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Construction and remote demonstration of an inexpensive but efficient experimental setup for studying self-inductance and mutual-inductance between two coils

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Abstract
Measurement of self-inductance and mutual-inductance has been demonstrated as a laboratory experiment with great simplicity. The novelty of this demonstration lies in its straightforward circuitry and methodology, enabling the experiment accessible to students with minimal prerequisite knowledge. A coil-pair setup was constructed using discarded common household articles, costing very low but provides high quality throughput in teaching-learning experience. The demonstration can be easily conducted online using a laptop without the need of extra power supply. The experiment suits for high school and pre-university students, as evident by twenty first-semester undergraduate physics and electronics students who found it both satisfying and enjoyable with a relatively flat learning curve.

Keywords: self-inductance, mutual-inductance, ExpEYES-17, COVID-19, low-cost apparatus

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1. Introduction

The elegance of physics lies in the intricate interplay between theories and experiments, with theories providing the conceptual framework that illuminates hidden connections between phenomena, and experiments bridging the gap between conjecture and truth. This article focuses on an essential experiment complementing its theory.

In 1831, Michael Faraday's [1, 2] discovery of electromagnetic induction, demonstrated using independent coils around a soft iron ring, fascinated students due to the absence of direct coil contact (See figure 1). Faraday's law defines induced electromotive force (emf) magnitude, while Lenz's law determines the induced current direction. Joseph Henry's 1832 interpretation established the SI unit of inductance (H). Hans Christian Oersted's 1820 discovery paved the way for inventions like electric motors and other related devices.

Amid the COVID-19 pandemic (2020–22), teachers globally innovatively tackled online laboratory sessions [3–7]. This article presents such a cost-efficient experiment determining self and mutual-inductances, showcasing a setup visible to students. Conventional methods' limitations drove the authors to devise a simple, accurate home-made kit demonstrated online during lockdowns, providing an alternative for physics and electronics education.

2. Measurement of self-inductance and mutual-inductance

Measuring self-inductance and mutual-inductance in physics laboratories involves various methods, each with its advantages and drawbacks. Experiment setups are often bulky, costly, require specialised equipment and complex theory, and error-prone. Here, we review briefly some of these methods.

The Bridge Method utilizes AC bridge circuits [8], like Wheatstone or Maxwell's bridge, balancing unknown inductance against known standards. These setups require a deep understanding of bridge circuits and are suitable for students with prerequisite knowledge.

The RL Circuit Method [9] connects a known resistance (R) and the inductor in series, determining inductance by measuring the time constant of the resulting RL circuit. A variant involves observing the transient response of an RL circuit to a step input voltage. These methods demand a digital storage oscilloscope and a strong grasp of circuit theory and mathematics.

The Transformer Method [10] measures mutual-inductance between coils using a transformer setup with known alternating current. However, it lacks the ability to study variations in mutual-inductance as a function of geometrical orientation.

The Time-Varying Current Method [11] passes a time-varying current through the primary coil, measuring induced electromotive force (emf) in the secondary coil. Analysing this relationship requires a deep understanding of electromagnetic theory.

The three-voltmeter method [12] is another popular method where three voltage values are measured in a series RL circuit, and a phasor diagram is drawn from which, the unknown inductance and its resistance can be measured in terms of reactance using phase angle θ. In our method, only one voltmeter is required, and the complexity of drawing phasors is not necessary.

The use of a Ballistic Galvanometer [13] in measuring self- and mutual inductances faces limitations due to slow response times, non-linear scaling, and lack of direct inductance calibration on its scale. Inductive circuits cause oscillations and skewed deflections, introducing errors. Calibration is rigorous, and the method is impractical for inductance measurement. Modern alternatives like oscilloscopes and LCR meters offer accurate solutions, bypassing inductive issues with real-time data and automation.

While advanced methods like the Digital Lock-in amplifier [14] suit research, the authors recommend against their use for undergraduate students.

3. Theory

3.1. Measurement of self-inductance

We devised a method to measure inductance using an AC potential divider circuit with the inductor as one of the impedances (figure 2). Practical inductors (L) have internal resistance (r), forming an equivalent circuit (inset of figure 2).

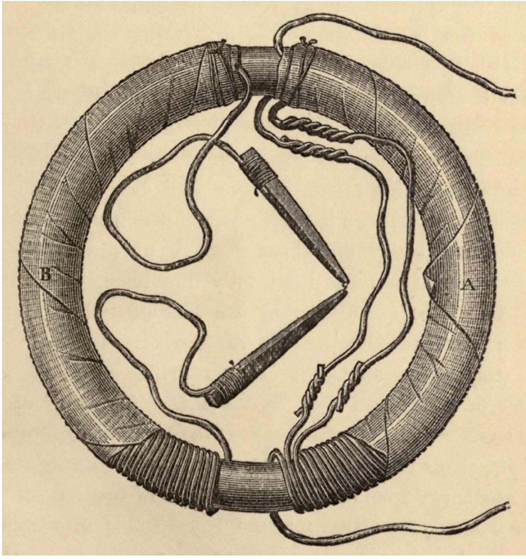


Figure 1. Faraday's type of transformer [1]. Reproduced with permission from [1].

For the circuit shown in figure 2, the variable resistor R_{var} was varied and $|v_{\text{out}}|$ was measured until $|v_{\text{out}}| = \frac{1}{2}|v_{\text{in}}|$ was achieved. Let this condition be achieved at $R_{\text{var}} = R$. Under this condition, the ratio ($\frac{v_{\text{out}}}{v_{\text{in}}}$) can be expressed as,

$$\frac{|v_{\text{out}}|}{|v_{\text{in}}|} = \frac{|Z_L|}{|Z_T|} = \frac{1}{2} \tag{1}$$

where $|Z_L| = \sqrt{r^2 + \omega^2 L^2}$ is the modulus of impedance of the inductor, and $|Z_T| = \sqrt{(R+r)^2 + \omega^2 L^2}$ is the modulus of total impedance of the circuit. The symbol $\omega(= 2\pi f, f \text{in Hz})$ represents angular frequency of the input voltage v_{in}.

Thus, we can rewrite the above ratio as

$$\frac{\sqrt{r^2 + \omega^2 L^2}}{\sqrt{(R+r)^2 + \omega^2 L^2}} = \frac{1}{2}. \tag{2}$$

Upon simplifying the above expression, one obtains L as

$$L = \frac{R}{(\sqrt{3})\,(2\pi f)} \sqrt{\left(1 + \frac{3r}{R}\right)\left(1 - \frac{r}{R}\right)} \tag{3}$$

(For ideal inductor, $r \to 0, L \to \frac{R}{(\sqrt{3})(2\pi f)}$) The equation, equation (3) is the master equation in determining inductance of an inductor experimentally. This master equation is depicted in the inset of the figure 2.

3.2. *Measurement of mutual-inductance*

If L_p and L_s be the self-inductances of two coils, then the mutual-inductance between the coils is expressed as:

$$M_i = \sqrt{L_p L_s}. \tag{4}$$

Equation (4) represents theoretically possible maximum mutual-inductance between two coils (in ideal case). In practice, the mutual-inductance between two coils is expressed as:

$$M = k\sqrt{L_p L_s}. \tag{5}$$

The coupling coefficient (k) ranges from 0 to 1, denoting weak to strong coupling. Factors affecting k include coil geometry, proximity, orientation, and winding uniformity. This article explores mutual-inductance variation due to coil orientation in undergraduate experiments. It presents simple methods, **direct** and **indirect** for determining mutual-inductance and coupling coefficients. An article [15] by Silveyra and Garrido may be consulted for more elaborate mathematical expressions.

3.2.1. *Indirect method: measurement of mutual-inductance and coupling co-efficient.*

Two inductors, L_p and L_s, initially measured separately, are then connected in series and placed in close proximity to couple. Under this condition, the resultant inductance of the pair of coils is expressed as:

$$L_{x,y} = L_p + L_s \pm 2M \tag{6}$$

where M is the mutual inductance.

For coils L_p and L_s wound in the same direction, use '+' in equation (6); otherwise, use

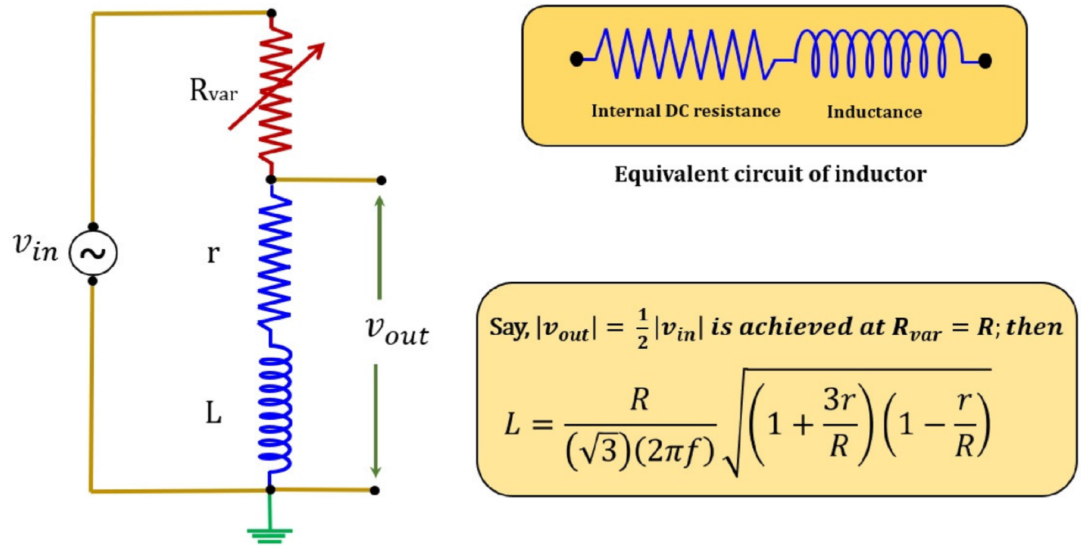


Figure 2. Circuit for determining unknown inductance.

'−' for subtractive series connections. Resultant inductance (L_x) is given by.

$$L_x = L_p + L_s + 2M. \tag{7}$$

Similarly, the expression for resultant inductance in subtractive series connection (L_y) is given by

$$L_y = L_p + L_s - 2M. \tag{8}$$

Now, by subtracting equation (8) from equation (7) we obtain:

$$M = \frac{L_x - L_y}{4}. \tag{9}$$

Since, M is a positive quantity, it is better to take modulus of the quantity at the right hand side of the equation (9). The inductance L_x and L_y were measured using the same method described in the section 'measurement of self-inductance'(section 3.1). Once, L_x and L_y were measured, the mutual-inductance between the coil can be determined using equation (9). The circuit for measuring L_x and L_y is shown in figure 3. In this case, the equation (3) for $L_{x,y}$ modifies to:

$$L_{x,y} = \frac{R_{x,y}}{(\sqrt{3})\,(2\pi f)}\sqrt{\left(1+\frac{3\,(r_p+r_s)}{R}\right)\left(1-\frac{r_p+r_s}{R}\right)}. \tag{10}$$

Experimentally, if the measured series inductance is more than $(L_p + L_s)$, then the connection between coils is in additive series and such inductance is represented here by L_x. The subtractive series inductance (L_y) is less than $(L_p + L_s)$. Once, L_x and L_y were measured, the mutual-inductance between the coils can be determined using the equation (9). After determining the mutual-inductance M, the coupling co-efficient can be determined using equation (5) as

$$k = \frac{M}{\sqrt{L_p L_s}}. \tag{11}$$

If we change the orientation between the coils, the mutual-inductance M will change and thus by determining M for various orientation between the coils, the variation of coupling co-efficient can be determined.

3.2.2. *Direct method: measurement of mutual-inductance and coupling co-efficient.*

Similar to previous method, the inductances of the two inductors L_p and L_s were first measured. The coils were then placed to close proximity of each

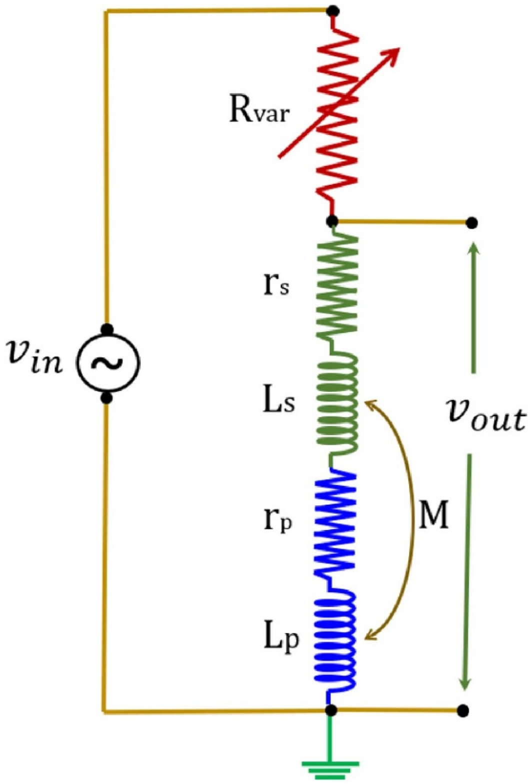


Figure 3. Circuit for measuring series inductance for a pair of coupled inductors.

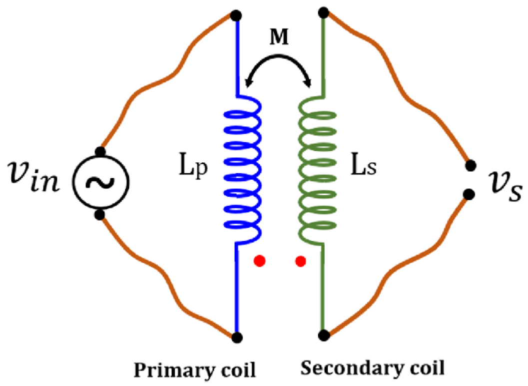


Figure 4. Circuit for measuring series inductance for a pair of coupled inductors.

other. The circuit for this method is shown in figure 4. The coils were designated as primary and secondary coil as commonly done for a transformer.

The primary coil was excited by an AC voltage source ($v_{\rm in}$) and the corresponding open circuited induced emf (v_s) was measured. The relation between v_s and $v_{\rm in}$ is expressed as:

$$v_s = \pm \frac{M}{L_p} v_{\rm in}$$

or,

$$M = L_p \frac{|v_s|}{|v_{\rm in}|}. \tag{12}$$

Now, replacing the input voltage source from primary coil to the secondary, the induced emf across the primary coil (v_p) was measured. Hence, the mutual-inductance can be expressed as:

$$M = L_s \frac{|v_p|}{|v_{\rm in}|}. \tag{13}$$

By multiplying the equations (12) and (13) we obtained the mutual-inductance as:

$$M = \left(\frac{\sqrt{|v_s||v_p|}}{|v_{\rm in}|} \right) \sqrt{L_p L_s}. \tag{14}$$

By comparing equations (5) and (14), we obtain

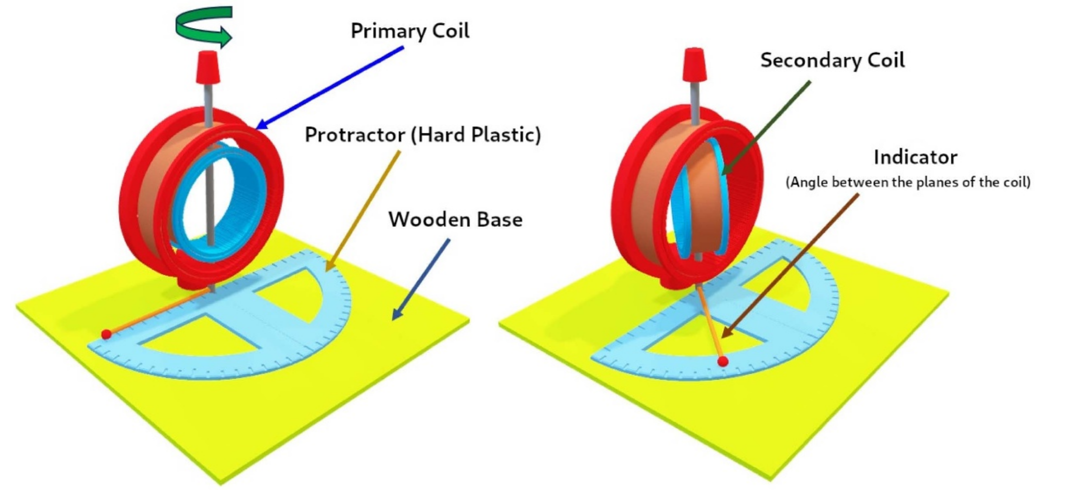
$$k = \left(\frac{\sqrt{|v_s||v_p|}}{|v_{\rm in}|} \right). \tag{15}$$

Thus, in this method, the mutual-inductance and coupling co-efficient were determined using equations (14) and (15) respectively. Similar to indirect method, by varying the orientation between the coils, the variation in mutual-inductance between the coils were obtained. We noticed that direct method was advantageous in comparison to indirect method and such advantages are described in the discussion section (section 5) of this article.

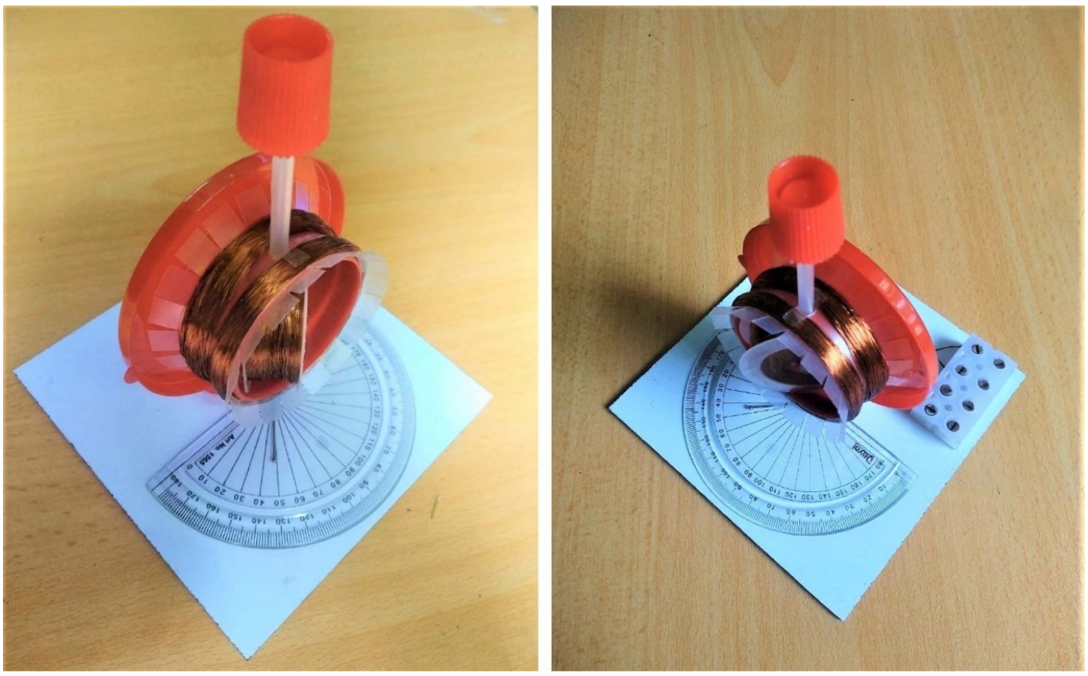
4. Experiment

4.1. Construction

The coil-pair setup, detailed in figure 5, utilized low-cost, scavenged household components, costing under € 6.50 (table 1). Construction focused on coils; the outer coil‘s spool came from a



(a) Schematic of the setup.



(b) Actual photographs of the constructed low-cost experiment setup.

Figure 5. Constructed coil-pair setup. Outer and inner, both the coils are visible. A pin, connected to the vertical shaft, points on the protractor for angle reading.

plastic bangle case, and the inner coil's from a spool for winding Teflon tape. Enamelled copper wire, sourced from doorbell coils, wound manually, formed both coils. The authors are not sure about the specification of the copper wire used in the coils, however, they ascertain

Table 1. Approximate cost of construction and source of the materials.

Item	Source and quantity	Approx. cost in INR
Wires for coils	Ding-dong Door Bell -2 pcs	INR 300.00
Base for the setup	Wooden Base ($4'' \times 4''$)- 1pc	INR 10.00
Outer Coil Spool	Case of Bangles- 1pc	INR 10.00
Inner Coil Spool	Teflon Tape Spool- 1pc	Scavenged, no cost
4-point Terminal Connector	4-point Terminal Connector - 1pc	INR 20.00
Angle Visualizer	Protractor - 1pc	INR 5.00
Variable Resistor	20 kΩ multiturn pot - 1pc	INR 200.00
Coils Shaft	Empty gel pen Refill-1 pc.	Scavenged, no cost
Coil Spacer	Cap of an empty soft drink bottle-1 pc.	Scavenged, no cost
Coil Rotator	Cap of an empty Toothpaste tube-1 pc.	Scavenged, no cost
Coil connectors	soft wires from a discarded earphone-2 pc.	Scavenged, no cost
Missc (Glue, wires etc)		INR 10.00
Total Cost	INR 555.00, ≡ € 6.50 in Sept–Oct 2021(1 € ≡ 86.35 INR)	

that such specification would be around 42 SWG with measured resistance of about 2.03 Ω per meter (Standard value of about 2.09 Ω per meter at 20 °C. [16]) Primary and secondary coil diameters are approximately 5.0 cm and 3.6 cm, respectively. The number of turns in the primary and secondary coils are about 1162 and 1500, respectively.

The primary coil, fixed to a wooden base with a soft drink bottle cap and glue, remains stationary. In contrast, the manually rotatable secondary coil attaches to a gel pen refill. The primary coil's holes allow free rotation of the refill, while the secondary coil rotates with it. A protractor on the wooden base measures the coil planes' angle. A toothpaste tube cap enhances manual refill (z-axis) rotation. A '4-point-terminal' affixed to the base connects coils via soft wire scavenged from a discarded earphone, preventing coil rotation interference. This wire, stripped of its plastic cover, serves its purpose with enamelled multi-strand construction.

4.2. The platform of the experiment: ExpEYES-17

To conduct the experiment, we need a ac signal generator, a multimeter, and a cathode ray oscilloscope to display the waveforms. However, the authors did not have access of the said equipments during designing the experiment due to lockdowns. Moreover, with the intention to demonstrate the experiment online, the authors have used the ExpEYES-17 kit as the platform of experiment, thereby having all the required devices on a single computer interfaced platform.

ExpEYES-17, an open-source platform from the PHOENIX [17] project at IUAC in India, serves educational and experimental purposes in electronics and physics. It offers a range of features for hands-on experiments in various fields. The kit's illustration (figure 6) reveals output signals on the left and input channels on the right, with channels A1 and A2 used for observing waveforms, and the waveform generator (WG) for coil input.

Designed for beginners and advanced learners, ExpEYES-17 enables exploration of electronics and physics concepts. Although the article does not delve into every detail, articles [3, 4], or the ExpEYES-17 [18] users manual may be consulted for comprehensive information. The discussion here focuses on three features that we have used:

1. **Resistance Measurement:** Internal coil resistances and potentiometer resistance were measured using terminals SEN and Ground without additional instruments.
2. **Signal Generation:** The kit's outputs generate sine and triangular waves with frequencies from DC to 5 kHz, and fixed amplitudes (80 mV, 1.0 V, and 3.0 V), used to energize coils without an external signal generator.

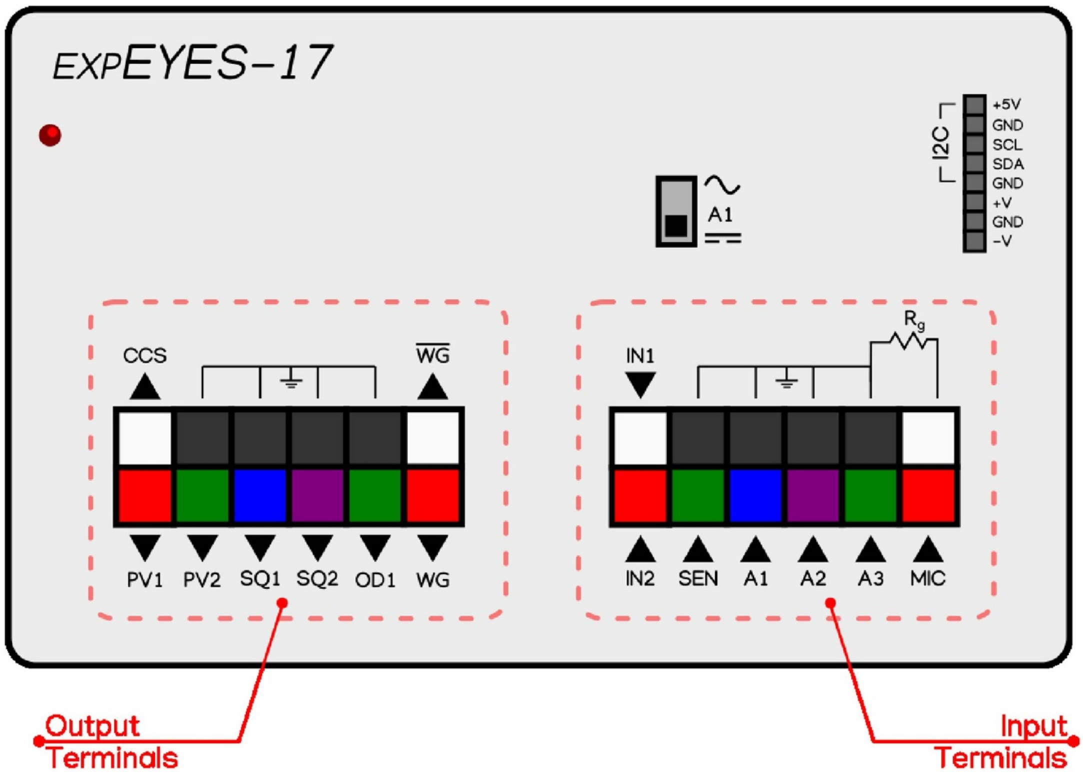


Figure 6. The illustration of the ExpEYES-17 kit [18, 19] displays output signals through terminal blocks on the left, while input channels are situated on the right. For this particular experiment, we have utilized input channels A1 and A2 as inputs to observe the waveforms on the screen, and the waveform generator (WG) was employed as an input source for the coils. Reproduced with permission from [11].

3. **Display of Waveforms:** ExpEYES-17 provides an oscilloscope display on the connected PC/laptop screen, facilitating result visualization with on-screen controls.

4.3. Setting up experiment

In this experiment, the ExpEYES-17 kit interfaced with a computer served as the platform, demonstrating online experimentation. Using a 5 kHz sinusoid from ExpEYES-17 as the primary coil input, the kit measured resistance, displaying outputs on its console. The entire setup, powered by a laptop's USB2.0 port, excluded external instruments like signal generators and oscilloscopes. Figure 7 depicts the setup, showcasing the low-cost authors' construction alongside ExpEYES-17 connected to a laptop. ExpEYES-17 was the sole instrument for resistance measurement, signal generation, and waveform viewing. The setup includes the coil-pair, a 20 $k\Omega$ Multi-turn Precision Potentiometer, ExpEYES-17, and a laptop (Ubuntu/Windows); alternatively, an Android device can be used. Note that the entire experiment can also be conducted with a signal generator, oscilloscope and a multimeter in undergraduate laboratory. The Multi-turn Precision Potentiometer uses bifilar coils on air-core to eliminate parasitic inductances.

4.4. Measurement and results

4.4.1. Measurement of individual self-inductances. First, experiment was performed to characterize the two self-inductors. Then the inductance of each coil was measured using the circuit shown in figure 2, and the characteristics of the two inductors are tabulated in table 2. A screenshot taken during the measurement of L_p is shown in figure 8.

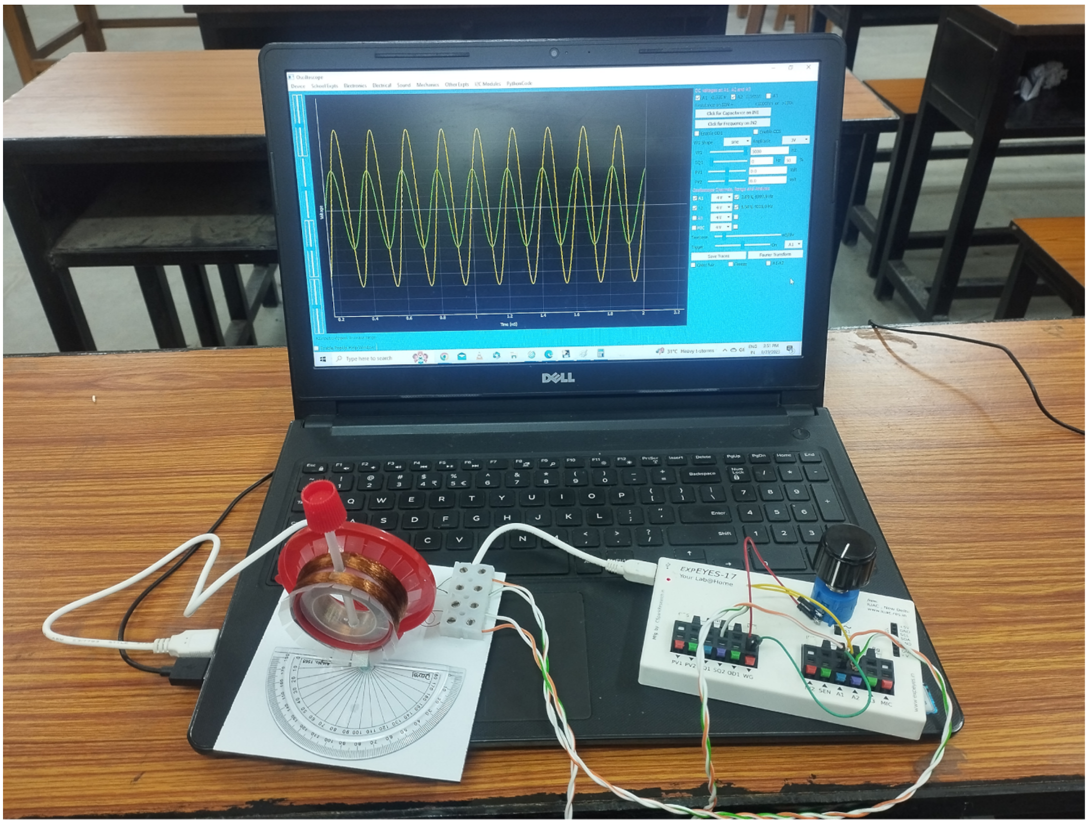


Figure 7. Actual photograph of the experiment setup. At the left, the low-cost setup constructed by the authors. At the right, the ExpEYES-17 kit, connected with a Laptop. The ExpEYES-17 GUI can be seen on the laptop screen behind. *Note:* ExpEYES-17 was the only instrument the authors have used in this experiment for the measurement of resistances, signal generation and viewing of waveforms on Laptop screen.

Table 2. Characteristics of two inductors (setting (i) $\theta = 0°$, (ii) $f = 5\ kHz$, (iii) $|v_{\text{in}}| = 3.00\ V$).

Inductor	Internal DC resistance (Ω)	R (Ω)	Inductance $L_{p,s}$ (mH) (Using equation (3))
Primary	368 ($= r_p$)	3330	66.63 ($= L_p$)
Secondary	352 ($= r_s$)	4037	79.65 ($= L_s$)

4.4.2. Indirect method: determination of mutual-inductance and coupling co-efficient. In order to measure mutual-inductance through indirect method, the coils were connected in series as shown in figure 3. Then for various θ (in the range of $0° - 180°$), $R_{(x,y)}$ was measured; the variable resistance (20 $k\Omega$ Pot) was varied to achieve $|v_{\text{out}}| = \frac{1}{2}|v_{\text{in}}|$ for each θ, and then, the resultant inductance was determined using equation (10). If the resultant inductance (at $\theta = 0°$) was more than $L_p + L_s$ (as indicated in table 2), then the coils were connected in additive series, else they were connected in subtractive series. The resultant inductances for different angles between the planes of the coils with additive and subtractive series configurations were measured. The experimental data of this measurement are shown in table 3. Using the experimental data from table 3, a graph was plotted to understand the variation of mutual-inductance due to the variation of angles between the planes of the coils. This plot is shown in figure 9.

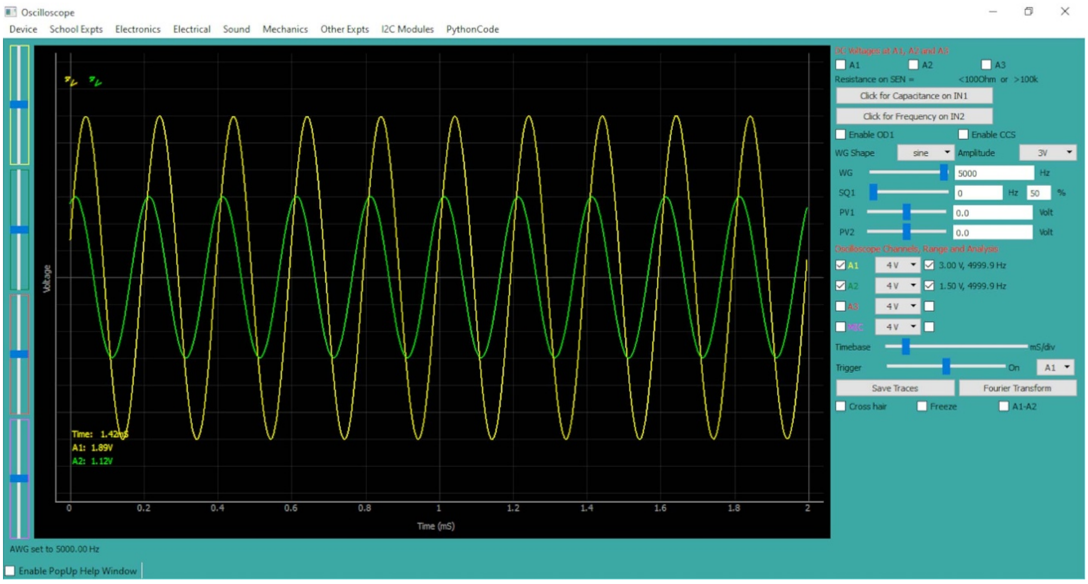


Figure 8. Screenshot taken during the experiment in the determination of self-inductance. Input voltage was set to 3.0 V, and output voltage was tuned to half of v_{in}, i.e. 1.5 V, by adjusting the 20 $k\Omega$ Pot.

Table 3. Measurement of mutual-inductance and coupling co-efficient using **indirect method** (setting (i) $f = 5\ kHz$, (ii) $|v_{\text{in}}| = 2.99\ V$).

θ (degree)	$R_x(\Omega)$	$R_y(\Omega)$	$L_x(mH)$ (Using equation (10))	$L_y(mH)$ (Using equation (10))	M (mH) (Using equation (9))	k (Using equation (11))
0	11 169	3238	233.44	67.67	41.44	0.56
10	11 063	3285	231.23	68.66	40.64	0.55
20	10 911	3584	228.05	74.91	38.28	0.52
30	10 442	3922	218.25	81.97	34.06	0.46
40	10 130	4442	211.73	92.84	29.72	0.40
50	9610	4951	200.86	103.48	24.34	0.33
60	8994	5560	187.99	116.21	17.94	0.24
70	8438	6101	176.36	127.51	12.21	0.16
80	7800	6728	163.03	140.62	5.60	0.07
90	7260	7280	151.74	152.16	0.10	0.00
100	6650	7820	138.99	163.44	6.11	0.09
110	6052	8442	126.49	176.44	12.48	0.17
120	5518	9068	115.33	189.53	18.54	0.25
130	4965	9632	103.77	201.32	24.38	0.33
140	4390	10 106	91.76	211.22	29.87	0.40
150	3900	10 474	81.51	218.91	34.35	0.47
160	3615	10 850	75.56	226.77	37.80	0.51
170	3415	11 021	71.38	230.35	39.74	0.54
180	3215	11 125	67.2	232.52	41.33	0.56

4.4.3. Direct method: determination of mutual-inductance and coupling co-efficient. The circuit for direct method is shown in figure 4. Direct method involves two steps. In the first step, the input, v_{in} was applied to the primary coil and $|v_p|$, and $|v_s|$ was noted (from the console display) for

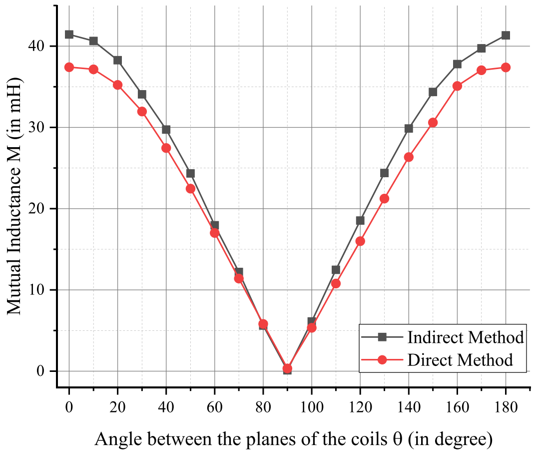


Figure 9. Plots of M (mutual-inductance) vs. θ (angle between the planes of the coils) obtained by using indirect and direct methods.

various θ (in the range of $0°$ to $180°$ in steps of $10°$). In the second step, instead of applying input to the primary coil, v_{in} was applied to the secondary coil, and the process was repeated. A screenshot captured during the experiment for $\theta = 50°$ is shown in figure 10. The waveforms of v_p and v_s were observed (on the console screen) and their amplitudes were noted for various values of θ. These experimental data is tabulated in table 4. From these experimental data, a graph of mutual-inductance as a function of θ (angle between the planes of the coils) was plotted and is shown in figure 9.

4.4.4. Effect of iron core on inductance. It would be interesting to observe the presence of iron core in the coils (this part of the experiment was conducted to add value to the overall learning).

The effect can be easily observed with the circuit for direct method. The input, v_{in} was applied to primary coil and emf at the secondary coil was observed with and without a iron core. The effect was studied by inserting a iron file into the coil-pair system. The result of these observations are tabulated in table 5. The screen shots of these observations are shown in figure 11.

5. Discussions

The plots, generated through both direct and indirect methods, closely match in mutual inductance values, displaying the well-known ‘V-shape’ curve (see figure 9). Maximum magnetic flux linkage occurs at $0°$ or $180°$, while no linkage is observed at $\theta = 90°$. The coupling coefficient k ranges from 0.56 to 0, indicating strong coupling at $0°$ to $\pm 20°$ and weak coupling from $\pm 30°$ to $90°$.

The indirect method, while requiring separate measurements of variable resistance for each angle setting, presents a disadvantage compared to our simpler direct method. Despite this drawback, studying both methods enhances students’ understanding. In direct method repetitions, the maximum result variation was $< 0.1\%$, ensuring high repeatability. In the indirect method, the maximum variation was $<1\%$. Undergraduate students verified these repeatability experiments, obtaining good results. Direct method accuracy slightly surpassed that of the indirect method, which involves both observation and measurement. Among the indirect and direct methods, a systematic error of about 7% was found. In comparison to direct method, the indirect method involves manual adjustment of R_{var} (see figure 2) and its measurement. As a result additional errors are introduced in the indirect method.

We have determined the self-inductance using the expression $L = \frac{\mu_0 \pi R n^2}{2}$, and found the values of the coils as $L_p = 66.56$ mH and $L_s = 79.86$ mH, very closely matching the measured values of 66.63 mH and 79.65 mH, respectively.

The effect of skin depth is insignificant in this experiment. At the highest frequency of our experiment, i.e. 5 kHz, the ideal value of skin depth for copper $\delta(= \sqrt{\frac{\rho}{\pi f \mu_0 \mu_r}})$ is calculated to be 0.922 mm, while the radius of a 42 SWG wire is about 0.05 mm, meaning, the whole thickness of the conductor is available for conduction.

Using a soft iron or ferrite rod as an inductor core increases inductance (see table 5) compared to an air-core inductor. The iron core (ferromagnetic material of high permeability) decreases the reluctance of the magnetic path to flow the

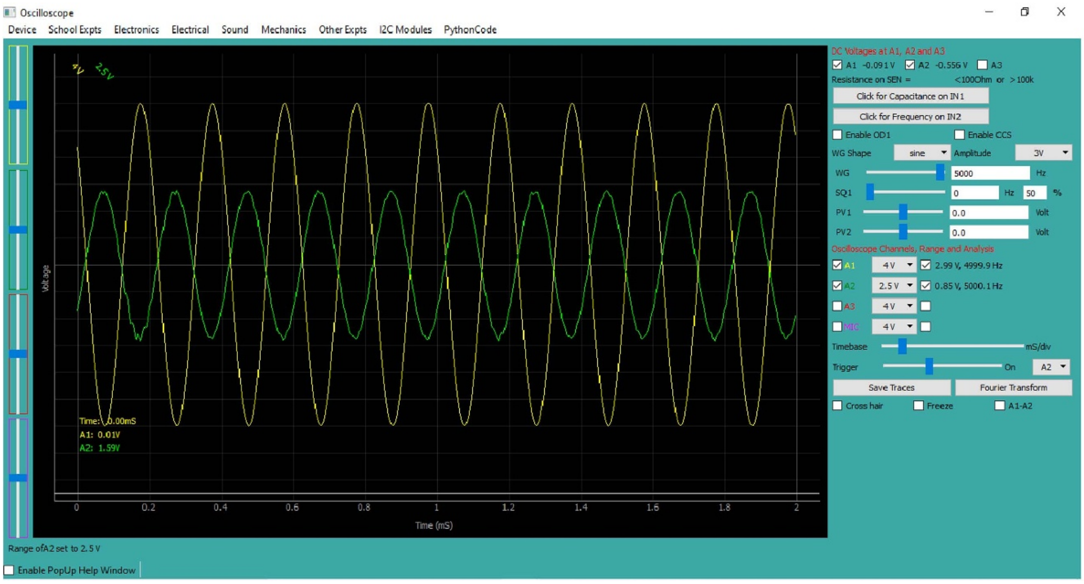


Figure 10. Screenshot captured during the experiment where $\theta = 50^{\circ}$, The Channel A2 showing the reading at the primary coil, while the secondary coil was excited by a 3.00 V, 5 kHz sinusoid.

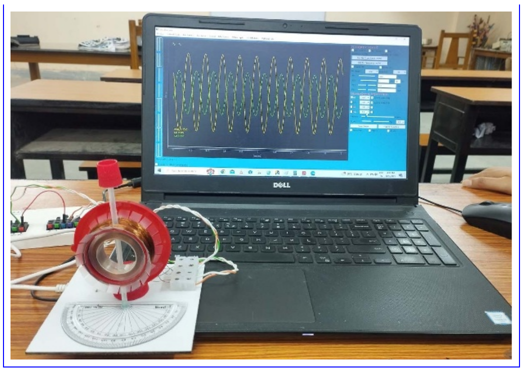
Table 4. Measurement of mutual-inductance and coupling co-efficient using **direct method**. (Setting (i) $f =$ 5 kHz, (ii) $|v_{\text{in}}| = 3.00$ V). The boldfaced reading is shown in the screenshot captured during the experiment (See figure 10).

θ(degree)	$\lvert v_s \rvert$(Volt)	$\lvert v_p \rvert$(Volt)	k (Using equation (15))	M(mH) (Using equation (14))
0	1.66	1.42	0.51	37.41
10	1.65	1.41	0.51	37.16
20	1.56	1.34	0.48	35.23
30	1.41	1.22	0.44	31.96
40	1.21	1.05	0.38	27.46
50	**1.00**	**0.85**	**0.31**	**22.46**
60	0.75	0.65	0.23	17.01
70	0.51	0.43	0.16	11.41
80	0.26	0.22	0.08	5.83
90	0.01	0.02	0.00	0.34
100	0.24	0.20	0.07	5.34
110	0.48	0.41	0.15	10.80
120	0.72	0.60	0.22	16.02
130	0.95	0.80	0.29	21.24
140	1.17	1.00	0.36	26.35
150	1.36	1.16	0.42	30.60
160	1.55	1.34	0.48	35.11
170	1.64	1.41	0.51	37.05
180	1.66	1.42	0.51	37.40

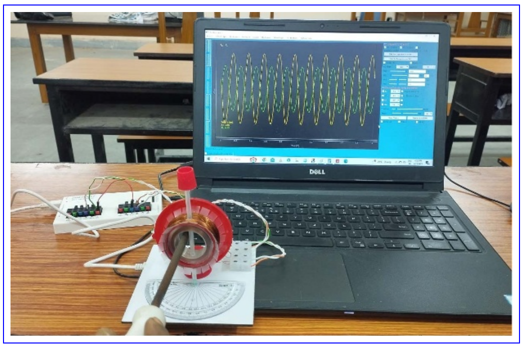
Table 5. Impact of placing iron-core (a iron file) inside the coils under direct method setup (with $\theta = 0^\circ$) (See figure 11).

Presence of iron core (a iron file)	$\|v_s\|$(Volt)
No	1.66
Yes	1.93

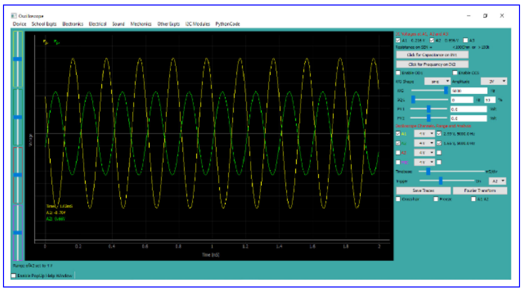
Remarks: The presence of iron core increases the individual inductances of the coils and hence, increases their mutual-inductance too (see the Discussion section, for the reason of this increase).



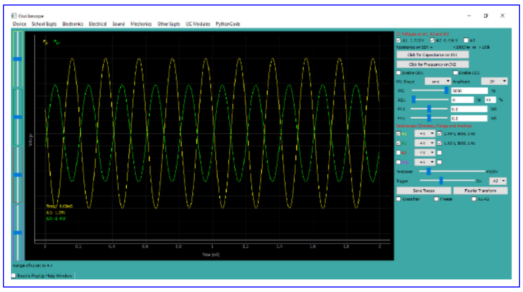
(a) Experiment setup, without iron core.



(b) Experiment setup, with a iron core.



(c) Plot without iron core.



(d) Plot with a iron core.

Figure 11. Experiment setup (figures (a) and (b)) and results (figures (c) and (d)) (see table 5).

magnetic flux. This is due to the alignment of magnetic domains along the magnetic field in a ferromagnetic material which in turn increases the linkage of the magnetic flux with the coil(s) [20]. In our experiment, a common iron core increased self-inductance and mutual inductance, as both coils shared the same core, enhancing understanding of these factors.

6. Conclusion

This study underscores the importance of accessible and simple laboratory setups, especially in experimenting with self- and mutual-inductance using a cost-effective coil-pair arrangement. The adapted circuitry is straightforward, requiring minimal hardware and components, making it suitable for undergraduate and pre-university students. The authors aim to simplify the experiment and its theoretical foundation, making it accessible even to 12th-grade students. The internal visibility of the coil-pair system aids efficient concept comprehension, addressing previous issues of experimental opacity. Additionally, the study enhances inductance understanding through an iron core experiment, offering advantages over conventional methods. The authors hope the article inspires the creation of low-cost setups for teaching self and mutual inductances, catering to both in-person and online learning-a teaching paradigm that gained significance post-COVID-19.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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