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Smartphones in the teaching of Physics Laws: Projectile motion

El teléfono inteligente en la enseñanza de las Leyes de la Física: movimiento de proyectiles

Pablo Martín-Ramos
Universidad de Zaragoza, EPS (España)

Manuela Ramos Silva
Pedro S. Pereira da Silva
Universidade de Coimbra, CFisUC (Portugal)

Abstract

New technologies are called upon to play an important role as beneficial tools for meaningful learning in the classroom. In particular, smartphones can be regarded as pocket computers that, in addition to a remarkable memory and computing capacity, incorporate sensors such as accelerometers, gyroscopes, magnetometers, light sensors, etc., which turn them into easily available measurement instruments for practical classes in an educational environment. In this study, the suitability of these devices for demonstrating Classical Mechanics, minimizing the use of resources and class time, has been assessed in two real classrooms (with 16 to 19 year-old students) by conducting experiments related to projectile motion (vertical free fall and parabolic motion). A simple methodology that only involves a mobile phone, a free burst camera application and open-source tools (GIMP and OpenOffice Calc) for data processing is presented. The results obtained in non-perfected conditions led to an estimate of the acceleration of gravity with an error lower than 2%. Further analyses and alternative procedures are also suggested in the discussion section. No major difficulties were encountered with the high school students or with the first year university ones, and a high degree of satisfaction was found.

Keywords: didactic use of computer; new technologies; physics; teaching practice.

Resumen

Las nuevas tecnologías están llamadas a jugar un papel importante como herramientas beneficiosas para el aprendizaje significativo en el aula. En particular, los teléfonos inteligentes son verdaderos ordenadores de bolsillo que, además de una notable capacidad de memoria y de cómputo, incorporan sensores como acelerómetros, giroscopios, magnetómetros, sensores de luz, etc. que los convierten en instrumentos de medida fácilmente disponibles para prácticas en un entorno educativo. En el presente estudio, la idoneidad de estos dispositivos para explicar conceptos de Mecánica Clásica, minimizando el uso de recursos y tiempo de clase, ha sido evaluada en dos clases reales (con estudiantes de edades comprendidas entre los 16 y los 19 años) mediante la ejecución de experimentos relacionados con el movimiento de proyectiles (caída libre y trayectoria parabólica). Se presenta una metodología sencilla, que únicamente hace uso de un teléfono móvil, una aplicación fotográfica gratuita para captura de imágenes en ráfaga y herramientas de código abierto (GIMP y OpenOffice Calc) para el procesado de los datos. Los resultados obtenidos en condiciones no optimizadas han conducido a una estimación de la aceleración de la gravedad con un error inferior al 2%. En la discusión de resultados se sugieren análisis más avanzados y otros procedimientos alternativos. No se encontraron problemas significativos en la ejecución de los experimentos ni con los alumnos de enseñanza secundaria ni con los de primer año de carrera, y el grado de satisfacción entre el alumnado fue alto.

Palabras clave: física; nuevas tecnologías; práctica pedagógica; uso didáctico del ordenador.

Physics, Chemistry, Biology or Geology are sciences that have been developed through experimental studies since the times of the ancient Greek civilization. Remember the episode of Archimedes discovering the law of buoyancy and the full bath overflowing when he lowered himself into it. Since then, thousands and thousands of other experiments have been conducted to establish the laws of Physics. Nowadays some of these experiments have even received worldwide coverage, such as the finding of Higgs boson in CERN – Switzerland (CMS collaboration, 2014). But why is the teaching of aforementioned subjects in high-school or in the first year of engineering degrees so theoretical? Why it is so difficult to do lab classes during the school year? The answer is complex, but the main cause is usually the lack of resources. The classroom has to be split at least into two groups, which demands more teachers and space, and an experiment requires equipment, reagents and such, which are expensive to buy and difficult to repair (Bennett, 2001; Great Britain Parliament. House of Commons. Science and Technology Committee, 2011; Hart, Mulhall, Berry, Loughran, & Gunstone, 2000; Heeralal, 2014).

In this paper we provide a way out when resources are scarce by showing that a smartphone can easily be used to study the Laws of Motion through the study of projectile motion. Most teenagers in developed-countries own a smartphone and bring it with them into the classroom, where the teacher either gathers them all before the class or repeatedly announces that they must be switched off during the entire class (Thomas, O'Bannon, & Britt, 2014). Nonetheless, smartphones are an excellent technological platform that may give a helping hand when performing experiments, reducing their cost to almost zero, and thus they should be incorporated in the classes instead of being banned from them (Baird, Secrest, Padgett, Johnson, & Hagrelius, 2016; Chevrier, Madani, Ledenmat, & Bsiesy, 2013; Forinash & Wisman, 2012, 2015; Hall, 2013; Kuhn & Vogt, 2013; MacIsaac, 2015; Mau, Insulla, Pickens, Ding, & Dudley, 2016; Monteiro, Stari, Cabeza, & Marti, 2015; Monteiro, Vogt, Stari, Cabeza, & Marti, 2016; Müller, Vogt, Kuhn, & Müller, 2015; Shakur & Kraft, 2016; Tornaría, Monteiro, & Marti, 2014; Vogt & Kuhn, 2012; Vogt, Kuhn, & Neuschwander, 2014).

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Let us recall that the processing ability of any mid-tier smartphone exceeds by far that of the computer used in our early space missions to the Moon!

Herein we are presenting an example of an experiment to study projectile motion and the determination of the acceleration of gravity. And for that purpose we only need a smartphone with a free burst camera app and a common beach ball. To analyze the results we need a computer with a photo editor (or a printer and a ruler). A free and open source photo editor, such as GNU Image Manipulation Program (GIMP), is the recommended choice.

We are showing the results attained in a non-perfected attempt without adjusting the focus of the camera, repeating the takes or re-measuring the position of the ball, so that the easiness of the experiment can be readily perceived. The measurements involved in this experiment take less than 5 minutes.

Projectile motion is something that we get used to before we can even walk. The game of tossing a ball to a toddler is something that we all have done and, later on, we have all played soccer or watched the game on television. How many kicks and headers have we seen from our favorite players, with the ball describing beautiful parabolic trajectories?

The study of projectile motion is part of the high-school and Physics 101 curriculum all over the world. There are two main reasons beneath this fact: the mathematics involved are simple enough for 16 year-old students and two types of movement can be studied, exemplifying the main Laws of Mechanics: the Law of Inertia and the Fundamental Law of Dynamics (Feynman, Leighton, & Sands, 2011; Tipler & Mosca, 2004).

As it will be further described in the next sections, by performing the proposed experiment, students will deal with new technologies (smartphones and computers), they will learn Physics and they will enhance their logic skills.

We show one way of introducing technologies in the classroom to enhance the teaching/learning process. The use of technologies in the classroom, although often praised (Clements & Sarama, 2003; Glaubke, 2007; Stošić, 2015), sometimes even at the highest level (President Obama started a *Computer Science For All* initiative), has not yet taken place (Lowther, Inan, Strahl, & Ross, 2012), in spite of the fact that the technological and information society keeps challenging the education system. The system should be able to educate high-school graduates so that they become technologically literate and productive employees in any world-competitive company. The introduction of new technologies in the classroom may find some resistance from the teachers' point of view (Becker, 2000; Hermans, Tondeur, van Braak, & Valcke, 2008; Stosic & Stosic, 2013; Wang, Ertmer, & Newby, 2004), but it will be happily received by the students. This generation of students has been brought up surrounded by gadgets and they appreciate the use of technologies, feeling more engaged in learning, staying focused and learning faster (Ifenthaler & Schweinbenz, 2013).

METHODOLOGY

We used an Android (v5.1.1, Lollipop) smartphone (Moto G 3rd gen, CPU Quad-core 1.4 GHz Cortex-A53, GPU Adreno 306, 8 GB internal storage, 1 GB RAM) with a 13 MP primary camera (f/2.0, autofocus, dual-LED flash), after having downloaded the free app Fast Burst Camera Lite from Google Play (Spritefish, 2016). We chose the no delay option in the app settings so that the phone would take a photo every 50 milliseconds approximately. The person tossing the ball stood near a white wall (standing on the seat of a chair to become taller) and threw the ball horizontally or vertically. The person taking the pictures stood facing the wall, at an approximate middle point, trying not to move during the brief data collection. Several pictures were taken, in an event lasting nearly 1 second, by synchronizing the beginning of the movement with tapping and holding the shutter button in the camera app.

Photos were downloaded to a computer using the Bluetooth connection (Figure 1). The 20-25 pictures were time stamped up to the millisecond, so the time of each ball position was known (see Figure 2). The height of the ball thrower was used to scale the position taken from the picture to the real distance covered by the ball.

Figure 1. Smartphone, computer and ball (*source*: taken by the authors)

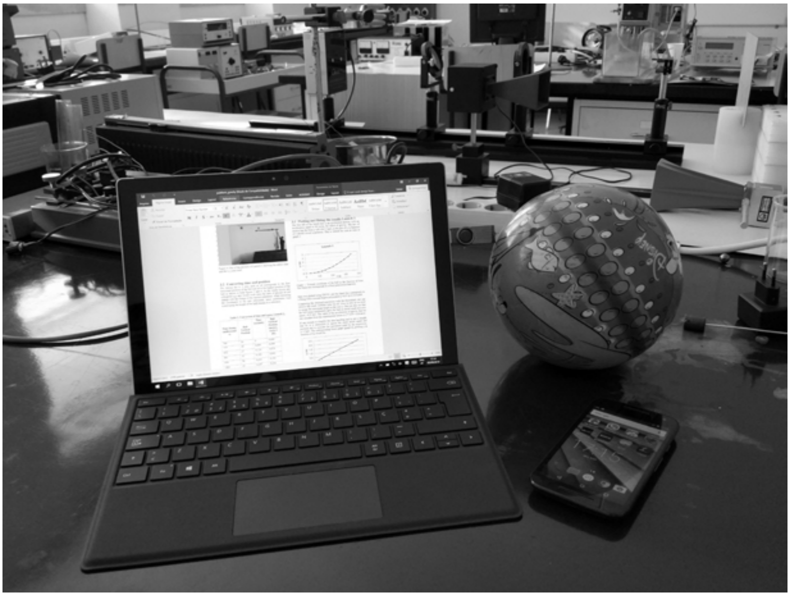

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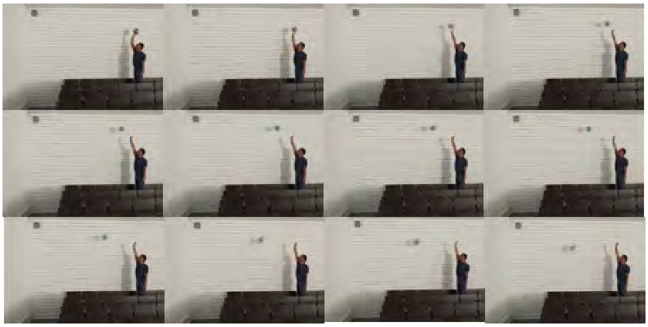
Figure 2. Some of the pictures taken during the flight of the ball (*source*: taken by the authors)



EXPERIMENTAL RESULTS

Photo editing, retrieving position and time

The pictures (Figure 3 and Figure 4) were opened in GIMP photo editor in a 100% size viewing option. Rulers were set and the position of the ball retrieved by positioning the cursor at the center of the ball or at the center of the ball blur (for pictures taken when the movement was very fast). Results were collected in Table 1.

Figure 3. One of the pictures of Launch 1 showing the editor ruler and the *y* axis used (*source*: taken by the authors)

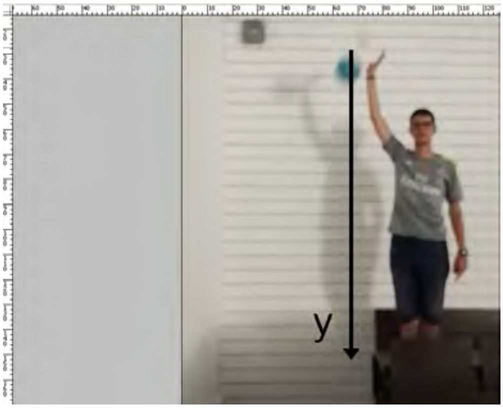


Figure 4. One of the pictures of Launch 2 showing the editor ruler and the *x*,*y* axes used (*source*: taken by the authors)

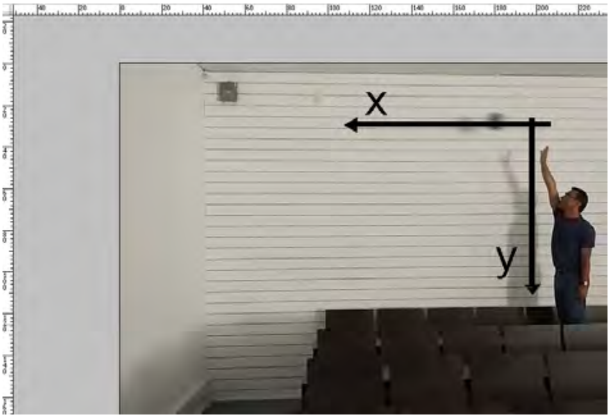


Table 1. Results of the Launch 1 (nearly vertical drop) and Launch 2 (nearly horizontal toss)

Timestamp (ms)	Vertical position	Timestamp (ms)	Horizontal position	Vertical position
708	26	359	208	41
777	26	407	201	36
832	27	457	194	31
891	31	508	188	29
950	36	560	181	28
1005	42	623	174	28
1061	54	678	166	29
1125	65	728	160	31
1180	79	776	152	36
1244	94	823	145	42
1299	110	878	138	48
1365	127	927	130	56
1408	147	978	122	63
		1024	116	75
		1074	110	86
		1123	103	98

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Timestamp (ms)	Vertical position	Timestamp (ms)	Horizontal position	Vertical position
		1175	96	113
		1228	91	127
		1284	85	144
		1325	77	159

Source: research results.

Converting time and position

We chose the *x*,*y* axes in such a way that x_0 corresponded to the first horizontal position of the ball and y_0 to the highest position of the ball, as shown in Figure 3 and Figure 4. As the reader knows, any orthogonal *x*,*y* axes system would work, since the Laws of Physics do not change with the change of the inertial referential. After converting the coordinates to the new referential, space coordinates were scaled using the height of the ball throwers as a reference.

Table 2. Conversion of time and space, Launch 1

Timestamp (ms)	Vertical position	Time (s)	Vertical position (m, scale ×1.83)
708	26	0.000	0.000
777	26	0.069	0.000
832	27	0.124	0.018
891	31	0.183	0.092
950	36	0.242	0.183
1005	42	0.297	0.293
1061	54	0.353	0.512
1125	65	0.417	0.714
1180	79	0.472	0.970
1244	94	0.536	1.244
1299	110	0.591	1.537
1365	127	0.657	1.848
1408	147	0.7	2.214

Source: research results.

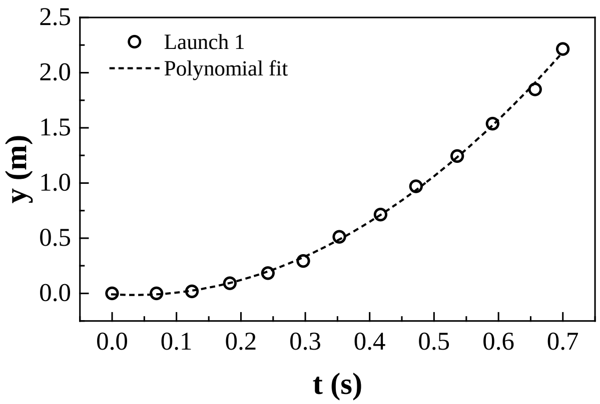
Plotting and fitting the results - Launch 1

The free fall of the beach ball is an accelerated motion, with an acceleration equal to 9.8 m/s^2, due to the effect of gravity. The Law of Motion has the form $y=y_0+v_0\bullet t+1/2\bullet g\bullet t^2$, so the plot of y as a function of t should reveal a parabola. This was indeed the case, as depicted in Figure 5.

Data was plotted using Calc in OpenOffice and the dashed black line corresponded to a fitting with the second degree polynomial $y=4.97\bullet t^2-0.35\bullet t-0.008$.

Comparing the obtained expression with the theoretical one, one can retrieve the small -0.008 m value for y_0, close to zero as we tried to assign the maximum height as the zero y. One can also see that the ball thrower accidentally gave the ball an initial small non-zero speed, -0.35 m/s. The value of the acceleration of gravity that one can calculate from the experimental values is 2·4.97=9.94 m/s^2.

Figure 5. Vertical coordinate of the ball as a function of time. The dashed black line corresponds to a fitted polynomial function



Source: research results

If one intends to simplify the data handling and to use a straight line fit, it is admissible to ignore the small initial speed and position and to consider the movement ruled by the expression, $y=1/2\bullet g\bullet t^2$. The corresponding linear graph, plotting y as a function of t^2, is shown in Figure 6.

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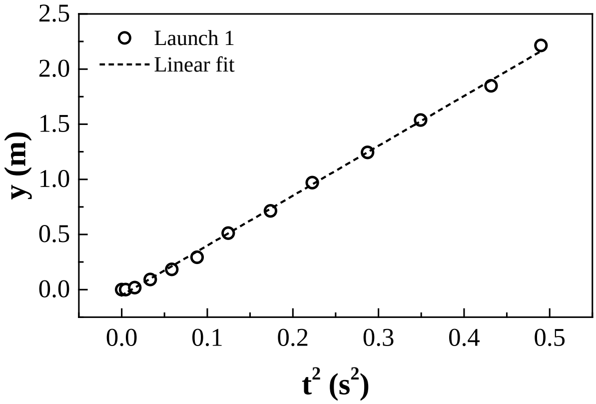
Figure 6. Vertical coordinate of the ball as a function of time squared. The dashed black line corresponds to a fitted straight line. *Source*: research results



With the equation of the best fitting straight line being and R^2=0.9985, the experimental g value equals 9.86 m/s². The standard error in the slope of the fitted straight line can be calculated using the formula $\sigma = m\sqrt{\frac{1}{N-2}\cdot\frac{1-R^2}{R^2}}$ where m is the slope, R the Pearson coefficient and N the number of points (Ramos Silva, Martín-Ramos, & Pereira da Silva, 2016), to yield 0.06, therefore g=9.86±0.06 m/s².

Plotting and fitting the results - Launch 2

The following table (Table 3) shows the ball positions as a function of time, as retrieved from the pictures taken at regular intervals. Space coordinates were transformed into real space dimensions using the scale factor of 2.07, calculated from the height of the ball thrower, and referred to the reference drawn in Figure 4.

Figure 7 shows a plot of the space coordinates of the ball as they changed with time of flight. It can be seen by the trajectory that the toss was not perfectly horizontal and that a small upward velocity component was given to the ball. The values on each axis were reversed to allow an easier comparison with Figure 4.

The ball had therefore two distinct and independent movements in the horizontal and vertical directions. Horizontally, without being acted by any significant force, the ball had a uniform motion with constant speed, $x=v_{0x}\bullet t$ (Law of Inertia). A plot of x as a function of t should therefore appeared as a straight line, with the slope matching the constant speed, which is exactly what we see in Figure 8.

Table 3. Time and coordinates of the ball in Launch 2

Timestamp (ms)	Horizontal position (m)	Vertical position (m)
0	0.00	0.27
0.048	0.15	0.17
0.098	0.29	0.06
0.149	0.42	0.02
0.201	0.56	0.00
0.264	0.71	0.00
0.319	0.87	0.02
0.369	1.00	0.06
0.417	1.16	0.17
0.464	1.31	0.29
0.519	1.46	0.42
0.568	1.62	0.58
0.619	1.79	0.73
0.665	1.91	0.98
0.715	2.04	1.21
0.764	2.18	1.46
0.816	2.33	1.77
0.869	2.43	2.06

Source: research results.

Figure 7. Vertical coordinate of the ball as a function of the horizontal coordinate showing the ball trajectory. *Source*: research results

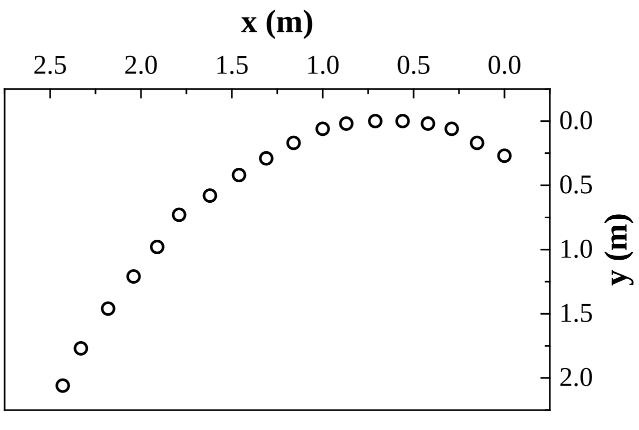


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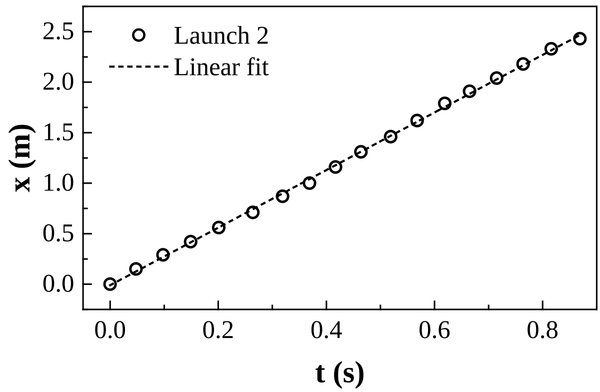
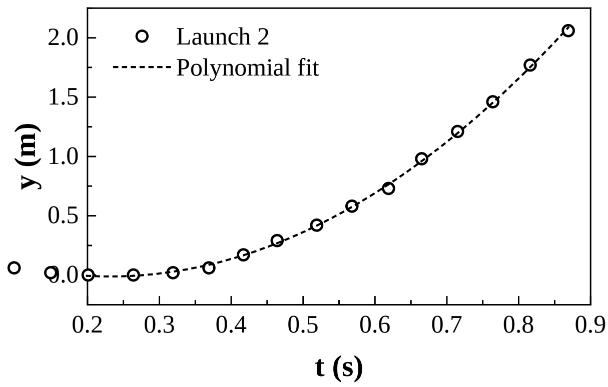
Figure 8. Horizontal position of the ball as a function of time. The dashed black line corresponds to a fitted straight line. *Source*: research results



The best fit to the experimental data yielded the equation *x=2.82t*.

On the vertical axis, the movement was uniformly accelerated with the acceleration of gravity pointing downwards in the positive direction of the *y* axis. Similarly to Launch 1, the plot of *y* as a function of *t* yielded a parabola (Figure 9).

Figure 9. Vertical position of the ball as a function of time. The dashed black line corresponds to a fitted polynomial function. *Source*: research results



The best fit corresponded to the quadratic expression $y=4.87 \cdot t^2-2.07 \cdot t+0.19$, so the experimental acceleration value was 9.74 m/s^2. With this simple measurement, the Fundamental Law of Dynamics, $\vec{F}=m\cdot\vec{a}$, was tested. If the only force acting on the ball is the vertical gravitational force, then the acceleration of the movement is $\vec{a} = \vec{F}_g / m = m \cdot \vec{g} / m = \vec{g}$.

Further analysis and alternative procedures

For a more advanced classroom, there are more aspects that can be explored with similar data collections, such as the small difference in ball acceleration in the upward and downward movement, caused by air resistance. It is also possible to experimentally calculate the initial ball velocity and compare between students' strengths. Moreover, one can even reproduce Galileo's experiment from the top of the Leaning Tower of Pisa, and determine if different balls left to fall at the same time hit the ground at the same instant.

It is also possible to direct the experiment to the comparison between smartphone performances (using several smartphones to shoot the same projectile motion) and give the students a first exercise on Metrology science.

If a laptop/desktop is not available, the printed photos (all in the same scale) can also be analyzed using a common ruler and a graph of $y(t^2)$ can be plotted in millimetric paper. A straight line can be drawn by hand.

The real classroom - Troubleshooting

The activity was conducted at two distinct educational levels: in a high-school (11^{th} grade) class where the vertical movement of a projectile was being studied and in a first-year Physics Engineering class, both in the city of Coimbra (Portugal).

For the high-school class, the activity had been previously announced and all the students brought to class their smartphones with the Fast Burst Camera Lite app already installed. Some of the students also brought, without being asked to, their laptop computers. The Physics lab was equipped with some old-fashioned desktop computers with internet access. The class was split into two, so that a group of fifteen students were at the lab at a time, further split into four subgroups. Balls were borrowed from the gym teacher on the spot. Each group collected their own data separately. For data collection, groups were instructed to place one of the students with the ball against a uniform wall, outside the classroom. The student that took the pictures was advised to keep a firm hand, to use a 960×720 resolution in the app preferences and to choose a 1/20 second delay between shots. The data collection for the entire group, taking into account the time required to get in and out the classroom, took less than 15 minutes.

Transferring the pictures to the computer was the most time-demanding step of the activity. The school's WiFi connection was slow and the students wanted to transfer all the photos (even those taken when the ball was at rest). Photos were analyzed with Microsoft Paint, a very simple image editing application, and the

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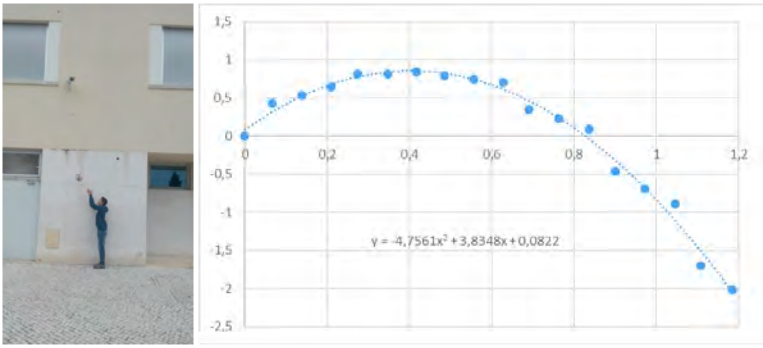
students very quickly figured out how to extract the ball coordinates from the figures. At this point we could see the students dealing with some issues and discussing within the group: '*should we consider the position of the ball while it is still in students' hands?*', '*why is the position of the ball almost the same in some pictures?*', '*has the ball already hit the floor in this picture?*', and so forth.

Students were alerted that the instant in which the picture was taken (in milliseconds) was part of the picture label. Students using an iPhone and the associated built-in camera burst feature had to calculate the time in which the picture was taken by considering a 0.1 s delay between shots. Data analysis and plotting followed next, and students filled two Excel columns with the time and ball vertical position (Microsoft Excel was used in this case instead of Calc, provided it is the most popular spreadsheet program and it was already installed in all lab computers and students' laptops).

As regards data manipulation, some instructions had to be given to the students on how to convert the measured time from milliseconds to seconds and on how to reset the time so that the first picture with ball movement would correspond to the t=0 s. The ball coordinates also had to be converted from pixels to meters, using the height of the student as the scale factor, and the y axis was set pointing upwards, as it was the students' preferred orientation. No help was required for $y(t)$ plotting and for fitting the data with a 2nd degree polynomial, since the students found these steps easy. One of the groups achieved a perfect value of 9.8 m/s^2, while the others showed a small spread around the ideal value. The graph of one of the groups showed the points grouped in bursts of 3 (see Figure 10), a situation that occurred again in the University-level class, and that is worth discussing in further detail.

Figure 10. One of the pictures taken in the high-school class (*left*) and vertical position of the ball as a function of time plotted by one of the groups (*right*). The dotted line corresponds to the polynomial function fit. *Source*: photograph taken by the authors and graph from research results



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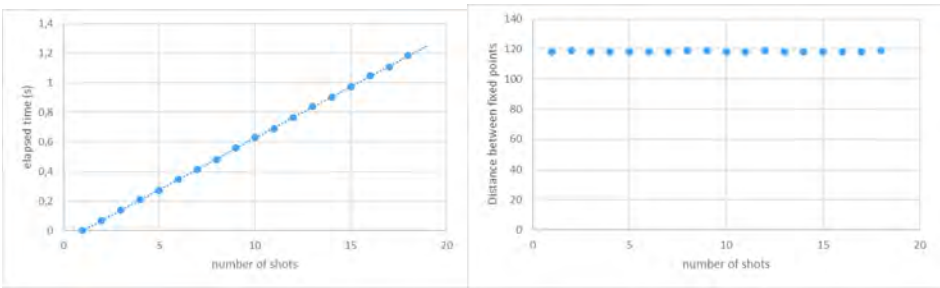
Having used the same app in all the mobile phones, the first explanation would be the unsteady hand of the student who took the pictures or the automatic zoom procedures of the camera, but a graph plotting the distance between two fixed points showed a constant value (see Figure 11). The difference in the pixel coordinates of a fixed point between the first and the last picture did not differ by more than 4 pixels (~8 cm).

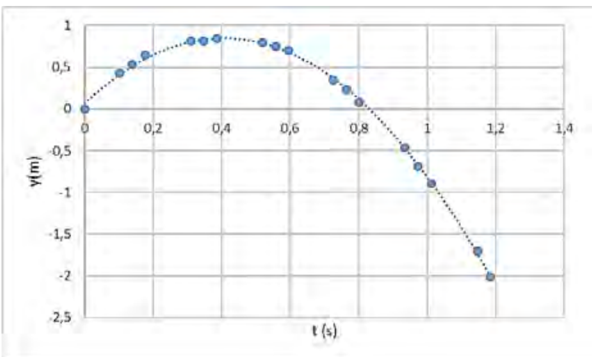
Figure 11. Timestamps in the saved pictures (*left*) and distance between fixed points (*right*)



Source: research results.

Although there is no easy way of correcting the experimental data, since both graphs in Figure 11 seem to point to a correct functioning of the smartphone, the positions of the ball cannot correspond to those of a body moving just under the influence of gravity for those particular instants. If one chooses the middle point of the trio burst and corrects the other points to be taken ~40 ms before and after the middle point, the positions start to fall under a parabolic line (see Figure 12).

Figure 12. Vertical position of the ball in function of the time, with time corrected, see text for details



Source: research results.

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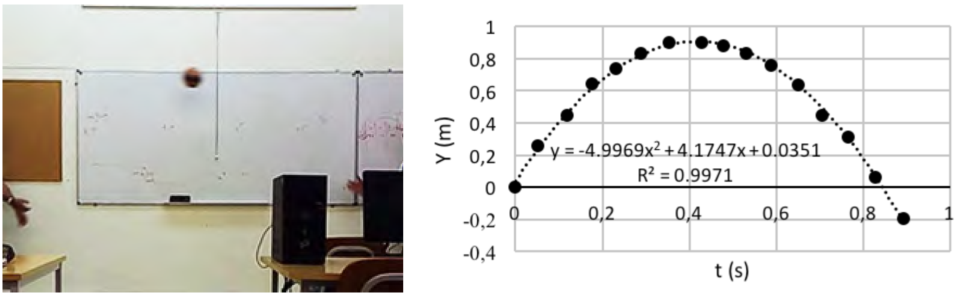
For the university freshman class, no warnings were given before class, so the students could not prepare or anticipate any of steps of the activity. They all had smartphones with them, mostly running Android. Some of them were carrying a laptop computer too. The classroom was equipped with 28 desktop computers running Windows 8 with Microsoft Office suite installed. A beach ball was taken into the class by the teacher. Students were briefly explained the activity (throwing a ball between two students within the classroom while taking periodic photos that had to be analyzed to retrieve the value of the acceleration of gravity), and what app to download and install. Being left alone, they tended to throw the ball at close proximity, therefore with few shots for each movement.

Most of them managed easily with Paint and with Excel. They were explained how to change the position units from pixel to meter by using the height of the board hanging on the wall. Results for the value of *g* were just slightly above and below 10 m/s^2. One of the groups obtained a graph with the burst pictures grouped in sets of 3 just like the one plotted in Figure 10.

Figure 13 shows one of the university-level students data sets.

Figure 13. One of the pictures taken in class (*left*) and (right) vertical position of the ball as a function of time. The dashed black line corresponds to a fitted polynomial function



Source: photograph taken by the authors and graph from research results.

Feedback from the students

A short survey was sent to the high school students after the experiment, using Google Forms, consisting of three questions: (*i*) if they enjoyed doing the experiment (rating it from 0 to 10); (*ii*) if they thought that their colleagues in other classes of the same school year would enjoy doing it also; and (*iii*) if it should be repeated the next academic year with the incoming students. Answering it was entirely voluntary and anonymous. 16 students responded, resulting in an average 8.81/10 rating in terms of satisfaction, and 100% agreement regarding the convenience of repeating the experiment in other classes and in the future.

CONCLUSIONS

In this article, we have shown that the lack of resources in a classroom can be easily overcome by the use of new technologies that are widespread amongst teenagers, such as smartphones and laptops. The applicability of a smartphone has been exemplified by the study of projectile motion with data collected in a first, non-perfected attempt, as it would be in a real classroom. A set of periodic pictures was taken following a ball toss, allowing the *x,y* coordinates of the ball to be tracked as a function of time. The uniform motion in the horizontal axis and the gravity accelerated vertical motion could be easily retrieved from the experimental data. The values for the acceleration of gravity calculated from the two independent launches were 9.94 and 9.74 m/s^2, with less than 2% difference from the known value of 9.8 m/s^2.

The activity was tested in two real classrooms, one for students aged 16-17 and the other with students aged 18-19. The same proliferation of smartphones amongst students was found (100%) and the willingness of the students to use them in class was very high. The activity can be implemented without previous preparation and the results are not deceiving. It was possible to see the students thinking about the characteristics of the ball movement while retrieving the ball coordinates from the pictures taken. Their degree of satisfaction after the conclusion of the activity was very high, with an 8.8/10 average rating in terms of satisfaction and 100% agreement concerning the convenience of extending it to other classes and future school years.

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ACADEMIC AND PROFESSIONAL PROFILE OF THE AUTHORS

Pablo Martín-Ramos. PhD in Telecommunications Engineering. Associate Professor at the Department of Agricultural and Environmental Sciences, University of Zaragoza, Spain. His main areas of interest include organic electronics, light-driven water-splitting on particulate inorganic photocatalyst systems and carbon nitride materials.
E-mail: pmr@unizar.es

AUTHOR' ADDRESS

Higher Polytechnic School
University of Zaragoza
Carretera de Cuarte s/n
22071 Huesca (Spain)

Manuela Ramos Silva. PhD in Solid State Physics. Professor at the Department of Physics, University of Coimbra, Portugal. She is interested in studying molecular compounds with interesting physical properties such as: molecular magnets; organic light-emitting diodes, multifunctional lanthanide based materials; organic non-linear optical materials.
E-mail: manuela@pollux.fis.uc.pt

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Pedro S. Pereira da Silva. PhD in Solid State Physics. Researcher at Tail-UC Laboratory, University of Coimbra, Portugal. Research lines: nonlinear optics; *ab-initio* studies of nonlinear optical properties; chiral molecular crystals; structural and physicochemical characterization of novel materials with applications in optoelectronics.
E-mail: psidonio@pollux.fis.uc.pt

AUTHORS' ADDRESS

CFisUC, Department of Physics
University of Coimbra
Rua Larga, P-3004-516
Coimbra (Portugal)

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