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Teaching remote laboratories using smart phone sensors: determining the density of air

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Abstract

During the COVID-19 pandemic and subsequent lockdown, both schools and universities faced significant challenges in moving teaching from an *in-situ* setting to a remote one, this included laboratory experiments. This paper presents an experiment developed to use a phone's in built pressure sensor, common to most smart phones. By using this sensor to measure the pressure at a series of known heights, the density of air was calculated with an accuracy of approximately $\pm 0.03\,\mathrm{kg\,m^{-3}}$. This was completed as part of a first year undergraduate course.

Keywords: COVID-19, remote experiment, pressure

1. Introduction

The COVID-19 pandemic and the associated lockdown has had a huge impact on teaching worldwide [1]. Almost overnight with no time to prepare, teaching had to switch from face-to-face to online. This included lectures, tutorials and laboratories. Teaching practical based laboratories presented a significant challenge, this was overcome in a variety of ways, through a mix of different approaches [2]. These included using Audrino or raspberry pi's [3], along with low cost sensors. The disadvantage of this method was that these would need to be purchased, the kits constructed and then posted in the limited timescale available. Another option was computational simulations [4], but since already most of the interaction was computational, it would be significantly more beneficial both in terms of skills and motivation, for students to have something practical and hands on.

Another approach was to utilise equipment/measurement tools that students would already have access to at home such a mobile phone [5].

This method had several advantages, principally that it could be done quickly and did not require administering any equipment loans.

Chances were very high that students already had a device capable of recording and logging precise physical quantities. According to ofcoms communications market report in 2020 [6], 98% of households had access to a smart device at that time. Packed into that small device is a host of sensors, which can be utilised to perform experiments and determine physical parameters [7].

The experiment discussed contributed to the laboratory component of a module called 'instrumentation physics', which is taught in the second semester of the first year of the undergraduate Physics course at Keele University in the UK. This module aims to develop underlying principles and characteristics of instrumentation which will enable students to choose or develop appropriate instrumentation for a specific application.

The intended learning outcomes of the laboratory were to:

(a) Describe and explain the fundamental methods of measuring various parameters important in Physics.
(b) Critically review the implications associated with various methods of measurements.
(c) Choose the appropriate measurement technique for various systems.
(d) Perform basic measurements and apply a calibration if necessary to the data in order to measure the intended physical parameter.

By enabling students to record and process measurements with there own instrument they would be able to meet all the intended learning outcomes.

Amongst the sensors packed into smart phones, it might be surprising to hear there should be a pressure sensor, this helps with location and navigating.

2. Theory

The pressure sensor works by using a small circuit on a flexible membrane. As the air pressure distorts the shape of the membrane, the resistance of the circuit changes. This change in resistance can be used to determine the pressure [8].

The relationship describing pressure as a function of height in the column of air with a height of h, and an area A at the bottom can be derived using the following simple relationships:

Force = Mass × Acceleration → $F = Ma$, $a = g$ where this instance the acceleration is due to gravity,

Pressure = Force/Area → $P = \frac{F}{A}$,

Mass = Density × Volume → $M = \rho V$ and

Volume of column = Area × height → $V = Ah$

These equations are combined as follows:

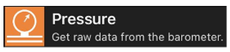
$$P = \frac{F}{A} = \frac{ma}{A} = \frac{\rho V g}{A} = \frac{\rho A h g}{A} = \rho h g$$
$$P = \rho h g \qquad (1)$$

Equation (1) is known as the hydrostatic pressure equation, which shows that the pressure, P in the column of air is related to the height, h by the acceleration due to gravity, g as well as the density of air, ρ.

This meant that by recording the pressure at various heights, the density of air could be determined.

3. Experimental procedure

Experimental readings from the pressure sensor (and various other sensors) can be accessed by using the phyphox app [9], which is available on both ios and android from the respective app stores.

(a) Once the app has been downloaded and opened, a list of sensors show what measurements are accessible on the device. Clicking on the 

sensor will show the atmospheric pressure as shown in figure 1. Within the app it is possible to switch between displays of 'simple', which simply states the pressure as a value, and 'graph', which plots the pressure against time, illustrated in figure 2. The icons in the top right,  are used to start/pause, clear the last run and further options, including exporting data and remotely accessing the app, using a web browser (need to be connected to same Wi-Fi).

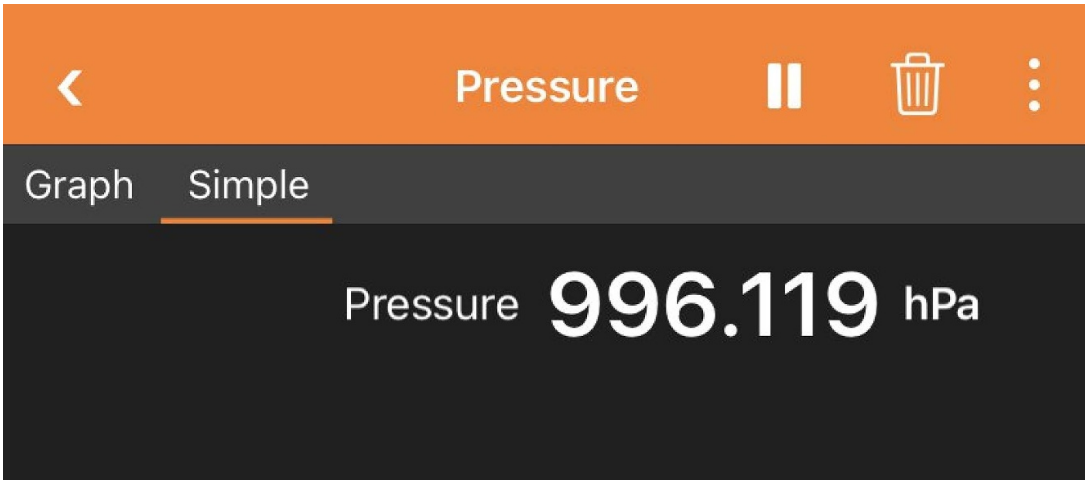


Figure 1. Absolute pressure as displayed by the phyphox app, note the value is in hPa, hecto ($\times 10^2$) Pascals.

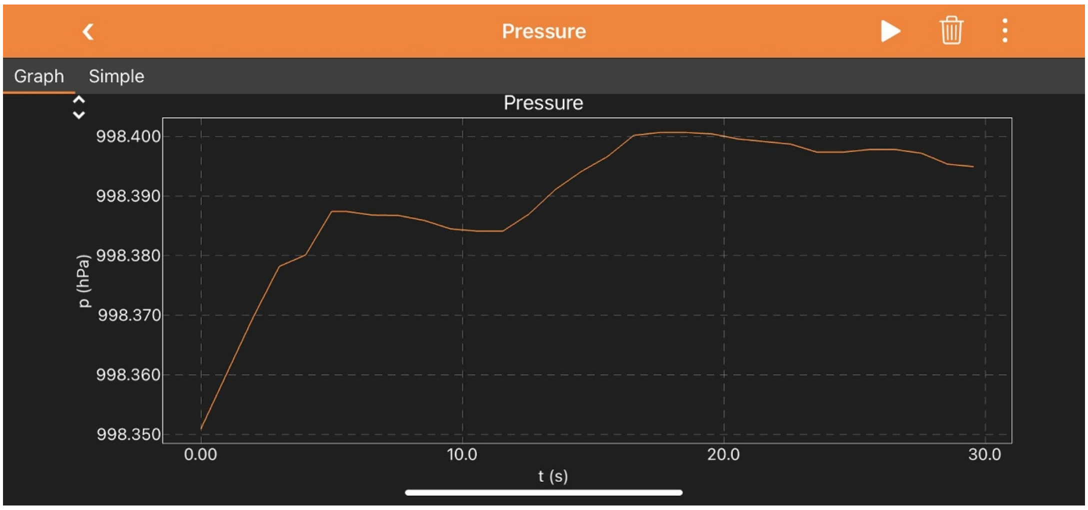


Figure 2. Pressure expressed as a function of time using the 'graph' feature of phyphox.

(b) Firstly students estimated the error in measurement values. With the phone placed on a steady surface, data was recorded using the 'graph' function for about 20 s. Using this data the error for the pressure readings can be estimated from the range in values.

(c) It was important to check that the error in the readings were not larger than the change in readings observed when varying the height. This was quickly checked by recording the pressure difference from the phone on the floor, to when the phone was lifted above head height. It was found that the change in pressure recorded was much higher than the error determined in the previous part.

(d) The pressure needed to be measured at a series of known heights. When students performed this experiment at home during lockdown, they were allowed and encouraged to do this however they wanted. There was a suggestion to measure the pressure at each step of a staircase or using a bookcase for example, it is also good practice to measure multiple readings at each height, in order to calculate an

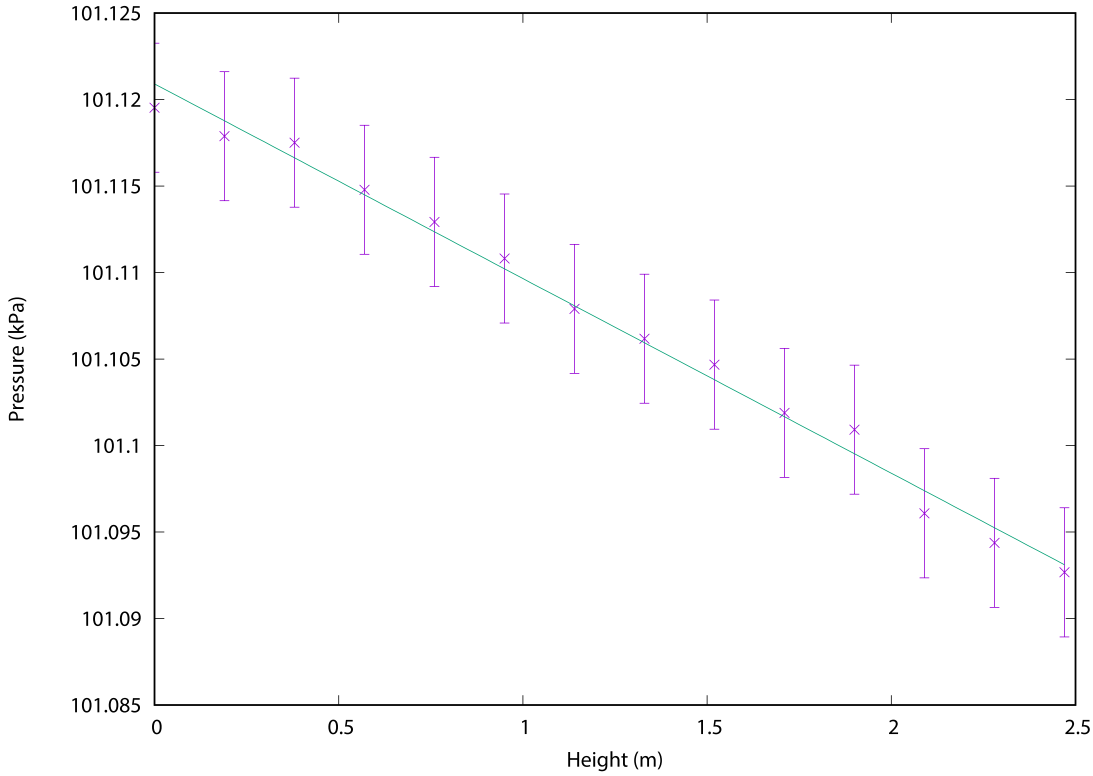


Figure 3. Example of collected data showing the decrease in pressure as the height is increased. A trend line was fitted to the data in order to calculate the density of air from the gradient.

error and check for reproducibility. Students could measure the height of one step and use this to calculate the height at each step. Most students used the method of stairs, one student however took very detailed measurements by using the brick pattern on their house.

(e) Lastly students plotted a graph of pressure, P against height, h, the gradient of this graph is $\rho \times g$ and hence ρ was found by dividing the gradient by g.

4. Results

Figure 3 shows an example of data collected using an iPhone 11 over a single flight of internal stairs. The gradient was determined by a least squares fit to be $-0.0113 \pm 0.0003\,\text{kPa m}^{-1}$, or since Pa = $\text{kg m}^{-1}\,\text{s}^{-2}$.

$$\frac{dy}{dx} = \frac{P}{H} = \rho g = 0.0113 \times 1000\,\text{kg m}^{-2}\,\text{s}^{-2}$$

where $g = 9.81\,\text{m s}^{-2}$.

The gradient is negative due to the direction of pressure change being such that the pressure decreases with height or altitude. The density of air is then calculated by dividing the gradient by g.

$$\rho = \frac{0.0113}{9.81} = 0.00115 \times 1000$$
$$= 1.15 \pm 0.03\,\text{kg m}^{-3}.$$

The density of air, ρ is usually given as $1.20\,\text{kg m}^{-3}$ for dry air at 20 °C and 101.325 kPa [10]. But it will depend on the altitude, temperature and humidity of where the measurements are taken, so the calculated value will likely be slightly different.

How each of the factors would effect the value for the density of air was a good discussion topic. Since the example measurements were carried out at a height above sea level and not using dry air, the expected value would be less than that of the given literature value since an increase in altitude and humidity would result in a lower density.

When this experiment was performed during lockdown, and students were spread out across the UK, differences in values could be discussed and how various geographical factors may be contributing to the determined value.

Whilst the effect of altitude was expected from previous knowledge and observations during the experiment. The effect of humidity surprised many students, typical interaction with water is in it is liquid form where it is clearly heavier than air. However the molar mass of water, H_2O is 18.02 g mol^{-1}, which is less than that of Nitrogen, N_2 (28.01 g mol^{-1}) and Oxygen, O_2 (32.00 g mol^{-1}) [10]. So adding water vapour displaces a heavier molecule, decreasing the density.

5. Conclusions

The experiment presented here shows that despite the disruption caused by the COVID-19 pandemic and associated lockdown, it was possible to perform investigations at home to determine fundamental physical quantities such as the density of air to a reasonable precision. Beyond the numerical results it is was also the authors goal to demonstrate that Physics does not only occur in a laboratory.

This experiment allowed students despite not having access to the laboratory and typical measurement equipment to meet the ILO's of the module.

(a) They were able to gain experience in a method for measuring pressure and apply this to determining the density of air.
(b) Review the implications associated with this method.
(c) Choose an appropriate measurement technique.
(d) Perform their own basic measurements and process the data to calculate the density of air.

73% of students who attended the session completed the experiment.

In the module feedback students said they were glad of the remote phone experiments but felt the remote labs were less engaging and missed performing experiments in the lab with fellow students. This was the inherent weakness with many of the remote activities, that many of them were performed largely in isolation. Even with webcam's and chat facilitates, the laboratory was significantly less social than a typical in-person laboratory where students work in pairs or small groups, this is consistent with the observations and finding of others [11].

This might be useful to teachers for future though, as no equipment needs to be purchased as the students can use their own devices to perform this experiment in school, or to utilise the technique to observe pressure changes around a three-dimensional environment with varying elevations, such as a school grounds.

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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