Development of Personal Desk Lab (PDL)

A Novel Experimental Apparatus with Desk Top Size, Ease of Restructure and Low Cost

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DEVELOPMENT OF "PERSONAL DESK LAB (PDL)": A NOVEL EXPERIMENTAL APPARATUS WITH DESK TOP SIZE, EASE OF RESTRUCTURE AND LOW COST

ABSTRACT

A series of novel experimental apparatus for use in learning physics is presented, with which people in the world can easily access to physical phenomena and to the world of experimental physics. Each apparatus is miniaturized to about a fifth of conventional one, built on a small steel plate of B5 size. Therefore, it is portable and can be placed on a classroom desk. Each set is constructed by a number of parts divided according to their functions, and some of them are interchangeably useable in other experiments. This saves material, cost, and space. The sets are flexible enough so that they can be modified for other purposes by the user according to his (or her) own idea. In the future, the function of the apparatus could be extended remarkably with the aid of the PC.

1. Introduction

Nowadays, the opportunities where youngsters can access to raw physical phenomena are limited. The opportunities where they could handle the equipment to learn physics are even scarcer. Consequently, they lack in chances for advancing their thoughts in physics. Scientific programs on the television capture the interest of children. However, the following step, i.e. hands-on trials of what they learn in the TV programs must be available for them to deepen their interest and develop their curiosity. The effectiveness of "active learning" has been well-documented[1, 2]. Thus, it is most important to introduce the youths to experimental physics and investigating activities. Such experiences extend their human senses and activity spaces as well as their knowledge.

Universities in developing countries, such as Royal University of Phnom Penh (RUPP, Cambodia) have rather limited equipments for physics experiments and hence self-directed programs are inadequate in the curriculum. The students attend almost the lectures only, and they have little opportunity to access the real physical phenomena and to examine their knowledge. Without the hands-on real physical phenomena, students cannot have confidence or realistic images of the knowledge, and they easily forget them. Besides, they do not have a chance to develop the skill of treating the real materials or tools. Thus, they cannot apply in the future what they have learned efficiently.

To improve this situation, the introduction of the useful experiment themes and apparatus is necessary. This is the reason why I conducted this research theme: “The development of desktop equipments” [3].

This thesis is divided into 6 sections. Section 1 is the introduction of the thesis. Section 2 deals about the research objective, while section 3 presents the description of the concept. The implementation of each apparatus, evaluation method, the result and some remarks are expressed in Section 4. The discussion of the performance achievement of each apparatus is shown in Section 5. Finally, the conclusion and the future work are noted in Section 6.

2. Research Objective

The main idea behind the development of desktop equipments or Personal Desk Lab (PDL) is to *help students in poor and developing countries to better understand the real physical phenomena which occur around them everyday*.

Once the students understand well about what is going on and what physicists are researching or developing, they would be able to make a plan for their futures and decide what to be done on their lives. To the best of the author’s knowledge about Cambodian students, most of them do not know what they are interested in. Hence, they just make their life plans according to their parent’s decisions or according to the demands of the present market. This may explain why some of them cannot perform their studies well because of no interest, and some of them do not use what they have learned at school in their works. Finally, not only the students who waste their time in the universities but also their parents lose their investments and their country loses her human resources. I submit that PDL can help students to understand more deeply about physical phenomena and this will most likely encourage them to choose science-related careers in the future.

In order to archive this main goal and *make it possible to be in hand for all kind of users, especially students interested in physics*, some basic requirements have to be satisfied. These requirements are:

- The cost of the apparatus is low enough for low-income people.
- The size of the apparatus is small enough to fit on desktop and portable so that each student can use it individually in a classroom.
- The apparatus are Battery-drivable: they are useable without power line.
- The experiment is attractive, interesting and reliable for both students and teachers.

3. Concepts

As mentioned in Section 2, many requirements are listed without answers. In this section, we will propose our concepts to answer the above requirements as follows.

3.1. Miniaturization

"Smallness in size" is required by two reasons: one is space and the other is cost. By miniaturization, the student can do experiment on his desk instead of heavy and long table, and cost, materials and energy consumed on both making and running can be saved. Many miniaturized apparatus can run on battery.

3.2. Modularization

The experimental apparatus is decomposed into some parts according to their functions. The user builds the apparatus on a B5 size (18×26 cm^2) plate with many parts for a specific experiment. Modularization technique is also a very important strategy to reduce the cost of the equipment. This is realized by the reduction in the number of pieces needed for many kinds of experimental apparatus because some parts can be used commonly in many experiments. The apparatus constructed by this technique are small in size, reproducible, and easy to be replaced/reconfigured/repaired. Furthermore, the division of one experimental apparatus into some modules provides a chance for the student to reassemble parts before starting the experiment. This gives good effects for him/her in that experiment. This activity strengthens his/her awareness and help memorization.

Finally, the experimental apparatus is not fixed rigidly but can be modified or improved easily by changing modules for advanced objectives.

3.3. Ease of construction, maintenance and repair

Almost all parts were hand-made. The design is simple and the task and the function of each module are clear. Its maintenance and repair are easy. 100 sets of each apparatus of optical experiments (*e.g.* Diffraction of light, Refraction of light, Polarization of light) were constructed without trouble in two months. They are served for high school now by High school-University liaison division of Chiba University. Mending of the broken parts by students themselves would be very useful exercises, which enhances their understandings of its mechanism and their practical skill of making.

3.4. Utilization of IC and PC technologies

With the help of our custom programs and high resolution ADC/DAC or special function IC (e.g. DDS, CPU), a laptop computer can be converted to an oscilloscope, a signal generator, a high-resolution digital voltmeter or an ammeter. Thus, the conventional experiment apparatus that require a signal generator and an oscilloscope can be converted to automated and more precise one by usage of such devices with a laptop computer.

4. Implementations

4.1. Diffraction of Light

This equipment evaluates the interference effect of light after passing through a narrow single slit.

4.1.1. Objective

The purpose of this equipment is to help students understand the principle of diffraction of light that come from the interference effect of electromagnetic wave and the limitation of straight-line model of geometric optic [4)].

4.1.2. Evaluation method

Measure the diffracted light intensity on the screen to find the single slit pattern and then compare this result with the theoretical one.

4.1.3. Experimental setup

Figure 1 shows Diffraction of Light equipment which is composed of:

- Experiment base: $18 \times 26 \times 0.3$ cm^3 Iron plate
- Power supply: composed of 2 pieces of 1.3 V rechargeable batteries in series.
- Light source: a miniature laser diode (wavelength $\lambda = 650$ nm)
- Single slit: width d = 0.09 mm (measured by microscope)
- Detector: a photodiode (PD) with slit
- Vernier caliper
- Digital multimeter
- Load resistor for PD: a 100 KΩ resistor
- Lead wires

At the beginning of the experiment, a user must place the light source in line with the slit, and the photodiode on the moving stage of the vernier caliper. The moving direction of the caliper should be perpendicular to the incident light's axis. Next, connect both outputs of the photodiode to a shunt resistor (100 KΩ) and inputs of the digital multimeter via lead wires. Finally, connect the light source to power supply via lead wires, then adjust the laser beam with the slit gap and photodiode. The picture of this setup is shown in Figure 1.

By moving the photodiode along the vernier caliper's axis, the diffracted light intensity is measured at the interval of every 0.2 mm using a digital multimeter (select voltmeter function at DC 2V). The photodiode is moved in the span of 13 mm (6.5 mm to both sides from the middle point at which the light is brightest).

From the measurement above, a graph of light intensity versus slit position is obtained as shown in Figure 2, where diffraction pattern of a single slit is plotted with the theoretical one in comparison.

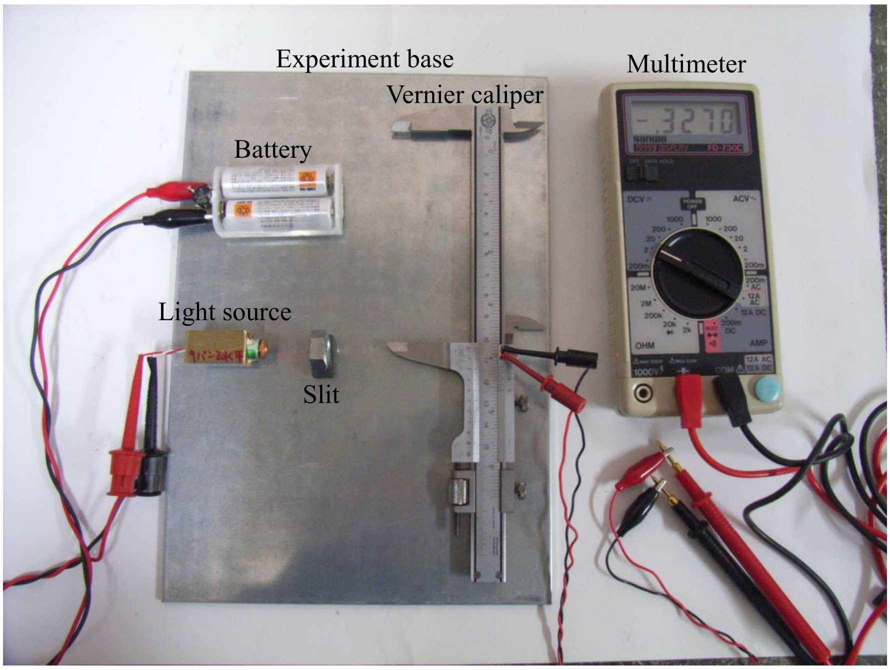


Figure 1. Experimental setup for Diffraction of Light

4.1.4. Physical phenomena

From the theoretical consideration, we know that the diffraction occurs when the electromagnetic wave passing through the aperture/slit disrupted that wave, which has the size on the order of wavelength. Diffraction also occurs according to the principles of quantum mechanics, just as any physical object that has wave-like properties.

In general, we can teach the diffraction effect by means of qualitative observations and/or quantitative descriptions [5)]. However, we just limit ourselves here to what is necessary for the evaluation of our apparatus.

- The *angular spacing, x,* of the diffraction pattern is inversely proportional to the dimensions of the object causing the diffraction. In other words, the smaller the diffracting object, the wider the resulting diffraction pattern, and vice versa.

- The *diffraction angles* θ are invariant under scaling; that is, they depend only on the ratio of the wavelength to the size of the diffracting object d.

The single slit diffraction pattern as shown in Figure 2 is called the *intensity profile*. The formula was originally given by Fraunhofer in Eq.(1) below.

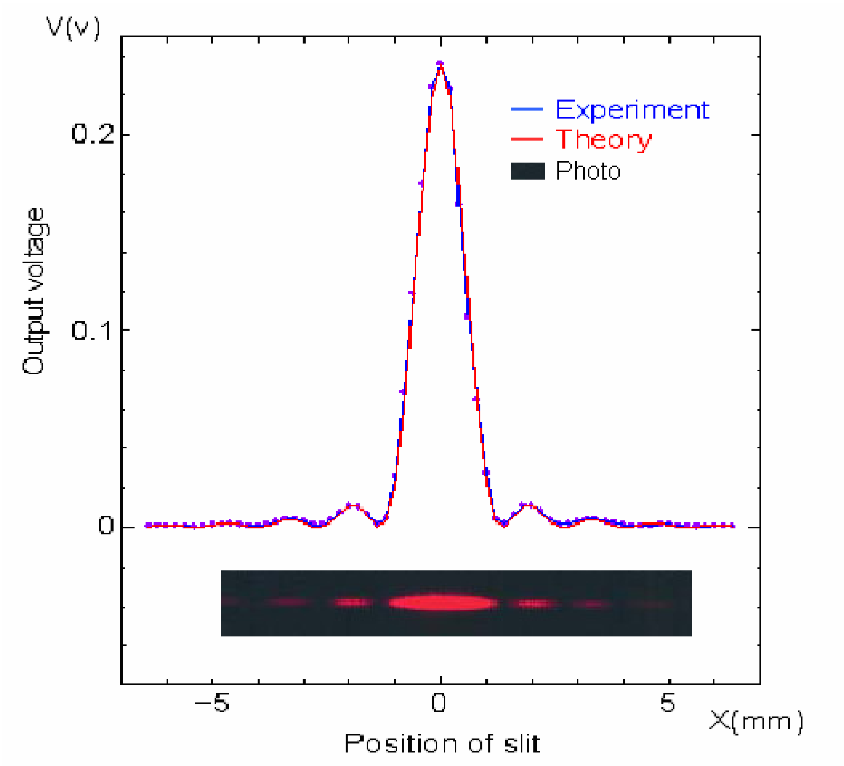


Figure 2. Single slit diffraction pattern: Intensity (proportional to voltage) vs. slit position.

Under the Fraunhofer conditions, the wave arrives at the single slit as a plane wave. It is divided into segments, each of which can be regarded as a point source. The amplitudes of the segments will have a constant phase displacement from each other, and will form segments of a circular arc when added as vectors [4, 6, 7]. The resulting relative intensity will depend upon the total phase displacement B according to the relationship below:

$$I(\theta) = I_0 \left(\frac{\sin(B/2)}{(B/2)} \right)^2 \tag{1}$$

where, I_0 is the maximum intensity of diffraction pattern. B is defined as,

$$B = \frac{2\pi d \sin\theta}{\lambda} \tag{2}$$

When the diffraction angle θ is small, the intensity profile as a function of position x in the image plane for small angle is:

$$I(x) = I_0 \left(\frac{\sin\left[\frac{\pi d x}{\lambda L}\right]}{\left[\frac{\pi d x}{\lambda L}\right]} \right)^2 \tag{3}$$

Figure 3 shows the diagram of a single slit diffraction pattern and the necessary variables used in the calculation of intensity profile. In this figure, m indicates the order of the minimum intensity in the diffraction pattern where $m \in (1,2,3,...)$.

By comparing the theoretical intensity profile formula, the result from our experimental apparatus can be checked, and the quality of our apparatus can be judged.

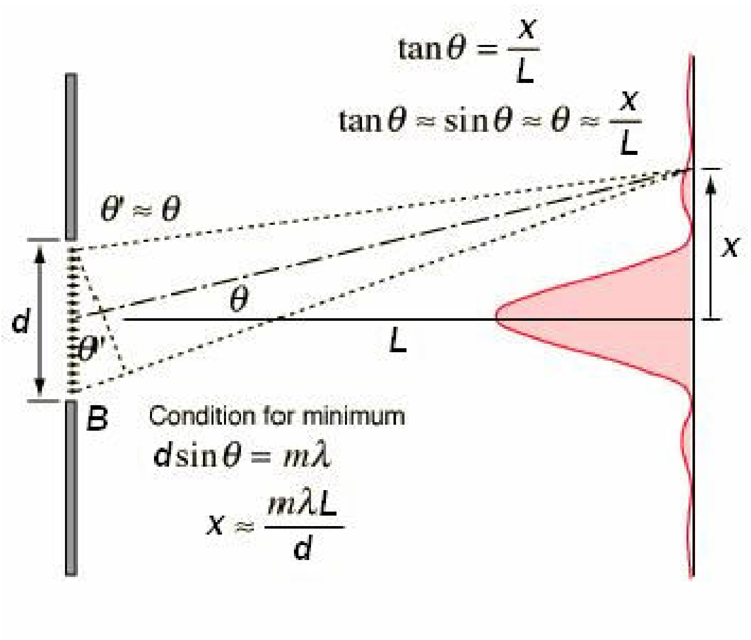


Figure 3. Single slit diffraction pattern diagram

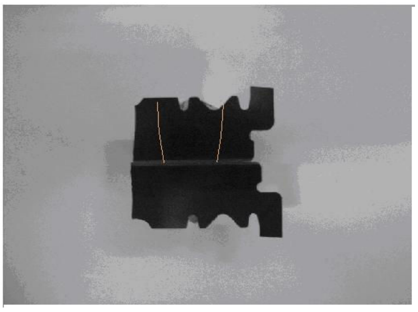
4.1.5. Making Process

In this apparatus set, there are two custom modules. They are slit module and photodetector module.

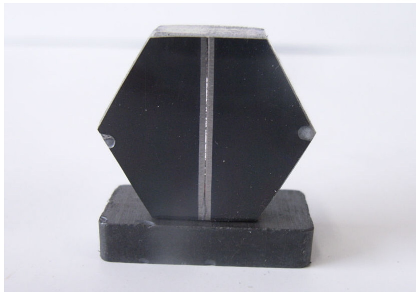
- **Slit module**: composed of nut and razor blade. At first, we make one side of nut flat by polishing. Then, the razor blade is fixed covering about a half face with adhesive. After solidification of the adhesive, we cover the other half face with the second razor blade inserting a wire (0.2 mm in diameter) between two blades at both end points of the slit to make two knife edges parallel. The measured width of the produced slit ranges between 0.09 mm to 0.1 mm. Finally, we cut out and grind the unnecessary parts of the blades. The making process of the slit is shown in Figure 4.
- **Photodetector module** (photodiode with slit): In order to measure the intensity of light at a given position, another slit working as a window is necessary in front of the photodiode. The complete form is shown in Figure 5; where, two apple bronze plates are fixed on surface of the photodiode by adhesive.

a. smooth the nut

b. fix razor blade on nut



c. fix other side of razor on nut



d. slit after polish

Figure 4. Process of making slit module

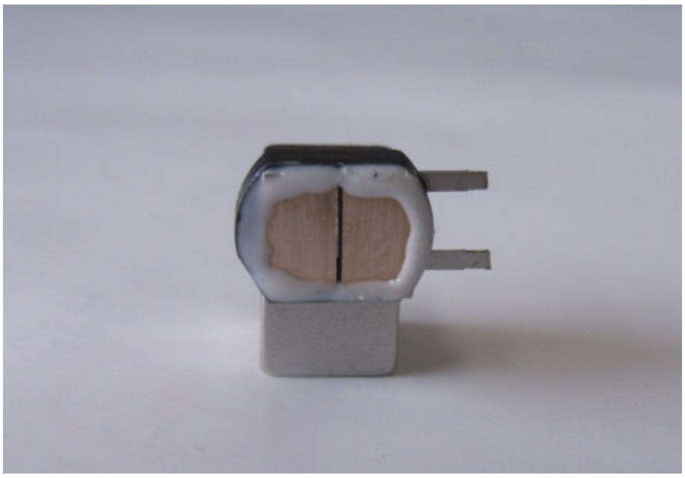


Figure 5. Photodetector module

4.2. Refraction of Light

This equipment shows the refraction of light phenomena by which a ray of light changes direction (bending effect of light) when it passes from one transparent material (an optical medium) into another.

4.2.1. Objective

The objective of this equipment is to help students to understand deeply about the refraction law by observing the paths of the incident and the refracted rays, and determining the refractive index of the two materials by using Snell's Law [8)].

4.2.2. Evaluation method

Calculate the refractive index of material under test and then compare this result with the reference value.

4.2.3. Experimental setup

The apparatus for Refraction of Light consists of:

- Experiment base: $18\times26\times0.3$ cm^3 Iron plate
- Power supply: composed of 2 pieces of 1.3 V rechargeable batteries in series.
- Light source: miniature laser diode (wavelength λ= 650 nm)
- Semi-circular water prism
- Protractor
- Screen: two 4×4 cm^2 hard white papers (one for refracted light and another for reflected light)
- Lead wire

To start this experiment, one must setup the apparatus as shown in Figure 6. The procedure to setup the apparatus is as follows:

1) Fix the semi-circular prism on the protractor, as both center points overlap on each other, with a piece of double side adhesive tape.
2) Fill the semi-circular prism with water about 2/3 of the depth.
3) Place the flat face (front side) of semi-circle prism perpendicularly to the incident light beam which is directed at the center line of the plane. Adjustment this setting so that the outlet beam from the circular surface falls at the same point as that without the prism.

Now, we can measure the refraction angle θ_2 and the corresponding incident angle θ_1, and then calculate the refractive index by using Snell's law. This process is repeated for the incident angle from 10° to 80° in every 10°. The refraction angle can be read by means of paper screen, on which the refracted light beam spots, and protractor. The incident angle can be double-checked by measuring the reflection angle.

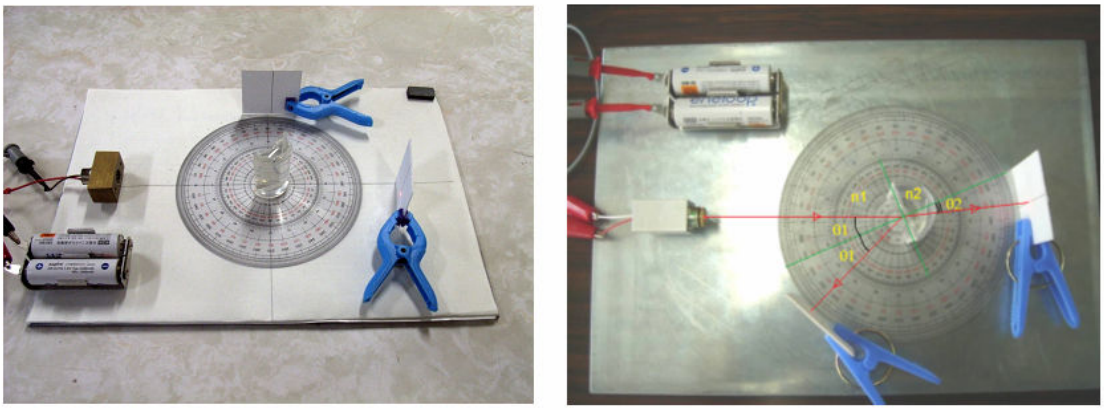


Figure 6. Experimental setup for Refraction of light

The measured incident and refraction angles, and the corresponding refractive indexes are shown in Table 1. The equation to calculate the indexes is described below.

Table 1: Refractive index of water

θ_1 (°)	θ_2 (°)	$n_2 = n_{water}$
10°	7.50°	1.3304
20°	15.10°	1.3129
30°	22.00°	1.3347
40°	28.50°	1.3471
50°	35.00°	1.3356
60°	40.50°	1.3335
70°	44.80°	1.3336
80°	47.75°	1.3304
		$\langle n_2 \rangle = 1.3323$

4.2.4. Physical phenomena

In order to understand the phenomenon of refraction, there are two key words to be clarified: "Refraction" and "Refractive index".

- **Refraction**: is the bending effect (changing direction of ray) of light beam when it passes from one transparent medium into another. Refraction is caused by the different light speeds in different optical media. The greater the optical density of the medium, the slower the speed of light in that medium.
- **Refractive index of the medium**: is a measure for how much the light speed (or other waves such as sound wave) is reduced in the medium. It is equal to the ratio of the light speed in vacuum to that in the medium. From Snell's law, it is equal to the ratio of the sine of the incident angle to the sine of the refraction angle [8, 9].

Snell's law is given as:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (4)$$

For vacuum, the refractive index $n_1 = 1.000293 \cong 1$

$$\Rightarrow \quad n_2 = \frac{n_1 \sin\theta_1}{\sin\theta_2} = \frac{\sin\theta_1}{\sin\theta_2} \qquad (5)$$

Using this formula, the refractive indices (indexes) of water are calculated for each incident angle θ_1: these values shown in Table 1 are almost same. We take the average value of them as the final refractive index of water given by experiment. Comparing this value, $\langle n_2 \rangle = 1.3323$, to the reference value of refractive index of water, $n_{water} = 1.33$, we can say that our experimental apparatus can provide a satisfactory result.

For more precise treatment, the effect of temperature and the dependence of the wavelength must be considered. Figure 7 shows the refractive index of water versus wavelength at different temperature. The refractive index of water $n_{water} = 1.3321$ at 20°C for wavelength $\lambda = 650$ nm [10]. The experiments on different temperature and/or using different color show us the optical property in detail. Thus, the equipment described here is satisfactory for an educational training material.

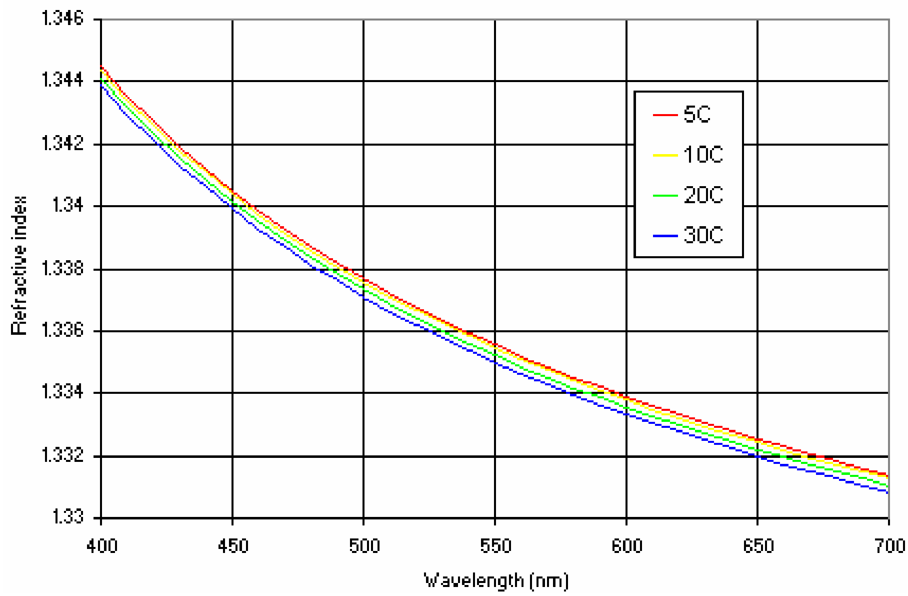
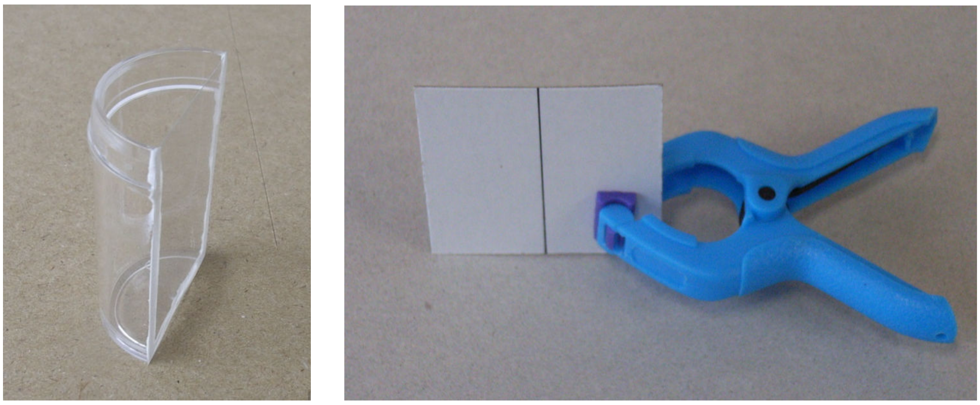


Figure 7. Variation of refractive index of water with temperature

4.2.5. Making Process

The equipment for this experiment contains two custom modules: they are Semi-circular prism and Optical screen.

- Semi-circle prism module is made of a transparent plastic beaker, a piece of over-head projector film (OHP) and adhesive. At first, we cut the beaker along its center axis from top to bottom by using a precision diamond cutter, and polish the cut face to be flat. Then the cut plane is covered with a piece of OHP film, and fixed using silicone rubber adhesive. The complete module of the semi-circle prism is shown in Figure 8(a).
- Screen module is shown in Figure 8(b). Screen is a simple white hard paper with a fine line at the middle. The screen is held by a pinch in such a way that the line is vertical. This line serves as the origin for the light position on the protractor.



a. Prism module b. Screen module

Figure 8. Custom module in Refraction of Light apparatus

Remark: This apparatus can also be used to find the critical angle by transmitting the optical beam from the semi-circular side to the flat plane. This semi-circular prism is usable with other transparent material beside water. For instance, sugar water, salt water and oil. In short, any transparent materials which cause no destruction to the plastic beaker can be used in this experiment.

4.3. Polarization of Light

This equipment is used to examine the polarization of light.

4.3.1. Objective

The objective of this equipment is to help students understand well about the characteristic of light (transverse wave) and how does it change after passing through a polarizer.

4.3.2. Evaluation method

Measure the light intensity after passing through an analyzer by a photodiode, then compare the experimental result with that given by theoretical consideration.

4.3.3. Experimental setup

Figure 9 shows Polarization of Light equipment which is consisted of:

- Experiment base: $18 \times 26 \times 0.3\ cm^3$ Iron plate
- Power supply: composed of 2 pieces of 1.3 V rechargeable batteries in series.
- Light source: a miniature laser diode (wavelength λ= 650 nm)
- Polarizer: a polarizing filter (attached to the bottom of plastic beaker)
- Analyzer: a polarizing filter (attached to the top cover of plastic beaker)
- Detector: a photodiode (PD)
- Load resistor for PD: a 100 Ω resistor
- Digital multimeter
- Lead wire

Before starting this experiment, the following setups have to be done. Place the light source in line with the polarizer and the analyzer (second polarizer) which are attached to the bottom and the top cover of plastic beaker, respectively. Locate the photodiode in line with the light source and polarizer. After that, connect the output of photodiode to the digital multimeter in parallel with the load resistance, and the light source to the power supply via lead wires as shown in Figure 9.

After the above setting, the measurement of transmitted light intensity is performed by reading the voltage displayed on the digital multimeter. This measurement is repeated by rotating the cover of the plastic beaker (analyzer) every 2.5 notches from 1 to 38 (the cover of plastic beaker has 95 notches which is corresponding to 360°, therefore, the rotation angle by 2.5 notches is equal to 360°/38).

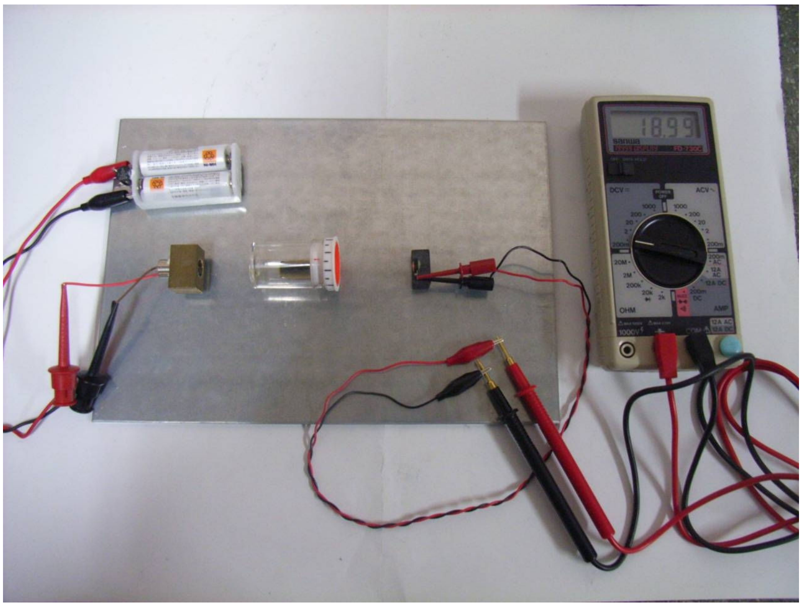


Figure 9. Experimental setup for Polarization of light

From the experiment above, a graph of the received light intensity versus rotation angle ϕ is plotted as shown in Figure 10.

4.3.4. Physical phenomena

Before mentioning about the formula of the received light intensity used in Figure10, four words must be clarified:

- **Polarization**: is a characteristic of all transverse waves. The light is the electromagnetic wave that is a transverse wave.
- **Unpolarized light or natural light**: is a random mixture of all possible polarization states, so on the average it has equal components in any two perpendicular directions.
- **Linearly polarized light**: is a light with a single polarization state, at which the electric or magnetic field oscillates and transmits in a constant plane. This linearly polarized light can be obtained from the unpolarized light by passing through a polarizer.
- **Polarizing filter or polarizer**: is a filter that permits only waves with a certain polarization direction to pass. One type of polarizer for visible

light is made up from long-chain molecules. These long-chain molecules are placed within the filter with their axis oriented perpendicular to the polarizing axis. These molecules preferentially absorb light that is polarized along their length.

Recall that the intensity of an electromagnetic wave is proportional to the square of the amplitude of the wave. As the ratio of transmitted to incident amplitude is $\cos(\phi)$, so the ratio of transmitted to incident intensity is $\cos^2(\phi)$, where ϕ is the angle between the first and second polarizer axes. Note that the incident wave to the analyzer is the wave that passed through the first polarizer, hence it is a linearly polarized wave. The transmitted wave is the wave passed through the analyzer (second polarizer).

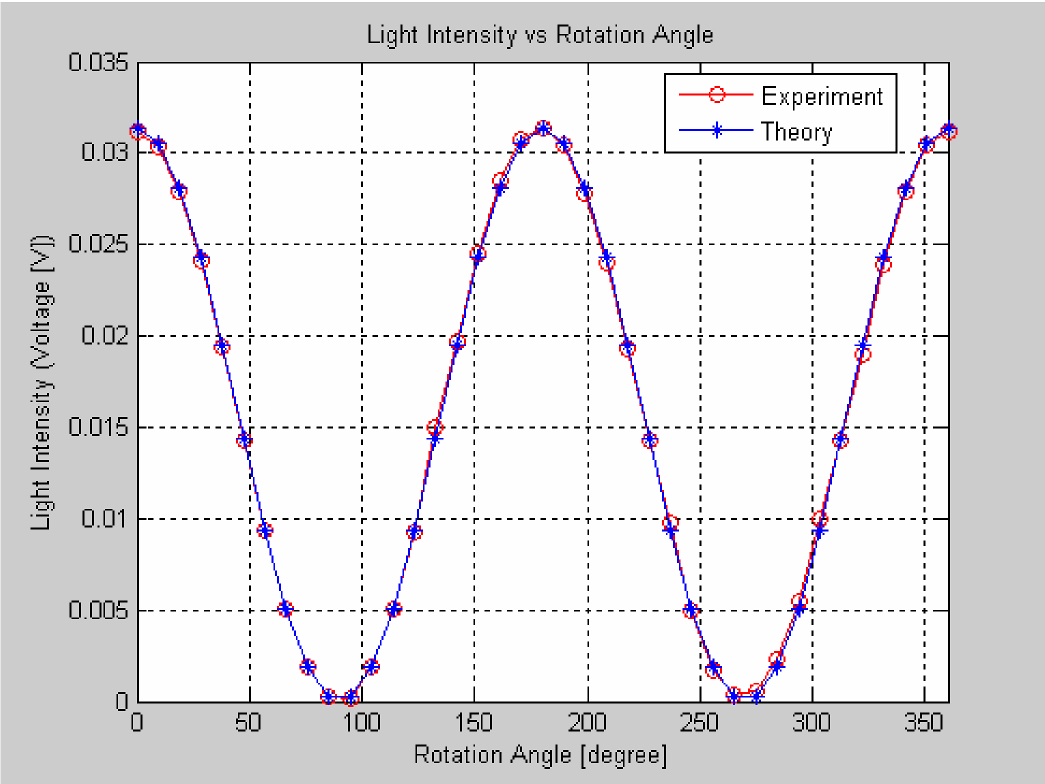


Figure 10. Light intensity vs. rotation angle

Finally, the intensity of the light transmitted through the analyzer is given by Malus's law [4] as shown below:

$$I = I_{Max} \cos^2 \phi \tag{6}$$

Using this formula, the theoretical results shown in Figure 10 are calculated.

Recall that the voltages V measured in this experiment are proportional to the currents I from the photodiode, $V = I \cdot R$, where R is the load resistance. As $I_{\max}$ is the maximum value from PD, it is also proportional to the maximum value read on the voltmeter. From these reasons, the graph in Figure 10 is plot in volt.

4.3.5. Making Process

The equipment for this experiment contains only one custom module; that is a plastic beaker with two polarizers attached at the bottom and the top, respectively.

The making process of this module is as follows:

1) Make a hole at the center point on each side of the beaker (top and bottom). The diameter of the hole is about 10 mm, which is much larger than that of light beam.
2) Cover the holes on each sides with the polarizer filters, and fix with adhesive.
3) Find the reference point at which the two polarizer axes is parallel to each other by rotating the top cover of the plastic beaker; and mark it on both cover and beaker sides. To find the reference point precisely, monitoring of the transmitted light intensity is useful. Turn on the light source and connect the output of PD to the voltmeter and then turn the analyzer little by little to find the point where the voltmeter displays the maximum value.
4) Grate scales on the cover in every 5 notches from the reference point to the same point after one revolution. The final figure is shown in Figure 11.

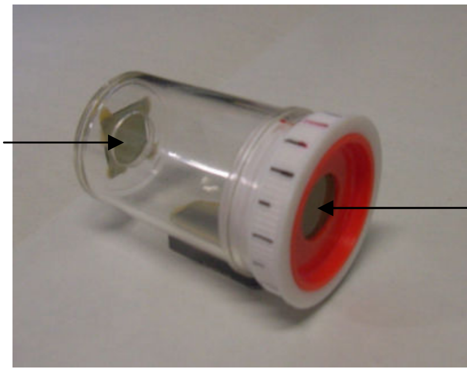


Figure 11. Set of polarizer and analyzer

4.4. Balance and Measurement of Force

This equipment is used to evaluate the moment of force and Archimedes's principle.

4.4.1. Objective

The objective of this equipment is to help students to understand about the principle of the turning effect of the force around a pivot (the moment of a force), and also to understand how this principle applies for body equilibrium.

Moreover, this equipment also helps them to understand about the buoyancy of a submerged object in liquid, and to use this principle to calculate the volume and the density of the object.

4.4.2. Evaluation method

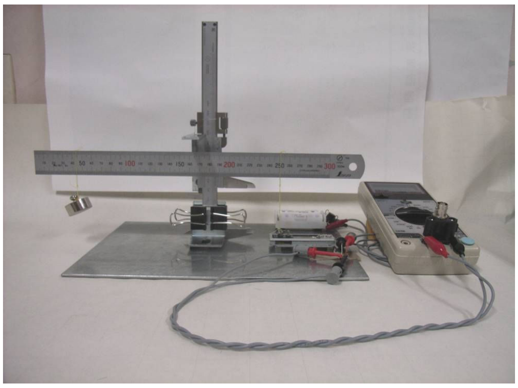
- Calibrate the force sensor by using the turning effect of the force around a pivot. Then, measure the force exerted on force sensor by reading the voltage shown in digital multimeter. Convert the voltage values to the corresponding forces. Compare the values with those given by the theory of rigid-body equilibrium.
- Determine the density of an object under test by using the Archimedes's principle. Compare this result with the reference value or that given from the measurements of volume and mass.

4.4.3. Experimental setup

The apparatus for Balance and Measurement of Force consists of:

- Experiment base: $18 \times 26 \times 0.3$ cm^3 Iron plate
- Power supply: composed of 2 pieces of 1.3 V rechargeable batteries in series.
- Force sensor: Load cell at a maximum weight of 300g, in which the strain gage bridge is used (Tanita Ltd.)
- Ruler: 30 cm Stainless ruler
- Weight: 50 g (Shimdzu Co., Material: brass)
- Digital multimeter
- Beaker
- Lead wire

The setting-up of the experimental apparatus is shown in Figure 12. The experimental setups for body equilibrium and for Archimedes's principle are almost the same. The only difference between them is that the plastic beaker is filled with water when the Archimedes's principle is examined. Therefore, in the following discussion, we consider these two configurations as one. Connect the power source to the force sensor and connect the output of this force sensor to the voltmeter via lead wires.



a. Body Equilibrium b. Archimedes principle

Figure 12. Setup of experiment apparatus

Now, start the first experiment which deals with the turning effect of force around a pivot. The force sensor is hanging on the ruler via a string at the position $d_2 = 50$ mm from the pivot whereas the other weight is hanging on the ruler via string at a different position. Note that, the maximum weight supporting by the force sensor is only 300 g. As this sensor is hanging at 50 mm from the pivot, the maximum distance for a 50 g weight is $d_{1\text{-Max}} = 300$ mm. The formula for this calculation is in the physical phenomena section. So, we can choose any position within this distance.

For the calibration of the force sensor, repeated measurements are conducted at different exerting forces with 50 g and 100 g weights. After the calibration, the characteristic of the sensor, the output voltage versus the exerted force, is calculated and plotted in Figure 13. The conversion formula is given as follow:

$$V = 0.8971 \times F + 2.7951 \tag{7}$$

Where V is the output voltage measured in (mV) which is corresponding to the exerted force F measured in (N).

However, the expression we use is the formula which gives the exerted force from the output voltage, that is:

$$F = 1.1144 \times V - 3.1145 \tag{8}$$

New experimental data given at the different hanging positions are shown in Table 2, and are plotted in Figure 14 as exerting force versus output voltage.

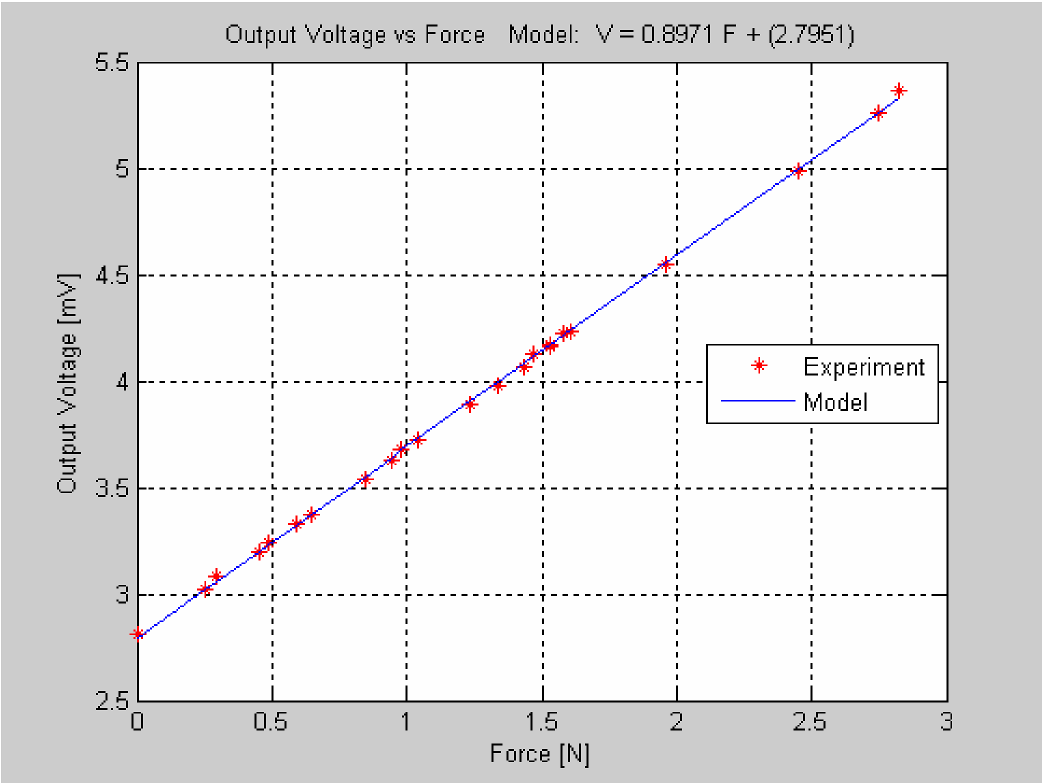


Figure 13. Characteristic of Force sensor

The force $F_{2\text{-Exp}}$ in Table 2 is calculated from the output voltage V_2 by using the Eq.8, whereas $F_{2\text{-The}}$ is calculated by using the balancing condition of moment (calibration).

Similarly to the first experiment, Archimedes's principle is examined with the above apparatus by adding a beaker filled with water. In order to do that, two measurements are needed for the same position of weight with the weight immersed in water and without water. Table 3 shows the experimental data with/without water and other necessary intermediate variables in the calculations of the volume and density of the weight under test.

Table 2: Output voltages of the force sensor and its corresponding forces

d_1 (mm)	m_1 (g)	F_1 (N)	d_2 (mm)	V_2 (mV)	M_1 (Nm)	$F_{2\text{-The}}$ (N)	$F_{2\text{-Exp}}$ (N)
26	50	0.4905	50	3.02	0.01275	0.255	0.251
46				3.20	0.02256	0.451	0.452
66				3.37	0.03237	0.647	0.641
86				3.54	0.04218	0.844	0.830
96				3.63	0.04709	0.942	0.931
106				3.72	0.05199	1.040	1.031
126				3.89	0.06180	1.236	1.220
136				3.98	0.06671	1.334	1.321
146				4.07	0.07161	1.432	1.421
156				4.16	0.07652	1.530	1.521
164				4.23	0.08044	1.609	1.599

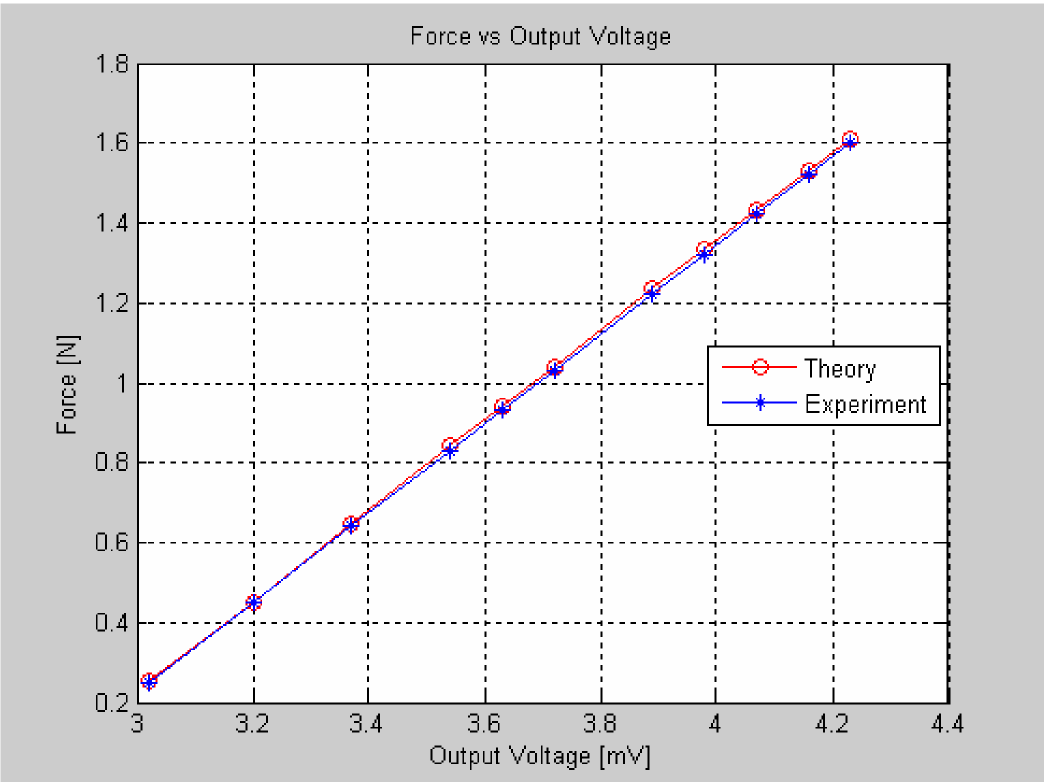


Figure 14. Force versus Output voltage

Table 3: Necessary data for the calculation of volume V and density ρ

d_1 (mm)	V (mV)	V' (mV)	F_2 (N)	F'_2 (N)	F_2-F'_2 (N)	F_1-F'_1 (N)	V (cm^3)	ρ (g/cm^3)
106	3.72	3.61	1.031	0.908	0.123	0.0578	5.895	8.48
126	3.89	3.76	1.220	1.076	0.145	0.0575	5.860	8.53
156	4.16	3.99	1.521	1.332	0.189	0.0607	6.190	8.08
							Average	8.36

4.4.4. Physical phenomena

As mentioned above, with this apparatus, two kinds of experiments can be tested against the theory. We will talk about three concepts: the principles of moment of force, of rigid body equilibrium, and of Archimedes.

- **Moment of a force**: is defined as the turning effects of the force about a pivot, and is calculated by the product of the force F(N) and the perpendicular distance d(m) from the line of action of the force to the pivot [8] as shown below.

$$M = F \times d \tag{9}$$

where M(Nm) is the moment of force or torque.

- **Rigid body equilibrium**: In general, there are two key principles of rigid body equilibrium. (1) The vector sum of the forces on the body must be zero. (2) The sum of torques about any point must be zero [4]. In the present case, the ruler can move only in vertical plane, therefore, we can ignore the first condition. Hence, the condition for equilibrium is given as:

$$\begin{aligned} &\sum M = 0 \\ &\Leftrightarrow M_1 = M_2 \\ &\Leftrightarrow F_1 \times d_1 = F_2 \times d_2 \end{aligned} \tag{10}$$

Using this formula, the force exerting on the force sensor by the weight, noted as $F_{2\text{-The}}$ in Table 2, is calculated.

- **Archimedes's principle**: when an object immersed completely or partially in a fluid, the upthrust is equal to the weight of the fluid displaced. In other word, the buoyant force on a submerged object is equal to the weight of the liquid displaced by the object [11, 12]. Let's say the mass of the object in air is m_x and its apparent mass in fluid with density ρ_f is m'_x, Archimedes's principle states that:

$$
\begin{aligned}
&m_x - m'_x = \rho_f \times V_x \\
&\Rightarrow V_x = \frac{m_x - m'_x}{\rho_f} = \frac{F_x - F'_x}{g \times \rho_f} \\
&\Rightarrow \rho_x = \frac{m_x}{V_x} = \frac{m_x \times g \times \rho_f}{F_x - F'_x}
\end{aligned}
\tag{11}
$$

where V_x is the volume displaced by the object under test. Using these formulas, the volumes and the densities of the weight under test are calculated. The results are shown in Table 3.

From the experimental result shown in Figure 14, it is clear that the force sensor works very well by measuring its output voltage. As to the value of density of the weight under test, the average value given from the experiment is *8.34* g/cm^3, which agrees very well with that for the reference value (density of brass: *8.4* g/cm^3). From the result mentioned above, we can conclude that our experiment apparatus is good enough to examine the above physical phenomena.

4.4.5. Making Process

In this apparatus, there is no custom module as in the Equipotential Line apparatus. The force sensor is supplied from a scale making company. Hence, instead of describing how to make it, we would pose the question to why the force sensor is used instead of traditional scale.

Recall that the traditional balance uses different weights at each side of the ruler. One weight is hanging on one arm at a distance d_1, and the other weight is hanging on the other side arm at a distance d_2. Because the weights are different, one must adjust the distance d_1 so that two weights are balanced. This process sounds very easy but it is very difficult to put into practice. It is hard and time consuming to adjust the distance d_1 to get the system balanced. This difficulty in the adjustment is solved by the usage of the force sensor. With this sensor, the measurement can be taken at any hanging position within the limit range.

4.5. Borda's Pendulum and Spring-Mass Oscillation

This equipment is used to demonstrate the periodic motion or oscillation, which is the kind of motion that repeats about the equilibrium position.

4.5.1. Objective

The objective of this equipment is to help students:

- Understand about the gravitational force exerted on an object of a certain mass, that is commonly, called weight.
- Understand more about the periodic motion or oscillation of a body and its special case called the simple harmonic motion. The latter is the oscillation that occurs when the restoring force is directly proportional to the displacement from the equilibrium position. The user will discover that the period of oscillation is mass-independent for Borda's pendulum.

4.5.2. Evaluation Method

Measure the period of Borda's pendulum and that of a spring-mass system. In both cases, calculate the gravitational acceleration and compare the results with the standard value.

4.5.3. Experimental setup

The apparatus consists of:

- Experiment base: $18 \times 26 \times 0.3$ cm^3 Iron plate
- Bob: Brass sphere with radius of 4.75 mm
- String: Nylon thread with the diameter of 23 μm and the length of 177 mm (mass less, flexible and un-stretchable wire is desirable)
- Spring
- Weight for spring: weight of 38.35 g
- Ruler
- Hangers
- Aluminum fixation base
- Stopwatch

Before starting the experiments, the setups shown in Figure 15 are needed. With this apparatus, two experiments are conducted separately one after another. The student can choose either Borda's pendulum or the spring-mass as their first experiment. However, in order to simplify the discussion below, Borda's pendulum will be chosen at first.

For Borda's pendulum, a bob is connected to the hanger via a massless and unstretchable string with length d = 177 mm. On the experiment base, which acts as a supporting wall here, we mark a line as reference point for the bob to pass. In this experiment, the bob is moved along the arc of the circle with the displacement length x about ± 15 mm from its equilibrium position, and then is released. When the bob pass through the reference point, let's say from left to right, we start the digital chronometer by clicking on Start/Stop button. Note that this chronometer is reset to 0 before use.

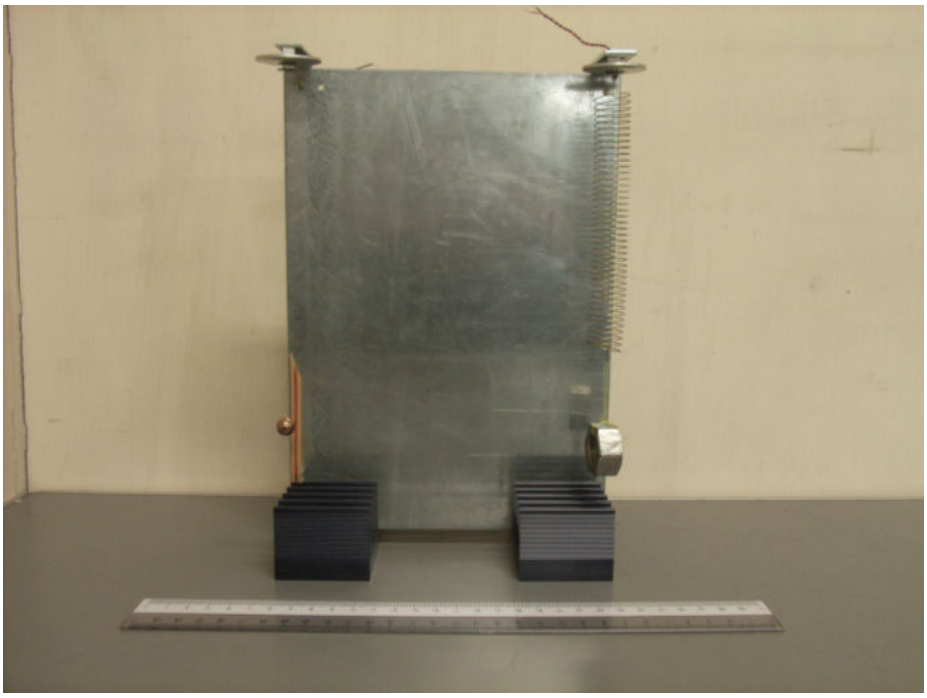


Figure 15. Pendulum and Spring-mass experimental setup

To get more reliable data, the measurement is made every 10 periods of oscillation and is repeated continuously for 19 times. To do that efficiently taking advantage of the feature of the stopwatch, the Reset/Record button is clicked to record the time when the oscillation counts are at 10, 20… and 190. These data are shown in Table 4.

For the spring-mass setup, firstly, suspend the spring on the hanger and measure the position of the lower edge of the spring, x_1. Secondly, connect the weight at the lower end of the spring via a fine string, and measure the position of the lower edge of the spring, x_2, at the balancing condition. Finally, mark this balancing position as a reference point. From now on, the measurement can be started by stretching the weight downward by an amount x and then release the weight smoothly.

Table 4: Time elapse for 100 periods of pendulum oscillation

N	t [s]	N	t [s]	Δt for 100 oscillations
0	0	100	85.45	85.45
10	8.7	110	94.17	85.47
20	17.07	120	102.78	85.71
30	25.81	130	111.34	85.53
40	34.24	140	119.83	85.59
50	42.74	150	128.33	85.59
60	51.36	160	136.73	85.37
70	59.96	170	145.28	85.32
80	68.39	180	153.83	85.44
90	77.07	190	162.36	85.29
			Average	85.476 second

Table 5: Time elapse for 10 periods of spring oscillation

N	t [s]	Δt for 10 oscillations
0	0	
10	6.26	6.26
20	12.75	6.49
30	19	6.25
40	25.33	6.33
50	31.72	6.39
60	38.04	6.32
70	44.37	6.33
80	50.76	6.39
90	57.12	6.36
100	63.51	6.39
	Average	6.351 seconds

Similarly to the Borda's pendulum, when the weight passes through the reference point, let say from bottom to top, we press the Start/Stop button of the chronometer to start the measurement. The times in which the weight passes the reference point every 10 times are recorded.

Unlike pendulum, we do not repeat this experiment continuously up to 190 times, because the oscillation life time of the spring-mass is so short in comparison with the Borda's pendulum that can oscillate more than hours. Table 5 shows the results of this experiment.

4.5.4. Physical Phenomena

As for the experimental setup, we will talk firstly about Borda's pendulum and secondly about the spring-mass oscillation.

For Borda's pendulum, since the point mass is small, we can model this system as a simple pendulum. Moreover, as the displacement distance $x \cong 15$ mm is much smaller then the distance from the pivot to the center of bob, it produces a small angle θ from the equilibrium position. Therefore, we can model this motion as a simple harmonic where the restoring force F_θ must be directly proportional to x or to θ. From Figure 16, the displacement x is defined as:

$$x = L\theta \tag{12}$$

where L is the distance from the pivot to the center mass of the bob and is defined as $L = d + r$ where d is the distance from the pivot to the top of the bob, and r is the radius of the bob. The restoring force F_θ is defined as:[4)]

$$F_\theta = -mg\sin\theta = -mg\theta = -mg\frac{x}{L} = -\frac{mg}{L}x \tag{13}$$

From this equation, we can see that the restoring force is proportional to the coordinate for small displacements and the force constant k is defined as:

$$k = \frac{mg}{L} \tag{14}$$

Recall that the angular frequency ω of a simple pendulum with small amplitude is defined as:

$$\omega = \sqrt{\frac{k}{m}} = \sqrt{\frac{mg/L}{m}} = \sqrt{\frac{g}{L}} \tag{15}$$

Therefore, the gravitational acceleration g is defined as:

$$g = \omega^2 L = \left(\frac{2\pi}{T}\right)^2 L \tag{16}$$

where T is the period of the oscillation. From Table 4, T can be calculated from the average value of 100 oscillation periods and found to be $T = 0.85476$ second. With Eq.16, g = 9.7937 m/s^2 which is very close to the standard value of 9.798 m/s^2. By comparing with this standard value, our result has only 0.04 % of errors which is very small. Thus, our apparatus is precise and can be used to evaluate the physical phenomena as expected.

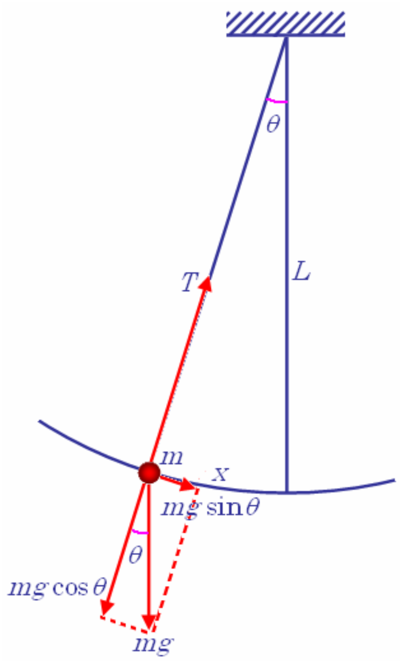


Figure 16. Pendulum system

For spring-mass oscillation, the spring is stretched from the equilibrium position by an amount $\Delta x=|x_2-x_1|$=100.0 ± 0.5 mm; just great enough that the spring's upward vertical force $F=k\Delta x$ on the body balances with its weight $P=mg$.

$$F = k\Delta x = mg \tag{17}$$

where k is spring constant. Now, let's take the position x=0 to be this equilibrium position. When the body is at distance $x \cong 20$ mm below/above its equilibrium position, the extension of the spring is $\Delta x \pm x$, thus the upward/downward force it exerts on the body is then $k(\Delta x \pm x)$, and the net force on the body, F_{net} is:

$$F_{net} = k(\Delta x \pm x) + (-mg) = k(\Delta x \pm x) - k\Delta x = \pm kx \tag{18}$$

From this equation, we can see that this restoring force F_{net} is directly proportional to the displacement x. See also Figure 17.

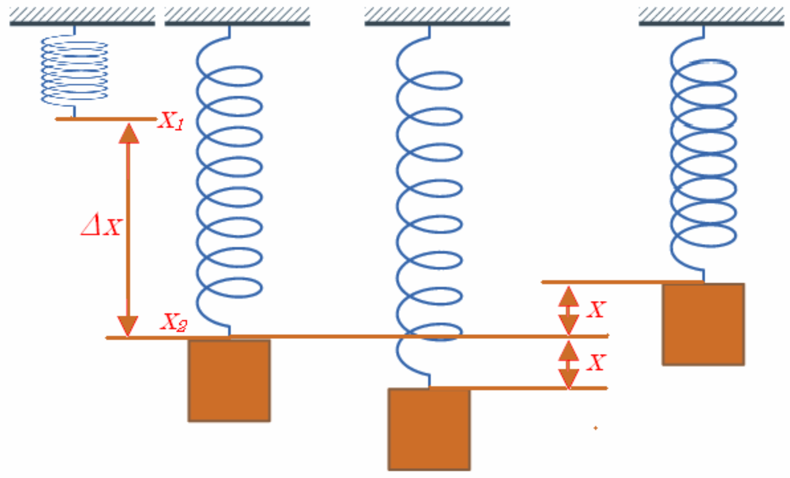


Figure 17. Spring-mass system

Thus, the system obeys Hooke's law, [4)] and the object's motion will be a simple harmonic. Recall that the angular frequency of such system is given as:

$$\omega = \sqrt{\frac{k}{m}}$$
$$T = 2\pi\sqrt{\frac{m}{k}} \tag{19}$$

From Eq.17 and Eq.19, the gravitational acceleration g is defined as:

$$g = \frac{k\Delta x}{m} = \frac{k}{m}\Delta x = \left(\frac{2\pi}{T}\right)^2 \Delta x \tag{20}$$

where T is the period of the oscillation. From Table 5, T can be calculated from the average value of 10 oscillation periods and found to be T=0.635 seconds. With Eq.20, the gravitational acceleration is calculated as g = 9.787 m/s^2 which is close to the standard value of 9.798 m/s^2. This error is only 0.1 %, thus we can conclude that this experimental apparatus is good enough to evaluate the simple harmonic motion system such as pendulum or spring.

4.5.5. Making Process

As this apparatus is very easy to make, we do not need any custom module. However, we will discuss about how to choose the spring, weight and displacement length x for spring-mass oscillation.

As shown in Eq.20, the gravitational acceleration g is in a function of Δx and T. So, the bigger Δx and T, the more accurate value of g is. To get a precise value for T is easy. Just measure the time for many oscillation periods, and then divide this amount by the number of oscillation as described in Experiment setup section. For the accurate determination of Δx, we need to have a heavy body. However:

- Make sure that the displacement distance of $\Delta x + x$ will not change the propriety of the spring.
- Make sure that $\Delta x - x > 0$ so that when the spring is compressed, the spring itself will not saturate.

In short, the body in the vicinity of the equilibrium position moves as a simple harmonic motion system.

4.6. Equipotential Line

This equipment serves to visualize the electric field as well as the equipotential surface/line between two electrodes.

4.6.1. Objective

The objective of this equipment is to help students to understand how the force between two electric charges works over a distance across vacuum.

4.6.2. Evaluation Method

Draw the equipotential lines (and field pattern) for a given set of two point electrodes, and then compare the result with that by theoretical considerations including the computer simulation.

4.6.3. Experimental setup

The equipment for the measurement of equipotential lines consists of:

- Experiment base: 18×26×0.3 cm^3 Iron plate
- Power supply: composed of 2 pieces of 1.3 V rechargeable batteries in series.
- Electrodes: two 6×6×4 mm^3 neodymium magnets with lead wires
- Conductive sheet: carbon rubber foil
- Isolator: Plastic sheet
- Tracing paper
- White pen
- Non conductive ferrite magnets
- Digital multimeter with resolution up to 0.1 mV
- Lead wires

The preparations before this experiment are as follows:

- Place the isolator on the experiment base and the conductive sheet on that isolator, and then fix them by using the non conductive ferrite magnets.
- Attach two electrodes on the conductive sheet firmly and then connect these electrodes to the power supply by mean of lead wires. Figure 18 shows the apparatus after this preparation.

There are many methods to provide acceptable results for this experiment. However, we want to share some experience of the measurement. The process described below is a guidance to get a good result without much trouble.

- Determination of a reference point: Connect the black test pin (COM or GND) of voltmeter to the reference 0V of the battery (GND).
- Determination of the number of equipotential lines: Since the voltage between the two electrodes is about 3V, and the difference voltage between neighboring equipotential lines is 0.2V; the equipotential lines between the electrodes is calculated to be *(15-1) = 14*. This number of line is enough to form a clear image of potential pattern.

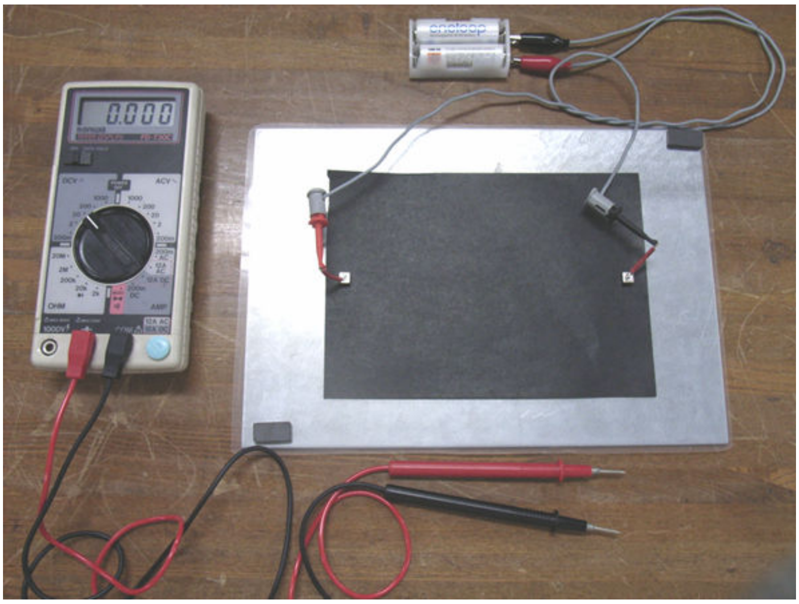


Figure 18. Experimental setup for Equipotential Line

- Determination of the reference voltage points: Fix the black test pin on the reference electrode, and move the red test pin (+) of the voltmeter on the conductive sheet softly between two electrodes to find the voltage points at which the voltages are equal to $0.2*n$ where $n \in$ (1, 2… 14). Mark these points with white pen.
- Finding the equipotential line: Fix the black test point on the reference voltage point, and move the red test point over the conductive sheet softly to search for the points at which the voltmeter indicates the voltage 0V. Mark the point with white pen. Repeat this process to find many points, and connect these points to draw an equipotential line. Repeat these processes for each values of voltage.

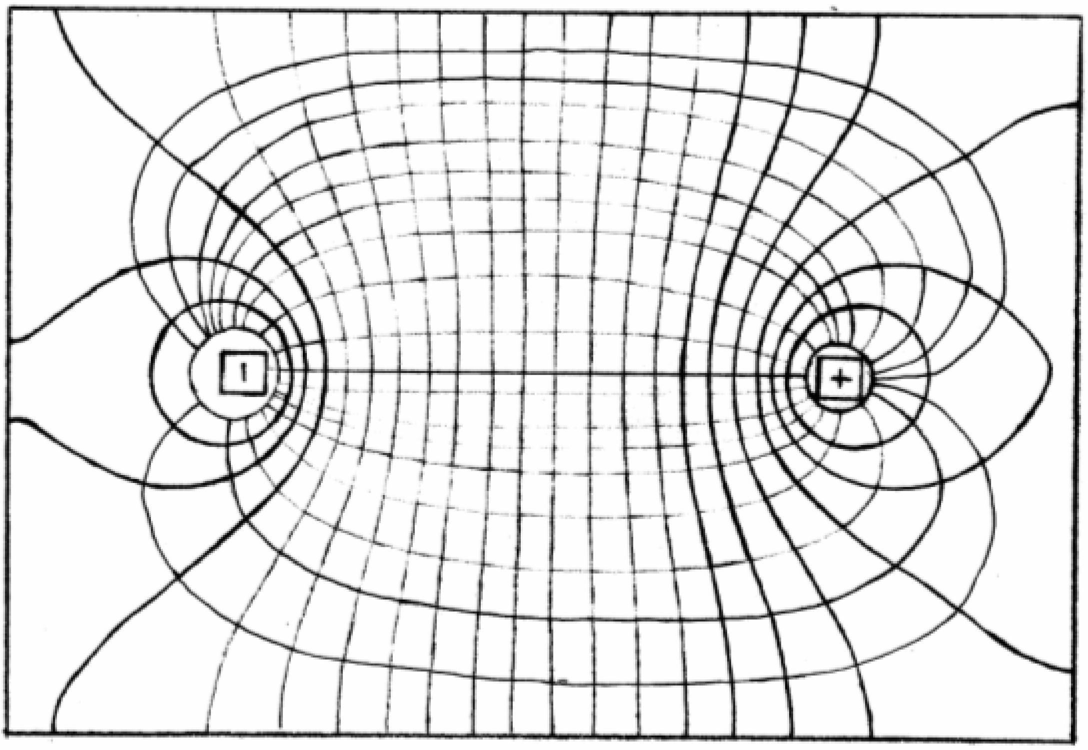


Figure 19. Result from experiment

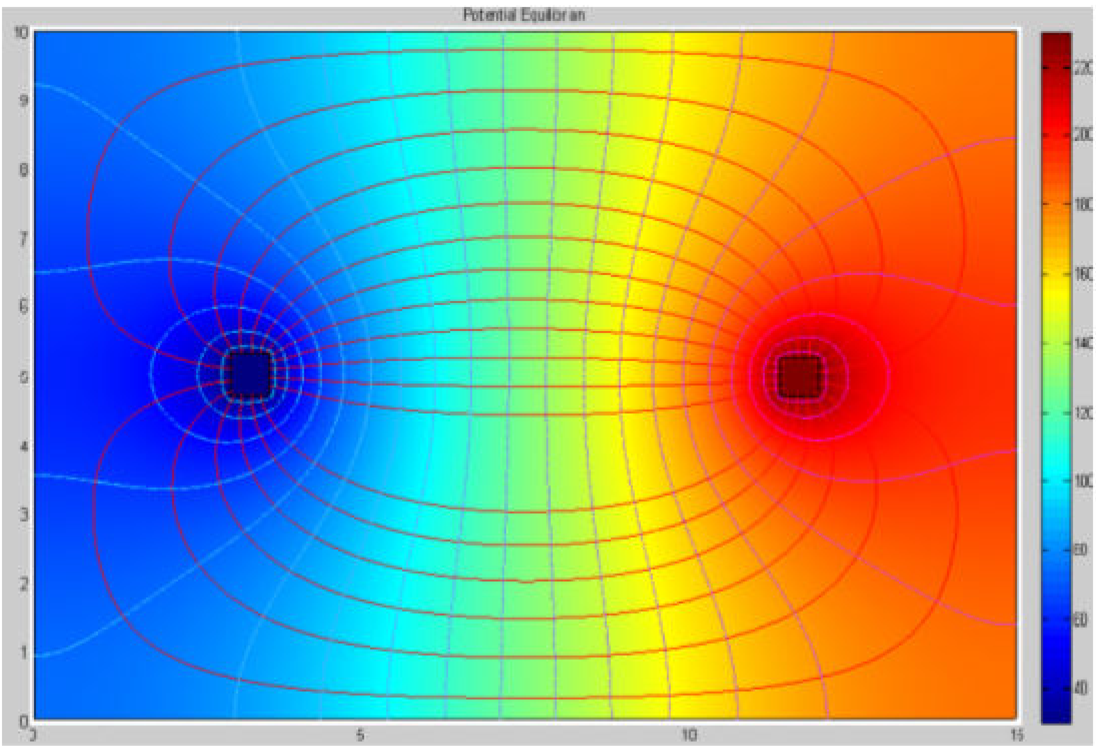


Figure 20. Result from simulation

- Finally, transfer the equipotential lines and the sheet fringe to a tracing paper on which the electric field lines (current lines) are drawn.

Figure 19 shows the result of the equipotential and field lines (current lines) drawn on the tracing paper, whereas Figure 20 shows the result given by computer simulation. The figures given by experiment and simulation agree very well; therefore, our method to visualize the equipotential lines and electric field is considered to be very useful.

4.6.4. Physical phenomena

A convenient way of visualizing electric field patterns is to draw curved lines that are parallel to the electric field vector at any point in space. These lines, called *electric field lines* and first introduced by Faraday, are related to the electric field in a region of space in the following manner:

- The electric field vector E is tangent to the electric field line at each point. The line has a direction, indicated by an arrow, which represents that of the electric field vector.
- The number of lines per unit area through a surface perpendicular to the lines is proportional to the magnitude of the electric field in that region. Thus, the field lines are close together where the electric field is strong and far apart where the field is weak.

For the electric field lines of two point charges of equal magnitude but opposite signs (an electric dipole) as shown in Figure 21, the number of lines that begin at the positive charge must be equal to the number that terminate at the negative charge. At points very near the charges, the lines are nearly radial. The high density of lines between the charges indicates a region of strong electric field [13)].

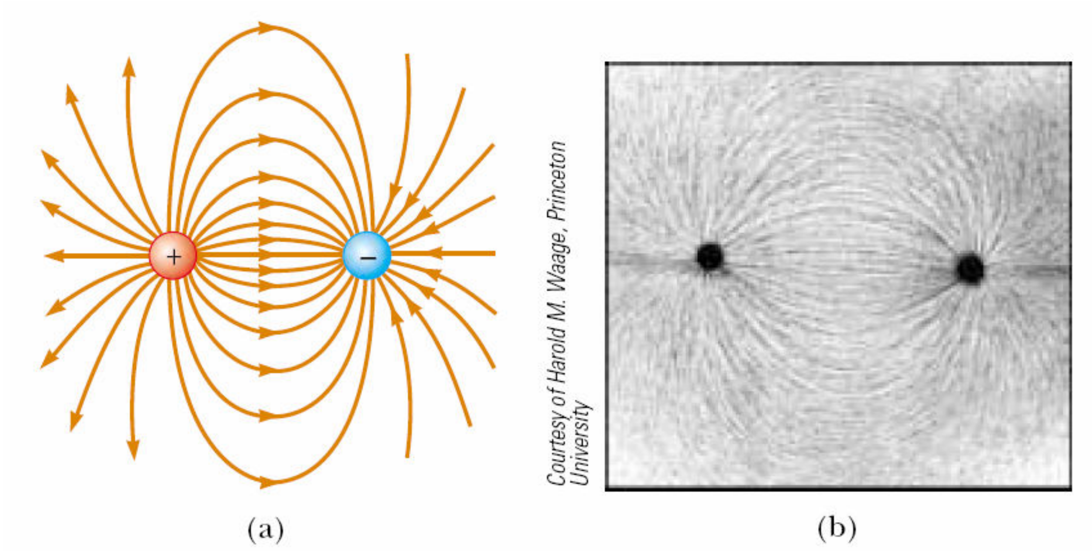


Figure 21. (a) The electric field lines for two point charges of equal magnitude and opposite sign (an electric dipole). (b) The dark lines are small pieces of thread suspended in oil, which align with the electric field of a dipole.

4.6.5. Making Process

In this apparatus set, there is no custom module. So, we would not talk about how to make it. However, we discuss why we use carbon rubber foil as conductive sheet.

The aluminum foil had been used as the conductive sheet more than 25 years. However, its resistance is rather low; 0.2 Ω across 18 cm. The electric contact of the electrodes into the Al foil is not stable enough. If 2V is applied between the electrodes, the current of 10A flows in the Al foil. This requires a big power source and the foil will be heated up. Therefore, the voltage of 0.2V and the current 1A were used as the working condition. This experimental condition is hard to be realized by battery. To get enough number of equipotential lines on this condition, say only 10 lines, the step between two potential lines become about 0.02V. This difference is not large enough to work with easily. Finally, the fixation of the Al foil on the base plate is normally done by using water, which is cumbersome.

To improve above problems, a conductive paper, the paper in which carbon powders are contained is chosen as a conductive sheet instead of Al foil. By this exchange, the resistance between two electrodes separated by 8cm increases to about 500 KΩ. This resistance value is large enough to feed the battery cells and to search equipotential lines with ease. However, this conductive sheet is not adequate to draw the equipotential lines, because its conductivity is not uniform in direction and distance.

Next, a conductive rubber foil, the rubber sheet in which carbon powders are contained, is chosen as a conductive sheet. The resistance between the two electrodes separated by 8cm for the thickness of 0.1 mm is about 42 KΩ, i.e. 10 KΩ for 0.3 mm distance. It is found from the present examination that the rubber foil with thickness of 0.1 mm is more suitable in this experiment.

Remarks

- Concerning the shape of electrodes, not only the point tip, but also other shapes of electrode such as line, circle or other irregular shape can be used to draw the equipotential line.
- Using the figure of equipotential and electric field lines (current lines), the surface resistance of the conductive sheet, σ (Ω), can be determined.

4.7. Magnetic Field Mapping

This equipment is used to measure the magnetic field strength of an object under test such as bar magnet or current loop.

4.7.1. Objective

The objective of this equipment is to help students:

- Understand about the magnetic field, including its direction and strength, of a bar magnet.
- Understand more about the induced Electromotive Force (emf) in a coil which is generated by rotating coil in the magnetic field.
- Experience how the Faraday's law is used to calculate the magnitude of magnetic field $\vec{B}$.

4.7.2. Evaluation method

Draw the magnetic field line and the equi-magnitude line of the magnetic field of a bar magnet by measurement; and compare the results with those written in the reference book.

4.7.3. Experiment setup

This apparatus consists of:

- Experiment base: $26\times36\times0.6$ cm^3 plastic plate
- Power supply: 6 volt AC/DC adaptor
- Multimeter: Digital Multimeter (Sanwa Ltd. PC5000) or any multimeter which has build-in frequency meter.
- Bar magnet: 8 pieces of the rectangular magnets connected in series ($6\times6\times36$ mm^3).
- Probe coil: hand made coil with N = 110 turns, rolled on a cylinder with diameter ϕ = 9.2 mm and length L = 4 mm.
- Motor: COPAL ELECTRONICS 22H055B050 is used to spin the probe coil.
- Lead wire
- Graph paper

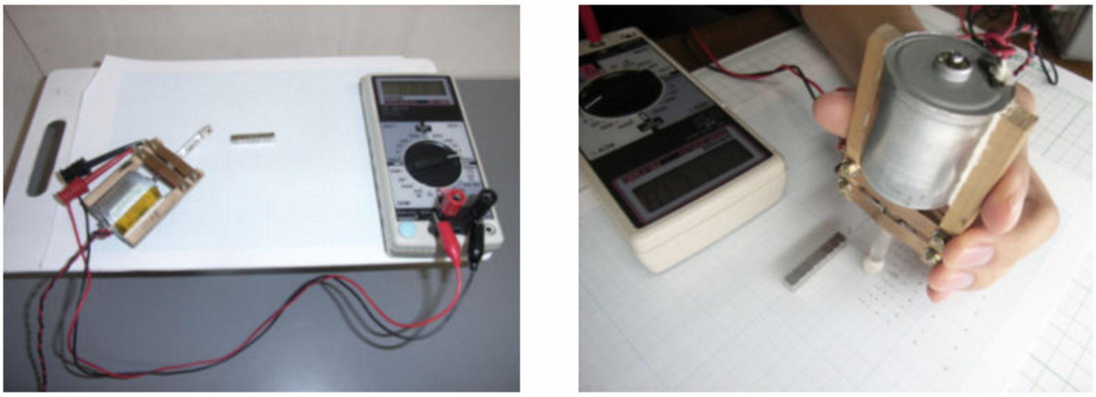
To start this experiment, one must setup the apparatus as shown in Figure 22(a). The setting procedure is as follow:

1) Place a graph paper on the plastic base plate, and then put the bar magnet on it.

2) Connect the coil to the digital multimeter, and the motor to the power supply via lead wires.

Since the magnetic field is a vector quantity, it has both a magnitude and a direction in space. To determine both quantities, two separate measurements are required.

- Step 1: Search many points at which the magnitude of the magnetic field $\vec{B}$ is equal. To do this, the rotating probe coil (which is constructed as described below, $7.5) must be scanned on the paper by keeping its rotating axis to be perpendicular to the paper plane, as shown in Figure 22(b). During the search, the induced AC voltage (emf) across the coil is read via a digital multimeter. The selected function and range of digital multimeter are AC voltage and 200 mV, respectively.



(a) (b)

Figure 22.(a) Experimental setup for Magnetic field mapping. (b) The motor with coil is placed on the paper vertically

- Step 2: Search the direction of the magnetic field $\vec{B}$ on the equi-magnitude line. To do this, tilt the direction of the rotating axis in such a way that the induced AC voltage becomes zero, when the direction of the rotating axis is same as that of magnetic field at the position of probe coil. Mark this direction by pencil. Repeat this process for many points on the each equi-magnitude line.

Note that, we can start on step 2 instead of step 1; however, from my experiences, the order of step 1 to 2 mentioned above is easier to get a good graph of the magnetic field.

Consequently, the magnitude and the direction of the magnetic field are drawn as shown in Figure 23. Figure 24 is the reference figure for comparison, it shows the magnetic field pattern surrounding a bar magnet by using irons filings [13]. From this figure, we can say that our method to map the magnetic field line, around a bar magnet or any magnetic object, is acceptable.

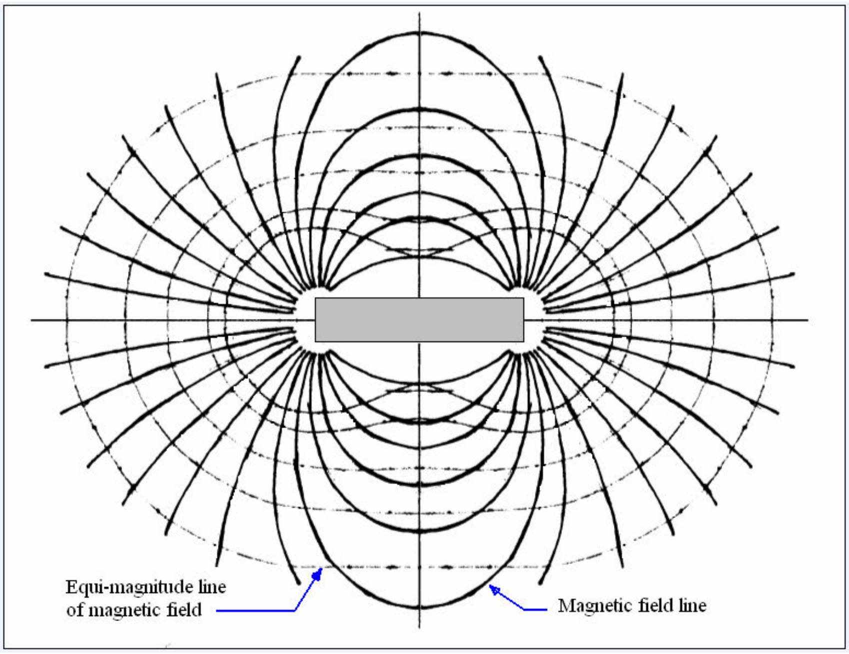


Figure 23. Magnetic field line and Equi-magnitude line of magnetic field

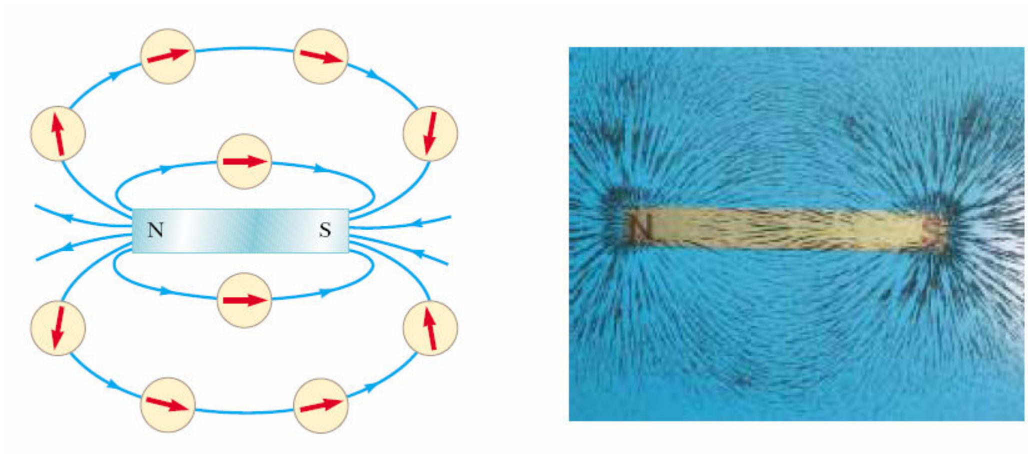


Figure 24. Magnetic field pattern surrounding a bar magnet as displayed with iron filings [13].

4.7.4. Physical phenomena

There are three key words that need to be well-defined which are:

- **Magnetic field**: is a space in which magnetic force works, and is produced by the moving charge or an electric current or a permanent magnet. The magnetic field is a vector quantity which can be represented by means of drawing with magnetic field lines. At each point a magnetic field line is tangent to the direction of the magnetic field $\vec{B}$ at that point. Where adjacent field lines with a constant difference in strength are close together, the field magnitude is large, where these field lines are far apart, the field magnitude is small [4].
- **Magnetic flux**: is simply a quantity of magnetic field passing through a cross sectional area. More generally, magnetic flux is defined by a scalar product of the magnetic field $\vec{B}$ and the area element vector $d\vec{A}$ [14].

$$d\Phi_B = \vec{B} \cdot d\vec{A} = B_\perp \, dA = B \, dA \cos\theta \tag{21}$$

Where $B_\perp$ is the component of $\vec{B}$ perpendicular to the surface of the area element, and θ is the angle between $\vec{B}$ and $d\vec{A}$.
The total magnetic flux Φ_B through a finite area is the integral of the magnetic field over the area:

$$\Phi_B = \int \vec{B} \cdot d\vec{A} = \int B \, dA \cos\theta = B \, A \cos\theta \tag{22}$$

- **Induced emf ε:** can be calculated from Faraday's Law of induction which states that the induced emf in a circuit is directly proportional to the time rate of change of the magnetic flux through the circuit [13].

$$\varepsilon = -\frac{d\Phi_B}{dt} \tag{23}$$

If the circuit is a coil with N identical turns, and Φ_B is the flux through each turn, the total emf in the coil with N turns is:

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{24}$$

In this experiment, the coil with N turns, all of the same area A, rotates in the magnetic field with a constant angular speed ω. From the relationship $\theta = \omega t$ between angular position and angular speed, the magnetic flux through each turn at any time t is:

$$\Phi_B = BA\cos\theta = BA\cos\,\omega t \tag{25}$$

The total emf in the coil with N turns is given by:

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -NAB\frac{d}{dt}(\cos\,\omega t) = NAB\omega\sin\,\omega t \tag{26}$$

This result shows that the emf varies sinusoidally with time, and the maximum emf value is:

$$\varepsilon_{\max} = NAB\omega \tag{27}$$

which occurs when $\omega t = 90^\circ$ or 270°.

From Eq. 27, the magnitude of the magnetic field has the value

$$B = \frac{\varepsilon_{\max}}{NA\omega} \tag{28}$$

Notice that the voltage measured by digital multimeter is the root mean square voltage $\varepsilon_{r.m.s}$. The value of $\varepsilon_{r.m.s}$ is related to the maximum emf as:

$$\varepsilon_{r.m.s} = \frac{\varepsilon_{\max}}{\sqrt{2}} \tag{29}$$

$$\Rightarrow\ B = \frac{\sqrt{2}\,\varepsilon_{r.m.s}}{NA\omega} \tag{30}$$

Recall that $\omega = 2\pi f$ and $A = \pi r^2$, where f (= 41.3 Hz) is the frequency of the rotating coil and r (= 4.6 mm) is radius of the coil.

4.7.5. Making Process

The custom module used in this experiment is the rotating coil module, which consists of coil, small motor (COPAL ELECTRONICS 22H055B050), plastic rod, two metal rings, and two couples of cupper brushes with wood supporters. The procedure on how to make this module is described below.

The cupper wire with insulation (diameter: 0.2 mm) is wound tightly 110 turns to make a coil (the number of turn is depending on the maker). One end of a plastic rod (length: *60* mm) is cut to make a ditch for the coil, and the another end has a hole for fixing to the motor axis. The coil is inserted in the ditch and molded by adhesive. The two end-wires of the coil are connected to the metal rings served as the electrodes. Next, the rod is fixed on the rotating axis of motor. Finally, two wood supporters are fixed to the motor body by adhesive, and two brushes with output pins are attached. The making process of the module is shown in Figure 25.

Figure 25. Process of making the rotating coil module

Note: For working of the motor, a power source of 6V/0.44A was used here. This amount of power can be supplied by battery only in a short time. Therefore, a small load on the motor is required so that a 3V motor can be used. Or a larger electric power supply such as solar battery will be necessary.

4.8. Thermal Analyzer

This equipment is comprised of three functions: measurements of the temperature and the heat flow, and the temperature control using heater. By controlling the temperature of the test substance at a constant heating/cooling rate, the heat flow from the substance is measured.

4.8.1. Objective

- To understand the state changes of the substances (materials) by measuring the heat flux caused by heat generation or absorption in the sample as a function of temperature.
- To consider the result from experiment and the relationship between the basis of thermodynamics and materials science.

4.8.2. Evaluation method

To measure the absorbing heat from the material caused by the phase transitions (the solid-solid and the melting transitions) by using the newly developed thermal analyzer at a constant heating rate. The test conditions are as follows: material: docosane ($C_{22}H_{46}$), heating rate: 0.5mK/s, and temperature range: 42 to 46°C.

To compare the experimental result with that given in the earlier study using a high resolution and super sensitive differential scanning calorimetry (DSC).

4.8.3. Experimental setup

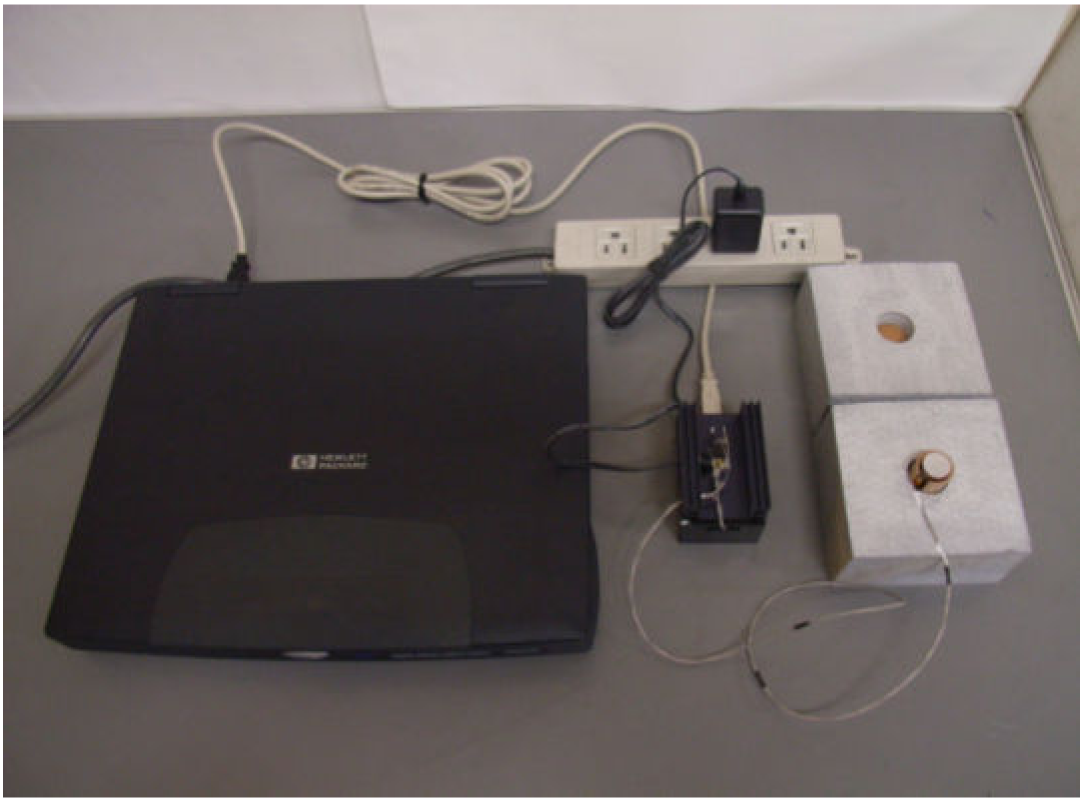
This apparatus consists of:

- Computer (Desktop or laptop)
- Miniature heat flux analyzer (MHFA)
- Circuit box: ADC/DAC, USB-I/O and power amplifier
- USB cable
- Power supply (6V, 0.5A, AC adopter or battery)
- Thermal isolator: Neoma-form (Asahi-kasei Ltd.)

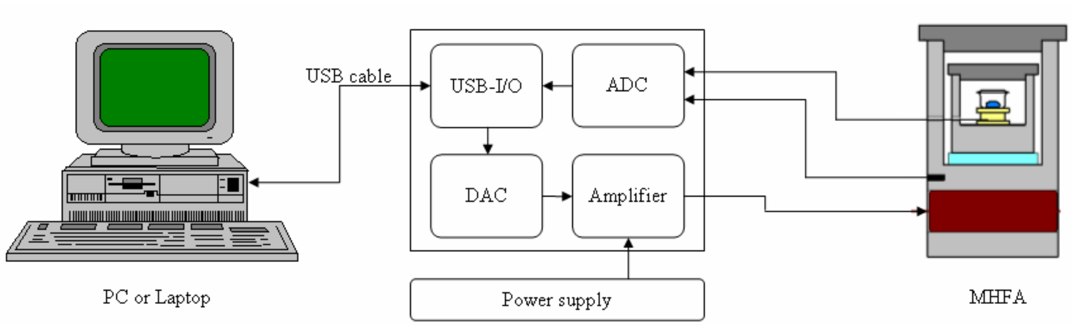
The apparatus is shown in Figure 26, and the preparations for this experiment are follows:

- Construction of the experimental system: At first, connect the circuit box to computer via a USB cable. Next, connect the power supply to the line power.

- Preparation of the sample: Docosane ($C_{22}H_{46}$) with the purity higher than 99.999% supplied from NIST is used as a reference material. The measurement result can be compared with that reported on the same material by S. Wang et. al [15)]. The sample, with amount of 2.48 mg, is enclosed in an aluminum capsule, and is placed on the top substrate of the heat flow sensor.



(a) Photo



(b) Schematic

Figure 26. Experimental setup of MHFA

- Running of the PC program: After finish the above setup, measurement can be started by clicking the icon on the desktop. Figure 27 shows the control panel of the measurement, where the following parameters are stated,
    - T_0 [deg] : Start temperature on the first heating scan.
    - T_1 [deg] : Stop temperature on the first heating scan.
    - T_2 [deg] : Start temperature on the continuing cooling scan.
    - T_3 [deg] : Stop temperature on the continuing cooling scan.
    - Step (0-1): Heat up temperature in every measuring time in Kelvin.
    - Interval [ms]: The time interval between the measurements in millisecond.

  The measurement starts by clicking START button.

The experimental result on heating process at a heating rate of 0.5 mK/s is shown in Figure 28. Figure 29 is the result given in S. Wang et. al [15] at the same material and measuring condition using a high resolution DSC.

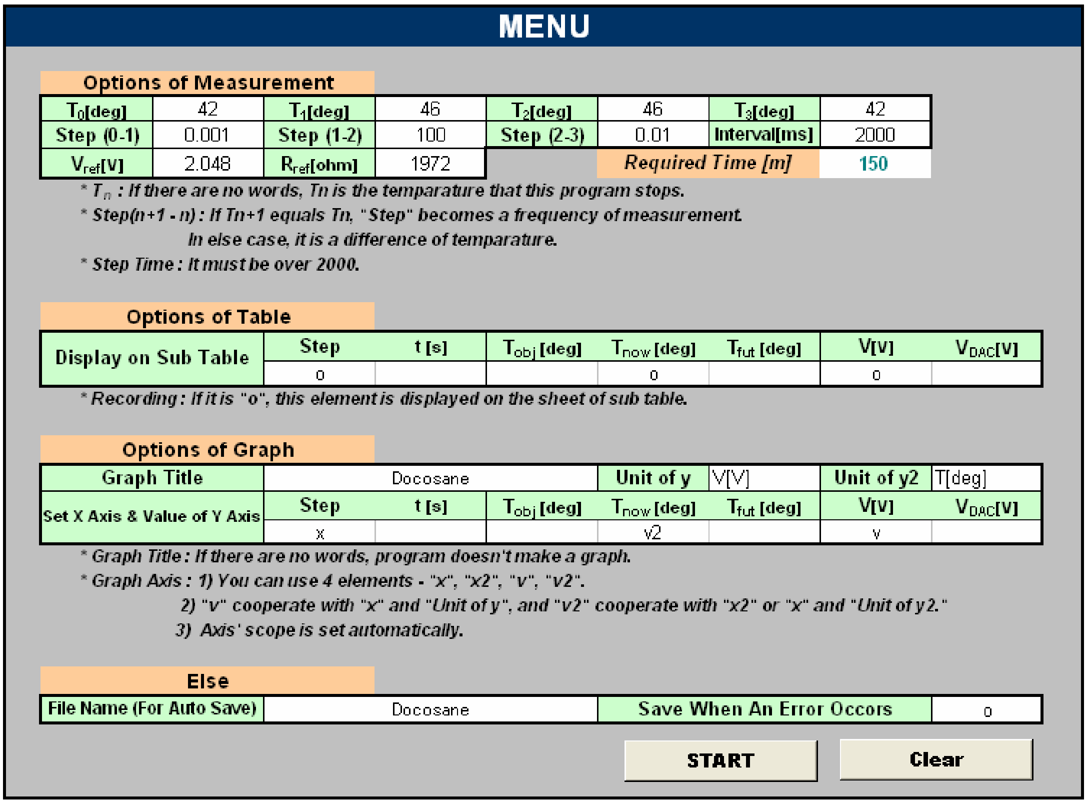


Figure 27. Control panel of the thermal analyzer

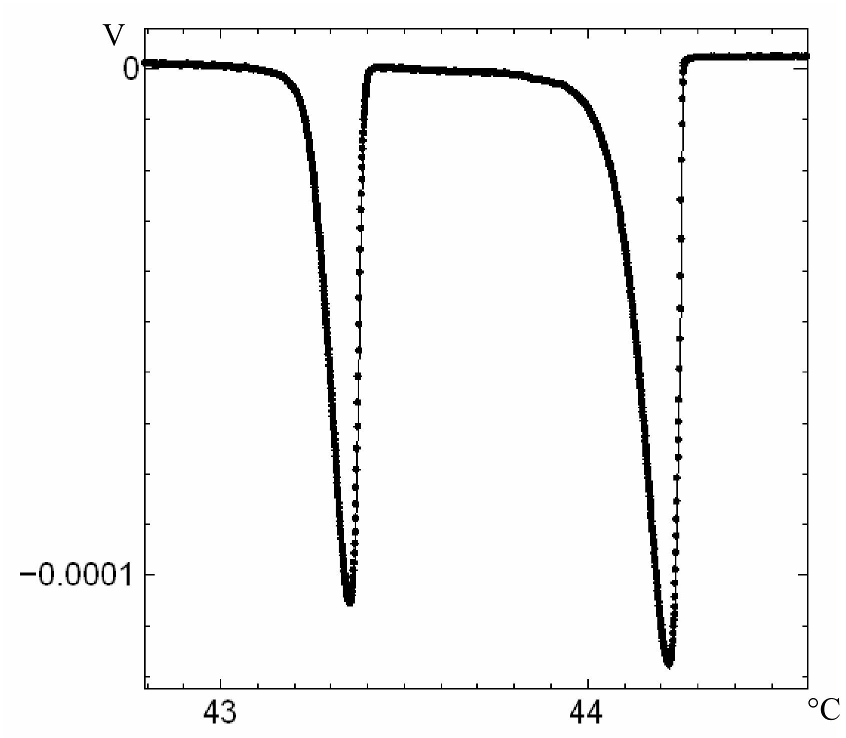


Figure 28. Thermal analysis curve of docosane at a heating rate of 0.5mK/s using MHFA

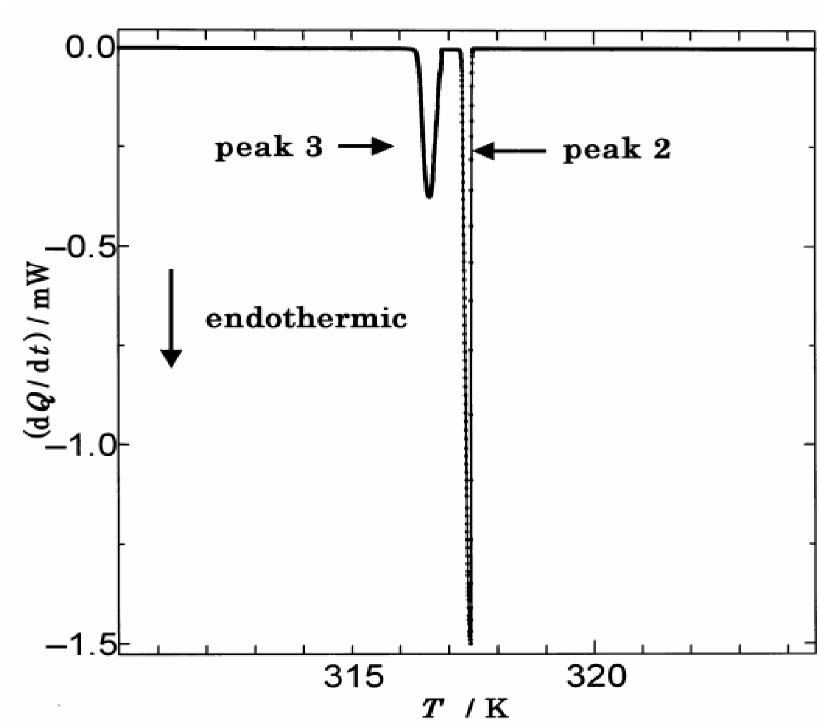


Figure 29. DSC curve of docosane at a heating rate of 0.5mK/s [15)]

The endothermic peak 3 in Figure 29 indicates that the transition from the crystalline phase to the rotator phase occurs around 316.6 K (43.45°C). The next endothermic peak 2 indicates that the transition from the rotator phase to the liquid phase (melting transition) occurs around 317.45 K (44.3°C). For the present measurement shown in Figure 28, the corresponding temperatures for peaks 3 and 2 are 43.4°C and 44.25°C, respectively.

The present results are 0.05°C lower. While this discrepancy is negligibly small, it is thought to be caused by the uncertainty of the Pt resistance temperature sensor. The small differences in peak shape between two figures are considered to be caused by the difference in thermal history of the specimen. Comparing MHFA with the high resolution DSC used by S. Wang et. al, it is estimated for MHFA that the apparatus constant to convert from output voltage to heat flow is about 3 W/V and the detectable minimum heat flow is about 0.1 μW. Thus, it is concluded that MHFA has a good quality for research for phase transitions. The working temperature range is room temperature to about 150°C at present. The temperature range will be expanded without much difficulty in future.

4.8.4. Making Process

In this experimental apparatus, the miniature heat flux analyzer (MHFA) is the custom module made by us; other custom module such as ADC/DAC interface adaptor; amplifier and program are made by our laboratory. The apparatus for the heat flux measurement, the main part of MHFA, is shown in Figure 30, which consists of the parts listed in Table 6.

Table 6: MHFA part list

N	Parts	Functions
1	Outer chamber	make the temperature homogeneous on it
2	Inner chamber	make the temperature homogeneous on it
3	Glass plate	use as a thermal resistance
4	Thermoelectric module (TM)	act as a heat flow sensor
5	Resistor	serve as a heater
6	Pt resistor	use as a temperature sensor

The making process of the parts of MHFA is shown as follows:

1) Outer chamber: The basic material is cupper cylindrical rod with 16 mm in diameter and 26 mm in length. At first, a cylindrical hole with

an inner diameter of 12 mm and a depth of 15 mm is bored on the body by a lathe. Then, a hole with 5 mm in diameter for thermal resistance heater is made by the drill, whose centerline is 5.5 mm in distance from the bottom plane of the cylinder (Figure 29, No.5). A ditch with 0.7 mm in width and 2 mm in depth is made for Pt resistor (Figure 29, No.6).

2) Inner chamber: The basic material is cupper cylindrical long rod with 10 mm in diameter. A cylindrical hole with 8 mm in inner diameter and 6 mm in depth is bored by the lathe, and the rod is cut at the 9.4 mm in length. The two small holes with 0.6 mm in diameter used for passing the lead wire are drilled at 5.5 mm from the top of cylinder.

Fabrication:

1) A fused quartz glass plate is fixed on the inner bottom flower of the outer chamber with adhesive (Figure 29, No.3).
2) The thermoelectric module is placed on the inner bottom flower of the inner chamber with adhesive (Figure 29, No.4).
3) The inner chamber is fixed on the glass plate with adhesive (Figure 29, No.2).
4) The resistance heater is inserted into the hole of the outer chamber and fixed with adhesive (Figure 29, No.5).
5) The Pt resistor is inserted in the ditch at the side of outer chamber and mounted with adhesive (Figure 29, No.6).

Figure 30. Hardware of MHFA

5. Discussions

In the previous sections, we discussed only on how to make these apparatus, what are the objectives for conducting these experiments, how to evaluate our experiment apparatus and what are the phenomena which lie behind these measurements. Here, we summarize the performance achievement that each apparatus met. The evaluation is listed in Table 7.

Table 7: Performance achievement of our PDL

	Low Cost	Small in Size	Run on Battery	Easy to use & Attractive	Research use
Diffraction of light	O (90$)*[1,5]	O	O	O	?
Refraction of light	O (20$)*[5]	O	O	O	?
Polarization of light	O (20$)*[1,5]	O	O	O	?
Balance & measurement of force	O (30$)*[1]	O	O	O	Δ
Borda's pendulum & Spring-mass oscillation	O (30$)	O	O	O	?
Equipotential line	O (0.5$)*[1]	O	O	O	?
Magnetic field mapping	O (25$)*[1]	O	Δ*[3]	Δ*[4]	?
Thermal analysis	Δ (300$)*[2]	O	×*[2]	O	O

[O]: Good, [Δ]: Fair, [×]: Not good, [?]: Unknown.
[*1]: The cost of a digital multimeter which is used for many experiments in common is excluded.
[*2]: The dominant cost is that of a PC, and can be reduced by the usage of One Laptop per Child (OLPC). This experiment needs a 6W power source for the resister heater, and is not possible with a battery. Moreover, the PC used for temperature control and for saving the experimental data cannot run on battery for long enough time. Therefore, this thermal analyzer depends on the power source than battery.
[*3]: The DC motor can be replaced with one driven by battery.
[*4]: It takes long time to map the magnetic field. Therefore, the method and the content of this experiment must be improved in future.
[*5] The cost of a laser diode (LD, about 10$) used in common as the light source is excluded.

The parts commonly used in many PDL experiments are a base plate, a digital multimeter, a rechargeable battery, a caliper, a laser diode (light source), two kinds of magnet tips and some lead wires. In future, a home-made synthesized signal generator, a PC, and a digital oscilloscope will be used in common.

From the results shown in Table 7, it can be concluded that our experimental apparatus satisfy our goal well.

6. Conclusions and Future works

The main theme of this thesis is, as mentioned in Introduction, to devise a number of hands-on experiments that help students learn concepts in physics; the experiments that could be set up in developing countries. To this end, we set our goals that experimental set-ups are prepared at low cost, small in size, run on battery, and applicable for research purpose. Namely, our guiding principles in this endeavor are miniaturization and modularization with ease in construction, maintenance and repair. In this age, we do not mind using integrated circuit (IC) and personal computer (PC). We found that it is not easy to achieve all the goals at the same time. Sometimes, we can make apparatus running on battery. But at other times, we need to use new material which is little more expensive, as shown in “Equipotential line” experiment. Generally speaking, however, thanks to our new guiding principles, the total cost-performance as well as the size of most apparatus is much reduced.

Due to the modularization technique and the usage of parts are common on many other experiments, we can remarkably reduce the size and the cost of the whole apparatus. The modularization technique also results in ease of new configuration, replacement and reparation of apparatus, which makes the students more interested in and understand more about the physical phenomena and the apparatus itself. As a result, these apparatus are now in use at our university (Chiba University, Japan).

Deep understandings about physical phenomena, in turn, help us to improve such apparatus with less complexity and cost.

The new custom ADC-DAC board and the development program, which convert any laptop to a low frequency oscilloscope and a low frequency signal generator, will help opening the PDL to the world in the near future.

As the time is limited, we cannot accomplish our entire goals to all our apparatus. However, with help of new laptops which cost about 100$, we can make our apparatus be in hand for all students in the classroom in the very near future.

In the future, the far distance learning with PDL will be used in developing countries which are eager for a good quality of a higher physics education.

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LIST OF ABBREVIATIONS

AC	Alternative Current
ACV	AC Voltage
ADC	Analog to Digital Converter
COM	Common
CPU	Central Processing Unit
DAC	Digital to Analog Converter
DC	Direct Current
DDS	Digital Data Storage
DMM	Digital Multimeter
DSC	Differential Scanning Calorimetry
EMF	Electromotive Force
GND	Ground
IC	Integrated Circuit
MHFA	Miniature Heat Flux Analyzer
OHP	Over-head Projector
OLPC	One Laptop per Child
PC	Personal Computer
PD	Photodiode
PDL	Personal Desk Lab
RMS	Root Mean Square
RUPP	Royal University of Phnom Penh
TM	Thermoelectric Module
USB	Universal Serial Bus

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