MAY 01 2022

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American Journal of Physics 90, 328–343 (2022)
https://doi.org/10.1119/5.0073317

RESOURCE LETTER

Resource Letter MDS-1: Mobile devices and sensors for physics teaching

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(Received 29 September 2021; accepted 31 January 2022)

This Resource Letter provides a guide to the literature on teaching experimental physics using sensors in tablets, smartphones, and some specialized devices. After a general discussion of hardware (sensors) and software (apps), we present resources for experiments using mobile-device sensors in many areas of physics education: mechanics, oscillations and waves, optics, electromagnetism, matter, modern physics, and astronomy.

https://doi.org/10.1119/5.0073317

I. INTRODUCTION

In recent years, there has been a revolution in the use of cell phones. In the late 2000s, smartphones appeared in the market and quickly became extremely popular: About 1.5×10^9 smartphones were sold in 2020, and the vast majority of physics students around the world have access to a smartphone.

Smartphones can be a useful experimental tool not only because they have a relatively powerful processor and can access wireless networks but also due to the presence of a number of built-in sensors (see Table I). Sensors can determine the orientation of the device, disable the touch screen, adjust the display's brightness according to external conditions to save the battery, geolocate the device, monitor the user's heart rate, and unlock the device. The set of sensors included in mobile devices is large and is expected to expand in the coming years.

The relevance of the sensors goes far beyond those everyday uses mentioned: In recent years, numerous educational and scientific applications have been proposed, including physics experiments. As the original intention of sensor manufacturers was not to use these sensors in science or physics experiments, some effort is needed to transform smartphones into scientific instruments. However, the reward for making this effort is considerable. Even mid-range smartphones incorporate a broad range of sensors that would otherwise be difficult to acquire. Since most students already have such a device, they can be combined with easily available equipment and materials to create a low-cost, compact, multisensor experimental platform with no need for complicated connections or setup. Another factor, less objective, is that students do not consider a smartphone to be a strange or magical device, since it is part of their daily lives. Whether or not this fact influences the learning process is still under examination.

We might compare smartphones to devices designed specifically for the use of instructional laboratory experiments in physics and science, including the SmartCart® (Pasco), PocketLab® (Myriad Sensors, Inc.), IOLab® (MacMillan), and Go Direct® Sensor Cart (Vernier). These devices share some capabilities with smartphones but do not offer the traditional phone functions. In these devices, the selection of sensors, the connectivity, and the software have been designed for pedagogy with student-friendly interfaces. However, these devices are still alien to the student's experience, as compared to a smartphone. In addition, these devices must be purchased specifically for the physics laboratory, as students will not already own them. There also exist several platforms, such as Arduino or BBC mibro:bit (see Refs. 5, 12, 14, 15, and 16 below), that have been adapted to perform experiments using sensors. Unlike smartphones in which the set of sensors is predetermined by the manufacturers, these programmable boards allow one to choose from a wide range of sensors and modules including ultrasound sensors, flame detectors, infra-red emitters and receptors, water level sensors, relays, PIR (Passive infrared), and metal detectors. We have included a few articles using Arduino boards as examples of experiments that could be accomplished using a combination of Arduino boards and smartphones.

Table I. Commonly used sensors.

Abbreviation	Sensor	Type	Quantity	Magnitude provided	Basic purpose
Ac	Accelerometer	Sensor	Vector	Apparent acceleration	Rotate screen
LAc	Linear accelerometers	Pseudosensor (a device that incorporates inputs from more than one sensor and after performing some calculations returns another magnitude)	Vector	Apparent acceleration minus gravitational acceleration	Detect motion
Gy	Gyroscope	Sensor	Vector	Angular velocity	Device's orientation
Mi	Microphone	Sensor	Scalar	Sound	Communication
Ca	Camera	Sensor	Matrix	Images	Take pictures
Prox	Proximeter	Sensor	Boolean	Near object detected	Disable the screen
Li	Light	Sensor	Scalar	Ambient light	Control display brightness
Pr	Pressure	Sensor	Scalar	Atmospheric pressure	Indoor and outdoor height location
Or	Orientation	Pseudosensor	Three angles	Around X axis (Pitch) Around Y axis (Roll) Around Z axis (Azimuth)	Device's orientation
GPS	GPS	Receptor	Location	Geographical location	Location
Ma	Magnetometer	Sensor	Vector	Local magnetic field	Device's orientation

Communication with sensors requires specific software, known as an *app*, specially designed to be executed by the mobile device. Since most of the mobile devices currently used are based on two operating systems, iOS and Android, we will discuss the most useful apps running in these operating systems, but many others also may be useful in specific circumstances.

This Resource Letter is aimed at physicists and scientists interested in adapting or performing experiments using mobile-device sensors to collect *real* physical data. Other potential uses of the mobile devices in the classroom, such as accessing the internet, sharing data among students, interacting with teachers, clicker-like activities, simulations, among many others, are not considered here. Video analysis of physical phenomena, which has received a lot of attention in the recent decades, is also not included in this Resource Letter. In the selection of references, preference has been given to papers in which the experiments can be performed using state-of-the-art software and hardware. Within the selection criteria, we prioritized articles published in journals—but we also cite some of the few books already published—that present experiments with sufficient detail and clarity that they will be straightforward to implement in a classroom.

The organization of this Resource Letter is as follows. As the topic is relatively new, there are only a few books that are cited in Sec. II. After that, resources about hardware and useful apps (software) are discussed. Next, we focus on experiments, starting with references covering multiple fields' topics and then focusing on specific fields (mechanics, oscillations and waves, optics, electromagnetism, matter, modern physics, and astronomy). Finally, we discuss citizen science, educational proposals, and impact in Physics Education Research (PER).

II. BASIC RESOURCES

A. Journals and special issues

The recent literature addressing physics experiments using smartphone and mobile-device sensors in physics is substantial. Since 2011, hundreds of journal papers have been published. Most of the articles cited in this Resource Letter have been published in the following journals:

American Journal of Physics: https://aapt.scitation.org/journal/ajp
European Journal of Physics: https://iopscience.iop.org/journal/0143-0807
Physics Education: https://iopscience.iop.org/journal/0031-9120
Revista Brasileira de Ensino de Física: http://www.sbfisica.org.br/rbef/
The Physics Teacher: https://aapt.scitation.org/journal/pte

It is worth highlighting that the regular column, *iPhysicsLab*, has been published monthly in *The Physics Teacher* since 2012. Also, the *Papers in Physics* journal published a Focus Series on *Low-cost Experiments in Physics using recent technologies as sensors or open source hardware,* located at https://www.papersinphysics.org/papersinphysics/lowcostexperimentsinphysics. Another mini review worth mentioning was published by J. Stoop, *New ways to use smartphones for science, J. Stoop (Elsevier Connect, 2017)* located at: https://www.elsevier.com/connect/new-ways-to-use-smartphones-for-science. This virtual special issue from Elsevier is a must-read ensemble of papers previously published in journals. It includes resources in citizen science relatively accessible to the public, covering topics such as environment, health, space, smart cities, and society. Emphasis is given to experiments or measurements that can be conducted by the public following collaborative or crowd-sourcing methodologies.

B. Books, eBooks, and internet resources

The following references are suitable choices for an introductory approach to the use of a smartphone sensor in the physics laboratories.

1. ***Kinematic Labs with Mobile Devices***, J. M. Kinser (Morgan & Claypool Publishers, 2015). DOI: https://doi.org/10.1088/978-1-6270-5628-1. This book (also

available as an eBook) presents a comprehensible introduction to the use of smartphone sensors by first-year students at home or in places where laboratories are not easily accessible. It presents 13 experiments requiring only a smartphone and widely available equipment and also includes a brief overview of typical sensors and data analysis using typical apps and PC software. (I)

2. ***iStage 2: Smartphones in Science Teaching***, edited by U. Hänsler, S. Schlunk, and J. Schulze (Science on Stage Deutschland e.V., Germany, 2014). Published by the Science on Stage Europe group (https://www.science-on-stage.eu/), it offers an introduction to the use of smartphones and a dozen simple experiments aimed at secondary-school teachers in mathematics, physics, chemistry, and biology. A free download available in German and English from this link: https://www.science-on-stage.eu/smartphones. (E)
3. ***Mobile Device Models***, W. Christian, C. Countryman, and F. Esquembre. This internet website https://www.compadre.org/books/?ID=49&FID=45990 hosted by the AAPT project ComPADRE, emerged from the popular computer-generated *Physlet* (**Phy**sics content simulated with Java app**lets**) animations and provides *Easy Java* simulations, problems, and lectures designed to demonstrate physical concepts involving sensors and mobile devices. It is especially devoted to the use of the accelerometer for experiments with inclines, pendulums, and rolling bodies. As accelerometers do not directly measure acceleration, but instead measure forces, the simulation of *spring-accelerometers* is useful to discuss these differences. This site provides not only the simulations but also learning objectives, exercises, and resources. (E)
4. **Amusement Park Science: An AAPT Digi Kit,** C. Hall and R. Vieyra. The site https://www.compadre.org/books/AmusementPark, also hosted by the AAPT project ComPADRE, is aimed at experimenting with motion and forces in amusement park rides. It proposes several activities related to circular motion and roller coasters and discusses pedagogical aspects of the implementation. (E)
5. ***Physics Experiments with Arduino and Smartphones***, G. Organtini (Undergraduate Text in Physics, Springer, 2021). Focused on experimental design, data acquisition, and processing at the intersection of Arduino and smartphone sensors, it discusses several experiments, especially in mechanics. Programming skills involving PYTHON, C, and data visualization are recommended. (A)
6. ***Smartphones as Mobile Minilabs in Physics***, edited by J. Kuhn and P. Vogt (Springer, 2021). This edited volume features more than 70 examples from 10 years of the *iPhysicsLabs* column of *The Physics Teacher* journal. (I)

III. HARDWARE

In Table I, we list the most common smartphone sensors and their main characteristics. This Resource Letter is not focused specifically on the hardware; however, there are many important aspects that should be considered when designing an experiment with these sensors. Perhaps, the most obvious fact is the existence of quantities of different physical characteristics. For example, there are sensors that measure scalar quantities, such as the ambient light sensor and the microphone, and sensors that measure vector quantities, such as the accelerometer and magnetometer. Other sensors are more difficult to classify such as the proximity sensor, on-off sensor, camera (which provides a single or a set of frames), or GPS (for geographical location). In the case of vector quantities, it is of importance to highlight that the axis refers to a system attached to the device. The orientation of the axis corresponds to the principal axis of a rectangular box (Fig. 1).

The precise location of the sensor inside the device could also be important in many experiments. In some cases, the location of a sensor is rather obvious: The ambient light sensor can be located simply by moving a finger back and forth above the device while watching the reading on the sensor. The magnetometer can be approximately located by scanning the device with a small magnet and watching the magnitude of the magnetic field detected. The precise location of the accelerometer is frequently needed but is difficult to find; one of the papers below describes a process for locating it.

Below, we provide a list of articles published in the physics literature that discuss the function of the sensors. In addition to the physics literature, there are also several engineering journals focused specifically on sensors, including electronics and data processing

7. "Familiarizing students with the basics of a smartphone's internal sensors," C. L. Countryman, Phys. Teach. **52**(9), 557–559 (2014). This paper provides a basic description of the functioning of *micro electromechanical systems* (MEMS) and accelerometers, discusses the orientation of the smartphone's axes, and, based on the ball-and-spring model, shows that accelerometers are, in fact, force sensors. (I)
8. "Gamified physics challenges for teachers and the public," R. Vieyra, C. Vieyra, A. M. Pendrill, and B. Xu, Phys. Educ. **55**(4), 045014 (2020). This paper describes the Physics Toolbox Play, a "gamified" component of the Android Physics Toolbox Sensor Suite app dedicated to introducing fundamental physics principles to children and discusses pedagogical aspects of the implementation of the approach with students and teachers of different educational levels. (E)

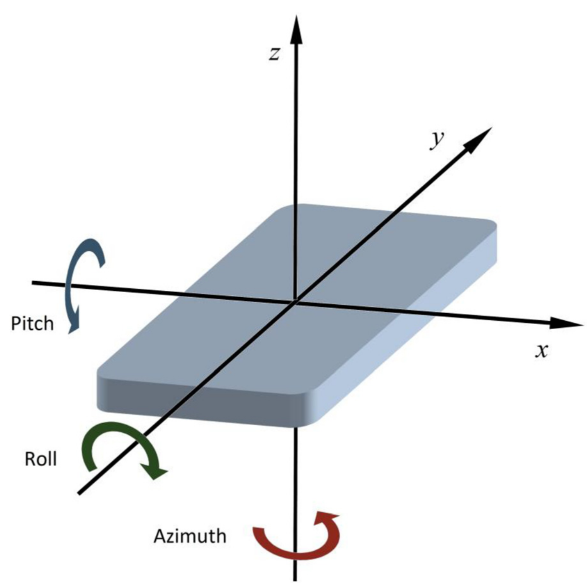

Fig. 1. Standard coordinate system of a smartphone and the orientation angles.

9. “Understanding the gyroscope sensor: A quick guide to teaching rotation movements using a smartphone,” V. L. B. de Jesus, C. A. C. Pérez, A. L. de Oliveira, and D. G. G. Sasaki, Phys. Educ. **54**, 015003 (2018). Using a simple setup consisting of a smartphone mounted on a turntable, this paper gives a quick overview of the use of the gyroscope sensor, explains how to interpret data of the three components of angular velocity, and discusses how to encourage teachers to incorporate smartphone sensors, especially in high schools and undergraduate physics. (I)
10. “Smartphone audio port data collection cookbook,” K. Forinash and R. Wisman, Pap. Phys. **10**, 100006 (2018). The audio port present in many mobile devices can be transformed to accurately measure a variety of other magnitude sources such as voltage, external temperature, or accurate timing of moving objects. This paper provides technical details on how to use the audio port to sense external phenomena. (A)
11. “On the determination of accelerometer positions within host devices,” C. I. Larnder and B. Larade, Am. J. Phys. **87**(2), 130–135 (2019). The precise location of the accelerometer within the device is an important input in several experiments. An experimental method to determine the accelerometer position is also discussed here. (I, A)
12. “Arduino-based data acquisition into Excel, LabVIEW, and MATLAB,” D. Nichols, Phys. Teach. **55**, 226 (2017). Arduino tools are rather primitive for plotting data, but this article shows how to acquire data by means of Arduino-compatible sensors and then analyze it with popular (although non-free) software packages such as EXCEL, LabVIEW, or MATLAB. (I, A)
13. “Open-source sensors system for doing simple physics experiments,” C. Llamas-Bello, J. Vegas, M. A. González-Rebollo, and M. A. González-Delgado, Pap. Phys. **10**, 100004 (2018). This paper describes an economical alternative to commercial platforms that allows interfacing sensors with a personal computer. The GitHub repository also allows collaboration between users that can add new characteristics to the platform. (I, A)
14. “Improving students’ skills in physics and computer science using BBC Micro:bit,” A. Teiermayer, Phys. Educ. **54**(6), 065021 (2019). The BBC Micro:bit is a programmable board that is less powerful than Arduino boards but simpler to program and includes several built-in sensors. Several activities are proposed in this article, ranging from measuring the statistic friction coefficient of a block to measuring the Planck constant using LEDs. (E)
15. “Arduino-smartphone device as a physical phenomena measurer,” S. Varela-Ballesta, R. Saez, J. Iglesias, and A. Vernet, Phys. Teach. **58**(9), 663–665 (2020). Popular Arduino sensors can be interfaced with smartphones using a small piece of hardware, allowing, for example, an experiment about electromagnetic induction in which the smartphone is turned into a simple oscilloscope. This article explores many novel experiments that make use of the expanded range of sensors available to the Arduino platform. (I)
16. “Enhance your smartphone with a Bluetooth Arduino nano board,” F. Bouquet, G. Creutzer, D. Dorsel, J. Vince, and J. Bobroff, Phys. Educ. **57**(1), 015015 (2022). The Arduino can easily be linked with the smartphone using Bluetooth, enabling a range of new experiments.
17. “Implementing Raspberry Pi 3 and Python in the physics laboratory,” A. Martínez, C. Nieves, and A. Rúa, Phys. Teach. **59**(2), 134–135 (2021). A project to measure the acceleration of falling objects is developed as an easy example of use of a low-cost Raspberry Pi 3 computer as an experimental tool. (I)

IV. USEFUL APPS

There are many apps in the digital app stores designed to interact with the sensors. Several of them propose lesson plans in their web sites. In Table II, we display some of them we found particularly useful and their main characteristics. We highlight Androsensor, Phyphox, and Physics Toolbox Suite for their multiplatform character, abilities to download files to the cloud, set up the sampling frequencies, documentation, and support availability.

18. “Advanced tools for smartphone-based experiments: phyphox,” S. Staacks, S. Hutz, H. Heinke, and C. Stampfer, Phys. Educ. **53**(4), 045009 (2018). Phyphox was specifically designed to improve the usefulness of smartphones in a wide range of physics experiments, and this paper describes some of its features including remote access, data analysis, and web-based programmable customization. (I)
19. “Phyphox app in the physics classroom,” R. Carroll and J. Lincoln, Phys. Teach. **58**(8), 606–607 (2020). The “technology in the classroom” column of *The Physics Teacher* journal reviews the main characteristics of phyphox and discusses some of the “ready-to-go” experiments proposed. (I)

V. GENERAL EXPERIMENTS

The following references cover a broad range of physics topics and are organized in the way that introductory courses are taught.

20. “Science in your pocket,” R. F. Wisman and K. Forinash, Int. J. Hands- Sci. **1**(1), 7–14 (2008). http://www.ijhsci.info/wp-content/uploads/2008/09/IJHSCI_volume1_numero1_2008_online.pdf. This paper makes the analogy between smartphones and Swiss-army (or a multi-tool pocket) knives as useful tools for multiple everyday tasks such as measuring acceleration, analyzing sound, or even performing fast-Fourier transforms (FFT). (I)
21. “Mobile science,” R. Wisman and K. Forinash, Ubiquitous Learn. **3**(1), 21–34 (2010). Students can collect and analyze experimental data in several setups using not only the accelerometer but also sound and data inputs, touch screens, vibration detection, GPS, and magnetometers. (E)
22. “Applications and examples of experiments with mobile phones and smartphones in physics lessons,” J. Kuhn and P. Vogt, Front. Sens. **1**(4), 67–73 (2013). Available at: https://ia802908.us.archive.org/13/items/FS3499/FS3499.pdf. This paper describes three experiments that require a minimum of equipment: (a) production of an acoustic beat using the loudspeakers of two smartphones, (b) determination of the acceleration of gravity by means of the Doppler shift of a falling smartphone, and (c) detecting infrared radiation from a remote control with the smartphone camera to demonstrate interesting diffraction phenomena. (E)

Table II. Useful general-purpose apps and their main characteristics.

Name and website	Sensors	OS	Setup	Documentation and support	Other
Androsensor http://www.fivasim.com	Almost all	Android	Yes	Commercial adds could be annoying for the user.	A simple but powerful app to record raw data, mainly to be exported to a personal computer. Allows recording background data or while the display is turned off.
Phyphox https://phyphox.org	Almost all internal and external	iOS and Android	⋯	Many packaged experiments are available, and a collaborative website offers the possibility of designing (programming) new experiments	Highly configurable app, provides the possibility of sharing screenshots, download a *csv* data file, remote controlled operation from a computer, and acquire data from external sensors.
Physics Toolbox Suite https://www.vieyrasoftware.net/	Almost all	iOS and Android	⋯	The website offers an extensive list of quick experiments and other educational apps (like Magna-AR) and games aimed at primary school and secondary students in STEM areas	A configurable app, provides the possibility of sharing screenshots or downloading a *csv* data file.
Arduino Science Journal https://science-journal.arduino.cc/	Almost all internal and external	IOS and Android	⋯	Former Science Journal or Google Science Journal. The web has a useful guided collection of science lessons suited for grades Pre-K to 12+	A good-looking interface to collect numerical or graphical data from internal or external sensors (from Arduino or other boards)
Sensor Kinetics https://www.innoventions.com/	Almost all	iOS and Android	⋯	⋯	A simple app to read data on the screen or to record data to be exported to a personal computer.
Pasco SPARKvue https://www.pasco.com/downloads/sparkvue	Internal accelerometer and many external sensors	iOS and Android	⋯	⋯	One of the few tools to analyze data on a mobile device. Despite being designed to work with external sensors, it also allows working with the internal accelerometer of the smartphone or tablet.
Magna-AR https://www.vieyrasoftware.net/	Magnetometer	iOS and Android	⋯	By the same developers as Physics Toolbox Suite devoted to experiment with augmented reality	Offers the possibility to visualize the magnetic field in simple setups.

23. "Five challenges that use mobile devices to collect and analyze data in physics," R. Vieyra, C. Vieyra, P. Jeanjacquot, A. Martí, and M. Monteiro, Sci. Teach. **82**(9), 32–40 (2015). The five challenges presented in this paper are designed to help high school students overcome common misconceptions about force and motion. They include measuring gravitational acceleration at home, analyzing the forces in an elevator, building a simple Atwood machine, measuring the centripetal acceleration while dancing, and locating the accelerometer inside a smartphone using a turntable. Each of the activities is related to instructional outcomes present in the Next Generation Science Standards (NGSS). (E)
24. "Teaching physics with a local positioning system," C. Siebert, P. R. DeStefano, and R. Widenhorn, Phys. Teach. **57**(6), 428–429 (2019). Local positioning systems (LPS) are local versions of the well-known *Global Positioning System* (GPS) with many industrial and commercial applications. LPSs are composed of mobile devices (known as "tags") that can be tracked by means of stationary devices (referred to as "anchors"). This article shows how to track an object, for instance, an Arbor Scientific air-powered projectile carrying a "tag." This two-dimensional version works with distance scales of several meters and has uncertainties of about ± 10 cm. The results are compared with those obtained using other sensors such as the accelerometer, magnetometer, and gyroscope of a smartphone, offering the possibility of several interesting discussions. (I)
25. "Time measurements with a mobile device using sound," R. F. Wisman, G. Spahn, and K. Forinash, Phys. Educ. **53**(3), 035012 (2018). The precise determination of time intervals by means of the smartphone microphone enables experiments including (a) comparing the free fall time of two balls with different initial horizontal velocity, (b) obtaining the coefficient of restitution of a bouncing object, (c) measuring the Doppler shift of a smartphone carried in a cyclist's pocket, and (d) measuring human reaction time. (I)
26. "Using mobile-device sensors to teach students error analysis," M. Monteiro, C. Stari, C. Cabeza, and A. C. Martí, Am. J. Phys. **89**(5), 477–481 (2021). In contrast with most of the experiments using smartphones which use the mean value of the measurements taken by the

sensors, this article focuses on the role of the fluctuations detected by the sensors. It shows how to use smartphone sensors to teach fundamental concepts in error analysis such as the physical meaning of the mean value and standard deviation and the interpretation of histograms and distributions. Applications to everyday situations are described, such as evaluating the steadiness of the device placed on a table or held in different ways and measuring the smoothness of a road. (I, A)

VI. MECHANICS

Since accelerometers were one of the first sensors to be repurposed for experimentation, classical mechanics is the discipline that has received most attention. In addition, in a wide range of situations, the microphone can be used as a stopwatch to accurately measure time intervals between sounds. Another sensor that can be useful in classical mechanics is the ambient light sensor that can be turned into a distance sensor after suitable calibration. This section is devoted to experiments in classical mechanics (see also Refs. 20–25).

27. "Determining ball velocities with smartphones," P. Vogt, J. Kuhn, and D. Neuschwander, Phys. Teach. **52**(6), 376–377 (2014). Using the sounds that result from kicking sport balls against a wall, the average ball velocity is obtained from the distance. This experiment gives students the opportunity not only to interpret the sound signals and extract information about distances and speeds but also to incorporate error analysis and statistics. (E)
28. "Finding the average speed of a light-emitting toy car with a smartphone light sensor," S. Kapucu, Phys. Educ. **52**(4), 045001 (2017). Transforming the smartphone ambient light sensor to a distance sensor allows measurement of the average speed of a light-emitting object moving along a line perpendicular to the light sensor, using a darkened room to determine the relationship between the illumination registered by the sensor and the distance. The measurement of a simple magnitude, the distance, could be an opportunity to discuss important photometric concepts. (I)
29. "Analyzing free fall with a smartphone acceleration sensor," P. Vogt and J. Kuhn, Phys. Teach. **50**(3), 182–183 (2012). A smartphone can serve both as a falling body and as an accelerometer to measure the free-fall time and obtain the gravitational acceleration. (E)
30. "Finding the acceleration and speed of a light-emitting object on an inclined plane with a smartphone light sensor," S. Kapucu, Phys. Educ. **52**(5), 055003 (2017). A modern version of the famous inclined plane experiment performed by Galileo: A light-emitting object instead a steel ball rolls down the plane and the light sensor serves as a ruler. The results are compared to those obtained by the analysis of video recordings. (E)
31. "Measurement of g using a magnetic pendulum and a smartphone magnetometer," U. Pili, R. Violanda, and C. Ceniza, Phys. Teach. **57**(5), 258–259 (2018). A small magnet glued to the bob of a simple pendulum generates a signal registered with a smartphone's magnetic field sensor. Looking at this signal, the period can be measured and thus, varying the length, it is possible to obtain an accurate measurement of the gravitational acceleration. (E)
32. "Determination of aerodynamic drag coefficients using a drop test with a wireless accelerometer and its application to model rockets," S. Pettersson Fors and C. Nord, Am. J. Phys. **87**(9), 714–719 (2019). An effective (and less expensive) alternative to wind tunnels: aerodynamic drag coefficients can be determined by dropping model rockets from heights of a dozen meters. The drag coefficient is modeled and compared with reference values available in the literature. (A)
33. "Determination of the drag resistance coefficients of different vehicles," C. Fahsl and P. Vogt. Phys. Teach. **56**(5), 324–325 (2018). This paper presents an outdoor experiment to measure the drag coefficient of different vehicles, such as a bicycle, car, or fire engine, using the acceleration sensor of a smartphone or tablet. Experimental values can be compared with reference values found in the literature. The impact of drag on energy dissipation and power consumption is also analyzed. (I)
34. "An experiment of relative velocity in a train using a smartphone," A. Priyanto, Y. Aji, and M. P. Aji, Phys. Teach. **58**(1), 72–73 (2020). Relative motion of near and distant objects, as seen from a train, is analyzed with a smartphone's camera and an app, *VidAnalysis*, that can perform video analysis to obtain the speed of objects in two different frames of reference. (E)
35. "Sports, smartphones, and simulation as an engaging method to teach projectile motion incorporating air resistance," E. Azhikannickal, Phys. Teach. **57**(5), 308–311 (2019). An app tracks the trajectory of a sports projectile in real time so that it can be compared with numerical and theoretical models of the trajectory of the projectile, taking into account the drag force. (I)
36. "Angular velocity and centripetal acceleration relationship," M. Monteiro, C. Cabeza, A. C. Martí, P. Vogt, and J. Kuhn, Phys. Teach. **52**(5), 312–313 (2014). One of the advantages of smartphones is the possibility of using more than one sensor simultaneously. Here, in the context of circular motion, the gyroscope (or angular velocity sensor) and the accelerometer are used to independently measure the angular velocity and the centripetal acceleration of a moving smartphone in a rotating frame. This experiment can be proposed as an outdoor activity, using a merry-go-round, or in the laboratory, using a bike wheel on a horizontal support. (E)
37. "Acceleration measurements using smartphone sensors: Dealing with the equivalence principle," M. Monteiro, C. Cabeza, and A. C. Marti, Rev. Bras. Ens. Fís. **37**(1), 1303 (2015). Because of the principle of equivalence, an accelerometer cannot distinguish acceleration from a gravitational field without additional information. Accelerometer sensors are, in fact, force sensors that provide an apparent acceleration, also known as a g-force or force per unit mass, given by the real acceleration minus the gravitational acceleration (all vectors). Using the information from the gyroscope and the accelerometer sensors, it is possible to obtain the real acceleration of the mobile device. This article implements this method for a physical pendulum supplemented with video analysis. (I)
38. "Using a smartphone acceleration sensor to study uniform and uniformly accelerated circular motions," J. C.

Castro-Palacio, L. Velázquez, J. A. Gómez-Tejedor, F. J. Manjón, and J. A. Monsoriu, Rev. Bras. Ens. Fís. **36**(2) 1–5 (2014). A smartphone is placed on a rotating table (an old-fashioned turntable), and the components of the accelerations are obtained and compared with results obtained using video analysis for uniform and uniformly accelerated circular motion. (E)

39. "Discovering quantities of circular motion of a light-emitting toy train using a smartphone light sensor," S. Kapucu, Phys. Teach. **57**(7) 480–482 (2019). Using a light-emitting toy train and a smartphone's light sensor, it is possible to measure kinematics magnitudes like linear speed, angular velocity, and centripetal acceleration. Video analysis is used to corroborate the results. This approach applies only to uniform circular motion and is indirect because it requires relating illumination values to mechanical quantities. (I)
40. "Determination of the angular velocity of a simple propeller with a smartphone proximity sensor," S. Kapucu and M. Şimşek, Phys. Educ. **56**(3), 033003 (2021). The only experiment referenced in this Resource Letter that uses the proximity sensor, this simple experiment that can be performed at home and measures the angular velocity of a home-made propeller. (E)
41. "Determination of the radius of curves and roundabouts with a smartphone," C. Fahsl and P. Vogt, Phys. Teach. **57**(8), 566–567 (2019). Two outdoor experiments are proposed to determine the radius of curvature of streets. The first one can be performed traveling in a car or other vehicle using data collected by the accelerometer. The second one follows the approach proposed in Ref. 36 that uses the accelerometer and gyroscope simultaneously to obtain the radius of curvature. In both cases, the results obtained can be compared with direct measurements or with road maps. (E)
42. "Measurement of Coriolis acceleration with a smartphone," A. Shakur and J. Kraft, Phys. Teach. **54**(5), 288–290 (2016). The Coriolis acceleration is rather difficult to measure in traditional undergraduate laboratories. In this ingenious experiment, a smartphone slides down a rotating vertical nearly semi-circular track. Thanks to the built-in gyroscope and accelerometer, the relationship between Coriolis acceleration and angular velocity is obtained. As the relative velocity is rather small, a discussion about the uncertainties is provided. (I)
43. "Angular acceleration of the non-linear pendulum," P. F. Hinrichsen, Phys. Educ. **55**, 055018 (2020). In this experiment, acceleration and rotation sensors installed in a pendulum provide the opportunity to analyze these magnitudes. Although simple pendulums could seem simple and straightforward, the large-amplitude nonlinear regime offers challenges such as the analysis of phase space and the effect of a weak damping. (I)
44. "Exploration of large pendulum oscillations and damping using a smartphone," D. Li, L. Liu, and S. Zhou, Phys. Teach. **58**(9), 634–636 (2020). Linear and nonlinear oscillations of a simple pendulum are investigated using a photogate built with a laser pointer as an emitter and the ambient light sensor of a smartphone as the receiver. By gluing a small piece of cardboard to the lower end of the pendulum, the effect of the damping is studied, and the coefficient of damping is obtained by means of a nonlinear fit. (I)
45. "Exploring phase space using smartphone acceleration and rotation sensors simultaneously," M. Monteiro, C. Cabeza, and A. C. Martí, Eur. J. Phys. **35**(4), 045013 (2014). In this experiment, a physical (or compound) pendulum is built with a smartphone fixed to a bike wheel oscillating or rotating in a vertical plane. Since smartphones provide simultaneous measurement with more than one sensor, it is possible, in a system with one degree of freedom like this, to measure the angular velocity and centripetal acceleration simultaneously. These two variables allow the determination of two generalized coordinates, and thus provide a simple way to discuss phase space and turn this advanced concept into a more tangible motion. (A)
46. "Phase plot of a gravity pendulum acquired via the MEMS gyroscope and magnetic field sensors of a smartphone," T. Splith, A. Kaps, and F. Stallmach, Am. J. Phys. **90**(4), 314–316 (2022). This work exploits the advantage of smartphones to take two or more simultaneous measurements from its sensors. Here the device is used as the bob of a pendulum, then the angular velocity is obtained from the smartphone's gyroscope, while the angular displacement is derived from the magnetometer and the orientation of the smartphone in the Earth's magnetic field. The data is used to analyze and plot the phase space of the motion of the smartphone as a damped oscillator. Detailed instructions are provided by the authors in a supplementary material to allow performing this experiment as a conventional lab, as a home-lab, or even as lecture demonstration. (A)
47. "The mobile phone as a free-rotation laboratory," M. S. Wheatland, T. Murphy, D. Naomenko, D. van Schijndel, and G. Katsifis, Am. J. Phys. **89**, 342–348 (2021). The tennis racket or Dzhanibekov effect is an interesting classical mechanics phenomenon only reported a few decades ago. When a rigid body is freely rotating about the principal axis of inertia, the motion is unstable around the intermediate axis but stable about the two other axes. Although more spectacular in a zero-gravity setup, the effect is also seen when a smartphone is thrown into the air while its angular velocity is recorded by the three-axis gyroscope sensor. Quantitative results are analyzed in the light of Euler's equations. (A)
48. "Pendulum rides, rotations and the Coriolis effect," A.-M. Pendrill and C. Modig, Phys. Educ. **53**(4), 045017 (2018). Amusement parks offer an opportunity to experiment with mechanical systems on a large scale. Although there is an extensive literature about field trips to amusement parks using traditional equipment, this article together with Refs. 49, 53, and 54 describes several experiments performed using mobile devices. The qualitative analysis of the data registered by the sensors involves several interesting tasks at different educational levels, from a two-dimensional ride in a pendulum to more complicated three-dimensional rotations. Moreover, in some amusement park attractions the Coriolis acceleration is sufficiently large to be detected by the accelerometer. (E)
49. "Mathematics, measurement and experience of rotations around three axes," A.-M. Pendrill, Eur. J. Phys. **40**(1), 015003 (2018). Rotations in 3D are thrilling but difficult to visualize and understand. Amusement parks, however, are places where three-dimensional rotations can be directly *felt* by the experimenter. This article (in conjunction with the previous reference) can be a starting

point for a field trip to an amusement park with the objective of analyzing the physics of rotations. (A)
50. "The Atwood machine revisited using smartphones," M. Monteiro, C. Stari, C. Cabeza, and A. C. Martí, Phys. Teach. **53**(6), 373–374 (2015). A historical experiment is transformed to be performed using a smartphone's accelerometer to measure the acceleration and compare it with the prediction given by Newton's second law. (E)
51. "Using iPads to illustrate the impulse-momentum relationship," J. W. Streepey, Phys. Teach. **51**(1), 54–55 (2013). A very simple experiment that only requires a smartphone with built-in accelerometer sliding on a table: The impulse when the smartphone is quickly pushed forward and released is obtained from the area under the curve of the acceleration vs time, allowing a semi-qualitative analysis of the relationship with the change of momentum. (E)
52. "Modelling of a collision between two smartphones," V. L. B. de Jesus and D. G. G. Sasaki Phys. Educ. **51**(5), 055006 (2016). A very simple setup consisting of two smartphones with a piece of sponge glued onto one of them, sliding on a lacquered-wood table. Acceleration and velocity, obtained by numerical integration, are the input elements to analyze collisions and the impulse-momentum theorem. (E)
53. "Smartphones and Newton's first law in escalators and roller coasters," A.-M. Pendrill, Phys. Educ. **55**, 035016 (2020). Using the smartphone sensors, photographs, and video analysis, it is possible to experiment with your own body to demonstrate basic kinematics and dynamics concepts and get insights into Newton's laws. (E)
54. "Virtual reality, video screen shots and sensor data for a large drop tower ride," M. Burt and A.-M. Pendrill, Phys. Educ. **55**, 055017 (2020). Amusement parks also allow measurement of the personal experience of large tower drops. Combining accelerometer and pressure sensors, acceleration and height can be obtained in two independent ways. (E)
55. "Impulse measurement using an Arduino," P. R. Espindola, C. R. Cena, D. C. B. Alves, D. F. Bozano, and A. M. B. Goncalves, Phys. Educ. **53**(3), 035005 (2018). A simple experiment to study the impulse-momentum theorem using a freely falling body attached to a rubber string. The force due to the tension on the rubber string is obtained by means of an Arduino board. It can be adapted to be performed with smartphone sensors. (E)
56. "A simple experiment to measure the maximum coefficient of static friction with a smartphone," S. Kapucu, Phys. Educ. **53**(5), 053006 (2018). The smartphone is used as an object placed on an inclined plane and the orientation pseudo sensor is used to determine the static friction coefficient between the smartphone and the plane. (E)
57. "Collecting data with a mobile phone: Studies of mechanical laws such as energy and momentum conservation," M. Hart and M. G. Kuzyk, Am. J. Phys. **88**(11), 948–957 (2020). The setup includes a smartphone as a zenithal high-speed camera to register the motion of billiard balls. Using video analysis, two-dimensional trajectories of the balls are obtained. This didactic paper presents an extensive analysis of momentum conservation, rolling and sliding friction, angular momentum, and dissipative forces. (A)
58. "Measuring a spring constant with a smartphone magnetic field sensor," U. Pili and R. Violanda, Phys. Teach. **57**(3), 198–199 (2019). The magnetometer of a mobile device is used to measure the period of oscillations in a mass-spring system and then to determine the spring constant dynamically. (E)
59. "Rotational energy in a physical pendulum," M. Monteiro, C. Cabeza, and A. C. Marti, Phys. Teach. **52**(3), 180–181 (2014). The angular velocity sensor (or gyroscope) is especially suited to measure the rotational kinetic energy in many experimental setups, including the physical pendulum in this experiment. (E)
60. "Physical pendulum experiment re-investigated with an accelerometer sensor," C. Dauphin and F. Bouquet, Pap. Phys. **10**, 100008 (2018). A low-cost experiment in mechanics with Arduino and an external accelerometer is described that measures radial and orbital accelerations at different positions of the axis of a compound pendulum. It can be easily adapted to be performed with a mobile device.
61. "Superposition of oscillation on the metapendulum: Visualization of energy conservation with the smartphone," D. Weiler and A. Bewersdorff, Phys. Teach. **57**(9), 646–647 (2019). The *metapendulum*, a combination of both the simple gravity pendulum and the spring pendulum, is a non-typical mechanical system with two degrees of freedom. This experiment is appropriate for studying normal frequency, normal modes, and resonances. The experimental setup turns out to be very simple when using the accelerometer of a smartphone to measure horizontal and vertical acceleration. (E)
62. "Newton's cradle: Using a smartphone sound sensor to extract *g* from the sound of impacts," U. B. Pili, Phys. Educ. **56**(4), 043005 (2021). The sound of impacts of the balls of the well-known Newton's cradle are used to obtain the period of oscillation of a simple pendulum and then, the gravitational acceleration. (E)
63. "Demonstration of the parallel axis theorem through a smartphone," I. Salinas, M. H. Gimenez, J. A. Monsoriu, and J. A. Sans, Phys. Teach. **57**(5), 340–341 (2019). A torsion pendulum, with a smartphone fixed to it, is useful for visualizing simple harmonic, damped, and forced motion. The components of the acceleration are measured with a smartphone sensor, and the analysis allows students to explore the parallel axis theorem. (E)
64. "Experimental analysis of a compound pendulum with variable suspension point," M. Monteiro, C. Stari, C. Cabeza, and A. C. Marti, Phys. Educ. (**55**)2, 023004 (2020). A large metallic bar with equidistant holes serves as a physical, or compound, pendulum with variable suspension point. The gyroscope sensor and photogate are used to measure the period of oscillations as a function of the position of the suspension point and compare it with a theoretical model. (I)
65. "Combined viscous and dry friction damping of oscillatory motion," P. F. Hinrichsen and C. I. Larnder, Am. J. Phys. **86**(8), 577–584 (2018). An external accelerometer mounted on a glider on an air track is used to analyze damped oscillations due to viscous and dry friction. It can be easily adapted to be performed with mobile-device sensors. The effect of both contributions to damping is analyzed by systematic variations of the air pressure in the air track. (I)

66. "Interactive modeling activities in the classroom–rotational motion and smartphone gyroscopes," R. Pörn and M. Braskén, Phys. Educ. **51**(6), 065021 (2016). This introduction to the use of gyroscope sensors in a classroom setting proposes several activities for experimenting with the dynamics of objects rotating about a fixed axis. (E)
67. "Analyzing the dynamics of a yo-yo using a smartphone gyroscope sensor," I. Salinas, M. Monteiro, A. C. Marti, and J. A. Monsoriu, Phys. Teach. **58**(8), 569–571 (2020). The yo-yo is a traditional toy with several interesting dynamical aspects, involving torque, rotational kinetic energy, and angular acceleration. In this experiment, the angular velocity of a fast-rotating object is successfully measured using the smartphone gyroscope attached to a homemade yo-yo. In this way, the dynamics can be analyzed and compared with independently measured quantities such as the moment of inertia. This experiment can be complemented with video analysis. (I)
68. "Angular momentum," A. Shakur and T. Sinatra, Phys. Teach. **51**(9), 564–565 (2013). Dropping weights onto a spinning turntable and measuring the change in angular velocity with a smartphone's gyroscope, the conservation of angular momentum is verified as well as the non-conservation of rotational kinetic energy. (E)
69. "Tilting motion and the moment of inertia of the smartphone," A. Kaps and F. Stallmach, Phys. Teach. **58**(3), 216–217 (2020). The moment of inertia of a smartphone is determined by measuring the angular velocity with its gyroscope during a controlled tilting motion. (E)
70. "Comment on 'Tilting Motion and the Moment of Inertia of the Smartphone'," P. F. Hinrichsen, Phys. Teach. **60**(3), 223–225 (2022). An enhanced analysis of the previous work is presented to obtain the moment of inertia of a smartphone. Analyzing the full set of angular velocity data from the gyroscope during the tilting motion, the author shows how to know if the pivot edge slips or does not slip during the toppling motion and consequently shows how to improve the precision of the value of the moment of inertia. (A)
71. "The toppling of a uniform rectangular block," P. F. Hinrichsen, Am. J. Phys. **89**(11), 1026–1032 (2021). The experiment setup analyzed in the two previous references is further investigated considering in this case a uniform rectangular box. The inclination angle is measured for different materials and, hence, friction coefficients between the pivot edge and the horizontal surface on which the box is at rest. Experimental data obtained with MEMs gyro/accelerometers is complemented with Tracker video analysis.
72. "Understanding coffee spills using a smartphone," F. Tornaría, M. Monteiro, and A. C. Martí, Phys. Teach. **52**(8), 502–503 (2014). A simple and economical experiment is proposed to explain the physics of the SpillNot, a device designed to carry a hot beverage in a cup without spilling. In this experiment, a smartphone substitutes for the cup. Its sensor measures the acceleration while the device is oscillating or turning in a vertical plane. The qualitative comparison of the radial and tangential components of the acceleration is used to explain the functioning of the device. (E)
73. "An Arduino investigation of simple harmonic motion," C. Galeriu, S. Edwards, and G. Esper, Phys. Teach. **52**(3), 157–159 (2014). An example of a useful and low-cost of Arduino-based experiment. An ultrasonic distance sensor connected to an Arduino board is used to measure the simple harmonic motion of a mass on a spring. (E)
74. "Analyzing simple pendulum phenomena with a smartphone acceleration sensor," P. Vogt and J. Kuhn, Phys. Teach. **50**(8), 439–440 (2012). In this setup, the smartphone acts as the bob of a pendulum allowing analysis of the relationship between period and length. (E)
75. "Analyzing spring pendulum phenomena with a smartphone acceleration sensor," J. Kuhn and P. Vogt, Phys. Teach. **50**(8), 504–505 (2012). This paper experiments with a mass-spring system and a system of two coupled oscillators. (E)
76. "Using a mobile phone acceleration sensor in physics experiments on free and damped harmonic oscillations," J. C. Castro-Palacio, L. Velázquez-Abad, M. H. Giménez, and J. A. Monsoriu, Am. J. Phys. **81**(6), 472–475 (2013). A smartphone is placed on a glider connected by a spring to a fixed support. In this article, results for the period, frequency, spring constant, and damping constant are obtained from the acceleration sensor experiments on free and damped oscillations. (E)
77. "Damped oscillations with a smart cart," A. Shakur and J. Emmert, Phys. Teach. **57**(7), 490–492 (2019). An experiment on damped oscillations is performed with the PASCO's wireless Smart Cart and the free SPARKvue app for smartphones to show the simplicity achieved by replacing many traditional laboratory sensors, wires, and other equipment. (E)
78. "Smartphones on the air track. Examples and difficulties," M. González-Delgado, A. Gómez, and M. González-Rebollo, Pap. Phys. **10**, 100005 (2018). In this work, a classic experiment is proposed with a smartphone on an air track to study the conservation of momentum in collisions and the effect of friction forces. In this, and in Ref. 76, only an air track, a couple of gliders, and springs are needed in addition to the smartphone. (E)
79. "A quantitative analysis of coupled oscillations using mobile accelerometer sensors," J. C. Castro-Palacio, L. Velázquez-Abad, F. Giménez, and J. A. Monsoriu, Eur. J. Phys. **34**(3), 737–744 (2013). Two smartphones are placed on gliders connected by springs on an air track. The accelerometers are used to perform a quantitative analysis of symmetric and asymmetric normal modes in a system of coupled oscillators. (E)
80. "Instrumentation for mechanical vibrations analysis in the time domain and frequency domain using the Arduino platform," M. Varanis, A. Langone Silva, P. H. Ayres Brunetto, and R. Ferreira Gregolin, Rev. Bras. Ens. Fís. **38**(1), 1301 (2016). A set of low-cost sensors such as accelerometers, gyroscopes, and ultrasonic distance sensors are used together with an Arduino board to measure vibrations in mechanical systems, like a beam, using PYTHON for signal processing. (I)
81. "Driven damped harmonic oscillator resonance with an Arduino," A. M. B. Goncalves, C. R. Cena, and D. F. Bozano, Phys. Educ. **52**(4), 043002 (2017). Resonance in a harmonic oscillator is quantitatively analyzed by means of an Arduino board that controls the oscillations with a servo motor and measures the oscillation amplitude with an ultrasonic position sensor. (I)

82. "Computer-based learning in an undergraduate physics course: Interfacing a mobile phone and MATLAB to study oscillatory motion," E. Momox and C. Ortega De Maio, Am. J. Phys. **88**(7), 535–541 (2020). This paper offers the possibility of experimenting with free and damped oscillations by interfacing mobile devices to widely used MATLAB software in real time, facilitating graphics visualization. (I)
83. "The parametric resonance-from LEGO Mindstorms to cold atoms," T. Kawalec and A. Sierant, Eur. J. Phys. **38**(4), 045001 (2017). A spectacular driven pendulum made with LEGO Mindstorm pieces is described to investigate the parametric resonance in a simple pendulum by means of an actuator and a wireless absolute orientation sensor. (I)
84. "Acceleration, velocity, and displacement for magnetically damped oscillations," P. F. Hinrichsen, Phys. Teach. **57**, 250–253 (2019). A wireless accelerometer mounted on the side of a cart is used to measure acceleration during oscillatory motion that is subject to velocity-dependent damping. Velocity and displacement are derived from the acceleration, allowing quantitative observation of some characteristics of the system dynamics, like the transition to critical damping and the velocity dependence of the drag and energy decay. (I)

VII. WAVES AND SOUND

Oscillations and waves can be studied using smartphone microphones and speakers. Several experiments typically performed using stopwatches have been redesigned to use smartphones, improving their precision. These experiments address concepts such as stationary waves, harmonics, resonance, the speed of sound in different media. In addition, the high processing speed of built-in CPUs allows real-time fast Fourier transform (FFT) analysis to identify the main frequencies of a sound wave, measure the resonant frequency of a system, or *visualize* a melody in a spectrogram. It is worth noting that most of the experiments proposed in this section are very economical (see also Refs. 21, 22, and 25). Also note that in some modern smartphones, the audio port is replaced by Bluetooth alternatives. Reference 16 describes how external sensors can be connected via Bluetooth.

85. "Analyzing acoustic phenomena with a smartphone microphone," J. Kuhn and P. Vogt, Phys. Teach. **51**(1), 118–119 (2013). This article takes advantage of the speed of smartphone CPUs to perform real-time FFT to analyze and visualize different sounds (noise, musical instruments, voices). (E)
86. "Smartphone-aided measurements of the speed of sound in different gaseous mixtures," S. O. Parolin and G. Pezzi, Phys. Teach. **51**(8), 508–509 (2013). A simple setup with a PVC pipe and two smartphones is described that measures the speed of sound in different gases by the time-of-flight technique. (E)
87. "Determining the speed of sound with stereo headphones," P. Vogt and J. Kuhn, Phys. Teach. **50**(5), 308–309 (2012). A simple experiment is described to measure the speed of sound by the time transit method using stereo headphones and a computer-aided data measurement system. (E)
88. "Measuring the speed of sound in air using a smartphone and a cardboard tube," S. Hellesund, Phys. Educ. **54**(3), 035015 (2019). In this very economical experiment, a cardboard tube is used as a Kundt's tube, and sound waves are generated with a smartphone, sweeping a range of frequencies to determine the values of resonance. (E)
89. "A bottle of tea as a universal Helmholtz resonator," M. Monteiro, C. Stari, C. Cabeza, and A. C. Martí, Phys. Teach. **56**(9), 644–645 (2018). A simple and novel setup for the classic experiment of the bottle as a Helmholtz resonator: The resonance frequency is measured with a smartphone for different levels of water inside the bottle. A digital balance is used to determine the volume of air in the bottle. In addition, the sound speed can be obtained by linearizing the relationship between resonance frequency and volume. (I)
90. "Measuring the speed of sound in air using smartphone applications," A. Yavuz, Phys. Educ. **50**(3), 281 (2015). An experiment for measuring the speed of sound in air is revisited. A smartphone is used as a signal generator, and a glass pipe is used as a resonator with one end immersed in water to change the length and find the nodes of sound waves. (E)
91. "Stationary waves in tubes and the speed of sound," L. Kasper, P. Vogt, and C. Strohmeyer, Phys. Teach. **53**(1), 52–53 (2015). An inexpensive experiment using only drainpipes and smartphones. Despite its title, in this article the speed of sound is determined by measuring the delay time of echoes produced in long pipes with a smartphone. (E)
92. "Measurement of sound velocity made easy using harmonic resonant frequencies with everyday mobile technology," M. Hirth, J. Kuhn, and A. Müller, Phys. Teach. **53**(2), 120–121 (2015). Harmonic resonant frequencies in a tube are simultaneously triggered by the sound created by crumpling paper. The resonant frequencies are measured by plotting a spectrogram using a smartphone. (E)
93. "Simple time-of-flight measurement of the speed of sound using smartphones," S. Staacks, S. Hütz, H. Heinke, and C. Stampfer, Phys. Teach. **57**(2), 112–113 (2019). Two smartphones, one used as an emitter and the other as a receiver, measure the time of travel of sound, allowing the determination of the speed of sound in air. (E)
94. "Measuring the acoustic response of Helmholtz resonators," M. Monteiro, A. C. Marti, P. Vogt, L. Kasper, and D. Quarthal, Phys. Teach. **53**(4), 247–249 (2015). A glass beaker filled with gas is used as an acoustic resonator. The acoustic response curves are obtained with a smartphone to determine the speed of sound in different gases. (E)
95. "Measuring the acoustic response of classrooms with a smartphone," E. Macho-Stadler and M. J. Elejalde-Garcia, Phys. Teach. **58**(8), 585–588 (2020). An active learning experimental activity on room acoustics is put forward, using smartphones as measuring tools of the acoustic parameters of a classroom, including reverberation and intelligibility. (I)
96. "Analyzing elevator oscillation with the smartphone acceleration sensors," J. Kuhn, P. Vogt, and A. Müller, Phys. Teach. **52**(1), 55–56 (2014). Vertical acceleration is measured with a smartphone during an elevator ride to analyze the oscillations of the elevator car. (E)

97. "Oscillations studied with the smartphone ambient light sensor," J. A. Sans, F. J. Manjón, A. L. J. Pereira, J. A. Gomez-Tejedor, and J. A. Monsoriu, Eur. J. Phys. **34**(6), 1349–1354 (2013). This article shows that a smartphone's light sensor can be used as a position sensor. This sensor is used to take measurements from a system of two coupled springs undergoing simple or damped oscillatory motion and the frequency, spring constant, and damping time are found. (I)
98. "Corkscrewing and speed of sound: A surprisingly simple experiment," K. Lutz and P. Vogt, Phys. Teach. **58**(4), 278–279 (2020). The cylindrical neck of a bottle partially filled with water is used as a one-side-closed pipe resonator. Students can systematically vary the resonator length by filling in water to different levels. When uncorking the bottle, or simply using a wet finger to generate a plop noise, a peak frequency is measured with a smartphone, for different levels of water. (E)
99. "Determining the speed of sound as a function of temperature using Arduino," M. Dumas Hahn, F. A. de Oliveira Cruz, and P. S. Carvalho, Phys. Teach. **57**(2), 114–115 (2019). A low-cost setup with an Arduino board, an ultrasonic distance sensor, and four temperature sensors is used to analyze the dependence of the speed of sound dependence on temperature. Although this experiment goes beyond the use of mobile-device sensors, it can complement other experiments focused on sound speed. (I)
100. "Using smartphones as hydrophones: Two experiments in underwater acoustics," M. Monteiro and A. C. Martí, Phys. Teach. **55**(3), 033013 (2020). In the first experiment, two smartphones, one of them submersible, are used to measure the ratio between the speed of sound in water and the speed of sound in air. This value is determined from the delay time of a sound signal traveling through air and water simultaneously. The second experiment is focused on the ranging of an underwater acoustic source. (E)
101. "Phonocardiography with a smartphone," L. J. Thoms, G. Colicchia, and R. Girwidz, Phys. Educ. **52**(2), 023004 (2017). Ideal for introductory physics for life sciences (IPLS): A very simple and economical experiment is proposed with a smartphone and a microphone used as an electronic home-made stethoscope to plot a phonocardiogram and to analyze characteristic heart sounds. (E)

VIII. LIGHT AND OPTICS

The integrated camera, the liquid crystal display, and the ambient light sensor are especially suited to perform experiments involving light and optics. The experiments cover a wide range of topics from geometrical optics to human vision or shadowgraphy. The use of smartphones as simple but powerful microscopes enables a range of experiments.

102. "Characterization of linear light sources with the smartphone's ambient light sensor," I. Salinas, M. H. Giménez, J. A. Monsoriu, and J. C. Castro-Palacio, Phys. Teach. **56**(8), 562–563 (2018). The illuminance of a linear fluorescent tube is measured with the ambient light sensor of a smartphone as a function of distance, verifying the well-known inverse-square law for distance. (E)
103. "Studying ray optics with a smartphone," A. Girot, N. A. Goy, A. Vilquin, and U. Delabre, Phys. Teach. **58**(2), 133–135 (2020). A simple experiment is proposed to determine the focal length of the converging lens of a smartphone camera, introducing students to ray optics and thin lenses. (E)
104. "Smartphone magnification attachment: Microscope or magnifying glass," T. Hergemöller and D. Laumann, Phys. Teach. **55**(6), 361–364 (2017). An improved low-cost smartphone microscope is proposed by means of a 3D-printed clip and a small glass bead, enabling pictures to be taken with up to 780× magnification. (EI)
105. "The polarization of light and Malus' law using smartphones," M. Monteiro, C. Stari, C. Cabeza, and A. C. Martí, Phys. Teach. **55**(5), 264–266 (2017). A simple and inexpensive setup is proposed to quantitatively verify Malus' law. A computer screen is used as a source of polarized light, and the ambient light sensor and the orientation sensors of a smartphone are used to take measurements of the intensity of light as a function of angle. (E)
106. "Video analysis-based experiments regarding Malus' law," T. Rosi and P. Onorato, Phys. Educ. **55**(4), 045011 (2020). An experimental setup, similar to the previous reference, to analyze Malus' law. The light from a source of polarized light is recorded with a camera while a polarizer is rotated in front of the camera lens. Video analysis software on a computer is used to obtain the intensity of light and the angle of the polarizer. (E)
107. "Color reproduction with a smartphone," L.-J. Thoms, G. Colicchia, and R. Girwidz, Phys. Teach. **51**(7), 440–441 (2013). A simple experiment, only requiring a microscope and a smartphone, that explores the relationship between RGB color generation and human vision. (E)
108. "A simple experiment to measure the inverse square law of light in daylight conditions," F. Vera, R. Rivera, and M. Ortíz, Eur. J. Phys. **35**, 015015 (2014). A simple device made with an Arduino board and a light sensor inside a tube is used to measure irradiance versus distance. (E)
109. "A simple experimental setup for teaching additive colors with Arduino," P. S. Carvalho and M. Hahn, Phys. Teach. **54**, 244–245 (2016). An Arduino board is designed like a game with the capability of easily changing the intensities in an RGB LED, as a way of improving students' understanding of color mixing. (E)
110. "Arduino-based experiment demonstrating Malus's law," W. P. S. Freitas, C. R. Cena, D. C. B. Alves, and A. M. B. Goncalves, Phys. Educ. **53**(3), 035034 (2018). A setup based on an Arduino board, a light sensor to measure transmitted light irradiance, and a potentiometer connected to a polarizer to measure the rotation angle. (E)
111. "Polarization imaging application with smartphones," P. Yan, H. Xia, J. Li, Y. Wang, Y. Wei, F. Ji, and S. Shu, Phys. Teach. **57**(9), 594–596 (2019). A simple imaging polarimeter made with a polarizer and a 3D printed structure attached to a smartphone's camera creates a tool for eliminating stray light and identifying objects with polarized light. (E)
112. "Demonstrating birefringence using a smartphone camera," C. Puttharugsa, P. Bintachitt, S. Wicharn, and

S. Plaipichit, Phys. Teach. **60**(3), 232–233 (2022). A simple experiment is proposed to observe birefringence in everyday materials, such polystyrene plastic spoons, using light emitted by a notebook screen, a smartphone camera and a polarizer filter. It provides a starting point to analyze internal stress and photoelasticity. (I)
113. "A practical classroom iPad shadowgraph system," B. Gearhart and D. MacIsaac, Phys. Teach. **58**(1), 8–11 (2020). A simple system is designed with an LED flashlight, a parabolic mirror, and a smartphone camera to perform many interesting activities in which invisible phenomena are made visible. Although it is less expensive than commercial setups, it does require a relatively expensive small telescope-like mirror. (I)
114. "Interference and diffraction in modern technology: A new approach for an introductory physics laboratory experiment," K. Rabosky, C. Inglefield, and K. Spirito, Phys. Teach. **58**(9), 646–648 (2020). In a non-traditional setup, a smartphone sensor is not used; rather the smartphone's screen is used as a reflective diffraction grating allowing the study of diffraction patterns, thin-film interference, and the effectiveness of anti-reflection coatings. An optical bench, a rotating turntable and a light source are needed for the setup. (I)

IX. ELECTRICITY AND MAGNETISM

Thanks to the magnetic field sensor, several experiments have been designed to measure magnetic fields produced by currents or magnets. Most of these experiments are easy and inexpensive to perform. In contrast, experiments involving measurements of voltages or currents are possible, using the microphone input, transforming the smartphone into a portable oscilloscope. These are limited due to the danger of damaging the mobile device by connecting a large voltage. A safer alternative is to send signals to the smartphone via Bluetooth from devices, such as Arduino BLE, as described in Ref. 16.

115. "Magnetic field sensor," N. Silva, Phys. Teach. **50**(6), 372–373 (2012). One of the most direct uses of the smartphone magnetometer measure the magnetic field of current-carrying coil as a function of the number of turns of the coil. (E)
116. "Demonstrations of magnetic phenomena: Measuring the air permeability using tablets," V. O. M. Lara, D. F. Amaral, D. Faria, and L. P. Vieira, Phys. Educ. **49**(6), 658 (2014). This paper describes a simple and economical experiment to find the dependence of a magnetic field on the distance to a permanent magnet or a coil carrying an electric current. Air permeability can also be accurately obtained. (E)
117. "Measurement of the magnetic field of small magnets with a smartphone: A very economical laboratory practice for introductory physics courses," E. Arribas, I. Escobar, C. P. Suarez, A. Najera, and A. Beléndez, Eur. J. Phys. **36**(6), 065002 (2015). The dependence of the magnetic field of small refrigerator magnets with distance is measured in this inexpensive experiment. It also provides a good opportunity to discuss least-square fitting and uncertainties. (E)
118. "Linear quadrupole magnetic field measured with a smartphone," E. Arribas, I. Escobar, R. Ramirez-Vazquez, C. del P. Suarez Rodriguez, J. Gonzalez-Rubio, and A. Belendez, Phys. Teach. **58**(3), 182–185 (2020). An experiment is described that uses widely available materials to find the dependence on distance of the magnetic field produced by a quadrupolar arrangement of permanent magnets. (E)
119. "Magnetic field 'flyby' measurement using a smartphone's magnetometer and accelerometer simultaneously," M. Monteiro, C. Stari, C. Cabeza, and A. C. Martí, Phys. Teach. **55**(9), 580–581 (2017). Taking advantage of the ability to simultaneously measure with more than one sensor, it is possible to find the spatial dependence of a magnetic field by just moving the smartphone. (E)
120. "Estimating RC time constants using sound," J. R. Groff, Phys. Teach. **57**(6), 393–396 (2019). An original approach to the study of a simple DC circuit. The sound produced by a piezoelectric buzzer and measured by a smartphone is used to estimate the discharging time constant of the circuit. (E)
121. "Smartphones and tracker in the e/m experiment," M. Pirbhai, Phys. Educ. **55**(1), 015001 (2019). This classic modern physics experiment can be performed using a smartphone to measure the magnetic field intensity and video analysis to obtain the radius of curvature of the beam of particles. (I)
122. "An Arduino investigation of the RC circuit," C. Galeriu, C. Letson, and G. Esper, Phys. Teach. **53**(5), 285–288 (2015). Arduinos enable an experiment on RC circuits in an introductory course. (E)
123. "Magnetic fields produced by electric railways," M. Monteiro, G. Organtini, and A.C. Marti, Phys. Teach. **58**(8), 600–601 (2020). In an outdoor experiment, students investigate large magnetic fields produced by electric railways. The measurements can be complemented with information about the terrestrial magnetic field and technical characteristics of the railways obtained on the internet. (I)
124. "Electrocardiography with a smartphone," L. J. Thoms, G. Colicchia, B. Watzka, and R. Girwidz, Phys. Teach. **57**(9), 586–589 (2019). By means of a smartphone, electrodes made with coffee spoons, and a suitable app, it is possible to record the variations in electrical potential due to cardiac activity in the body of a volunteer. Especially suitable for Introductory Physics for Life Sciences, it involves the concepts of electric potential, oscillating dipoles, current, electrodes, and impedance. (It is not intended for medical use.) (I)
125. "Simple determination of Curie temperature using a smartphone magnetometer," B. W. Nuryadin and R. Rusman, Phys. Teach. **57**(6), 422–423 (2019). When the temperature of a ferromagnetic sample is raised above the Curie point, it becomes a paramagnet. In this experiment, the Curie temperature of a permanent magnet is analyzed quantitatively using a smartphone magnetometer. This is one the few experiments involving statistical concepts such as phase transitions and mean field approach. (I)
126. "Electric circuits as seen by thermal imaging cameras," P. Kácovský, Phys. Teach. **57**(9), 597–599 (2019). Thermal cameras designed to be attached to smartphones provide the opportunity to perform several interesting experiments and demonstrations. Pointing the thermal camera at a DC circuit allows visualization

of thermoelectric processes involving Kirchhoff's or Ohm's laws. (E)
127. "An indirect measurement of the speed of light in a general physics laboratory," E. Arribas, I. Escobar, R. Ramirez-Vazquez, T. Franco, and A. Belendez, J. King Saud Univ. Sci. **32**(6), 2797–2802 (2020). The speed of light is obtained from measurements of the permeability and permittivity of free space. These experiments require a parallel-plate capacitor, coils, multimeters, and a smartphone used as a magnetometer. (I)
128. "A semester-long study of magnetic fields using smartphones to engage non-physics majors," S. A. Hootman and C. Pickett, Phys. Teach. **59**(2), 108–110 (2021). Students take part in a project to measure the magnetic field at different locations on their university campus. This activity is especially suited for life sciences students since it also discusses health-related and geophysical issues. (E)

X. MATTER, FLUIDS, THERMAL PHYSICS

Since smartphone batteries dissipate a considerable amount of energy, temperature sensors are not usually included in these devices (but see commercial attachments at https://thermodo.com). Thus, thermodynamics experiments for smartphones are rare.

Nonetheless, pressure sensors are available in several smartphone models and experiments in a variety of topics have been discussed. Other experiments have been proposed using Arduino-based sensors, and other ingenious setups are based on the cellular radio-frequency receptor.

129. "Exploring the atmosphere using smartphones," M. Monteiro, P. Vogt, C. Stari, C. Cabeza, and A. C. Martí, Phys. Teach. **54**(5), 308–309 (2016). Altitude and pressure of the lowest layer of the atmosphere are measured using a smartphone mounted on a quadcopter. Measurements can be compared with other simple approximations: Isothermal, constant density, and the International Standard Atmosphere. (I)
130. "Using smartphone pressure sensors to measure vertical velocities of elevators, stairways, and drones," M. Monteiro and A. C. Martí, Phys. Educ. **52**(1), 015010 (2017). Pressure sensors, or barometers, although not present in many smartphones, are very useful to measure heights and vertical velocities in several contexts allowing a wide variety of indoor and outdoor experiments. (I)
131. "Using a cell phone to investigate the skin depth effect in salt water," J. Rayner, Phys. Teach. **55**(2), 83–86 (2017). This article describes a simple demonstration of skin depth using only a small container filled with salty water and a waterproof smartphone as a sensor. Several interesting activities are proposed; however, the experimental conditions are not fully controlled, and there is no direct calibration of the relationship between the amplitude of the field and the cellphone's measurements. (I)
132. "Analyzing Stevin's law with the smartphone barometer," S. Macchia, Phys. Teach. **54**(6), 373–373 (2016). The barometer sensor also offers the opportunity to study the dependence of pressure on the depth of a smartphone submerged in a bucket of water. This very simple setup only requires a waterproof smartphone (or a smartphone in a waterproof case) with a barometer. (E)
133. "Kitchen physics: Lessons in fluid pressure and error analysis." R. Vieyra, C. Vieyra, and S. Macchia. Phys. Teach. **55**(2), 87–90 (2017). Two simple experiments on pressure and density in fluids can be done at home using, as in the previous reference, a waterproof case and the pressure sensor (barometer). In the first experiment, the density of several fluids is obtained through the relationship between depth and pressure. The second experiment is devoted to the relation between pressure and temperature given by Gay-Lussac's law. (E)
134. "Transient heat conduction in a heat fin," J. Brody and M. Brown, Am. J. Phys. **85**(8), 582–586 (2017). An inexpensive experiment on heat conduction uses an Arduino board and temperature sensors. The experimental results can be readily compared with fundamental laws. (I)
135. "Temperature-dependent transport measurements with Arduino," A. Hilberer, C. Laurent, A. Lorin, A. Partier *et al.*, Pap. Phys. **10**, 100007 (2018). This article offers an extensive and somewhat technical analysis of the measurement of temperature and resistance of a sample. Also, the details of two experiments are given: observing the magnetocaloric effect in gadolinium and measuring the resistive transition of a high-Tc superconductor. (A)
136. "Studying Avogadro's law with Arduino," A. A. Moya, Phys. Teach. **57**(9), 621–623 (2019). Another example of the many applications of Arduino boards, an experiment is described to estimate Avogadro's number from the kinetic theory of ideal gases through simultaneous measurements of temperature, pressure, and volume. (E)
137. "Experimental analysis of the free surface of a liquid in a rotating frame," M. Monteiro, F. Tornaría, and A. C. Martí, Eur. J. Phys. **41**(3), 035005 (2020). The shape of the surface of a fluid in a rotating container is obtained using a gyroscope sensor and video analysis, and its dependence on the angular velocity is analyzed. (I)
138. "Surface tension measured with Arduino," A. M. B. Goncalves, W. P. S. Freitas, D. D. Reis, C. R. Cena, D. C. B. Alves, and D. F. Bozano, Phys. Teach. **57**(9), 640–641 (2019). Through measurements of the weight of a water droplet suspended at the tip of a pipette and video analyses, the surface tension between air and water is obtained. (E)
139. "Measuring the viscosity of air with soapy water, a smartphone, a funnel, and a hose: An experiment for undergraduate physics students," A. Delvert, P. Panizza and L. Courbin, Am. J. Phys. **90**, 64–70 (2022). A device to measure the air viscosity is proposed with low cost equipment: soapy water, a funnel, some tubing, a smartphone camera and free software. The spontaneous motion of a soap bubble film inside the sloping sides of an inverted funnel is recorded with a camera, while the film moves, pushing air, from the wide opening toward the narrow end of the funnel. The kinematics of the film is directly related to the viscosity of air. Then, analyzing the video and knowing the geometric and physicochemical parameters of the system, the viscosity of air can be found. (A)

XI. MODERN PHYSICS

Although smartphones are not especially well-suited to performing experiments in modern physics, several creative experiments have been put forward, including ones that enable experiments on radioactivity or requiring particle detectors. The advantage of smartphones in these contexts is clear.

140. "iRadioactivity—Possibilities and limitations for using smartphones and tablet PCs as radioactive counters," J. Kuhn, A. Molz, S. Gröber, and J. Frübis, Phys. Teach. **52**(6), 351–356 (2014). By covering the camera with a black tape, it is possible to experiment with radioactivity in an educational setting. The experiments proposed focus on the inverse-square law for distance, absorption laws, and decay of meta-stable isotopes. Although camera sensors are sensitive to radiation, the characteristics strongly depend on the specific sensor. Since general sensors are not sensitive enough to experiment with background radiation, a standard radioactivity source, like those present in many educational laboratories, is needed. A Geiger counter is advisable for comparison.
141. "Using smartphones and tablet PCs for β^--spectroscopy in an educational experimental setup," S. Gröber, A. Molz, and J. Kuhn, Eur. J. Phys. **35**(6), 065001 (2014). A β^-spectrometer can be built using a PC or a mobile device, a magnetometer, a simple electric circuit, and a commercial ^{90}Sr/Y source. A Geiger-Müller tube is also advisable for comparison. As in the previous reference, the app, RadioactivityCounter, measures radioactive radiation with the camera sensor. (A)
142. "A low-cost computer-controlled Arduino-based educational laboratory system for teaching the fundamentals of photovoltaic cells," K. Zachariadou, K. Yiasemides, and N. Trougkakos, Eur. J. Phys. **33**, 1599–1610 (2012). This paper describes an experiment to learn about semiconductor physics. Note that there are currently more suitable alternatives to be used than the apps proposed here. (I)
143. "The desktop muon detector: A simple, physics-motivated machine- and electronics-shop project for university students," S. N. Axani, J. M. Conrad, and C. Kirby, Am. J. Phys. **85**, 948 (2017). For less than \$100, it is possible for undergraduates to construct a muon detector using a silicon photomultiplier to detect scintillation light from particles and an Arduino board for data acquisition. Its construction develops machine-shop, electronics-shop, and programming skills. (A).

XII. ASTRONOMY

Experiments related to astronomy make use of the camera as an observational tool or that simulate astronomical concepts such as parallax, planetary transits, and occultations. The ambient light sensor also plays a key role in several of these experiments.

144. "Using smartphone camera technology to explore stellar parallax: Method, results, and reactions," M. T. Fitzgerald, D. H. McKinnon, L. Danaia, and S. Woodward, Astron. Educ. Rev. **10**(1), 010108 (2011). A simple and practical method is proposed to introduce the parallax technique to determine distances in a scaled system that uses data from a smartphone's camera, simulating the way astronomers measure some stellar distances. (I)
145. "Smartphone astronomy," M. Meißner and H. Haertig, Phys. Teach. **52**(7), 440–441 (2014). In a hands-on introductory astronomy activity for college or university, students measure the speed of the International Space Station by means of a smartphone's camera. (E)
146. "Analyzing planetary transits with a smartphone," A. Barrera-Garrido, Phys. Teach. **53**(3), 179–181 (2015). A smartphone's light sensor is used to obtain the light curve from a scaled stellar system, simulating the transit method used by astronomers to discover exoplanets. (E)
147. "A smartphone-based introductory astronomy experiment: Seasons investigation," J. Durelle, J. Jones, S. Merriman, and A. Balan, Phys. Teach. **55**(2), 122–123 (2017). The origin of the seasons is explained by means of a model of the Earth-Sun system using a smartphone's light sensor. Light curves are obtained as a function of latitude, and solstices and equinoxes are identified. (E)
148. "Practicing spatial relationship skills using an asteroid 3-D tool," J. Ziffer, W. Morse, T. Nelson, P. Nakroshis, B. T. Rudnick, M. Brautigam, and W. Parke, Phys. Teach. **57**(1), 14–16 (2019). An Arduino board and a light sensor is used to measure the light curve of different 3D-printed asteroids while they rotate. (I)
149. "Determination of the orbital inclination of the ISS with a smartphone," J. VanderMarlière, Phys. Teach. **57**(7), 502–503 (2019). A simple experiment to determine the inclination of the International Space Station using triangulation from two different locations, making use of smartphone sensors to measure azimuth and elevation. (E)

XIII. PHYSICS EDUCATION RESEARCH

Although the use of smartphones in physics laboratories is a recent introduction, researchers have already started to explore their impact on student learning.

150. "An investigation into the effectiveness of smartphone experiments on students' conceptual knowledge about acceleration," A. Mazzella and I. Testa, Phys. Educ. **51**(5), 055010 (2016). This paper investigates the impact on secondary school students of using smartphone sensors vs traditional technologies. It provides detailed information about the activities performed and the assessment questionnaires. Although there were no great differences in the performance of the groups, the results suggest that smartphone-based activities may represent a valuable tool for teachers who want to implement laboratory activities at secondary-school level. To achieve a proper conceptual understanding, specific issues about the smartphone as a transformative scientific instrument must be addressed. (I)
151. "The effects of integrating mobile devices with teaching and learning on students' learning performance: A meta-analysis and research synthesis," Y. T. Sung, K. E. Chang, and T. C. Liu, Comp. Educ. **94**, 252–275 (2016). A meta-analysis synthesizing more than one hundred research reports showed that the application of mobile devices in education has a moderate sized mean effect. As it focused neither on sensors nor on

experimental activities, the results should be considered with caution. (I)

152. "Project-based physics labs using low-cost open-source hardware," F. Bouquet, J. Bobroff, M. Fuchs-Gallezot, and L. Maurines, Am. J. Phys. **85**(3), 216–222 (2017). This paper proposes an extensive list of projects aimed at third-year university students using open-source, low-cost Arduino boards, and compatible sensors (voltage, magnetic field, temperature, light, sound, acceleration, and force). The topics include acoustics, thermodynamics, waves, and matter (including superconductivity, Peltier cells, and mechanical properties). It offers technical specifications and case studies useful to implement the projects, describing not onlytechnical aspects but also pedagogical and motivational aspects. (A)
153. "Adapting *RealTime Physics* for distance learning with the IOLab," E. Bodegom, E. Jensen, and D. Sokoloff, Phys. Teach. **57**(6), 382–386 (2019). While this paper uses IOLab's sensor cart to enable distance learning laboratories, many of the same ideas could be implemented using smartphone sensors. (I)
154. "Using smartphones as experimental tools—Effects on interest, curiosity, and learning in physics education," K. Hochberg, J. Kuhn, and A. Müller, J. Sci. Educ. Tech. **27**, 385–403 (2018). One of the main conclusions of the work that investigated students' learning in pendulum experiments is that "the often-supposed cognitive disadvantage of distracting learners with technological devices did not lead to reduced learning, whereas interest and curiosity were apparently fostered. (I)
155. "Using smartphones as experimental tools - a follow-up: Cognitive effects by video analysis and reduction of cognitive load by multiple representations," K. Hochberg, S. Becker, M. Louis, P. Klein, and J. Kuhn, J. Sci. Educ. Tech. **29**, 303–317 (2020). An investigation about the cognitive effects of working with video analysis on tablets instead of working with traditional experimental tools. No significant differences were found on interest, curiosity, or cognitive load. (I)
156. "Studies the use of smartphone sensor for physics learning," L. Sukariasih, L. Erniwati, L. Sahara, L. Hariroh, and S. Fayanto, Int. J. Sci. Tech. Res. **8**(10), 862–870 (2019). The authors offer an extensive list of demonstrations across diverse physics fields, showing how to adapt classic experiments to use smartphone sensors. (I)
157. "Implementation of smartphone-based experimental exercises for physics courses at universities," A. Kaps, T. Splith, and F. Stallmach, Phys. Educ. **56**(3), 035004 (2021). In this investigation, traditional theoretical exercises are partially replaced by experimental mini projects using smartphones. While the students found the experimental exercises slightly more difficult, they resulted in a better understanding of the physical concepts and a much improved motivation to solve the challenges.
158. "A guide for incorporating e-teaching of physics in a post-COVID world," D. J. O'Brien, Am. J. Phys. **89**(4), 403–412 (2021). In a paper discussing many aspects of e-learning, the advantages of smartphones are explored as educational and experimental tools. Nearly 80 examples of smartphone-based labs and home introductory physics experiments are provided and sorted by subject. (I)
159. "Lessons from transforming second-year honors physics lab," D. Doucette, B. D'Urso, and C. Singh, Am. J. Phys. **88**, 838 (2020). Focused on the introduction of new technology, this paper proposes three laboratory modules encouraging students' initiative in opposition to a "black box" philosophy. (I)

XIV. CITIZEN SCIENCE

Mobile-device sensors are especially suited to a broad range of experiments that enable public participation in identifying research questions, collecting and analyzing data, and understanding environmental problems.

160. **iSPEX** (http://ispex.nl/en/). **Air pollution.** A citizen science project developed in the Netherlands in 2012 to measure atmospheric aerosols, based on a free app and a low-cost add-on for smartphone cameras. The instrument is based on that of the Spectropolarimeter for Planetary EXploration (SPEX). The citizen scientists scan the sky while the phone's camera takes pictures through the add-on, recording the spectrum and the linear polarization of the sunlight that is scattered by suspended dust particles, making a map of contaminants. (A)
161. **CrowdMag** (https://www.ngdc.noaa.gov/geomag/crowdmag.shtml). **Geomagnetic field.** A citizen science project developed by the geomagnetism group of NOAA's National Centers for Environmental Information (NCEI). The CrowdMag app uses the built-in magnetometer of the phone of volunteers around the world to send magnetic field data to the server of the research group. The main goal is to use the citizen generated information to fill in gaps in measurements of Earth's magnetic field. (I)
162. **MyShake** (https://myshake.berkeley.edu/)**. Earthquake** detection. A citizen science app developed by researchers from the University of California, Berkeley, that takes advantage of the ubiquity of smartphones, their built-in GPS, and tri-axis accelerometers to detect earthquakes. The aim is to build a global earthquake early warning network that does not replace the standard networks but could be useful in some seismically active places. More information about the technical development of the project can be found in the research paper, "MyShake: A smartphone seismic network for earthquake early warning and beyond," Q. Kong, R. M. Allen, L. Schreierand, and Y. Kwon, Sci. Adv. **2**(2), e1501055 (2016). (A)
163. **DECO** (https://wipac.wisc.edu/deco). Cosmic Rays. The Distributed Cosmic-ray Observatory (DECO) is a citizen science project led by Justin Vandenbroucke at the University of Wisconsin–Madison supported by the National Science Foundation and the American Physical Society, among others. The DECO app enables users around the world to detect cosmic rays and other energetic particles using the camera sensors of their smartphones and tablets. The recorded events are automatically uploaded to a central database. In addition to detecting particle events, users can analyze the data produced by their own or other users' phones. This work is described in the paper: "Particle identification

in camera image sensors using computer vision," Astropart. Phys. **104**, 42–53 (2019). (A)

164. "Gravimetric detection of Earth's rotation using crowdsourced smartphone observations," S.F. Odenwald and C. M. Bailey, IEEE Access **7**, 148131–148141 (2019). The rotation of the Earth is detectable by means of crowdsourcing measurements of the slight changes in local gravity that can be detected by smartphone accelerometers. (I)
165. "Smartphone science: Apps test and track infectious diseases," S. Ravindran, Nature **593**(7858), 302–303 (2021). An example of unexpected applications of mobile-device technology. The less surprising one is tracking of disease using geolocalization, but a more surprising example is the use of the smartphone as a tool to facilitate tests for certain diseases by means of the camera and the processor. (A)

XV. FINAL REMARKS

In the last few years, the use of smartphones and their sensors has had a great impact on physics teaching. In this Resource Letter, we have concentrated on the application of sensors available in a wide range of mobile devices, setting aside other uses such as access to information on the internet, preparation of presentations, exchange of ideas between peers or with the teacher, and more.

It is our view that the most important characteristic in the use of these devices and their sensors is their adaptability to a wide range of applications. While sensors are most easily applied to experiments in mechanics or waves, they can be used in every possible field. They enable experiments illustrating elementary concepts but also can be used in advanced projects that require considerable mathematical and experimental skills. While accelerometers are most commonly used, the camera, microphone, and GPS locator are also frequently used, even though they do not fall within the usual definition of a sensor. Some experiments are based on measuring scalar quantities, but others involve vectors, logical variables, or matrices. The software used, which works under different operating systems, ranges from very elaborate programs to simple applications, free or purchased. In some cases, data are transferred to a computer for processing; in others, they are processed on the device itself. Many of the experiments proposed are carried out in laboratories; however, others are carried out outdoors, in amusement parks, or on means of transport. Some require laboratory materials or equipment, while others can be carried out with material available in many homes. There are many advantages to the use of these sensors. Their wide availability is an important factor. Even in socially disadvantaged contexts there is usually access to mobile devices at no additional cost, while access to traditional educational materials may be limited or nonexistent. Their portability and the convenience of having multiple sensors in one device that communicate directly with each other is another great advantage, allowing measurements and connections that would otherwise be difficult to achieve.

It is worth asking whether using the sensors in mobile devices represents a significative advance or only a marginal one. The same question could be asked about the use of smartphones in other areas, and we believe the answers are essentially the same: access to a set of resources in a single device, at an affordable price, and in a compact size, is, by itself, a great advantage. The definitive answer will be provided by users themselves when they choose one alternative or another.

There are many unknown factors to be faced in the coming years. Mobile devices have incorporated sensors only over the last decade. We do not know whether manufacturers will continue to include new sensors, or whether their calculation capacity will continue to increase at the same rate as in recent years.

Perhaps, future advances will improve the ease of use of software and data processing. Physics education research also has much to say, indicating whether future change will be significant or merely marginal, and in what aspects improved learning outcomes will be noted. In any case, what we can state is that these devices and sensors are here to stay. As with all new tools or technology that appear, the best attitude seems to be to analyze their contributions and use them critically and reflectively.

ACKNOWLEDGMENTS

The authors are very grateful to the anonymous reviewers for their careful reading and thoughtful comments. The authors appreciate their suggestions and have included many of them in this Resource Letter.

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