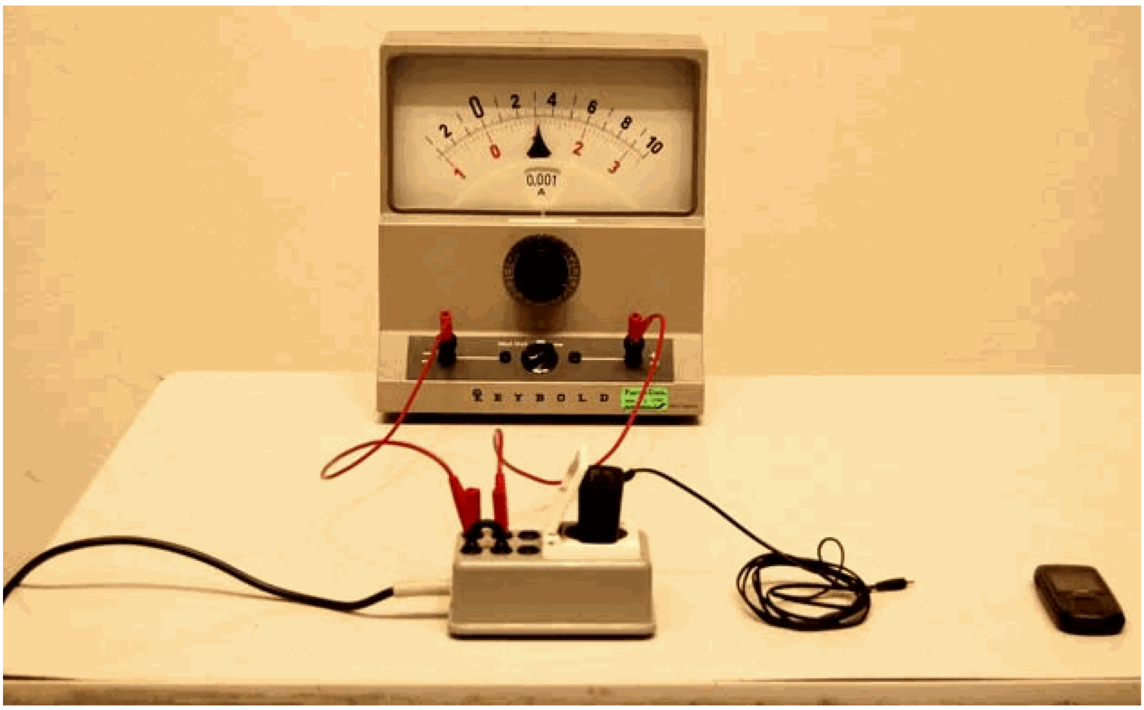


Figure 6.101: .

6.8.1.1.7 Explanation

The emf induced in a coil is, from Faraday's law: $E = -N\frac{d\Phi_B}{dt} = -L\frac{dI}{dt}$; L being the coefficient of self-inductance. For a solenoid with a core (μ_r) this is:

$L = \frac{\mu_r \mu_0 N^2 A}{l} L = \frac{\mu_r \mu_0 N^2 A}{l}$. This shows that the higher L, the higher the emf of self-inductance. Shifting the bar across the core changes L, and so the induced emf.

6.8.1.1.8 Remarks

- The core on the bar makes a lot of noise. This is a 100 Hz mains hum due to the mains frequency (50 Hz).
- The effect of self-inductance can also be translated into impedance of the circuit. In our demonstration 4. the circuit shows an impedance of $220\ \text{V}/0.4\ \text{A} = 550\Omega$ instead of the 2.5Ω of the copper coil.
- In figure B we read $V_{coil} = 130$ V and $V_{lamp} = 110$ V. Students easily read this as a total of 240 V, so higher than the applied 220 V. Phase-shift between these two voltages is responsible for that. The situation must be something like Figure 6 below shows.

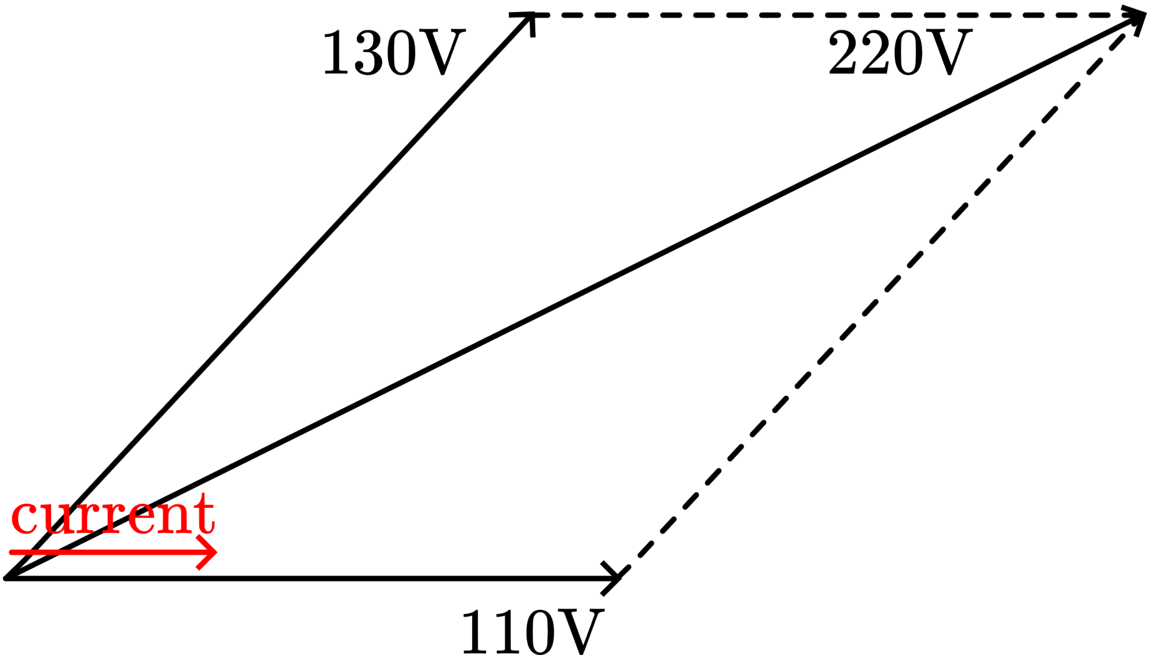


Figure 6.102: .

6.8.1.1.9 Video Rhett Allain

(a)

(b)

Figure 477: Video embedded from - Scan the QR code or click here to go to the video.

6.8.1.1.10 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 758-759 and 773-774.
- Wolfson, R., Essential University Physics, pag. 474-477 and 491-492. 110V

6.9 5K Electromagnetic Induction

6.9.1 5K10 Induced Currents and Forces

6.9.1.1 02 Damped Galvanometer

6.9.1.1.1 Aim

To show various modes of damping (under-, critical- and overdamping)

6.9.1.1.2 Subjects

- 3A50 (Damped Oscillators) 5K10 (Induced Currents and Forces)

6.9.1.1.3 Diagram

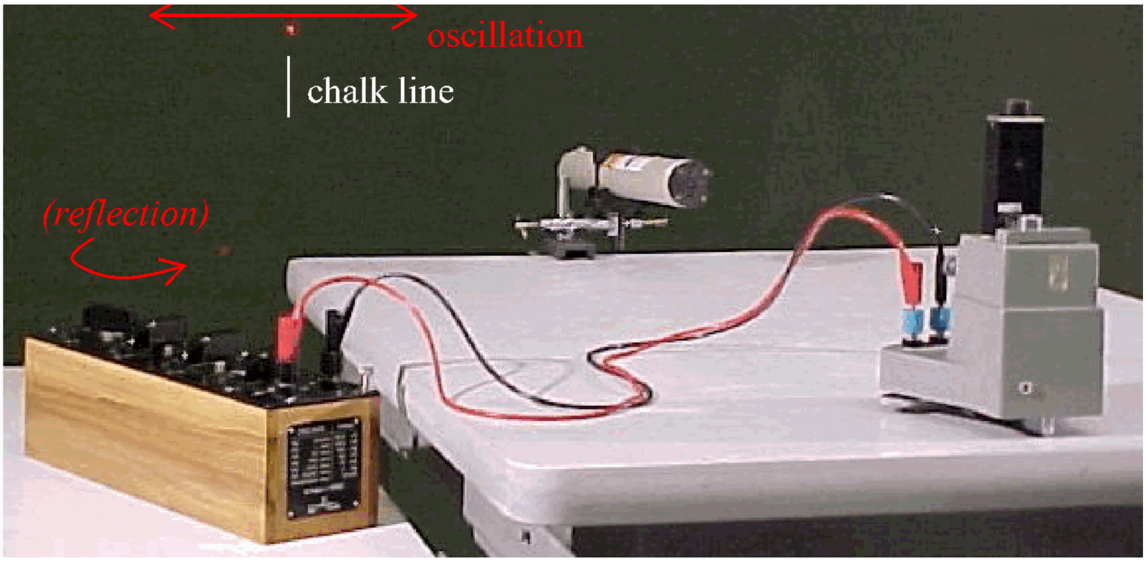


Figure 6.106: .

6.9.1.1.4 Equipment

- Lightspot galvanometer
- Resistance-box (10 kΩ)
- Laser
- Stopwatch
- (Torsionwire model, see Figure 3).

6.9.1.1.5 Presentation

Galvanometer and laser are positioned in such a way that, in the neutral position of the galvanometer, the reflected laser beam is projected on the blackboard behind the laser (see Figure 2). This neutral position is chalk-marked on the blackboard.

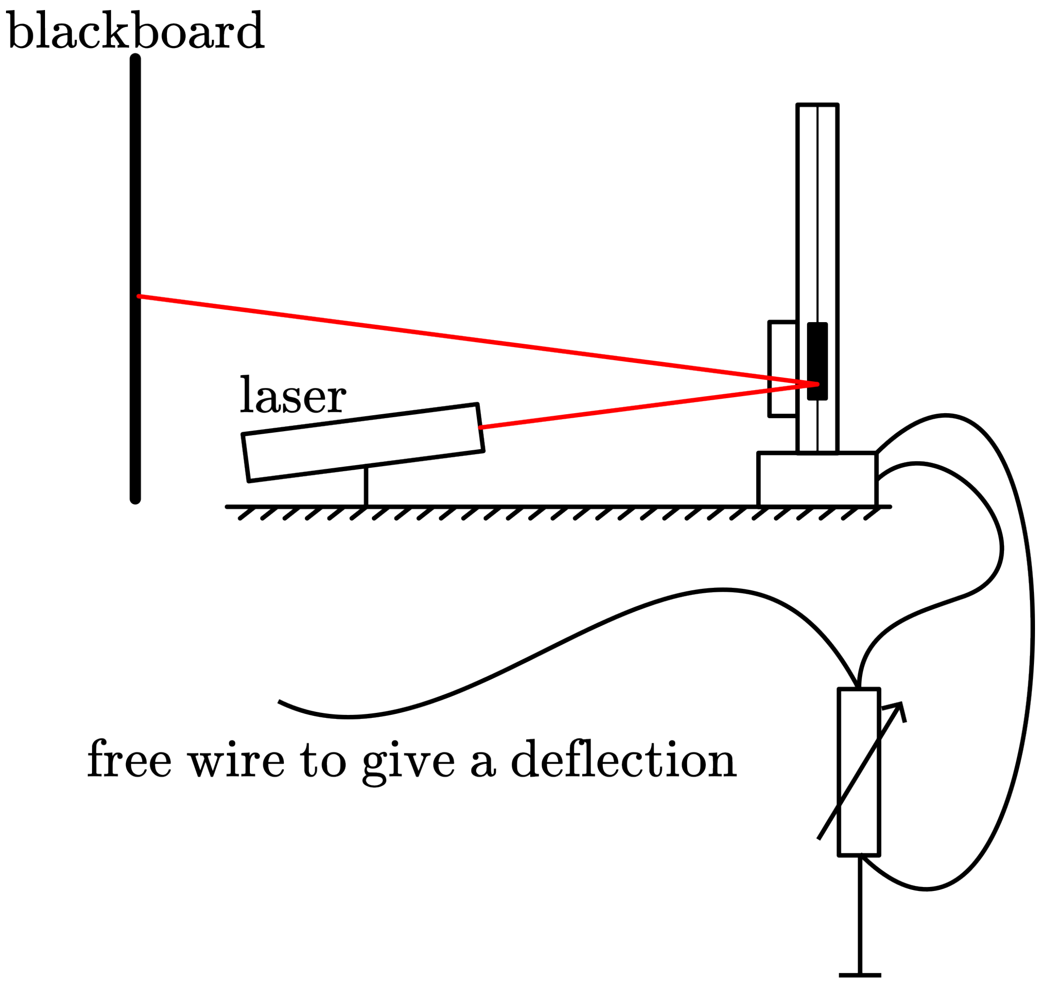


Figure 6.107: .

Now the suspension system of the galvanometer is given a deflection by just touching the leads to the galvanometer with your hands. (Charge on your body usually suffices to make the galvanometer deflect.) The movement of the lightspot on the blackboard shows the free oscillation of the galvanometer-mirror-suspension system. After some oscillations the system comes to rest again. The movement is a damped harmonic motion.

Now the resistance box is connected to the galvanometer (after it has been given a deflection again). The oscillation is observed and the difference in damping, compared to the first situation, is clear. The experiment is repeated with 10 kΩ, 6 kΩ and 1 kΩ. We have critical damping using 6 kΩ and 1 kΩ gives very clear overdamping. Overdamping can be made extreme when the leads are shorted (0Ω).

- Make the students notice that 'critical damping' means 'reaching equilibrium (the chalk mark) in the shortest time'
- When using a stopwatch, it is possible to measure period-times, in order to show the influence of damping on the frequency of the oscillations.

6.9.1.1.6 Explanation

Textbooks give a lot of information about damped harmonic motion. Usually the description is about a simple one dimensional mass-spring system.

The galvanometer-system in our demonstration is a torsion pendulum in which a coil is suspended from a wire. The analysis of such a torsion pendulum can be done analog to that of a mass-spring system.

When the torsion pendulum is twisted an angle θ there will be a torque (τ) that tries to undo the twisting: $\tau = -\kappa\theta$. (κ is the torsion constant.) The equation of motion will be:

$I\ddot{\theta} = -\kappa\theta$ or

$I\ddot{\theta} + \kappa\theta = 0$.

The motion will be a harmonic oscillation with $\omega^2 = \kappa/I$ (/ is the rotational inertia). The coil of the galvanometer oscillates in a radial magnetic field and an emf will be induced. The coil is connected to a resistor and a current will flow. A Lorentz force results, giving a torque that counteracts the movement that produces the induction (Lenz's law) and so this torque will be a damping torque. This damping torque (τ_d) is directly proportional to the angular velocity (like the counter torque in an electric generator): $\tau_d = -r\dot{\theta}$, and now the dynamic equation of motion will be:

$I\ddot{\theta} + r\dot{\theta} + \kappa\theta = 0$ (there is no driving torque).

The demonstration shows a (co)sine-like motion that is multiplied by a factor that decreases in time.

A solution of this differential equation is:

$\theta = \Theta e^{-\alpha t} \cos \omega t$,

where $\Theta = \theta$ at $t = 0, \alpha = \frac{r}{2I}$, and $\omega^2 = \frac{\kappa}{I} - \left(\frac{r}{2I}\right)^2$.

$\alpha = \frac{r}{2I}$ is a measure of how quickly the oscillations decrease towards zero. The

larger r, the more quickly the oscillations die away. Three cases of damping are distinguished:

Overdamping when $r^2 >> 4I\kappa$,

Underdamping when $r^2 < 4I\kappa$ and

Critical damping when $r^2 = 4I\kappa$. Then equilibrium is reached in the shortest time. r is changed, when the value of the external resistance is changed, as seen in the Presentation.

$\omega^2 = \frac{\kappa}{I} - \left(\frac{r}{2I}\right)^2$ shows that ω has a lower value than in the undamped situation. ω

6.9.1.1.7 Remarks

- When the students have not seen a torsionwire system before, such a system is shortly explained to them using a large scale model (a piece of rope, having a rectangular sheet of metal and a small coil, taped to it. See Figure 3.)

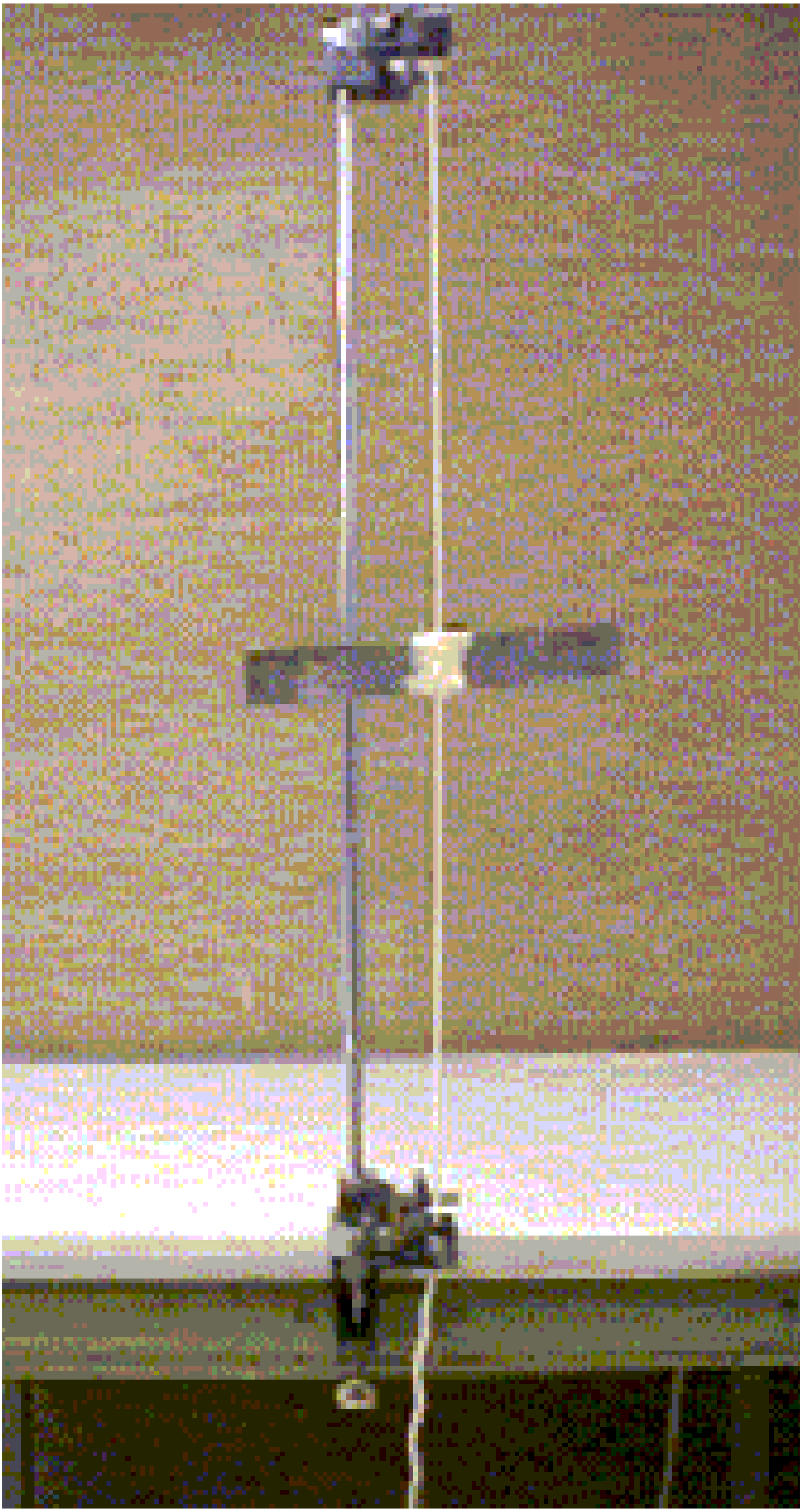


Figure 6.108: .

- The resistance-box is placed on a separate table, so that manipulating the box will not disturb the very sensitive galvanometer.
- There are three laser spots visible on the blackboard. The first is a reflection of the front glass of the housing of the galvanometer (a fixed spot). The second is the reflection of the mirror (that's the one we use in the demonstration). The third is a second reflection of the mirror (the first reflection of the mirror reflects partially on the inside of the front glass of the housing) and so shows a double deflection compared to the second spot.

6.9.1.1.8 Sources

- Borghouts, A.N., Inleiding in de Mechanica, pag. 264
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 99-101
- Roest, R., Inleiding Mechanica, pag. 269
- Young, H.D. and Freeman, R.A., University Physics, pag. 411
- Alonso, M/Finn, E. J., Fundamentele Natuurkunde, part 1, Mechanica, pag. 278
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 374-376

6.9.1.2 02 Skipping Rope

6.9.1.2.1 Aim

To show that in a skipping rope an electric voltage is induced. (The strength of the Earth's magnetic field can be determined.)

6.9.1.2.2 Subjects

- 5K10 (Induced Currents and Forces)

6.9.1.2.3 Diagram

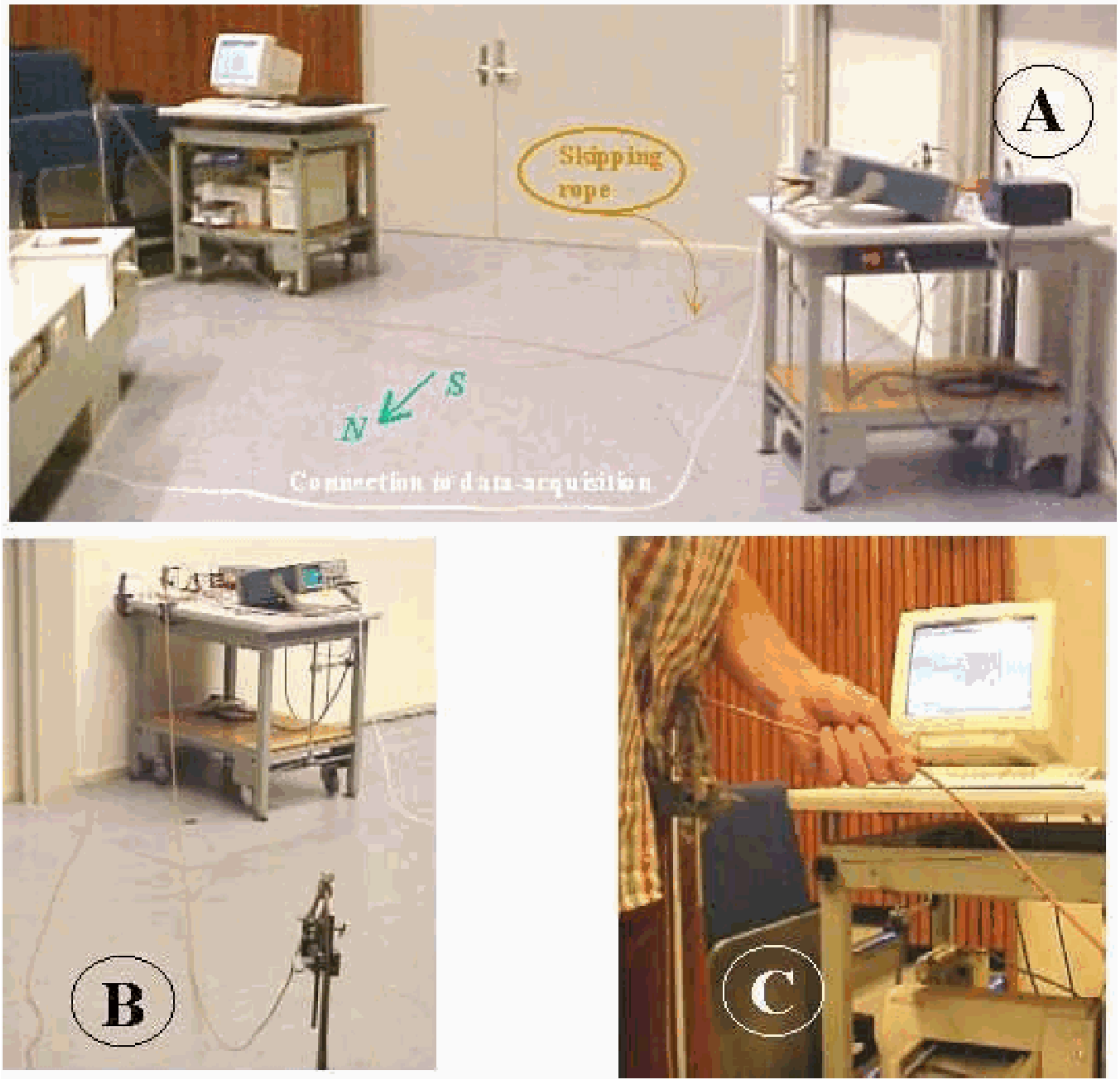


Figure 6.109: .

6.9.1.2.4 Equipment

- Compass needle.
- Skipping rope; 10 m of a heavy flexible insulated copper wire.
- Overheadsheet with drawing of skipping rope catenary, to determine area.
- Operational amplifier, amplification factor = 1000.
- Oscilloscope.
- Data-acquisition system .
- Projector to project monitor image.

6.9.1.2.5 Presentation

The compass needle is placed on the overheadprojector to indicate the North-South direction in the lecturehall.

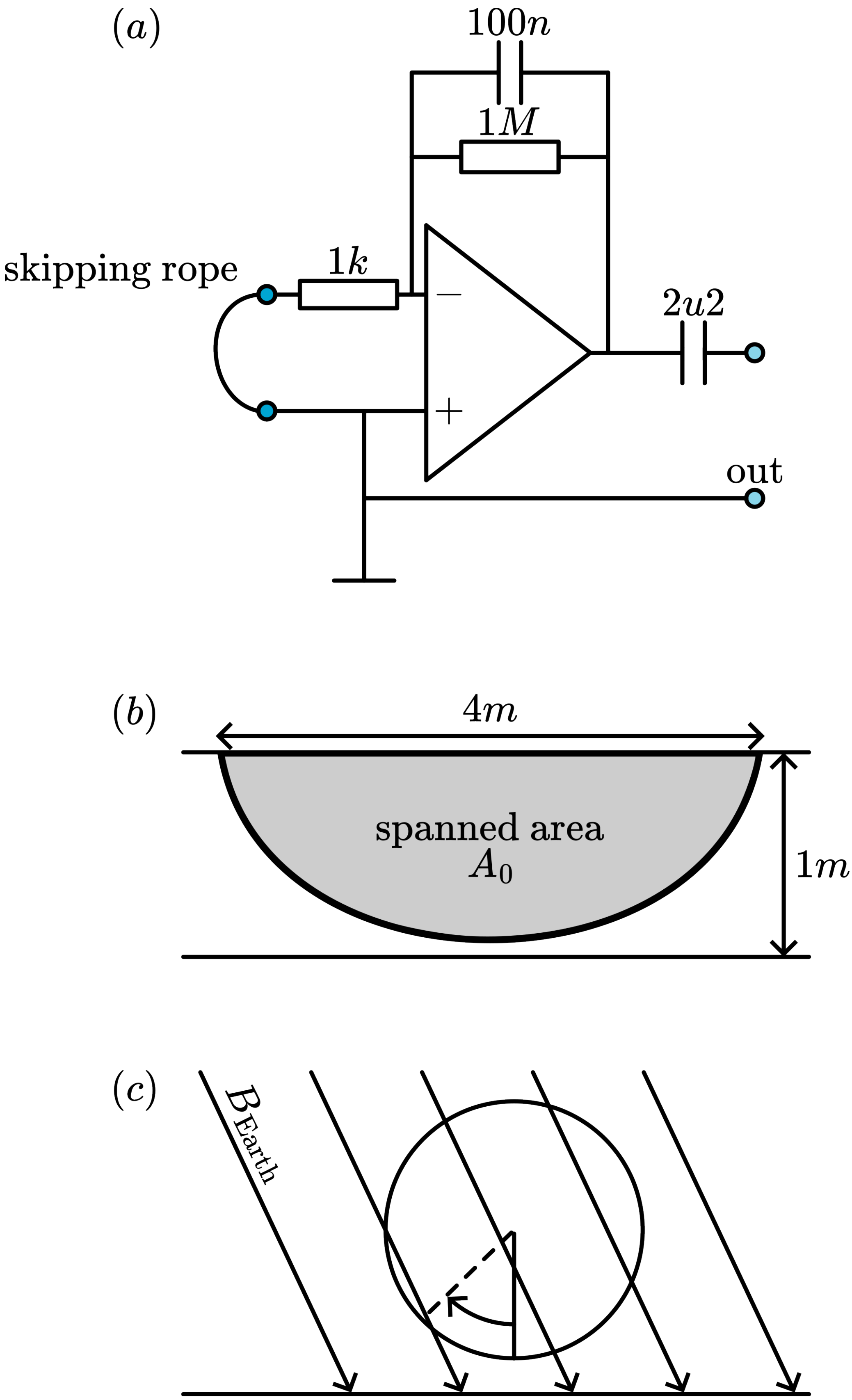


Figure 6.110: .

The demonstration is set up as shown in Diagram, and positioned so that the axis of rotation of the skipping rope is perpendicular to the indicated N-S direction (see Diagram A). The skipping rope is connected to the operational amplifier circuit (see Figure 2A). The output of the amplifier is connected to the oscilloscope, having a slowly moving time-base (.1sec/DIV).

The skipping rope is set in rotation (see Diagram C) and the moving spot on the oscilloscope screen is seen to move up and down, showing positive - and negative induced voltages. When the skipping rope is speeded up the amplitude of the induced voltage increases.

In order to observe the induced voltage more in detail, the output is also connected to the interface of the data-acquisition system. A voltage-time graph is displayed to the students and they observe the registration of the (1000 times amplified) induced voltage while the skipping rope is making about 15 full turns, some slow, some fast (see Figure 3). Clearly the sinusoidal shape of the induced voltage can be observed.

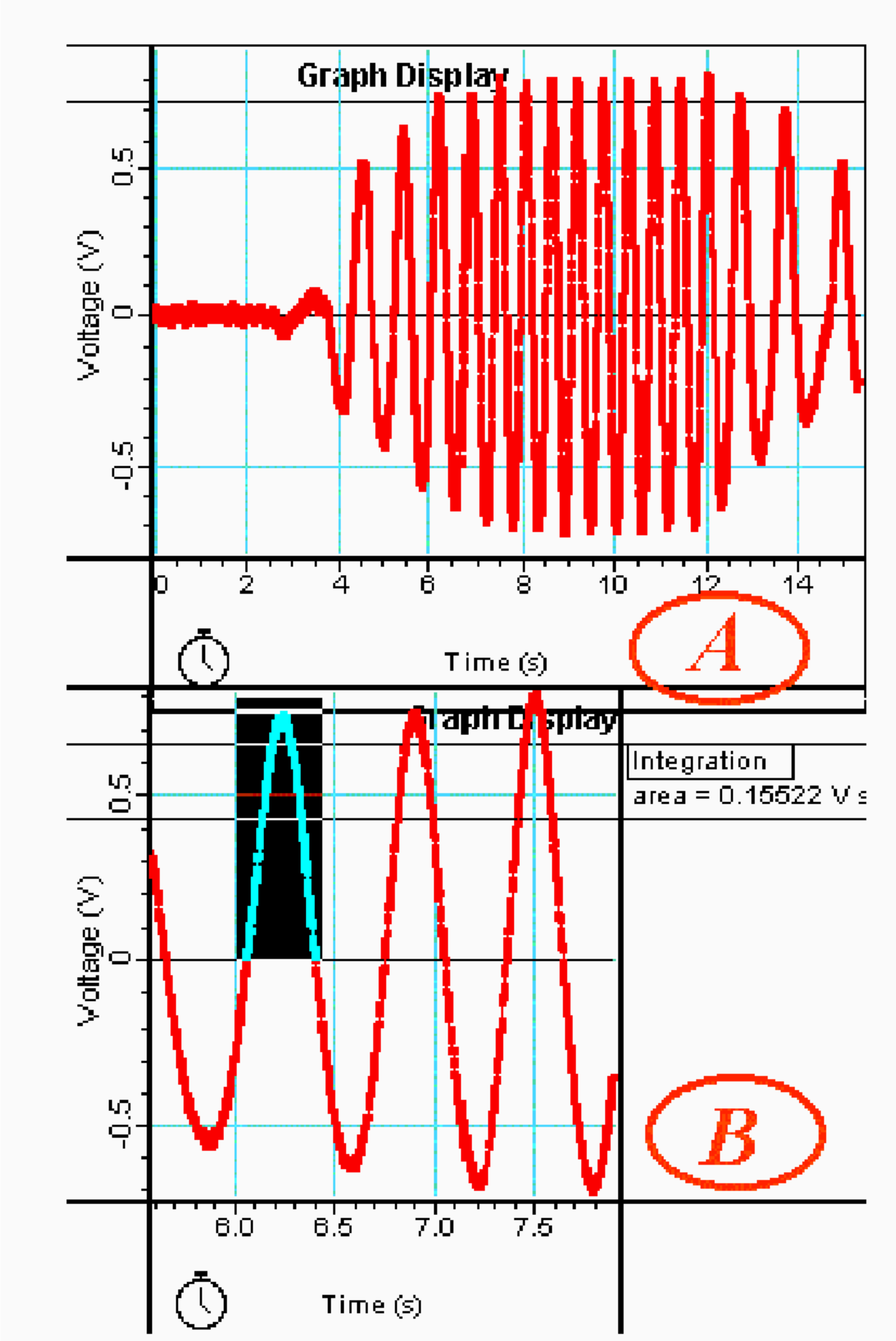


Figure 6.111: .

Finally, a part of the graph with a full cycle is selected and by means of the graph features in the statistics software the integration of a selected one half of a sine is determined (see Figure 3B). We read 0.155 V. Applying Faraday's induction law and estimating the area of the skipping rope (use the overheadsheet), we find for the Earth's magnetic field $B_0 = 28UT$ (see Explanation). This is good enough (good enough for a demonstration) when compared with values given in literature.

6.9.1.2.6 Explanation

The induced voltage (E) is given by Faraday's induction law as $E(t) = B_0 \frac{dA}{dt}. B_0$ is the magnetic flux density; A is the area spanned by the skipping rope and its rotational axis. The plane of the skipping rope changes as $A = A_0 \cos \omega t$ (see Figure 2C), so $\frac{dA}{dt} = -A_0 \sin \omega t$, and $E(t) = B_0 A_0 \omega \sin \omega t$: the induced voltage (E) changes sinusoidally as the registered graph shows convincingly.

An interesting quantity is $\int E(t)dt$ (voltage surge, or voltage impulse, in units [Vs]). We will use this quantity to determine the Earth's magnetic field.

From Faraday's induction law: $E(t)dt = -B_0 dA$ and $\frac{dA}{dt} = -A_0 \omega \sin \omega t$, we get:

$\int E(t)dt = -B_0 A_0 \omega \int \sin \omega t dt$. When we look at one half of a full cycle, we have:

$\int E(t)dt = -B_0 A_0 \cos (\omega t)_0^{\pi} = 2B_0 A_0$. From Figure 3B we read $\int E(t)dt$ equals

$0, 155$ V. Figure 2B is used to estimate the area A_o of the catenary of the suspended skipping rope. With the dimensions given, we estimate a little less than 3 m^2, so let us say 2.8 m^2. With these numbers we find for the Earth's magnetic field: $B_0 = 28UT$.

6.9.1.2.7 Remarks

- In the operational amplifier circuit the 100nF capacitor is needed to reduce the noise of the mains. The $2, 2$uF capacitor is applied to block the dc-offset that is usually present at the output of such amplifiers.
- The table with amplifier and oscilloscope has to stand firmly on the ground (see DiagramB), because rotating the rope gives forceful jerks to that table.
- The registered induced voltage is not really symmetrical (see Figure 3) this is due to the way of turning such a skipping rope: at each cycle you give a kind of jerk when swinging the rope upwards, so in its cycle the angular speed is not really constant.
- During the first run, when registering the voltage-time graph, we make the statistics software indicate the mean y-value (voltage). In that way it is seen that the first and last not so beautiful movement of the skipping rope has not really a significant influence on our further measurements.

6.9.1.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 514-515 and 524-525
- The Physics Teacher, pag. Vol.41, nr.5, pp295-297

6.9.2 5K20 Eddy Currents

6.9.2.1 01 Arago's Compass Needle

6.9.2.1.1 Aim

To show the historic experiment of Arago on eddy currents.

6.9.2.1.2 Subjects

- 5K20 (Eddy Currents)

6.9.2.1.3 Diagram

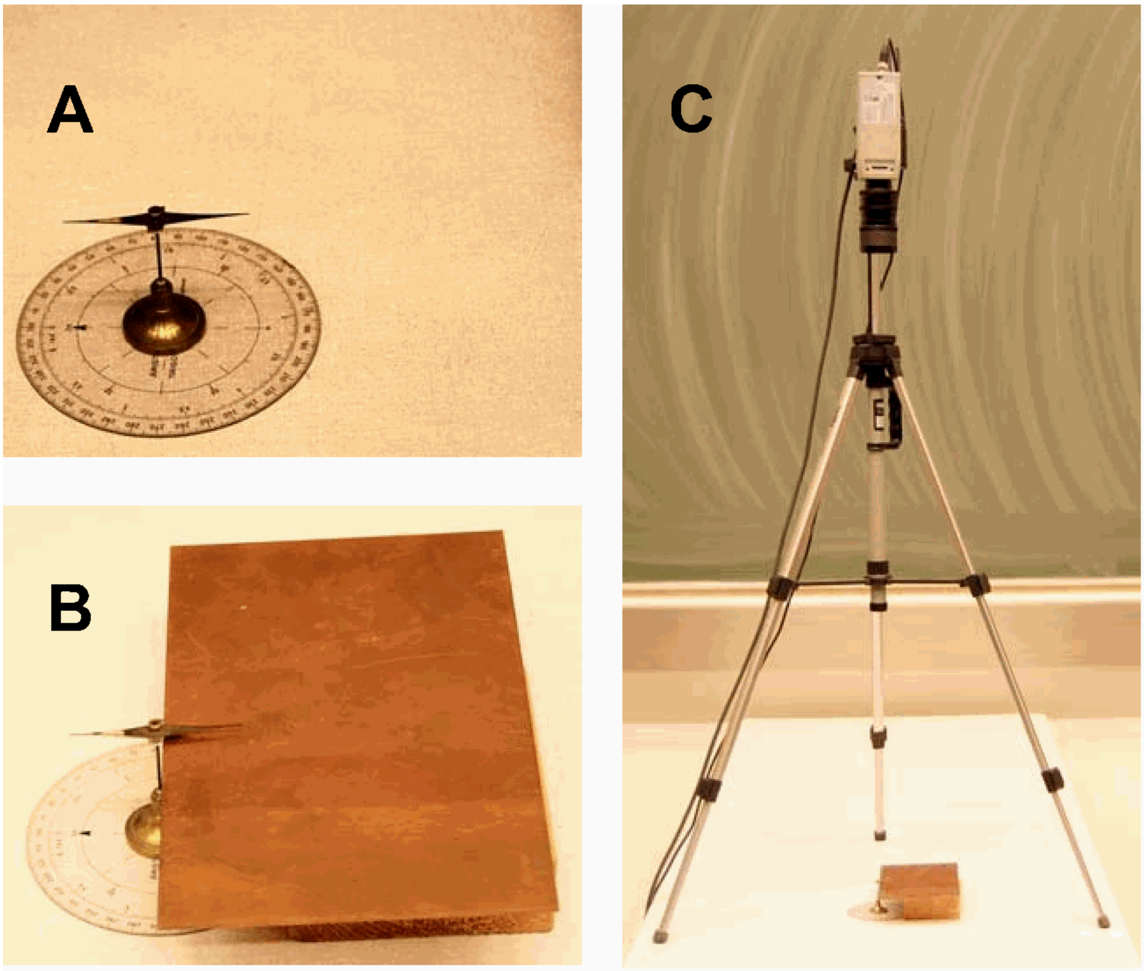


Figure 6.112: .

6.9.2.1.4 Equipment

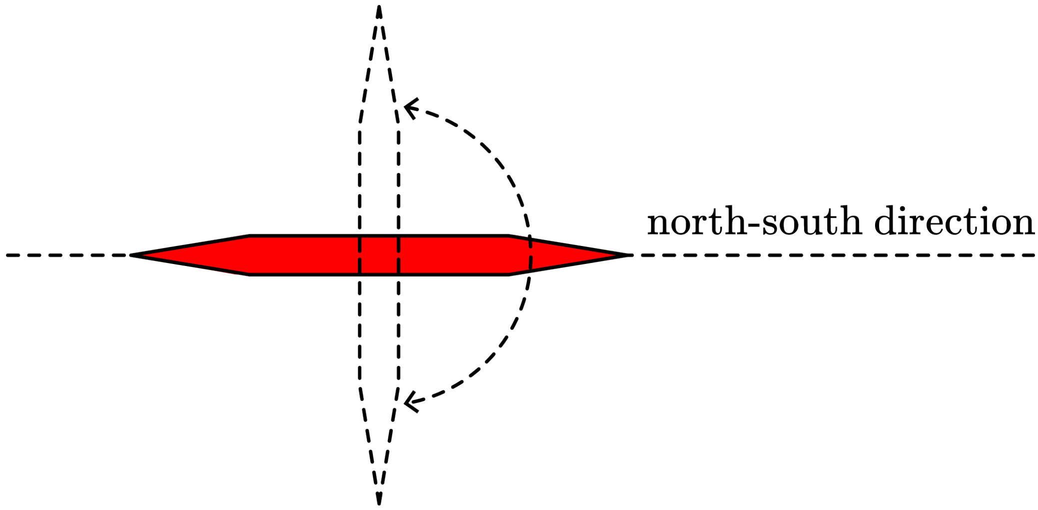
- Compass needle on needle point support.
- Copper sheet 12×20 cm^2, supported by a wooden block
- Graduated arc (optional).
- Camera on tripod.

Warning

The needle point support is very sharp!

6.9.2.1.5 Presentation

A top-view image of the compass-needle is presented to the audience (see Figure 2).



It is standing still, pointing in the magnetic North-South direction. By hand we deflect the needle 90°. Then let it go. The needle swings quite some time before it comes to a rest again. We count around 30 complete swings in total.

Then the copper sheet is shifted close under the magnetic needle (see Diagram B and Figure 3).

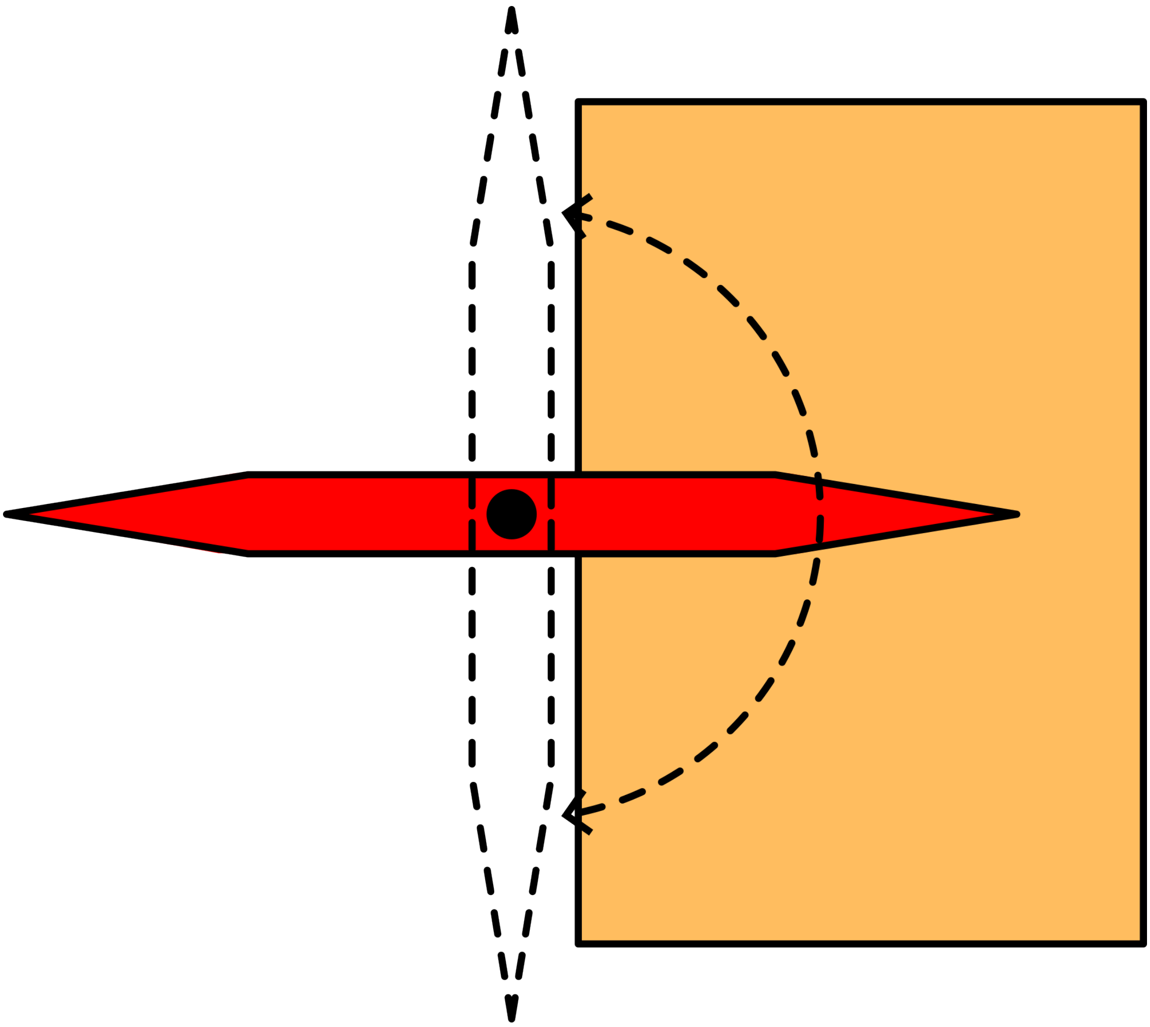


Figure 6.114: .

Again the needle is deflected 90° by hand. Then let it go and count again the number of swings before it comes to a rest. Now we count only around 15 complete swings.

So, the presence of the copper sheet has tremendous influence. The presence of the copper plate slows down and dampens the oscillating movement of the swinging needle.

Historically the phenomenon was observed by Arago in 1825. He observed that a compass needle in the vicinity of a piece of copper "reduces the effect of the earth's magnetic field on the needle". He could not explain it.

6.9.2.1.6 Explanation

Faraday's law explains the slowing down.

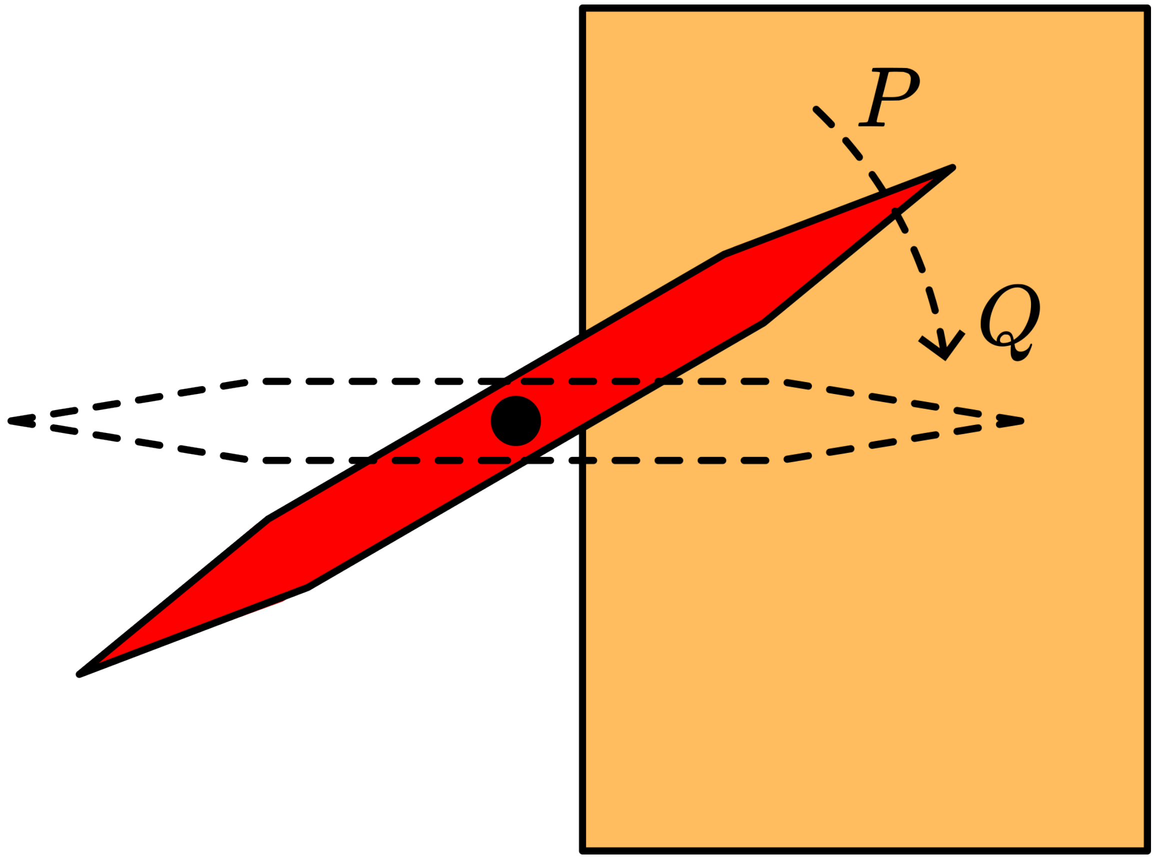


Figure 6.115: .

An emf is induced in the copper plate when there is a change in magnetic field. There is a change in magnetic field at position P and Q in Figure 2: In P there is a decrease in magnetic field; in Q an increase. According to Lenz's law, currents are induced in the copper plate such that they oppose that change in flux. Opposing change in flux means that the needle has to move slower (when the needle stands still there is no change in flux at all). So, at P an eddy-current will flow as to produce a S-pole in the copper plate, that slows down the moving away N-pole of the needle. In the same way an eddy-current will flow at Q in such a way as to produce a N-pole in the copper plate, that slows down the approaching N-pole of the needle.

6.9.2.1.7 Remarks

- Counting the number of oscillations of the needle takes some time. Yet, the students, only seeing the needle swinging to and fro, show no signs of impatience. Our experience is that they even become very focussed on the experiment!
- After this demonstration we show [Aragos disc](../5K2002 Aragos Disk/5K2002.md).

6.9.2.1.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 5/6 vwo, pag. 138.

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 744. N S

6.9.2.2 02 Arago’s Disk

6.9.2.2.1 Aim

- To show an example of eddy currents.
- To show the power of Lenz’s law to explain the occurring Lorentz force.

6.9.2.2.2 Subjects

- 5K20 (Eddy Currents)

6.9.2.2.3 Diagram

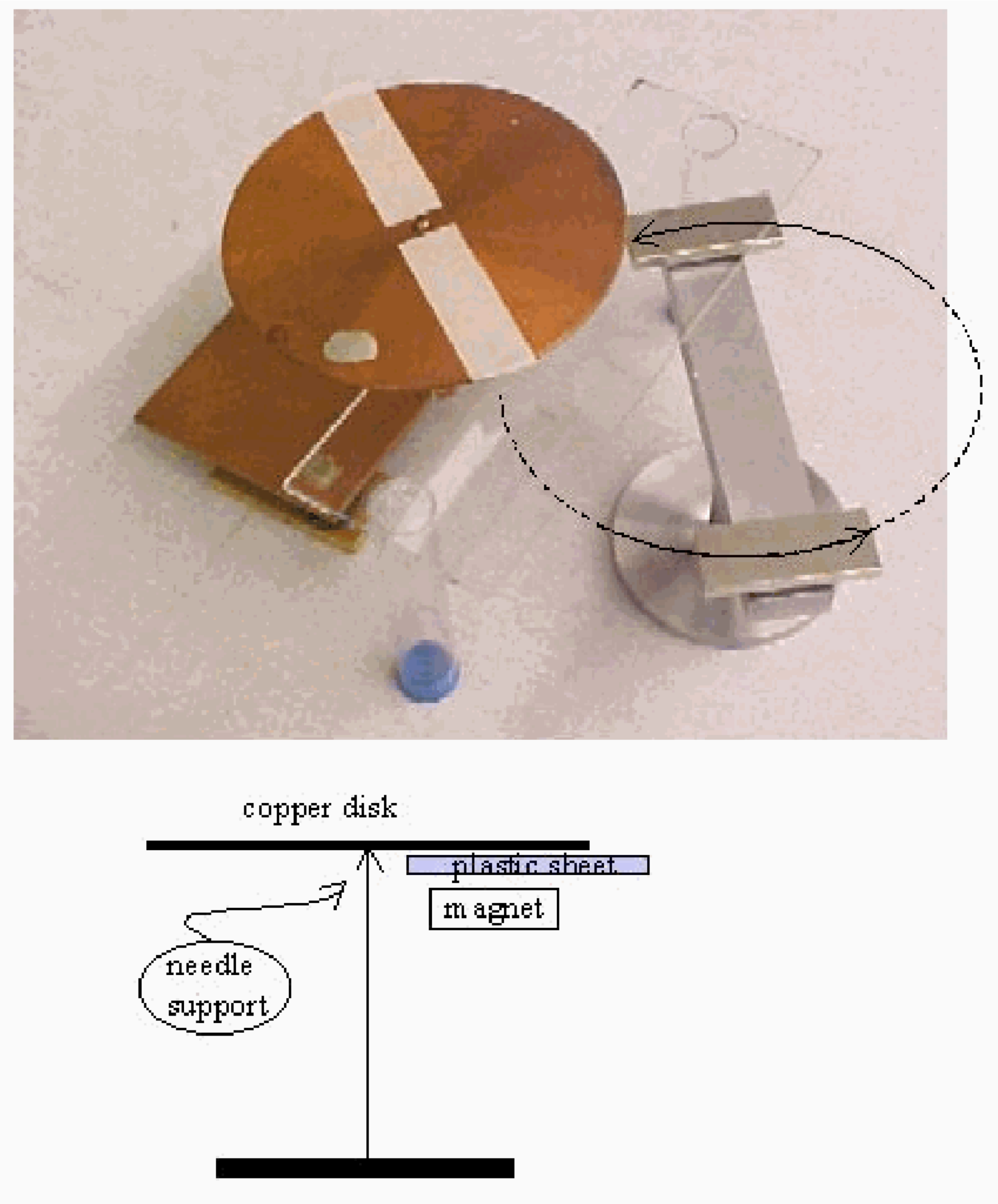


Figure 6.116: .

6.9.2.2.4 Equipment

- Circular copper disk on needle point.

- Two strong magnets (neodymium) on rotating support.
- Sheet of Perspex or glass.

6.9.2.2.5 Safety

- The needle that supports the copper disk is very sharp. Arago's Disk

6.9.2.2.6 Presentation

At first we show that the copper disk experiences no attraction to a magnet: the copper disk is not ferromagnetic.

Then the circular copper disk and the rotating magnets are positioned such that the magnets pass closely by under the rim of the disk. The sheet of perspex fits freely between the copper disk and rotating magnets (this sheet prevents that the audience might think that air-currents make the copper disk move).

-Now, by hand, the magnets are given a push so they turn at high speed.

Immediately the copper disk starts turning as well, trying to follow the magnets. -When next the magnets are made turning in the other direction, the copper disk slows down and soon follows again the movement of the magnets.

-When we stop the rotation of the magnets, the copper disk brakes and will stop its movement soon.

6.9.2.2.7 Explanation

We explain the first presented demonstration (see Figure 2). The other two demonstrated situations can be explained similarly.

In general, an emf is induced in the copper disk when there is a change in magnetic field. This happens at the front- and backside of the passing magnet. At these points, eddy currents flow in the copper disk.

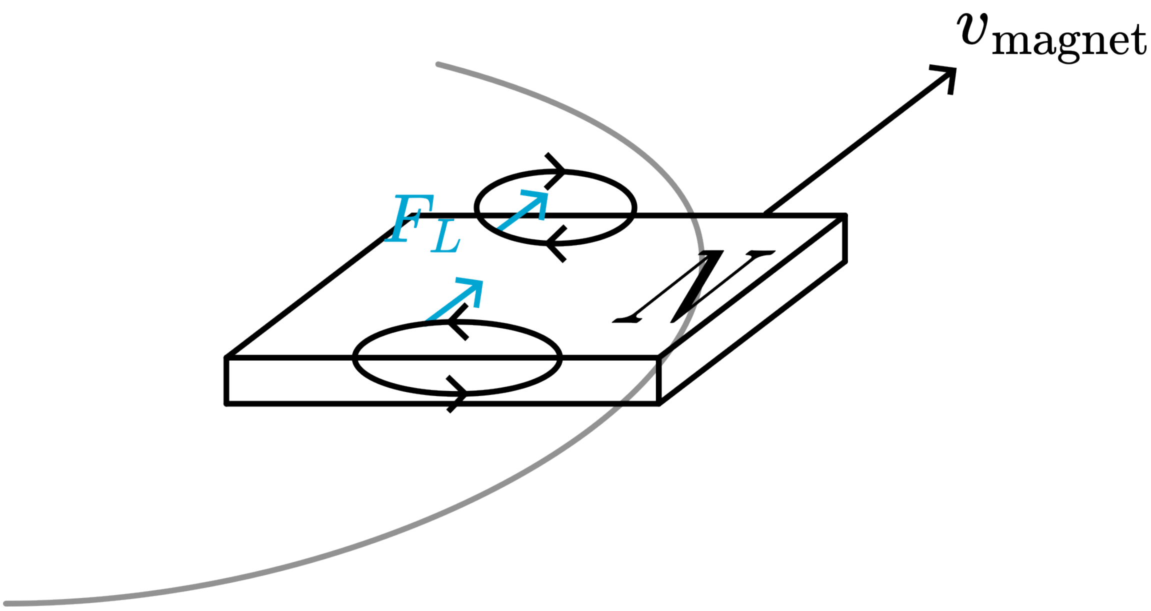


Figure 6.117: .

6.9.2.2.7.1 Explaining with Lenz's law.

According to Lenz's law, the direction of these induced currents is such that they oppose the occurring change of flux:

-When flux is approaching the copper disk, the copper disk “wants” to move away from that approach in order to maintain the flux-free situation (this happens at front side of the moving magnet).

-When a flux is moving away from the copper disk, the copper disk “wants” to move with it in order to maintain its flux-present situation (this happens at tail-side of the moving magnet).

Both front- and tail-side will make the copper disk move with the movement of the magnet.

6.9.2.2.7.2 Explaining with Lenz’s law and Lorentz-force.

-When flux is approaching the copper disk, the copper disk “wants” to move away from that approach in order to maintain the flux-free situation.

So, in the disk a current is induced such that it produces a flux opposing that of the magnet (this happens at front-side of the moving magnet).

-When a flux is moving away from the copper disk, the copper disk “wants” to move with it in order to maintain its flux-present situation. So, in the disk a current is induced such that it produces a flux in the same direction as that of the magnet (this happens at tail-side of the moving magnet).

Looking at the induced currents and the subsequent Lorentz-force (induced current in magnetic filed), both forces on the front- and tail-side make the copper disk move with the magnet (see Figure 2), showing the direction of the Lorentz forces (F_L) making the disk move in the same direction as the magnet does. (Only the forces closest to the magnet are drawn.)

6.9.2.2.8 Remarks

- A piece of tape is stuck on to the copper disk to make the rotation easily visible to the audience.
- The copper disk is balanced using small pieces of wax.
- The demonstration can be performed the other way round: rotating the copper disk makes the magnet assembly on the rotating support go around. In such a way the demonstration is usually described in literature (a magnet needle over a fast spinning copper disk). Historically the phenomenon was observed by Arago in 1825. He observed that a compass needle in the vicinity of a piece of copper *“reduces the effect of the earth’s magnetic field on the needle”* (= damping of the needle’s oscillations; see the demonstration [Aragos compass needle](../5K2001 Aragos Compass Needle/5K2001.md) in this database) and that a rotating copper disk deflects a compass needle from its north-south orientation. Arago did not understand it; Faraday did in 1832.

6.9.2.2.9 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 5/6 vwo, pag. 138
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 344
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 744

6.9.3 5K30 Transformers

6.9.3.1 01 Electric Power Transmission Line

6.9.3.1.1 Aim

To show and explain why it is needed to transport electric power at high voltages.

6.9.3.1.2 Subjects

- 5K30 (Transformers)

6.9.3.1.3 Diagram

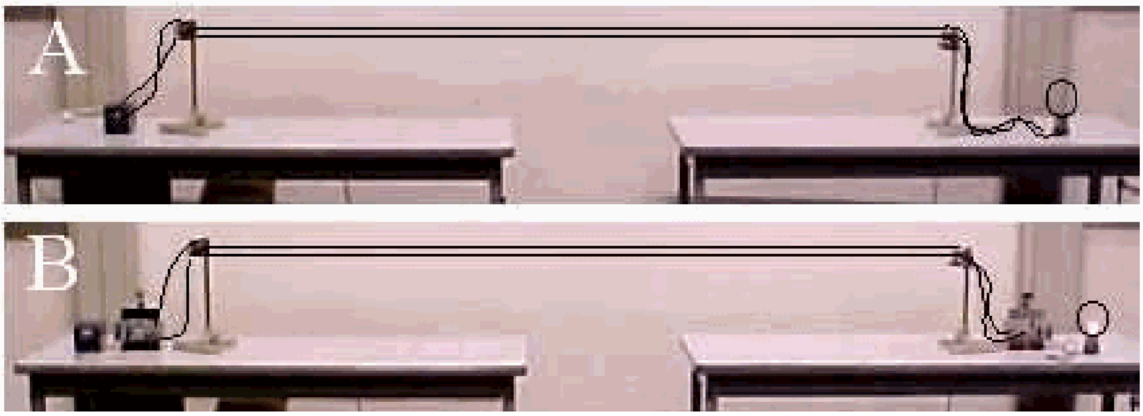


Figure 6.118: .

6.9.3.1.4 Equipment

- 6 Vac-source.
- Lamp, 6 V/30 W
- NiCr-wire; $d = .25$ mm: $22\Omega/\mathrm{m}$; two lengths of 5 m each.
- 4 insulated clamps to mount wires to standing posts.
- 2 transformers, $n_1 = 15, n_2 = 500$.
- Multi scale voltmeter, large display.

6.9.3.1.5 Presentation

First it is shown that the 6 V/30 W glows brightly when connected to the 6 V power supply. The demonstration is set up as shown in Diagram and Figure 2A. Tell the students that in order to simulate a long distance between the power supply and the lamp resistance wire is used between them.

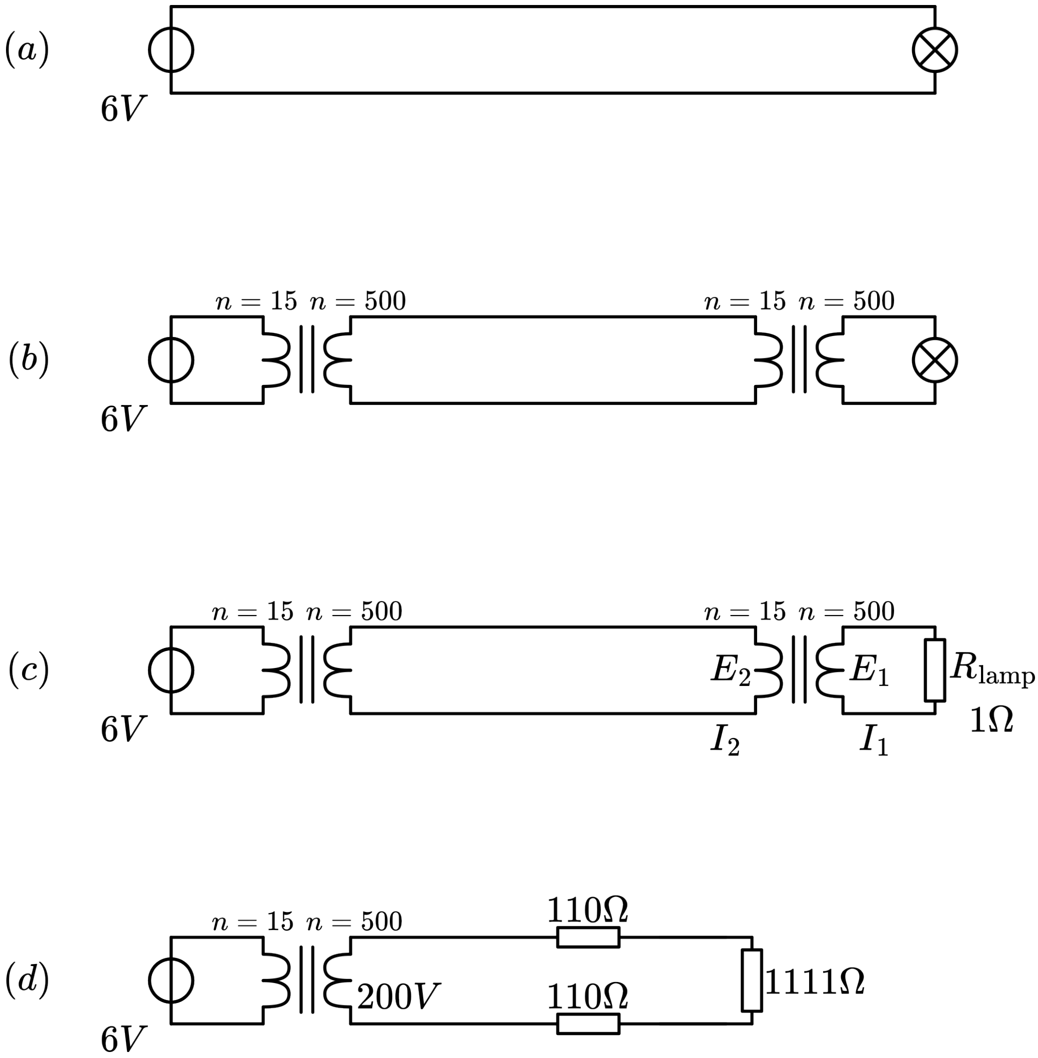


Figure 6.119: .

The power supply is switched on, but the lamp shows no light. Using the voltmeter it is seen that there is no voltage across the lamp. Sliding the leads of the voltmeter along the long wires shows that all the voltage of the power supply is lost in these wires. The two identical transformers are connected into the circuit (see Figure 2B). The power supply is switched on and the lamp lights brightly!

6.9.3.1.6 Explanation

In the first part of the demonstration almost all power is lost in the long wires, because of the high resistance of these wires compared to the resistance-value of the lamp. In the second part of the demonstration, the first transformer steps the 6 V up to 200 V (using the voltmeter this can be checked). To transport power at such a higher voltage a much lower current is needed; the current in the "long" wires is now $500/15$ times lower than in part A of the demonstration. Then the power lost in these wires is $(500/15)^2$ times lower; the power loss in the transport wires is reduced more than a factor 1000! To calculate exactly we have to consider Figure 2C.

The lamp has a resistance of about 1Ω. Since $E_2 = E_1(n_2/n_1)$ and $I_2 = I_1(n_1/n_2)$, we find $E_2/I_2 = R_{lamp}(n_2/n_1)^2$. This results in that E_2 'sees' R_{lamp} as 1111Ω.

Figure 2D explains the rest: The 6 V of the power supply is transformed by the first transformer to 200 V. Considering the resistance values, 167 V remains at the second transformer. This second transformer steps this voltage down to 5 V. This is enough to make the lamp glow.

6.9.3.1.7 Remarks

- Take care with the 200 V in the second part of the demonstration.
- If relevant, you can show that a bird is safe on such a high-voltage transmission line. Just grab one lead and hold it. Nothing happens. There will happen only something when you grab also the other lead by your other hand (do not try this!).

6.9.3.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 527-529

6.9.3.2 02 Transformer

6.9.3.2.1 Aim

To verify the relationship between the voltages and the number of turns in the coils.

6.9.3.2.2 Subjects

- 5K30 (Transformers)

6.9.3.2.3 Diagram

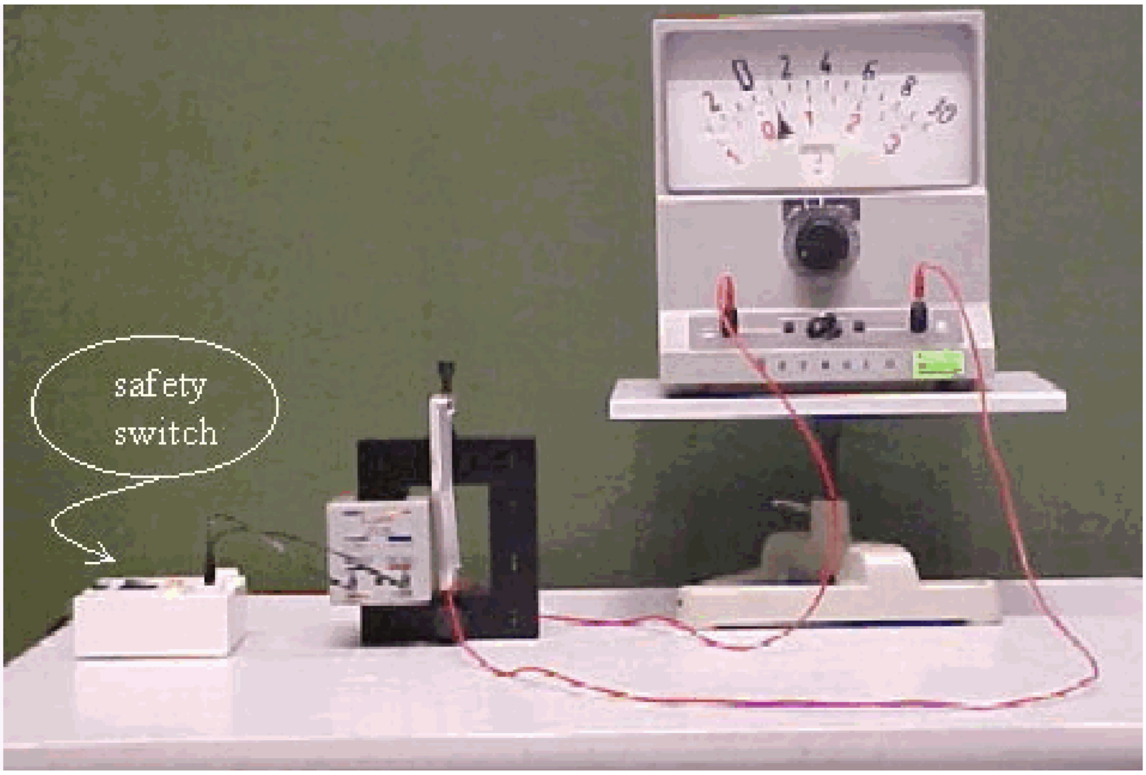


Figure 6.120: .

6.9.3.2.4 Equipment

- 220 V mains safety switchbox.
- U-core with bar and clamping device.
- Coil, $n = 500$.
- Multiscale voltmeter with large display.
- Long wire.

6.9.3.2.5 Safety

- Applying the 220 V mains is done via a safety switch box that switches both connectors ON/OFF. When ON, a red light appears on the box; when OFF a green light shows, indicating that it is safe to manipulate the circuit.

6.9.3.2.6 Presentation

The demonstration is set up as shown in Diagram and Figure 2.

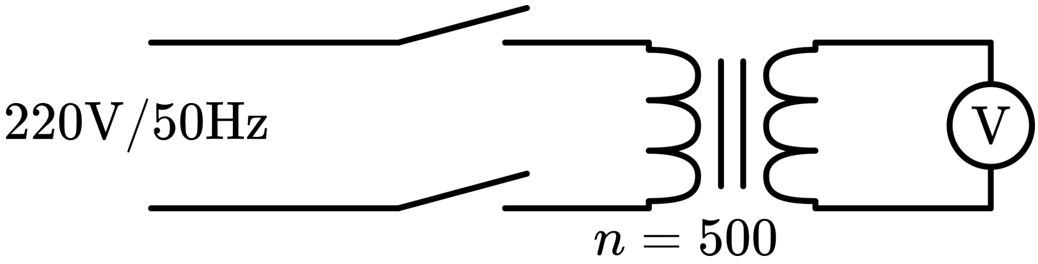


Figure 6.121: .

The 220 V is switched on and the students can read on the V-meter that in the loop around the core a voltage of around .4 V is induced.

Then the demonstrator makes the wire go round the core in two loops. Again the induced voltage is read and a doubling is observed. Then make the wire go round the core three times (see Figure 3). And so on, as long as the length of the wire enables it.

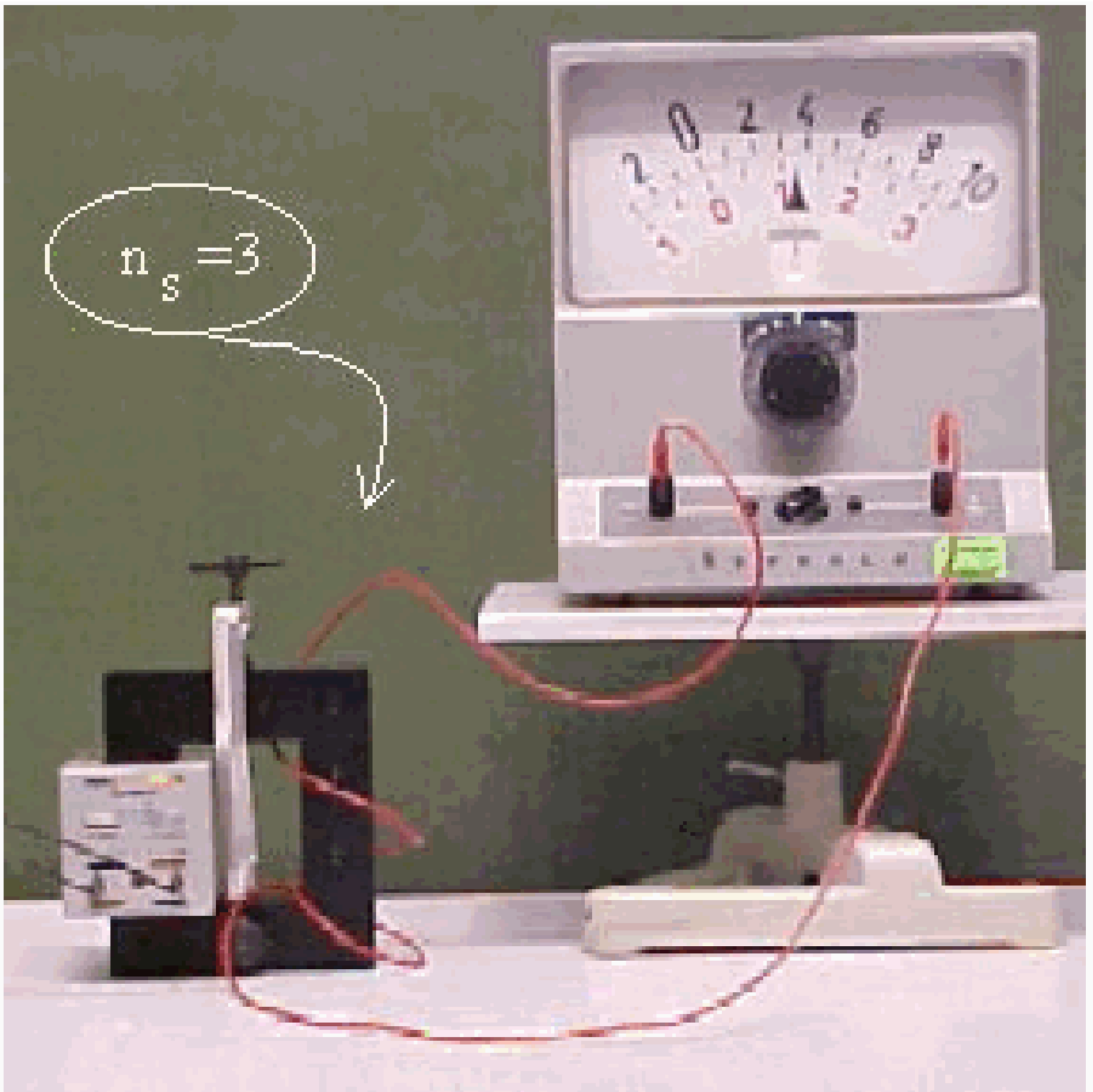


Figure 6.122: .

Clearly the proportionality between induced voltage and the number of turns is observed.

6.9.3.2.7 Explanation

When an alternating voltage $\left(E_p\right)$ is applied across the primary coil of a transformer and there is no flux leakage, then the emf induced in the secondary coil is given by: $E_s = \frac{n_s}{n_p} E_p$. This demonstration verifies this:

- 1 turn: $E_{\mathrm{s}} = 1/500(220) = .44$ V.
- 2 turns: $E_s = 2/500(220) = .88$ V.
- Etc.

6.9.3.2.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 527-529

6.9.4 5K40 Motors and Generators

6.9.4.1 01 Electric Motor (Synchronous Motor)

6.9.4.1.1 Aim

To show the basic principle of an electric motor

6.9.4.1.2 Subjects

- 5K40 (Motors and Generators)

6.9.4.1.3 Diagram

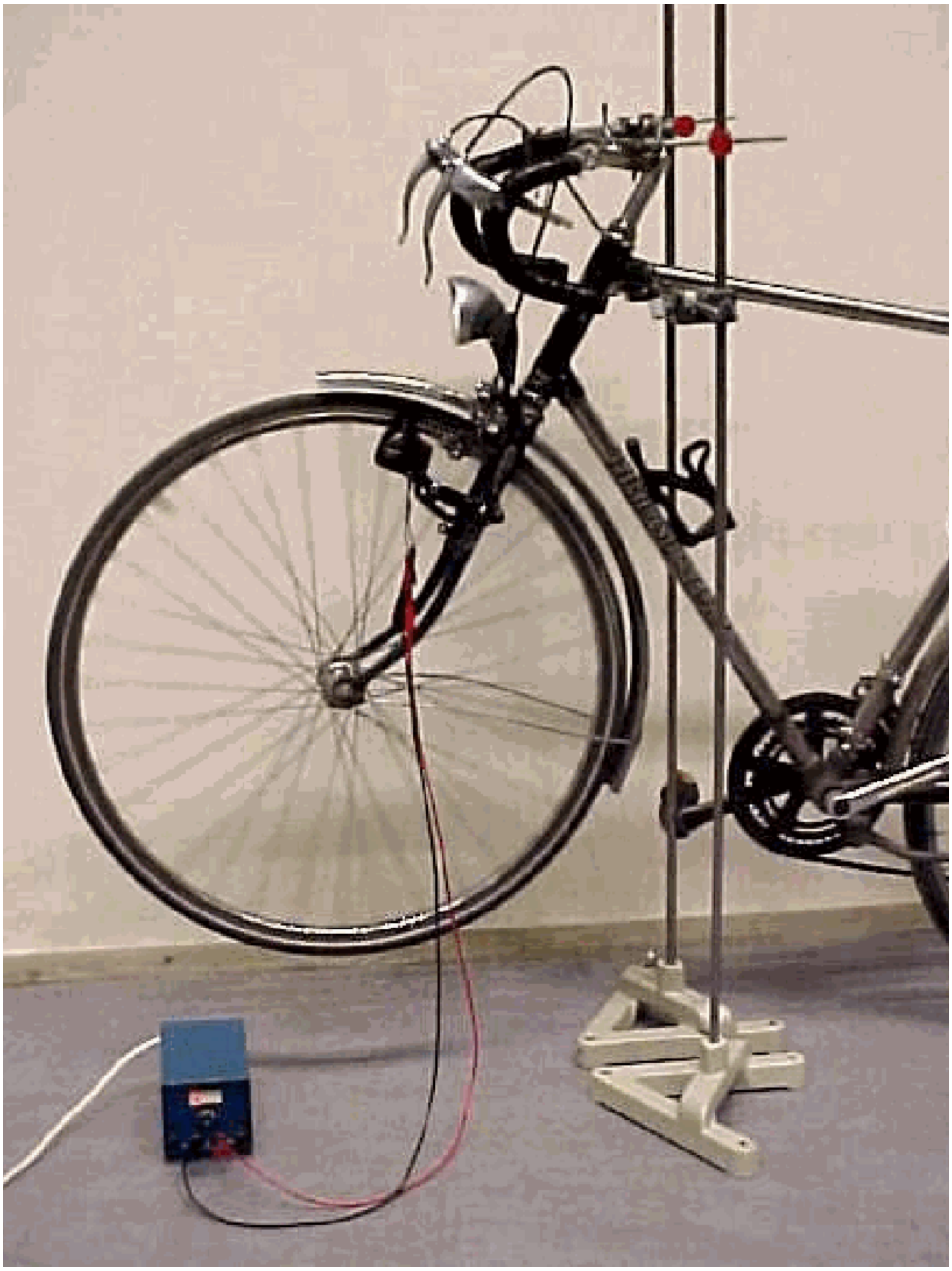


Figure 6.123: .

6.9.4.1.4 Equipment

- Bicycle with 6 V ac dynamo.

- Transformer, 6 V ac output.
- Disassembled dynamo.

6.9.4.1.5 Presentation

The bicycle has his front wheel lifted from the ground (see Diagram). The dynamo is pressed against the rim of the front wheel-tire. The 6 V ac output of the transformer is connected to the dynamo and switched on. Now the dynamo is shaking and makes a humming sound.

When the front wheel is given a turn by hand, the wheel will continue turning, driven by the dynamo. The dynamo is working as an electric motor now. When the wheel is loaded (braking it lightly by means of your hand on the tire) then the wheel stops abruptly and the dynamo shakes and hums again.

When you give the wheel a push into the other direction the dynamo will also drive the wheel into that direction.

6.9.4.1.6 Explanation

Inside the dynamo we find a static coil and a rotating permanent ceramic magnet. The ceramic magnet has 8 poles and turns inside the coil (see Figure 2 and a disassembled dynamo).

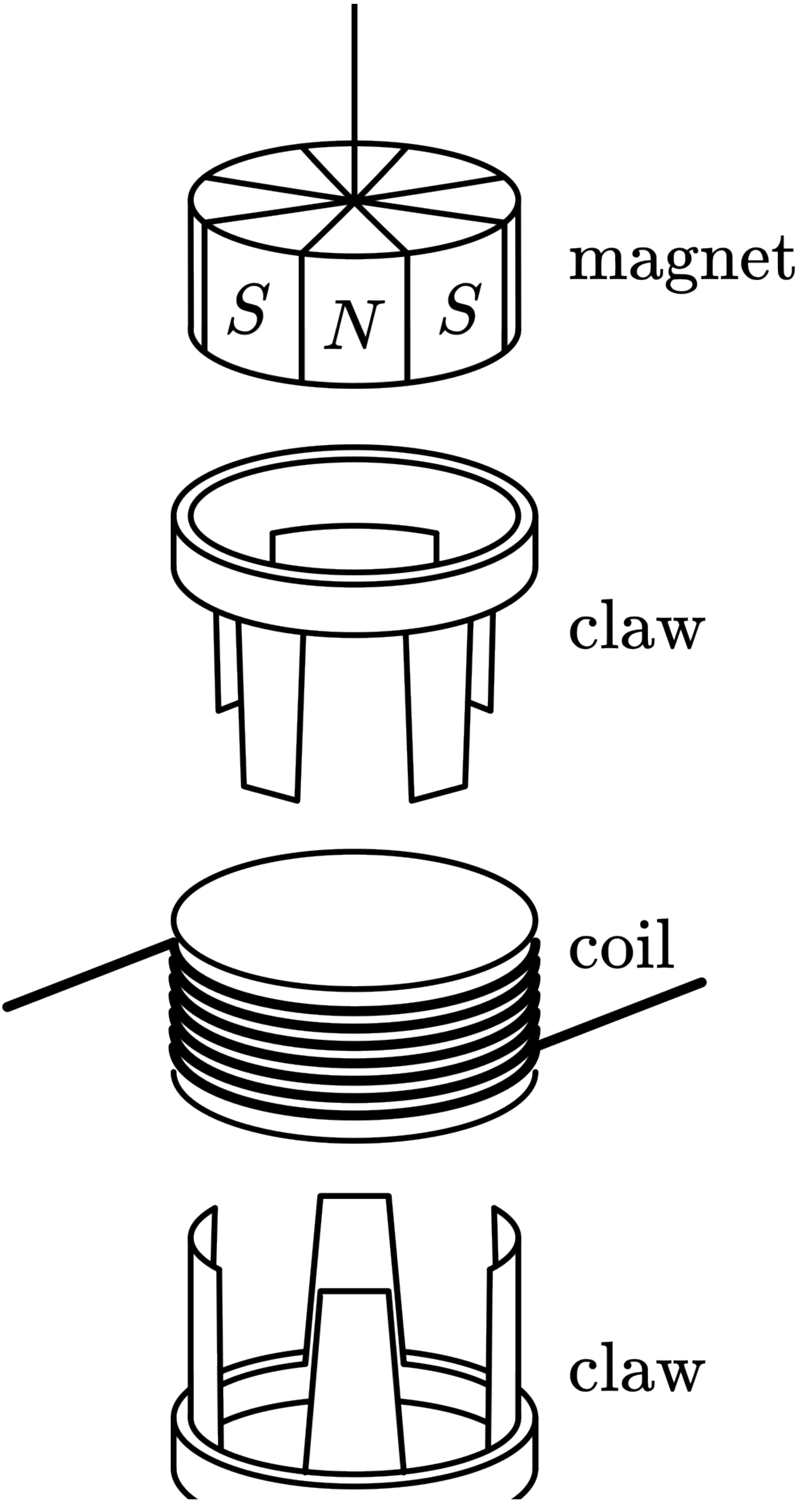

magnet
S
N
S
claw
coil
claw

Figure 6.124: .

By means of two claw rings, whose claws fit in the inside of the coil, the magnetic North- and South pole “appear” perpendicular to the coil. Turning the magnet makes the North- and South pole switch their position. And turning the magnet will induce an emf in the coil.

When a power supply makes an ac current flow through the coil, the claws change their North-South polarity continuously, attracting and repelling the poles of the ceramic magnet. When the magnet has the right speed, movement into one direction will continue (see Figure 3a).

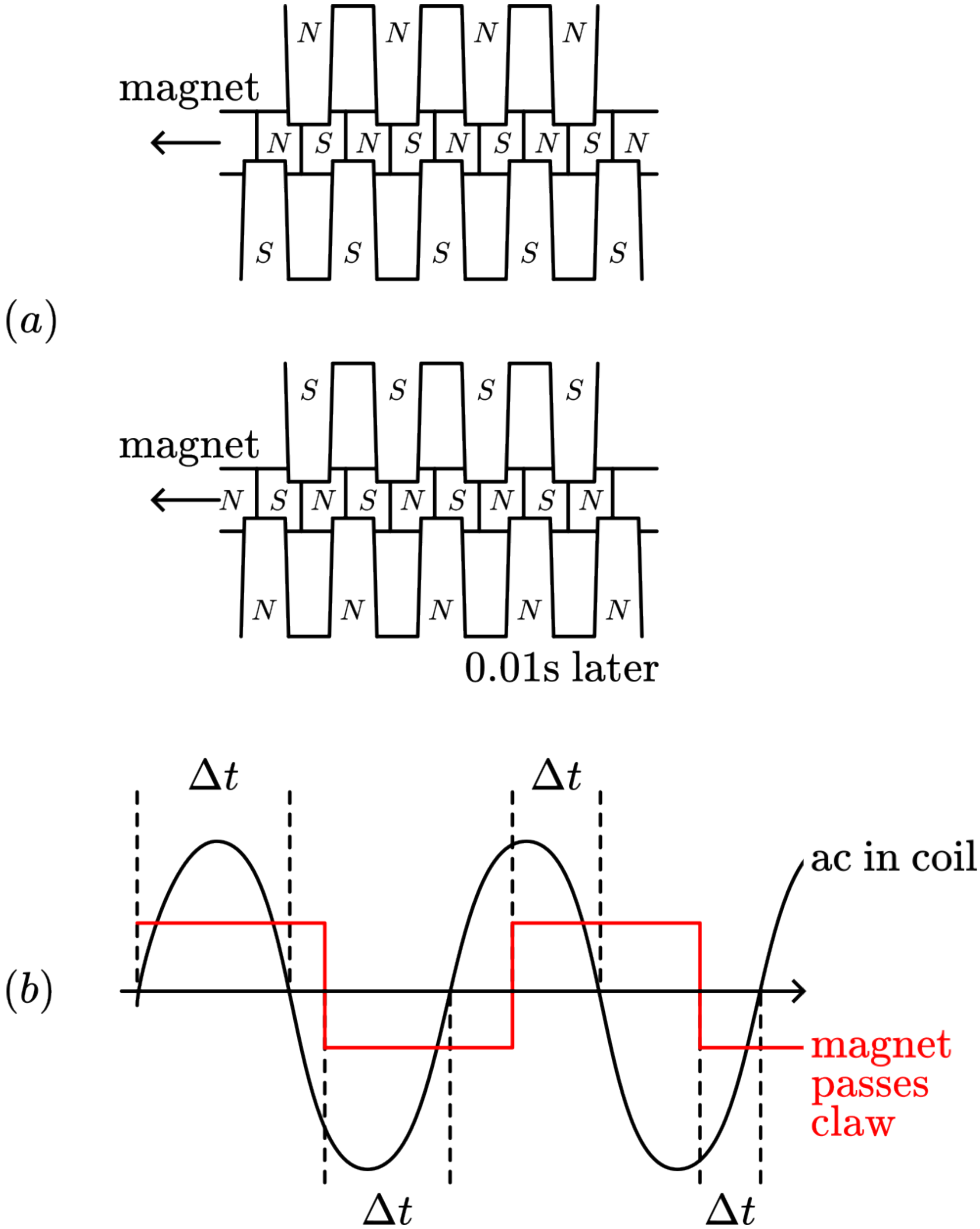


Figure 6.125: .

When the magnet is too slow just a little bit the driving momentum, $F\Delta\Delta$ on the magnet becomes smaller and smaller, because Δt becomes smaller and smaller and the magnet will stop (see Figure 3b).

The magnet cannot start turning by itself because its rotational inertia is too high to pick up the right speed within 0.01sec. When standing still the magnet is repelled and then attracted and so on, so it will make a vibrating movement.

The rotational speed of the magnet is directly related to the ac frequency of the power supply. (This is why this type of motor is called a synchronous motor.) We have $f = 50$ Hz, so every 0.01sec. the claws switch polarity. With 8 poles in the magnet, the magnet will make a full turn in 0.08sec. This is in 4 cycles of the ac-current. So the magnet will turn round with a frequency of $50/4 = 12.5$ Hz. The diameter of the dynamo's wheel will determine how fast the frontwheel of the bicycle will go round.

6.9.4.1.7 Video Rhett Allain

See 9:59 minutes

(a)

(b)

Figure 498: :align: center - Scan the QR code or click here to go to the video.

6.9.4.1.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 495-496
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 348

6.10 5L AC Circuits

6.10.1 5L20 LCR Circuits AC

6.10.1.1 01 Self-Inductance in AC Circuit

6.10.1.1.1 Aim

To show how alternating current depends on the value of self-inductance.

6.10.1.1.2 Subjects

- 5J10 (Self Inductance) 5L20 (LCR Circuits – AC)

6.10.1.1.3 Diagram

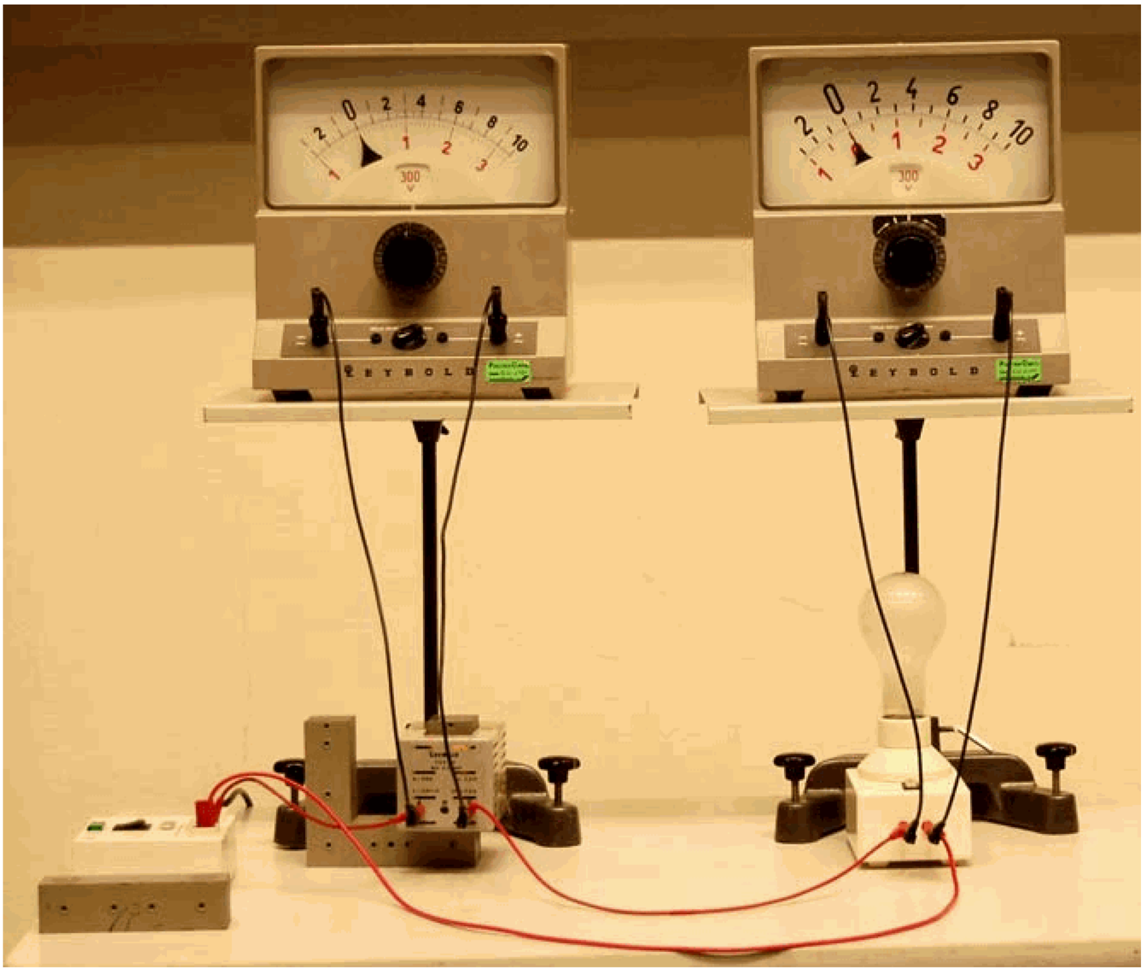


Figure 6.129: .

6.10.1.1.4 Equipment

- Lamp, 220 V/200 W.
- Coil, n = 500; R = 2.5Ω.
- U-core with bar.
- 2 Demonstration meters.
- Safety connection box .
- Measuring junction box (See Figure 5).
- Net-adapter for mobile telephone (or other appliance).

6.10.1.1.5 Safety

- It's a circuit connected to mains voltage (220 V/50 Hz). That's why we use a safety connection box. This box shows a green light when the mains is disconnected and a red light when the mains is connected. Self-inductance in AC-circuit

6.10.1.1.6 Presentation

The circuit is build as shown in Figure 2 and in Diagram. First we show the circuit setup to the students and then connect the two Voltmeters.

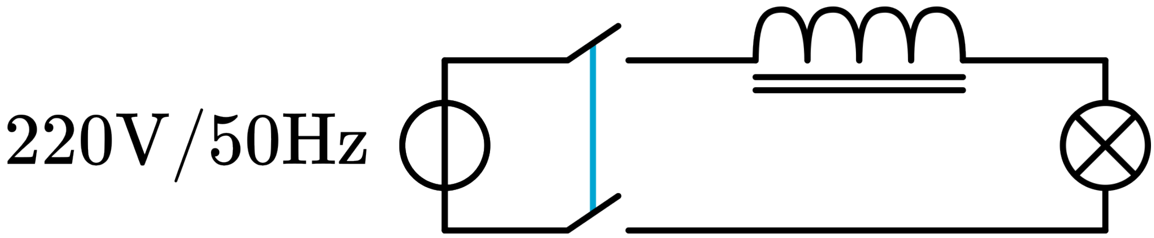


Figure 6.130: .

1. Connecting the 220 V to the circuit makes the lamp glows strongly (see Figure 3A). The Voltmeter connected to the lamp reads almost 220 V : All voltage appears across the lamp; just a very little voltage is read across the coil.

Conclusion is that only a very small emf of self-inductance is generated in the coil.

1. The bar is partly shifted on to the U-core. As soon as the bar touches the second leg of the U-core the lamp dims (see figure $2B$). the Voltmeter across the lamp shows a lower voltage now and at the same time we observe an increase in voltage across the coil.

Conclusion is that there is now a higher emf of self-inductance that opposes the 220 V.

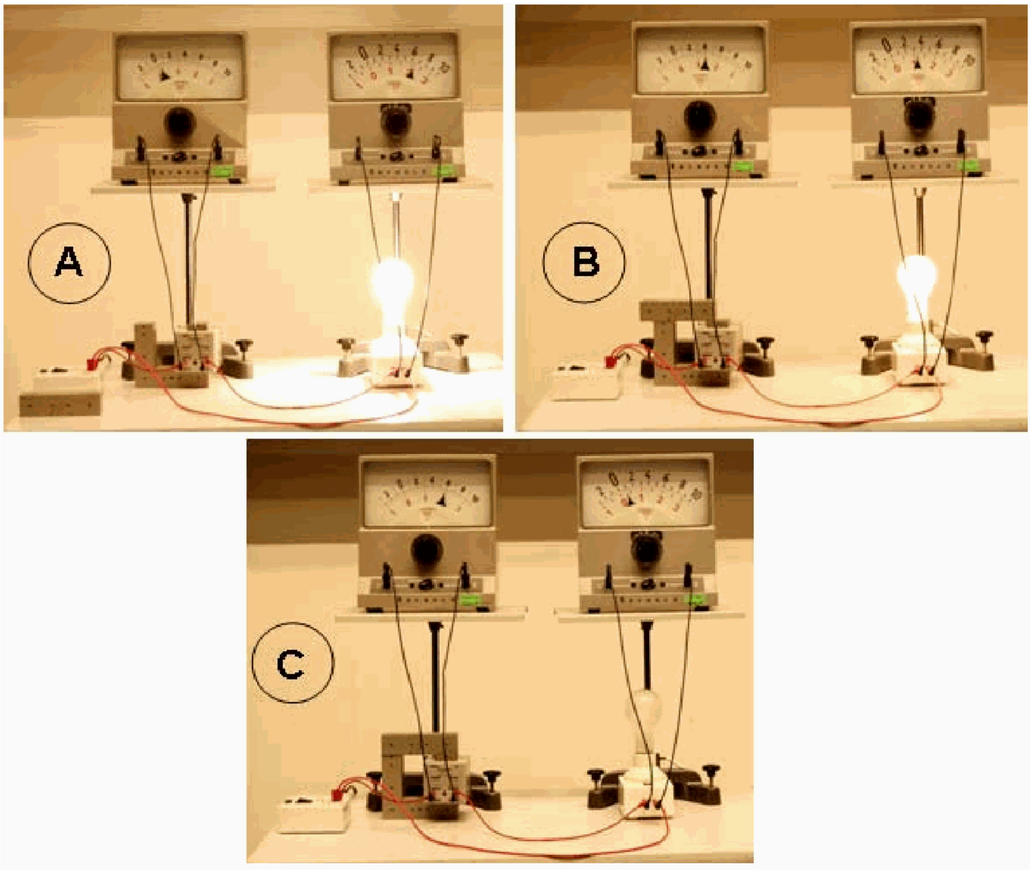


Figure 6.131: .

3. When the bar is shifted completely on to the U-core, the lamp only glows very faintly. The voltage read across it is very low. The voltage across the coil is almost 220 V now!

Conclusion is that the emf of self-inductance generated in the coil is almost 220 V now.

Shifting the bar back and forth across the U-core makes the lamp dim less or more.

3. Finally we disconnect the lamp. Now only the self-inductance is connected to the 220 V (see Figure 4).

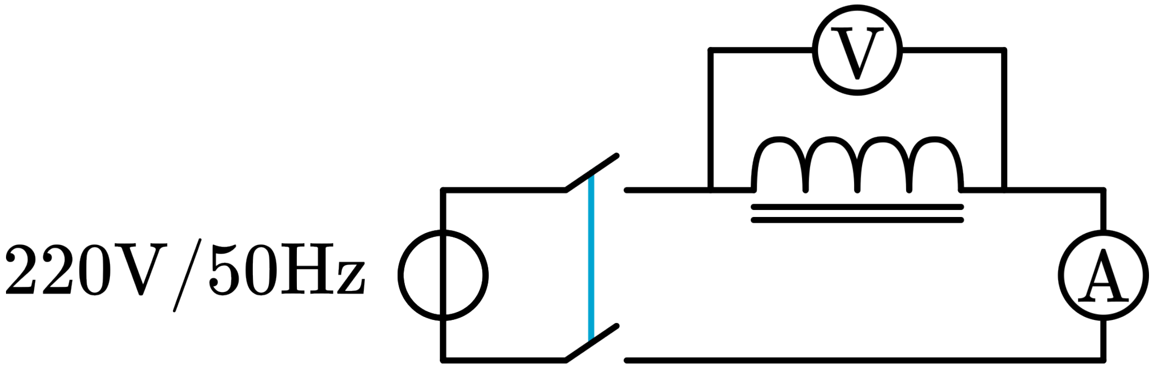


Figure 6.132: .

Now the effect of self-inductance is most clear: the voltmeter reads 220 V across the coil, and only a small current is flowing (we measure 0.4 A). When there would be no self-inductance, the current would be 220 $\mathrm{V}/2.5\Omega = 88$ A !

Conclusion is that the emf of self-inductance really opposes the applied voltage. 5. The same demonstration is performed with a commercial net-adapter (used as charger for a mobile telephone; see Figure 5). Here also only the primary coil of the adapter is connected to the mains. We read a current of only 0.3 mA!

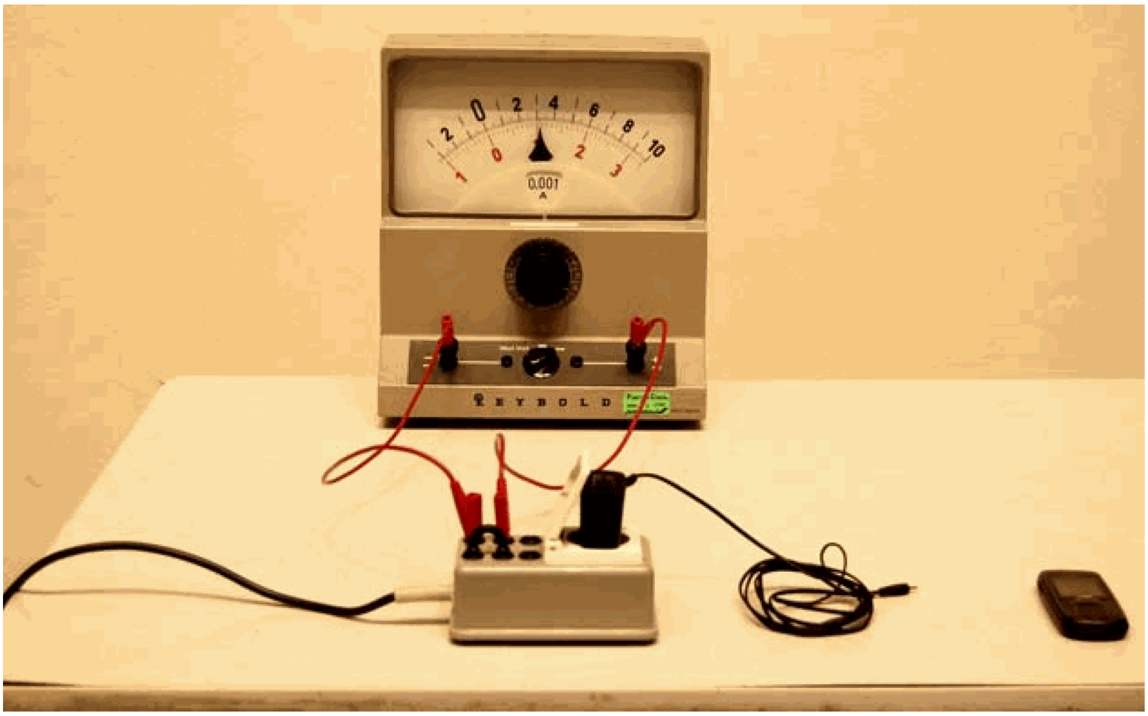


Figure 6.133: .

6.10.1.1.7 Explanation

The emf induced in a coil is, from Faraday's law: $E = -N\frac{d\Phi_B}{dt} = -L\frac{dI}{dt}$; L being the coefficient of self-inductance. For a solenoid with a core (μ_r) this is:

$L = \frac{\mu_r \mu_0 N^2 A}{l} L = \frac{\mu_r \mu_0 N^2 A}{l}$. This shows that the higher L, the higher the emf of self-inductance. Shifting the bar across the core changes L, and so the induced emf.

6.10.1.1.8 Remarks

- The core on the bar makes a lot of noise. This is a 100 Hz mains hum due to the mains frequency (50 Hz).
- The effect of self-inductance can also be translated into impedance of the circuit. In our demonstration 4. the circuit shows an impedance of 220 V/0.4 A $= 550\Omega$ instead of the 2.5Ω of the copper coil.
- In figure B we read $V_{coil} = 130$ V and $V_{lamp} = 110$ V. Students easily read this as a total of 240 V, so higher than the applied 220 V. Phase-shift between these two voltages is responsible for that. The situation must be something like Figure 6 below shows.

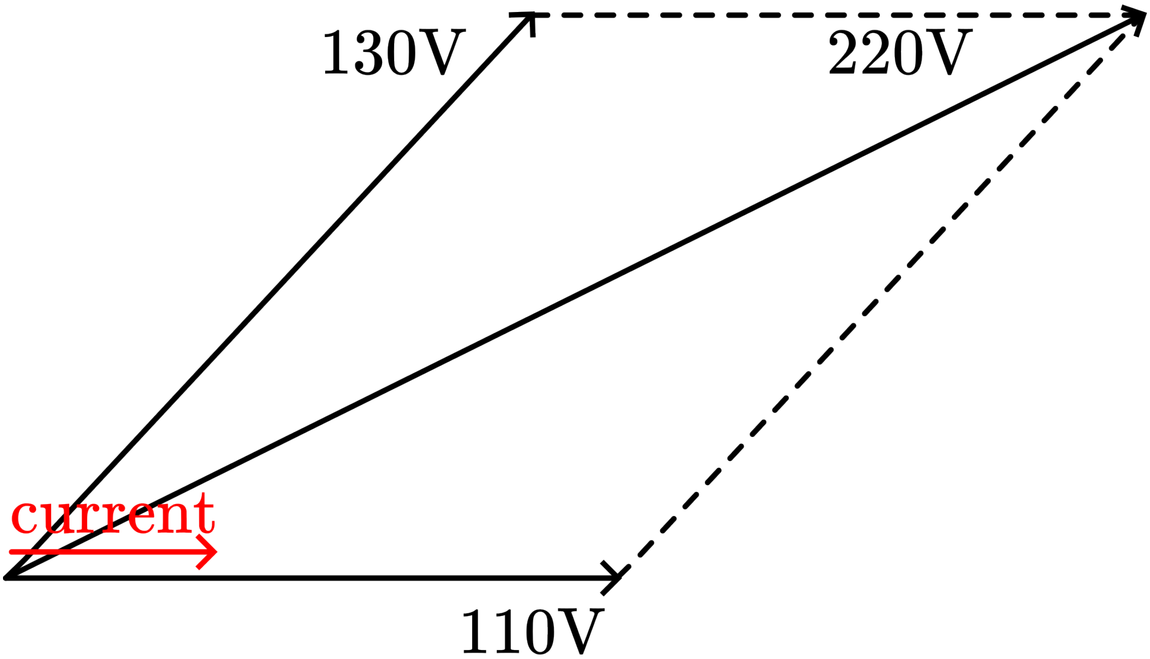


Figure 6.134: .

6.10.1.1.9 Video Rhett Allain

(a)

(b)

Figure 505: :align: center Video embedded from - Scan the QR code or click here to go to the video.

6.10.1.1.10 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 758-759 and 773-774.
- Wolfson, R., Essential University Physics, pag. 474-477 and 491-492. 110V

6.10.1.2 02 Phase

6.10.1.2.1 Aim

To show the phase-relationship between current and applied voltage when using R or L or C in an a.c. circuit.

6.10.1.2.2 Subjects

- 5L20 (LCR Circuits - AC)

6.10.1.2.3 Diagram

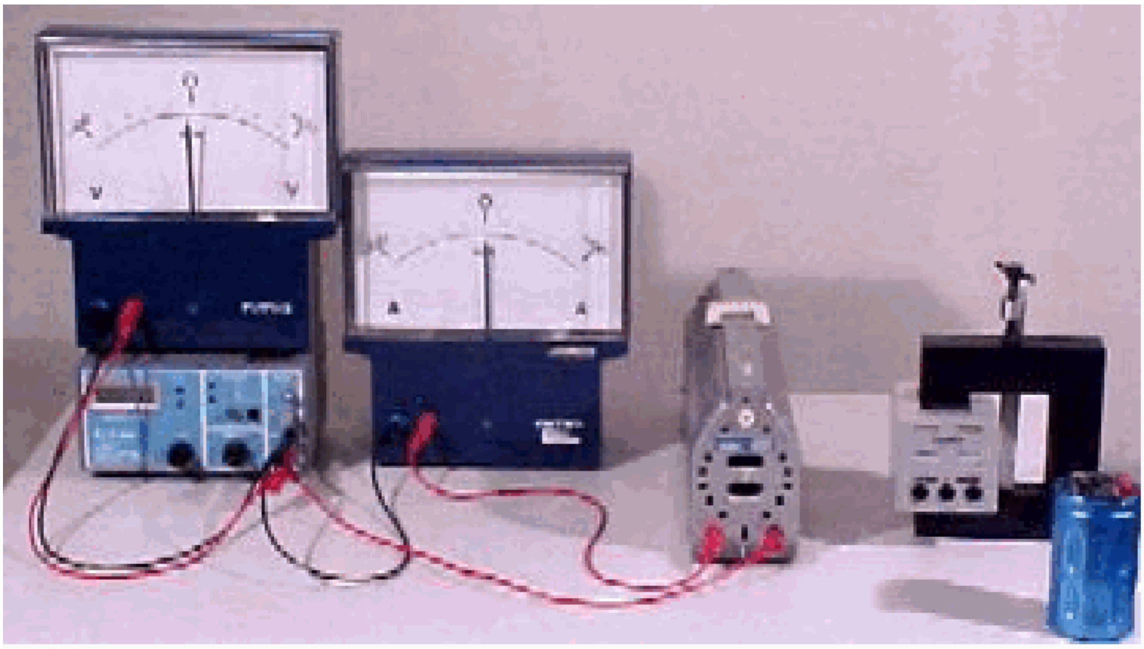


Figure 6.138: .

6.10.1.2.4 Equipment

- Signal generator, low frequency
- Large display analog DC V-meter $(-5/0/+5\ \mathrm{V})$
- Large display analog DC A-meter $(-0.5/0/+0.5\ \mathrm{A})$
- Resistor,$11\Omega(8\ \mathrm{A})$
- Capacitor, $68\ \mathrm{mF}/10\ \mathrm{V}$
- Coil, $n = 500$ with ferromagnetic core.

6.10.1.2.5 Presentation

Switch on the signal generator and set the frequency at $0,3$ Hz. Build the circuit with the resistor (see Figure 2).

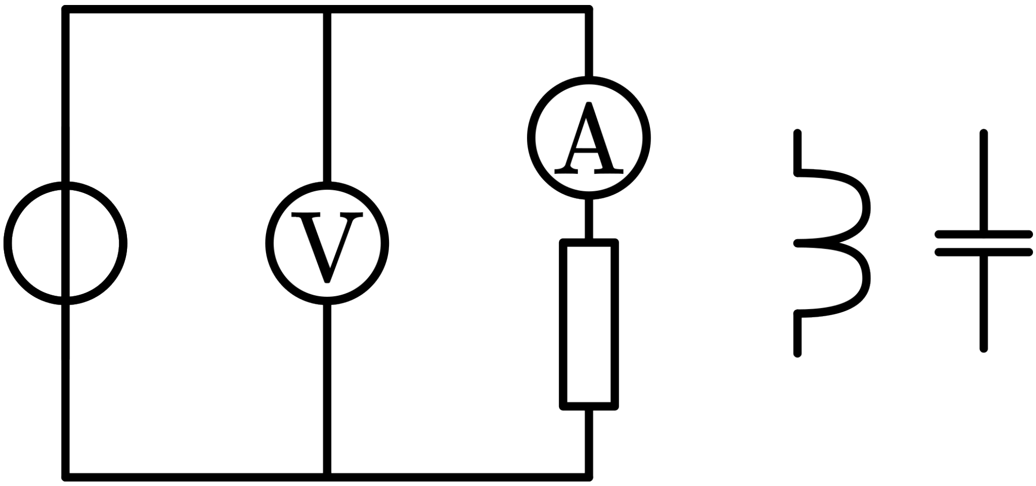


Figure 6.139: .

Adjust the voltage until about 3 V amplitude is read on the voltmeter. Observing also the A-meter scale, it is observed that the applied voltage and current are in phase.

Reduce the voltage to zero and replace the resistor by the coil. Again adjust the voltage at about 3 V amplitude. Observing the A-meter and V-meter, it is observed that the current lags the applied emf by 90°.

Reduce the voltage to zero and replace the coil by the capacitor. Adjust the voltage until about 3 V amplitude is read on the V-meter. Observing the A-meter and V-meter it can be seen that the current leads the applied emf by 90°.

6.10.1.2.6 Explanation

In case of the resistance, the current in it at any time is given by $I = \frac{E(t)}{R}$. E(t) is the applied emf. When $\mathrm{E(t)} = \mathrm{E_0} \sin \omega \mathrm{t}$, then $I = \frac{E_0}{R} \sin \omega t$. So current and applied emf are in phase.

In case of the coil the applied emf is opposed by a 'back emf' $E_{ind} = L\frac{dI}{dt}$. When there is no R in the circuit, then $E(t) - L\frac{dI}{dt} = 0$. This can be rewritten as $I = \frac{E_0}{\omega L} \sin(\omega t - \frac{\pi}{2})$. So the current has a phase difference of $-\pi/2$ when compared with the applied emf ($\mathrm{E_0} \sin \omega \mathrm{t}$).

In case of the capacitor, the applied emf is opposed by the voltage due to the charge of the capacitor $\mathrm{Q = CV(t)}$. $\mathrm{Q = CE_0}\ \sin\omega$. By differentiating it can be written as

$I = \omega C E_0 \sin(\omega t + \frac{\pi}{2})$. So the current has a phase difference of $+\pi/2$ when compared with the applied emf $\mathrm{E_0} \sin \omega$.

6.10.1.2.7 Remarks

- We have chosen the R- and C-values such that they will give around the same voltage - and current values as in case of the demonstration with the coil.
- When changing the coil, always reduce the amplitude to zero, otherwise high induction voltages can occur damaging your signal generator.
- When applying the capacitor, be sure it has no stored charge in it.

6.10.1.2.8 Sources

- Wolfson, R., Essential University Physics, pag. 490-494

6.10.1.3 03 LRC Circuits

6.10.1.3.1 Aim

To show the effect of frequency on current and voltages in an LRC-series (and -parallel) circuit.

6.10.1.3.2 Subjects

- 5L20 (LCR Circuits - AC)

6.10.1.3.3 Diagram

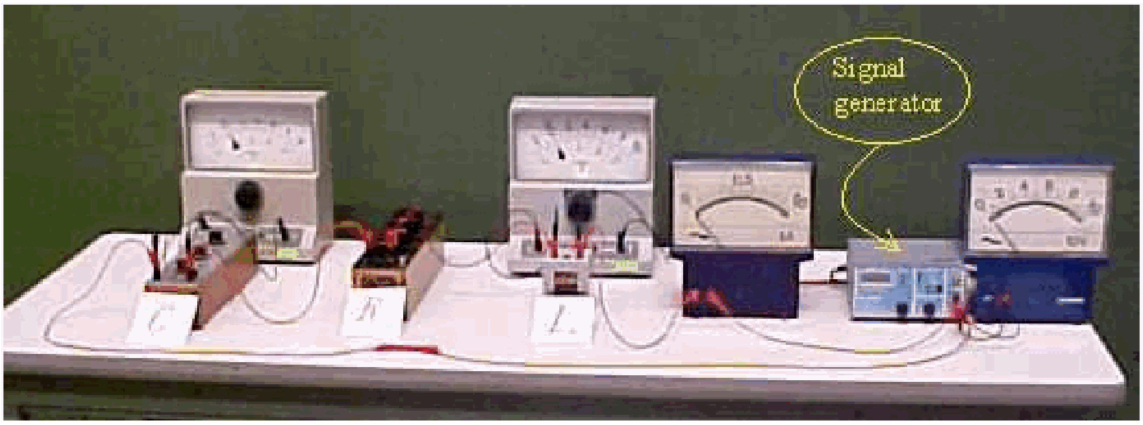


Figure 6.140: .

6.10.1.3.4 Equipment

- Signal generator.
- Large display to show frequency-setting of signal generator.
- Resistance box.
- Capacitor box.
- Coil, $n = 500$, with iron core.
- 3 multiscale V-meters.
- A-meter.

6.10.1.3.5 Presentation

The circuit is made as shown in Diagram and Figure 2.

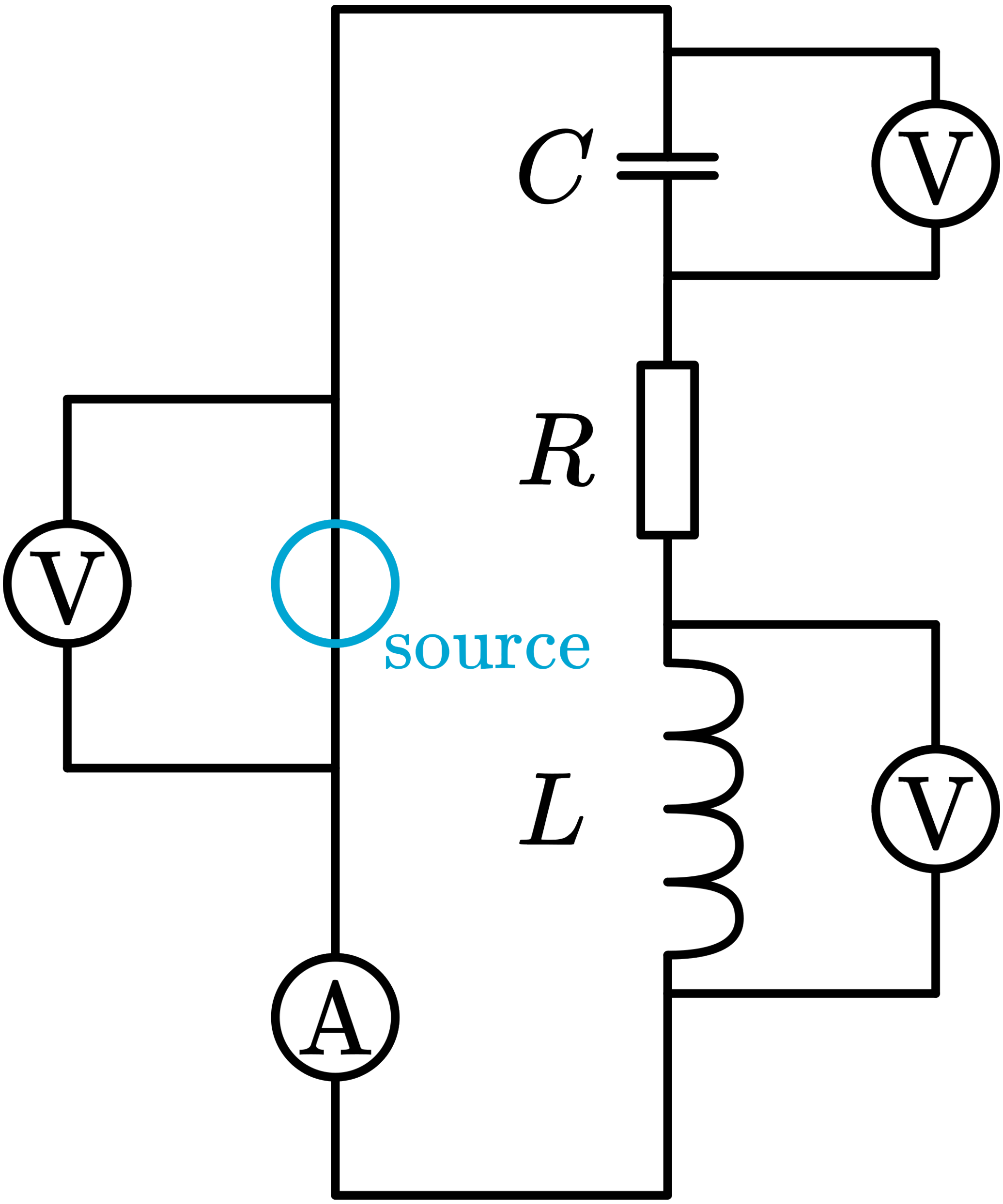


Figure 6.141: .

C is made $1uF$. The value of R is made zero. The voltage of the signal generator is made 6 V.

- The frequency is set at 100 Hz. Students can read that all the voltage appears at C : $V_C = 6$ V; $V_L = 0$ V
- The frequency is made 10kHz. Students can read that now all the voltage appears at L : $V_C = 0$ V; $V_L = 6$ V.

These first two measurements can be discussed now. After this discussion the question is raised: "what happens between 100 Hz and 10kHz ?"

- The frequency is set at 1kHz. Students can read now that $V_C = 5$ V; $V_L = 11$ V. When it is the fist time that students are confronted with ac-circuits, these readings will produce many questions: "How is it possible that a 6 V power supply gives in the circuit $(11 + 5 =)16$ V ?; is Kirchhoff's rule no longer valid?, etc.". The vectorconcept of ac using a phasordiagram can be introduced to explain the observed phenomenon.
- Now it is interesting to explore the region between 100 Hz and 10kHz. Lowering the frequency from 1kHz downwards, both V_C and V_L will rise steeply. We measure at

670 Hz $V_C = V_L = 140$ V ! Students can also observe that in this situation I is at a maximum.

The results can be discussed now.

It is easy to change the circuit into a LC-parallelcircuit ($R = \infty$). L and C have now an ammeter in series. Again measurements are made at f $= 100$ Hz, f $= 10$kHz and f $= 1$kHz and after that going down to resonance. We measured:

-100 Hz : $I_{\mathrm{C}} = 0; I_{\mathrm{L}} = .16$ A; $I_{total} = .16$ A

-10kHz : $I_{\mathrm{C}} = .35$ A; $I_{\mathrm{L}} = .0; I_{total} = .35$ A

-1kHz : $I_{\mathrm{C}} = 35$ mA; $I_{\mathrm{L}} = 17$ mA; $I_{total} = 18$ mA

-670 Hz : $I_{\mathrm{C}} = 25$ mA; $I_{\mathrm{L}} = 25$ mA; $I_{total} = 1.4$ mA

These results are similar to those measured in the seriescircuit but now the questions will be raised in relation to the currents.

6.10.1.3.6 Explanation

The first readings of the demonstration can be explained when students have a basic idea of a capacitor and inductance.

- Supposing the frequency extremely low (dc) it is clear that a capacitor conducts no current (it is an insulator) and so it will have a very high resistance. At low frequencies the capacitor is charged in a time very small compared to the period time of the ac-source and so the capacitor has constantly the same voltage (almost) as the source. This voltage opposes the source voltage and so no current will flow. At very high frequencies the charging time of the capacitor is equal to or larger than the period time and so the capacitor is charging (and discharging) continuously: a current is flowing.
- At extreme low frequencies the coil has a very low inductance (Dt=large) and only a voltage due to its resistance of the copper wires appears across its terminals. At high frequencies the coil will produce a high induced voltage (Dt=small), so at high frequencies a high voltage can be expected across it. In this qualitative way the opposite frequency-response of C and L can be talked into the students. A more thorough analysis is needed to understand all the results that can be shown in this demonstration. A phase-diagram is needed.

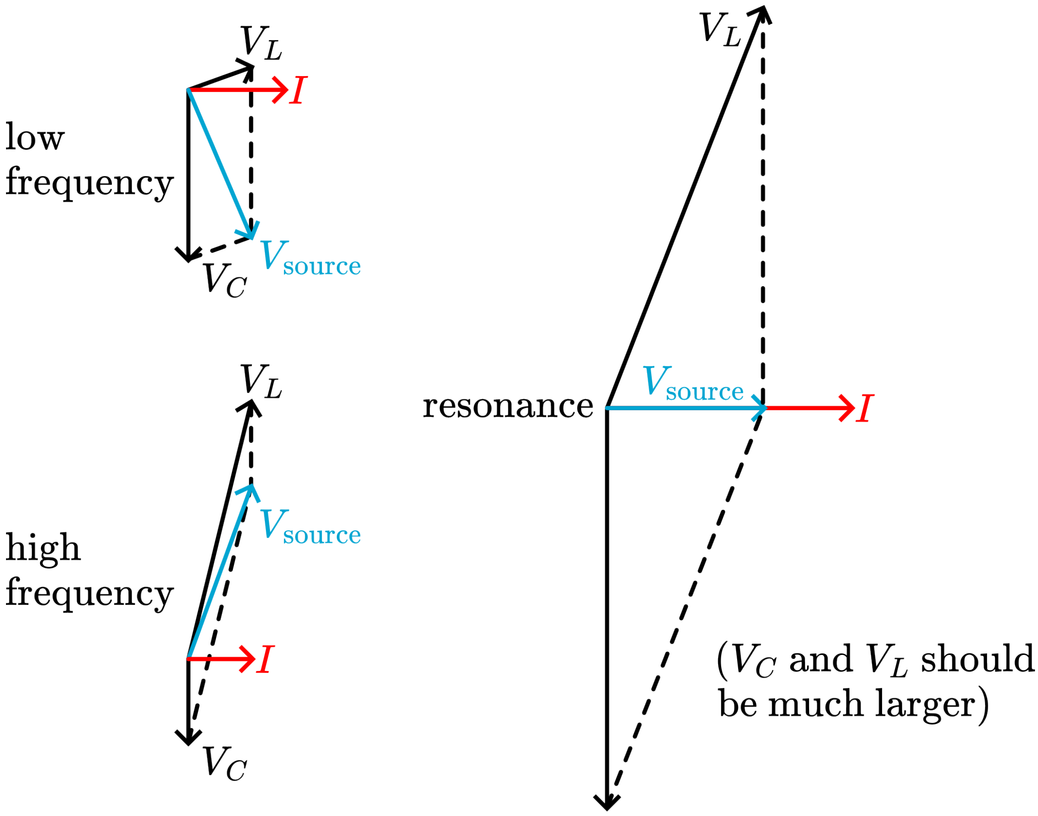


Figure 6.142: .

Many textbooks show these diagrams. Figure 3 shows the diagrams that apply to our demonstrations.

The explanation of the results measured in the parallel circuit can be explained using a current phase-diagram.

6.10.1.3.7 Remarks

- A lot more can be shown with this demonstration. For instance the influence of R.
- Also a mathematical analysis is possible using the capacitance $X_C = (\omega C)^{-1}$ and inductance $X_{\mathrm{L}} = \omega\mathrm{L}$. Many textbooks show how to do this.

6.10.1.3.8 Sources

- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 531-535
- McComb,W.D., Dynamics and Relativity, pag. 84-86
- Roest, R., Inleiding Mechanica, pag. 281-283
- Young, H.D. and Freeman, R.A., University Physics, pag. 987-1013

6.11 5N Electromagnetic Radiation

6.11.1 5N10 Transmission Lines and Antennas

6.11.1.1 01 Electromagnetic Waves (Lecher Lines)

6.11.1.1.1 Aim

To show wave characteristics of electromagnetic waves (UHF) on conducting bars (Lecher lines), in air and in water.

6.11.1.1.2 Subjects

- 5N10 (Transmission Lines and Antennas)

6.11.1.1.3 Diagram

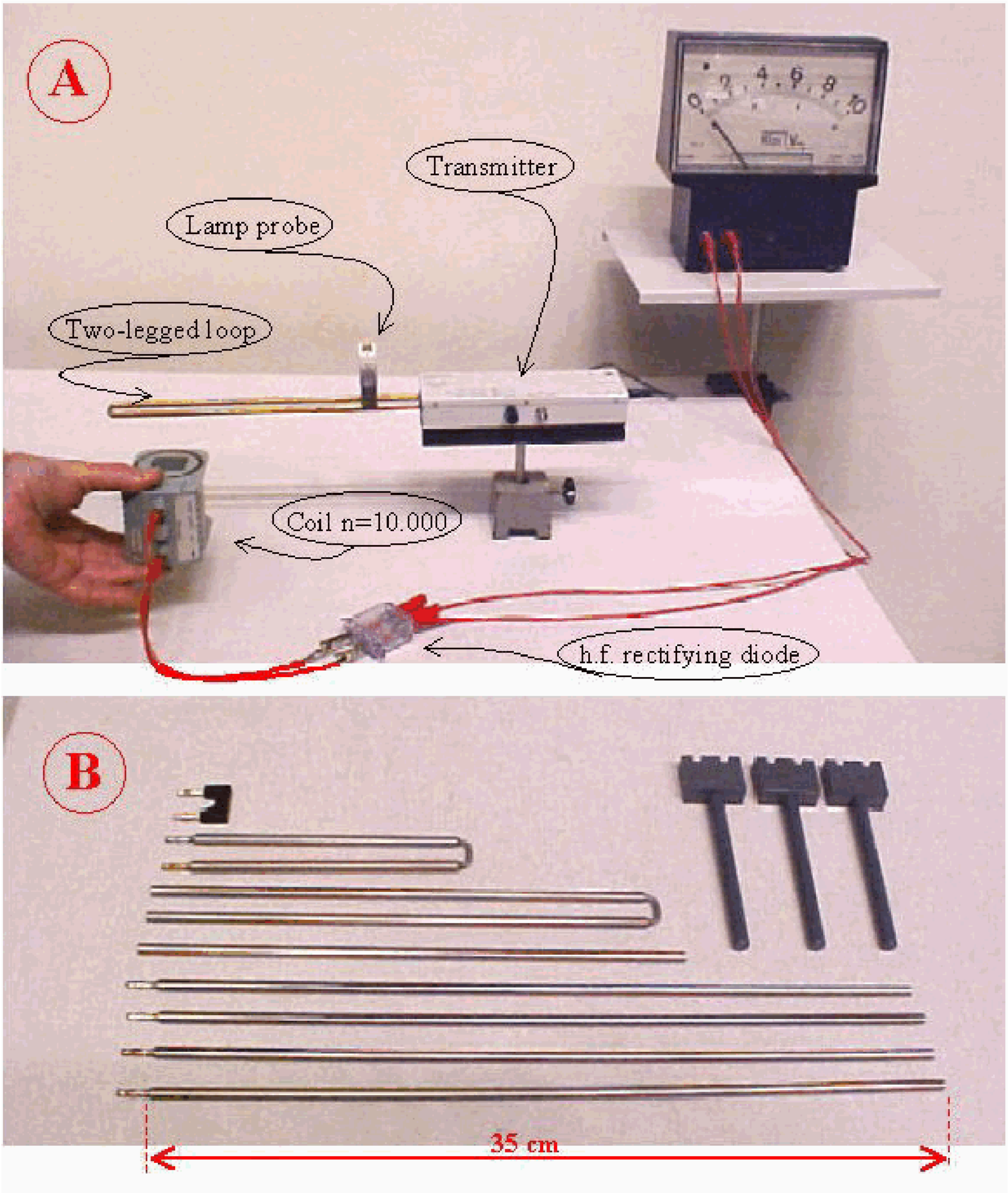


Figure 6.143: .

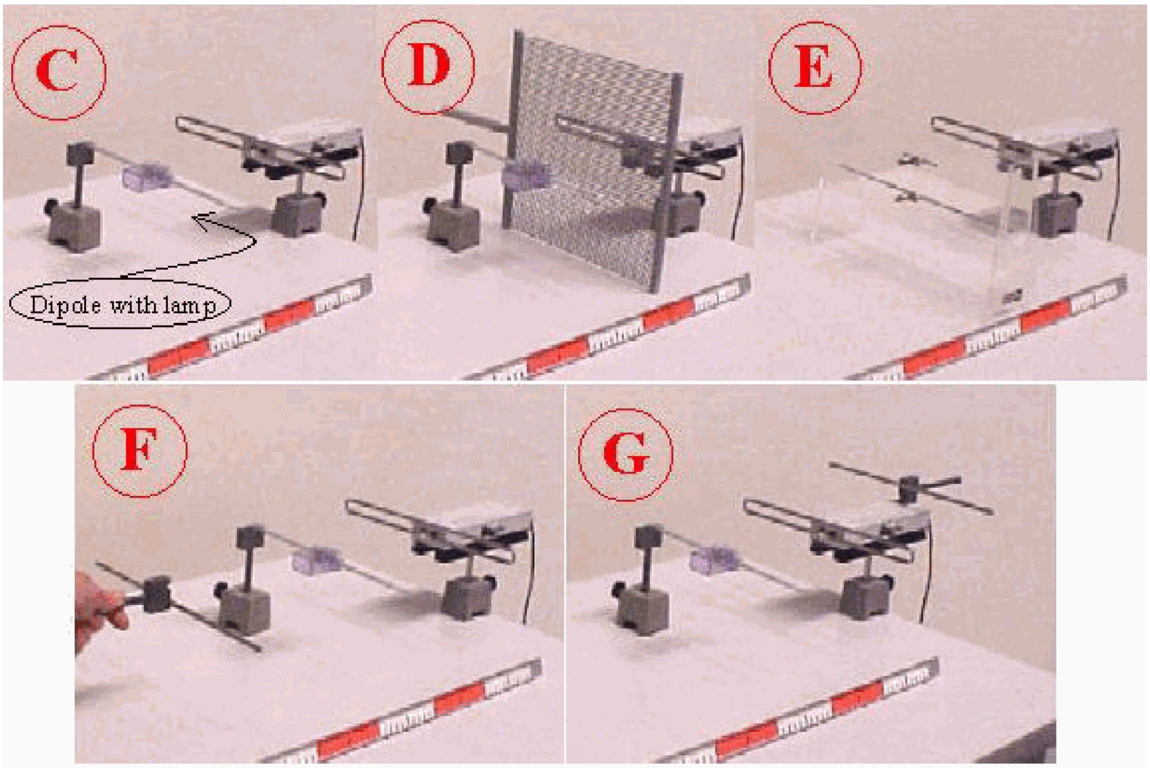


Figure 6.144: .

6.11.1.1.4 Equipment

- UHF-transmitter.
- Dipole loop.
- Transmitter dipole model (box with rope, mid $= \lambda$; see Figure1E).
- Lecher system, a set of metal rods and loops of different length:
  - 4 rods of $3\lambda/4$
  - 1 rod, $\lambda/4$
  - 1 loop, $\lambda/2$ (35 cm)
  - 1 loop, $\lambda/4$
  - 1 shorting plug.
  - 3 PVC rods to support conducting rods.
- Lamp-probe for E-field. This is a lamp socket with lamp, 3.8 V/70 mA, fitted in a PVC block in such a way that the leads of the socket are inside the plastic block and cannot be touched.
- Receiver dipole with lamp 3.8 V/70 mA.
- Coil, $n = 10.000(R = 1350\Omega)$.
- Receiver dipole with h.f. rectifying diode.
- 100vA(1kΩ) demonstration meter.
- Aluminum sheet.
- Metal grated sheet
- Water tank with long and short $\lambda/2$ dipole with lamps 3.8 V/70 mA.
- Demineralized water.
- Ohp-sheet with Figure 3.

6.11.1.1.5 Safety

- No remarks. Electromagnetic waves

6.11.1.1.6 Presentation

6.11.1.1.6.1 Preliminary explanation.

The UHF transmitter box contains a circuit that resonates at around 434MHz. In the output of this circuit, conducting rods of different length can be plugged in. When the wavelength (λ) of the E-field of this 434MHz signal is calculated, we find λ is around 70 cm (the electric field E travels at 3×10^8 m/s).

6.11.1.1.6.2 A. STANDING ELECTROMAGNETIC WAVES ON CONDUCTORS.

The metal two-legged loop, having a length of 35 cm (Lecher-line), is plugged into the transmitter output. Place the lamp-probe with its pvc block on the two-legged loop and slide it along the legs of the loop (see Diagram A). The lighting lamp shows: $V_{R-R} = 0$, rising to $V_{S-S} = max$. and then diminishing to $\mathrm{V}_{\mathrm{T-T}} = 0$.

This pattern can be understood when showing that a full standing E-wave fits into the total length of 70 cm. Then there are E-nodes at 17.5 cm($\lambda/4$) and at 52.5 cm($3\lambda/4$). At 35 cm($\lambda/2$) there is an antinode. Figure1A shows this E-pattern and clarifies that maximum potential difference occurs between S and S. (S-S is an in intensity oscillating dipole.)

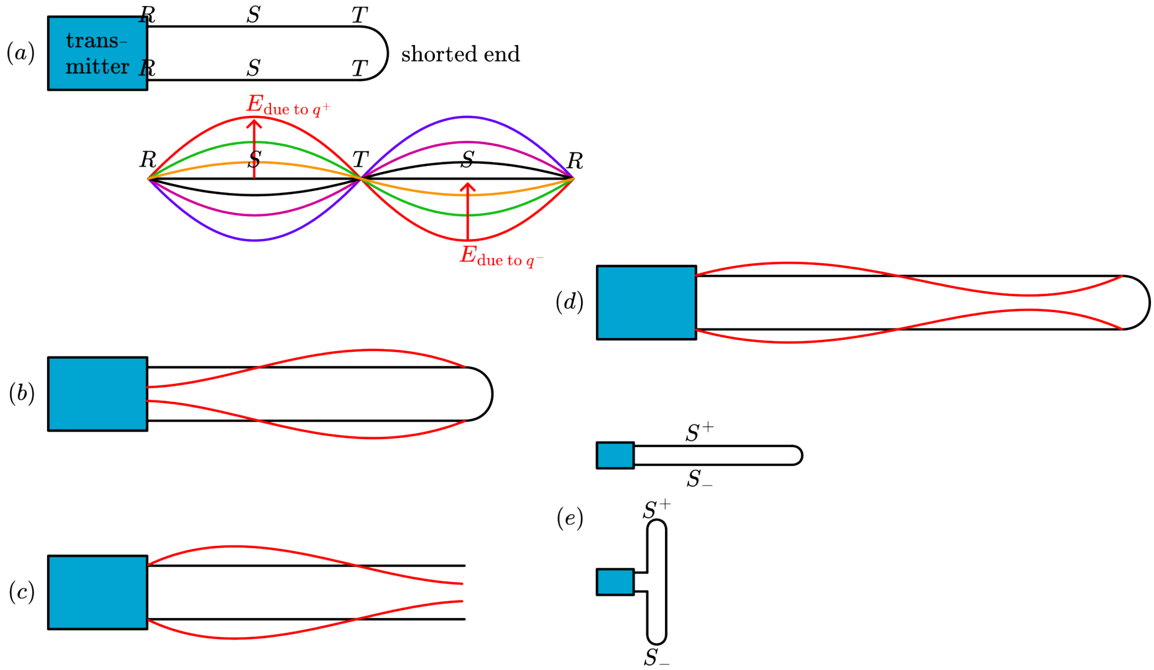


Figure 6.145: .

Then the coil with $n = 10.000$ is connected to a 100vA demonstration meter via the h.f. rectifier diode (see Diagram A). The coil is placed on a cart and slides slowly and close (2 cm distance) along one of the legs of the conducting rods. The demonstration meter shows where induction along the leg happens, it shows the nodes and anti-nodes of the magnetic field B along the conducting rod; so it shows the standing current pattern in the conducting rod. We find B-nodes and anti-nodes on the places opposing those of the E-field. (see also: Remarks)

Then longer two-legged loops are build (Lecher system; see Diagram B). This Lecher system makes i possible to investigate the standing electromagnetic wave in longer variants, either shorted or open ended (Figure 3B, C and D are possible examples). Sliding the lamp-probe and/or the coil in these examples will strengthen the idea of standing E- and B-waves on the conductors.

(When needed to illustrate that a standing wave is related to length, the demonstration "Handheld standing waves" in this database can be used. Also "Kundt's tube" can be used as an analogy.)

6.11.1.1.6.3 B. ELECTROMAGNETIC WAVES IN AIR (DIPOLE LOOP).

The dipole loop is fitted into the transmitter output. This loop has the same total length as the metal two-legged loop of 35 cm used in the first demonstration. The difference is that this dipole loop is folded in a different way: On the overhead projector the transmitter dipole model with rope is used to demonstrate the similarity between the two-legged $\lambda/2$-loop and the dipole loop (see Figure1E). This dipole form is such that the dipole moment (p) of the oscillating positive and negative charges on the loop is maximum, because d is maximum in $p = qd$ (q being the charge at S). (The resulting E-field is proportional to p and the irradiance proportional to p^2; so it is profitable to make p as large as possible [see E.Hecht's "Optics", pg. 62 or another text on electric dipole radiation]).

- Radiation. When the transmitter is switched on, the receiver dipole with lamp shows that at a distance there is also an electric filed (see Diagram C). The measured intensity depends on the distance. Conclusion can be that a field is radiated by the dipole loop.
- Absorption. The receiver dipole is stationed horizontally at around 20 cm distance from the transmitter dipole loop. The absorption of different materials is investigated in placing sheets or blocks of material between the transmitter and receiver dipole. We try: wood, glass, Perspex, Teflon, stone bricks, my arm, water. Only my arm shows absorption, the other materials are transparent to the radiation.
- Polarization. Observing the lamp in the receiver dipole while rotating it shows that the E-field is polarized and stands in the direction of the loop dipole that is plugged into the transmitter. Placing a metal grated fence between the transmitter and the receiver and slowly rotating thi grating, affirms the polarization of the E-field (see Diagram D).
- Reflections. At 17.5 cm ($1/4\lambda$ from the transmitter the receiver dipole is placed. At 35 cm an Al sheet is put in the radiated beam: the receiver dipole shows a rather strong increase in intensity. Shifting the Al sheet produces variations in intensity on the receiver dipole. Putting in at 52.5 cm shows a reduction of intensity, while putting in at 70 cm should show again an increase in the intensity; this is faintly visible. Then from 70 cm the distance is decreased again and after the maximum intensity at 35 cm we approach the receiver dipole still closer causing finally the lamp to dim completely. This last part of this demonstration shows that there is an anti-node at the reflecting sheet. All this can be explained by standing E-waves, similar as in the demonstrations with the conducting rods. When the sheet is replaced by a metal rod of the same length as the receiver dipole, the same demonstrations as with the metal sheet can be performed, also finally completely dimming the lamp of the receiver dipol (see Diagram F). (Instead of using a metal rod in order to increase the intensity at reflection, you can as well use your arm!)

But now we continue!

Move the metal rod from the receiver dipole towards the transmitter and the lamp of the receiver dipole remains extinguished. While close at the transmitter this can be explained suggesting that the rod, that also receives energy from the transmitter, emits the energy again but now with a phase-change of π. A simple test then is to touch the metal bar with your hand in order to absorb part of the energy received by the metal bar and while doing so you will see that while touching, the lamp of the receiver dipole lights again. Another test of the π-phase-shift-hypothesis is placing the metal bar $1/4\lambda$ behind the transmitter dipole in an attempt to increase the lighting of the receiver dipole and amazingly (to the students) this succeeds (see Diagram G). (A/so here you can use your arm as a reflector.)

- EM-waves in water. At 17.5 cm from the transmitter dipole the acrylic box with two lamps is placed (see Diagram E). The lamp with the longer metal rods will lighten. Then demineralized water is poured into the box. When the water level reaches the longer metal rods, the lamp turns out. When finally the water level reaches the short metal rods the lamp connected to those rods lights up. This shows that the wavelength in water is much shorter than the wavelength in air (the rods are 9 times shorter). This corresponds with the dielectric constant of water being around 80: $c_{medium} = \frac{C}{\sqrt{\varepsilon_r \mu_r}} \cdot c_{water} = \frac{1}{9}c$, making $\lambda 9$ times smaller. Behind the waterbox the wavelength is again 70 cm as placing of the lamp probe with longer rods at that position will show.

6.11.1.1.7 Explanation

Figure 3 explains the polarized E-field that is produced by the loop dipole. This loop dipole is effectively the two-legged loop of Figure 3A, but folded in a different way. Figure1E makes clear that there is a resulting E-field pulsating with a frequency of 434MHz. The explanation is already done in the description “PresentationXX”. More details can be found in the presented “SourcesXX”.

6.11.1.1.8 Remarks

- The $\pi/2$ phase-shift between E and B on the Lecher line should not be confused with the in-phase situation of E and B of the EM-field in vacuum (air). The in-phase situation belongs to the EM-field as detected relatively far away from the emitting dipole.
- Detecting the magnetic field is very difficult, because the B-field is very, very weak. It is even advisable not to perform this part of the demonstration with this equipment. A much stronger sender is needed for that!
- Do not touch the metal bar and Al-sheet and the metal grated fence with your hands, because then energy is absorbed and the metal is no perfect reflector any longer.
- Mind that anything made of metal in the neighborhood of your demonstration is a possible reflector. (For instance the metal frame of your table.)
- In the demonstration with the Lecher-lines mind that the detector lamp is not touching the conducting lines, because this will destroy your lamp.

6.11.1.1.9 Sources

- Buijze W. en Roest R., Inleiding electriciteit en Magnetisme, pag. 172-173.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 792-794.
- Hecht, Eugene, Optics, pag. 43-46 and 62-63.
- Leybold Didactic GmbH, Gerätekarte, pag. 58751-58755.
- Vogel, H, Physik, pag. 290-299.

6.11.1.2 06 Microwave Oven Standing Waves

6.11.1.2.1 Aim

To show a standing electromagnetic wave.

6.11.1.2.2 Subjects

- 3B22 (Standing Waves) 5N10 (Transmission Lines and Antennas)

6.11.1.2.3 Diagram

Figure 6.146: .

6.11.1.2.4 Equipment

- Microwave oven. The oven is adapted so it can operate with its door open.
- Piece of cardboard covered with marsh-mallows.
- Video-camera and projector to project an image of the marsh-mallows to the students.

6.11.1.2.5 Safety

- We operate the microwave oven with its door open, so keep enough distance away from it. One hazard is well known and documented: As the lens of the eye has no cooling blood flow, it is particularly prone to overheating when exposed to microwave radiation. This heating can in turn lead to a higher incidence of cataracts in later life.
- There is also a considerable electrical hazard around the magnetron tube, as it requires a high voltage power supply.

6.11.1.2.6 Presentation

Shortly the operation of the microwave oven is explained to the students. This is done by showing the cavity magnetron to them and explaining its operation (see Figure 2). See for instance: https://www.radartutorial.eu/08.transmitters/tx08.en.html

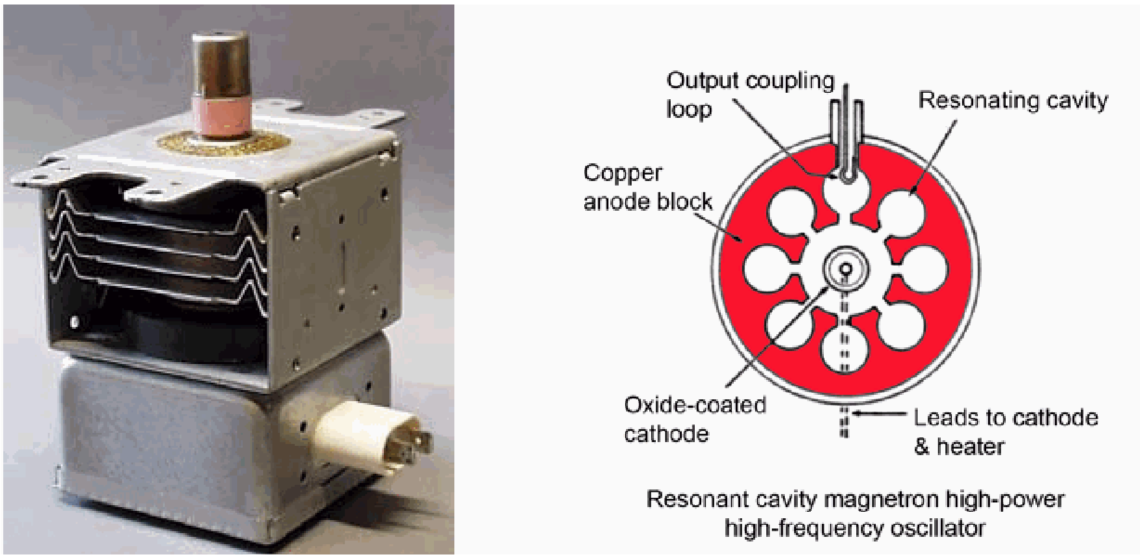


Figure 6.147: .

The oven is switched ON for around 2 minutes. After around 30 seconds it is observed that the marsh-mallows rise. After two minutes it is clearly observed that the rising occurs only at certain spots (see Figure 3).

Figure 6.148: .

We measure $d = 10$ cm.

6.11.1.2.7 Explanation

The rising of the marshmallows at certain spots only, shows that there is heating only at certain spots. This can be explained by assuming a standing em-wave in the cavity that the oven is.

6.11.1.2.7.1 Discussion:

Knowing that the magnetron-frequency is 2.45Ghz, makes that the wavelength in air of the em-wave equals 12.2 cm. Then possible standing waves are standing waves with $n(12.2)\text{cm}[n = 1, 2, 3, ...]$, and we expect heating at multiples of half wavelength distances, so at $\text{n}(6.1)\text{cm}$. We measure heating hills at 10 cm separation (see Figure 3). This means that the standing wave has a wavelength of 20 cm. This can only mean that the frequency of the em-wave inside the oven is less than 2.45MHz. supposing it is half that frequency, then we expect standing waves with $\text{n}(24.4)\text{cm}$, and heating hills at 12.2 cm separation. That we measure 10 cm can be caused by the dielectric constant of marshmallows being > 1, causing a smaller wavelength inside the marshmallows.

6.11.1.2.8 Sources

- https://www.radartutorial.eu/08.transmitters/tx08.en.html

7. 6 Optics

7.1 6A Geometrical Optics

7.1.1 6A01 Speed of Light

7.1.1.1 01 Speed of Light; Foucault-Michelson

7.1.1.1.1 Aim

To “measure” speed of light

7.1.1.1.2 Subjects

- 6A01 (Speed of Light)

7.1.1.1.3 Diagram

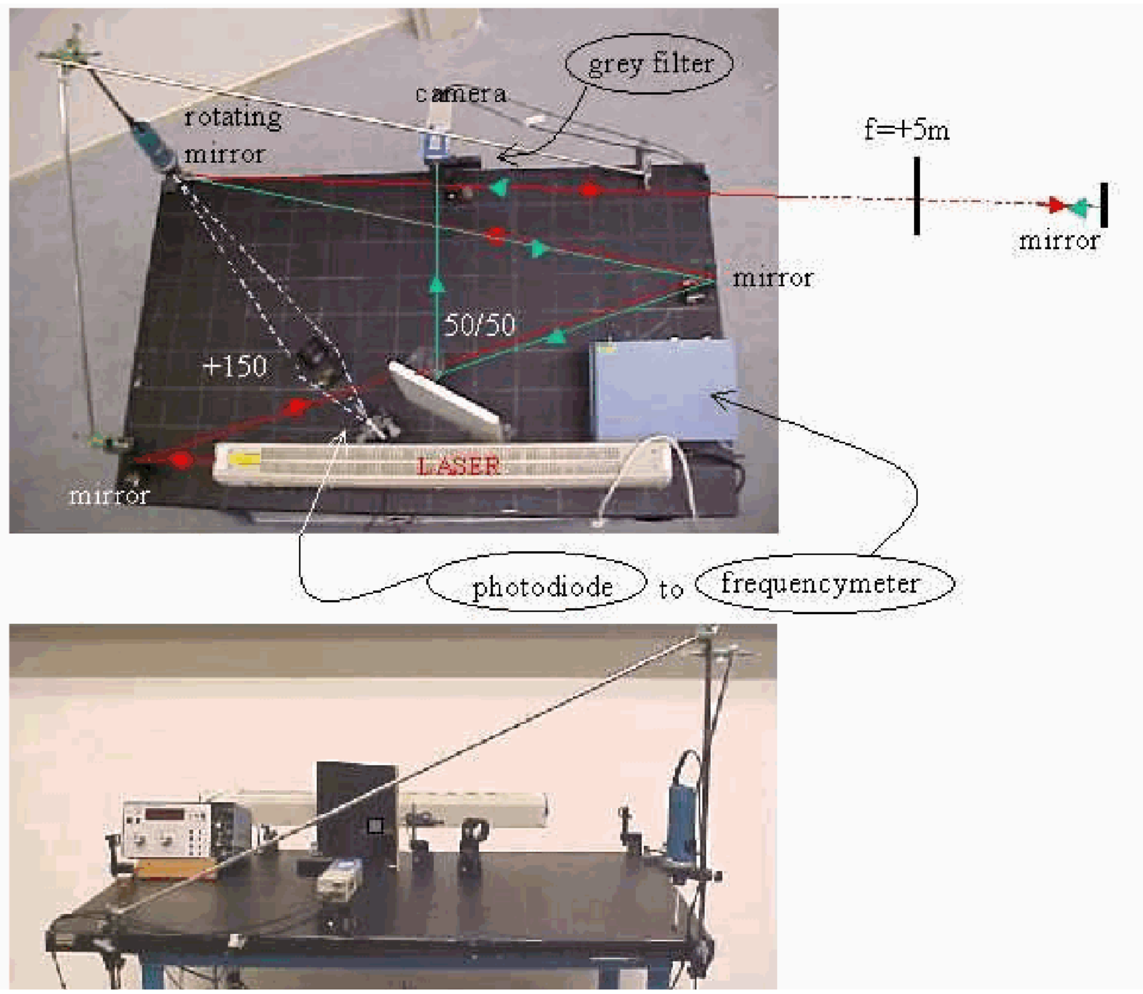


Figure 7.1: .

7.1.1.1.4 Equipment

- Optical components (see Diagram).
- Camera without lens (see Diagram).
- Variable transformer to supply the motor of the rotating mirror.
- 5Vdc to supply the photo-diode circuit.
- Monitor, connected to camera.
- Double overhead sheet, explaining the assembly.

7.1.1.1.5 Presentation

7.1.1.1.5.1 Preparation:

Make the laser beam go as horizontal as possible; careful alignment is essential in this demonstration. (Start at the laser and work step by step working yourself through the light path.)

The +5 m-lens is positioned at about 5 m distance from the rotating mirror.

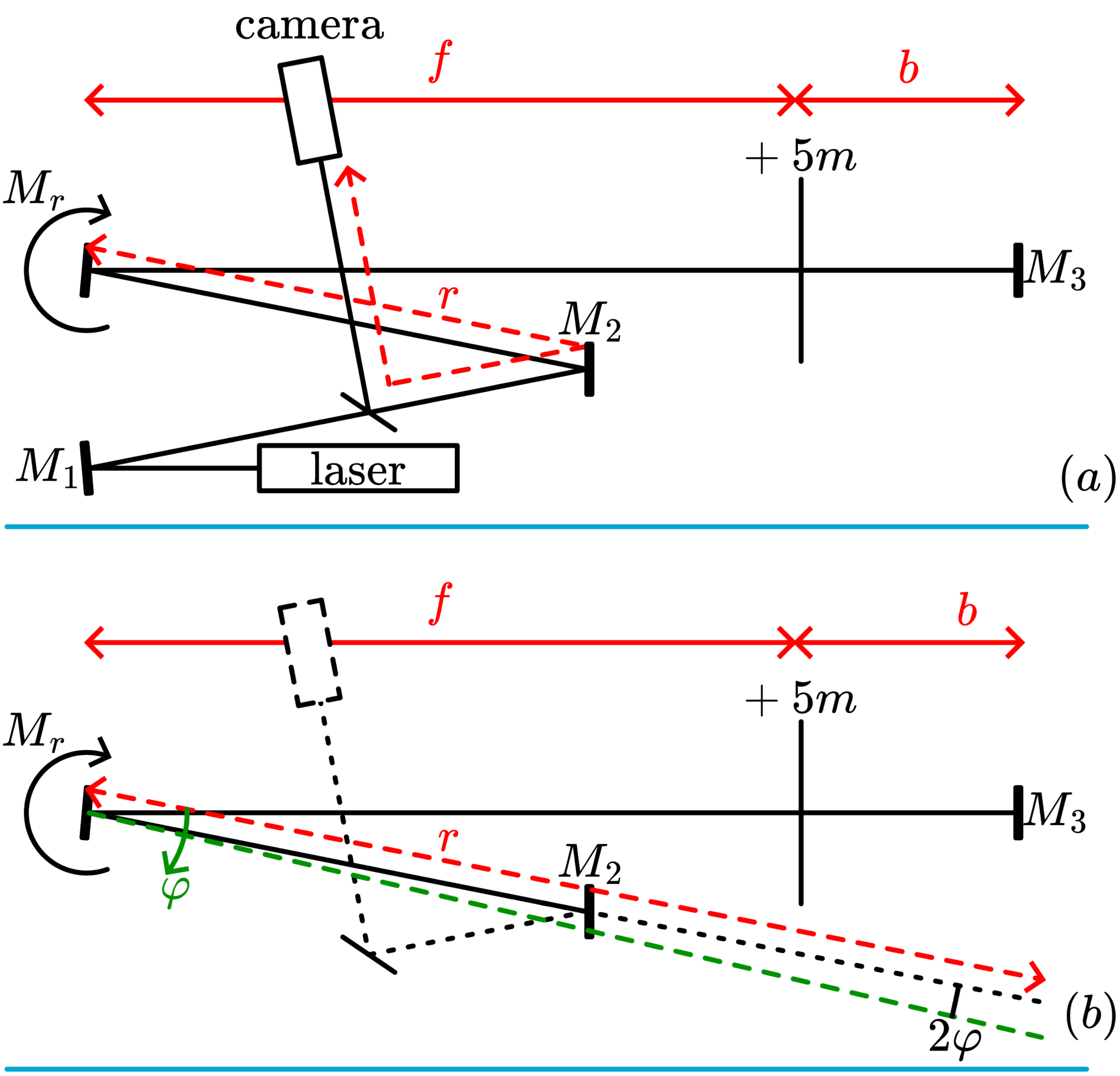


Figure 7.2: .

Image-distance b (see Figure 2A) is chosen such that the image of the first mirror (M_1) is sharp at $M_3\left(\frac{1}{f}=\frac{1}{r+f}+\frac{1}{b}\right)$. (In our assembly this means that b is around 25 meters.) Lens +5 m and M_3 are carefully adjusted until, in the right postion of the rotating mirror (M_r) the laserbeam is reflected to the camera (the camera and M_1 have the same distance to M_3). Making the rotating mirror turn at its highest speed (about 500 rev. per second) the light spot displaces, in our assembly, the whole width of the monitor screen. This displacement is calibrated by placing a plastic ruler between the grey filter and the camera (see Figure 3A).

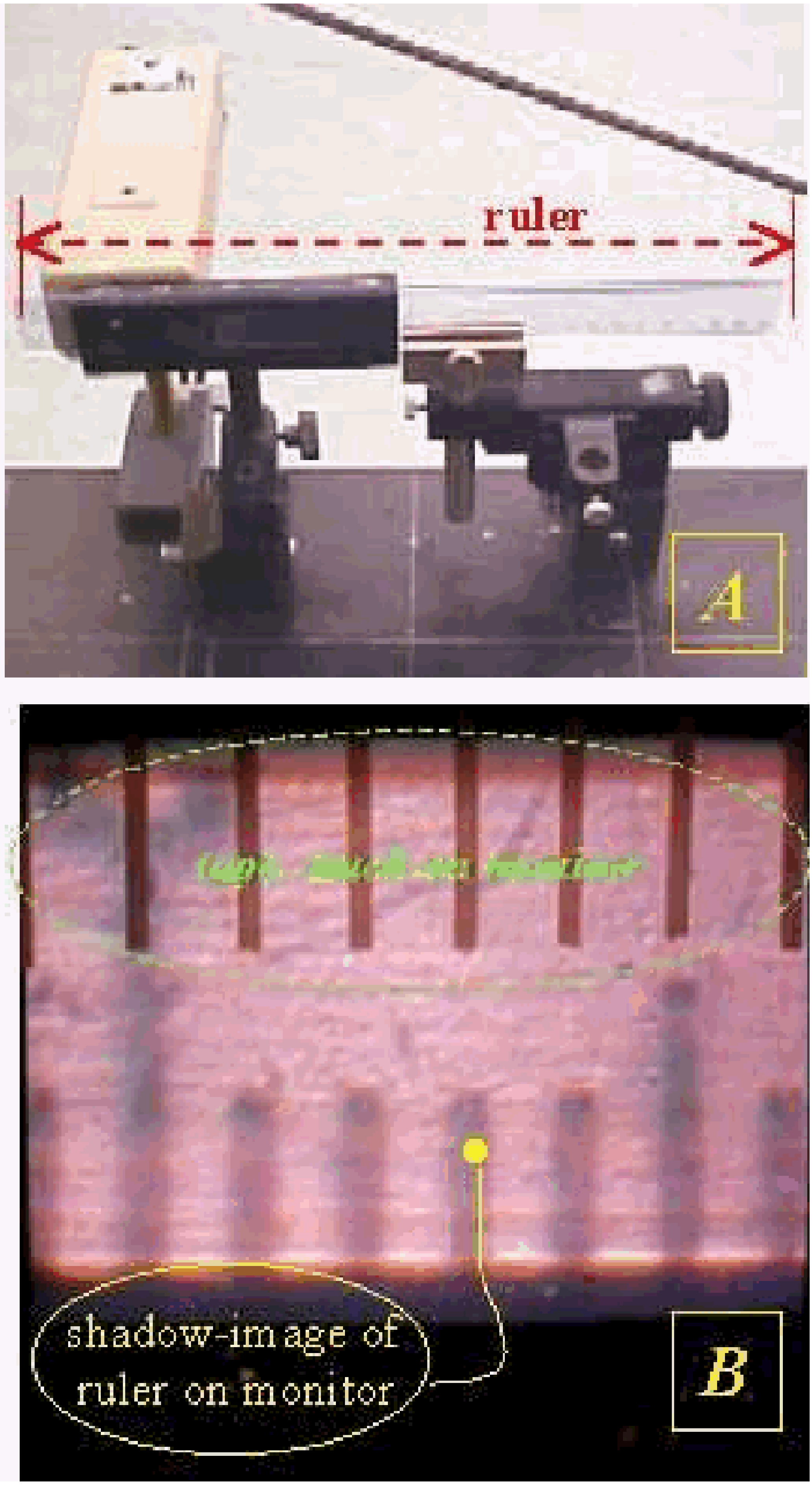


Figure 7.3: .

Shadow projection of the mm-lines on the sensitive layer of the camera show these lines on the monitor (we have 7 mm across the full width of the monitor screen; see Figure 3B). The geometry of the assembly makes it possible to link the rotation of the mirror to the displacement on the monitor screen (we have a displacement of around

2.5 mm on the camera, corresponding to $\phi = \frac{d}{2r} = \frac{2.5 \times 10^{-3}}{2 \times 2.6} = 0.48 \times 10^{-3}$rad of $\mathrm{M_r}$).

7.1.1.1.5.2 Demonstration:

The laser is switched on and the light path is shown to the students. By hand the rotating mirror is turned until a flash is seen on the monitor screen. In this position the light path is as drawn in the Diagram. The principle of operation is explained to the students: In the time it takes the light beam to travel the distance $M_r - M_3 - M_r$ the rotating mirror has made a little angle (ϕ). This is observed on the monitor screen (angle 2ϕ, see Figure 2B).

Also the calibration is explained to the students.

While the speed of rotation of M_r increases the students see an increasing displacement of the light spot on the monitor screen. While running at a convenient speed (we use $n = 500\ \mathrm{s}^{-1}$ to make calculations easy), this reading and that of the displacement on the monitor screen are used to calculate the speed of light.

7.1.1.1.6 Explanation

During the time (Δt) it takes the light beam to travel the distance $M_r - M_3 - M_r$ the rotating mirror has made a little angle (ϕ) that is read from the monitor screen. Observing the speed of rotation on the frequency meter, the time it took to make this little angle can be calculated. For instance we measure when M_r runs at $500\ \mathrm{s}^{-1}$, a light spot displacement of $d = 2.5$ mm on the monitor screen. This means an angle of rotation of that mirror of $\phi = \frac{d}{2r} = \frac{2.5 \times 10^{-3}}{2 \times 2.6} = 0.48 \times 10^{-3}$rad. With $n = 500\ \mathrm{s}^{-1} (500 \times 2\pi \mathrm{rad/sec})$

this means a time-span of $\Delta t = \frac{0.48 \times 10^{-3}}{500 \times 2\pi} = 0.15 \mu$sec. (So, the displacement measurement on the monitor screen becomes in this way a Δt-measurement.) Our distance f + b = 23 meter. This gives us $c = \frac{2 \times 23}{0.15 \times 10^{-6}} = 3.1 \times 10^8$ m/s. (The measurement of the light spot displacement on the monitor screen is done very roughly, so our result of c = 3.1×10^8 m/sec is satisfying.)

7.1.1.1.7 Remarks

- Since 1984 the speed of light is a universal constant (having the exact value of 299792458 m/s; in vacuum). So principally it cannot be measured. Doing this experiment means measuring the distance $f + b$. But we just do the demonstration and “measure” the speed of light and in the end we mention this “complication” to the students.
- Measuring the speed of rotation with the photo-diode is complicated since the light spot sweeps very fast across the photo-diode. We use a +150 mm lens to make the light spot stay longer on the photo-diode during its sweep (see Diagram).
- The “grey filter” shown in the Diagram is a variable neutral density filter used to adjust the light intensity to the camera.

7.1.1.1.8 Sources

- Hecht, Eugene, Optics, pag. 5
- Leybold-Heraeus, Physikalische Handblätter, pag. DK535.222;b

7.1.2 6A10 Reflection From Flat Surfaces

7.1.2.1 01 Confusing Mirrors (mirrors at 90 degrees)

7.1.2.1.1 Aim

To show just plane mirrors in which the images are rather complicated.

7.1.2.1.2 Subjects

- 6A10 (Reflection From Flat Surfaces)

7.1.2.1.3 Diagram

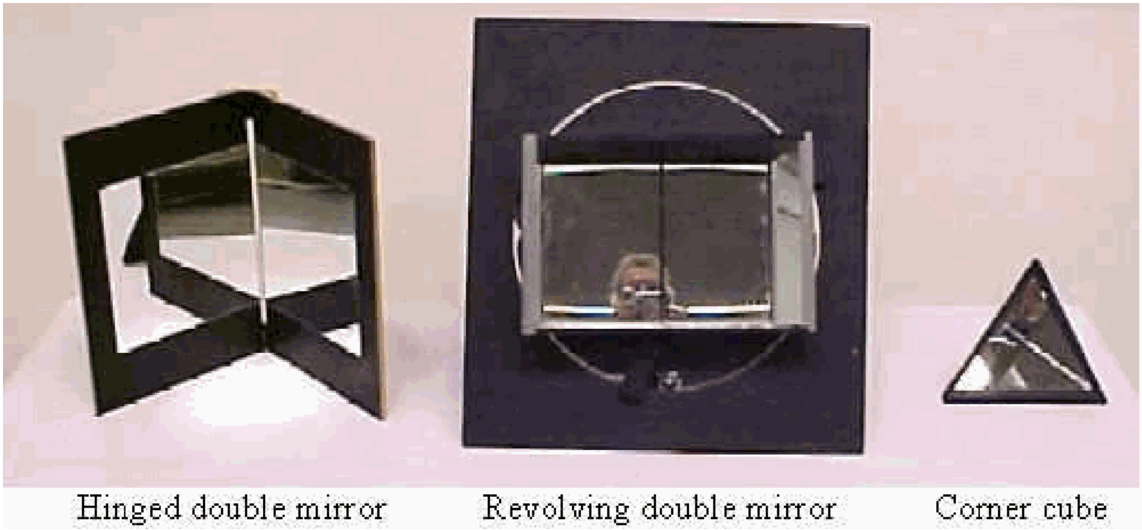


Figure 7.4: .

7.1.2.1.4 Equipment

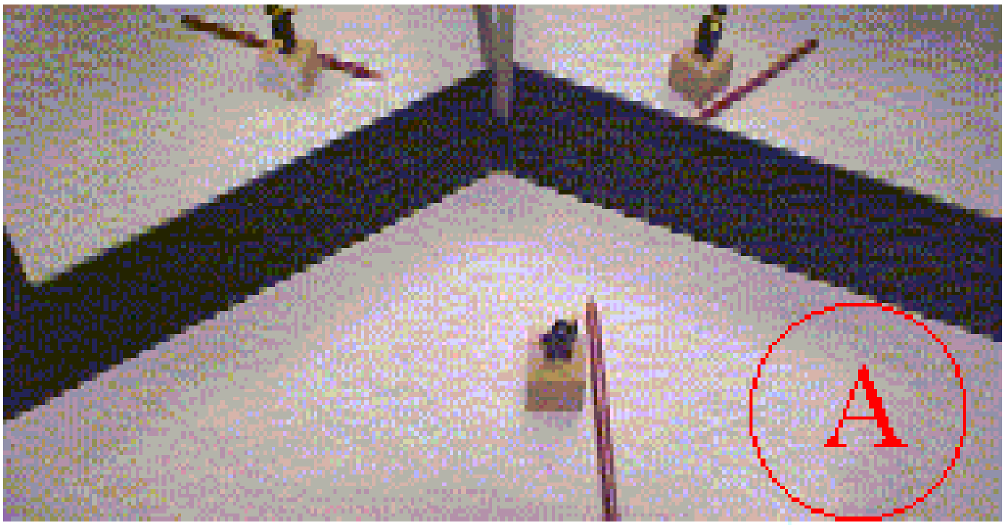
- Planar mirror.
- Two hinged planar mirrors.
- Revolving double mirror; the mirrors stand perpendicular to each other.
- Three planar mirrors arranged as a corner cube. .

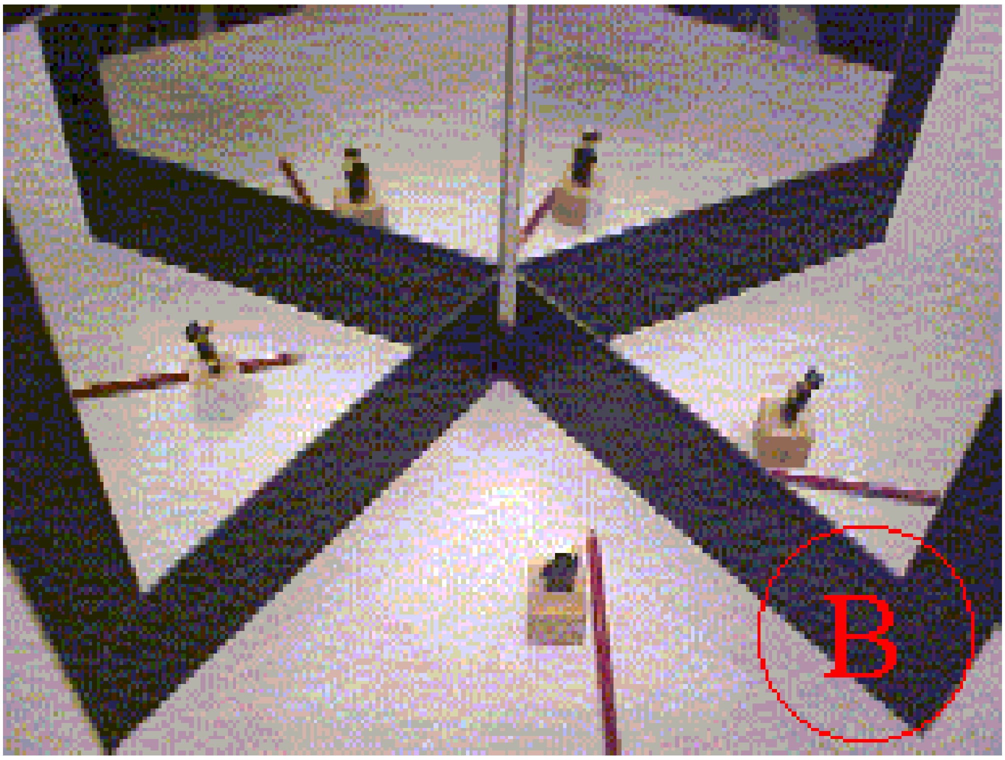
7.1.2.1.5 Presentation

1. Look into the planar mirror.

As is known very well,the image of the left hand is a right hand. But why are top and down not interchanged?.

2. Look into the hinged double mirror (see Figure 2), the angle between the two mirrors (α is larger than 90°. Moving your eyes you see left and right an image of your head (Figure 2A). Left/right is interchanged in the images.


A


B

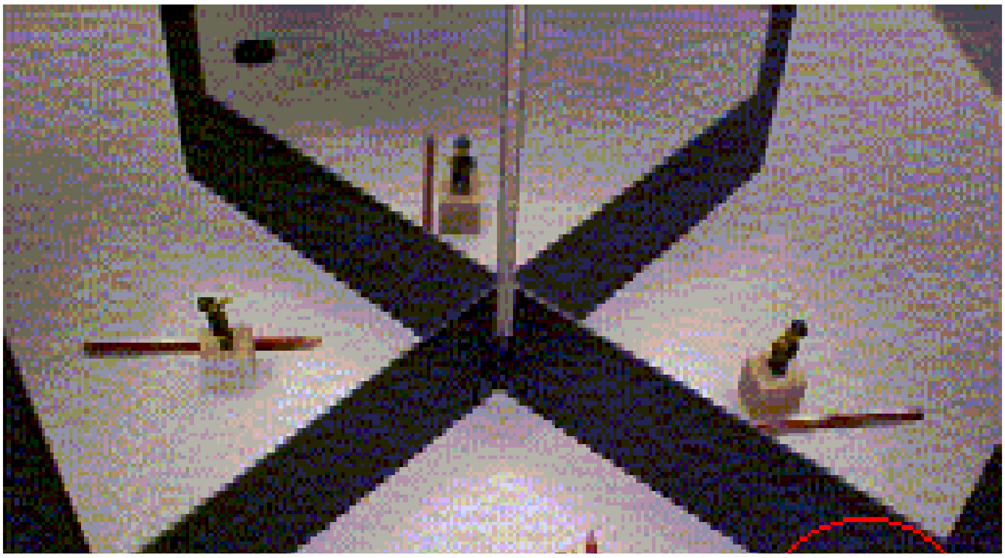


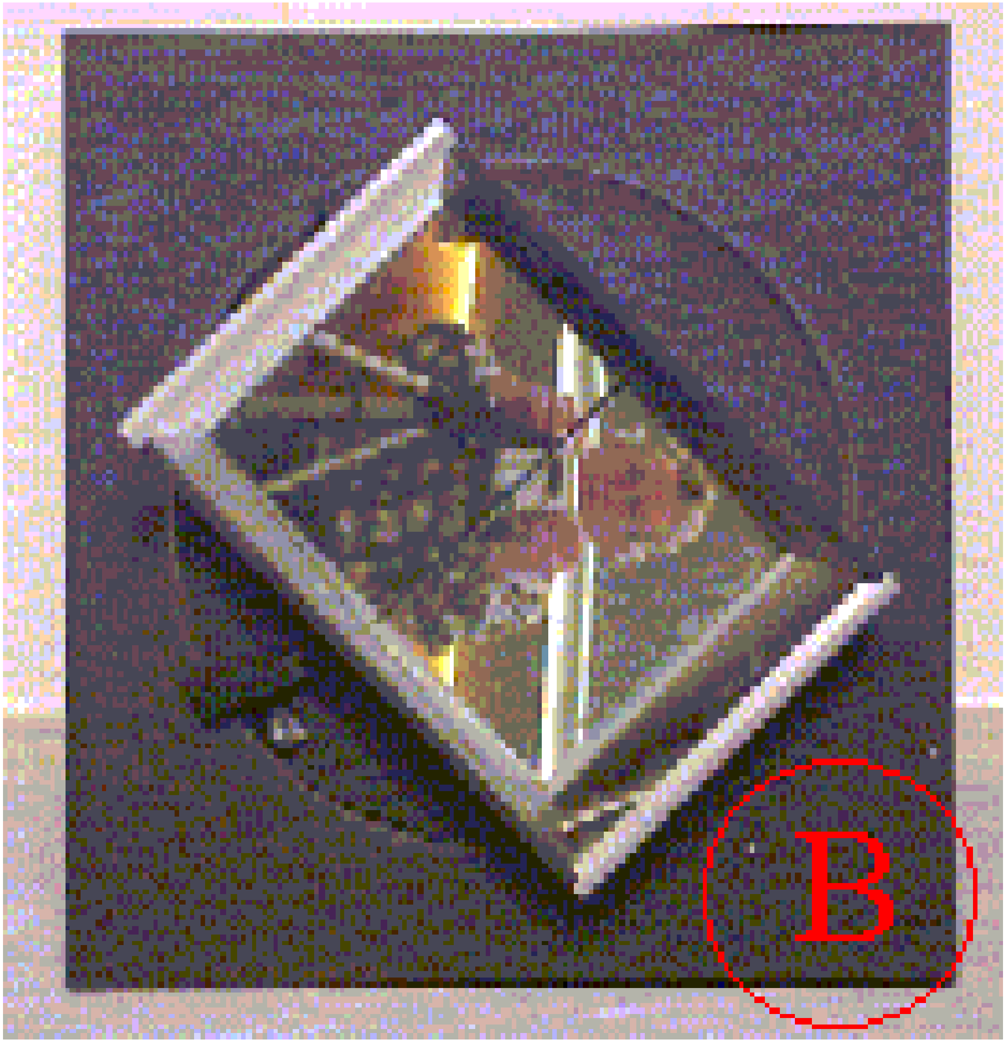
Figure 7.5: .

Now make the α smaller than 90°. At around $\alpha = 60°$ you see four images (see Figure 2B): The image in the left mirror is again imaged in the right mirror and viceversa.

Slowly the α is made smaller and the two imaged images fall together (at $\alpha = 90°$) (see Figure 2C). Move your head on one side to observe this particular image and see that in this image left is still left.

3. Look at the revolving double mirror (see Figure 3A). Turn it round slowly and observe that you are upside down (your image is rotated 180° when the mirror.


A


B

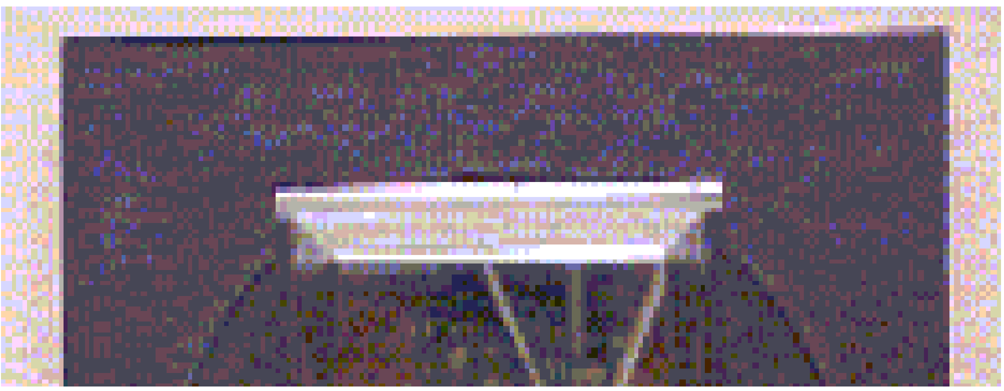


Figure 7.6: .

4. Look (close one eye) into the arrangement of three planar mirrors (see Figure 4).

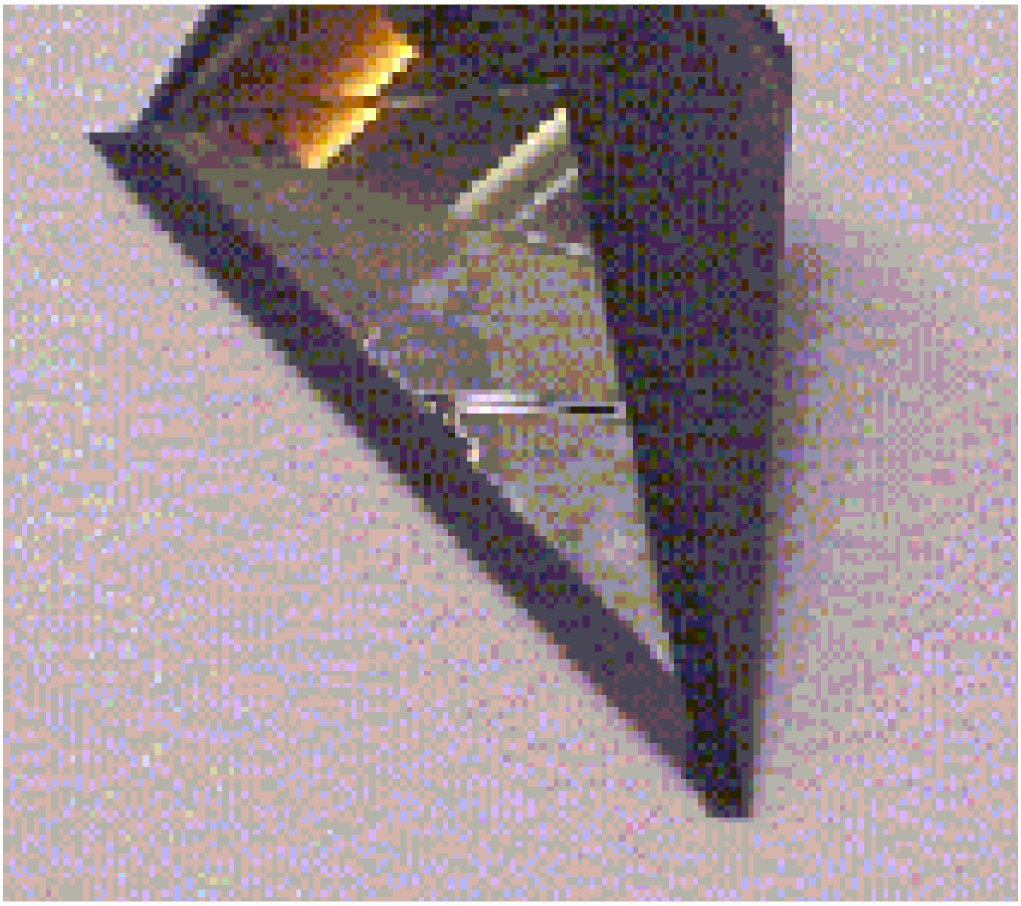


Figure 7.7: .

Observe:

- left remains left and up becomes down;
- your eye remains caught in the middle of the arrangement; it won't help moving your head up-down/right-left.

7.1.2.1.6 Explanation

For explanation see the demonstration Corner cube.

7.1.2.1.7 Sources

- Hecht, Eugene, Optics, pag. 178-180 and 195
- Stewart, J, Calculus, pag. 791 and 796

7.1.2.2 02 Corner Cube

7.1.2.2.1 Aim

To show that the reflecting light ray in a corner cube is always parallel to the entering ray.

7.1.2.2.2 Subjects

- 6A10 (Reflection From Flat Surfaces)

7.1.2.2.3 Diagram

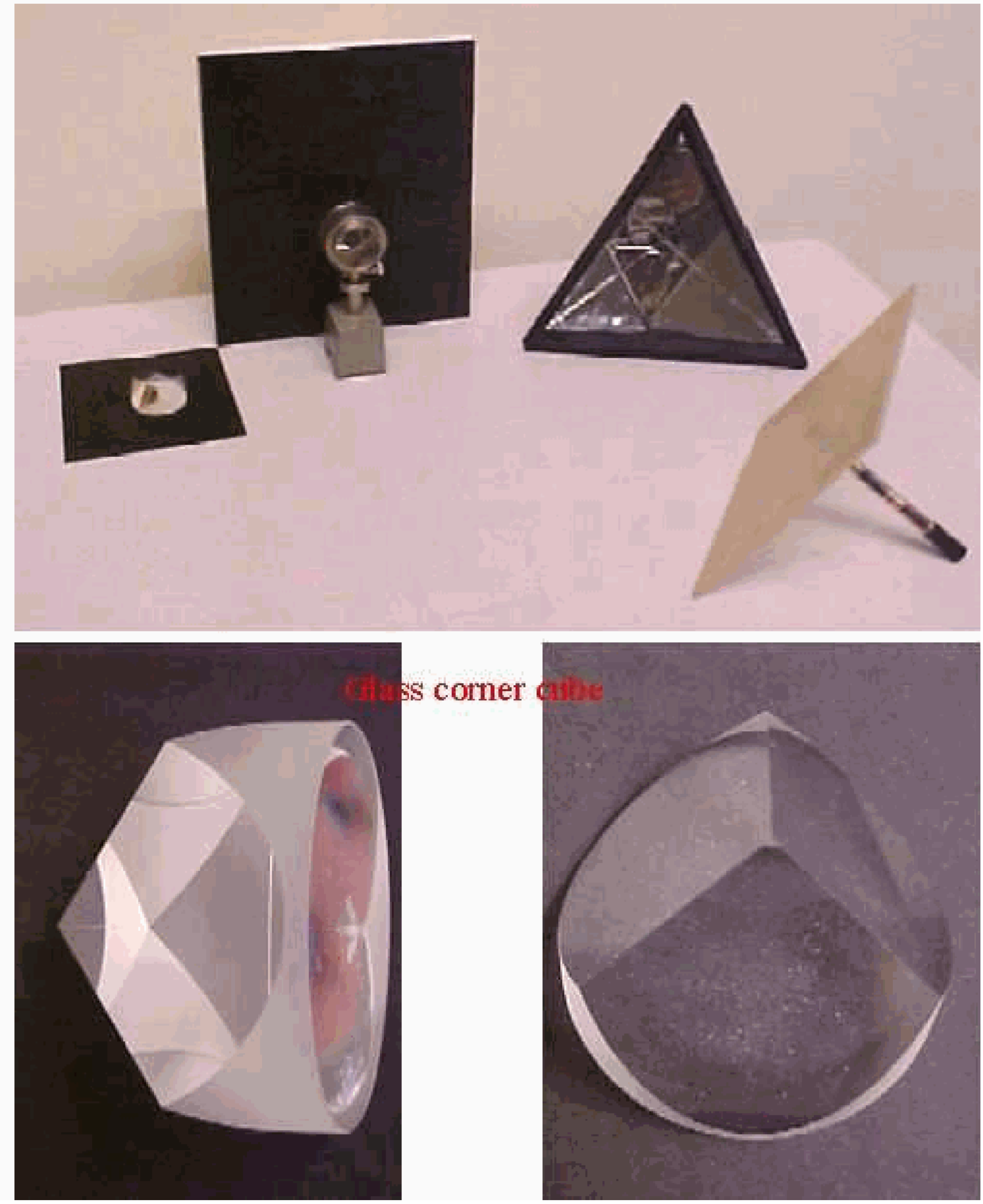


Figure 7.8: .

7.1.2.2.4 Equipment

- Prism corner cube, glass.
- Prism corner cube in fitting.

- Three planar mirrors arranged as corner cube.
- Laser pointer fitted in transparent ground perspex.

7.1.2.2.5 Presentation

The objects are presented to the students. They are invited to look with one eye closed into the corner cube and move their head. They will notice that their eye remains caught in the center of the corner cube and that up-down and left-right are reversed.

Directing a laser beam towards a corner cube produces a reflection back to the laser pointer as reflection on the ground screen shows: the reflection is always parallel to the incident beam on the corner cube, It does not matter from which direction the laser beam is coming as long as it "sees" the three mirrors.

7.1.2.2.6 Explanation

In a planar mirror the image and object are equidistant from the mirror surface. But there is also inversion:

a right-handed coordinate system is converted into a left-handed one (see Figure 2).

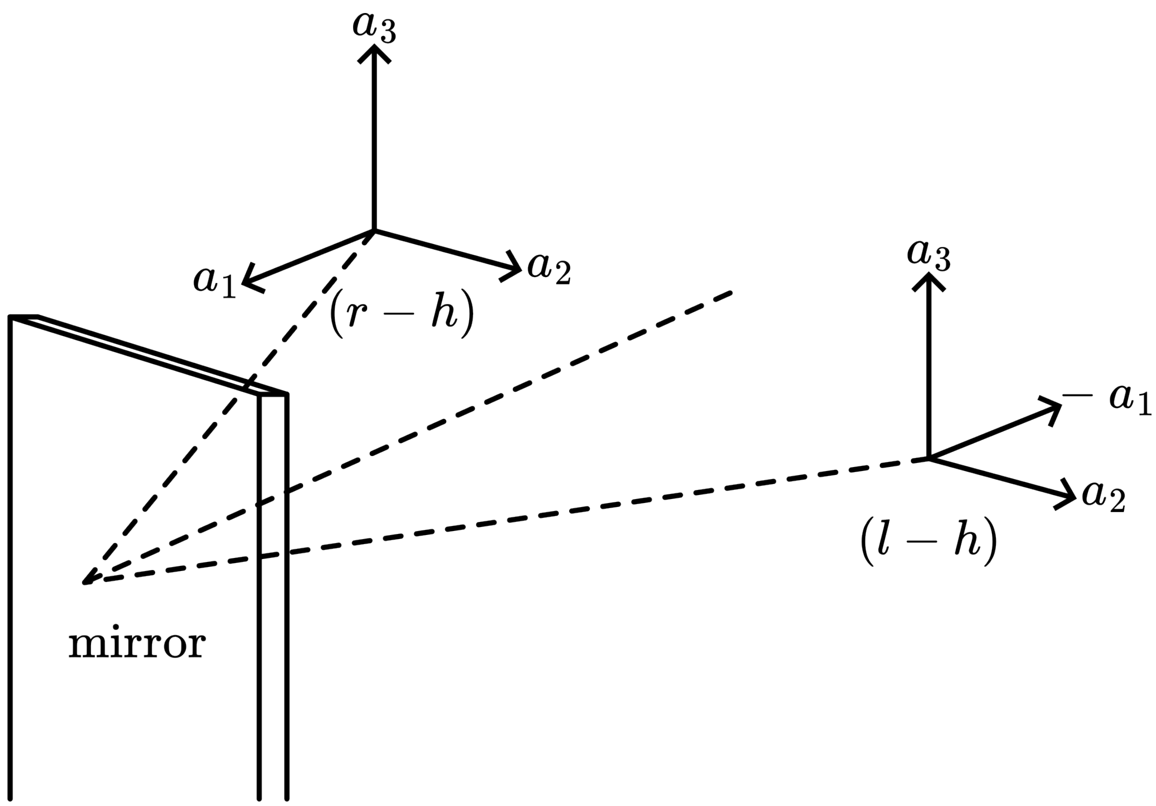


Figure 7.9: .

We see that after reflection a_1 has changed into $-a_1$, while a_2 and a_3 remain the same. Vector notation is applied to treat this.

Figure 3 shows that reflection in three mutually perpendicular mirrors (xz, xy, yz) will produce ray (vector) inversion. Three reflections occur:

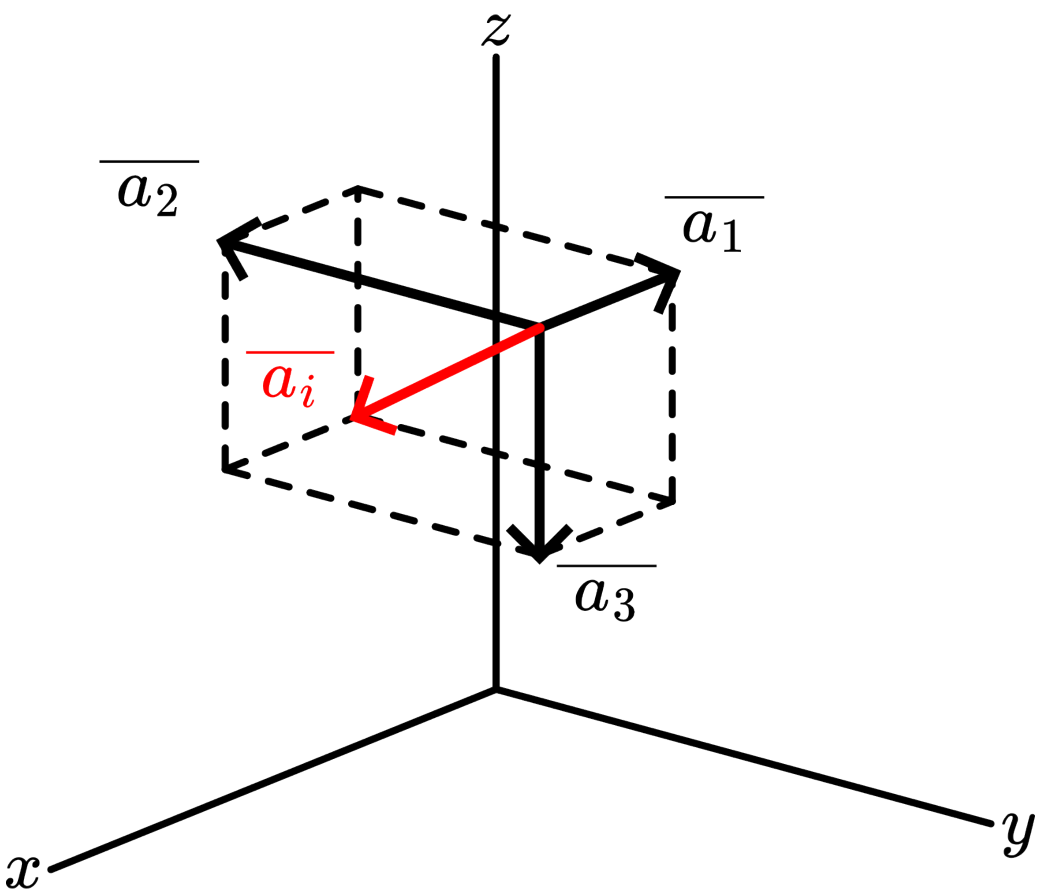


Figure 7.10: .

- against xz-plane, a_2 changes into $-a_2$,
- against xy-plane, a_3 changes into $-a_3$ and
- against yz-plane, a_1 changes into $-a_1$.

So the finally reflected ray is $a_r \leq -a_1, -a_2, -a_3 \leq -a_\text{a}$. So the reflected ray is parallel to the incident ray.

7.1.2.2.7 Remarks

- The principle that the resulting reflection is always perpendicular to the initial ray is used in an array of corner cubes on the moon. Together with a laser beam from earth the measurement of the reflection is used to calculate very precisely the distance from Earth to the Moon.

7.1.2.2.8 Sources

- Hecht, Eugene, Optics, pag. 178-180 and 195
- Stewart, J, Calculus, pag. 791 and 796

7.1.3 6A40 Refractive Index

7.1.3.1 01 Chromatic Aberration

7.1.3.1.1 Aim

To show that different “colored” rays traverse a lens along different paths.

7.1.3.1.2 Subjects

- 6A40 (Refractive Index) 6A60 (Thin Lens) 6F30 (Dispersion)

7.1.3.1.3 Diagram

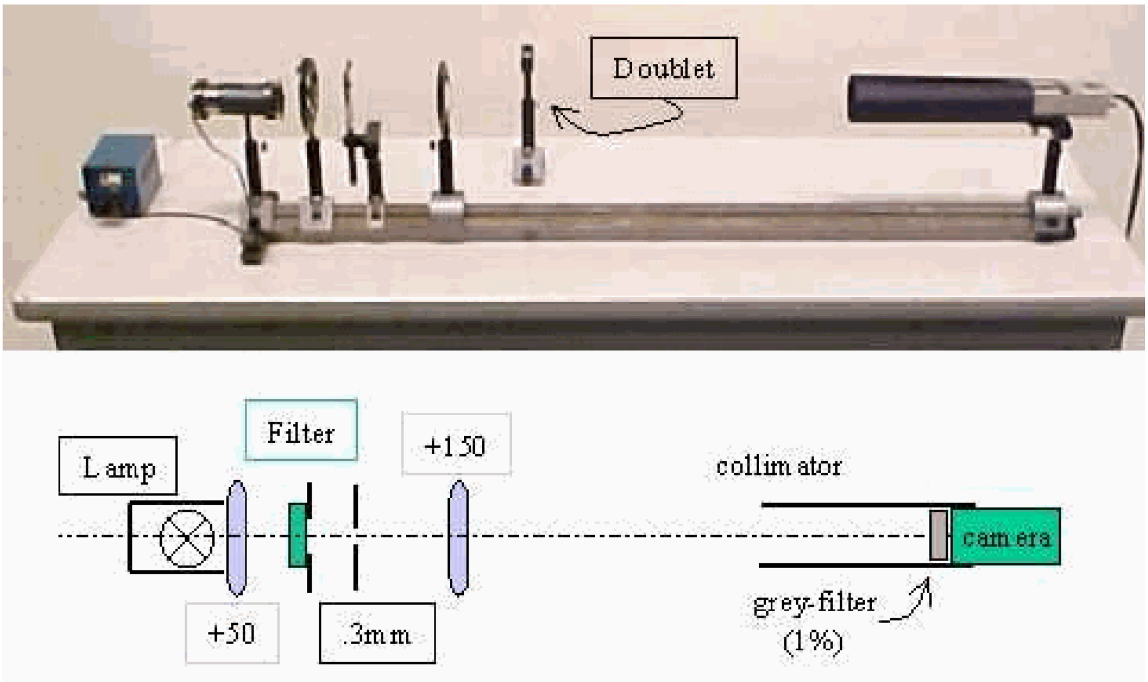


Figure 7.11: .

7.1.3.1.4 Equipment

- Optical rail, 1.5 m.
- Lamp 6 V/5 A, fitted with a condenser lens +50 mm.
- Four interference filters: 644 nm; 578 nm; 546 nm; 436 nm (normally used to select H_a spectral lines).
- Wheel to mount these filters.
- Diafragm, diam. = .3 mm.
- Single lens, f = 150 mm, diam. = 75 mm.
- Doublet, f = 150 mm.
- White screen, used to align the optical components.
- Camera, lens removed.
- Grey filter (.01), stuck to camera.
- Collimator (made of black paper, see Diagram).
- Projector, to project image of camera.

7.1.3.1.5 Presentation

The lamp and camera are positioned each at the end of the rail. The camera has its lens removed; a .01 grey filter is placed on it. The other components are placed and carefully aligned; see Diagram (use the white screen at the position of the camera).

Using the red interference filter the .3 mm-diaphragm is pictured on the camera at the end of the optical rail. To get a sharp picture the diaphragm is shifted. The projector projects this image to the students. The red filter is turned away and the yellow filter is now in position. Clearly can be seen that this picture is not sharp. To get it sharp we need to shift the camera towards the lens. The same happens when next we apply the green and then the blue filter. Going from red to blue we need to shift the camera about 20 cm in total. This is clearly observable to the students. And the conclusion can be that the lens has a smaller focal distance for shorter wavelength.

When the 150 mm single lens is replaced by the doublet of 150 mm, changing filters will result in sharp images all at the same position of the camera on the rail: no shifting is needed. There is no chromatic aberration.

7.1.3.1.6 Explanation

Since the thin-lens equation $\frac{1}{f} = (n_t - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$ is wavelength-dependent via $n_1(\lambda)$

(dispersion), the focal length must also vary with λ (Figure 2 shows the graph of n, versus λ of crown-glass.).

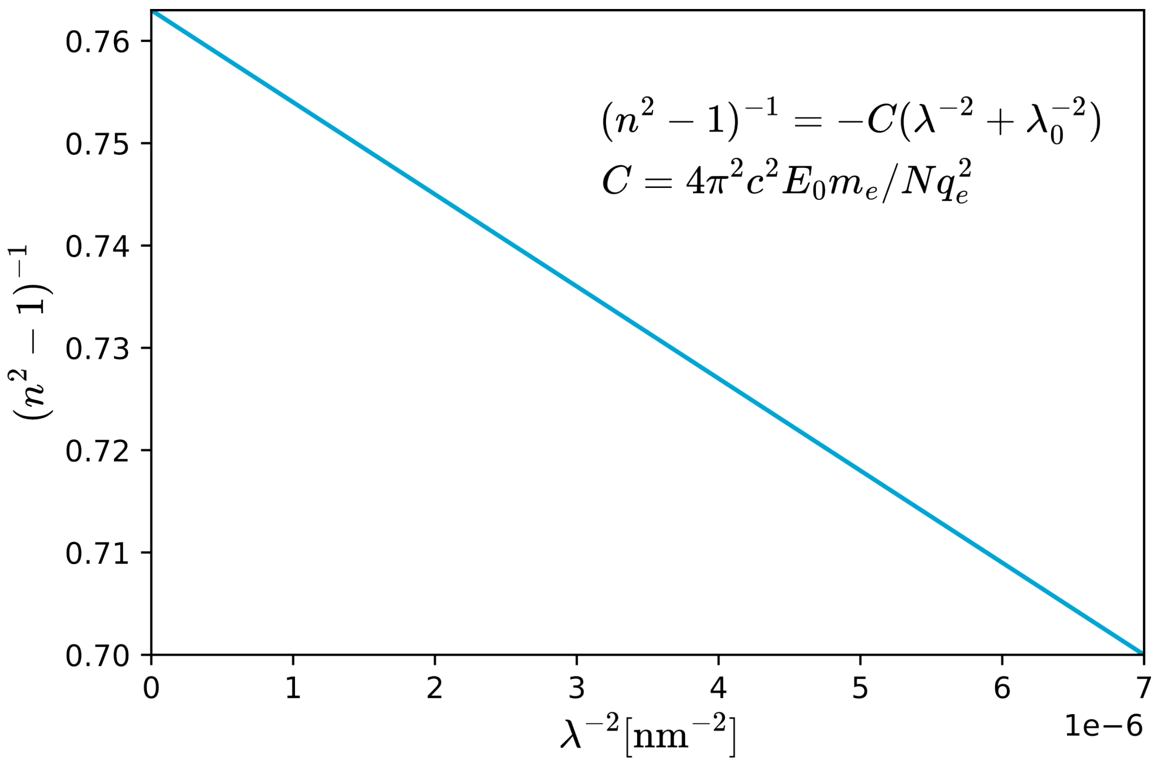


Figure 7.12: .

In general $n_1(\lambda)$ decreases with wavelength over the visible region, and thus $f(\lambda)$ increases with λ. And when $f(\lambda)$ increases with λ, then also the image-distance increases with λ (object-distance is constant). The demonstration shows this: the red image being sharp at a larger distance than the blue image.

A negative lens would generate "negative" chromatic aberration. This suggests that a combination of a positive - and a negative lens could result in an overlapping of f_{red} and f_{blue}. This is the way an achromatic doublet functions.

7.1.3.1.7 Remarks

- Careful alignment is essential to this demonstration: The optical axis needs to be in good parallelism with the optical rail, so that when shifting the camera the light spot stays on the center of the screen.

- The demonstration can also be done without using filters; Then the diaphragm is imaged at the camera as good as possible. When now we shift the camera towards the single lens we will get a concentration of blue near the optical axis and red in a circle around it. Shifting the camera away from the lens the opposite happens: we see red near the optical axis and a blue circle around it. Going from one position to the other also yellow and green near the axis can be observed.
- The demonstration can also be done using a Hg-lamp in stead of an incandescent lamp. However, in that way the demonstration is more complicated due to the high differences between the intensities of the separate spectral lines: Every spectral line will need its own grey-filter in order not to saturate the light sensitive layer of the camera.

7.1.3.1.8 Sources

- Hecht, Eugene, Optics, pag. 66-73, 157-159 and 271-277
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 389-390
- The Physics Teacher, pag. march 1986, 160-163
- The Physics Teacher, pag. nov. 1987, 502-503

7.1.3.2 02 Chromatic Aberration

7.1.3.2.1 Aim

To show that different “colored” rays traverse a lens along different paths.

7.1.3.2.2 Subjects

- 6A40 (Refractive Index)

7.1.3.2.3 Diagram

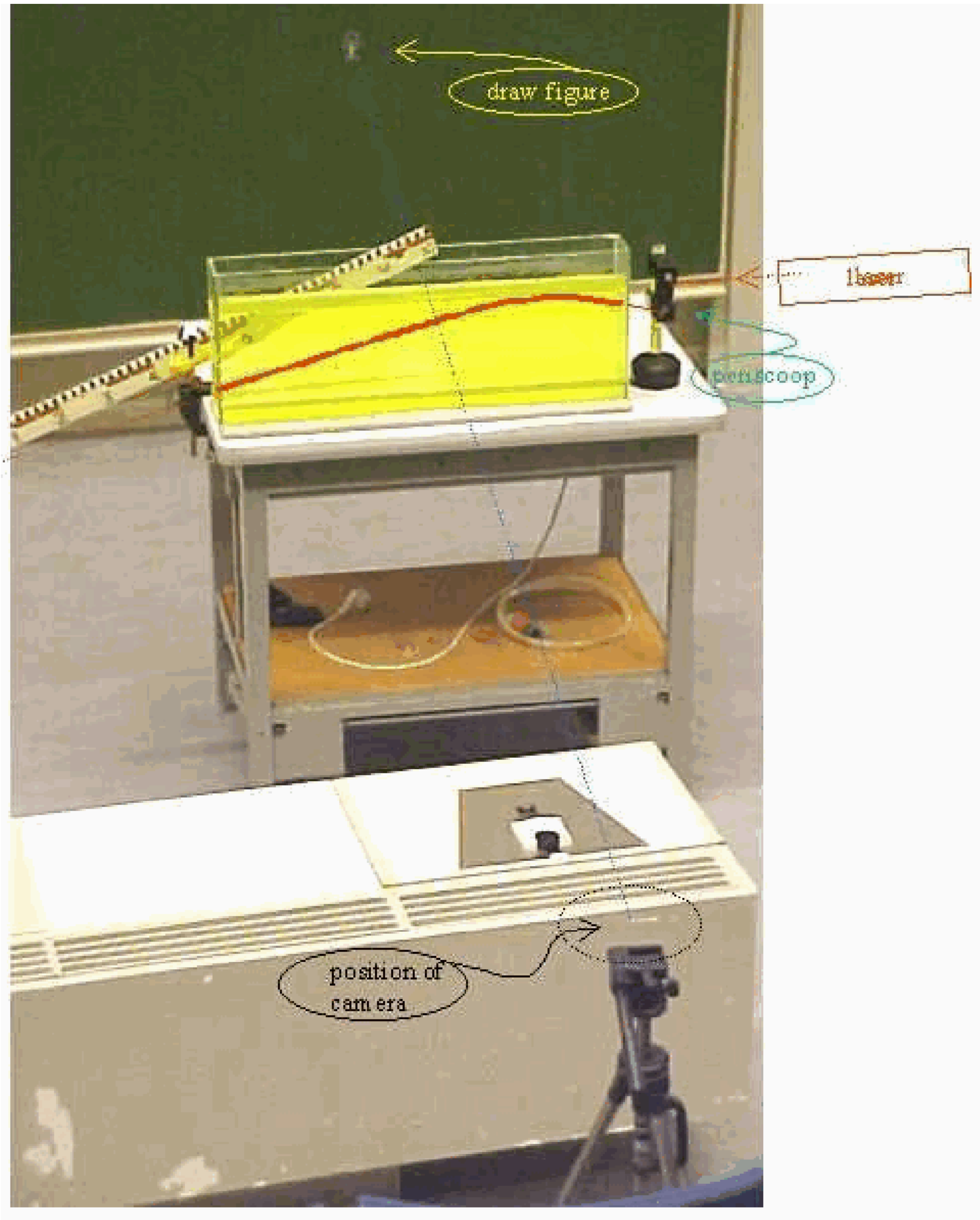


Figure 7.13: .

7.1.3.2.4 Equipment

7.1.3.2.5 Presentation

7.1.3.2.6 Figures

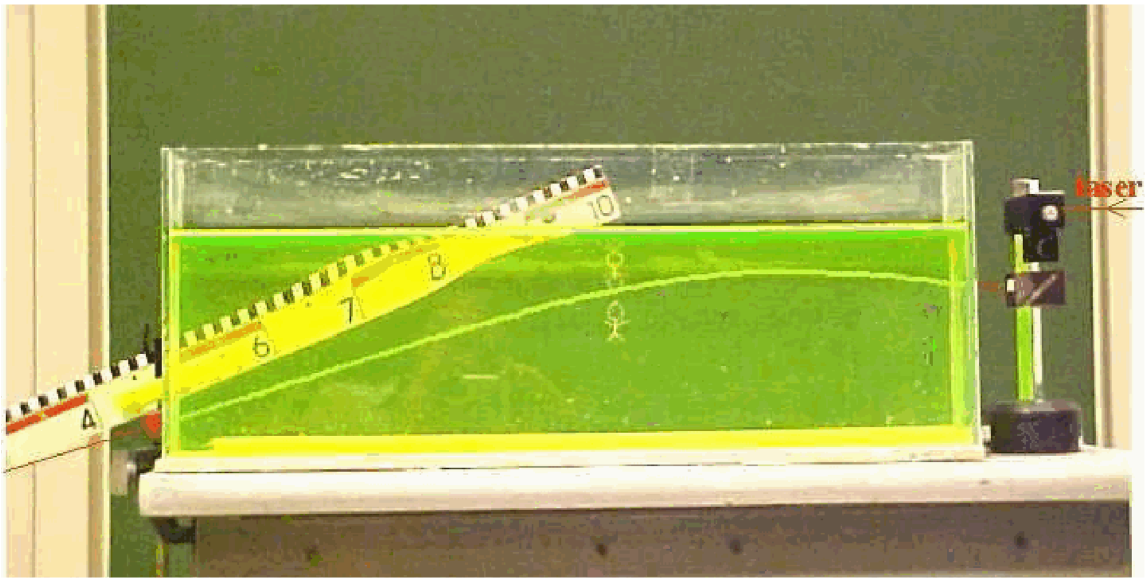


Figure 7.14: .

7.1.3.2.7 Remarks

7.1.3.2.8 Sources

- Hecht, Eugene, Optics, pag. 66-73, 157-159 and 271-277

7.1.4 6A42 Refraction at Flat Surfaces

7.1.5 6A44 Total Internal Reflection

7.1.5.1 02 Tunneling

7.1.5.1.1 Aim

To show tunneling of a wave through a barrier.

7.1.5.1.2 Subjects

- 7A50 (Wave Mechanics)

7.1.5.1.3 Diagram

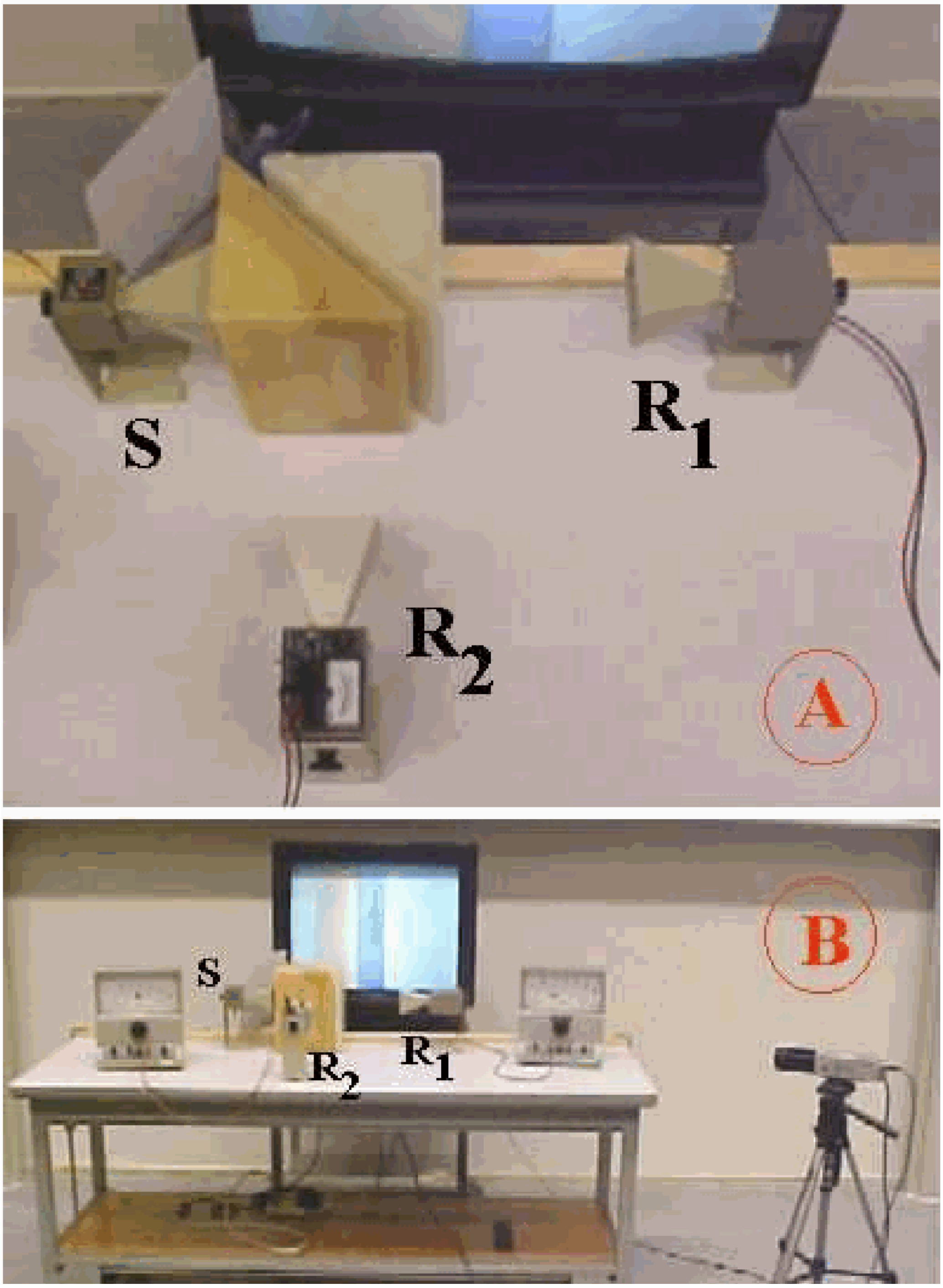


Figure 7.15: .

7.1.5.1.4 Equipment

- Microwave transmitter ($f = 10GHz; \lambda = 3$ cm) (S in Diagram).
- 2 Microwave receivers (R1 and R2 in Diagram).
- 2 large demonstration meters.
- 2 Triangular blocks of paraffin wax.
- Beam of wood ($I = 2$ m), used as a slideway
- Transparant ruler ($I = 30$ cm).
- White screen to be placed behind the transparent ruler.
- Video camera.
- Large monitor
- (Laser, two rectangular prisms,a square block of glass and a beam splitter).

7.1.5.1.5 Presentation

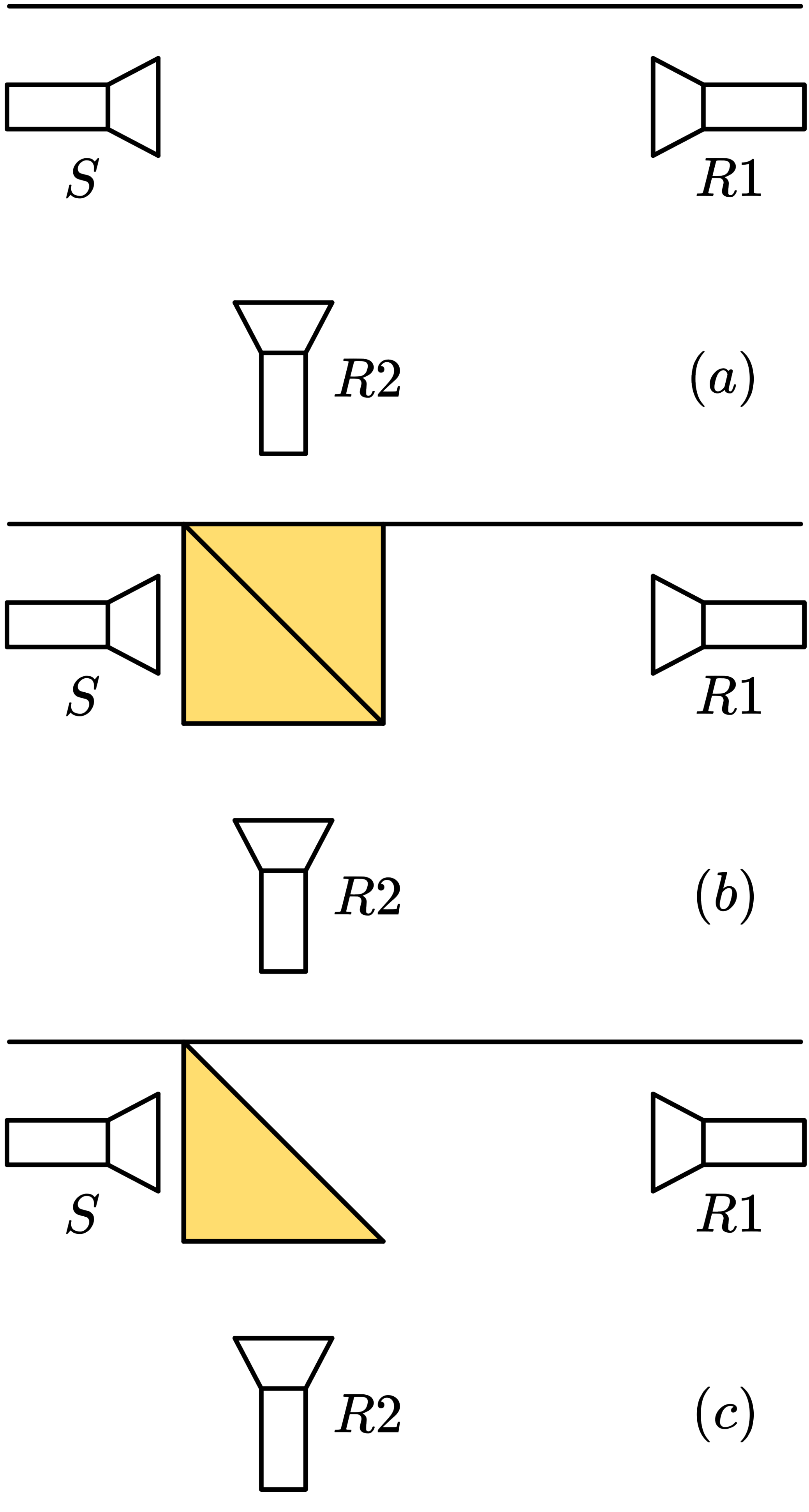
7.1.5.1.5.1 Preparation

The demonstration is set up as shown in Diagram A and B.

The camera and monitor are placed in order to make the gap between the paraffin wax blocks visible to the audience.

The slideway is needed in order to shift one of the paraffin wax triangles along a straight line.

When you prepare the demonstration, use the set ups as shown in Figure 2B and -C: In Figure 2B, the meter, indicating the signal received by R1, should be equal to the signal that will be received by R2 in the situation of Figure 2C. To achieve this, careful positioning is needed for sender S, the paraffin wax blocks and both receivers.



S
R1
R2
(a)
S
R1
R2
(b)
S
R1
R2
(c)

Figure 7.16: .

7.1.5.1.6 Presentation

The demonstration is following a sequence as shown in Figure1 through 2 (A-E).

Figure A

The sender and receivers are switched on. Receiver R1 shows a deflection. (R2 has no deflection.) Placing your hand in front of S will make clear that $R1$ really receives the signal send by S.

Fiqure B

Both triangular blocks are, as one square block, placed between sender S and receiver R1. The receiver will show the same deflection as in the foregoing situation (A). Conclusion is that the paraffin wax is completely transparent to the microwaves. It can be compared with the transparency of glass to light. (Optional: show this also with laser and a square piece of glass)

Figure C

A triangular block of paraffine wax is placed in front of the sender S as shown in Figure B. Receiver R1 has no deflection, so it receives no signal. But receiver R2 shows a deflection, and this deflection is equal to that of the previous situation (Figure A). Clearly the signal from the sender is deflected by the paraffin block towards R2. Again the comparison with glass and light can be made. (Optional: show this with a laser and a rectangular prism)

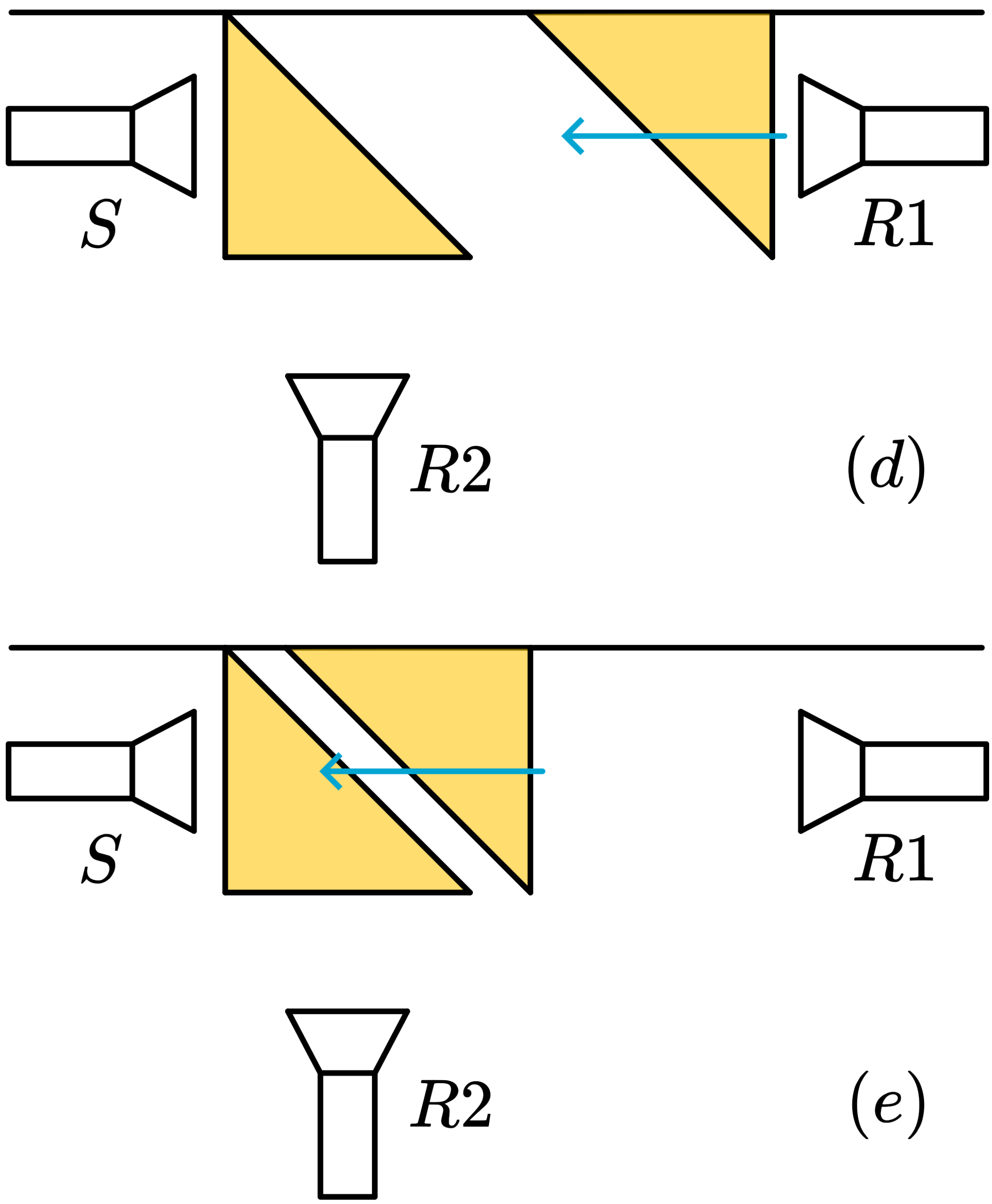


Figure 7.17: .

7.1.5.1.7 Figure D-E

The second triangular paraffin block is placed close to the receiver as Figure D shows. Then this block slides along the slideway slowly towards the other paraffin block. In the beginning nothing is different from the foregoing situation: R2 has still full deflection and R1 has no deflection. But when the blocks come within a distance smaller than the wavelength of the microwaves, R1 starts receiving signal and R2 receives less. Clearly there is barrier penetration! Making the separation still smaller this take-over continues until situation B is there again.

The weirdness of this phenomenon should be stressed, by mentioning that if in situation E part of the signal clearly passes the air gap, this means that also in situation C and D the signal from S also passes the wall between wax and air to a certain depth, but when the signal "feels" no wax at that depth it "chooses" deflection towards R2. Between D and E the "penetration depth" can be determined.

(Optional: Show that laser light that enters a beam splitter is partially transmitted and partially deflected)

7.1.5.1.8 Explanation

Apparently, the transition from wax to air into the straight on direction towards R1, as in Figure 2C, is a barrier to the microwaves, but not completely (as in Figure 3D and $-\mathrm{E}$). Solving the Schroedinger wave equation provides a satisfying solution, because this shows that within a barrier the solution to the wave equation is decaying exponential, dying away to zero, and so, if that barrier ends before this zero is reached, then there is again a sinusoidal wave function. (See the many textbooks on this subject.)

7.1.5.1.9 Remarks

- While shifting it might seem to the audience that there are situations that the total deflection of R1 and R2 is every now and then more than the original value. For example, when we start without the block (situation A), the deflection of R1 is 10 units (fsd). While shifting (situation D) a possible situation is $\mathrm{R1} = 8$ units, and $\mathrm{R2} = 6$ units, adding to 14 in total! But we read voltage, so in order to compare intensities we need to square these readings, giving $8^2 + 6^2 = 100 = 10^2$. So nothing strange is happening. Actually we show this specific 6-8-10 situation as an extra to the students to explain these peculiar meter readings.

7.1.5.1.10 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 996-998

7.1.6 6A60 Thin Lens

7.1.6.1 01 Chromatic Aberration

7.1.6.1.1 Aim

To show that different "colored" rays traverse a lens along different paths.

7.1.6.1.2 Subjects

- 6A40 (Refractive Index) 6A60 (Thin Lens) 6F30 (Dispersion)

7.1.6.1.3 Diagram

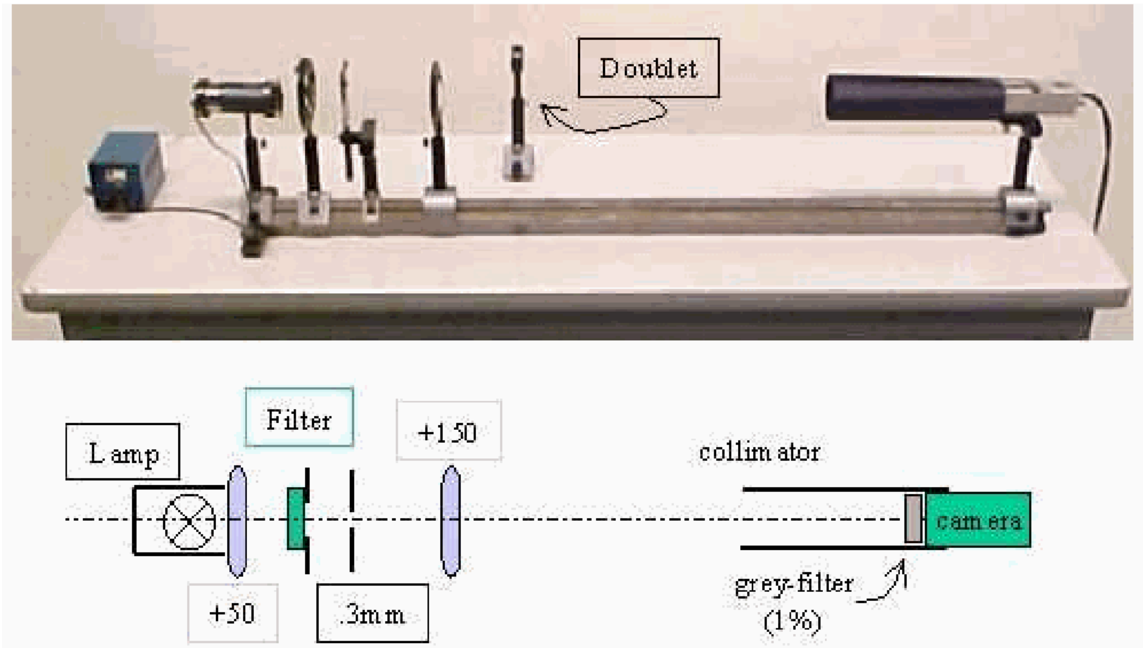


Figure 7.18: .

7.1.6.1.4 Equipment

- Optical rail, 1.5 m.
- Lamp 6 V/5 A, fitted with a condenser lens +50 mm.
- Four interference filters: 644 nm; 578 nm; 546 nm; 436 nm (normally used to select H_a spectral lines).
- Wheel to mount these filters.
- Diafragm, diam. = .3 mm.
- Single lens, f = 150 mm, diam. = 75 mm.
- Doublet, f = 150 mm.
- White screen, used to align the optical components.
- Camera, lens removed.
- Grey filter (.01), stuck to camera.
- Collimator (made of black paper, see Diagram).
- Projector, to project image of camera.

7.1.6.1.5 Presentation

The lamp and camera are positioned each at the end of the rail. The camera has its lens removed; a .01 grey filter is placed on it. The other components are placed and carefully aligned; see Diagram (use the white screen at the position of the camera).

Using the red interference filter the .3 mm-diaphragm is pictured on the camera at the end of the optical rail. To get a sharp picture the diaphragm is shifted. The projector projects this image to the students. The red filter is turned away and the yellow filter is now in position. Clearly can be seen that this picture is not sharp. To get it sharp we need to shift the camera towards the lens. The same happens when next we apply the green and then the blue filter. Going from red to blue we need to shift the camera about 20 cm in total. This is clearly observable to the students. And the conclusion can be that the lens has a smaller focal distance for shorter wavelength.

When the 150 mm single lens is replaced by the doublet of 150 mm, changing filters will result in sharp images all at the same position of the camera on the rail: no shifting is needed. There is no chromatic aberration.

7.1.6.1.6 Explanation

Since the thin-lens equation $\frac{1}{f} = (n_t - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$ is wavelength-dependent via $n_1(\lambda)$

(dispersion), the focal length must also vary with λ (Figure 2 shows the graph of n, versus λ of crown-glass.).

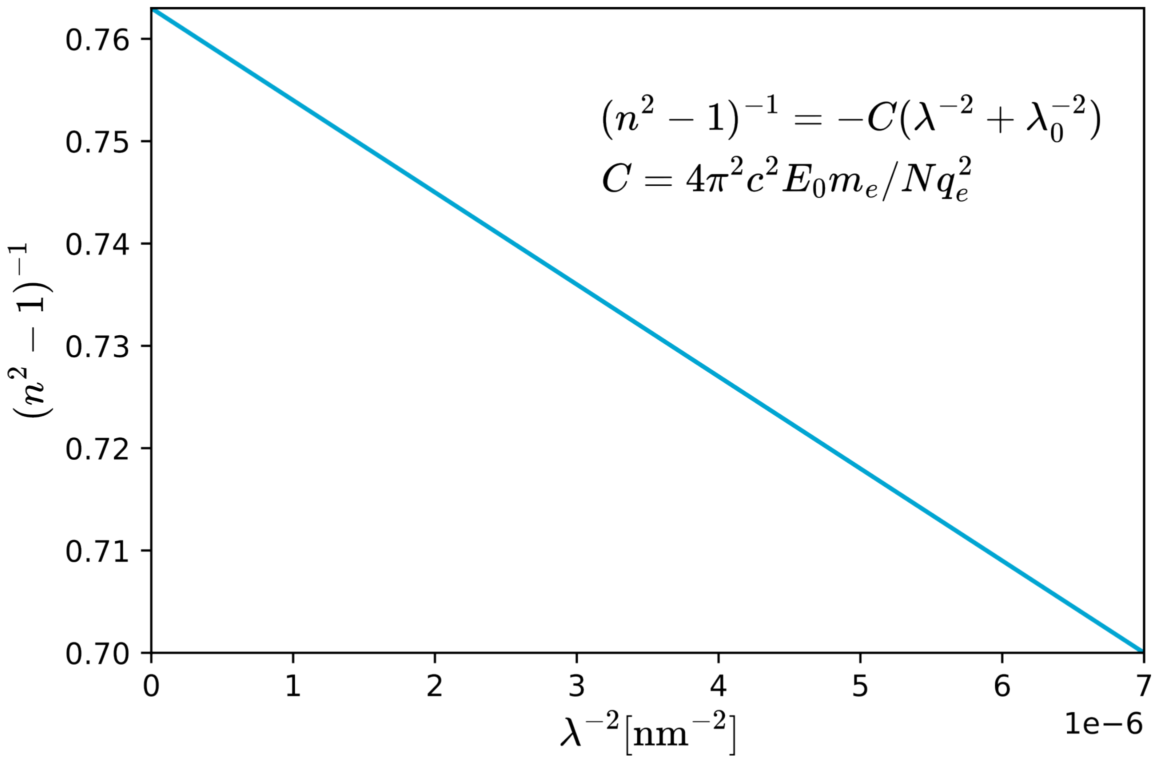


Figure 7.19: .

In general $n_1(\lambda)$ decreases with wavelength over the visible region, and thus $f(\lambda)$ increases with λ. And when $f(\lambda)$ increases with λ, then also the image-distance increases with λ (object-distance is constant). The demonstration shows this: the red image being sharp at a larger distance than the blue image.

A negative lens would generate "negative" chromatic aberration. This suggests that a combination of a positive - and a negative lens could result in an overlapping of f_{red} and f_{blue}. This is the way an achromatic doublet functions.

7.1.6.1.7 Remarks

- Careful alignment is essential to this demonstration: The optical axis needs to be in good parallelism with the optical rail, so that when shifting the camera the light spot stays on the center of the screen.
- The demonstration can also be done without using filters; Then the diaphragm is imaged at the camera as good as possible. When now we shift the camera towards the single lens we

will get a concentration of blue near the optical axis and red in a circle around it. Shifting the camera away from the lens the opposite happens: we see red near the optical axis and a blue circle around it. Going from one position to the other also yellow and green near the axis can be observed.

- The demonstration can also be done using a Hg-lamp in stead of an incandescent lamp. However, in that way the demonstration is more complicated due to the high differences between the intensities of the separate spectral lines: Every spectral line will need its own grey-filter in order not to saturate the light sensitive layer of the camera.

7.1.6.1.8 Sources

- Hecht, Eugene, Optics, pag. 66-73, 157-159 and 271-277
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 389-390
- The Physics Teacher, pag. march 1986, 160-163
- The Physics Teacher, pag. nov. 1987, 502-503

7.1.7 6A70 Optical Instruments

7.1.7.1 01 Magnifying Glass

7.1.7.1.1 Aim

To show three ways to use a magnifying glass.

7.1.7.1.2 Subjects

- 6A70 (Optical Instruments)

7.1.7.1.3 Diagram

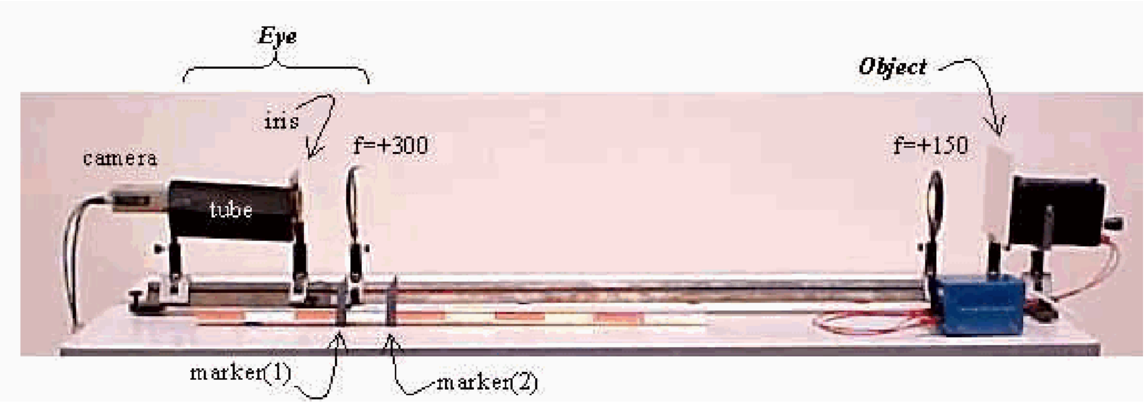


Figure 7.20: .

7.1.7.1.4 Equipment

- Optical rail (2 m).
- Measuring tape.
- Ruler, 1 m.
- Two position markers.
- Video beamer or monitor. “Object”:
- Lamp, 12 V/100 W.
- Sheet of graph paper, clamped between acrylic sheets ($18 \times 18\ \mathrm{cm}^2$).

“Eye”:

- Video camera without lens.
- Iris diaphragm.
- Lens, f $=+300$ mm; d $=75$ mm.
- Tube, I $=25$ cm; $d=10$ cm; dull black.

“Magnifying glass”:

- Lens, f $=+150$ mm; d $=75$ mm.

7.1.7.1.5 Presentation

On a table there is a piece of text. You stand close to the table. First show what you do when you use a magnifying glass. There are three possible ways:

(a)Hold the lens ($+150$ mm) very close to your eye and show the students that you have to bend towards the text until you can read it sharp. The distance between lens and text is smaller than f_{lens} (we measure around 10 cm).

(b)Hold the lens 15 cm (=f lens) away from the text, allowing you to relax your eye. When reading your text you still have to bend.

(c)Hold the lens a comfortable distance away from the eye so that you do not have to bend. Adjust the distance between lens and text until a clear enlarged image appears. The lens has to be close to the text now (always a distance smaller than 15 cm). This is how people mostly use a magnifying glass.

Now we turn to the demonstration set up (see Diagram).

First we use only the “Eye-part” and focus it at an object in the lecture-room far away (infinity): Adjust the iris diaphragm and eye lens position to obtain a clear image on the screen. This situation corresponds to the eye muscles completely relaxed. At this position of the eye lens a marker (1) is placed on the table.

“Eye” and “Object” are each at the outer ends of the optical rail. The lamp is switched on and illuminates the graph paper diffusely. The iris diaphragm and the position of the eye lens are adjusted until a sharp image of the graph paper is seen on the screen. On the screen the distance between the mm-lines of the graph paper is measured (x_1). This situation corresponds to normally reading a text on the table with an unaided eye: The “Object” is at the so-called near point. Also place a marker (2) at the position of the eye lens in this situation.

(a’)Leaving the eye lens in this position, the magnifying glass is fixed to the eye lens by means of tape. The “Object” is shifted towards the “Eye” + magnifying glass until the image of the graph paper is sharply seen on the screen (the “Eye” again sees the virtual image at the near point). On the screen the distance between the mm-lines of the graph paper is measured (x_2). The magnification equals (x_2/x_1).

(b’)Again focus the “eye lens” at infinity (the first marked position). In this way the “Eye” will view in a relaxed way. The magnifying glass is positioned 15 cm in front of the object, in order to obtain a virtual image at infinity. The “Object” + magnifying glass combination is shifted towards the “Eye” until the image of the graph paper is sharply seen on the screen. On the screen the distance between the mm-lines is measured (x_3). The magnification equals x_3/x_1.

(c’)The “Object” is placed at the end of the optical rail and the magnifying glass closer than 15 cm to the object. The eye lens is shifted until a sharp image of the graph paper is seen on the screen. On the screen the distance between the mm-lines is measured (x_4). The magnification equals x_4/x_1.

Notify the results obtained and discuss them.

7.1.7.1.6 Explanation

When no lens is used, the object is at the near point and observed at an angle α_u (see Figure 2).

When the lens is directly in front of the eye, the image is virtual and erect and must be observed at near point. To have this, the object has to be less than one focal length away from the lens (see Figure 2b). Analysis shows that the angular magnification equals $M = \frac{\alpha_a}{\alpha_u} = \frac{d_0}{f} + 1$

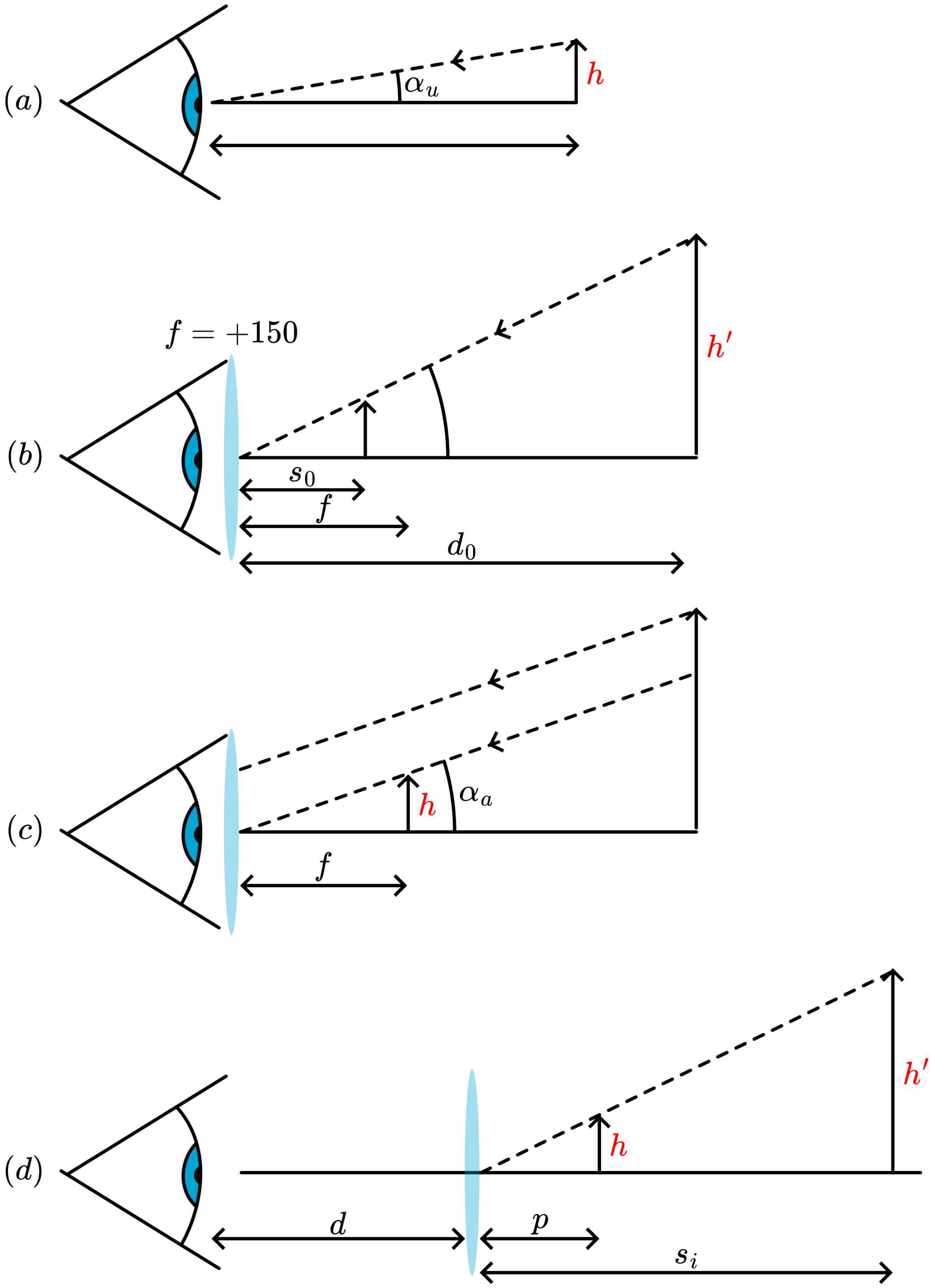


Figure 7.21: .

When the lens is placed a distance f from the object, angular magnification becomes

$$M = \frac{\alpha_a}{\alpha_u} = \frac{d_0}{f} \tag{7.1}$$

Still the eye is close to the object. (see Figure 2c) (Theoretically a larger distance between magnifying glass and object is possible but then distorsion occurs, since the eyelens sees the imageforming rays no longer paraxial.)

When the object is a comfortable reading distance away analysis shows

$$M = \frac{L}{p\left[1 + \frac{(f-p)d}{pf}\right]} \tag{7.2}$$

(see Figure 2d).

So for maximum magnification the magnifying glass should be hold closely to the eye. To have a more comfortable situation you have to be content with a lower magnification.

7.1.7.1.7 Remarks

- The first part of the demonstration can be done also by handing out lenses to the students so they can do the three ways themselves.

7.1.7.1.8 Sources

- Hecht, Eugene, Optics, pag. 212-215
- The Physics Teacher, pag. Vol. 39, May 2001
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 853-854

7.2 6B Photometry

7.2.1 6B30 Radiation Pressure

7.2.1.1 01 Radiation Pressure?

7.2.1.1.1 Aim

To discuss radiation pressure.

7.2.1.1.2 Subjects

- 6B30 (Radiation Pressure)

7.2.1.1.3 Diagram

Figure 7.22: .

7.2.1.1.4 Equipment

- incandescent lamp, 100 W
- Crooks radiometer
- large glass tank (we use $5 \times 10 \times 10\ \mathrm{cm}^3$), filled with water
- white screen

7.2.1.1.5 Presentation

First, the radiometer is shown to the students so that they have a good impression of its construction: the black- and mirror-like vanes are shown.

The radiometer is places about 1 meter away from the incandescent lamp. When the lamp is switched on, the radiometer starts rotating. In order to observe in which direction the radiometer rotates, it should not rotate too fast. Now a discussion can be started about why the radiometer rotates.

The large tank filled with water is places between the lamp and the radiometer. On the white screen it can be observed that this does not change the amount of light. Yet, the radiometer slows down and stops rotating.

The discussion about why the radiometer rotates can continue now.

7.2.1.1.6 Explanation

Based on conservation of momentum, we know that a ball which bounces off a wall delivers a greater momentum to the wall than another ball of the same mass and velocity that sticks to the wall. In fact, for an elastic ball which bounces backward with its initial speed, the momentum delivered to the wall is twice as great as the ball's original momentum. In just the same way, we expect that a photon of light gives more momentum to a surface when it is reflected than when it is absorbed. Therefore, light should exert a greater pressure on the mirrored sides of the vanes than the absorbing black sides.

According to this explanation, the radiometer turns in the wrong direction!

The effect of light pressure is overwhelmed by another: the greater heating of the blackened sides. This greater heating causes residual air molecules in the globe to recoil more forcefully when they hit the black sides than when they hit the mirrored sides, thereby giving them a greater impact than the mirrored sides.

When the light passes through a layer of water, the vanes will not turn because the water filters out the infrared radiation that causes most of the heating.

7.2.1.1.7 Remarks

When placing the water tank, be sure that there is no reflection from the surface increasing the light intensity towards the radiometer.

7.2.1.1.8 Sources

- Ehrlich, R., Why Toast Lands Jelly-Side Down: Zen and the Art of Physics Demonstrations, pag. 15
- Ehrlich, Robert, Turning the World Inside Out and 174 Other Simple Physics Demonstrations, pag. 117
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 242

7.3 6C Diffraction

7.3.1 6C10 Diffraction From Two Sources

7.3.1.1 01 Resolution

7.3.1.1.1 Aim

To show how diffraction limits the resolution of an optical system.

7.3.1.1.2 Subjects

- 6C10 (Diffraction From Two Sources)

7.3.1.1.3 Diagram

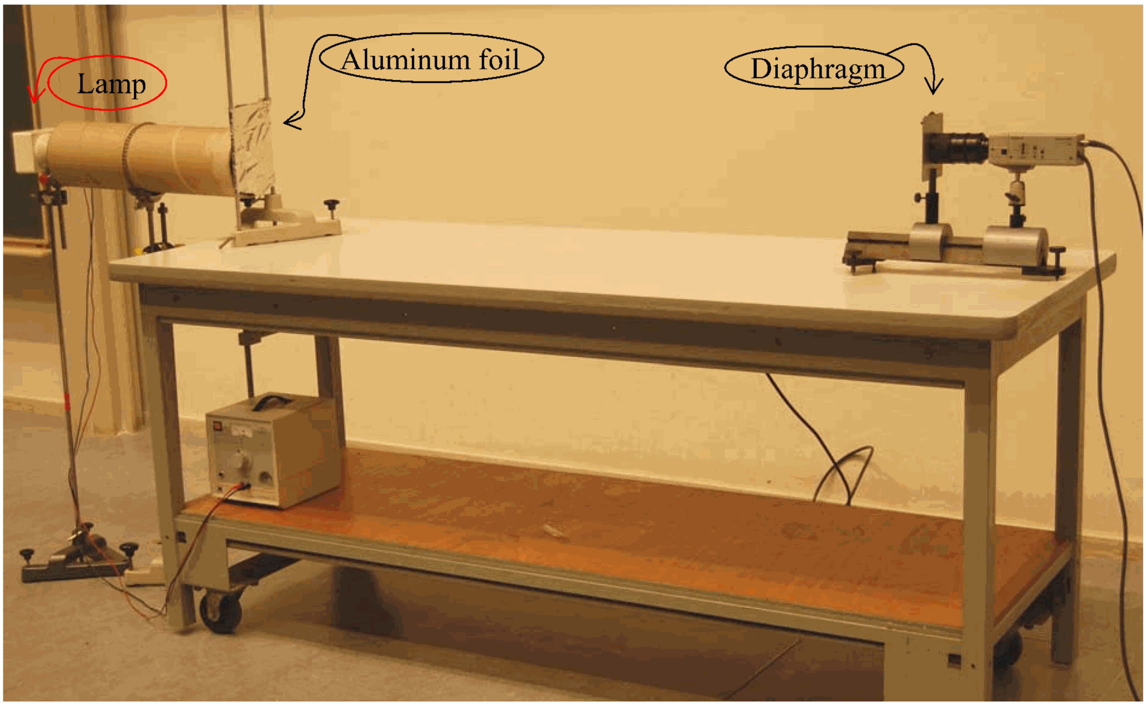


Figure 7.23: .

7.3.1.1.4 Equipment

- Rotatable disc with 8 holes: 3.0, 2.5, 2.0, 1.5, 1.0, 0.5, 0.4 and 0.3 mm (see Figure 2).
- Aluminium foil with 2 pair of holes fitted on a stand (see Diagram and Figure 3).
- Lamp, 220V/200W.
- Variable transformer on the 220 V line voltage.
- Camera with zoom lens.

7.3.1.1.5 Presentation

7.3.1.1.5.1 Preparation

Built the demonstration as shown in the Diagram:

-Focus the camera on the Aluminium foil.

-The rotatable disc is placed as close as possible to the camera.

-The lamp should not be too close to the Aluminum foil, because we need parallel light beams from the holes in the Aluminium foil. To avoid scattered light a cardboard tube is placed between lamp and the Aluminium foil.

-Adjust the vertical and horizontal position of the lamp and also its intensity to get a satisfying illumination of the small holes in the foil.

Figure 7.24: .

The lamp is switched on. The rotatable disc has its largest hole in position. The camera is focussed at the pairs of holes in the aluminium foil. The holes of both pairs in the aluminium foil are observed as separate images.

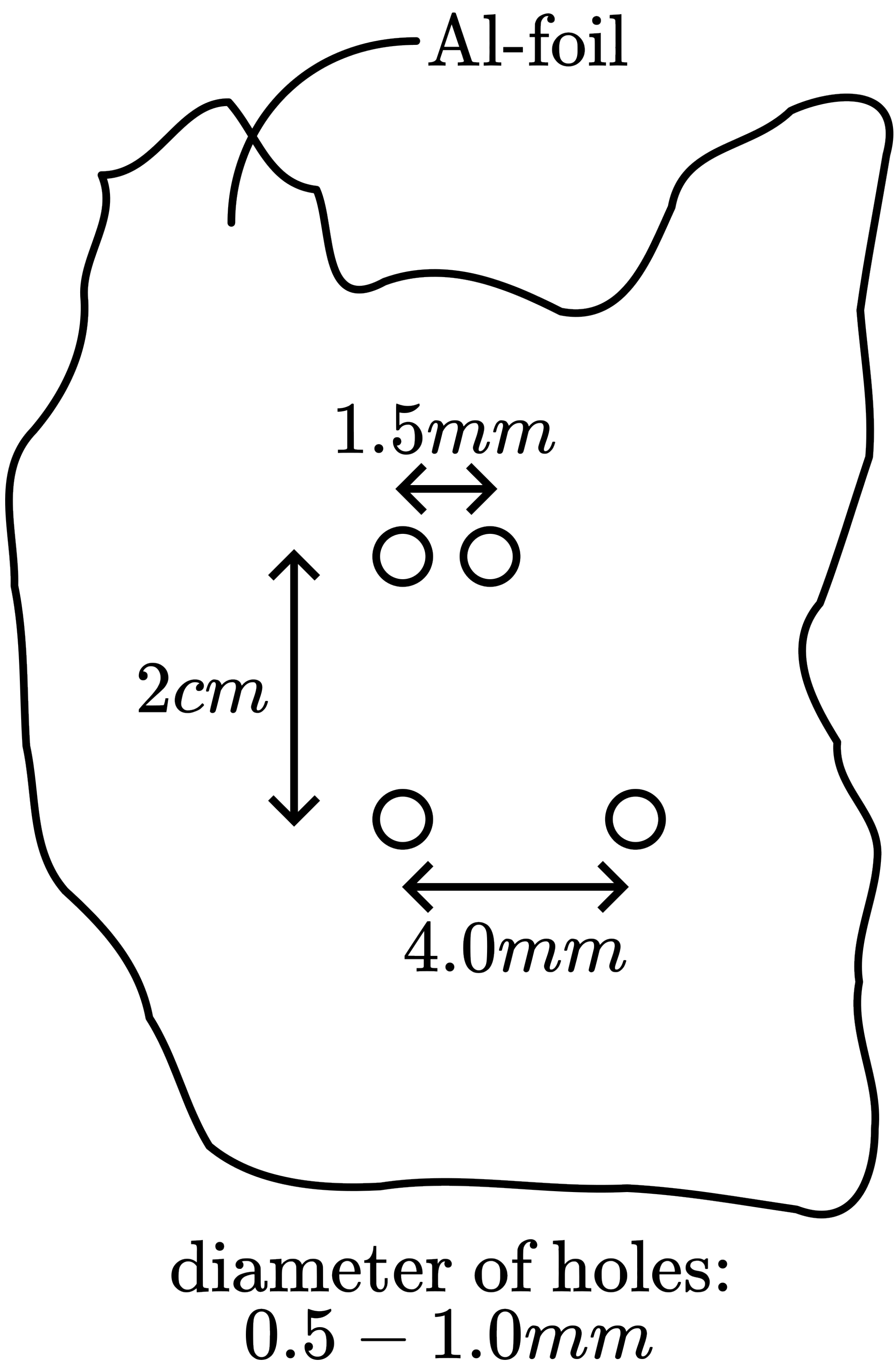
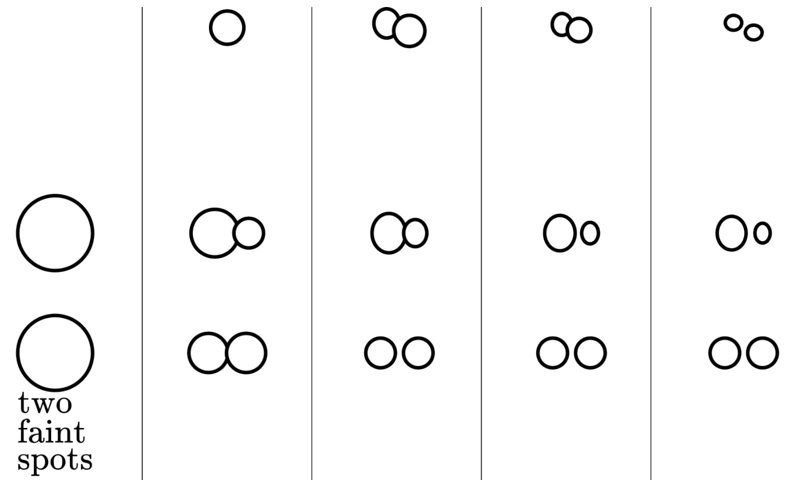


Figure 7.25: .

7.3.1.1.5.2 Presentation

Choose the smallest hole in the rotatable disc. Two rather hazy patches of light are observed by the camera. One of the two patches gives the idea that it could be a double spot. Then a larger hole is selected on the rotatable disc and we see that our idea of one of the light patches being two separate spots is strengthened.

When we continue to select larger holes on the rotatable disc the light spot resolves as really consisting of two light spots. Even the other light spot finally resolves into two! Figure 4 shows the sequence of the observed light spots.



diaphragm [mm]	.3	.4	.5	1.0	1.5
$\frac{1.22\lambda}{D}$	.002	.0015	.0012	.00061	.00041

Figure 7.26: .

(In demonstrating we also go again backwards to smaller holes in the diaphragm.)

7.3.1.1.6 Explanation

If two point objects are very close, the diffraction patterns of their images will overlap. As the objects are moved closer, a separation is reached where you can't tell if there are two overlapping images or a single image. The separation at which this happens is stated by Lord Rayleigh: two images are just resolvable when the centre of the diffraction disk of one image is directly over the first minimum in the diffraction disc of the other. A circular hole shows a diffraction pattern with a central maximum of half :width: $\theta = \frac{1.22\lambda}{D}$, where D is the diameter of the circular opening. Calculating with $\lambda = 500$ nm we get for the smallest hole on the rotatable disc $D = .3\ \mathrm{mm}, \theta = 2 \times 10^{-3}$.

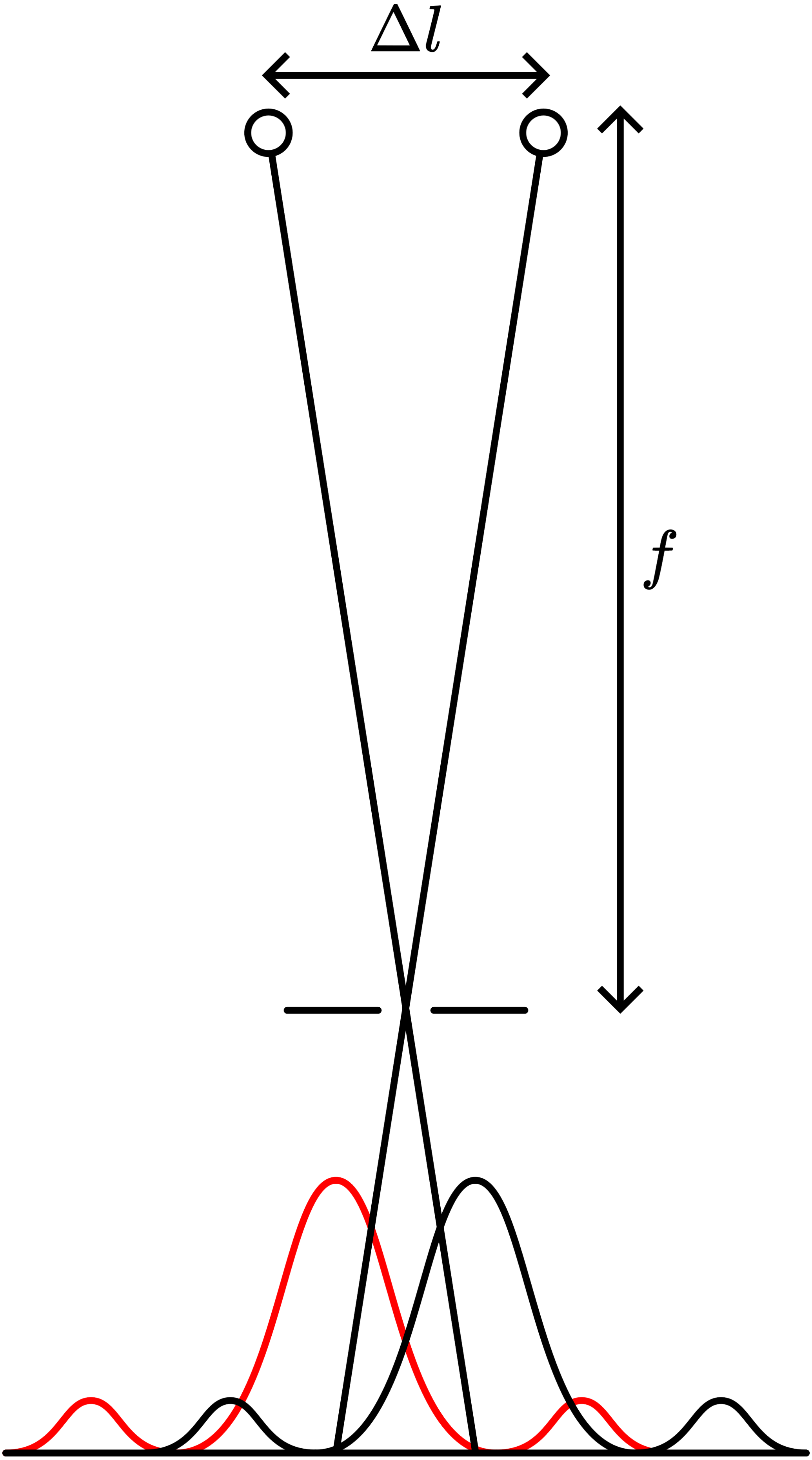


Figure 7.27: .

In our demonstration: $\theta = \frac{\Delta l}{f}$ (see Figure 5).

The distance $f = 2$ meter, and calculating θ for both pair of holes, we get $\theta = .75 \times 10^{-3}$ for the pair of holes with a separation of 1.5 mm and $\theta = 2 \times 10^{-3}$ for the pair of holes with a separation of 4 mm.

These calculations compared with the Rayleigh criterion (that is expressed as $\theta = \frac{1.22\lambda}{D}$ and is calculated and listed in the bottom row of Figure 4), shows that the two holes with a separation of 4 mm will be resolved when the diaphragm is larger than .3 mm and that the holes with a separation of 1.5 mm will be resolved when the diaphragm is larger than .5 mm. The observed light spots in Figure 4 show that this is more or less right!

7.3.1.1.7 Remarks

Since $\theta = \frac{1.22\lambda}{D}$, it is useful to do this demonstration in different colours. (We didn't try this yet.)

7.3.1.1.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 896-899
- Hecht, Eugene, Optics, pag. 416 and 461-465
- PSSC, College Physics, pag. Laboratory Guide, Experiment 22

7.3.1.2 02 Fraunhofer and Fresnel Diffraction

7.3.1.2.1 Aim

To show how light illuminating a slit gives different regions of diffraction. Close to the slit: Fresnel diffraction and at some distance: Fraunhofer diffraction. To determine where the one type of diffraction transforms into the other.

7.3.1.2.2 Subjects

- 6C20 (Diffraction Around Objects)

7.3.1.2.3 Diagram

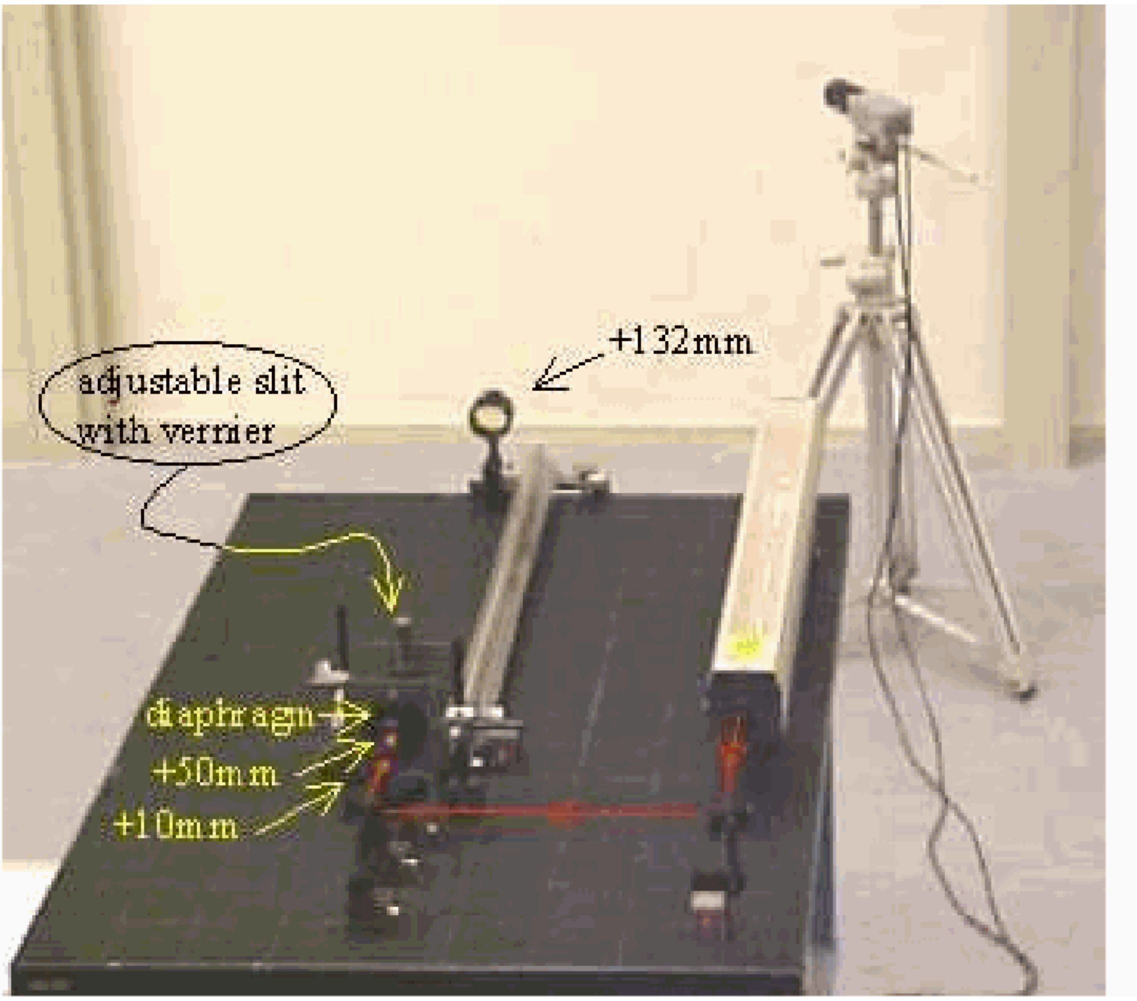


Figure 7.28: .

7.3.1.2.4 Equipment

- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50 mW.
- Two surface mirrors ($1/10\lambda$).
- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm.
- Slide holder.
- Lens, f = 132 mm.
- Optical rail, I = 1 m, as guiding ruler.
- Adjustable slit.
- Video camera.

- Projector to project diffraction-image.
- Overheadsheet with Figure 10.5 (“Optics” by Hecht; see Sources).

7.3.1.2.5 Presentation

7.3.1.2.5.1 Preparation

The demonstration is set up as shown in Diagram:

-The two mirrors are positioned in such a way that the laserbeam passes parallel to the table.

- The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laserbeam is broadened. Take care that the broadened beam is still parallel to the table.

-The lens of 132 mm can easily be shifted in this beam up and down using the carefully positioned guidance rail.

7.3.1.2.5.2 Demonstration

The set-up as described in “Preparation” is explained to the students, so that it is clear to them that the adjustable slit is placed in a beam of light consisting of parallel rays. The adjustable slit is set at .6 mm. The +132 mm lens is shifted close to this slit to project a sharp image of it on the wall: a smooth red region, having a sharp boundary on both sides (see Figure 2A). Considering the wall to be far away, the lens needs to be +132 mm away from the slit (the slit is in the focus of the projecting lens).

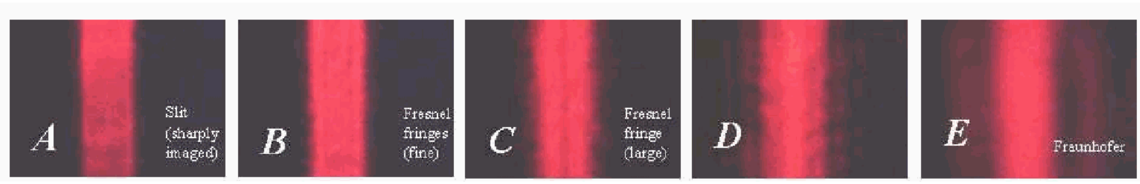


Figure 7.29: .

Then the +132 mm lens is slowly shifted away from the slit. The projected image changes: in the originally smooth red region domains of higher and lower intensity (fringes) can be discerned (see Figure 2B). Moving out still farther, the fringe pattern changes continuously: the number of fringes diminishes while the fringes themselves broaden (compare the pictures in Figure 2; reality is better than the quality of these pictures). When the +132 mm lens has reached the end of the guidance rail the familiar diffraction pattern as shown when introducing diffraction, is visible (see the demonstration “Diffraction(2), single slit”).

Leaving the +132 mm lens in this far away position, the transformation from Fresnel to Fraunhofer can also be shown when you vary the width of the slit.

It will be clear now that distance form the slit and slit-width have both something to do with this transformation of one type of diffraction into the other.

7.3.1.2.6 Explanation

The +132 mm lens being for away from the wall projects an image of an “object” that is 132 mm away form it. At first we seen the sharply imaged slit; moving away from the slit, for instance 10 mm, then the image of this position is projected on the wall. In this way the lens scans the region close to the slit (near field) and farther away (far field). Considering far field diffraction (Fraunhofer diffraction) the slit is that narrow compared to the distance in the field, that the secondary wavelets emerging from the slit proceed as being planar. This relative simplicity of Fraunhofer diffraction is explained in the demonstration “Diffraction(2), single slit” in this database.

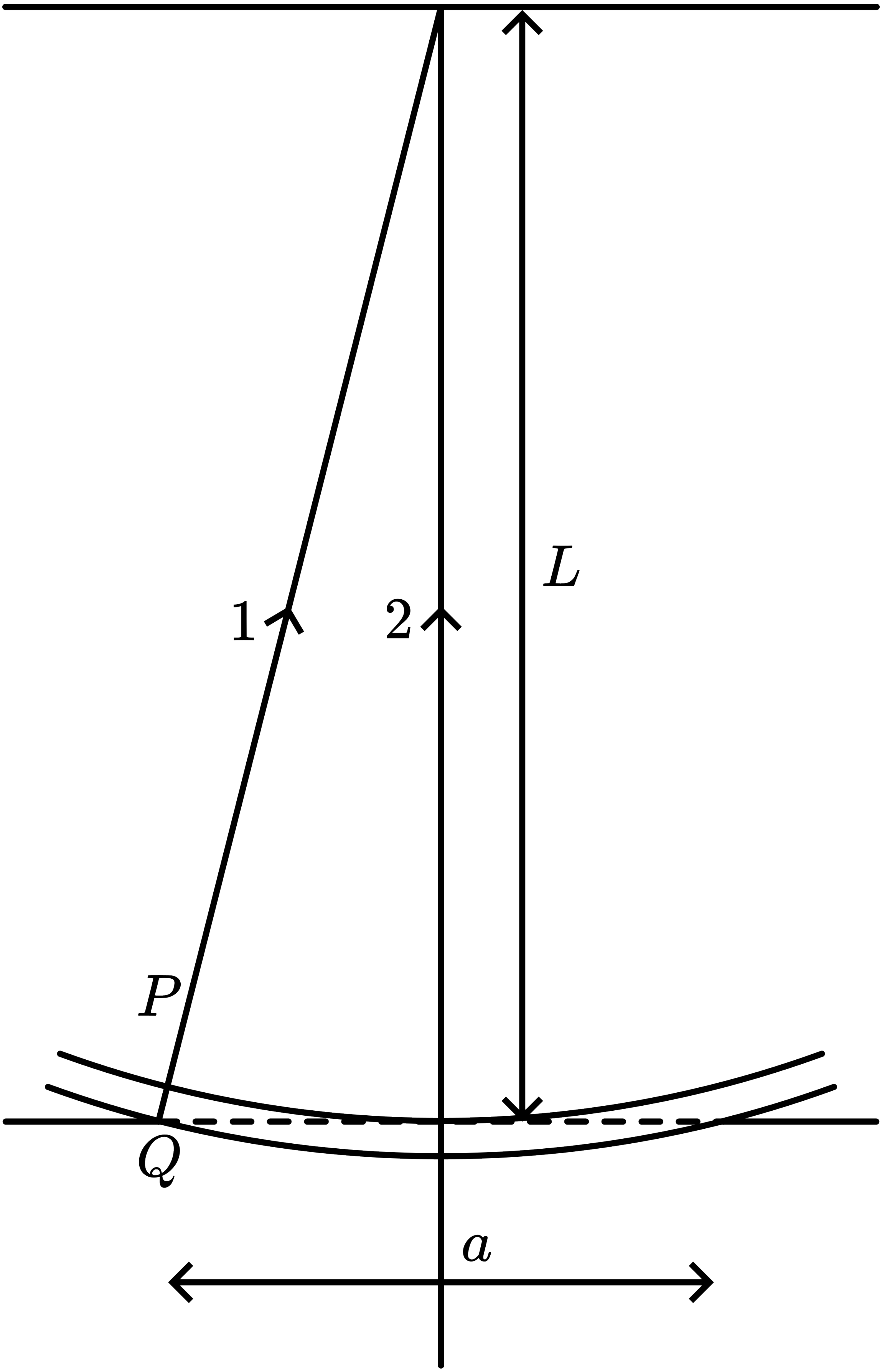


Figure 7.30: .

In the near field configuration the width of the slit cannot longer be neglected. Due to this an extra path difference (PQ) between ray 1 and ray 2 is introduced (see Figure 3).

Applying Pythagoras shows $L^2 + \frac{a^2}{4} = (L + PQ)^2$, and $PQ = \frac{a^2}{8L}$. If, as a rule of thumb, this extra path difference is neglected if it is smaller than $\lambda/4$, we find that for the distance L we need $L > \frac{a^2}{2\lambda}$. So, the distance $L \approx \frac{a^2}{2\lambda}$ can be considered as the "border" between Fresnel - and Fraunhofer diffraction. Applying the data In this demonstration ($a = .6$ mm; $\lambda = 650$ nm), we find: $L = .25$ m. Performing the demonstration confirms this.

7.3.1.2.7 Remarks

- In preparing this demonstration we used of course $L = .25$ m (means: lens at .382 m from slit) and then calculated the needed slit width, so that both types of diffraction can be clearly shown in one shift of the $+132$ mm lens.
- The demonstration can also be performed having the $+132$ mm lens fixed at the end of the table ($L = .85$ m) and then slowly increase the width of the slit. Then the distinction between Fresnel - and Fraunhofer diffraction is at a slit width of around 1 mm. But realize that turning a vernier is less visible to an audience than shifting a lens across the table.
- The different patterns can also be registered using a pattern scanner as described in ["Diffraction(1), introduction"](../../6C20 Diffraction Around Objects/6C2001 Diffraction introduction/6C2001.md>) in this database. Particularly the fine fringes close to the slit can be made visible in this way.

7.3.1.2.8 Sources

· Hecht, Eugene, Optics, pag. 437-438 and 495-499

7.3.1.3 03 Young's Double Slit

Young's double slit

7.3.1.3.1 Aim

To show a double slit interference pattern and the influence of slit-separation.

7.3.1.3.2 Subjects

- 6D10 (Interference From Two Sources)

7.3.1.3.3 Diagram

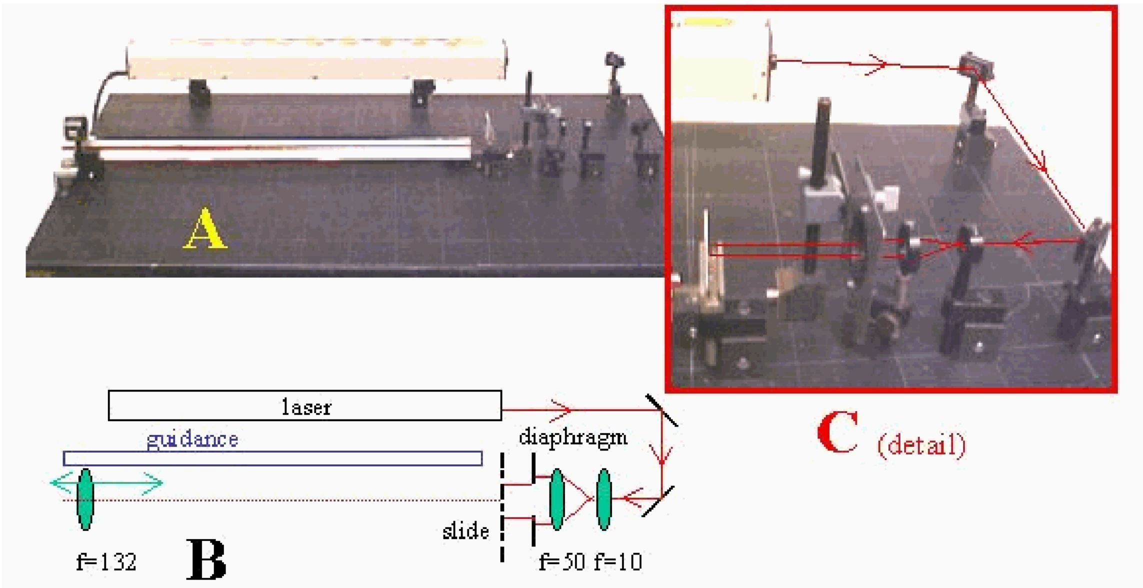


Figure 7.31: .

7.3.1.3.4 Equipment

- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50 mW.
- Two surface mirrors (1/10 1).
- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm (when needed).
- Slide holder.
- Lens, f = 132 mm.
- Optical rail, I = 1 m, as guiding ruler.
- Slide with four double slits (Leybold 46985), all slits having a width of . 20 mm and slitseparation of: a, 1.00 mm; ***b***, .75 mm; ***c***, .50 mm; ***d***, .25 mm.
- Overhead sheet with slit dimensions on it.

7.3.1.3.5 Safety

- Even relatively small amounts of laser light can lead to permanent eye injuries. The laser we use is a class 3B laser. A Class 3B laser is hazardous if the eye is exposed directly, but diffuse reflections such as from paper or other rough surfaces are not harmful. Protective eye wear is typically required where direct viewing of a class 3B laser beam may occur. In our demonstration we always take measures such that no direct or reflected laser light is directed towards the audience. When needed we use black screens to block such light: all beams are stopped at the edge of the optical table. No watches or other jewelry are carried by the demonstrator. As an extra safety measure is our Class-3B laser equipped with a key switch, so unauthorized people cannot switch the laser on. Young's double slit

7.3.1.3.6 Presentation

7.3.1.3.6.1 Preparation

The demonstration is set up as shown in Diagram:

-The two mirrors are positioned in such a way that the laser beam passes parallel to the table.

-The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laser beam is broadened (and a little divergent). Take care that the broadened beam is still parallel to the table.

-The lens of 132 mm can easily be shifted in this beam up and down using the carefully positioned guidance rail.

7.3.1.3.6.2 Demonstration

The set-up as described in Preparation is shortly explained to the students. The most important in this explanation is that the double slit will be placed in a broadened beam and that the double slit will be illuminated by plane waves.

The slide with the double slits is placed on an overhead projector, so the students can see the configuration. The dimensions are indicated on an overhead sheet that is projected at the same time.

The laser is switched on, the broadened beam projects on the wall. When the +132 mm lens is placed at the end of the table, this spot is enlarged (see Figure 2A; the diameter of the projected spot is around 1 m). Then the double slit is shifted into the beam starting with configuration a (see Equipment).

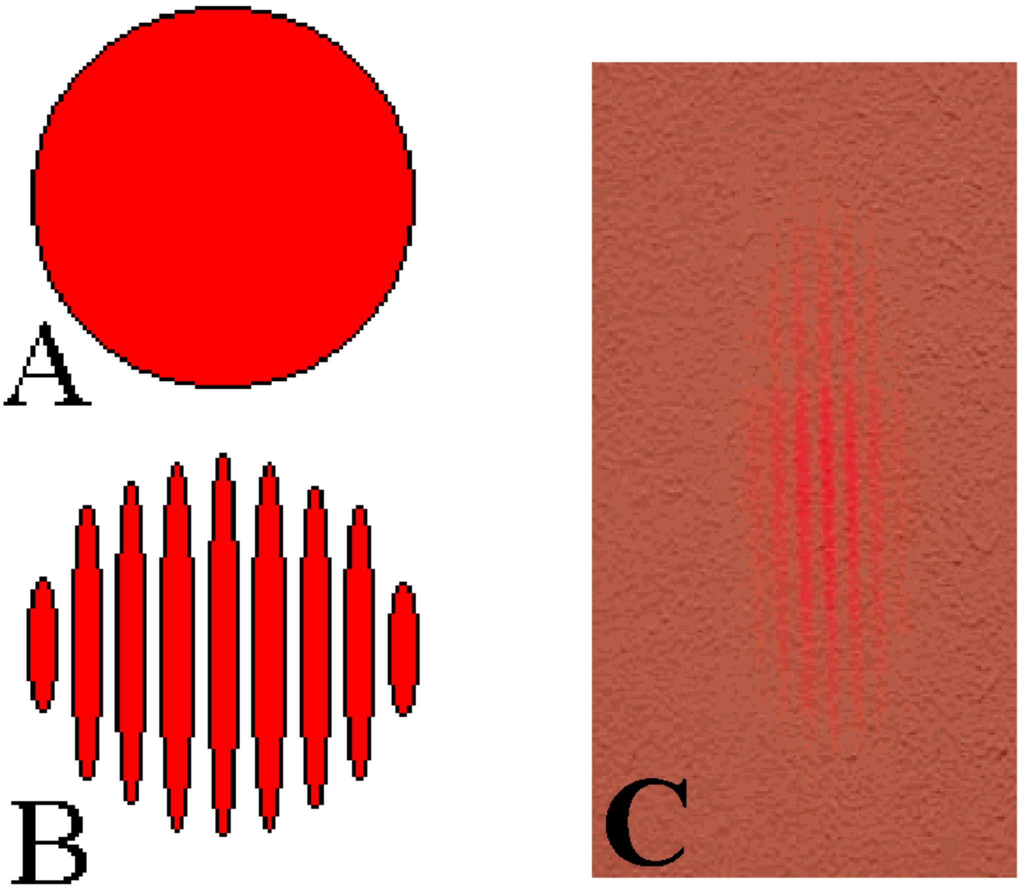


Figure 7.32: .

The typical interference pattern appears (see Figure 2B; Figure 2C shows a snapshot of a real projection on the wall). Then we shift to configuration ***b***, then ***b*** and finally ***b***; in that way going from large to smaller slit-separation. It is observed that with smaller slitseparation the distance between the lines of interference increases

7.3.1.3.7 Explanation

Young explained the observed pattern with the Huygens wave theory and so introduced the principle of interference. Many textbooks give the explanation. Figure 3 shows the arrangement: s is very large compared to the slit separation b.

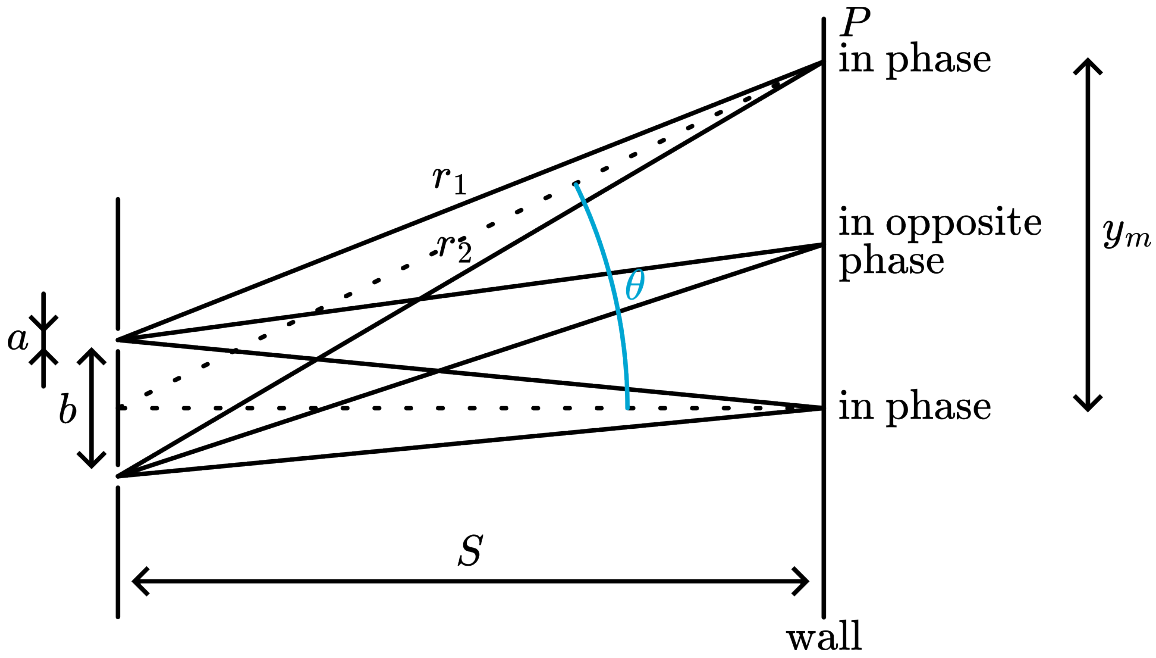


Figure 7.33: .

In P, ray r_1 and ray r_2 interfere. This interference will be constructive when $r_1 - r_2 = m\lambda$ $(m = 0, 1, 2, 3, ...)$.

Also $y_m \approx \frac{s}{b} m\lambda$, and the difference in position of two constructive maxima is $\Delta y \approx \frac{s}{b}\lambda$, explaining the equidistance between the observed maxima and the influence of b in consistency with what we saw in the Presentation. Interference term

7.3.1.3.8 Remarks

- A more complete analysis, also including the diffraction of each slit gives for the

intensity $(/)$ at P : $I(\theta) \approx \underbrace{\left[\frac{\sin\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\frac{\pi a \sin\theta}{\lambda}}\right]^2}_{\substack{Diffraction \\ envelopterm}} \times \underbrace{\cos^2\left(\frac{\pi b \sin\theta}{\lambda}\right)}_{\substack{Interference \\ term}}$

If a becomes vanishingly small, then the diffraction envelope term approaches 1 , and only interference is present. This is the condition for a good Young's double slit experiment. With $a =$ .20 mm this appears to work satisfactory. Using double slits with larger a, then next to interference also diffraction becomes visible in our set-up and that is a different demonstration.

- The $+132$ mm lens is positioned at a distance of about 1 m away from the slide with the double slit. This means that on the wall an image is projected of a point around 85 cm (1m-132mm) away from the double slit. In that way it is assured that the diffraction envelope is really wide (Fraunhofer diffraction). Closer to the slide, the diffraction envelope will transfer into a Fresnel diffraction pattern, spoiling our demonstration. The transition

form Fraunhofer to Fresnel diffraction occurs in this set-up at around $(\mathrm{s} = \mathrm{a}^2/2\lambda =)$ 28 cm (see the demonstration [Fraunhofer-Fresnel diffraction](../6C1002 Fraunhofer and Fresnel Diffraction/6C1002.md)).
- In Young's historical experiment plane waves were obtained using a pinhole through which sunlight passed before illuminating two close-together pinholes. In this way he obtained spatial coherence between the two pinholes. Since we use a laser, the initial pinhole is not needed.
- When in the demonstration the $+132$ mm lens is removed we see that the interference-pattern is enveloped in a wider diffraction-pattern. This can be shown when diffraction has been treated.

7.3.1.3.9 Sources

- Hecht, Eugene, Optics, pag. 385-388 and 447-451
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 329-331
- Young, H.D. and Freeman, R.A., University Physics, pag. 1142-1148
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 870872 and 893-895

7.3.2 6C20 Diffraction Around Objects

7.3.2.1 01 Diffraction (1), introduction

7.3.2.1.1 Aim

To introduce the phenomenon of diffraction with a razorblade and a finger.

7.3.2.1.2 Subjects

- 6C20 (Diffraction Around Objects)

7.3.2.1.3 Diagram

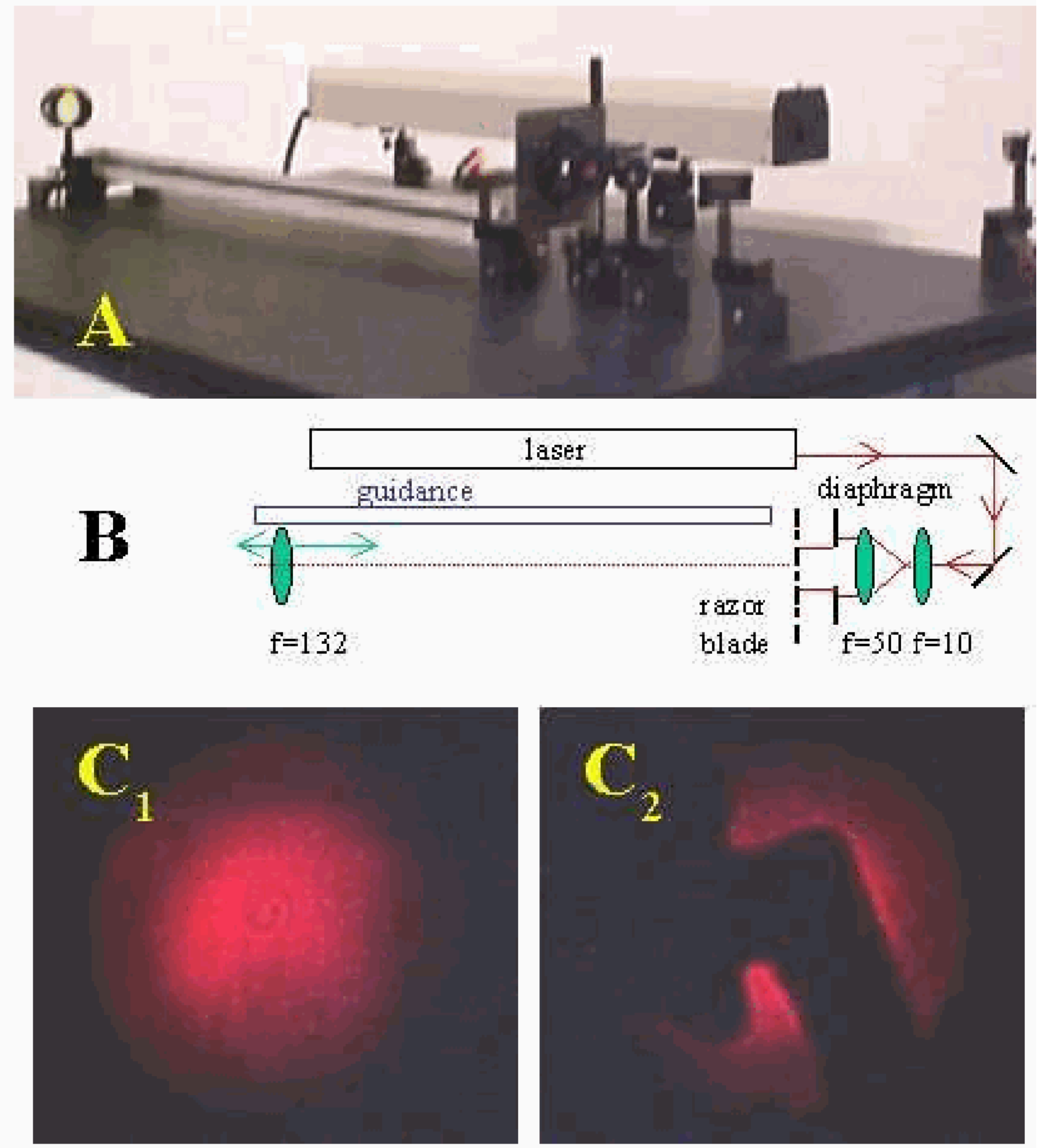


Figure 7.34: .

7.3.2.1.4 Equipment

- Steel table.
- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50mW.
- Two surface mirrors ($1/10\lambda$).

- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm.
- Slide holder.
- Lens, f = 132 mm.
- Optical rail, I = 1 m, as guiding ruler
- Slide-holder with razorblade.
- Pattern scanner:
    - Lightsensor;
    - Rotary motionsensor;
    - Linear translator, with aperture .1mm .
- Interface
- Software.
- Projector to project monitor image.

7.3.2.1.5 Presentation

7.3.2.1.5.1 Preparation

The demonstration is set up as shown in Diagram:

- The two mirrors are positioned in such a way that the laser beam passes parallel to the table.
- The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laserbeam is broadened. Take care that the broadened beam is still parallel to the table.
- The lens of 132 mm can easily be shifted in this beam up and down using the carefully positioned guidance rail.

7.3.2.1.5.2 Demonstration

The set-up as described in Preparation is shortly explained to the students. The most important in this explanation is that the razorblade will be placed in a broadened beam and that the razorblade will be illuminated by plane waves. The +132 mm-lens will project an enlarged image of the shadow of the razorblade.

The razorblade is placed on an overhead projector, so the students can see its shape. The laser is switched on and the broadened beam projects on the wall (see Diagram, C_1; the diameter of the projected spot is around 1 m). Then the razorblade is shifted on the slide holder into the beam. The typical diffraction pattern appears (see Diagram, C_2). This photograph is of a poor quality as compared to what we see in the projection: we easily see around 10 fringes. The razorblade is removed and the demonstrator holds his fingertip in the broadened beam. Also now a fringed shadow pattern appears. Then the razorblade is set vertically in the slide holder and the shadow of one side of the razorblade is observed more carefully: We see many fringes in the region of uniform illumination. The distance between the fringes diminishes as we move away from the geometrical shadow line. Also very clear is that the intensity of the first fringe is higher then the intensity of the uniform illumination.

###optional

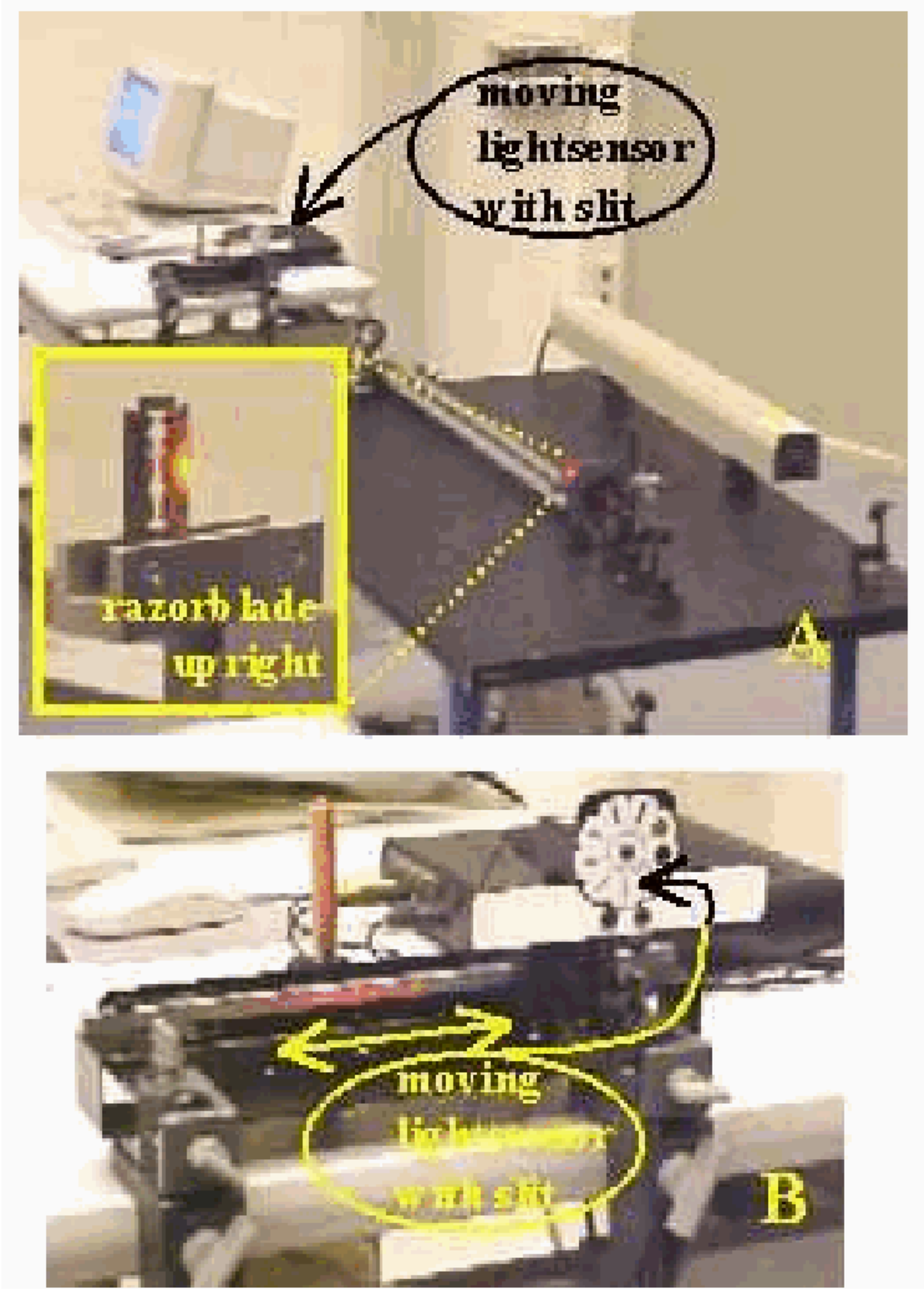


Figure 7.35: .

The pattern scanner, as described in the list of equipment,is placed in the projected beam (see Figure 2) and connected to the interface to scan and record position and intensity of the image on the pc. First the intensity of the broadened laserbeam is registered (see Figure 3, red line). Then the razorblade is positioned vertically, blocking half the beam and again the whole pattern is scanned (see Figure 3, green line).

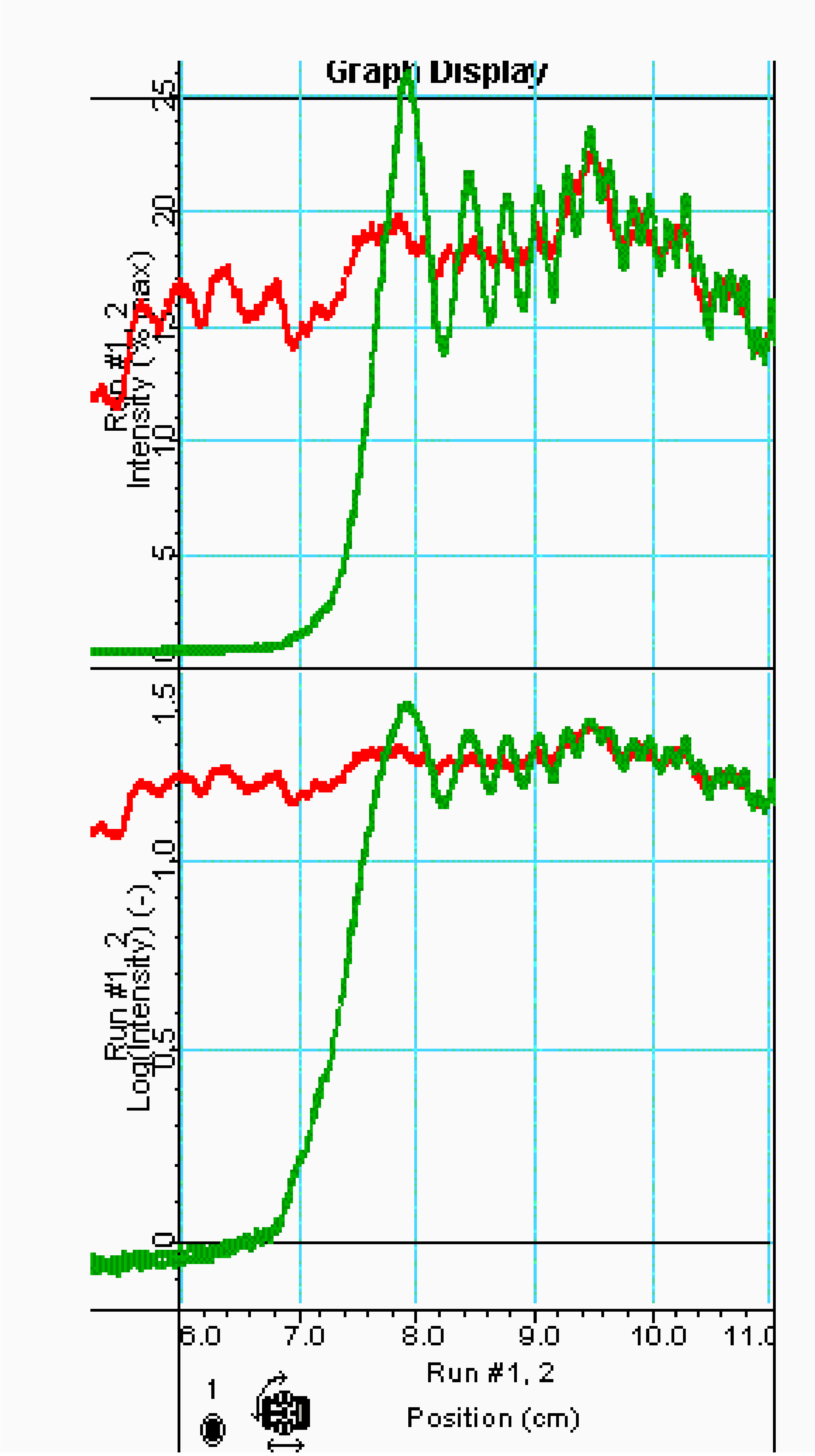

Graph Display
Run #1, 2
Intensity (% max)
25
20
15
10
5
0
Run #1, 2
Log(Intensity) (-)
1.5
1.0
0.5
0
6.0
7.0
8.0
9.0
10.0
Run #1, 2
Position (cm)
1

Figure 7.36: .

In this registration it is very clear that there is an increase and decrease all over the fringe pattern (by eye we see only the increase in intensity of the first fringe). When the fringe pattern is enlarged, the continuing fringing can be seen at all points of the registered intensity. Also the change in fringe separation is very clear. We also see that in the shadow region the intensity drops off rapidly.

7.3.2.1.6 Explanation

The first part of the demonstration is used as an introduction to diffraction, to give some idea of the richness and complexity of "just casting a shadow by an opaque object". The second part of the demonstration shows that in the shadow image there are points of constructive - and destructive interference. An extensive explanation of the fringed pattern is not appropriate when this demonstration is used just as an introduction to diffraction.(Such an explanation needs Fresnel equations and the visualization by means of the Cornu spiral.) At such an introductory stage it suffices to look at Figure3, where the secondary wavelets emitting from the red points (Huygens-Fresnel principle) next to the edge of the razorblade meet at P.

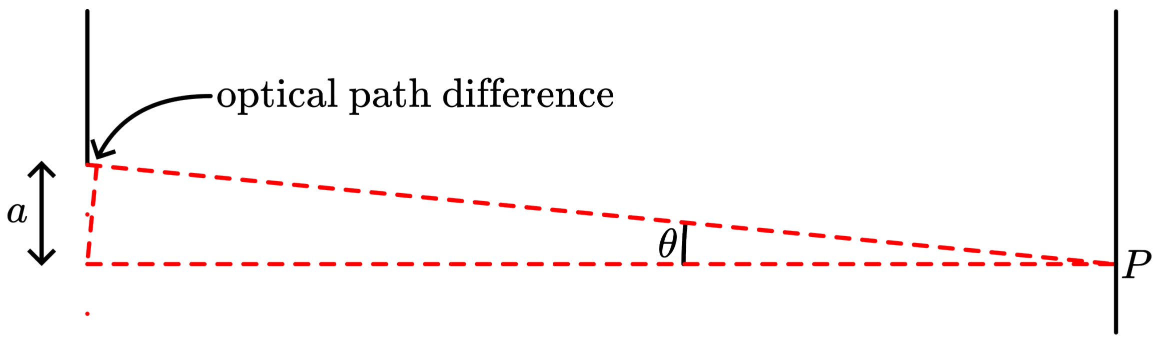


Figure 7.37: .

The two rays drawn enhance when the optical path difference $a \sin \phi = m\lambda$; $(m = 1, 2, 3, ...$ $)When$ asin $\phi = m(\lambda/2)$ then the two rays cancel. This too short explanation makes the observed fringe pattern just plausible.

7.3.2.1.7 Remarks

- When introducing diffraction (for instance by means of a ripple tank) the phenomenon is often described as waves entering the shadow region. In this demonstration with the razorblade the observed phenomenon is in the lightened region.
- The observed diffraction pattern is of the Fresnel type and not of the usually described Fraunhofer type. This is, because the "aperture" of the razorblade edge is very large compared to the distance of observation. (See the demonstration Fraunhofer-Fresneldiffraction.)

7.3.2.1.8 Sources

- Hecht, Eugene, Optics, pag. (introductory): 433-436 (extensive); chapter 10
- Young, H.D. and Freeman, R.A., University Physics, pag. 1165-1167

7.3.2.2 02 Diffraction (2a), Single Slit

7.3.2.2.1 Aim

To show Grimaldi's diffraction.

7.3.2.2.2 Subjects

- 6C20 (Diffraction Around Objects)

7.3.2.2.3 Diagram

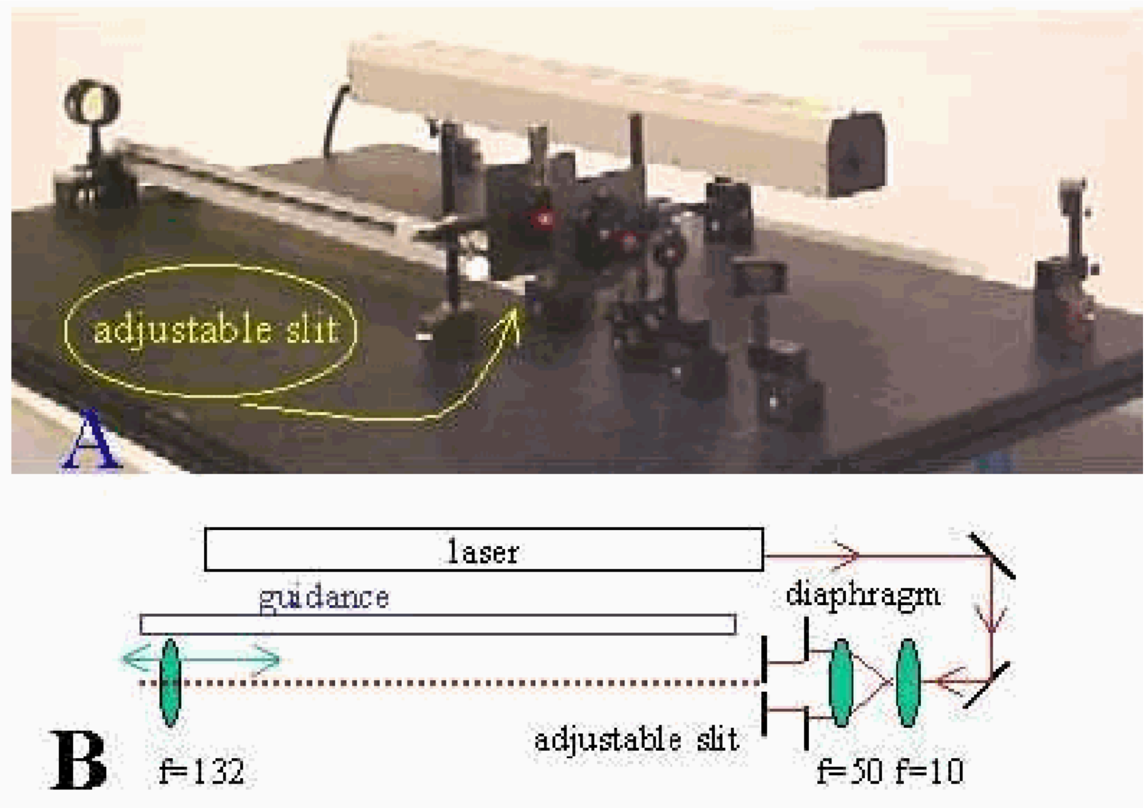


Figure 7.38: .

7.3.2.2.4 Equipment

- Steel table.
- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50 mW
- Two surface mirrors (1/10λ).
- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm.
- Opticail rail, I = 1 m, as guiding ruler.
- Variable slit with vernier adjustment.

7.3.2.2.5 Presentation

7.3.2.2.5.1 Preparation

The demonstration is set up as shown in Diagram:

-The two mirrors are positioned in such a way that the laserbeam passes parallel to the table.

-The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laserbeam is broadened. Take care that the broadened beam is still parallel to the table.

(We are not using the +132 mm-lens that is shown in Diagram A.)

7.3.2.2.5.2 Demonstration

The set-up as described in “Preparation” is shortly explained to the students. The most important in this explanation is that the slit will be placed in a broadened beam and that the adjustable slit will be illuminated by plane waves. Moving a white screen through the beam will show this broadened parallel beam; a lightspot of around 2 cm diameter is observed. The lightspot projects on the wall. Just below the lightspot we stick a ruler of 30 cm length to the wall. A camera observes ruler and lightspot and a videobeamer projects an enlarged image to the audience. We adjust the camera such that the length of the ruler is clearly observed: The projected image has a width of around 20 cm. The adjustable slit is closed and placed in the beam. The room is darkened and slowly the slit is opened, until a weak broad band of light appears on the wall. The length of this broad line is approximately 20 cm. Reading the vernier on the variable slit shows a slit-opening of only . 02 mm !

Increasing the opening of the variable slit shows the well known diffraction pattern. Especially notice:

-The appearance of dark and brighter patches on the sides of the ever decreasing central spot;

-The high intensity of the central maximum when compared to the patches on the sides.

7.3.2.2.6 Explanation

The first part of this demonstration introduces diffraction as a phenomenon in a way similar to Grimaldi’s description of 1665. (He used sunlight and describes shadows.) In our demonstration we use a parallel laserbeam.

When the light, passing through the .02 mm slit, would pass in straigth lines, a .02 mm wide line would appaer on the wall. However we see a 20cmm wide “line”: The slit causes a bending!

The appearance of dark and bright patches on the sides of the centre means that there must be areas of destructive and constructive interference.

To explain the intensity see the demonstration “Diffraction(2b), single slit”.

7.3.2.2.7 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 888-889
- Hecht, Eugene, Optics, pag. 3 and 442-447

7.3.2.3 03 Diffraction (2b), Single Slit

7.3.2.3.1 Aim

To show diffraction on a variable single slit.

7.3.2.3.2 Subjects

- 6C20 (Diffraction Around Objects)

7.3.2.3.3 Diagram

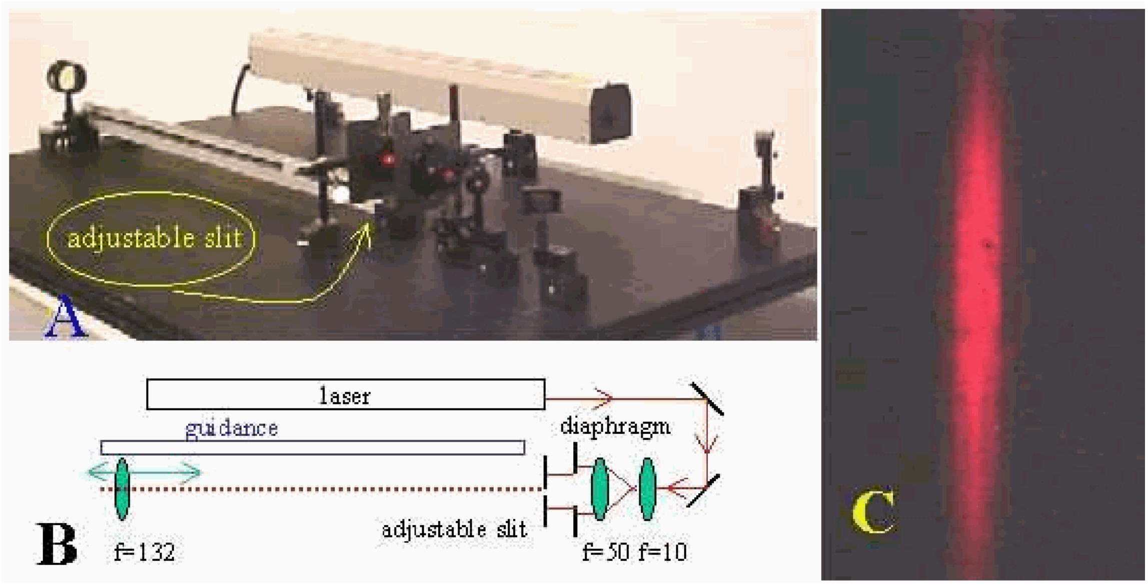


Figure 7.39: .

7.3.2.3.4 Equipment

- Steel table.
- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50 mW.
- Two surface mirrors ($1/10\lambda$).
- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm.
- Slide holder.
- Lens, f = 132 mm.
- Opticail rail, I = 1 m, as guiding ruler.
- Variable slit with vernier adjustment.
- Overheadsheet with Figure 2.

7.3.2.3.5 Presentation

7.3.2.3.5.1 Preparation

The demonstration is set up as shown in Diagram:

-The two mirrors are positioned in such a way that the laserbeam passes parallel to the table. - The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laserbeam is broadened. Take care that the broadened beam is still parallel to the table.

-The lens of 132 mm can easily be shifted in this beam up and down using the carefully positioned guidance rail.

7.3.2.3.5.2 Demonstration

The set-up as described in Preparation is shortly explained to the students. The most important in this explanation is that the slit will be placed in a broadened beam and that the adjustable slit will be illuminated by plane waves.

The laser is switched on. A spot of 2 cm projects on the wall (see ["Diffraction(2a)](../6C2002 Diffraction Single Slit/6C2002.md>)). The +132 mm-lens is placed at the end of the guiding ruler, to project an enlarged image of the interference-pattern as it will be "seen" around 85 cm (1m-132mm) behind the slit. The broadened and enlarged beam projects as a spot on the wall (diameter of the spot is around 40 cm). The slit is closed and positioned in the beam. (By means of an overheadsheet it is shown to the students what the geometrical projection will show to us (see Figure 2): When the wall is at a distance as indicated in this figure, then the slit width a is projected 20 times larger on the wall. So when the slit width is 0, 1 mm, then we will see a width of 2 mm.)

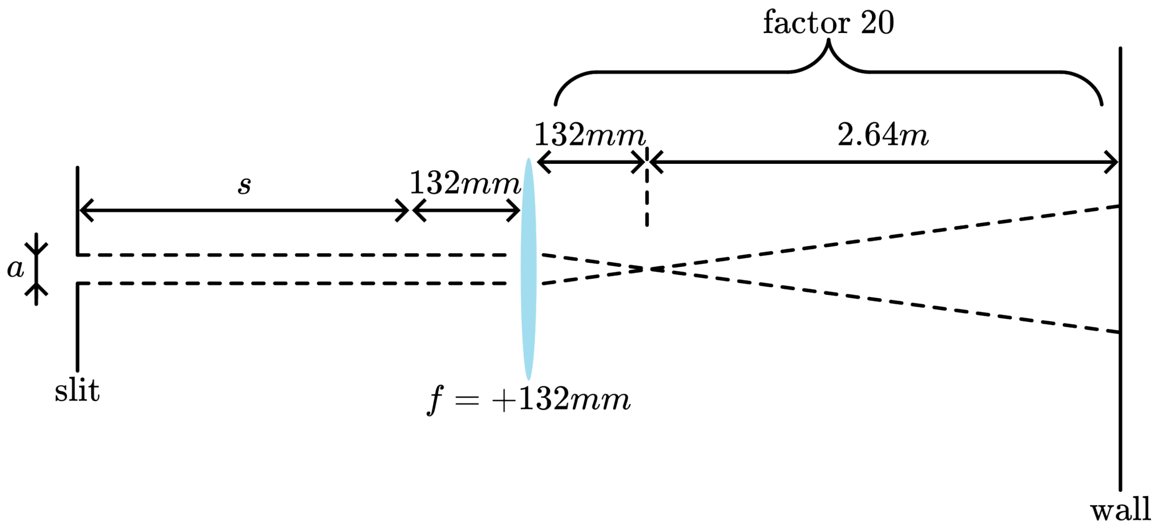


Figure 7.40: .

-slit at 0.2 mm, band of light = 15 cm, first subsidiary maxima appear;

-slit at 0.3 mm, central band of light = 8 cm, four subsidiary maxima on both sides;

-further opening of slit compresses the observed diffraction pattern;

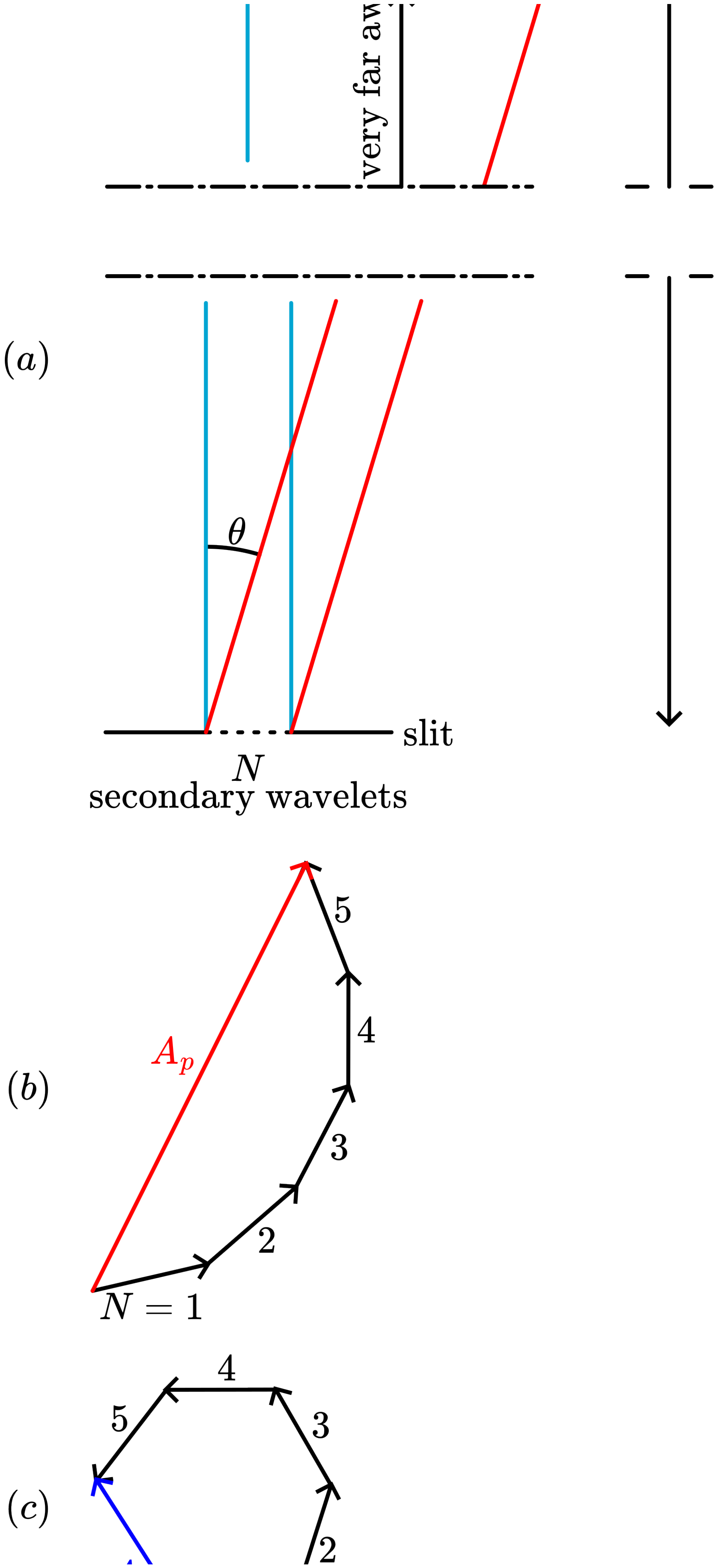
-slit at 0.7 mm, central band of light = 1 cm, around 10 subsidiary maxima on both sides (see Diagram C; reality is much better than this photograph).

At this 0.7 mm slit width the first subsidiary maxima are almost as intens as the central maximum. Usually here we stop the demonstration (see Remarks).

7.3.2.3.6 Explanation

When the slit is 0.1 mm and the geometrical projection would be only 2 mm wide, clearly light is bending, broadening the band to 20 cm.

Many textbooks give a detailed explanation (see Sources). We consider Figure 3.



very far aw
(a)
θ
slit
N
secondary wavelets
(b)
A_p
5
4
3
2
N = 1
(c)
4
5
3
2

Figure 7.41: .

At P, N secondary wavelets superimpose, having a path difference of $\frac{a}{N}\sin\theta$. Applying phase addition (see Figure 3B), A_p is the resultant wave amplitude at P. At O, the total amplitude of the secondary wavelets will be the arclength in that phasor diagram, since all vectors then have the same phase. At Q (θ is larger) the phase difference between the "individual" secondary wavelets is larger and the phase diagram (Figure 3C) shows that the total amplitude can eventually be zero.

Analysis gives for the intensities (I_θ) (see textbooks): $\frac{I_\theta}{I_0} = \left[\frac{\sin\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\frac{\pi a \sin\theta}{\lambda}}\right]^2 = \left[\frac{\sin\alpha}{\alpha}\right]$. Minima occur at $\sin\alpha = 0$, so when $\alpha = \mathrm{n}\pi$, and maxima at $\alpha = \left(\frac{2n+1}{2}\right)\pi$. The intensities of these maxima are then given by $\frac{I_\theta}{I_0} = \frac{\sin^2\alpha}{\alpha} = \frac{4}{(2n+1)^2\pi^2}$.

$\mathrm{n} = 1$ gives $\mathrm{I}_1 = 0.045\mathrm{I}_0$;

$\mathrm{n} = 2, \mathrm{I}_2 = 0.016\mathrm{I}_0$, etc.

So, the subsidiary maxima are comparatively weak, but yet clearly visible as the demonstration showed.

7.3.2.3.7 Remarks

- The $+132$ mm lens is positioned at a distance of about 1 m away from the slit. This means that on the wall an image is projected of a point around 85 cm (1m-132mm) away from that slit. In that way it is assured that the diffraction pattern is far field Fraunhofer pattern. Increasing the slit opening beyond 0.7 mm will transfer the projected pattern into a Fresnel diffraction pattern, spoiling (complicating) our demonstration. The transition form Fraunhofer to Fresnel diffraction occurs in this set-up at around (see Figure 2): $s = a^2/2\lambda$, $s = 85$ cm, so $a = 1$ mm. In this single slit introductory demonstration we should not go beyond that width. (See the demonstration "Fraunhofer-Fresneldiffraction".)

7.3.2.3.8 Sources

- Hecht, Eugene, Optics, pag. 442-447
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 325-327
- Young, H.D. and Freeman, R.A., University Physics, pag. 1167-1169
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 890-893

7.3.2.4 04 Fraunhofer and Fresnel Diffraction

7.3.2.4.1 Aim

To show how light illuminating a slit gives different regions of diffraction. Close to the slit: Fresnel diffraction and at some distance: Fraunhofer diffraction. To determine where the one type of diffraction transforms into the other.

7.3.2.4.2 Subjects

- 6C20 (Diffraction Around Objects)

7.3.2.4.3 Diagram

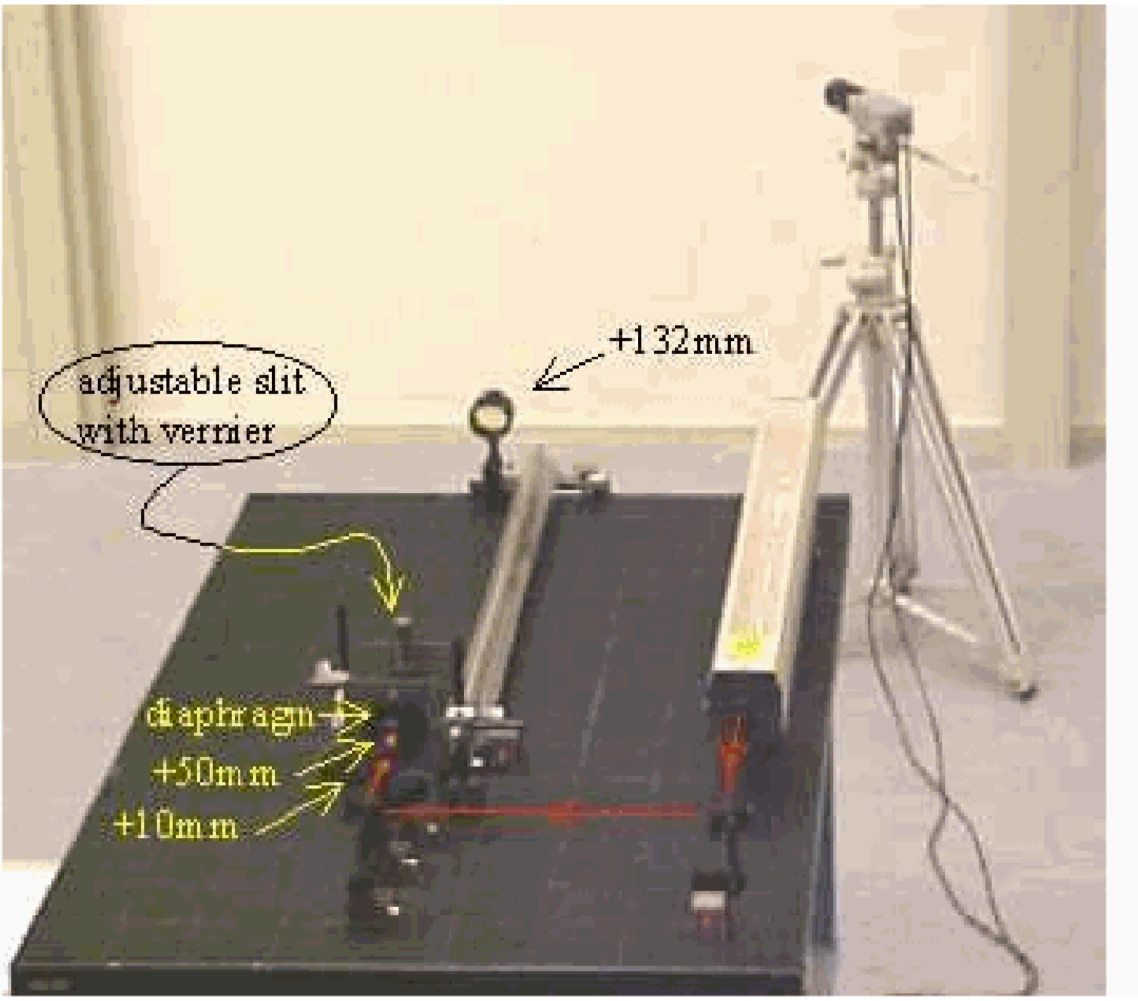


Figure 7.42: .

7.3.2.4.4 Equipment

- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50 mW.
- Two surface mirrors ($1/10\lambda$).
- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm.
- Slide holder.
- Lens, f = 132 mm.
- Optical rail, I = 1 m, as guiding ruler.
- Adjustable slit.
- Video camera.

- Projector to project diffraction-image.
- Overheadsheet with Figure 10.5 ("Optics" by Hecht; see Sources).

7.3.2.4.5 Presentation

7.3.2.4.5.1 Preparation

The demonstration is set up as shown in Diagram:

-The two mirrors are positioned in such a way that the laserbeam passes parallel to the table.

- The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laserbeam is broadened. Take care that the broadened beam is still parallel to the table.

-The lens of 132 mm can easily be shifted in this beam up and down using the carefully positioned guidance rail.

7.3.2.4.5.2 Demonstration

The set-up as described in "Preparation" is explained to the students, so that it is clear to them that the adjustable slit is placed in a beam of light consisting of parallel rays. The adjustable slit is set at .6 mm. The +132 mm lens is shifted close to this slit to project a sharp image of it on the wall: a smooth red region, having a sharp boundary on both sides (see Figure 2A). Considering the wall to be far away, the lens needs to be +132 mm away from the slit (the slit is in the focus of the projecting lens).

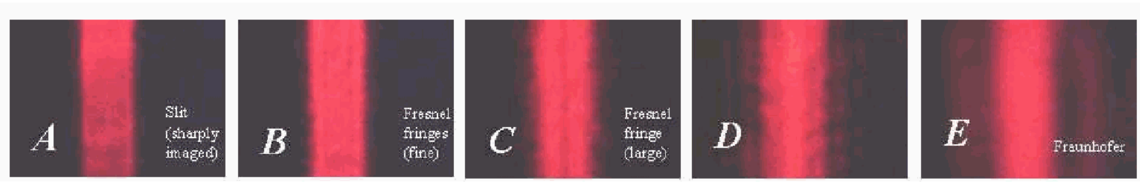


Figure 7.43: .

Then the +132 mm lens is slowly shifted away from the slit. The projected image changes: in the originally smooth red region domains of higher and lower intensity (fringes) can be discerned (see Figure 2B). Moving out still farther, the fringe pattern changes continuously: the number of fringes diminishes while the fringes themselves broaden (compare the pictures in Figure 2; reality is better than the quality of these pictures). When the +132 mm lens has reached the end of the guidance rail the familiar diffraction pattern as shown when introducing diffraction, is visible (see the demonstration "Diffraction(2), single slit".

Leaving the +132 mm lens in this far away position, the transformation from Fresnel to Fraunhofer can also be shown when you vary the width of the slit.

It will be clear now that distance form the slit and slit-width have both something to do with this transformation of one type of diffraction into the other.

7.3.2.4.6 Explanation

The +132 mm lens being for away from the wall projects an image of an "object" that is 132 mm away form it. At first we seen the sharply imaged slit; moving away from the slit, for instance 10 mm, then the image of this position is projected on the wall. In this way the lens scans the region close to the slit (near field) and farther away (far field). Considering far field diffraction (Fraunhofer diffraction) the slit is that narrow compared to the distance in the field, that the secondary wavelets emerging from the slit proceed as being planar. This relative simplicity of Fraunhofer diffraction is explained in the demonstration "Diffraction(2), single slit" in this database.

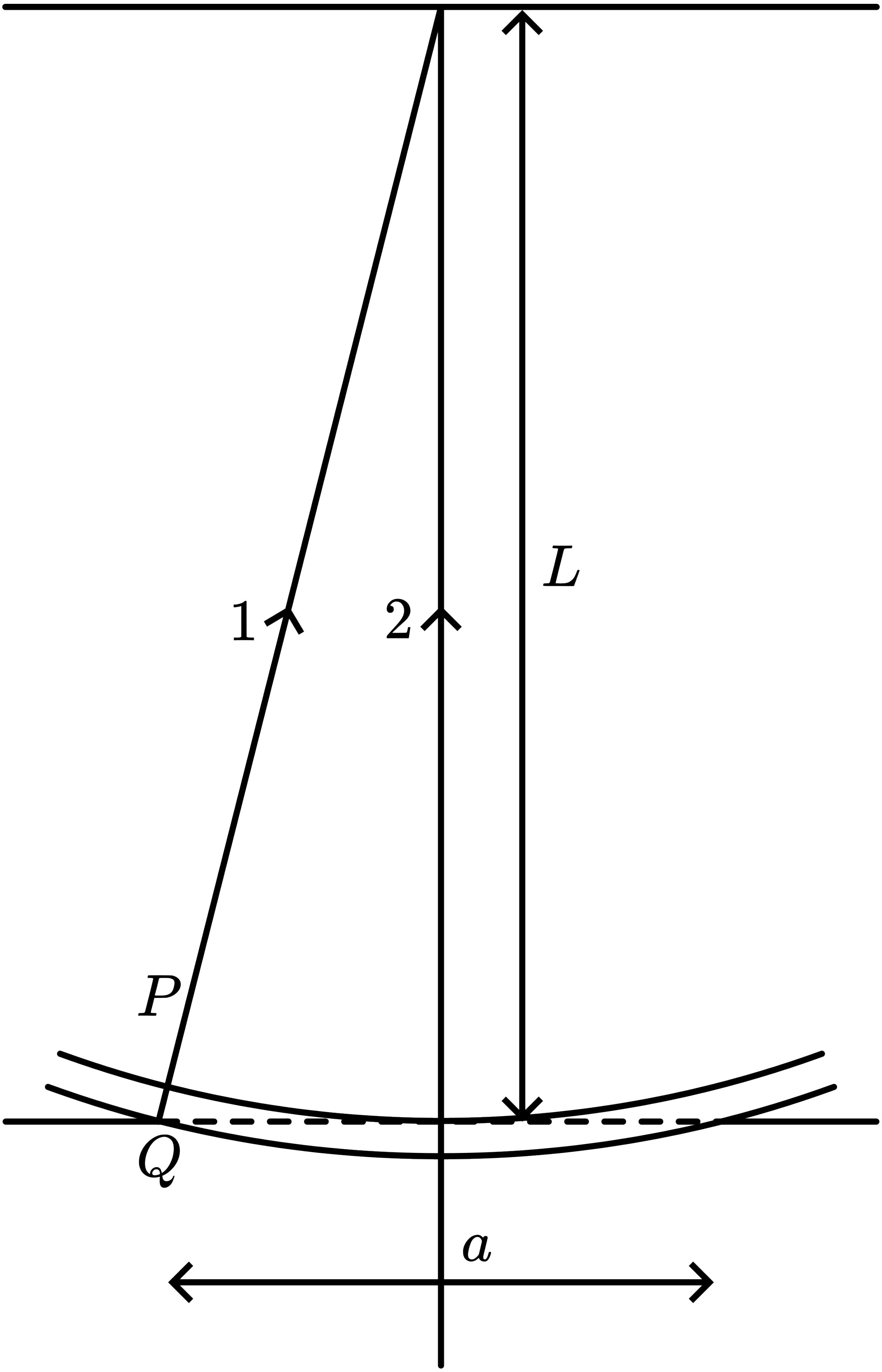


Figure 7.44: .

In the near field configuration the width of the slit cannot longer be neglected. Due to this an extra path difference (PQ) between ray 1 and ray 2 is introduced (see Figure 3).

Applying Pythagoras shows $L^2 + \frac{a^2}{4} = (L + PQ)^2$, and $PQ = \frac{a^2}{8L}$. If, as a rule of thumb, this extra path difference is neglected if it is smaller than $\lambda/4$, we find that for the distance L we need $L > \frac{a^2}{2\lambda}$. So, the distance $L \approx \frac{a^2}{2\lambda}$ can be considered as the "border" between Fresnel - and Fraunhofer diffraction. Applying the data In this demonstration $(a = .6 \text{ mm}; \lambda = 650 \text{ nm})$, we find: $L = .25$ m. Performing the demonstration confirms this.

7.3.2.4.7 Remarks

- In preparing this demonstration we used of course $L = .25$ m (means: lens at .382 m from slit) and then calculated the needed slit width, so that both types of diffraction can be clearly shown in one shift of the $+132$ mm lens.
- The demonstration can also be performed having the $+132$ mm lens fixed at the end of the table $(L = .85 \text{ m})$ and then slowly increase the width of the slit. Then the distinction between Fresnel - and Fraunhofer diffraction is at a slit width of around 1 mm. But realize that turning a vernier is less visible to an audience than shifting a lens across the table.
- The different patterns can also be registered using a pattern scanner as described in "Diffraction(1), introduction". Particularly the fine fringes close to the slit can be made visible in this way.

7.3.2.4.8 Sources

· Hecht, Eugene, Optics, pag. 437-438 and 495-499

Diagram

7.4 6D Interference

7.4.1 6D10 Interference From Two Sources

7.4.1.1 01 Fresnel Double Mirror

7.4.1.1.1 Aim

To show the interference of two coherent beams of light.

7.4.1.1.2 Subjects

- 6D10 (Interference From Two Sources)

7.4.1.1.3 Diagram

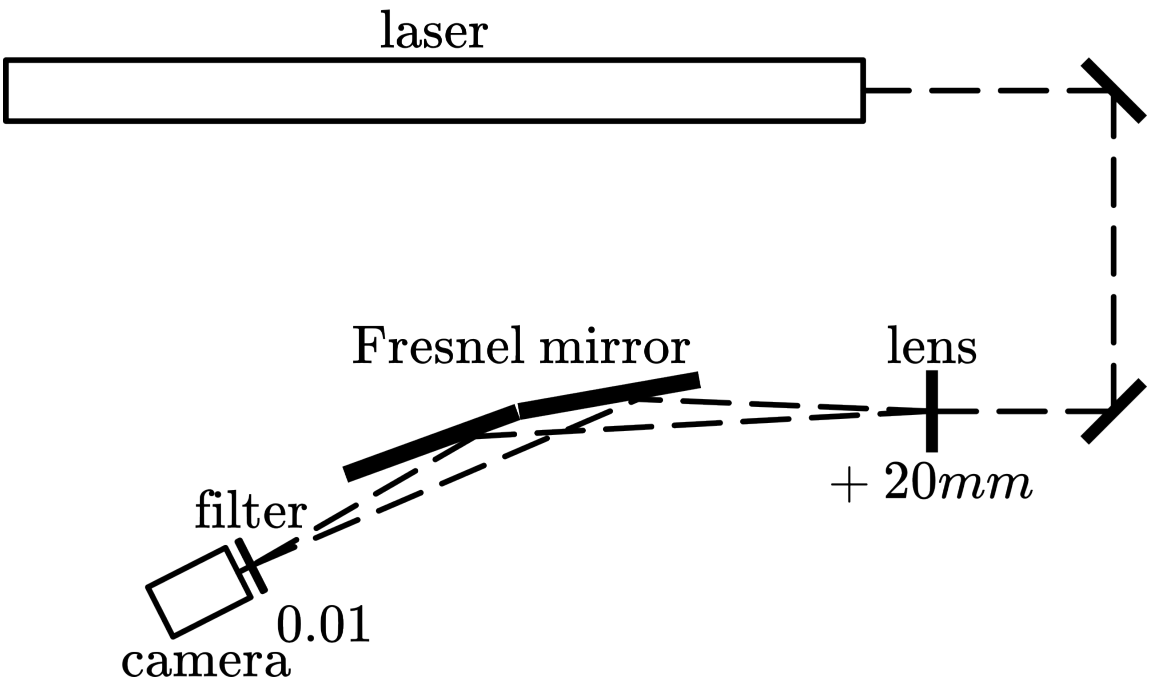


Figure 7.45: .

7.4.1.1.4 Equipment

- Laser (50mW)
- Simple lens (we use +20 mm)
- Fresnel double mirror
- White screen/wall
- Video-camera.
- (Video-camera, lens removed. Instead of the lens we use a grey filter, 1/100; see “Remarks”).
- Large-screen video-monitor, or projector.

7.4.1.1.5 Presentation

The room is darkened and the laser is switched on. By means of the +20 mm lens an illuminated disk is projected on the white screen. The Fresnel double mirror is adjusted so that the two halves of the mirror are parallel. The mirror surface is shifted into the diverging light beam, approximately parallel to it and turned just that much so that the beam of rays strike both mirror halves equally. Two light spots (half circles) are visible on the screen/monitor, separated by a dark zone (see Figure 2).

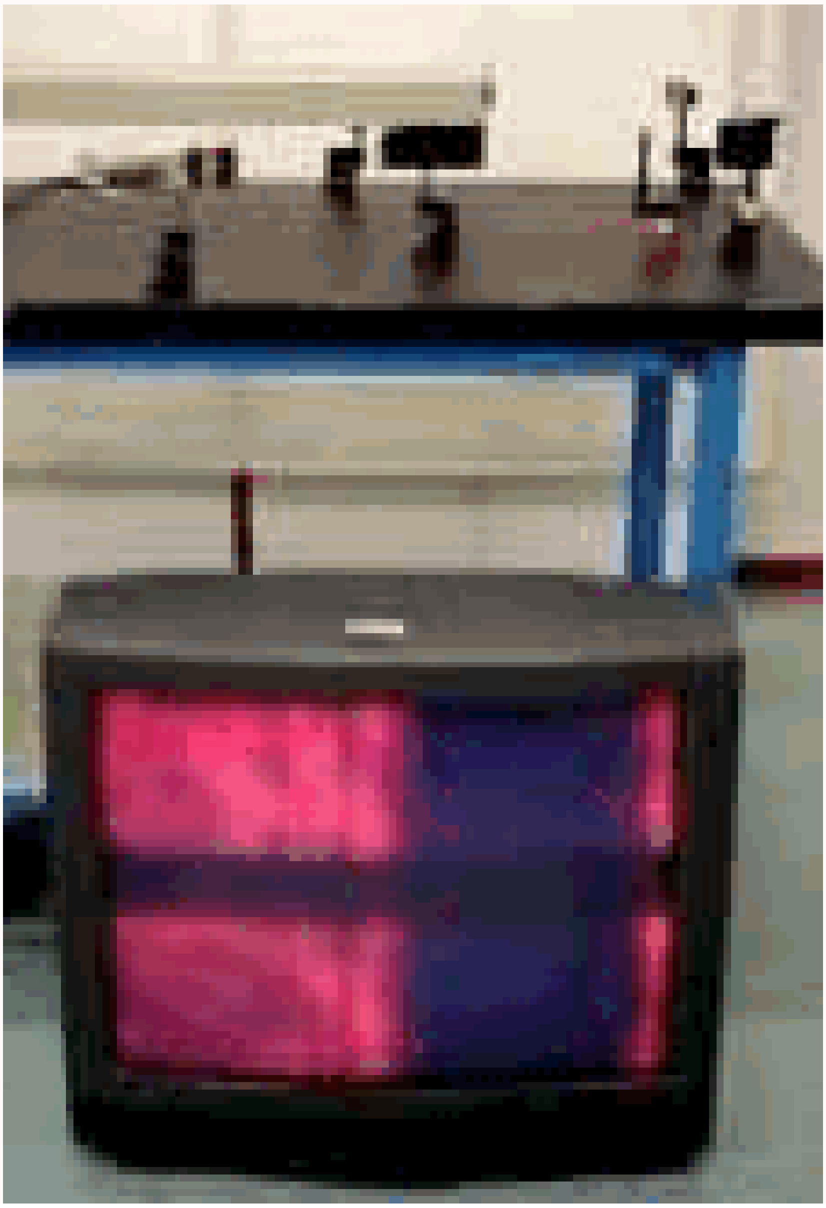


Figure 7.46: .

Turning the adjustment screw of the Fresnel mirror, the movable part of the mirror is tilted and the two light spots start overlapping. From a distance, an intensification of the light in the overlapping zone is clearly observed. Then, at a closer look, by means of a camera, a clear interference pattern is observed. (see Figure 3).

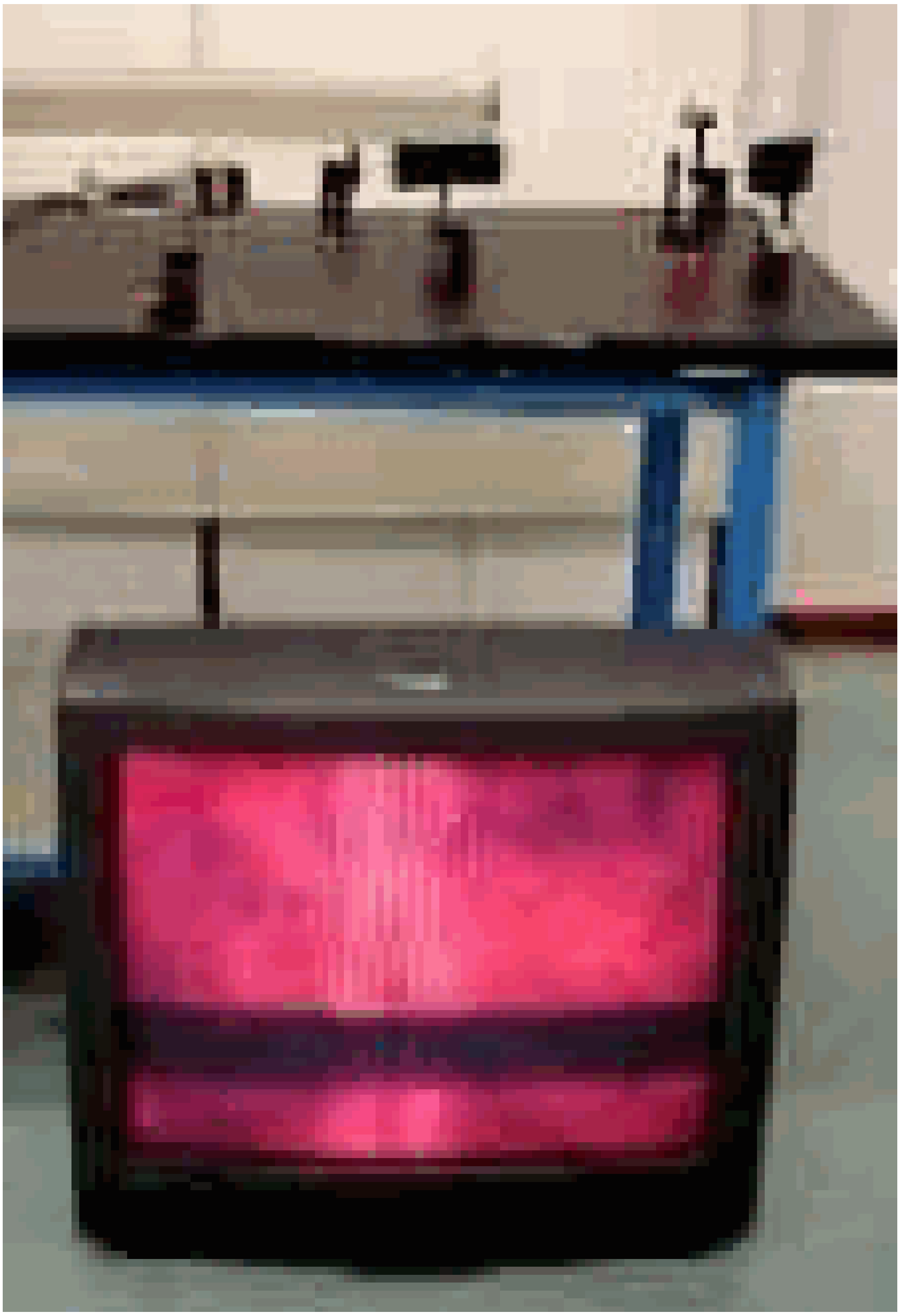


Figure 7.47: .

Stress especially the clearly visible increase in intensity of the fringes themselves and the zero intensity between them, illustrating respectively the constructive - and destructive interference. The separation between the fringes becomes less the more the movable mirror is pivoted.

7.4.1.1.6 Explanation

One part of the wavefront coming from point S is reflected from the first mirror and the other part is reflected from the second mirror (see Figure 4).

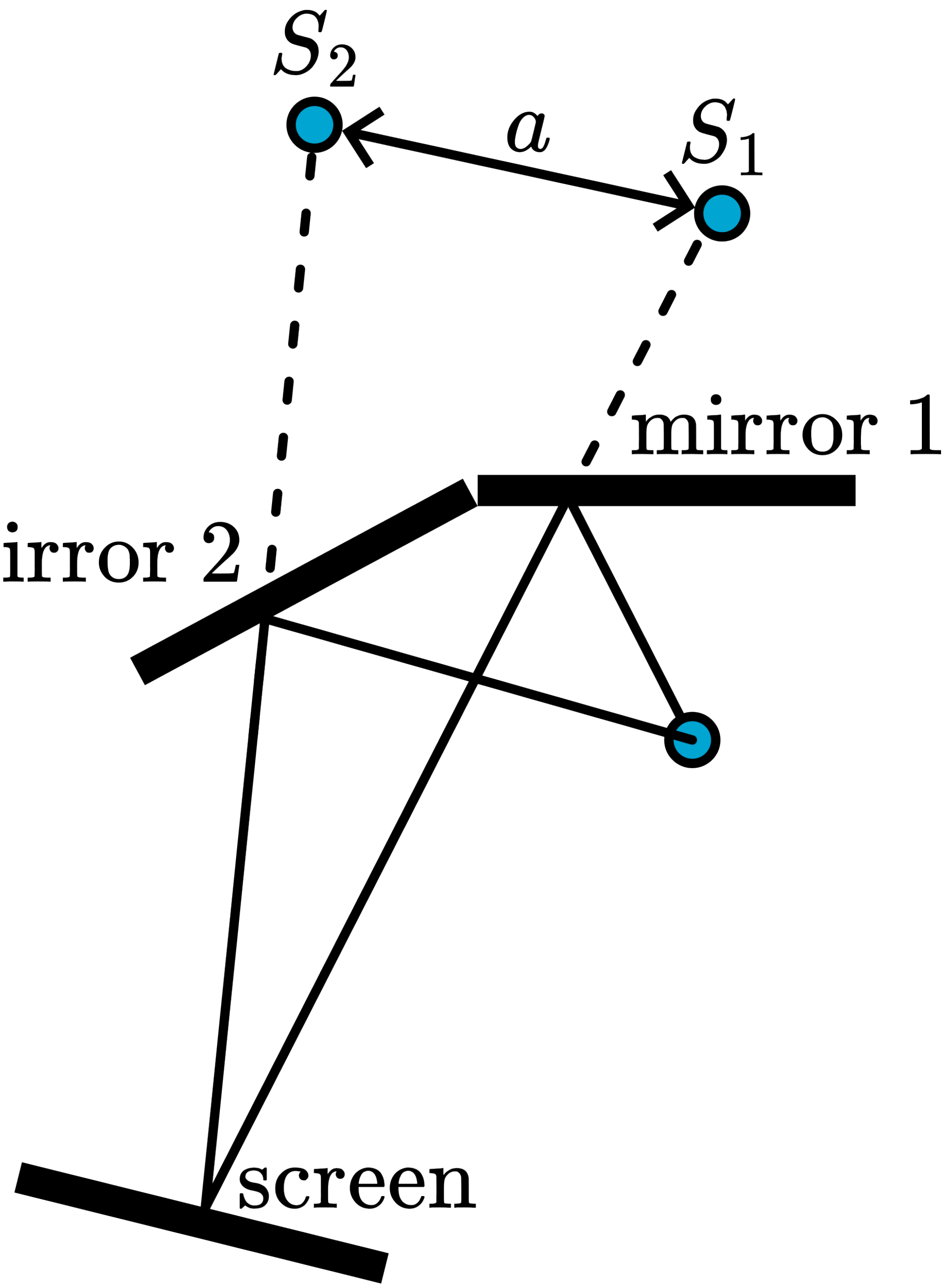


Figure 7.48: .

An interference field exists in the region where the two reflected waves are superimposed. The mirror images S_1 and S_2 can be considered as separate coherent sources, placed a distance a apart. The separation (Δy) between the fringes is given by $\Delta y \approx \frac{s}{a}\lambda$ (s being the distance between the plane of the two sources and the screen).

So the more the double mirror is pivoted, the larger the distance between the images S_1 and S_2 will be and thus the fringe separation Δy decreases.

7.4.1.1.7 Remarks

- In the demonstration the distance between the fringes can be enlarged by placing the screen not perpendicular but more and more parallel to the reflected beams.
- You can also use the sensitive screen of a video-camera as a screen on which the interfering beams are projected. Then a video-monitor shows the much enlarged pattern.

7.4.1.1.8 Sources

- Hecht, Eugene, Optics, pag. 390

- Phywe, University Laboratory Experiments, part Vol. 1-5, pag. 2.5
- Leybold-Heraeus, Physikalische Handblätter, pag. DK 535.412;c

7.4.1.2 02 Fresnel Double Prism

7.4.1.2.1 Aim

To show the interference of two coherent, virtual, sources (wavefront splitting).

7.4.1.2.2 Subjects

- 6D10 (Interference From Two Sources)

7.4.1.2.3 Diagram

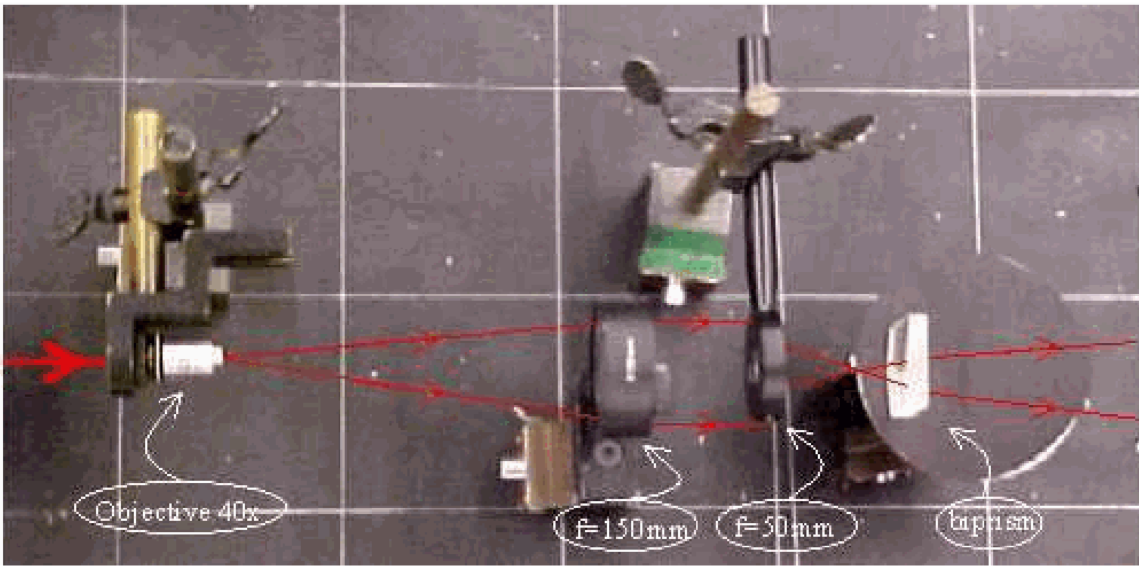


Figure 7.49: .

7.4.1.2.4 Equipment

- Laser.
- Microscope objective (40x)
- Lens, 150 mm.
- Lens of short focal length (we use 50 mm)
- Double prism.
- Viewing screen/wall.

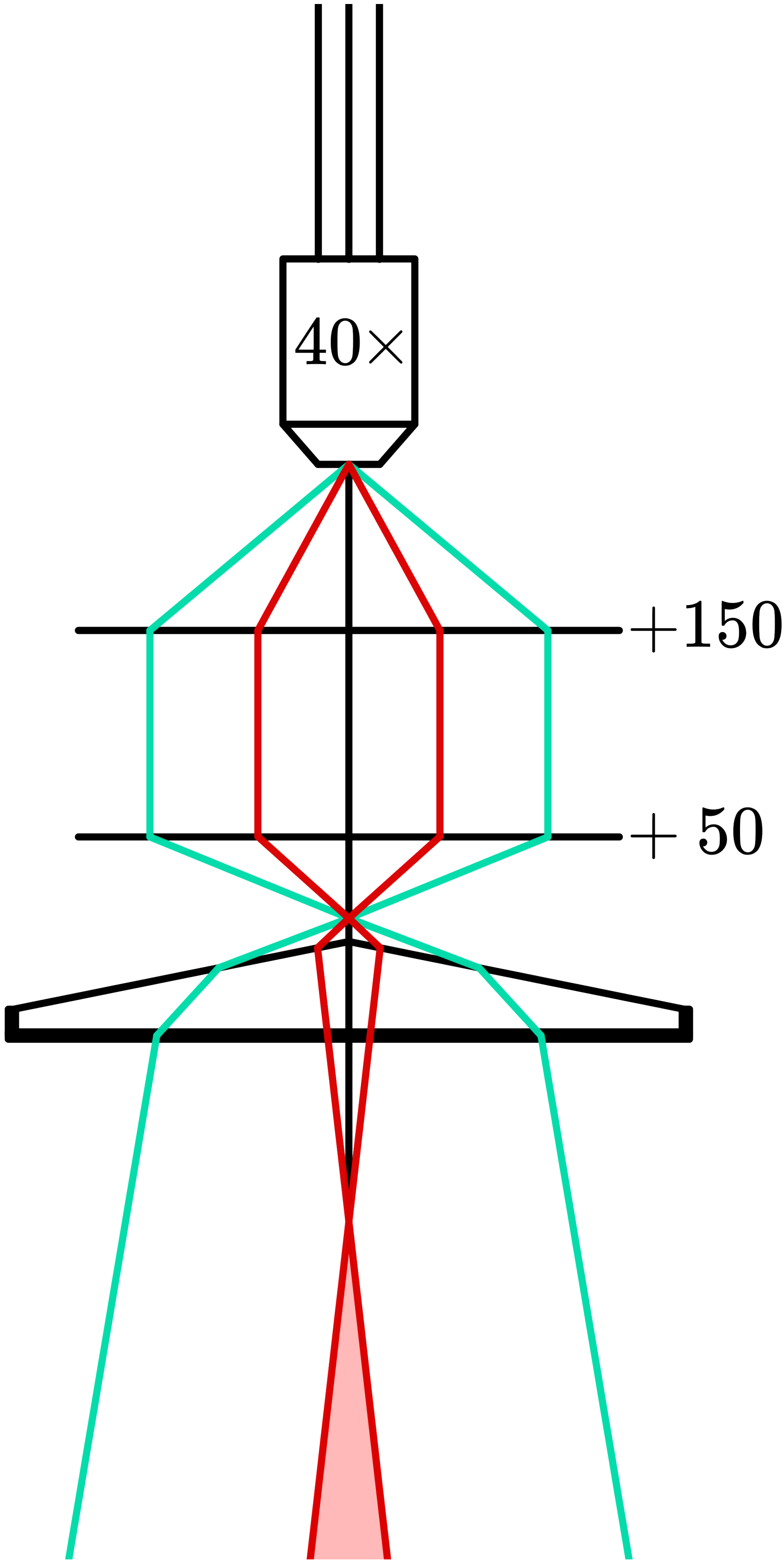
7.4.1.2.5 Presentation

7.4.1.2.5.1 Preparation

The laserbeam is switched on and expanded using a telescope consisting of the microscope objective and the converging lens of 150 mm. The expanded beam is then focussed by the lens of 50 mm.

7.4.1.2.5.2 Presentation

On the viewing screen, a couple of meters away we see a large circular light spot. (Blowing smoke into the lens set-up enlightens the light path).



$40\times$
$+150$
$+\ 50$

Figure 7.50: .

When descending the biprism (apex line vertical) into the diverging beam, close to the focal point (see Figure 2), we see that the original circular light spot is refracted into two half circle segments and that in the centre these two halves overlap (see Figure 3), narrowing the original lightspot.

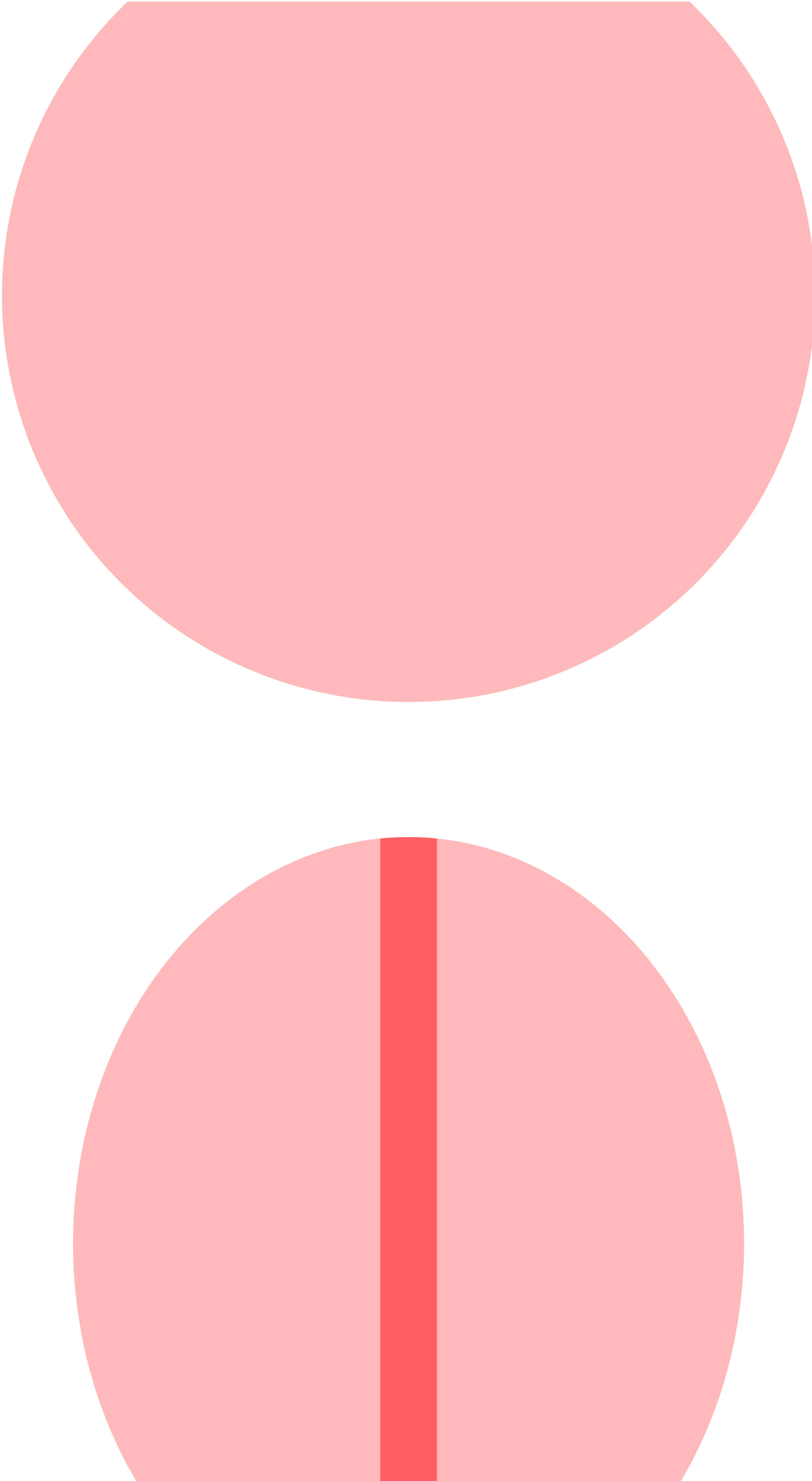


Figure 7.51: .

The centre shows an increase in light intensity. When the biprism is moved closer to the focal point of the 50 mm lens, we will easily see that the centre contains fringes, lines of positive and negative interference. When the biprism is close to this focal point the fringe spacing is large; when the biprism is moving away from the focal point, the fringe spacing is smaller but can still be observed when the viewing screen is tilted.

7.4.1.2.6 Explanation

See Figure 4. The left portion of the wavefront is refracted to the right, the right portion to the left. In the region of superposition interference occurs.

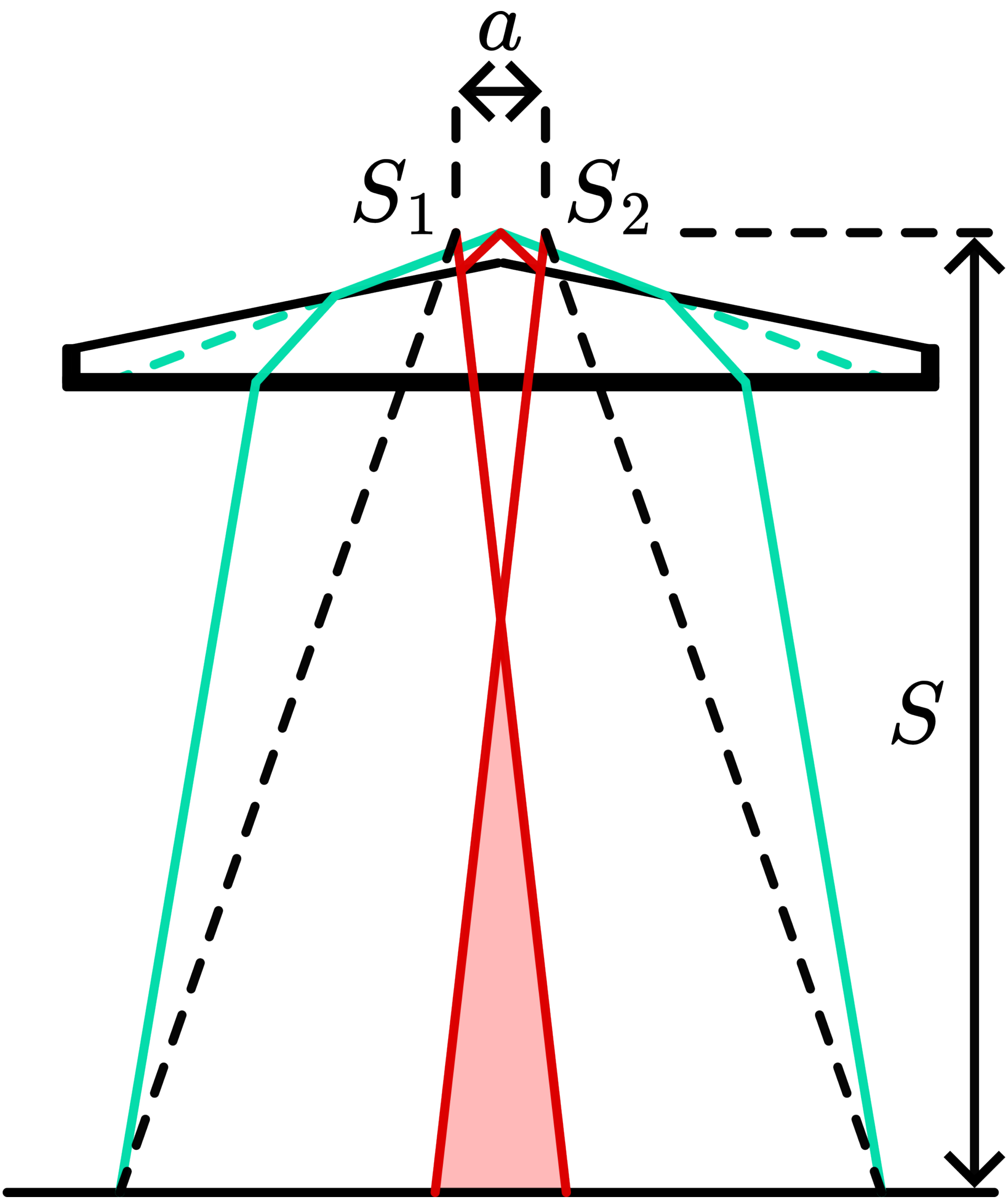


Figure 7.52: .

The virtual sources S_1 and S_2 can be considered as separate virtual coherent sources placed a distance a apart. The separation of the fringes (Δy) is given by: $\Delta y \approx \frac{s}{a}\lambda$ (s being the distance between the plane of the two sources and the screen).

7.4.1.2.7 Remarks

When the biprism approaches the focal point too close, the interference image becomes distorted. This happens largely due too the fact that we use spherical lenses in stead of cylindrical.

7.4.1.2.8 Sources

- Hecht, Eugene, Optics, pag. 391
- Leybold-Heraeus, Physikalische Handblätter, pag. DK 535.412;d
- Phywe, University Laboratory Experiments, part Vol. 1-5, pag. 2.5
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 403

7.4.1.3 03 Lloyds Mirror

7.4.1.3.1 Aim

To show the interference of two coherent beams of light.

7.4.1.3.2 Subjects

- 6D10 (Interference From Two Sources)

7.4.1.3.3 Diagram

Diagram

7.4.1.3.4 Equipment

- Laser
- Simple lens (we use +10 mm)
- Surface mirror
- White screen/wall

7.4.1.3.5 Presentation

The room is darkened and the laser is switched on. By means of the +10 mm-lens an illuminated disk is projected on the white screen. The surface mirror is placed parallel to the diverging light beam (see Figure 1A)

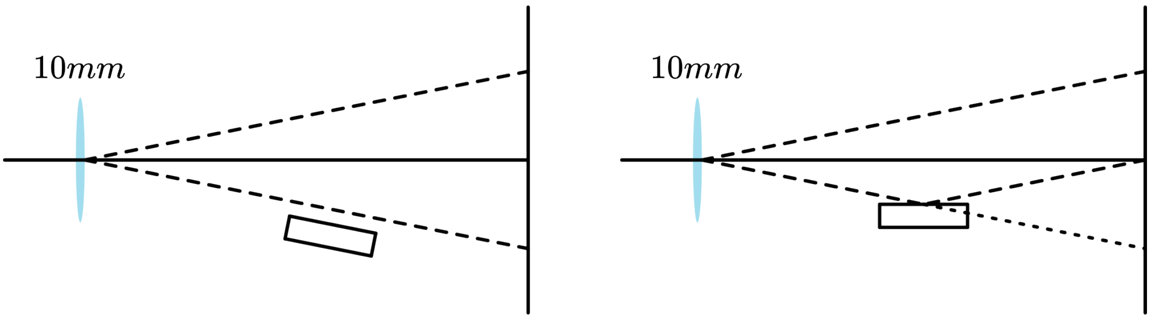


Figure 7.53: .

and then turned just a little, so that the outer rays of the beam are reflected (see Figure 1B). In the light spot on the wall the fringes are visible now.

7.4.1.3.6 Explanation

A portion of the wavefront is reflected from S (see Figure 2).

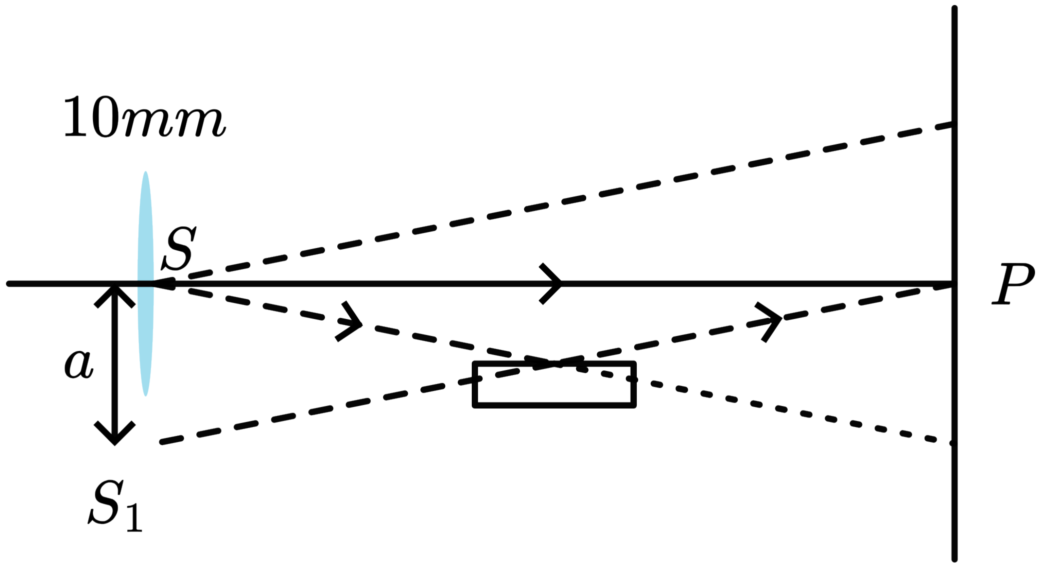


Figure 7.54: .

The other portion proceeds directly to the screen. Interference occurs in the region where the two portions are superimposed S and its mirrorimage S_1 can be considered as separate coherent sources, placed a distance a apart. Then the separation (Δy) between the fringes is given by $\Delta y \approx \frac{S}{a}\lambda$ (s being the distance between the plane of the two sources and the screen).

7.4.1.3.7 Remarks

In the demonstration the distance between the fringes can be enlarged by placing the screen not perpendicular but more parallel to the beam.

7.4.1.3.8 Sources

- Hecht, Eugene, Optics, pag. 391-392
- Leybold-Heraeus, Physikalische Handblätter, pag. DK 535.412;b

7.4.1.4 04 Young's Double Slit

Young's double slit

7.4.1.4.1 Aim

To show a double slit interference pattern and the influence of slit-separation.

7.4.1.4.2 Subjects

- 6D10 (Interference From Two Sources)

7.4.1.4.3 Diagram

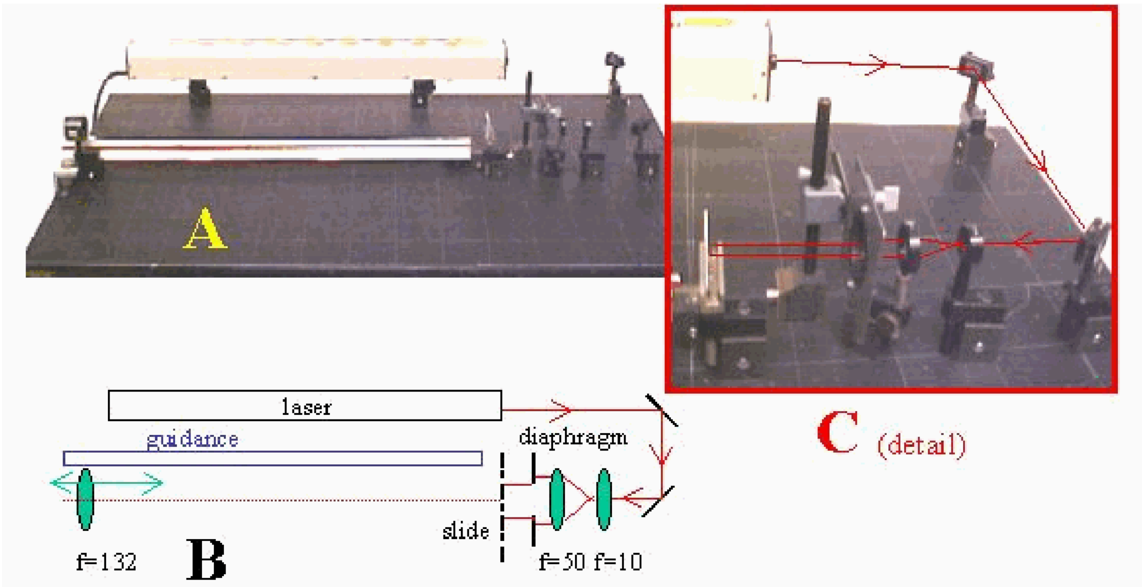


Figure 7.55: .

7.4.1.4.4 Equipment

- Magnetic clamps, used to fix the components to the steel table.
- Laser, 50 mW.
- Two surface mirrors (1/10 1).
- Lens, f = +10 mm.
- Lens, f = +50 mm.
- Adjustable diaphragm (when needed).
- Slide holder.
- Lens, f = 132 mm.
- Optical rail, I = 1 m, as guiding ruler.
- Slide with four double slits (Leybold 46985), all slits having a width of . 20 mm and slitseparation of: a, 1.00 mm; ***b***, .75 mm; ***c***, .50 mm; ***d***, .25 mm.
- Overhead sheet with slit dimensions on it.

7.4.1.4.5 Safety

- Even relatively small amounts of laser light can lead to permanent eye injuries. The laser we use is a class 3B laser. A Class 3B laser is hazardous if the eye is exposed directly, but diffuse reflections such as from paper or other rough surfaces are not harmful. Protective eye wear is typically required where direct viewing of a class 3B laser beam may occur. In our demonstration we always take measures such that no direct or reflected laser light is directed towards the audience. When needed we use black screens to block such light: all beams are stopped at the edge of the optical table. No watches or other jewelry are carried by the demonstrator. As an extra safety measure is our Class-3B laser equipped with a key switch, so unauthorized people cannot switch the laser on. Young's double slit

7.4.1.4.6 Presentation

7.4.1.4.6.1 Preparation

The demonstration is set up as shown in Diagram:

-The two mirrors are positioned in such a way that the laser beam passes parallel to the table.

-The two lenses (+10 mm and +50 mm) are positioned at an intermediate distance of 60 mm. Having passed these lenses, the laser beam is broadened (and a little divergent). Take care that the broadened beam is still parallel to the table.

-The lens of 132 mm can easily be shifted in this beam up and down using the carefully positioned guidance rail.

7.4.1.4.6.2 Demonstration

The set-up as described in Preparation is shortly explained to the students. The most important in this explanation is that the double slit will be placed in a broadened beam and that the double slit will be illuminated by plane waves.

The slide with the double slits is placed on an overhead projector, so the students can see the configuration. The dimensions are indicated on an overhead sheet that is projected at the same time.

The laser is switched on, the broadened beam projects on the wall. When the +132 mm lens is placed at the end of the table, this spot is enlarged (see Figure 2A; the diameter of the projected spot is around 1 m). Then the double slit is shifted into the beam starting with configuration a (see Equipment).

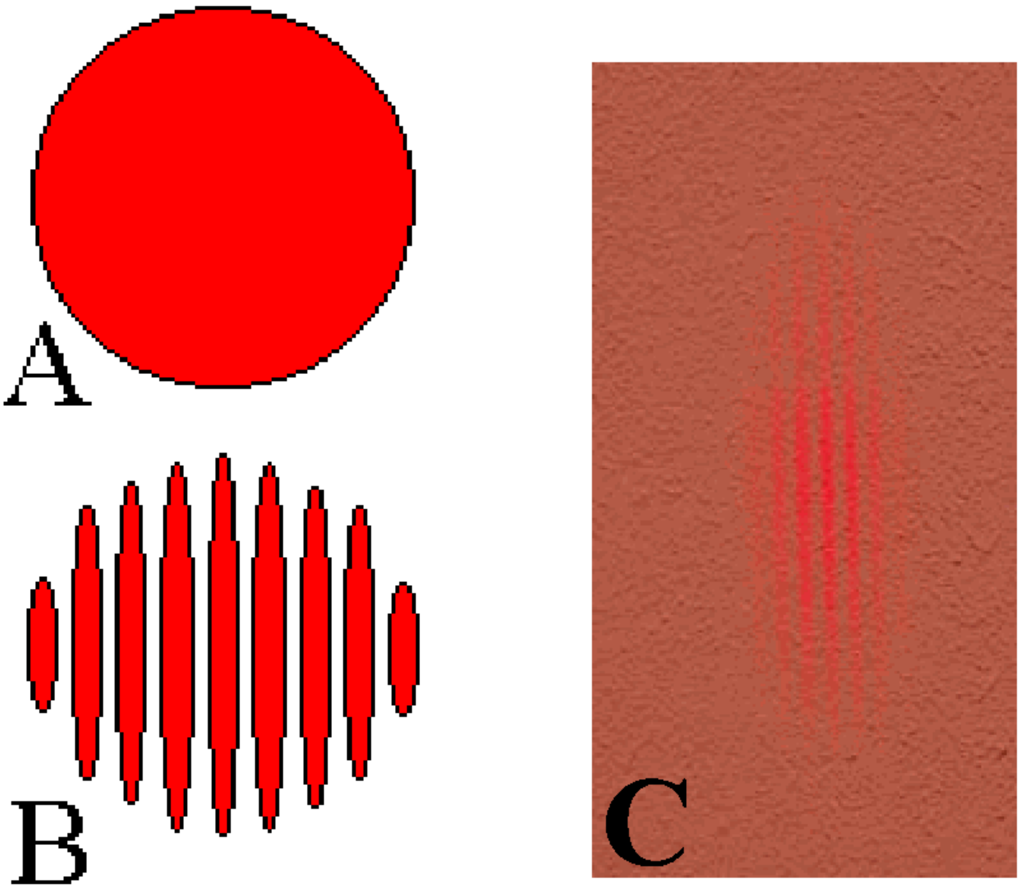


Figure 7.56: .

The typical interference pattern appears (see Figure 2B; Figure 2C shows a snapshot of a real projection on the wall). Then we shift to configuration ***b***, then ***b*** and finally ***b***; in that way going from large to smaller slit-separation. It is observed that with smaller slitseparation the distance between the lines of interference increases

7.4.1.4.7 Explanation

Young explained the observed pattern with the Huygens wave theory and so introduced the principle of interference. Many textbooks give the explanation. Figure 3 shows the arrangement: s is very large compared to the slit separation b.

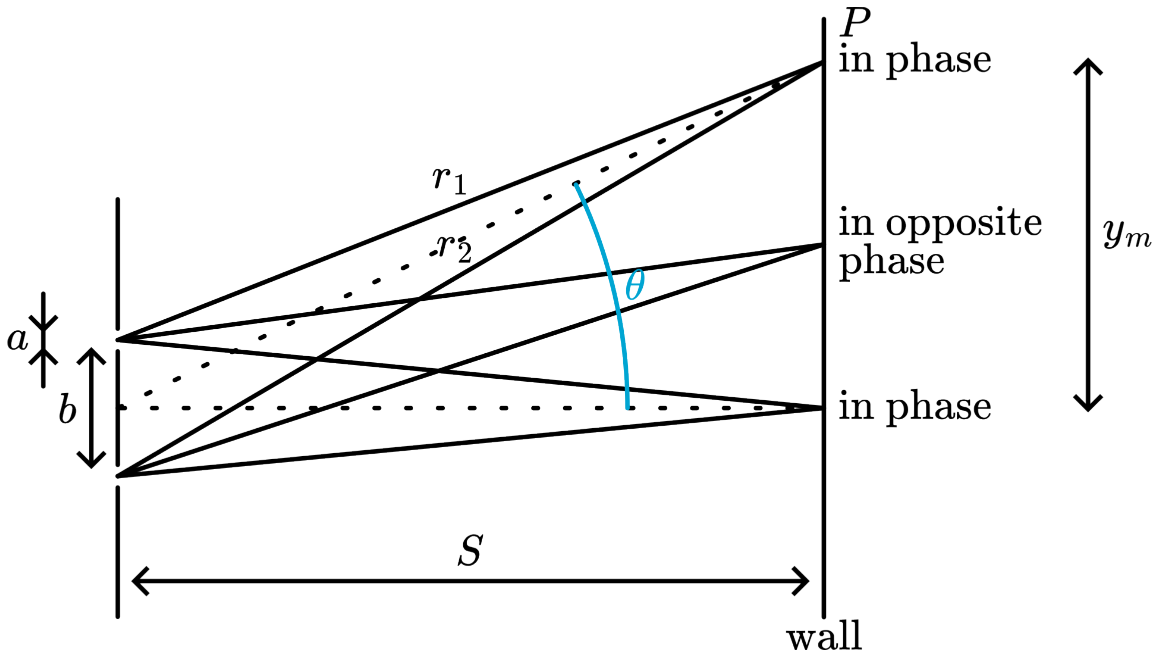


Figure 7.57: .

In P, ray r_1 and ray r_2 interfere. This interference will be constructive when $r_1 - r_2 = m\lambda$ $(m = 0, 1, 2, 3, \ldots)$.

Also $y_m \approx \frac{s}{b} m\lambda$, and the difference in position of two constructive maxima is $\Delta y \approx \frac{s}{b}\lambda$, explaining the equidistance between the observed maxima and the influence of b in consistency with what we saw in the Presentation. Interference term

7.4.1.4.8 Remarks

- A more complete analysis, also including the diffraction of each slit gives for the

intensity $(/)$ at P : $I(\theta) \approx \underbrace{\left[\frac{\sin\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\frac{\pi a \sin\theta}{\lambda}}\right]^2}_{\substack{Diffraction \\ envelopterm}} \times \underbrace{\cos^2\left(\frac{\pi b \sin\theta}{\lambda}\right)}_{\substack{Interference \\ term}}$

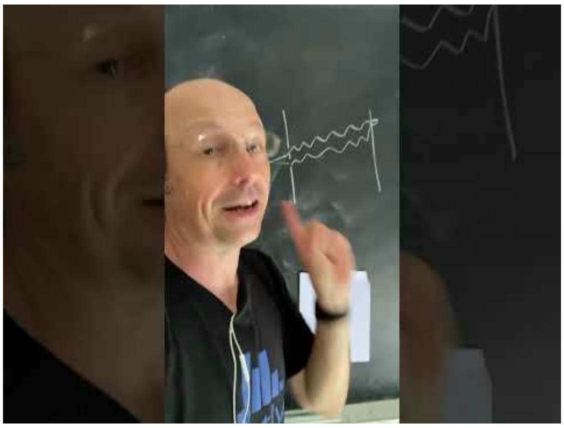
If a becomes vanishingly small, then the diffraction envelope term approaches 1 , and only interference is present. This is the condition for a good Young's double slit experiment. With $a =$ .20 mm this appears to work satisfactory. Using double slits with larger a, then next to interference also diffraction becomes visible in our set-up and that is a different demonstration.

- The +132 mm lens is positioned at a distance of about 1 m away from the slide with the double slit. This means that on the wall an image is projected of a point around 85 cm (1m-132mm) away from the double slit. In that way it is assured that the diffraction envelope is really wide (Fraunhofer diffraction). Closer to the slide, the diffraction envelope will transfer into a Fresnel diffraction pattern, spoiling our demonstration. The transition form Fraunhofer to Fresnel diffraction occurs in this set-up at around $(s = a^2/2\lambda =)$ 28 cm (see the demonstration “FraunhoferFresneldiffraction”.

- In Young’s historical experiment plane waves were obtained using a pinhole through which sunlight passed before illuminating two close-together pinholes. In this way he obtained spatial coherence between the two pinholes. Since we use a laser, the initial pinhole is not needed.
- When in the demonstration the +132 mm lens is removed we see that the interference-pattern is enveloped in a wider diffraction-pattern. This can be shown when diffraction has been treated.

7.4.1.4.9 Video Rhett Allain

(a)



(b)

Figure 574: :align: center - Scan the QR code or click here to go to the video.

7.4.1.4.10 Sources

- Hecht, Eugene, Optics, pag. 385-388 and 447-451
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 329-331
- Young, H.D. and Freeman, R.A., University Physics, pag. 1142-1148
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 870872 and 893-895

7.4.2 6D20 Lasers

7.4.2.1 01 Speckle Spots and random Diffraction

7.4.2.1.1 Aim

To show the granular appearance of laser light on reflection from a diffuse surface.

7.4.2.1.2 Subjects

- 6D20 (Lasers)

7.4.2.1.3 Diagram

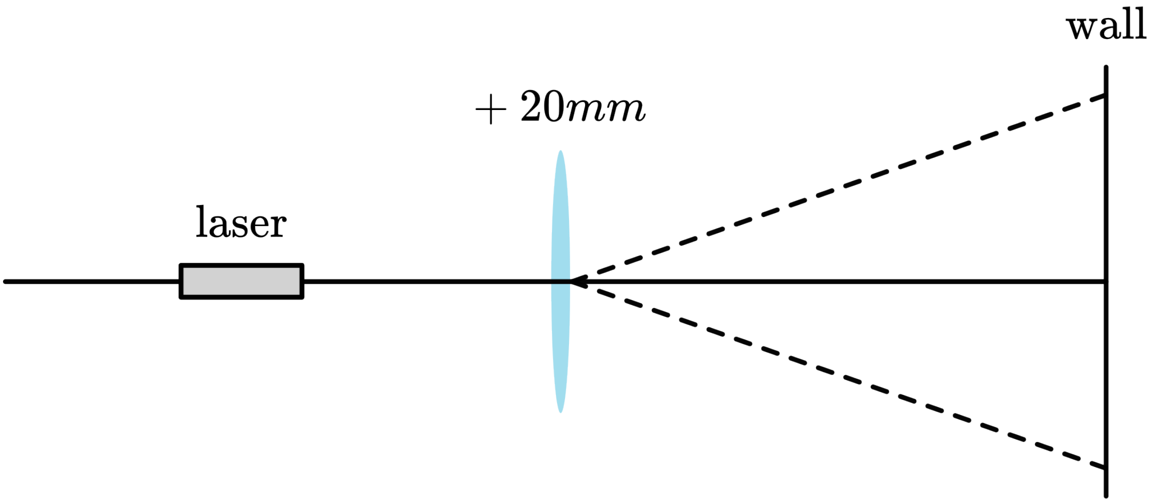


Figure 7.61: .

7.4.2.1.4 Equipment

- Laser
- Simple lens (we use +20 mm)
- Wall (diffuse surface)

7.4.2.1.5 Presentation

The room is darkened and the laser is switched on. An illuminated disk is projected on the wall. To the observers, this disk appears with bright and dark regions.

- Stepping away from the screen makes the grains grow in size.
- Squinting also makes the grains grow.
- Move your head to the right and the pattern will also move to the right.
- Hold a pencil at varying distances from your eye so that the disk appears just above and around it and at each position focus on the pencil. At every focus the grains are clear.
- Put a lens in front of your eye (we use +50 mm), blurring everything but the granular appearance of the spot remains perfectly distinct.

7.4.2.1.6 Explanation

The laser light is scattered from a diffuse surface. This light is spatially coherent and it will fill the surrounding region with a stationary interference pattern. At any position in space the resultant field is the superposition of many contributing scattered wavelengths. A real system of fringes is formed of the scattered waves that converge in front of the screen. After forming the real image in space, the rays proceed to diverge, and any region of the image can therefore be viewed directly with the eye approximately focussed.

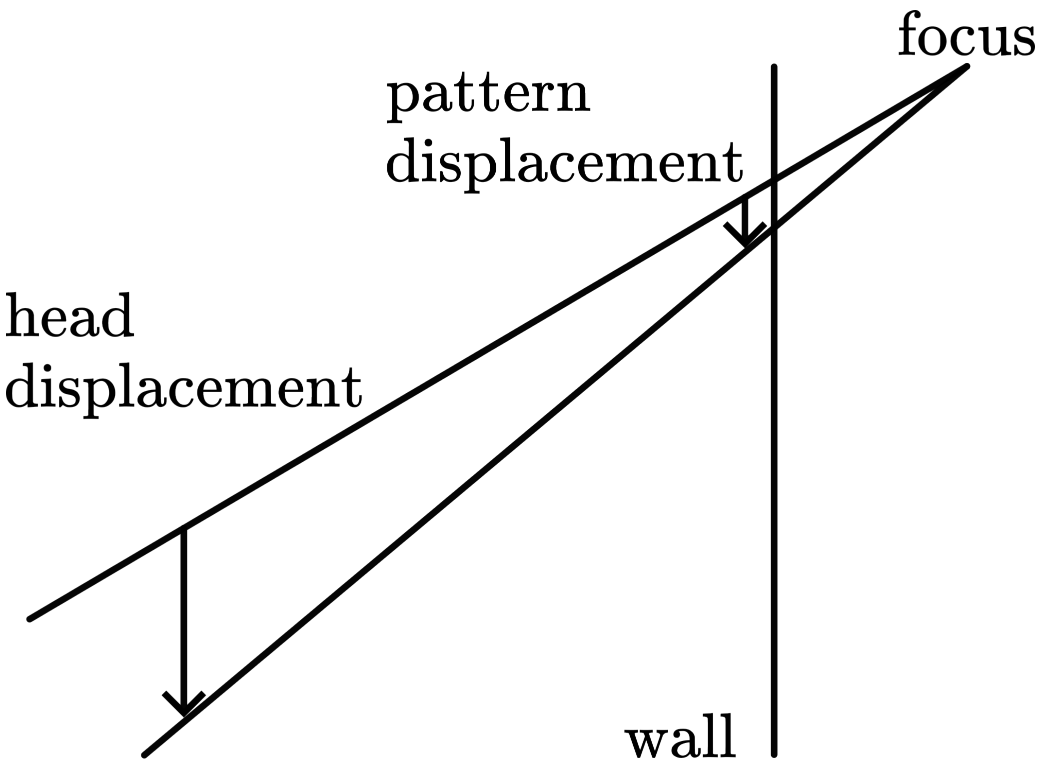


Figure 7.62: .

The constructive and destructive interference occur in the eye.

The diverging rays appear to the eye as if they had originated behind the scattering screen (see Figure 2). This is a result of chromatic aberration: normal and farsighted eyes tend to focus red light behind the screen. (A nearsighted person in front of the screen.)

7.4.2.1.7 Sources

- Hecht, Eugene, Optics, pag. 595-596
- Jewett Jr., John W., Physics Begins With an M… Mysteries, Magic, and Myth, pag. 387, 397

7.4.3 6D30 Thin Films

7.4.3.1 01 Newton's Rings (1)

7.4.3.1.1 Aim

To show Newton's rings.

7.4.3.1.2 Subjects

- 6D30 (Thin Films)

7.4.3.1.3 Diagram

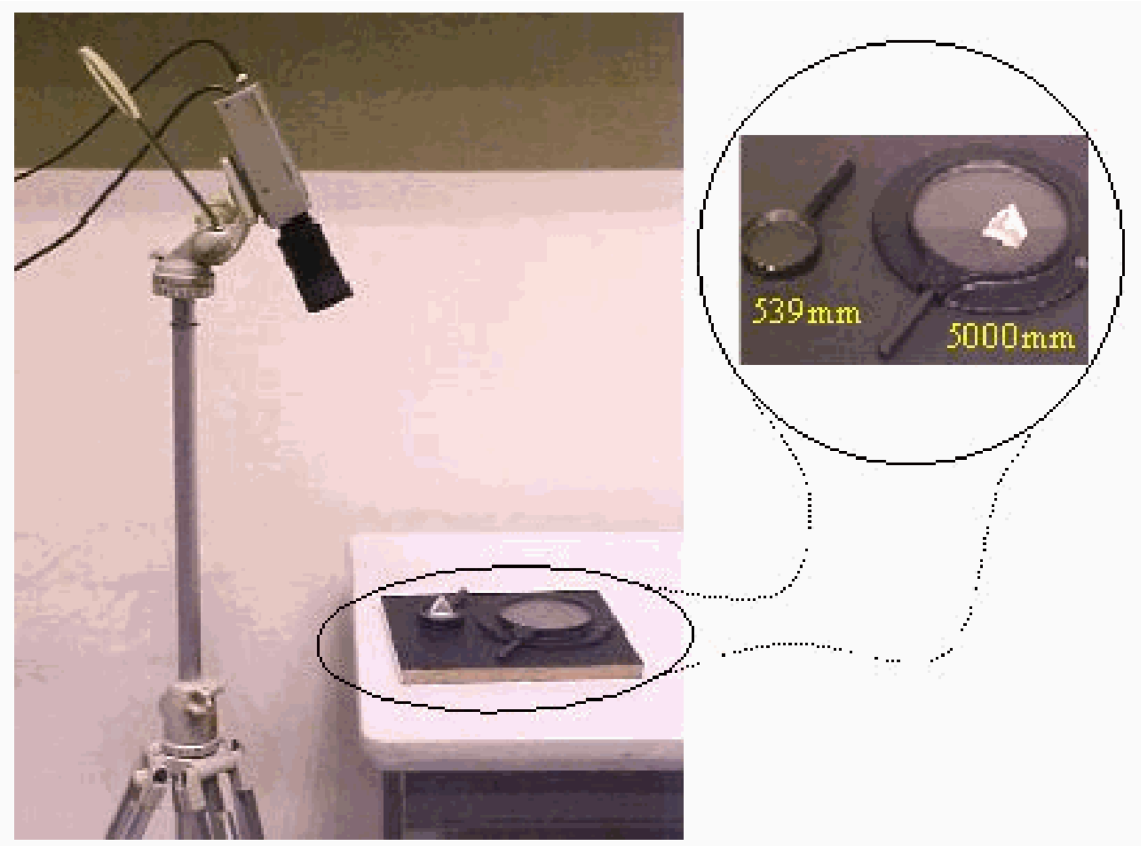


Figure 7.63: .

7.4.3.1.4 Equipment

- Lens, $f = 539$ mm.
- Lens, $f = 5000$ mm (plano-convex).
- Equilateral prism.
- Camera.
- Projector to project image.

7.4.3.1.5 Presentation

The prism is placed on the convex side of the 5000 mm-lens. The camera looks almost perpendicular at a side of the prism (see Diagram). The image is projected. Concentric Newton's rings are observed (see Figure 2).

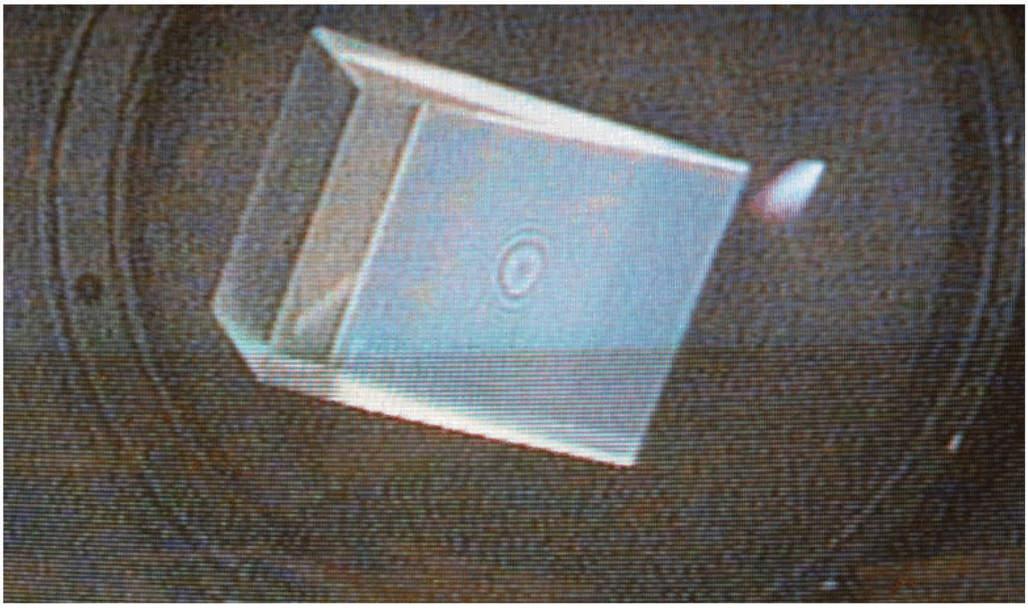


Figure 7.64: .

7.4.3.1.6 Explanation

Figure 3 shows the setup of the demonstration and the way the light rays go towards the camera (eye). The thin film between the flat and convex surface causes a phase difference between the two reflected rays: Reflection from the plane gives a phase change of $\Delta\phi = 0$ (the black ray); reflection from the convex surface gives a phase change of $\Delta\phi = \pi$, and next to this phase change of π the transit-time in the short air wedge adds to this phase difference (the red ray).

The incoming light is diffuse, so when the camera (eye) is shifted, another pair of interfering rays is caught by the camera, and a changed pattern is observed (see the black- and green colored ray in Figure 3).

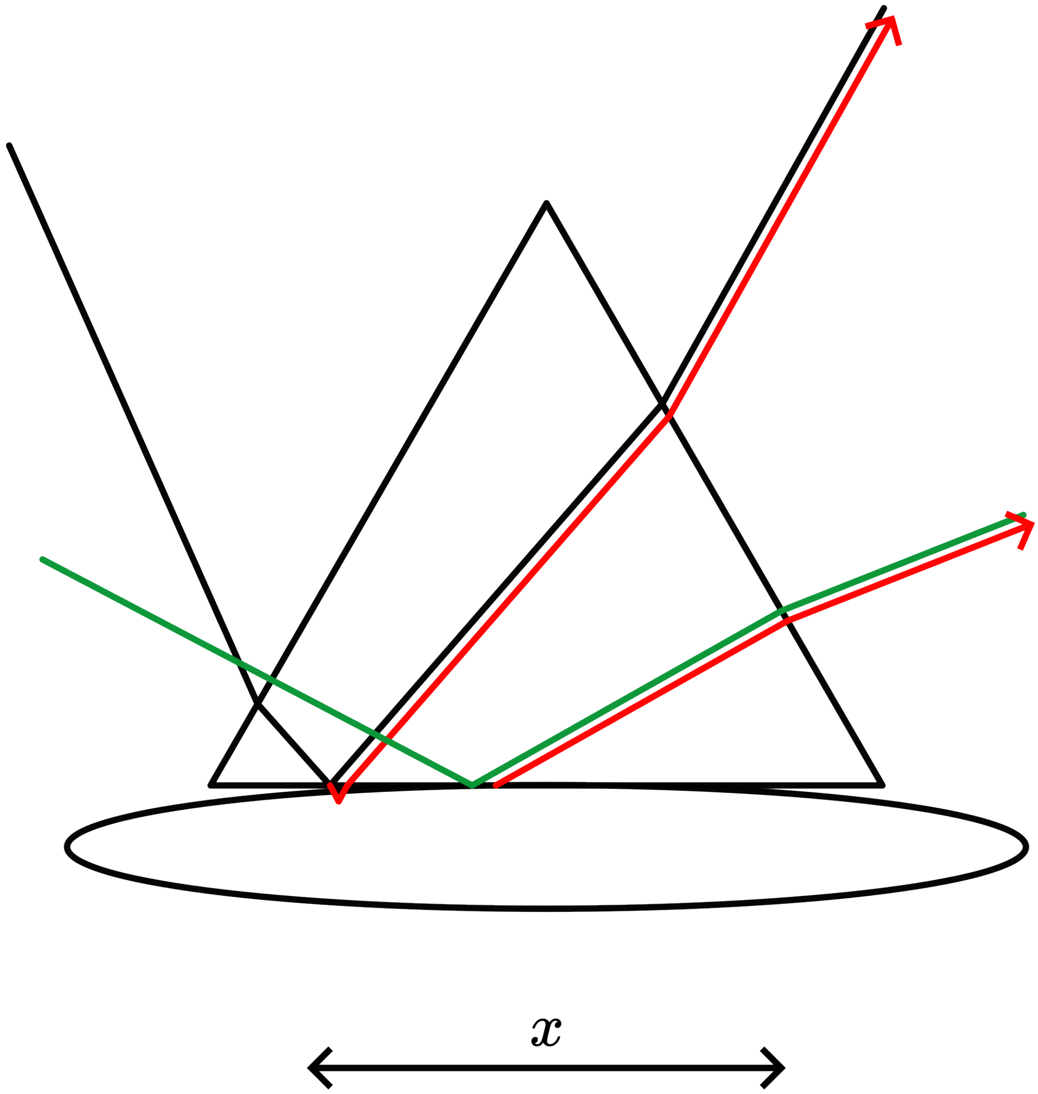


Figure 7.65: .

Using the 5000 mm-lens makes the curvature in Figure 3 much less and so the layer of air will change much slower in the x-direction, broadening the distance between the fringes.

7.4.3.1.7 Remarks

- In literature this setup is also known as “interference prism”.
- The phenomenon is easily seen by eye. So encourage your students to look at the setup when the lecture is over. The eye-observation is of such a higher quality than the observation through a camera that this is worth doing it.
- It wouldn’t surprise me when Newton saw this phenomenon for the first time just accidentally. Supposing he had lenses and prisms littering around, it suddenly stroke him! By eye the phenomenon is so easily observed, so it could be possible.
- Newton tried to explain this phenomenon using his particle theory of light, with its hypothesis of ‘fits of easy transmission refraction and reflection’, but he also suggests to associate the rings with vibrations in the medium.

7.4.3.1.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 879-880
- Hecht, Eugene, Optics, pag. 398-399

7.4.3.2 02 Newton's Rings (2)

7.4.3.2.1 Aim

To show Newton's rings, and that its color sequence is not a rainbow.

7.4.3.2.2 Subjects

- 6D30 (Thin Films)

7.4.3.2.3 Diagram

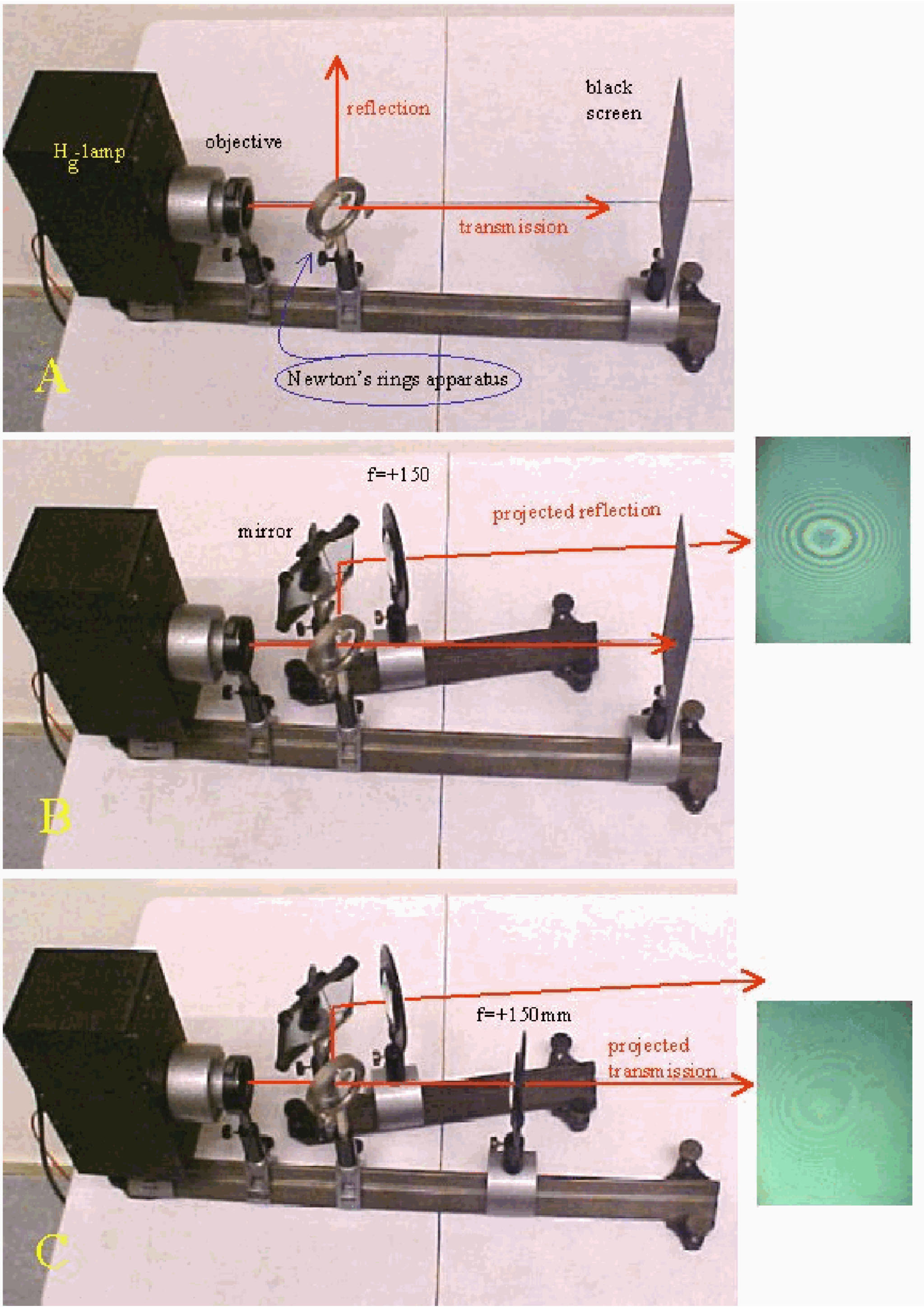


Figure 7.66: .

7.4.3.2.4 Equipment

- Newton's rings apparatus (convex lens pressed against flat glass plate; pressure can be adjusted by screws in the ring-mount).
- Hg-lamp, with power-unit.
- Objective lens.
- Two lenses $f = 150\,\mathrm{mm}/diam. = 70\,\mathrm{mm}$.
- Flat surface mirror.
- Black screen.

7.4.3.2.5 Safety

- The Hg-lamp needs some time to come to its full light intensity. It also becomes very hot! Do not touch it.

7.4.3.2.6 Presentation

Set up the equipment as shown in Diagram. Images are projected on the wall (see Figure 2A)

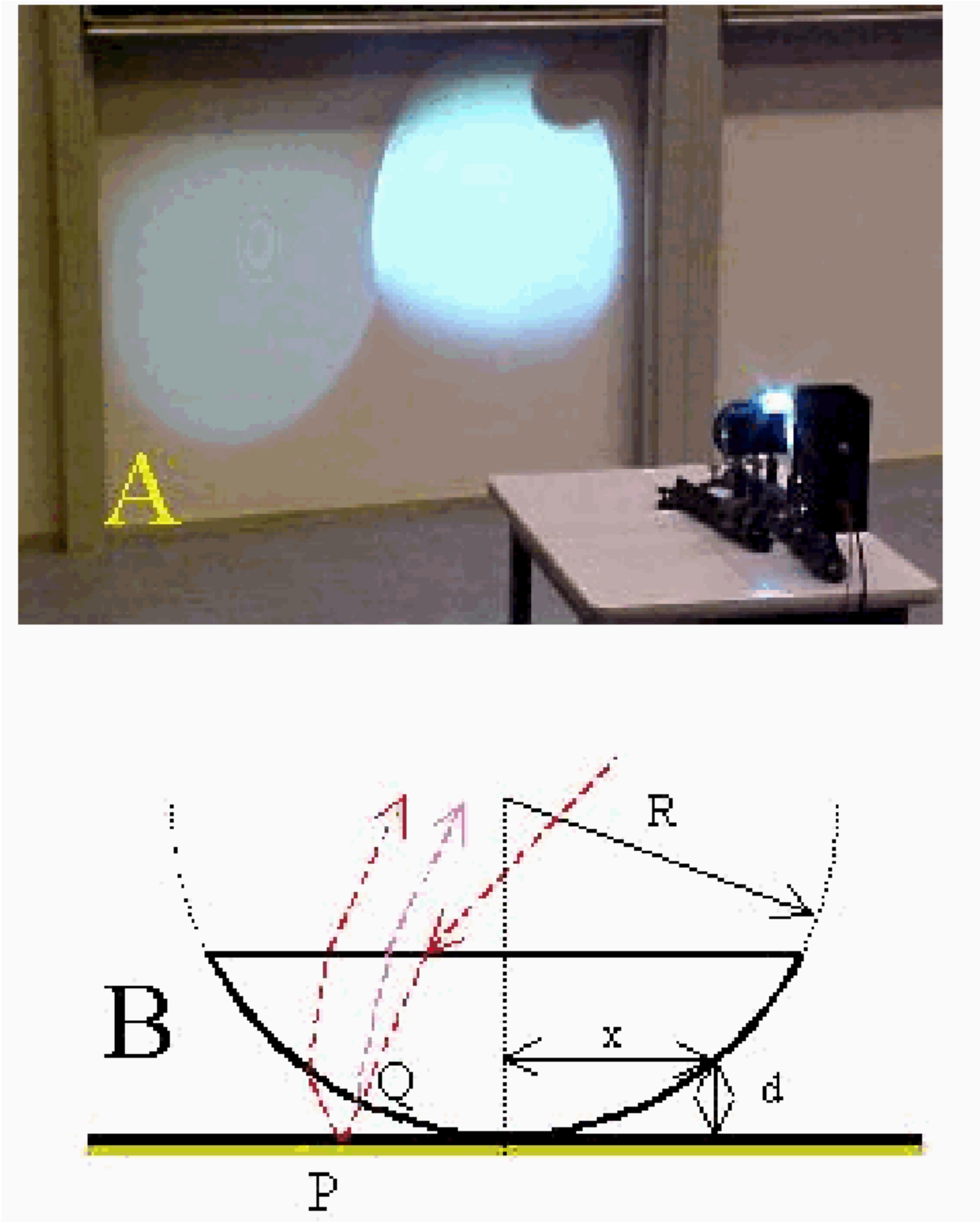


Figure 7.67: .

After the lamp is heated up, situation of Diagram A is presented to the students, to indicate that there will be a reflected and a transmitted beam of light. Then the transmitted beam is blocked (black screen) and using the mirror and a +150 mm-lens the reflection image is projected (Diagram B). Clearly Newton's rings are observed. Observe the central dark spot (see also: Remarks) observe the colored rings, the color-sequence and observe the diminishing distance between the rings when moving away from the centre. Changing the pressure on the Newton's rings apparatus will change/move the reflected image. Then the black screen is removed and using the second +150 mm-lens the transmitted image is projected next to the reflected image (see Diagram C and Figure 2). It is clearly visible that both images are complementary.

At first glance, the observed colors look rainbowlike, but careful observation shows that it differs from a rainbow (see Figure 3; reality is much better than this photograph).

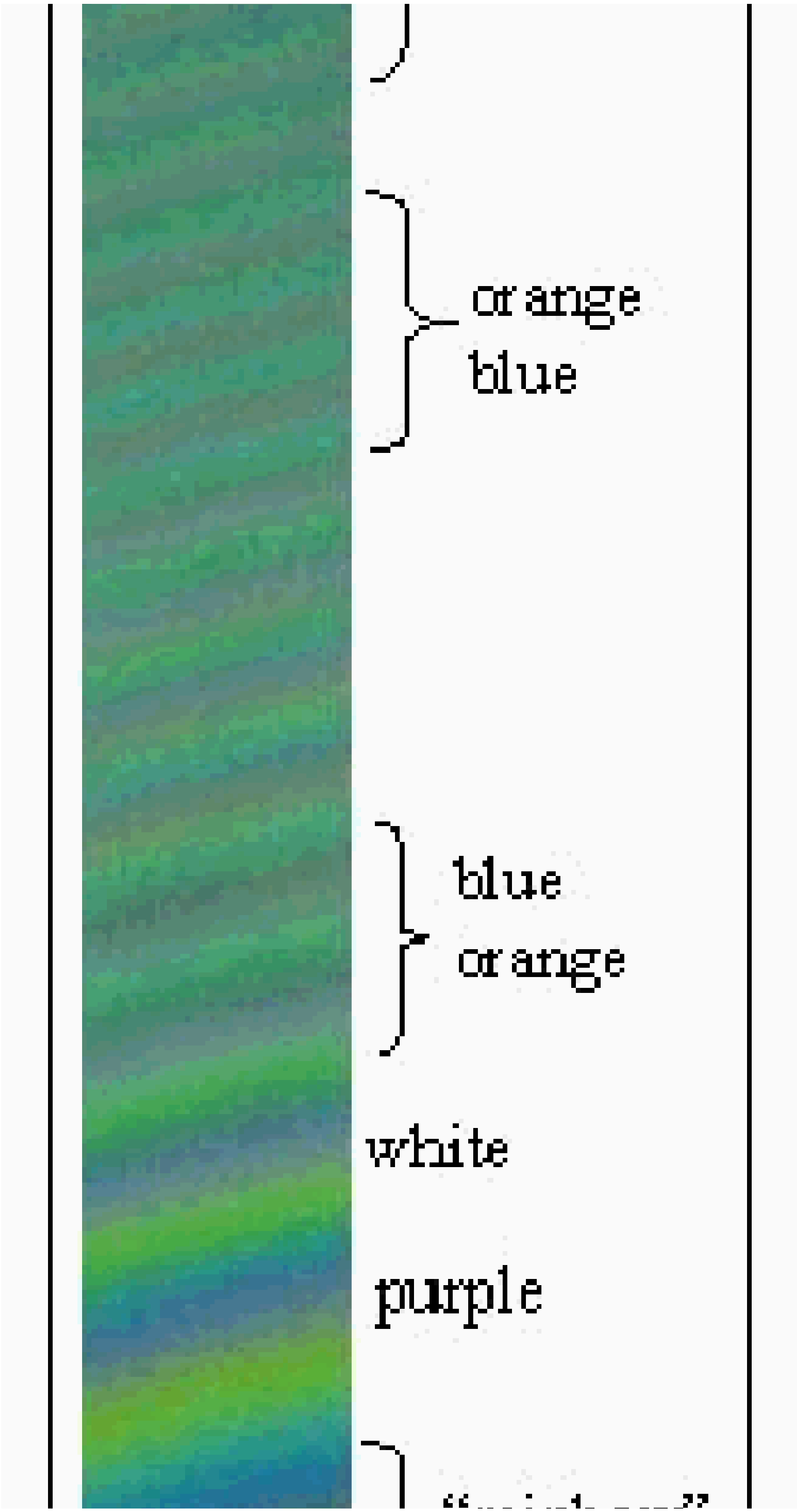

orange
blue
blue
orange
white
purple

Figure 7.68: .

Observing the reflected image shows, when moving away from the central dark spot, at first a rainbow, but already in the next ring the color purple appears; in the next rings white and orange are dominating; around ring 10 there is a repeating sequence of blue and orange and around ring 16 repeating bands of dark violet and yellowish rings are visible giving form a distance the impression of a continuity of black and white fringes.

7.4.3.2.7 Explanation

See Figure 2 B. Looking at the two red rays drawn in this figure, we see that it is the height d that introduces the phasedifference. $d = R - \left(R^2 - x^2\right)^{1/2}$.

The two rays, one reflecting from the hemisphere and the other reflecting from the plane, will have a phasedifference of $\Delta\phi = k(2d) - \pi$ (π at reflection off the plane).

Maximum, constructive interference will occur at $\Delta\phi = \frac{4\pi d}{\lambda} - \pi = m2\pi$, so when $d = 1/2\lambda(m + 1/2)$.

This result translated to the distance x (because x lies in the plane we are watching/projecting) yields $1/2\lambda(m + 1/2) = R - \left(R^2 - x^2\right)^{1/2}$, giving $x = \{\lambda R(m + 1/2)\ 1/4\lambda^2(m + 1/2)^2\}^{1/2}$. And R being much larger than λ will give $x = \{\lambda R(m + 1/2)\}^{1/2}$. First conclusion is that x is proportional to the squareroot of wavelength. So a higher wavelength yields a higher x. blue is on the inside, red on the outside. Second, the proportionality in $(m + 1/2)^{1/2}$ shows that the sequence of the bright fringes follows a square root: moving away from the centre the fringes come closer and closer together.

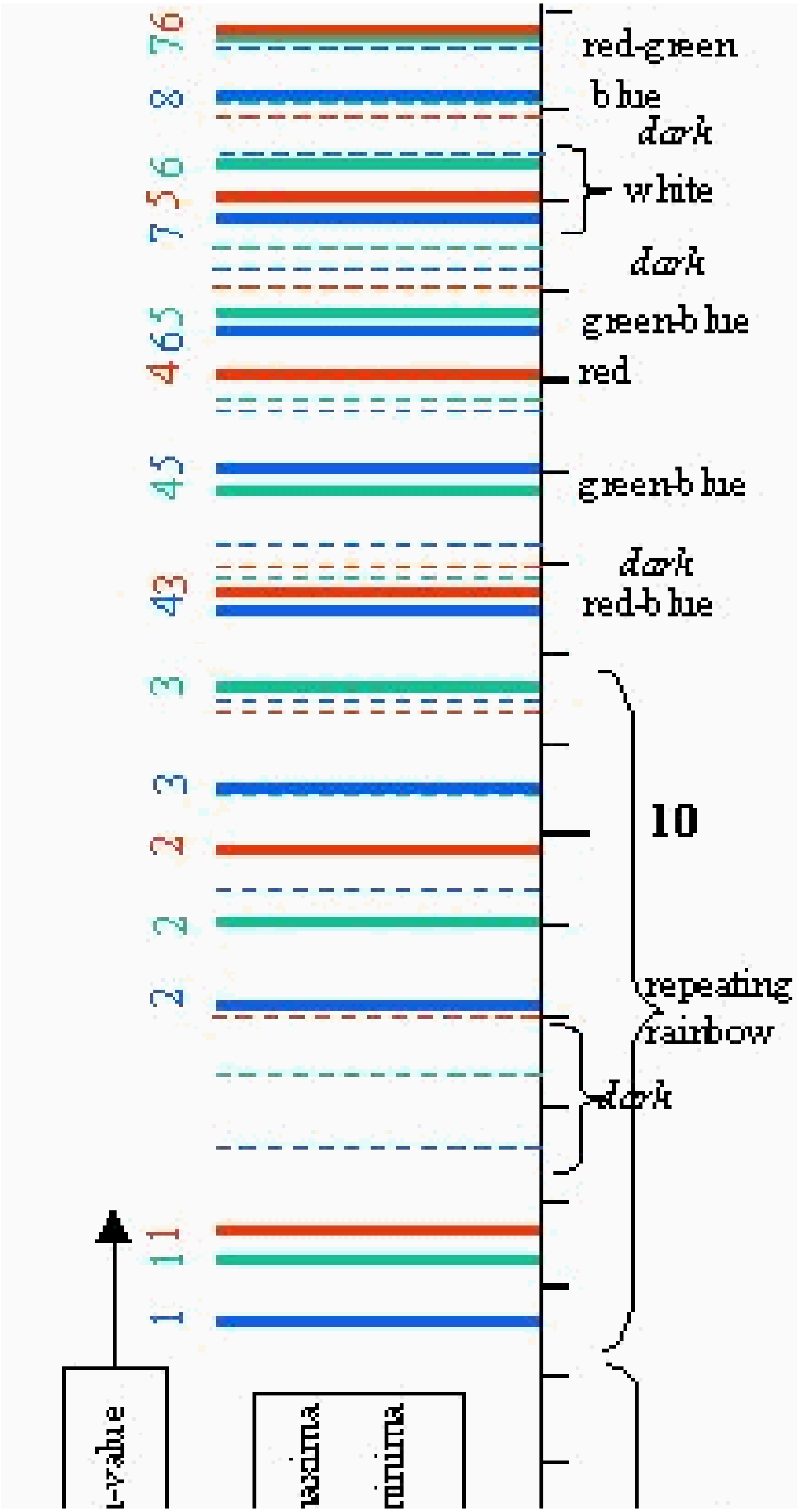

red-green
blue
dark
white
dark
green-blue
red
green-blue
dark
red-blue
10
repeating
rainbow
dark

Figure 7.69: .

Finally, we calculated for a number of m-values x. Figure 4 shows the calculated results ($10^{-5}; \mathrm{R} = 1\ \mathrm{m}$) for the red, green and blue line of H_0-light. In this way it is clear that the colours observed are the result of different combinations. Only near the centre a rainbow pattern appears.

It is not difficult now to show that for destructive interference we get $x = (\lambda R\ \mathrm{m})^{1/2}$. This yields that the centre of the reflected Newton's rings must be a dark spot. Figure 4 shows the minima as dashed lines for red, green and blue.

7.4.3.2.8 Remarks

- Using filters, it is possible to show a monochromatic interference pattern. Especially in the yellow line of Hg the pattern is bright.
- In the projected reflection image the central area should be dark. But usually there is a coloured spot instead. This is probably due to trapped dirt in the contact area between the two surfaces.

7.4.3.2.9 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 878-879
- Hecht, Eugene, Optics, pag. 398-399
- Young, H.D. and Freeman, R.A., University Physics, pag. 1152-1153

7.4.3.3 03 Oil Film

7.4.3.3.1 Aim

To show the interference in thin oil films.

7.4.3.3.2 Subjects

- 6D30 (Thin Films)

7.4.3.3.3 Diagram

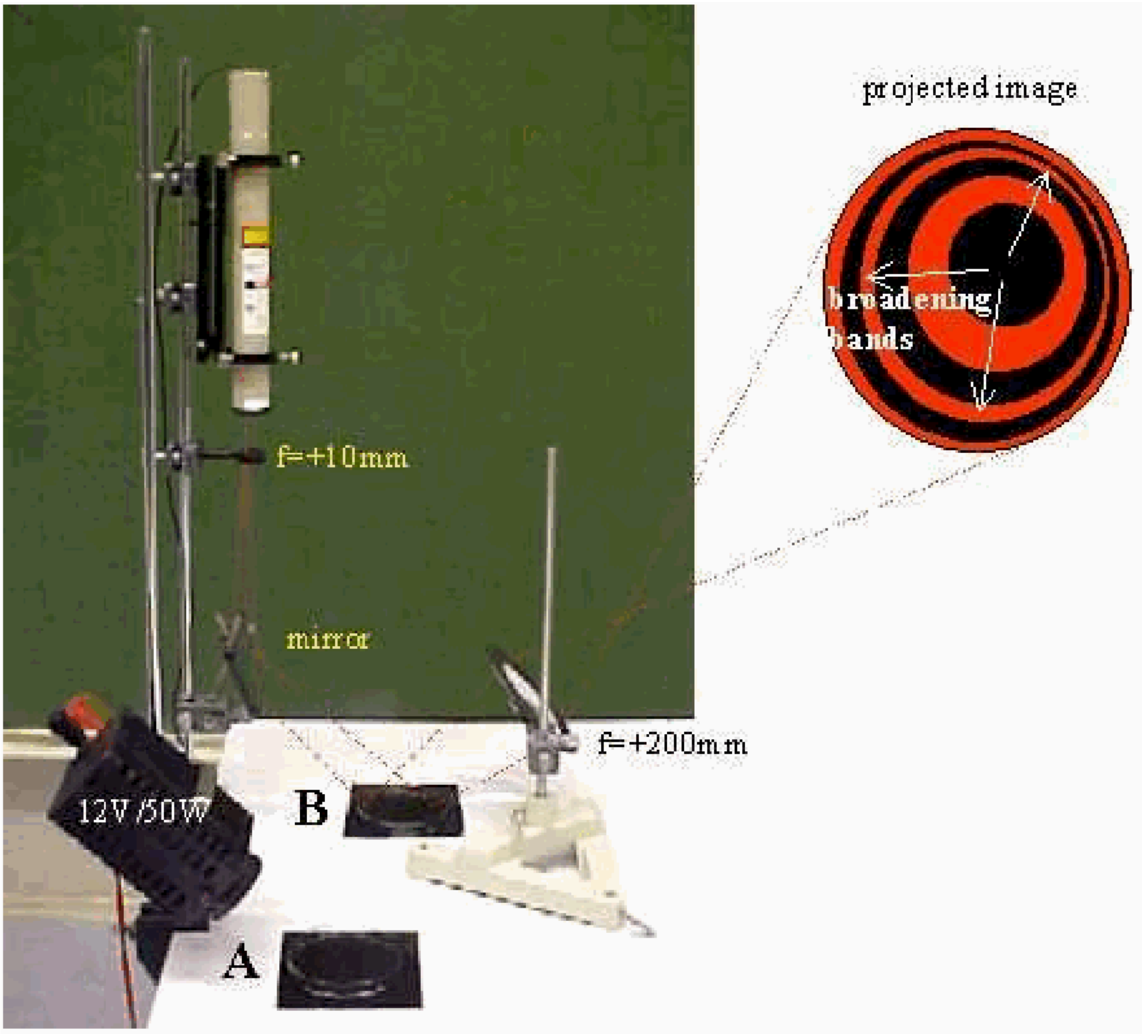


Figure 7.70: .

7.4.3.3.4 Equipment

- Two Petri dishes, diam. = 12 cm.
- Two square pieces of mat black paper, wetted and put under Petri dishes.
- Lamp, 12V/90W.
- Condensorlens, f = 50 mm
- Lens, f = 200 mm, diam. = 12 cm (we use Leybold 46010).
- Laser, red, 15 mW.
- Lens, f = 10 mm.
- Adjustable mirror.
- Motor oil in wash bottle.
- Stick, diam.=2.5 mm.

7.4.3.3.5 Presentation

The demonstration is prepared as shown in Diagram.

First the demonstration is performed with white light, so the 200 mm lens should be placed near the Petri dish A. The dish is filled with a layer tap water. The lens projects an image of the water surface on the wall (see Figure 2A). By means of the wash bottle a drop of oil is deposited on the water surface. The drop spreads out quickly, no colors are observed; only the very attentive students have seen colors at the rim of the oil spot that moved quickly outwards.

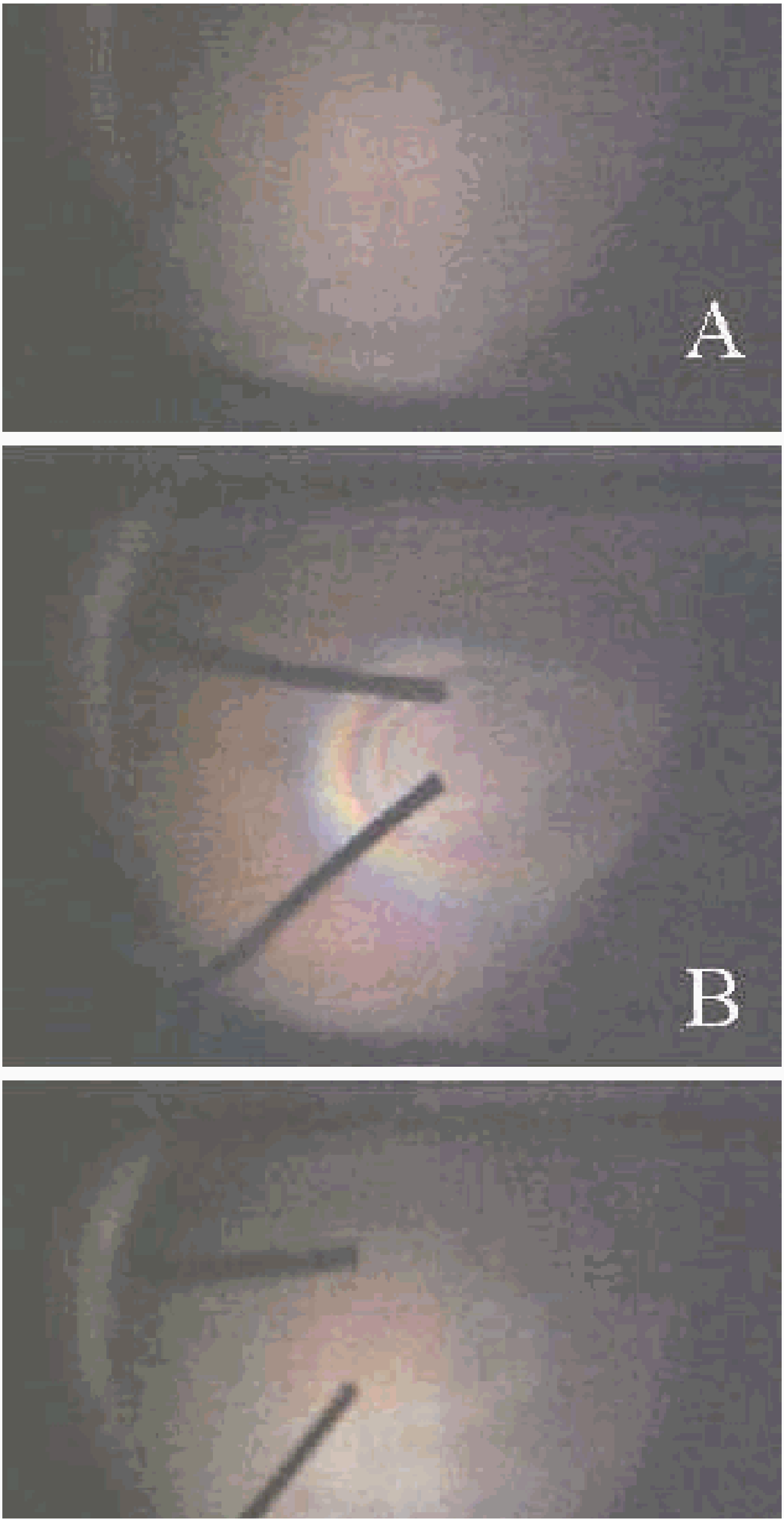

A
B

Figure 7.71: .

The Petri dish is cleaned and a new layer of tap water is poured in it. The thin stick is dipped in the oil and by tipping the stick on the water surface a small oil drop is positioned on it. Immediately it spreads outward in a spot and clearly colors are observed (see Figure 2B). After a short while the broadening stops and the oil spot is seen showing one color only (sometimes reddish or yellowish or green or blue or.. -see Figure 2C). In applying more small drops of oil on the preceding oil spot, the process of observing changing color patterns can be repeated. The advantage of placing drops on the preceding oil spots is that the speed by which the colors move and change diminishes and the process can be followed better.

The demonstration is repeated in monochromatic red laser light. The 10 mm-lens makes a diverging bundle of light and via the surface mirror the water in Petri dish B is exposed. Using the stick, a small drop of oil is put on the water surface. It is really amazing how clearly visible the fringed pattern of closely spaced black and red circles appears and broadens. Also in this demonstration the process of broadening is slowed down when applying more drops of oil on the foregoing oil spots.

7.4.3.3.6 Explanation

The thin oil film (thickness in the order of the wavelength used) serves as an amplitude splitting device (see Figure 3).

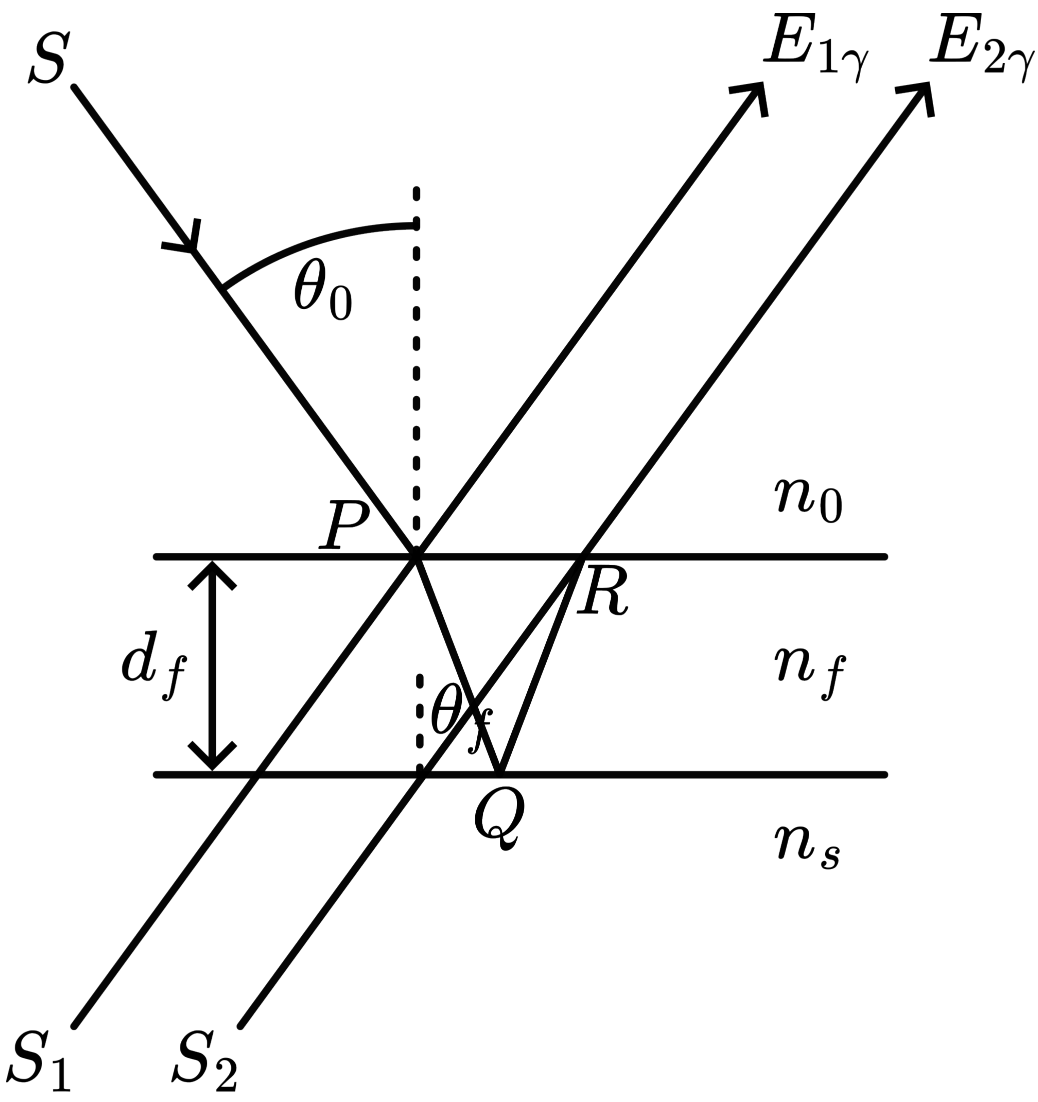


Figure 7.72: .

Light reflects from the top and from the bottom of the oilfilm (from the first - and the second interface), so that E_{1r} and E_{2r} may be considered as arising from two coherent sources (S_1 and S_2). When the two parallel reflected rays are brought together on the retina of the eye, they add up, producing interference of light. (In this demonstration the 200 mm lens brings the parallel rays together in the projection on the wall.) There is a phas edifference between the two rays of

$\delta = k_0\{[PQR] - [P)S]\} = k_0\left\{\frac{2n_f d_f}{\cos\theta_f} - 2n_0 d_f \tan\theta_f \sin\theta_0\right\}$. Using Snell's law

$n_0 \sin\theta_0 = n_f \sin\theta_f$, we obtain $\delta = 2k_0 n_f d_f \cos\theta_f$. So the phase difference is proportional to d, and for a certain thickness of film some wavelength add up out of phase and are cancelled while other wavelength add up in phase and are strengthened: Different thicknesses of oil film cancel/strengthen different colors.

While the oil spreads out across the water surface, thickness varies and a changing color pattern appears. When the spreading stops, the oil film will finally have equal thickness everywhere and only one color appears.

When the oil film is very thick (the first demonstration described in "PresentationXX") E_{2r} becomes too weak to give a visible result in interference. This is also observed in the part of the demonstration where we heap oil spot on oil spot and colors appear weaker and weaker.

When the demonstration is performed in monochromatic light k_0 in $\delta = 2k_0 n_f d_f \cos\theta_f$ has only one value and for a number of thicknesses $\delta = \pi$ or $\delta = \pi\pi$, (n being any odd integer) giving the possibility of complete extinguishing that light.

7.4.3.3.7 Remarks

- The black paper under the Petri dishes is wetted in order to make the underground more black.
- See also the demonstration "Soap film".

7.4.3.3.8 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 877-879
- Hecht, Eugene, Optics, pag. 393-399
- Karel Knip, Alledaagse wetenschap, Wetenschapsbijlage, pag. 17mei-2003

7.4.3.4 04 Soap Film

7.4.3.4.1 Aim

To show the interference in a thin soap film.

7.4.3.4.2 Subjects

- 6D30 (Thin Films)

7.4.3.4.3 Diagram

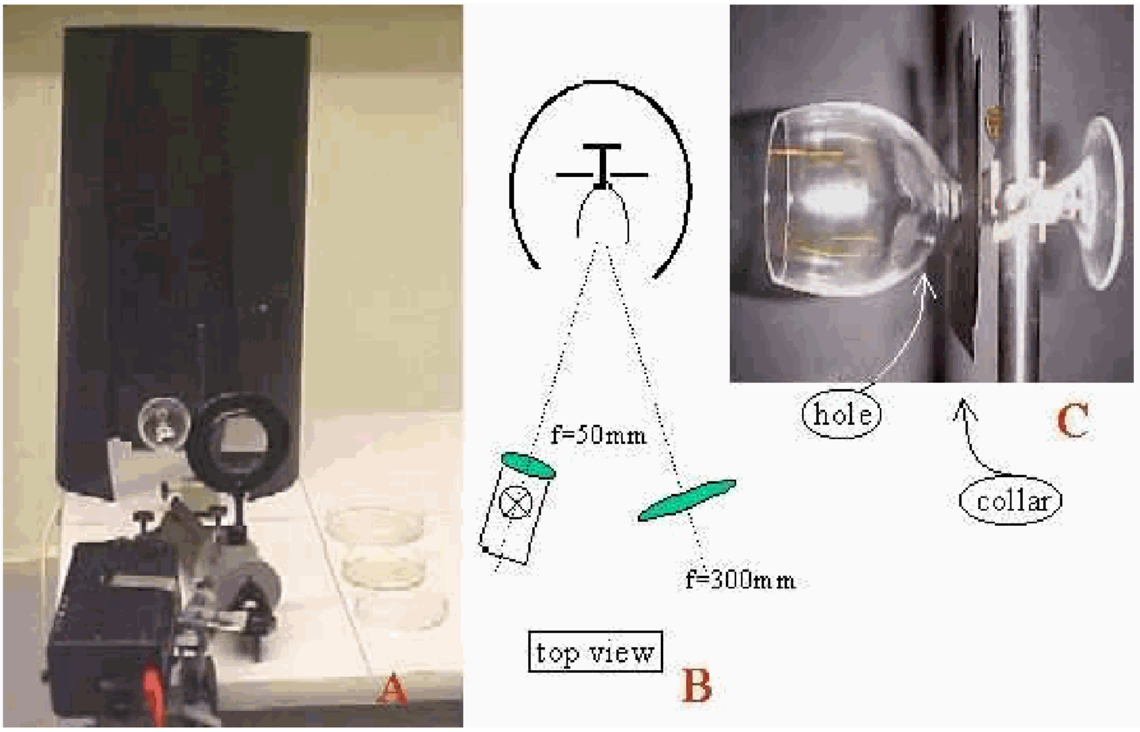


Figure 7.73: .

7.4.3.4.4 Equipment

- Wineglass with a small hole cut in its cup, and a collar of black paper around its stem (see Diagram C).
- Lamp, 12V/90W
- Condenser lens, $f = 50$ mm.
- Imaging lens, $f = 300$ mm.
- Short optical rail.
- Round screen of black paper, to screen straight transmitted light (see Diagram C).
- Petri dish with a soap solution

7.4.3.4.5 Presentation

Having set up the demonstration as shown in Diagram, an image of the rim of the wineglass is projected on the wall. Using a felt pen you mark the position of the wineglass on the table. Using your finger you can show that the projected image is upside down. Dip the wineglass in the soap solution, so that the rim of the glass has a film on it. Put the glass back in its marked position.

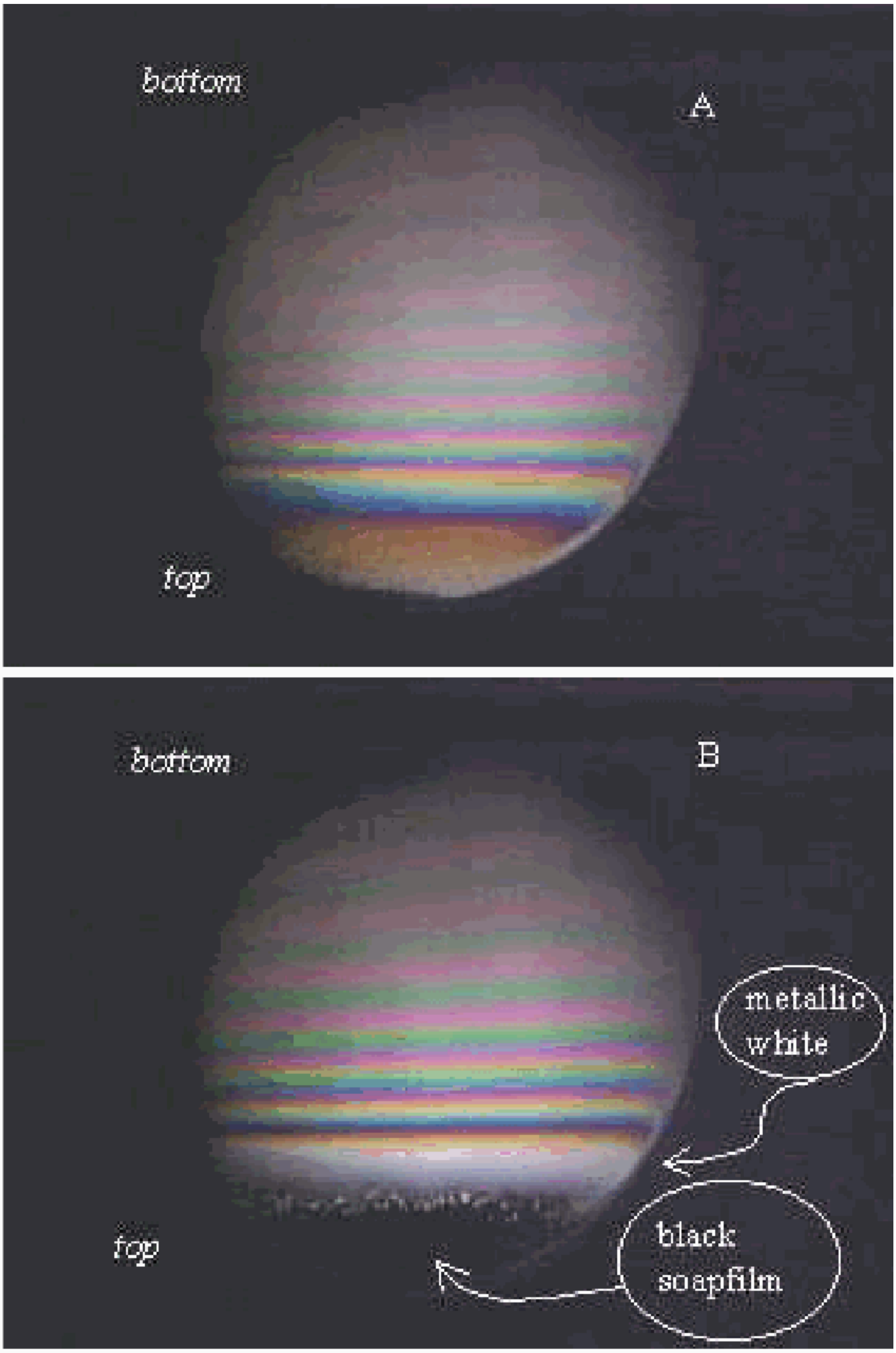


Figure 7.74: .

First, the image is whitish, but very soon a reddish haze appears, transforming into red and white stripes. Gradually more colors appear (see Figure 2A) and when full color rainbows appear, also black stripes show themselves. Finally a broad whitish band appears on the upper side, abruptly followed by complete darkness (see Figure 2B). Then the film breaks.

The demonstration is repeated a couple of times because the color transformations go pretty fast. Sometimes it needs to be repeated because the soap film breaks too soon.

7.4.3.4.6 Explanation

The soap film is a water sandwich. A layer of water is held between two layers of soap molecules. When the soap film is vertical the water drains down under the pull of gravity so that the top of the film becomes thin while the bottom becomes thick. Light reflects from the front and from the back of the soap film. These two reflections add up producing interference of light. Some wavelengths (colors) add up out of phase and are canceled while other colors add up in phase and are strengthened. Different thicknesses of soap film cancel/strengthen different colors.

7.4.3.4.6.1 Black region

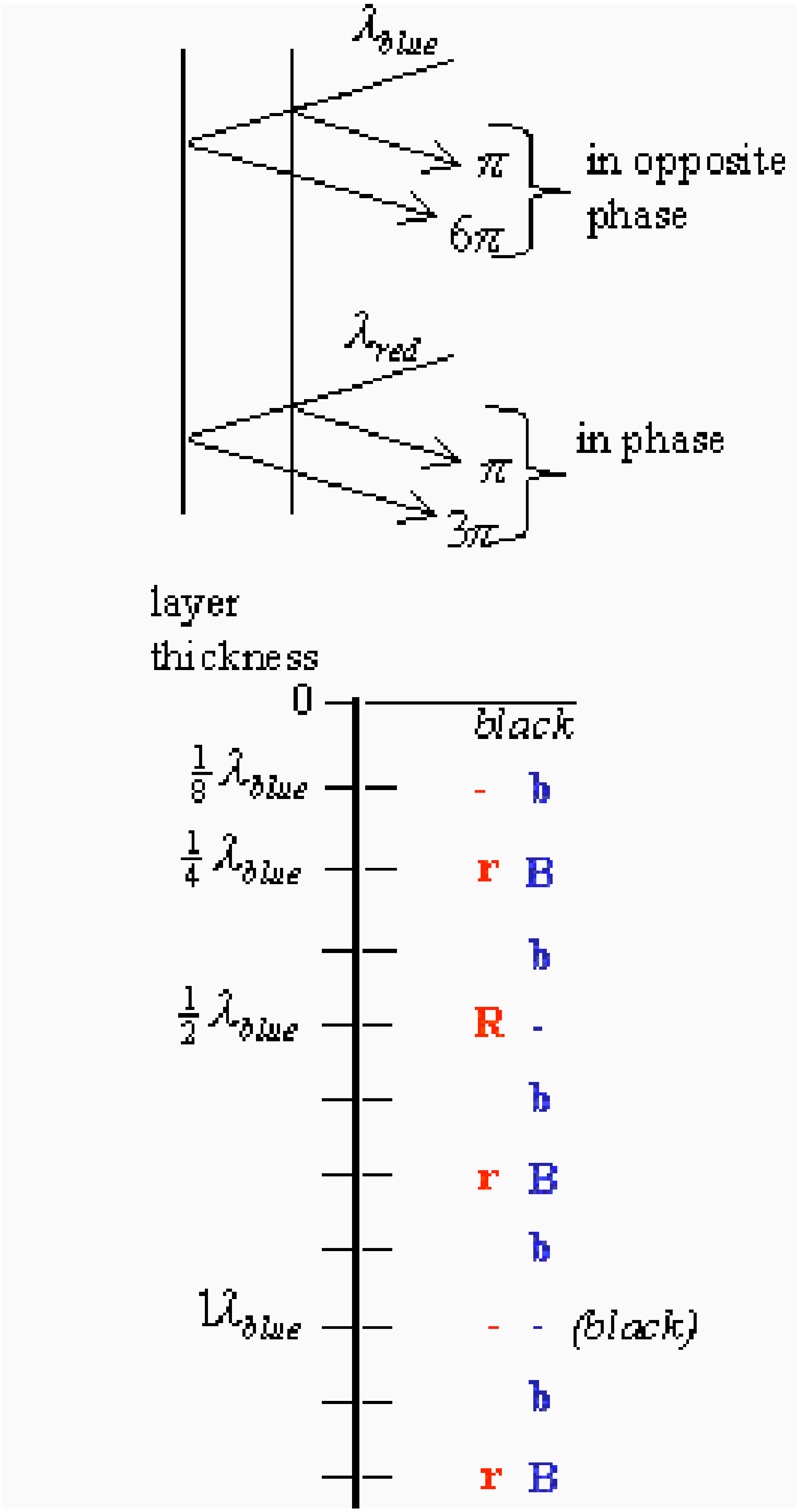
The light waves reflected from the front of the soap film are inverted (phase shift π), while those from the back are not. Thus, soap films that are thin compared to all wavelength of light reflect no light at all.

7.4.3.4.6.2 White region

Going down the film until it is 1/4 wavelength of blue light in thickness the blue light is reflected strongly. At this point the film is about 1/8 of a wavelength of red light thick (taking that the wavelength of red light is about twice that of blue). So some red light is reflected. The result is that the transparent film shows a metallic white sheen that grows bluer and bluer towards the black region.

7.4.3.4.6.3 Regions of thicker films

When the film is 1/2 of a wavelength of blue light thick the blue waves cancel. But now the film is also 1/4 of the wavelength of red light thick, and the red light is reflected strongly. Every integral multiple of 1/2 blue wavelength, blue light is removed, every odd multiple of 1/4 wavelength of blue light is strengthened.



λ_{blue}
π
6π
in opposite phase
λ_{red}
π
3π
in phase
layer thickness
0
black
$\frac{1}{8}\lambda_{blue}$
- b
$\frac{1}{4}\lambda_{blue}$
r B
b
$\frac{1}{2}\lambda_{blue}$
R -
b
r B
b
$1\lambda_{blue}$
- - (black)
b
r B

Figure 7.75: .

The same holds for red light. Figure 3 shows the result of this simplified blue-red dance. This figure clarifies that red dominates blue: the maximum of blue has always some red in it, while the maximum of red is “pure” red. In incandescent lamplight this is even stronger, due to the fact that red has a higher intensity in that light than blue.

7.4.3.4.7 Remarks

- The color pattern can also be easily observed in normal daylight. But for a larger group projection will be necessary.
- The wineglass has a small hole cut in its cup. When you use an ordinary wineglass you will notice that the soap film will bend inward. Colors can still be observed, but projecting a sharp image is not possible.
- Robert Hooke first reported observing the transparent film in a letter to the Royal Society. His letter indicates that he thought that the film actually did not exist where it was transparent. A simple experiment of poking the invisible film and so breaking it proves the existence of the invisible film.
- See also the demonstration “Oil film”.

7.4.3.4.8 Sources

- Biezeveld, H. and Mathot, L., Scoop, Natuurkunde voor de bovenbouw, part 4/5 vwo, pag. 128-129
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 877-879 and 880
- Hecht, Eugene, Optics, pag. 398
- PSSC, College Physics, pag. 137-141

7.5 6F Color

7.5.1 6F30 Dispersion

7.5.1.1 01 Chromatic Aberration

7.5.1.1.1 Aim
To show that different “colored” rays traverse a lens along different paths.

7.5.1.1.2 Subjects
- 6A40 (Refractive Index) 6A60 (Thin Lens) 6F30 (Dispersion)

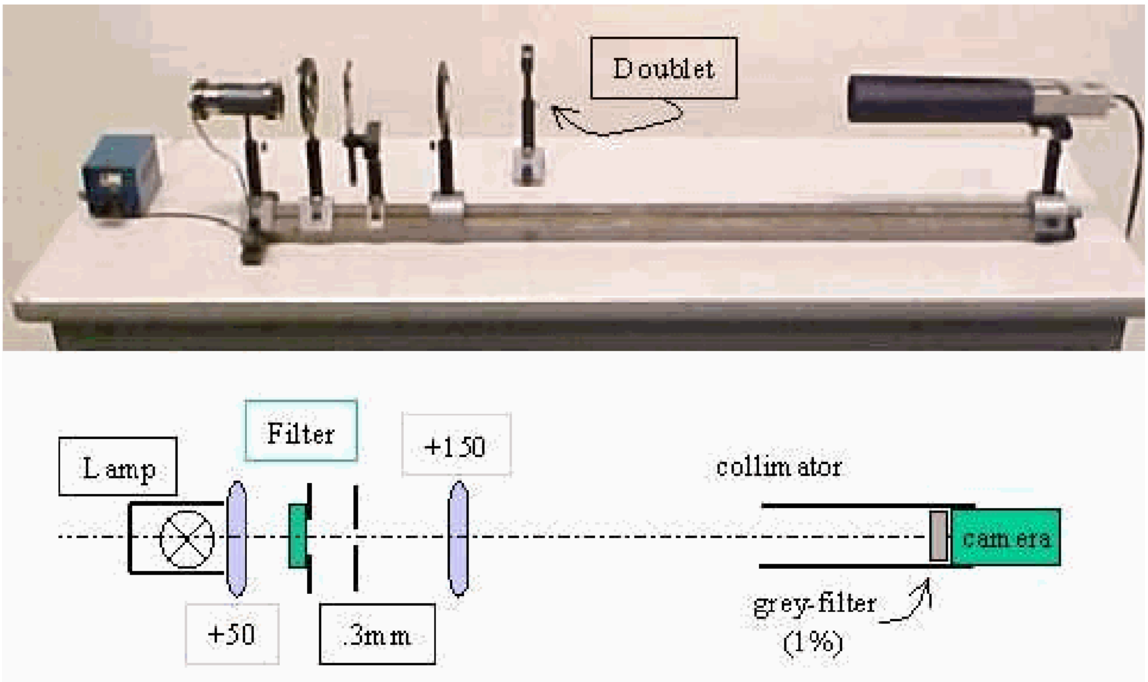
7.5.1.1.3 Diagram


Figure 7.76: .

7.5.1.1.4 Equipment
- Optical rail, 1.5 m.
- Lamp 6 V/5 A, fitted with a condenser lens +50 mm.
- Four interference filters: 644 nm; 578 nm; 546 nm; 436 nm (normally used to select H_a spectral lines).
- Wheel to mount these filters.
- Diafragm, diam. = .3 mm.
- Single lens, f = 150 mm, diam. = 75 mm.
- Doublet, f = 150 mm.
- White screen, used to align the optical components.
- Camera, lens removed.
- Grey filter (.01), stuck to camera.
- Collimator (made of black paper, see Diagram).
- Projector, to project image of camera.

7.5.1.1.5 Presentation
The lamp and camera are positioned each at the end of the rail. The camera has its lens removed; a .01 grey filter is placed on it. The other components are placed and carefully aligned; see Diagram (use the white screen at the position of the camera).

Using the red interference filter the .3 mm-diaphragm is pictured on the camera at the end of the optical rail. To get a sharp picture the diaphragm is shifted. The projector projects this image to the students. The red filter is turned away and the yellow filter is now in position. Clearly can be seen that this picture is not sharp. To get it sharp we need to shift the camera towards the lens. The same happens when next we apply the green and then the blue filter. Going from red to blue we need to shift the camera about 20 cm in total. This is clearly observable to the students. And the conclusion can be that the lens has a smaller focal distance for shorter wavelength.

When the 150 mm single lens is replaced by the doublet of 150 mm, changing filters will result in sharp images all at the same position of the camera on the rail: no shifting is needed. There is no chromatic aberration.

7.5.1.1.6 Explanation

Since the thin-lens equation $\frac{1}{f} = (n_t - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$ is wavelength-dependent via $n_1(\lambda)$

(dispersion), the focal length must also vary with λ (Figure 2 shows the graph of n, versus λ of crown-glass.).

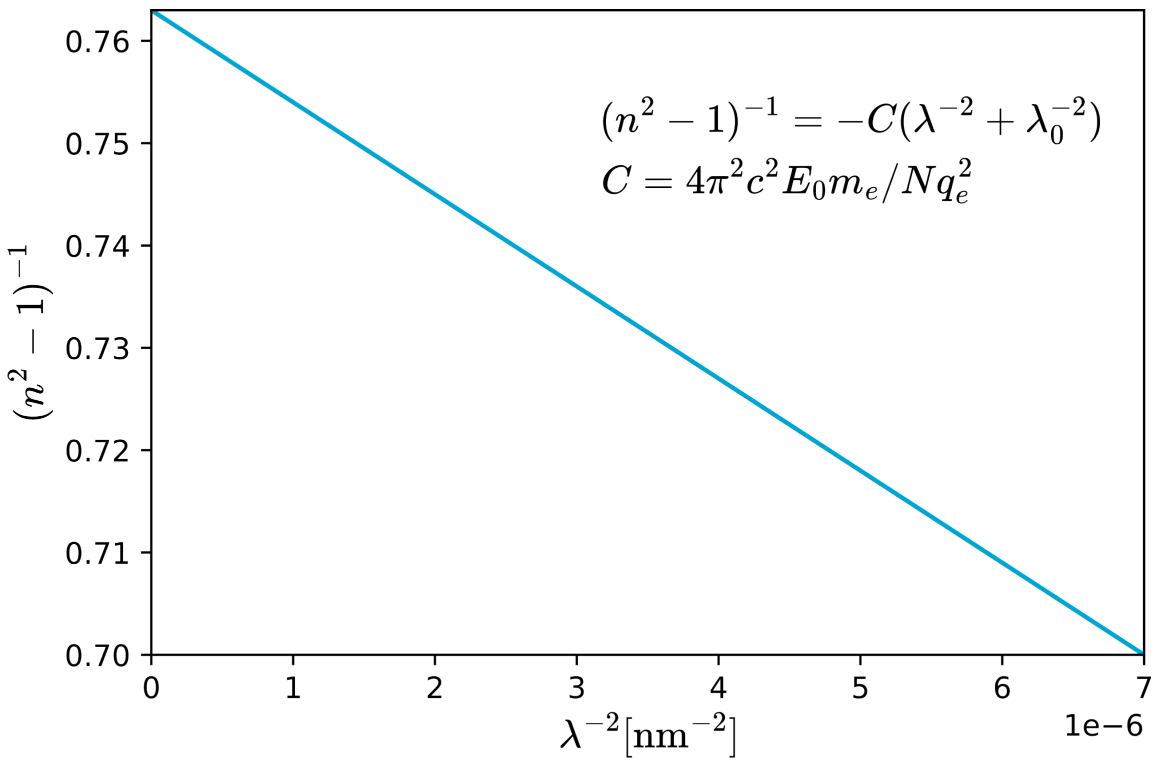


Figure 7.77: .

In general $n_1(\lambda)$ decreases with wavelength over the visible region, and thus $f(\lambda)$ increases with λ. And when $f(\lambda)$ increases with λ, then also the image-distance increases with λ (object-distance is constant). The demonstration shows this: the red image being sharp at a larger distance than the blue image.

A negative lens would generate “negative” chromatic aberration. This suggests that a combination of a positive - and a negative lens could result in an overlapping of f_{red} and f_{blue}. This is the way an achromatic doublet functions.

7.5.1.1.7 Remarks

- Careful alignment is essential to this demonstration: The optical axis needs to be in good parallelism with the optical rail, so that when shifting the camera the light spot stays on the center of the screen.

- The demonstration can also be done without using filters; Then the diaphragm is imaged at the camera as good as possible. When now we shift the camera towards the single lens we will get a concentration of blue near the optical axis and red in a circle around it. Shifting the camera away from the lens the opposite happens: we see red near the optical axis and a blue circle around it. Going from one position to the other also yellow and green near the axis can be observed.
- The demonstration can also be done using a Hg-lamp in stead of an incandescent lamp. However, in that way the demonstration is more complicated due to the high differences between the intensities of the separate spectral lines: Every spectral line will need its own grey-filter in order not to saturate the light sensitive layer of the camera.

7.5.1.1.8 Sources

- Hecht, Eugene, Optics, pag. 66-73, 157-159 and 271-277
- Sutton, Richard Manliffe, Demonstration experiments in Physics, pag. 389-390
- The Physics Teacher, pag. march 1986, 160-163
- The Physics Teacher, pag. nov. 1987, 502-503

7.6 6H Polarisation

7.6.1 6H20 Reflection

7.6.1.1 01 Brewster's Angle (1)

7.6.1.1.1 Aim

To show the most common source of polarized light: polarization by reflection, as observed for the first time by Etienne Malus (1808).

7.6.1.1.2 Subjects

- 6H20 (Polarization by Reflection) 6H35 (Birefringence)

7.6.1.1.3 Diagram

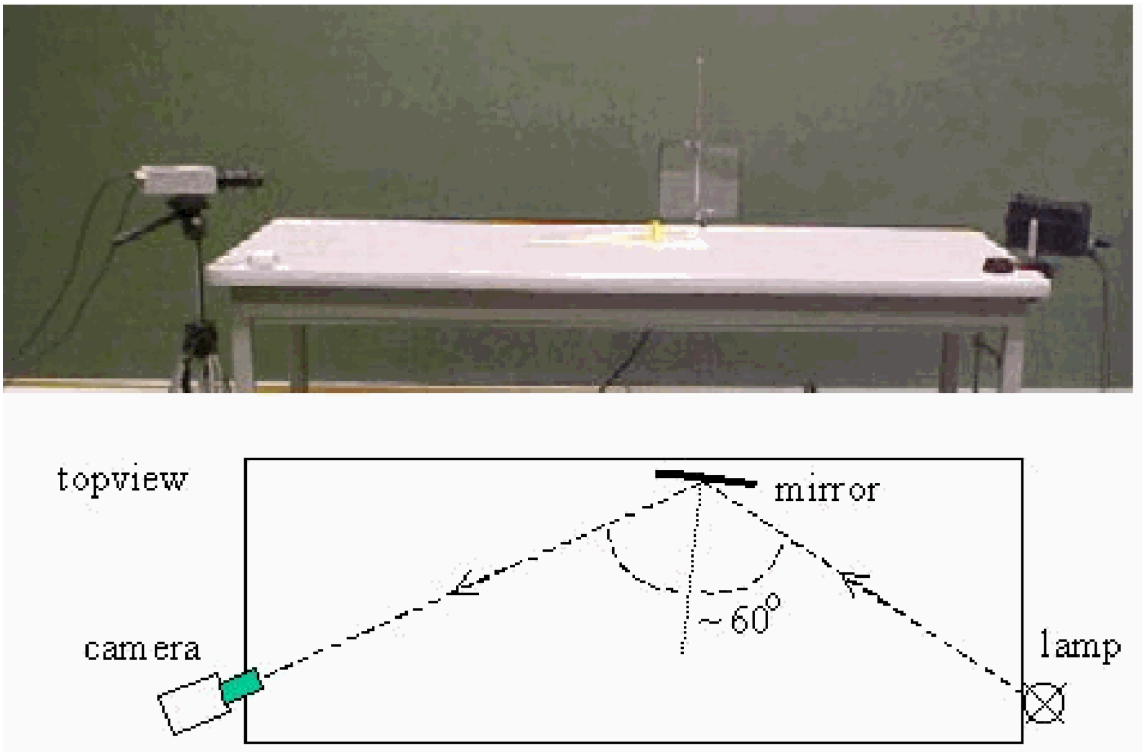


Figure 7.78: .

7.6.1.1.4 Equipment

- Lamp, 12 V, halogen
- Transformer, 2 — 12 V.
- Resistor, 2Ω/20 W.
- Acrylic sheet (mirror).
- Camera.
- Calcite crystal.
- 30-60-90 triangle.
- Projector to project the camera-image.

7.6.1.1.5 Presentation

Etienne Malus was standing at the window of his house in the Rue d'Enfer (Paris) examining a calcite crystal. The sun was setting, and its image reflected towards him from the windows of the Luxembourg Palace not far away. He held up the crystal and looked through it at the sun's reflection. To his astonishment, he saw one of the double images of the sun disappear as he rotated the calcite!

This historical situation is presented in our demonstration (see Diagram). The 12Vlamp is in our situation operating at 6 V in series with a 2Ω/20 W resistor. This is the red glowing setting sun. The acrylic sheet is a window of the palace and the camera is the eye of Etienne Malus. The beamer projects to the audience the image that Etienne saw: “window” and reflected image of the “sun” (see Figure 2A). Take care that the camera is focussed on the light spot and not on the “window” itself.

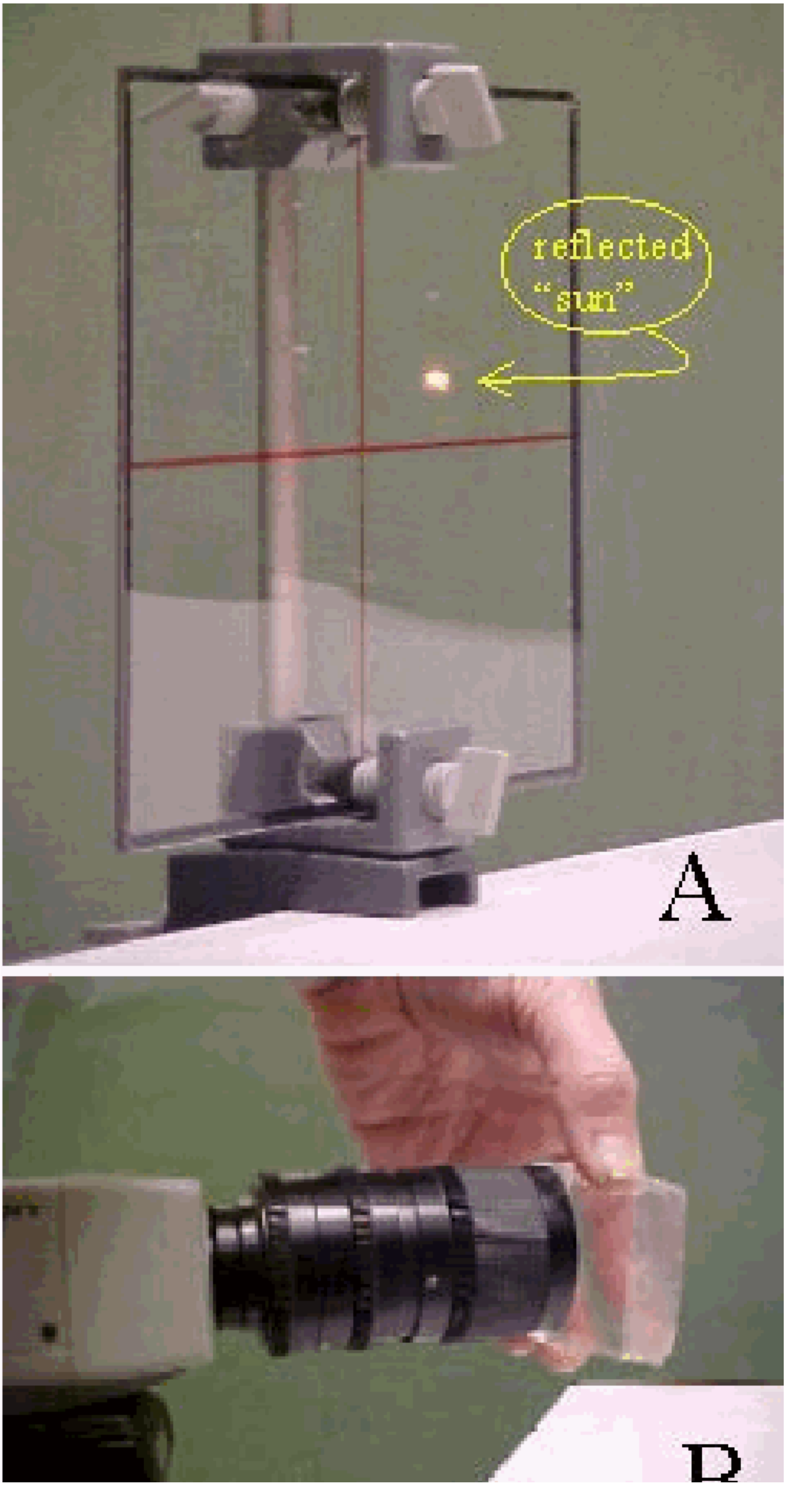

reflected
"sun"
A

Figure 7.79: .

The lay-out of the demonstration is such that the angle of incidence is about 60°. The large 30 — 60 — 90° triangle shows this to the students. Now the calcite crystal is placed in front of the camera-lens (see Figure 2B). Everything in the projected image is doubled. While rotating the crystal also the double images rotate, but at two positions of rotation the doubling of the reflected "sun" disappears and only one "sun" is seen!
Observe also that the double image of the window never disappears.

7.6.1.1.6 Explanation

In the time of Malus the birefringent action of calcite was known (see the demonstration 'Calcite crystal' in this database). That Malus was experimenting with such a crystal was because the French Institute had offered a prize for a mathematical theory of the double refraction. In 1821 the work of, principally Thomas Young and August Fresnel finally led to such a mathematical theory: the representation of light as some sort of transverse vibration. The so-called Fresnel equations express the effect of an incoming (plane) wave falling on an interface between two different media. These equations relate the reflected and transmitted field amplitudes to the incident amplitude:

- When the E-field is parallel to the plane of incidence (the so-called p-polarization), the reflection coefficient equals: $r_{par} = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_i \cos\theta_t + n_t \cos\theta_i}$ and the transmittance

coefficient equals: $t_{par} = \frac{2n_i \cos\theta_i}{n_i \cos\theta_t + n_t \cos\theta_i}$

- When the field is perpendicular to the plane of incidence (the so-called s-polarization): $r_{perp} = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t}$

and $t_{perp} = \frac{2n_i \cos\theta_i}{n_i \cos\theta_i + n_t \cos\theta_t}$

Figure 3 shows these formulas in a graph (as function of the angle of incidence).

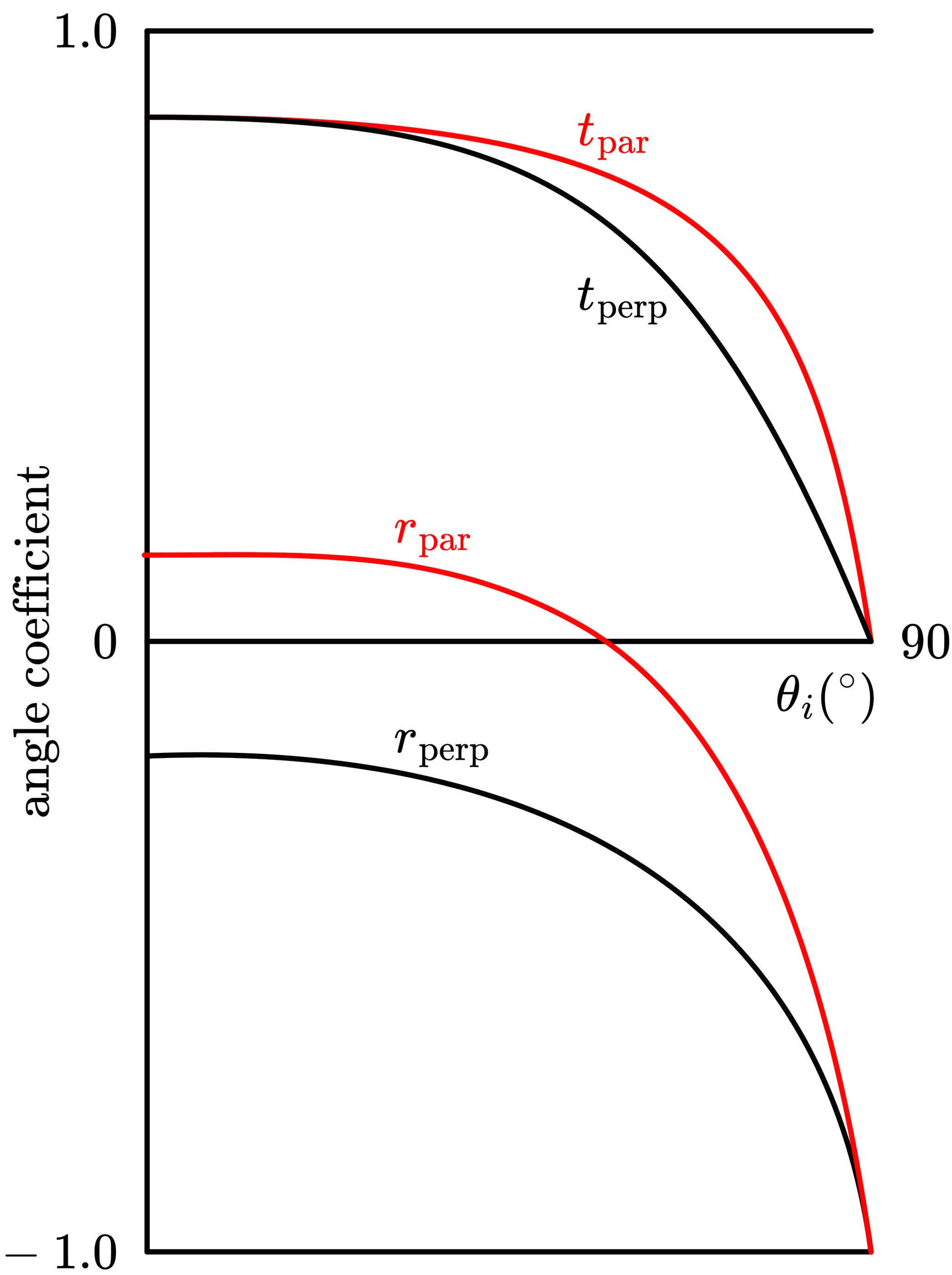


Figure 7.80: .

There appears zero amplitude for r_{par} at a certain angle. This angle can be found when using Snell's law in r_{par} : $r_{par} = \frac{\sin\theta_i \cos\theta_i - \sin\theta_t \cos\theta_t}{\sin\theta_i \cos\theta_i + \sin\theta_t \cos\theta_t}$. Rewriting (see textbooks) $r_{par} = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta + \theta_i \theta_t)}$

This can be zero when the denominator is infinite, so when $\theta_i + \theta_t = 90°$. In this situation, using Snell's law $n_i \sin\theta_i = n_t \sin\theta_t$ yields $n_i \sin\theta_i = n_t \cos\theta_i$, so $\tan\theta_i = \frac{n_t}{n_i}$, or $\theta_i = \arctan\frac{n_t}{n_i}$

This is Brewster's law, formulated correctly in 1815. (Brewster was honoured half the prize of the French Institute in 1816.)

Acrylic sheet has n $= 1.5$, so here Brewster's angle is: $\theta_t = 56°$. This is in correspondence with our setting up of the demonstration (angle of incidence is set at about 60°).

7.6.1.1.7 Remarks

- In this demonstration the historical approach is chosen in order to intensify the astonishment aroused by the phenomenon (the doubling of the sun that vanishes, but not so the doubling of the window).
- It is a lucky incident that Malus lived at the right spot to have Brewster's angle at his position relative to the Luxembourg Palace.
- Mention also to the students that Fresnel is long before electromagnetic field theory. In those days their theory mentioned "luminous waves" and "ethereal vibrations".
- Before doing this demonstration the birefringent crystal calcite should be introduced to the students. You can use the demonstration "Calcite crystal" in this database.
- Since we work in this demonstration with the amount of light our eyes see, we should work with the squares of the field amplitude, finally leading to $\theta_i = \arctan \frac{n_t}{n_i}$. This produces the same results.
- When electromagnetic theory is known to the students the situation of $\theta_i + \theta_t = 90^\circ$ in Brewster's law can be explained: The refracted wave entering the medium drives the bound electrons and they in turn reradiate. A portion of that re-emitted energy appears in the form of a reflected wave. If the situation is arranged so that $\theta_i + \theta_t = 90^\circ$, the reflected wave vanishes, since linear oscillating charges will not emit in their direction of oscillation. This happens at Brewster's angle (see also the second figure in [Brewster's angle (2)](../6H2002 Brewsters Angle/6H2002.md) in this database and the demo [Brewster's angle (3)](../6H2003 Brewsters Angle/6H2003.md)).

7.6.1.1.8 Sources

- Hecht, Eugene, Optics, pag. 111-115; 342-346; 658-659.

7.6.1.2 02 Brewster's Angle (2)

7.6.1.2.1 Aim

To show when unpolarized light is reflected by a surface at Brewster's angle, the component polarized parallel to the incident plane (normal to the reflecting surface) will not be reflected.

7.6.1.2.2 Subjects

- 6H20 (Polarization by Reflection)

7.6.1.2.3 Diagram

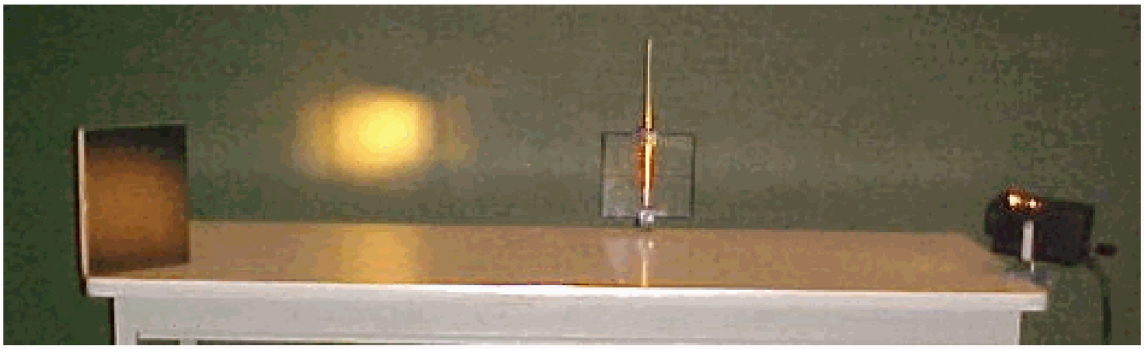


Figure 7.81: .

7.6.1.2.4 Equipment

- Lamp, 12 V, halogen
- Transformer, 2 — 12 V.
- Acrylic sheet.
- 30-60-90 triangle.
- Polaroid filter.
- Black screen.

7.6.1.2.5 Presentation

The demonstration is presented as shown in Diagram. The angle of incidence is about 60°. In this lay-out the plane of incidence is horizontal.

Switching on the lamp and shifting the condenser, a parallel beam of light is made. On the blackboard the transmitted beam through the acrylic sheet is observed and the black screen shows that there is also a (weaker) reflected beam (see Diagram). When the Polaroid filter is placed in the beam of light, having its direction of polarization parallel to the plane of incidence, the reflected wave disappears (see Figure 2A): there is only transmission.

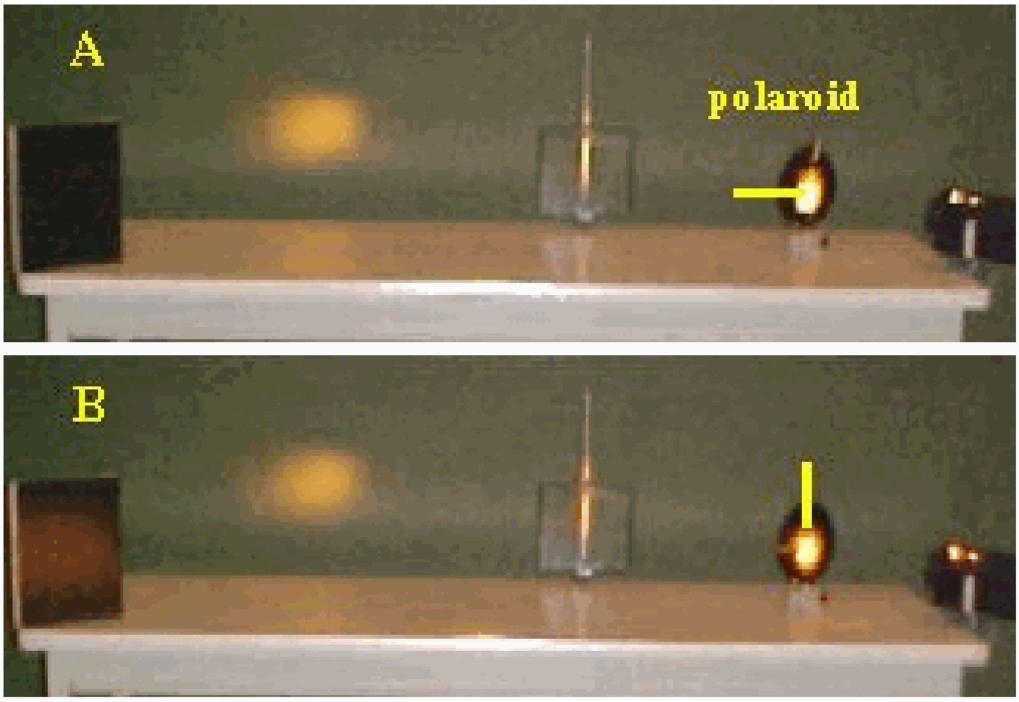


Figure 7.82: .

When the Polaroid is rotated there is again reflection. Figure $1B$ shows the situation when the direction of polarization is perpendicular to the plane of incidence.

7.6.1.2.6 Explanation

The refracted wave entering the acrylic sheet drives the bound electrons and they in turn reradiate.

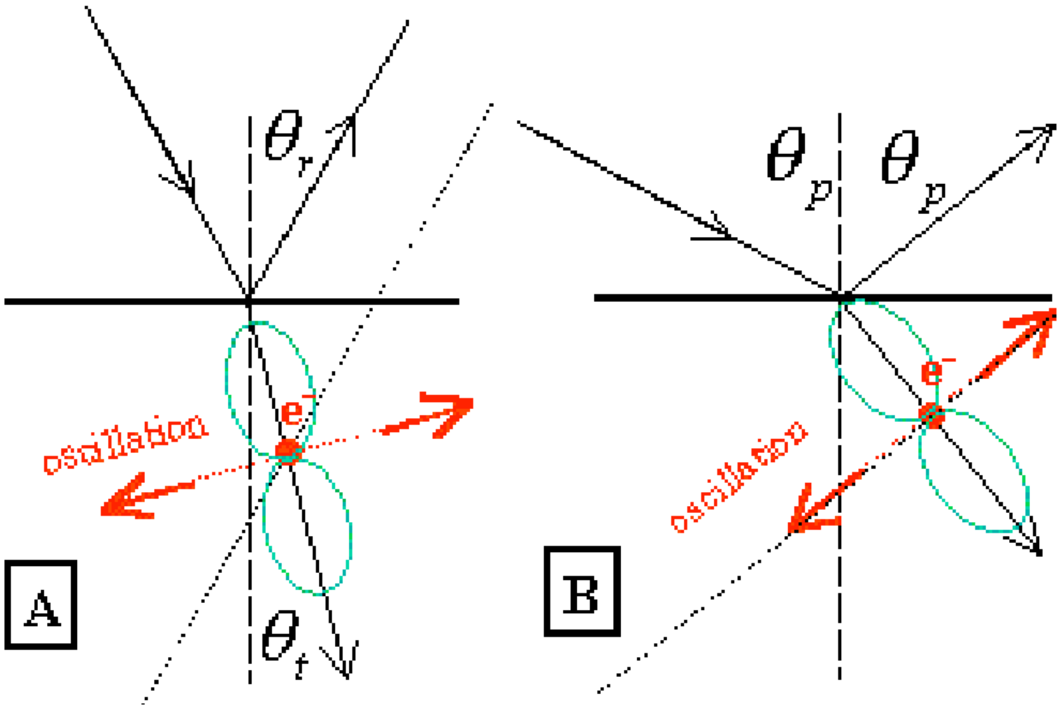


Figure 7.83: .

Figure 3A shows such a dipole radiation pattern (green line is the envelope) of such an oscillating charge. If the situation is arranged such that $\theta_r + \theta_t = 90^{\circ}$, there is no reradiation into the direction of reflection (see Figure 3B): the reflected wave vanishes. (In a simple way you can say that in the direction of reflection an observer “sees” no oscillation). The angle at which this situation happens is called Brewster’s angle (θ_p)

7.6.1.2.7 Remarks

- Also see the demonstration [Brewster’s angle (1)](<../6H2001 Brewsters Angle/6H2001.md) .
- The pictures in Diagram, Figure 2A and −1B show that in this demonstration you can also say something about the intensities of the reflected and transmitted beams. Figure 3 in the demonstration [Brewster’s angle](../6H2001 Brewsters Angle/6H2001.md) can be used to elucidate the observed differences in intensities.

7.6.1.2.8 Sources

- Hecht, Eugene, Optics, pag. 111-115; 342-346

7.6.2 6H35 Birefringence

8. 7 Modern Physics

8.1 7A Quantum Effects

8.1.1 7A50 Wave Mechanics

8.1.1.1 01 deBroglie Applied to Bohr

8.1.1.2 02 Tunneling

8.1.1.2.1 Aim

To show tunneling of a wave through a barrier.

8.1.1.2.2 Subjects

- 7A50 (Wave Mechanics)

8.1.1.2.3 Diagram

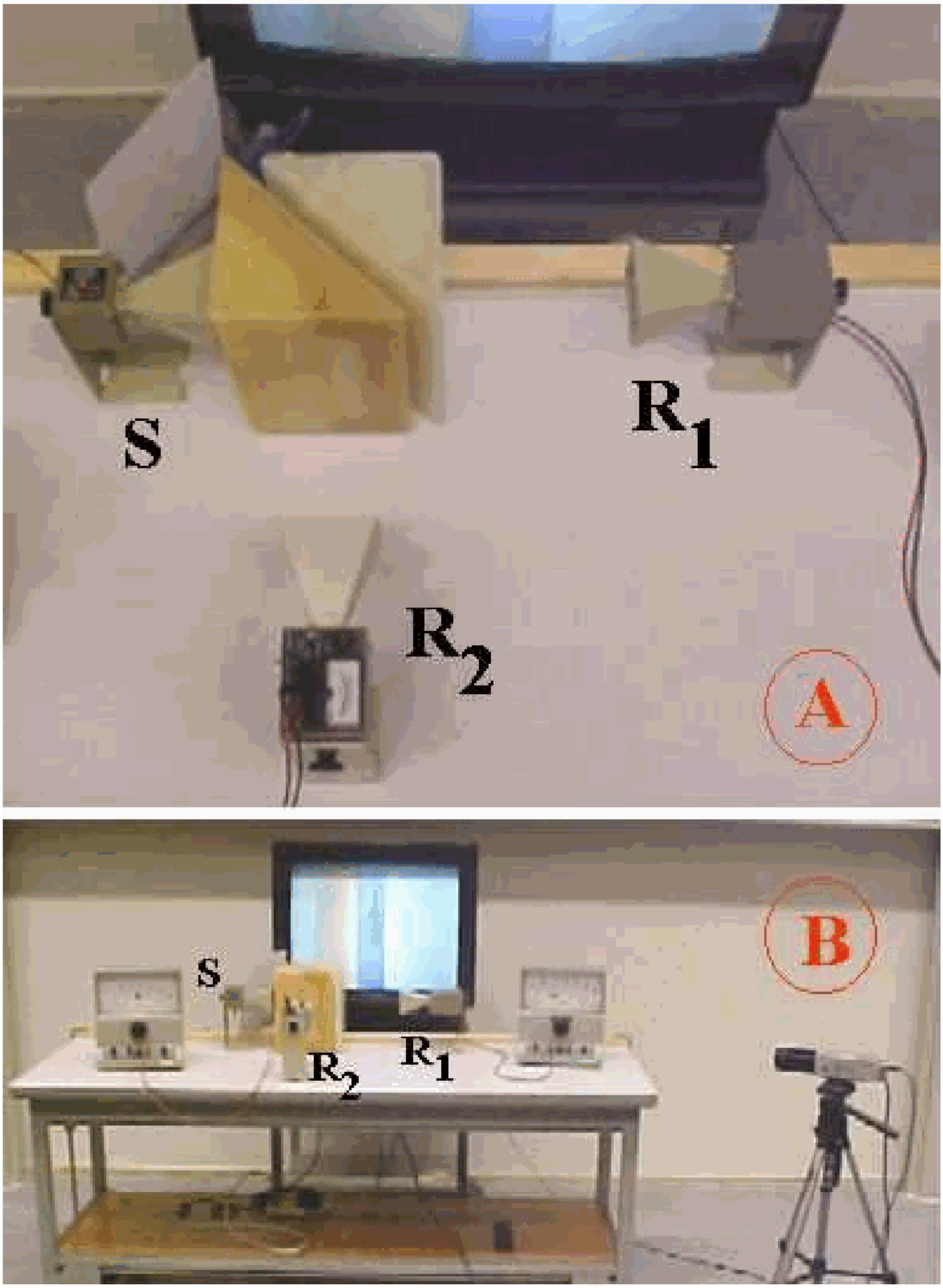


Figure 8.1: .

8.1.1.2.4 Equipment

- Microwave transmitter ($f = 10GHz; \lambda = 3$ cm) (S in Diagram).
- 2 Microwave receivers (R1 and R2 in Diagram).
- 2 large demonstration meters.
- 2 Triangular blocks of paraffin wax.
- Beam of wood ($I = 2$ m), used as a slideway
- Transparant ruler ($I = 30$ cm).
- White screen to be placed behind the transparent ruler.
- Video camera.
- Large monitor
- (Laser, two rectangular prisms,a square block of glass and a beam splitter).

8.1.1.2.5 Presentation

8.1.1.2.5.1 Preparation

The demonstration is set up as shown in Diagram A and B.

The camera and monitor are placed in order to make the gap between the paraffin wax blocks visible to the audience.

The slideway is needed in order to shift one of the paraffin wax triangles along a straight line.

When you prepare the demonstration, use the set ups as shown in Figure 2B and -C: In Figure 2B, the meter, indicating the signal received by R1, should be equal to the signal that will be received by R2 in the situation of Figure 2C. To achieve this, careful positioning is needed for sender S, the paraffin wax blocks and both receivers.

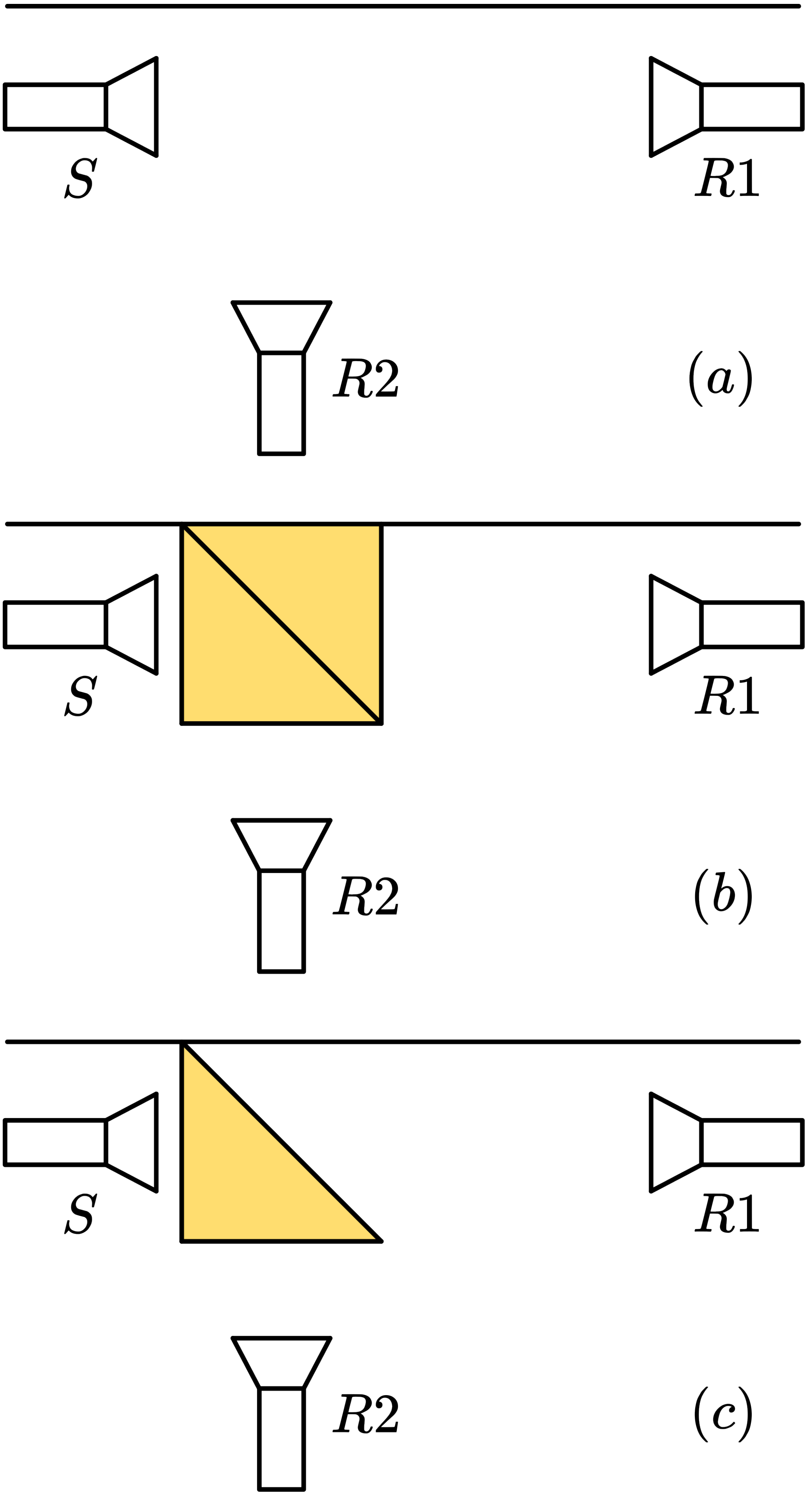

S
R1
R2
(a)
S
R1
R2
(b)
S
R1
R2
(c)

Figure 8.2: .

8.1.1.2.6 Presentation

The demonstration is following a sequence as shown in Figure1 through 2 (A-E).

Figure A

The sender and receivers are switched on. Receiver R1 shows a deflection. (R2 has no deflection.) Placing your hand in front of S will make clear that $R1$ really receives the signal send by S.

Fiqure B

Both triangular blocks are, as one square block, placed between sender S and receiver R1. The receiver will show the same deflection as in the foregoing situation (A). Conclusion is that the paraffin wax is completely transparent to the microwaves. It can be compared with the transparency of glass to light. (Optional: show this also with laser and a square piece of glass)

Figure C

A triangular block of paraffine wax is placed in front of the sender S as shown in Figure B. Receiver R1 has no deflection, so it receives no signal. But receiver R2 shows a deflection, and this deflection is equal to that of the previous situation (Figure A). Clearly the signal from the sender is deflected by the paraffin block towards R2. Again the comparison with glass and light can be made. (Optional: show this with a laser and a rectangular prism)

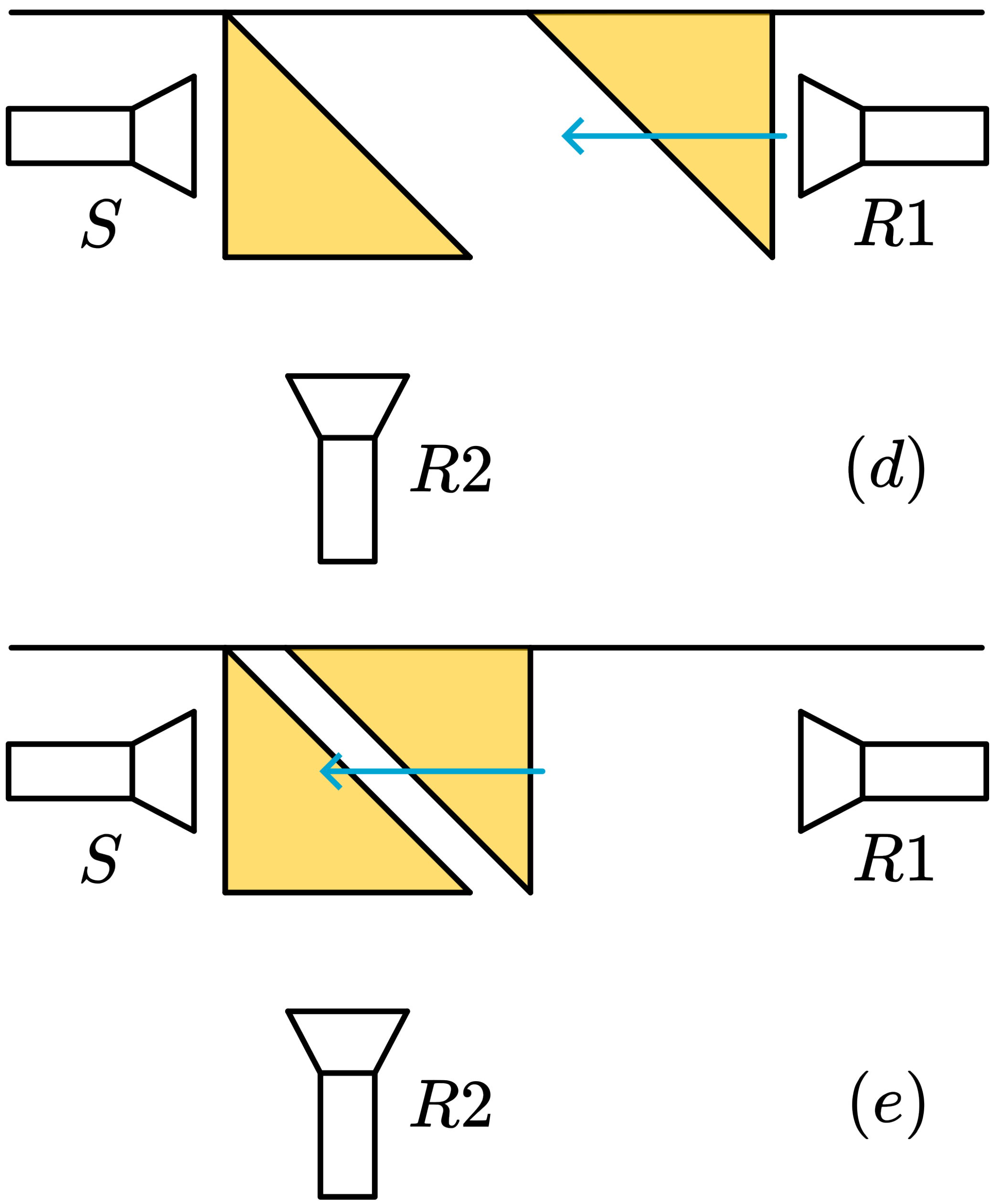


Figure 8.3: .

8.1.1.2.7 Figure D-E

The second triangular paraffin block is placed close to the receiver as Figure D shows. Then this block slides along the slideway slowly towards the other paraffin block. In the beginning nothing is different from the foregoing situation: R2 has still full deflection and R1 has no deflection. But when the blocks come within a distance smaller than the wavelength of the microwaves, R1 starts receiving signal and R2 receives less. Clearly there is barrier penetration! Making the separation still smaller this take-over continues until situation B is there again.

The weirdness of this phenomenon should be stressed, by mentioning that if in situation E part of the signal clearly passes the air gap, this means that also in situation C and D the signal from S also passes the wall between wax and air to a certain depth, but when the signal "feels" no wax at that depth it "chooses" deflection towards R2. Between D and E the "penetration depth" can be determined.

(Optional: Show that laser light that enters a beam splitter is partially transmitted and partially deflected)

8.1.1.2.8 Explanation

Apparently, the transition from wax to air into the straight on direction towards R1, as in Figure 2C, is a barrier to the microwaves, but not completely (as in Figure 3D and $-\mathrm{E}$). Solving the Schroedinger wave equation provides a satisfying solution, because this shows that within a barrier the solution to the wave equation is decaying exponential, dying away to zero, and so, if that barrier ends before this zero is reached, then there is again a sinusoidal wave function. (See the many textbooks on this subject.)

8.1.1.2.9 Remarks

- While shifting it might seem to the audience that there are situations that the total deflection of R1 and R2 is every now and then more than the original value. For example, when we start without the block (situation A), the deflection of R1 is 10 units (fsd). While shifting (situation D) a possible situation is $\mathrm{R1} = 8$ units, and $\mathrm{R2} = 6$ units, adding to 14 in total! But we read voltage, so in order to compare intensities we need to square these readings, giving $8^2 + 6^2 = 100 = 10^2$. So nothing strange is happening. Actually we show this specific 6-8-10 situation as an extra to the students to explain these peculiar meter readings.

8.1.1.2.10 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 996-998

8.1.2 7A60 X ray and Electron Diffraction:

8.1.2.1 01 Bragg Scattering

8.1.2.1.1 Aim

To show why symmetry is needed in the set-up of a Bragg scattering experiment.

8.1.2.1.2 Subjects

- 7A60 (X-ray and Electron Diffraction)

8.1.2.1.3 Diagram

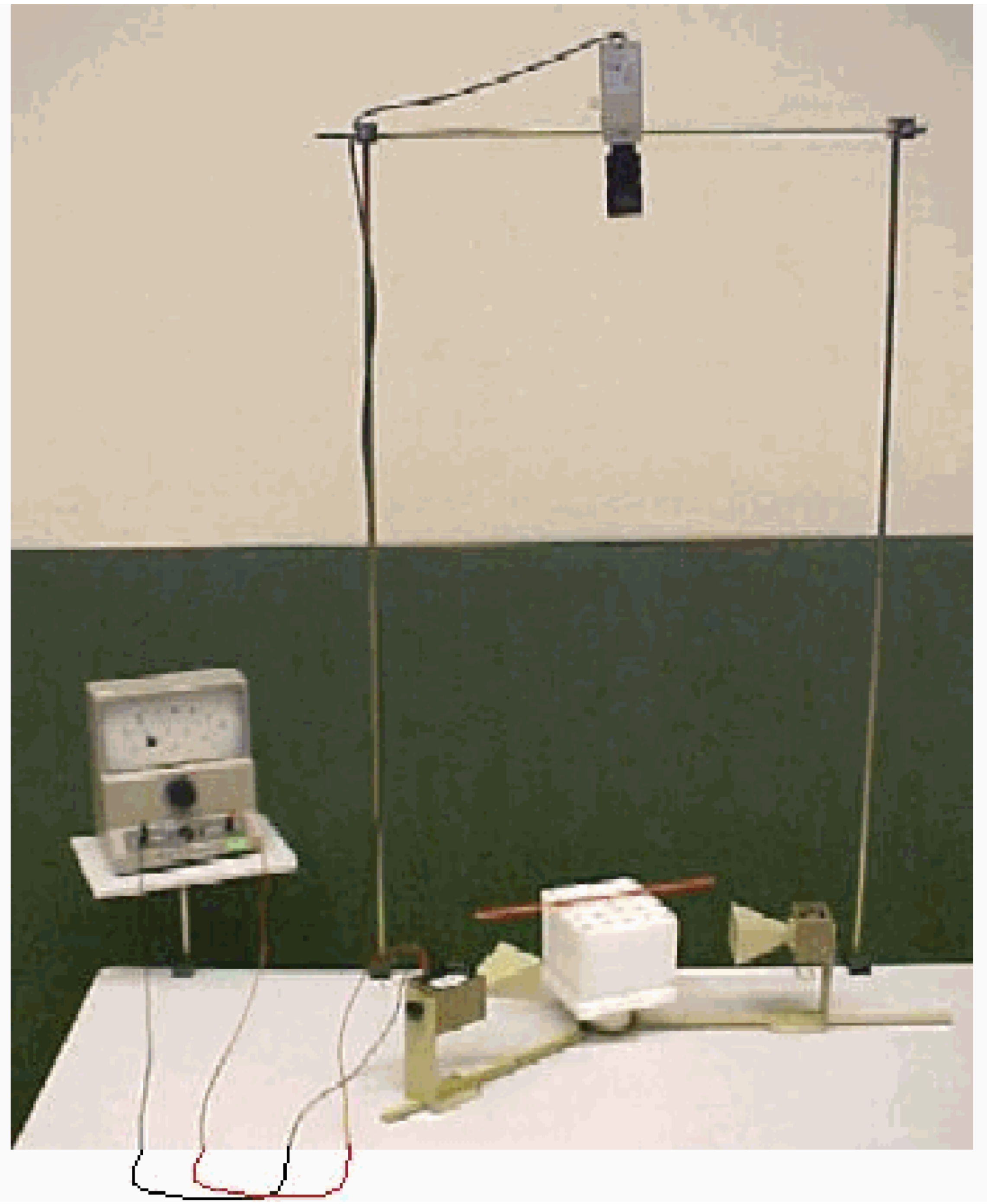


Figure 8.4: .

8.1.2.1.4 Equipment

- Microwave optics set of sender and receiver.

- Fixed- and rotatable- arm assembly.
- Rotatable table.
- "Crystal" of 100 metal spheres in a $5 \times 5 \times 4$ cubic array, mounted in plastic foam.
- Red and green stick to indicate orientations.
- Camera, to look on the set up (see Diagram).
- Large demonstration meter; f.s.d. = 30 mA.
- Large piece of plastic foam.

8.1.2.1.5 Presentation

Von Laue suggested that a crystal might serve as a diffraction grating for very short wavelength (1912). X-ray experiments showed the truth of this.

We simulate such an experiment using cm-waves instead of X-rays and a lattice of steel balls as a "crystal".

First, the sender and receiver face each other. (A camera, perpendicular above the set-up, projects the lay-out to the audience.) The large demonstration meter is adjusted to give a sufficient deflection. Putting your hand between sender and receiver reduces the received signal to zero. Then a large piece of plastic foam is placed between the sender and receiver. It fills that space completely, but the receiver still shows the same intensity of received signal: To these cm-waves the plastic foam is perfectly transparent.

Then the crystal model is placed between the sender and receiver on the rotatable table The crystal's plane $\mathrm{A}(100)$ is perpendicular to the incident microwave beam (see Figure 2A). The received signal is lower now. Conclusion must be that the array of steel balls is responsible for this signal reduction (see also Remarks).

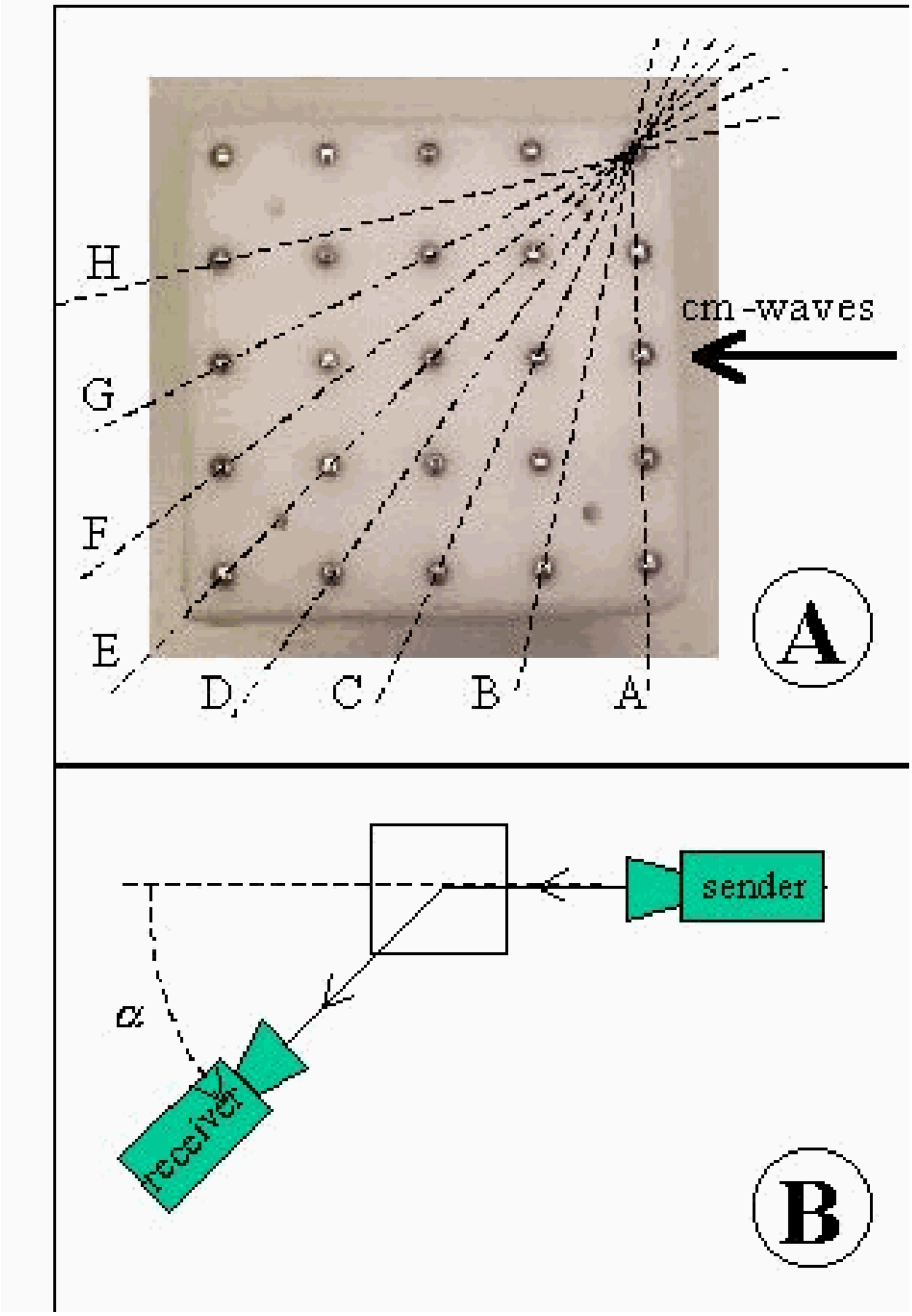


Figure 8.5: .

Following the suggestion of Von Laue that there could be diffraction due to the crystal lattice, we rotate (α) the receiver slowly around the crystal, using the arm of the goniometer (see Figure 2B). Off $\alpha = 0^\circ$ the receiver signal diminishes and no relevant signal is found at any angle α.

The demonstration is repeated with a different orientation of the crystal. The number of orientations is, of course, infinitive, so we choose a number of possibilities (see Figure 2A). Orientation $\mathrm{A}(100)$ is done, next we try $\mathrm{B}(410)$, then $\mathrm{C}(210)$ and so on. (The green bar shows the orientation to the audience; see green bar in Figure 3.)

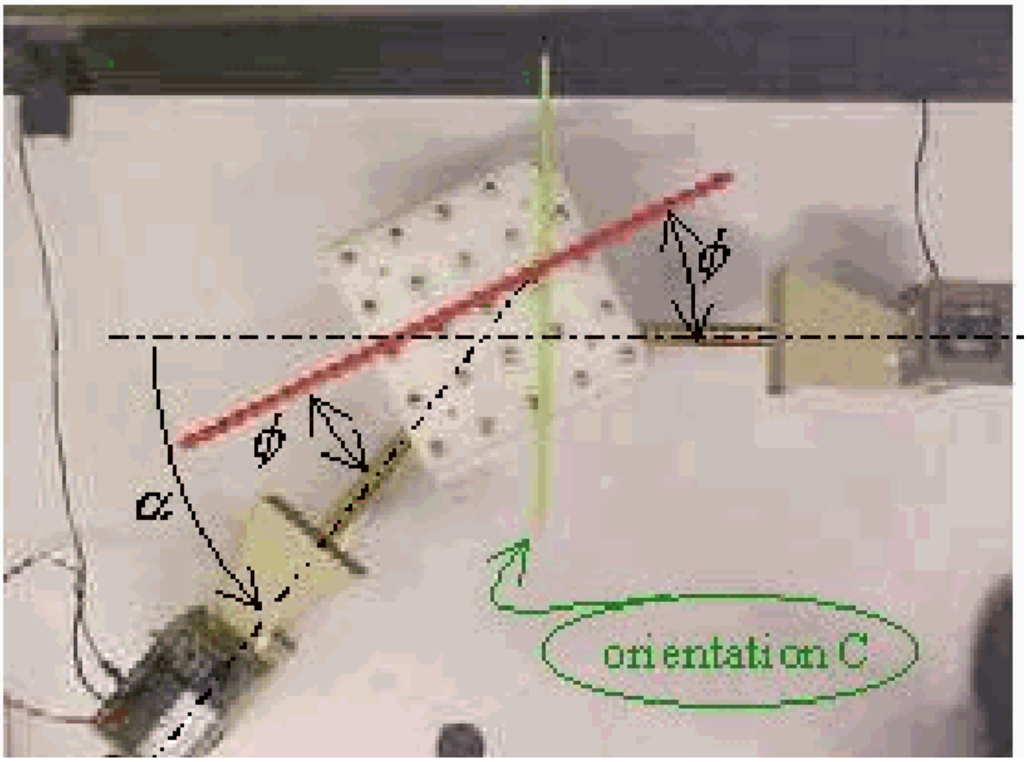


Figure 8.6: .

B shows no relevant result, but C shows a peak when the angle of rotation, α, is a little bit more than 45°. Observing the position of sender receiver and crystal planes, symmetry is observed! We aid this observation by placing the red stick in the direction of the (100) plane (see Figure 3). This strongly suggests that the peak measured is due to reflections off the (100) planes of the crystal. In this symmetry-situation $\alpha = 2\phi$, ϕ being the so-called grazing angle (or glancing angle). In this situation that grazing angle is around 22.5°.

All other orientations of the crystal give no relevant result, except orientation G, where a weak peak is measured at α of around 60°. Observing the position of sender, receiver and crystal in this situation makes us placing the red-stick-of-symmetry along the diagonal of the crystal (plane (110)). The grazing angle ϕ is then around 30°.

These two examples stress that in order to measure peaks symmetry is needed in the set-up of the experiment. This leads us to the demonstration "Bragg diffraction" in this database.

8.1.2.1.6 Explanation

In Bragg diffraction constructive interference will occur when $m\lambda = 2d \sin \phi$ (see textbooks) and so: $d = \frac{m\lambda}{2 \sin \phi}$

In situation C we measured $\phi = 22.5°$. With $\lambda = 3$ cm and $m = 1$, we find for the distance between the layers (100) of the crystal $d_c = 3.9$ cm.

In situation G (reflection from the layers (110)), we measured a peak at $\phi = 30°$. Then we find $d_G = 3$ cm.

The crystal is cubic, so the relation between d_C and d_G should be: $d_C/d_G = 2^{1/2}$.

8.1.2.1.7 Remarks

- When in the beginning you place the crystal model between sender and receiver, the received signal will reduce. Depending on the separation chosen between sender and receiver, the received signal might even reduce to zero.

8.1.2.1.8 Sources

- Callister, Jr. William D., Material Science and Engineering, an introduction, pag. 53-57.
- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 905-906.
- Mansfield, M and O'Sullivan, C., Understanding physics, pag. 335-336.
- Pasco Instruction Manual, Microwaves Optics (WA9314B), Exp. 12, pag. 33-34 and 44.

8.2 7B Atomic Physics

8.2.1 7B10 Spectra

8.2.1.1 01 Balmer Series

8.2.1.1.1 Aim

To show the visible hydrogen spectrum and its regularity.

8.2.1.1.2 Subjects

- 7B10 (Spectra)

8.2.1.1.3 Diagram

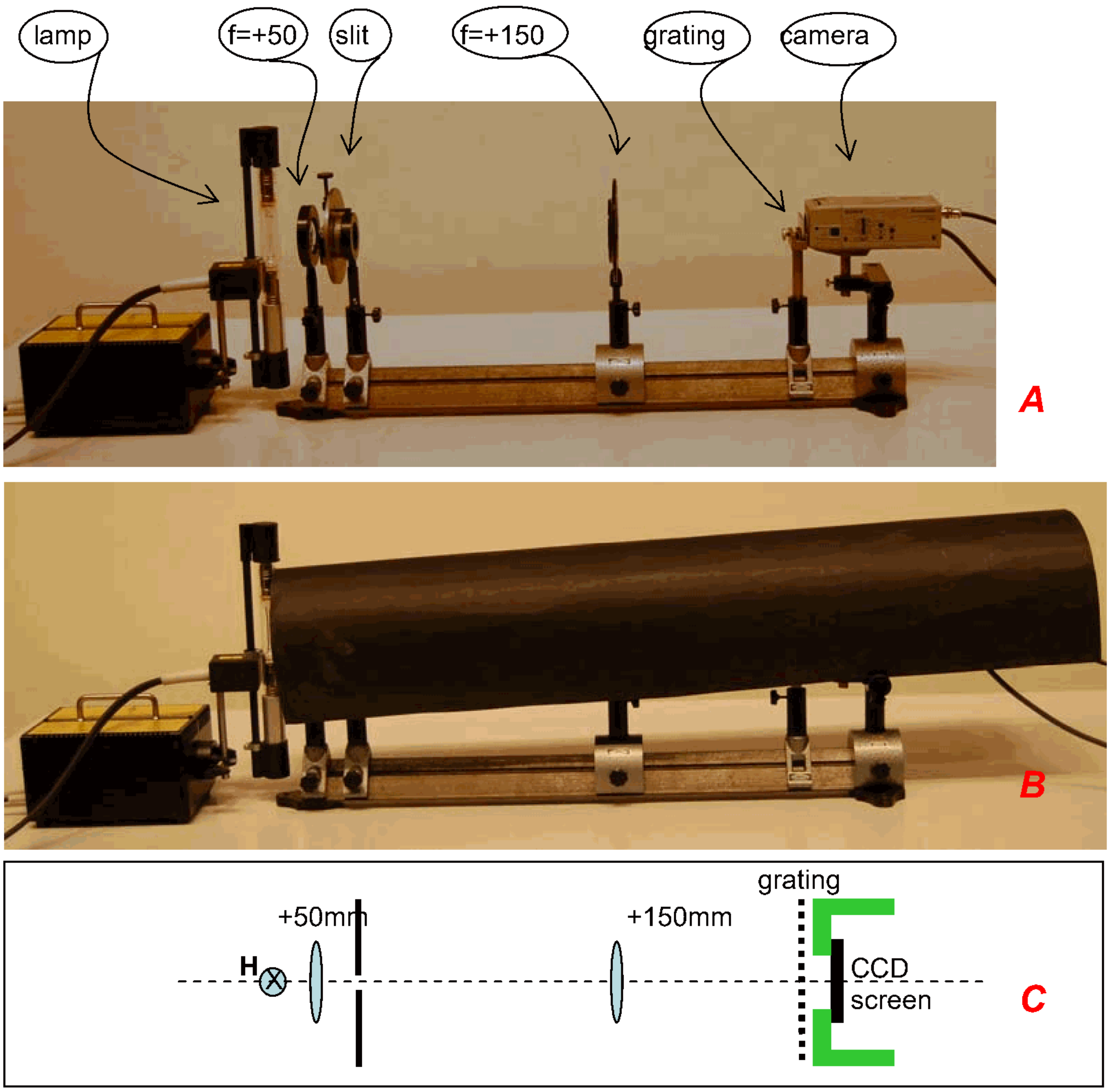


Figure 8.7: .

8.2.1.1.4 Equipment

- Gas discharge lamp, filled with water vapor.
- High voltage power supply, 3.5kV V_{rms}. (see Safety)
- Lens, f $= +50$ mm (used as condenser lens).
- Lens, $+150$ mm (to focus the slit on the camera-screen).
- Adjustable slit.
- Grating 100 lines/mm.

- Camera, lens removed.
- Linear positioner.
- Optical rail.
- Beamer.
- Large sheet of black paper, rolled as a tube (see Diagram B).

8.2.1.1.5 Safety

- The high voltage power supply is operated from the AC mains outlet. Always disconnect the mains plug from the wall outlet before making any changes to the demonstration setup (e.g. changing the Balmer lamp or changing the fuse). See the Leybold Didactic instruction sheet.

8.2.1.1.6 Presentation

8.2.1.1.6.1 Preparation

The gas discharge lamp and the two lenses are placed on the optical rail. The power supply of the lamp is switched on. Steady discharge is reached after approx. 15 minutes (see "notes on operation" of Leybold Didactic).

The +50 mm lens is shifted close to the lamp to focus as much light as possible through the +150 mm lens. Both lenses are fixed. Then the variable slit and camera (mounted on the linear positioner and connected to the beamer; see Figure 2) are positioned on the optical rail. The slit is shifted to image it sharply on the camera CCD-screen. The linear positioner is shifted also, until the slit can be seen on the middle of the projected image.

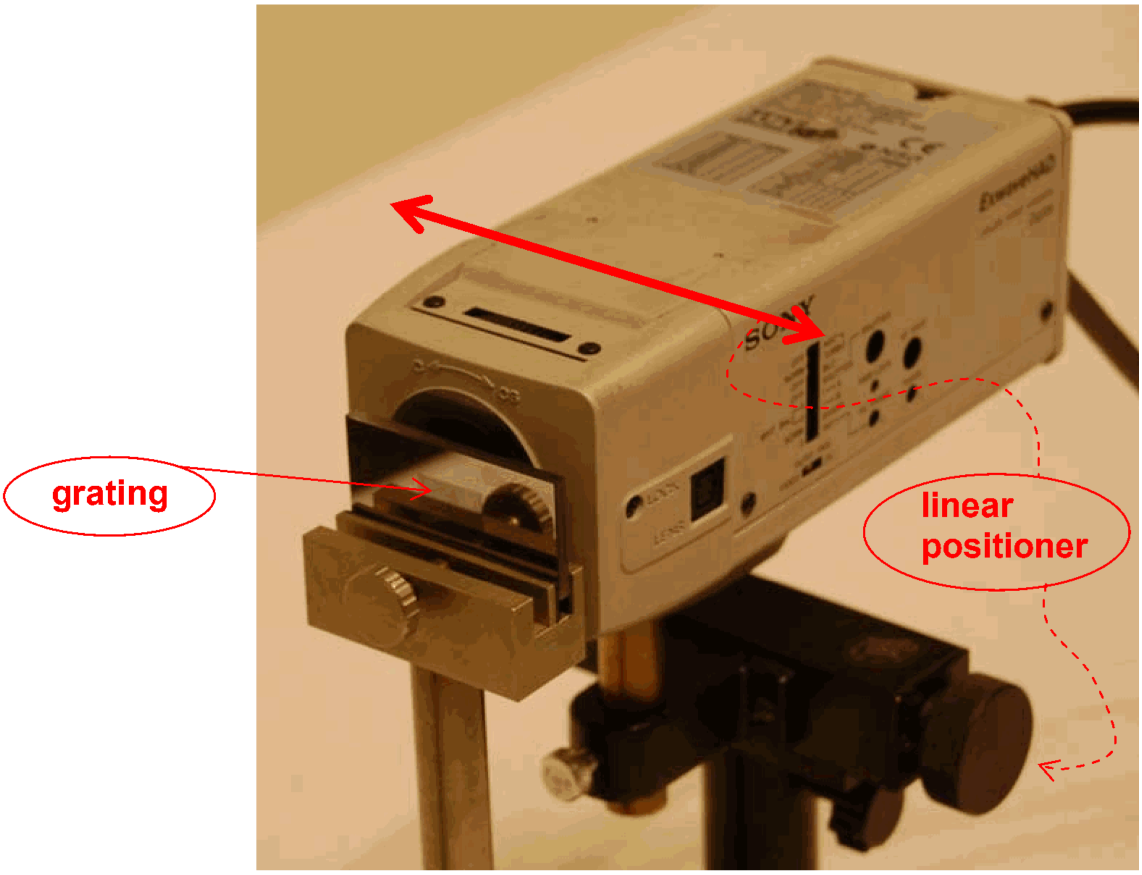


Figure 8.8: .

8.2.1.1.7 Demonstration

The room is darkened and a sharp and intense image of the slit is visible to the audience. Then the grating is placed in its holder as close as possible to the camera. We also place the black tube around the set-up (see Diagram B). Blue and red lines appear (also a fainting of the slit-image can be observed when the grating is placed). In this way we have build a spectroscope, like Fraunhofer did (1814).

The students are invited to describe what they see:

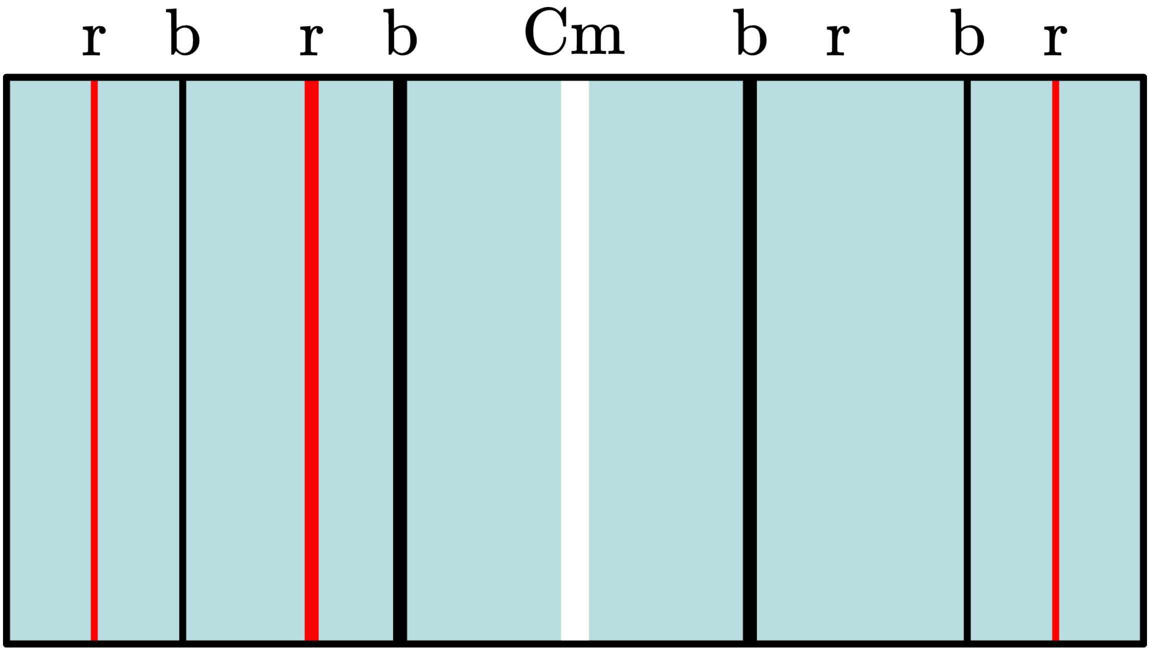


Figure 8.9: .

"... diffraction pattern of a grating; first and second orders on both sides of the central maximum; blue is closer to the central maximum then red; ..."
We shift the camera sideways so that the central maximum is on one side of the projected image. Then we ask the students what will happen when we shift the grating away from the camera. After their answering we shift it away and observe the broadening of the orders, but the pattern remains the same. In the shifting also a faint violet line (v) can be seen.

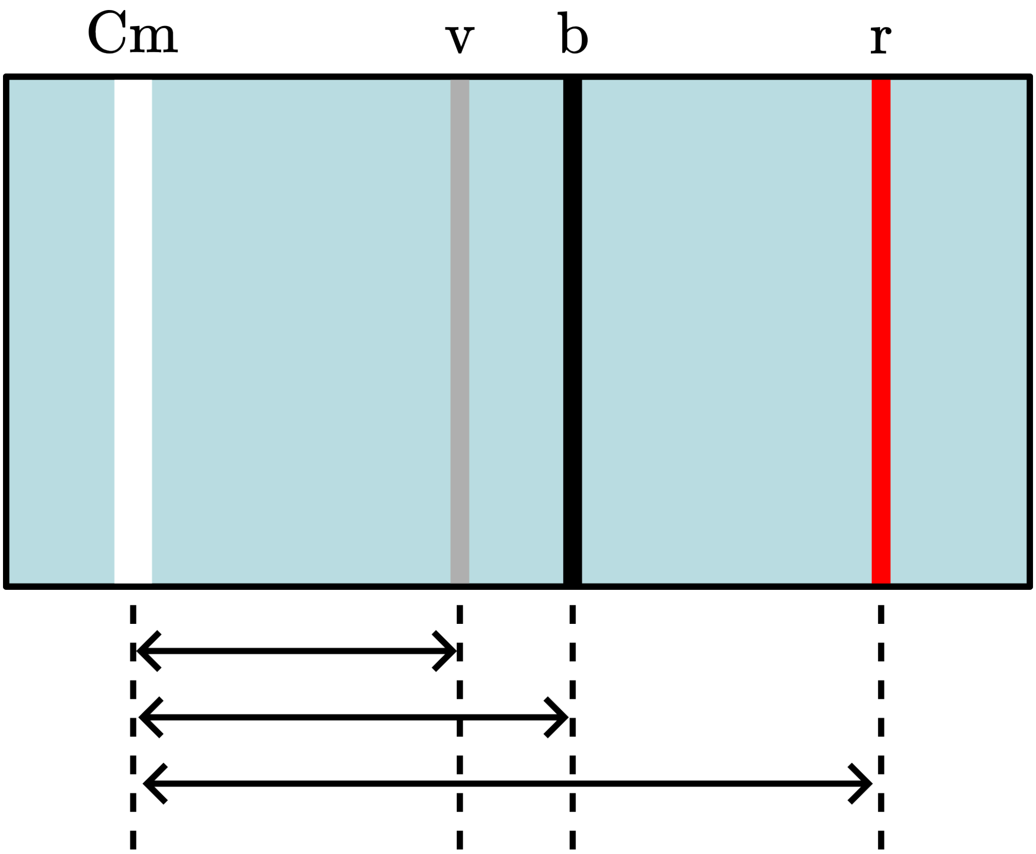


Figure 8.10: .

The image is partly projected on the blackboard and we indicate with chalk the horizontal positions of: Central maximum (Cm), violet(v) -, blue(b) - and red(r) line. With a measuring tape we found:

$Cm - v = 170$ cm

$Cm - b = 188$ cm

$Cm - r = 256$ cm

An explanation of what is observed now follows.

8.2.1.1.8 Explanation

Calibration is performed by using $\sin\theta = \frac{\lambda}{d}$ (first order maximum of a diffraction pattern created by a grating, d being the distance between the slits of the grating.), see Figure 3.

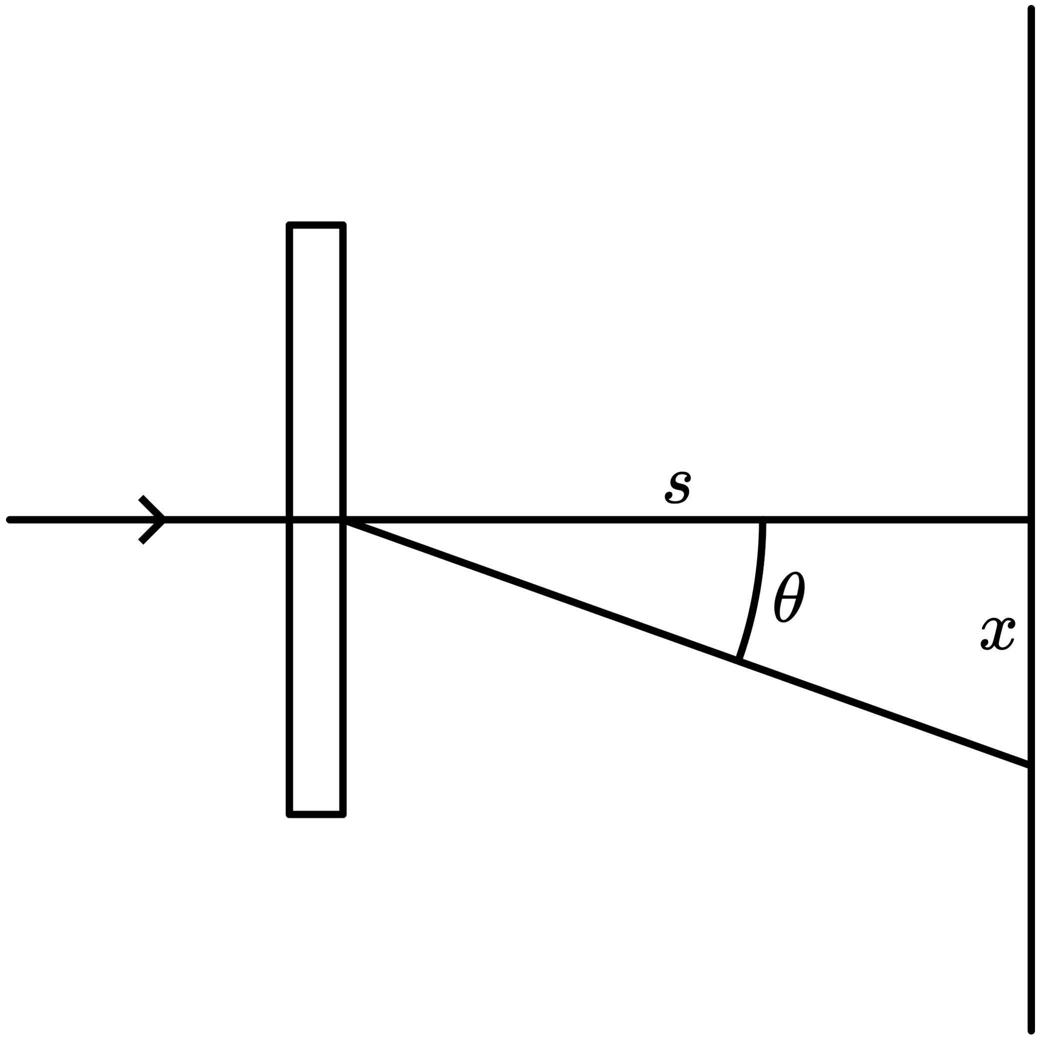


Figure 8.11: .

Figure 3 shows: $\sin\theta = \frac{x}{\sqrt{x^2+s^2}}$. Rewriting we get: $x = s\frac{\lambda}{\sqrt{d^2-\lambda^2}}$. When $\lambda \ll d$ then x is directly proportional to λ. Since we do not know s exactly we cannot calibrate our spectroscope. But we can compare the different first order colors like Balmer did. Using our tape measurements we find:

$$\frac{Cm-r}{Cm-b} = \frac{256}{188} = 1,36; \frac{Cm-r}{Cm-v} = \frac{256}{170} = 1,51; \frac{Cm-b}{Cm-v} = \frac{188}{170} = 1,11 \tag{8.1}$$

The empirical formula as stated in 1885 by Balmer (while studying the experimental results of Ångström) says: $\lambda_5, n = 3, 4, ...$

Using the right numbers for n gives us:

$$\begin{aligned} \text{n} = 3: \ \tfrac{1}{\lambda_3} &= R\left(\tfrac{1}{2^2} - \tfrac{1}{3^2}\right) = R\tfrac{5}{36} \\ \text{n} = 4: \ \tfrac{1}{\lambda_4} &= R\left(\tfrac{1}{2^2} - \tfrac{1}{4^2}\right) = R\tfrac{3}{16} \\ \text{n} = 5: \ \tfrac{1}{\lambda_5} &= R\left(\tfrac{1}{2^2} - \tfrac{1}{5^2}\right) = R\tfrac{21}{100} \end{aligned} \tag{8.2}$$

Now calculating: $\frac{\lambda_4}{\lambda_3} = 1,35; \frac{\lambda_5}{\lambda_3} = 1,51; \frac{\lambda_5}{\lambda_4} = 1,12.$

The conformity with the results obtained in our simple demonstration is striking, and we identify λ_3 as the red line, λ_4 as the blue line and λ_5 as the violet line.

The measurements are easy; the excellence of Balmer is in the mathematical formulation. He really did a terrific job

8.2.1.1.9 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, Third edition, pag. 900-901 and 963-965.
- Wolfson, R., Essential University Physics, First edition, pag. 616.

8.2.2 7B50 Atomic Models

8.2.2.1 01 deBroglie Applied to Bohr

8.2.2.1.1 Aim

To introduce how matter waves can be associated to Bohr's model of an atom; a classical analogy.

8.2.2.1.2 Subjects

- 3B22 (Standing Waves) 7A50 (Wave Mechanics) 7B50 (Atomic Models)

8.2.2.1.3 Diagram

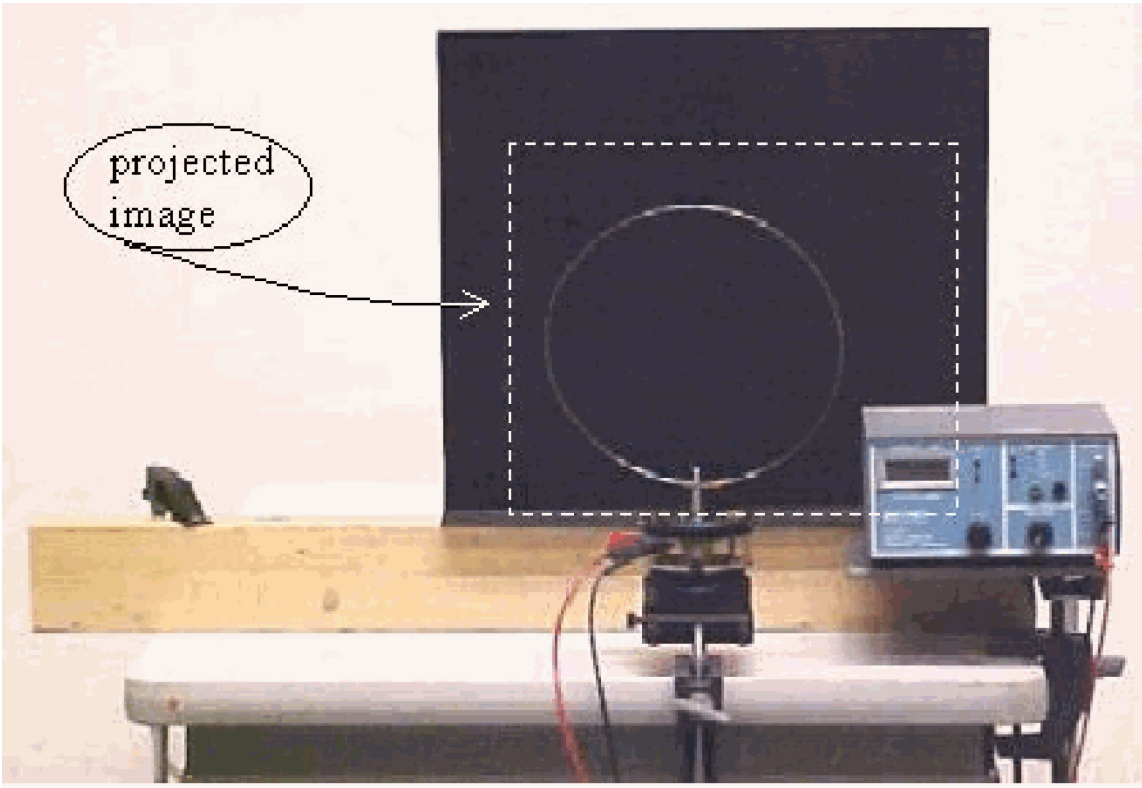


Figure 8.12: .

8.2.2.1.4 Equipment

- Wire loop of spring steel (round, 1mm), bend into a circular loop with a diameter of around 25 cm, and fixed to a banana plug (Pasco SF-9405).
- Mechanical wave driver (Pasco SF-9324), actually an adapted loudspeaker.
- Signal generator.
- Black screen.
- Camera and beamer to show the demonstration to a large audience.

8.2.2.1.5 Safety

- The loop is fixed to the wave driver. When the loop is agitated heavily it is possible that it loosens itself. Then a free end sweeps around dangerously. So fix the loop tightly.

8.2.2.1.6 Presentation

The wire loop is fitted to the mechanical wave driver shaft. The wave driver is connected to the signal generator. The image of wire loop and display of the frequency of the driving generator is projected (see Diagram).

Start at low frequency (around 5 Hz) and low amplitude, making the loop starting to vibrate. Increase the frequency to see various modes of standing waves in the circular loop. (At higher frequencies the amplitude of the signal generator has to increase to obtain visible amplitude in the oscillating wire loop.) We observe:

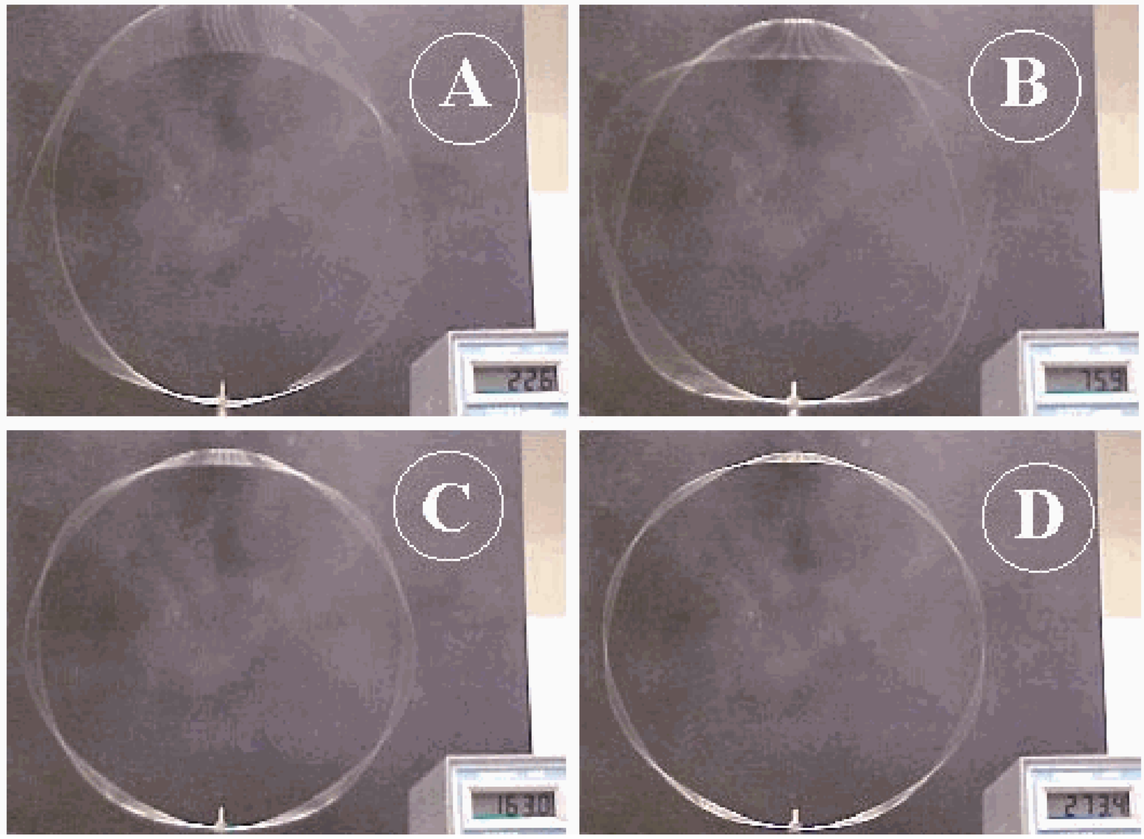


Figure 8.13: .

- 2 nodes and anti-nodes at 14 Hz;
- 3 nodes and anti-nodes at 23 Hz (very large amplitude) (see Figure 2A);
- 4 nodes and anti-nodes at 30 Hz;
- 5 nodes and anti-nodes at 76 Hz (see Figure 2B);
- 7 nodes and anti-nodes at 163 Hz (see Figure 2C);
- 9 nodes and anti-nodes at 273 Hz (see Figure 2D);

−11 nodes and anti-nodes at 398 Hz (this last one is not so good visible to a larger audience due to its low amplitude).

8.2.2.1.7 Explanation

According to Bohr electrons move in circles.

DeBroglie argued that the "electron wave" was a circular standing wave that closes in itself (in order to obtain constructive interference). So, for persisting waves: $2\pi r_n = n\lambda, n = 1, 2, 3, \ldots$.. This is what we observe in our demonstration.

DeBroglie: $\lambda = h/mv$ and we get: $mvr_n = nh/2\pi$. In this way the ad hoc quantized orbits of Bohr are derived form deBroglie. This "shown" wave-particle duality is at the root of atomic structure.

(In discussing the analogy it should be remembered that the "electron wave" is not in reality a standing wave along a line, but it extends through all space.)

8.2.2.1.8 Remarks

- For the lower frequencies, 14 −, 23 − and 30 Hz, the successive patterns (2,3 and 4 half wavelengths) are “logic” when we suppose that $1/2\lambda$ is obtained at around 6 −, 7 Hz. For higher number of nodes/anti-nodes this logic order is apparently a different one.

8.2.2.1.9 Sources

- Giancoli, D.G., Physics for scientists and engineers with modern physics, pag. 971-972
- Mansfield, M and O’Sullivan, C., Understanding physics, pag. 573-574
- Meiners,H., Physics demonstration experiments, part 2, pag. 1185-1188

8.3 7F Relativity

8.3.1 7F10 Relativity

8.3.1.1 01 E = mc^2 (Einstein)

8.3.1.1.1 Aim

To show a copy of a detail of Einsteins' original manuscript.

8.3.1.1.2 Subjects

- 7F10 (Relativity)

8.3.1.1.3 Diagram

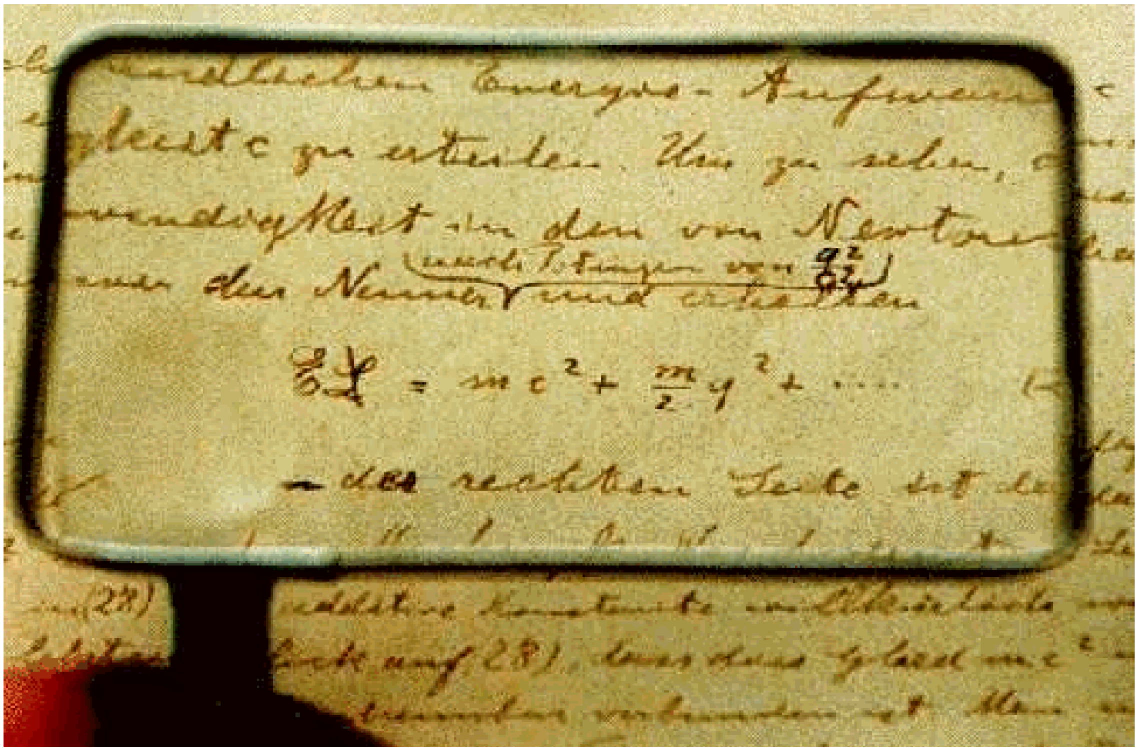


Figure 8.14: .

8.3.1.1.4 Equipment

- Picture of original manuscript (see Diagram).
- Beamer to project image. E=mc2

8.3.1.1.5 Presentation

The theory has already been treated, and somewhere on the blackboard there is

$$E = \gamma(v) mc^2, and$$
$$\gamma(v) = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} \approx 1 + \frac{1}{2}\frac{v^2}{c^2} + \frac{3}{8}\frac{v^4}{c^4} + ... \tag{8.3}$$

Coffeebreak follows and during that break we project the image of the manuscript. When students enter again they see the manuscript.

At restart of the lecture the correspondence between the manuscript and the writing on the blackboard is shown to the students.

8.3.1.1.6 Explanation

Textbooks present the explanation.

Importance of the demonstration is that it can be stressed that $E = mc^2$ as you see it on T-shirts etc. is an interpretation of Einstein's way of presenting kinetic energy: When you write $E = mc^2$,$E = mc^2$ is interpreted as an expansion for the inertial mass:

$$m\gamma(v) \approx m_0 + \frac{1}{2}m_0\frac{v^2}{c^2} + \frac{3}{8}m_0\frac{v^4}{c^4} + ... \tag{8.4}$$

8.3.1.1.7 Sources

- McComb,W.D., Dynamics and Relativity, pag. 247-248 and 301

9. 9 Miscellaneous

9.1 Test

9.2 Show the Physics

References

Crouch, C., Fagen, A. P., Callan, J. P., & Mazur, E. (2004). Classroom demonstrations: Learning tools or entertainment?. *American Journal of Physics*, *72*(6), 835–838.

Pols, F. (2024). *Show the Physics*. TU Delft OPEN Publishing. https://doi.org/10.59490/tb.101

Roth, W.-M., McRobbie, C. J., Lucas, K. B., & Boutonné, S. (1997). Why may students fail to learn from demonstrations? A social practice perspective on learning in physics. *Journal of Research in Science Teaching: The Official Journal of the National Association for Research in Science Teaching*, *34*(5), 509–533.