

## Using an iPad to Learn Motion Concepts in Introductory Physics

Tarlok S. Aurora

Department of Mathematics, Physics and Statistics,  
University of the Sciences,  
600 South 43<sup>rd</sup> Street,  
Philadelphia, PA 19104 USA

*(Submitted 05-01-2016)*

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### Abstract

Mobile computing devices such as tablet computers provide an opportunity to record motion of objects with built-in digital video recorders, and to analyze a movie on the device itself. Smartphones can upload a movie to a desktop computer for analysis. This article describes the use of an iPad, Video Analysis and Graphical Analysis apps with examples so that students can learn to explore motion concepts in real life situations; and later share their findings with peers. Examples described here may be used by an instructor in a classroom for purpose of illustration, and to engage students to use their own mobile devices. In the first example described, motion of two balls falling simultaneously was analyzed to show the same rates of fall; and to study kinematics and determine acceleration due to gravity. In the second example, it is shown that circular motion of a ball rolling on a surface, with friction, is equivalent to two damped harmonic motions in two perpendicular directions. In the last example, motion of a foot of person pushing a cart is described. It is suggested that by using mobile digital recorders with traditional experiments, students may gain deeper insight into kinematics and acquire discipline based knowledge.

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### 1. Introduction

Mobile computing devices such as an iPad, tablet computers and smartphones offer a new opportunity to collect and analyze information to facilitate teaching and learning physics concepts in an introductory physics course, both inside and outside a classroom [1, 2]. Motion of an object can be recorded and analyzed on these devices by using Vernier applications such as Video Analysis and Graphical Analysis [3]. If needed, this information may be uploaded to

a desktop computer for a deeper analysis using Vernier's Logger Pro software. A similar analysis application, SparkVue, is available from Pasco [4].

This article describes the use of an iPad to study motion concepts with Video Analysis and Graphical Analysis applications. Three examples and suggestions are presented for use in a classroom to enable students to use their own mobile devices to study motion concepts in a classroom and continue in real life situations. In the first example, motion of

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two steel balls dropped simultaneously from the same height - one falling vertically down, and the other one as a projectile – is analyzed to show that the two balls fall at the same rates, and acceleration due to gravity is determined. In the second example, it is shown that a (uniform) circular motion can be decomposed into two (simple) harmonic motions, in two perpendicular directions. In the last example, motion of a foot of person pushing a cart is described. It is shown that by using an iPad along with traditional demonstration equipment one can gain more insight into the underlying physics concepts.

The work described here may be done with the use of a traditional video camera and a desktop PC, but that would not adequately prepare student to use their own mobile

## 2. Free-fall and projectile motion

The demonstration apparatus, shown in figure 1, is used in a physics classroom to demonstrate that two objects released simultaneously from a given height – one falling vertically down and the other one moving like a projectile – would reach the floor at the same time. When the two balls hit the floor, students hear two simultaneous impacting sounds, thereby proving that times of flight for the two balls are equal. No additional information is obtained from this demonstration when performed in this traditional way [5].

The free fall apparatus consists of a simple arrangement of a horizontal rod with an elastic spring pushing on it. When the rod is pushed against the spring, it is locked in that position with a lever. Two steel balls are placed at the two ends of the rod. When the locking lever is released, the spring forces the rod to move to its original central position. As a result, one ball is released to fall vertically

devices to study motion in real life situations. The work described here was performed by the author on an iPad, and is shared hereto stimulate further exploration of use of mobile technology in a physics classroom. The author has not had an opportunity to use it in a classroom yet, so no student data is included. It is suggested that when an instructor performs these activities in a classroom, students be asked to participate in it by using their own mobile digital recorders, and analyze it using the appropriate free (or affordable) software like Video Analysis and Graphical Analysis. Students may work in small groups to study the motion under teacher's supervision, and later use mobile devices in real life situations for further exploration, and bring back their findings to share with the class.

downward while the other one is launched as a horizontal projectile.



Figure 1. Free-fall and projectile motion demonstration apparatus, shown locked in a “loaded” position.

To study motion of two falling balls with an iPad, the motion was captured with its built-in digital video recorder, against a dark background to enhance visibility. Only one ball can be selected at a time with the help of

the circular cross-hair. In figure 2, both balls are seen to be at the same vertical level during their downward fall, implying that their time of fall toward the floor were equal. In addition, two sounds are heard when the balls hit the floor.

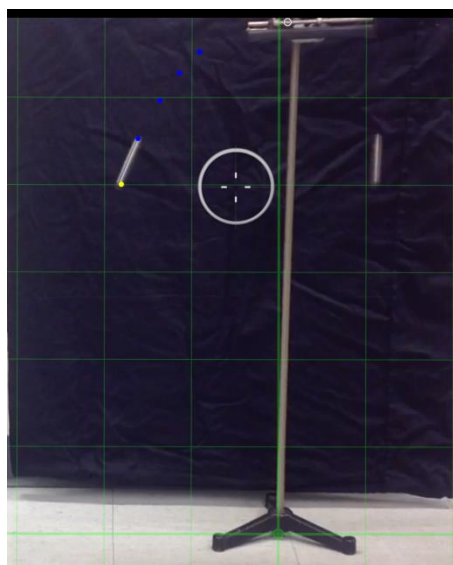


Figure 2. Digital video recording of two balls falling downward. Dots on the left side are the marked positions of the projected ball in several frames of the recording.

For further analysis of the motion recording, the movie was opened in an application named Video Analysis. For the projected ball, positions were marked by tapping on the ball by manually advancing the movie frames. As the ball speeds up, its image becomes a blurred circle with a trail. For consistency, the ball positions were marked at the leading edge of the ball images in all frames. Initial height (position) of the ball is entered in video analysis. Positive y-axis was selected vertically down and x-axis horizontal. Origin was selected at the top - the initial position of the balls. Initial height entered in frame 1 serves as a distance scale in subsequent frames. After the initial height of the ball, with respect to the floor is entered

in Video Analysis, subsequent y-coordinates are calculated by the software. So, parallax was not a concern. The results obtained from data analysis by this application are shown in graphs below. These graphs were saved in a camera roll. In camera roll, the pictures were enhanced by using built-in editing, and were uploaded to a desktop computer for writing purposes.

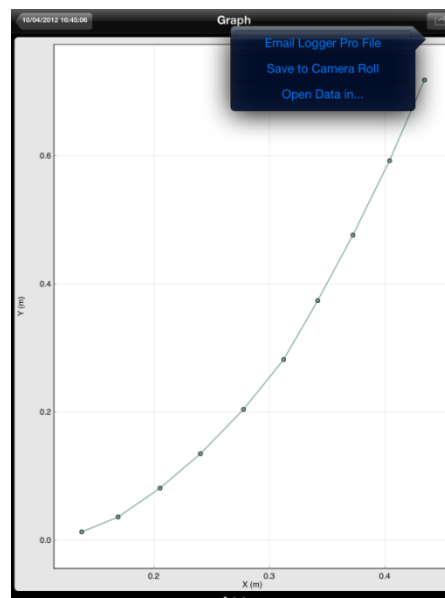


Figure 3. Graph of variation of y-coordinate with x-coordinate.

In Figure 3 shows variation of  $y$  with  $x$  coordinate. The data points are shown with a connecting line only since regression analysis requires opening data in graphical analysis, by using the “Open Data in ....” button in figure 3, and which yields figure 4. In figure 4, for the projectile ball,  $(x, y)$  graph appears to be a parabola and a quadratic regression line was fitted through it. The  $x$ -coordinate varies linearly with time while the  $y$ -coordinate is quadratic. Similarly,  $x$ -component of velocity appears to be constant while its  $y$ -component increases linearly. In figure 4, regression analysis was performed using graphical analysis on the iPad itself and results are shown below.

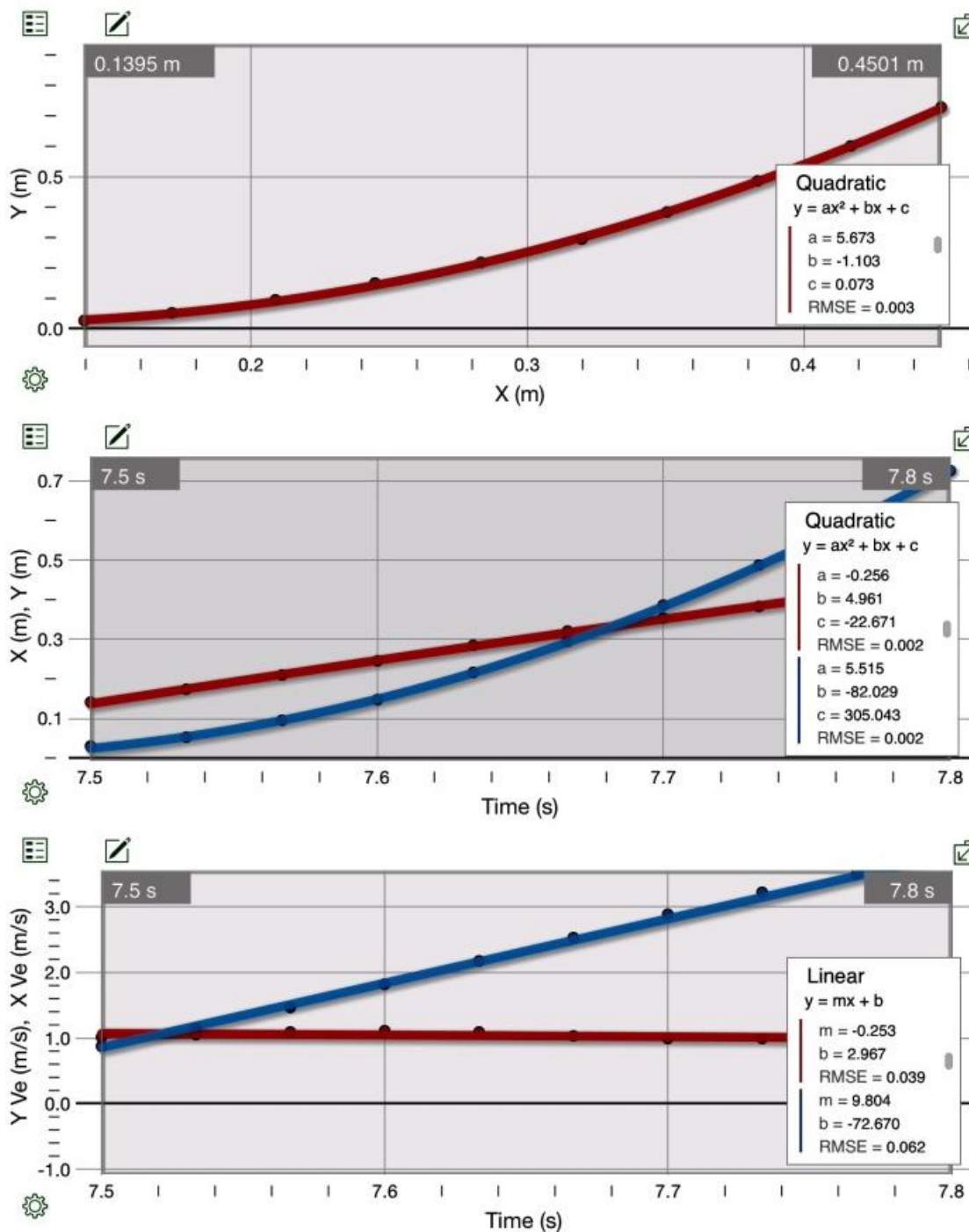


Figure 4. Graphs of x and y components of position and velocity, obtained by opening data in graphical analysis. The top graph is variation of y with x with a quadratic regression line. The middle graph shows variations of x and y coordinates with time, and shown with a quadratic fits. The lower graph shows variation of x and y components of velocity with time, and linear regression lines.

The regression information in figure 4 can be used to understand kinematic equations of motion with zero friction. For this purpose, x-axis is defined in the horizontal plane with y-axis in the vertical direction. (x,y) are position coordinates, and ( $v_x$ ,  $v_y$ ) are components of velocity. ( $a_x$ ,  $a_y$ ) are components of acceleration, which for a freely falling object are  $a_x = 0$  and  $a_y = g = 9.8$  m/s<sup>2</sup>. Kinematic equations are given below and the subscript o refers to an initial value:

$$x = x_o + v_{ox} t + \frac{1}{2} a_x t^2$$

$$y = y_o + v_{oy} t + \frac{1}{2} a_y t^2$$

$$v_x = v_{ox} + a_x t$$

$$v_y = v_{oy} + a_y t$$

A theoretical plot of these equations with  $g = 9.8$  m/s<sup>2</sup> and initial values zeros is shown in figure 5, and the graphs resemble the corresponding lines in figures 4.

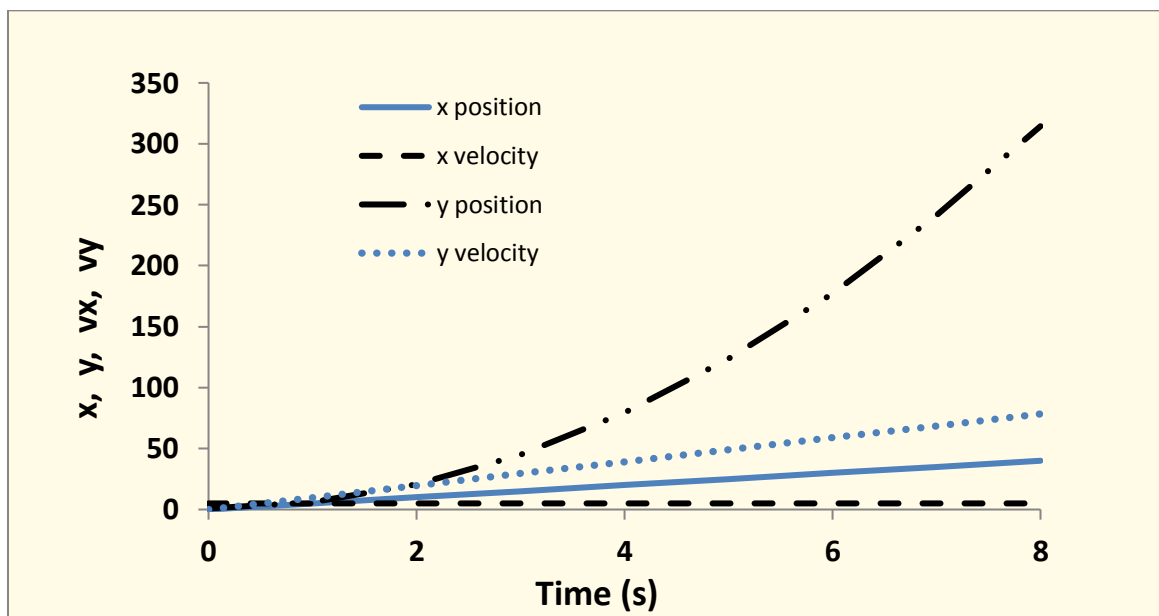


Figure 5: Theoretical graphs for an object moving with a constant acceleration of 9.8 m/s<sup>2</sup>.

From Figure 4, equations and root mean square errors (RMSE) for the regression lines are found to be

$$x = -22.7 + 4.96t - 0.256t^2, \quad RMSE = 0.002$$

$$y = 305 - 82.0t + 5.52t^2, \quad RMSE = 0.002$$

$$v_x = 2.97 - 0.253t, \quad RMSE = 0.04$$

$$v_y = -72.7 + 9.80t, \quad RMSE = 0.06$$

Slope of the  $v_y$  graph is 9.8 m/s<sup>2</sup>, which is close to the accepted value of acceleration due to gravity. A small value of acceleration (0.25 m/s<sup>2</sup>) in the x-direction may be due to the fact that the setup was visually aligned horizontal – not with a precision liquid level. The large values of the intercepts are due to the fact that the video recording was started at time zero while the ball was released around 7 seconds, after the author walked over to the free-fall setup. The values from  $x(t)$  position graph are not used since it was fitted to a quadratic line (though it is linear)

due to an inability to fit a curve to individual data sets in the graphical analysis app.

Motion of the second ball, falling vertically downward, was similarly analyzed, and figure 6 shows the regression coefficients for it. Value of  $g$  is found to be  $9.54 \text{ m/s}^2$  from the slope of  $v_y$  graph. In figure 6, it is seen that  $x$ -coordinate and  $x$ -velocity do not change significantly, and have only a slight acceleration in the  $x$ -direction for the ball falling vertically down. This small acceleration  $a_x$  is perhaps due to an

equipment misalignment with the  $x$ - $y$  grid in figure 2 which may have prevented it from falling exactly vertically down; or may be due to vertical axis being not perfectly aligned. The data has not been analyzed for error propagation as the main focus of the article is to prepare students to use their mobile devices to engage in further exploration in real life situations. However, the main source of error lies in marking the positions of the moving ball in a movie, due to blurriness of image, which can be reduced with practice.

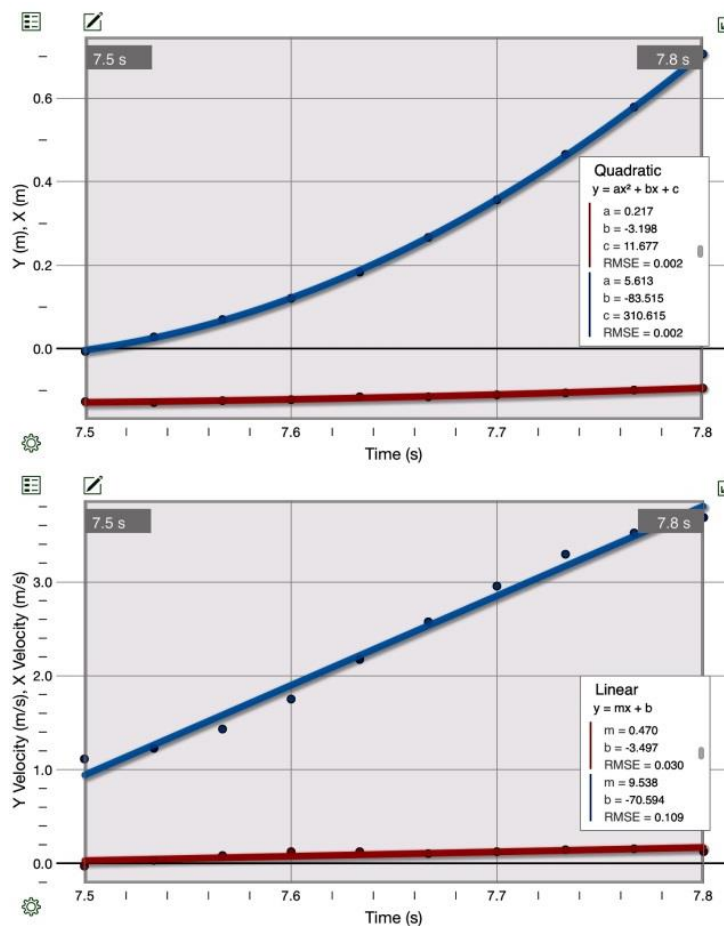


Figure 6. Graphs of motion of a ball falling vertically down. The upper line in both graphs is the  $y$  component of position or velocity, and the lower line is the corresponding  $x$ -component. Velocity data was fitted to a linear regression line, while a quadratic fit was used for position.



This simple activity shows that by using a digital motion recorder along with a traditional equipment one can demonstrate that both objects fall toward the ground at the same rate (assuming zero or negligible air resistance), learn kinematics and determine acceleration due to gravity.

### 3. Circular motion

In an introductory physics course, a simple rotational motion is taught by using an object, moving counter-clockwise, in a circular path with a linear (tangential) velocity ( $v$ ), and a rotational velocity ( $\omega$ ). In figure 7, an object traverses an angular displacement  $\theta = \omega t$  in time  $t$ . In a classroom, it is shown using trigonometry, that values of  $x$  and  $y$  component of object's position vector  $r$  and velocity vector  $v$  are given by

$$x = r \cos \theta, \quad y = r \sin \theta$$

$$v_x = -v \sin \theta, \quad v_y = v \cos \theta$$

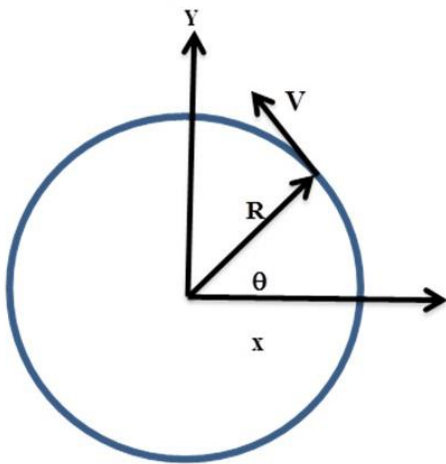


Figure 7. A particle moving in a circular path.  $R$  is the radius of the circle,  $v$  is tangential velocity, and  $\theta$  is the angular displacement at time  $t$ .

Using properties of trigonometric functions, students learn that position and velocity components are simple harmonic functions, and that sine and cosine functions are  $90^\circ$  ( $\pi/2$  radians) out of phase with each other since

$$\sin \theta = \cos(\pi/2 - \theta) \text{ and}$$

$$\cos \theta = \sin(\pi/2 - \theta).$$

To illustrate connection between circular and harmonic motion, often a demonstration apparatus, shown in figure 8, is used.



Figure 8. A demonstration equipment illustrating relation between a circular and harmonic motions.

In this equipment, when a handle is manually turned, one piece moves in a circle along the rim while another connected part is constrained to move along a straight line passing through the center of disc [6] thereby establishing a connection between circular and simple harmonic motions. However, an iPad may be used to gain more insight into the two afore-mentioned motions as follows.

In the iPad example described here, circular motion was recorded and analyzed to illustrate its connection with a harmonic motion, and to show the effect of damping. It is suggested that when an instructor performs this activity in a classroom, students be asked to record the motion on their own mobile devices and analyzed it. In this example, motion of a steel ball rolling around the inner rim of a food bowl lid (a common household item) was recorded. The plastic lid was placed on a horizontal surface and a steel ball was manually set in motion to roll along the rim of the lid. In Video Analysis, origin was selected at the center of the bowl lid, and x and y axes were selected to lie in a horizontal plane. Bowl diameter was about 8.4 cm and lid was 10.5 cm, should one be interested in studying centripetal acceleration. In figure 9, a few marked ball positions are shown, and figure 10 displays the variation of x and y components of position and velocity, obtained from graphical analysis.



Figure9. Positions of ball rolling in a circle in a food lid with Video Analysis.

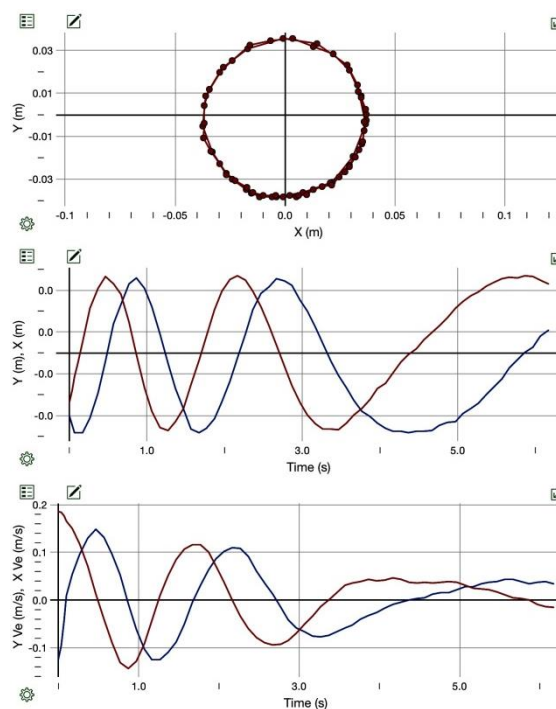


Figure10. The first graph shows a circle which is formed by variation of (x, y) coordinates of a rolling ball. The second graph is variation of x and y coordinates with time and the third graph is variation of velocity components with time. The first graph shows the actual data points while the other two graphs show only the connecting, not the regression lines.

It is seen in figure10 that a (uniform) circular motion can be decomposed into two (simple) harmonic motions in two perpendicular directions. In the example shown here, the motion is damped due to the presence of friction. Further, it is seen that position and velocity graphs are  $90^{\circ}$  degrees out-of-phase. When position coordinates have maximum values at the extreme (turning) points, the corresponding velocities are zero [7]. Trigonometric regression analysis was not done on the graphs due to a lack of this



choice in the app. It is clear that a simple activity like this one can be used to demonstrate several aspects of circular motion.

To demonstrate the mobility of an iPad, a video recording of a person pushing a cart on a boardwalk was made, and analyzed with Graphical Analysis to study position and velocity of a foot during walking. The position of heel of the right foot was marked in video analysis. Length of person's step was estimated to be about 1.0 m. Figures 11 and 12 on the following page show the motion of the heel. The x and y coordinates and the corresponding velocities of the foot are shown to vary as the cart is being pushed to the right side at a steady speed. (Graphical motion of the cart is not shown for the sake of brevity). From the slopes of velocity graphs, one can see that a leg goes through acceleration and deceleration during a leg swing. Such observations can be particularly useful in studying kinesiology for a physical therapy course [8].

To build upon in-class learning, students may be assigned to explore examples of motion in real life situations, such as motion of a flying airplane, roller coaster, simple pendulum, mass on a rubber band or spring (slinky), pendulum clock, child on a slide or swing, water droplet on the wind shield of a car (as a passenger) and a falling leaf. Students could even use smartphones to gather relevant information and upload it to a desktop computer in a physics laboratory for graphical analysis, and to share it with classmates.

Mobile devices may be used in conjunction with the traditional mechanics experiments in an introductory physics course; no need to jettison the old experiments. Briefly, for example, in a laboratory experiment, one may record the sliding motion of a wooden block or cart rolling down an inclined plane to calculate variation of velocity, acceleration and force of friction on the track. Further, by observing the change in velocity and vertical position of the cart on an inclined plane, one could illustrate concept of conservation of mechanical energy and role of friction. In another traditional experiment with a ballistic pendulum, students launch a metal ball projectile from a spring gun, and calculate its launch velocity by measuring its horizontal and vertical displacements when it lands on the floor. With a digital recording of its motion, students could easily observe that the horizontal component of velocity of a projectile stays nearly constant (due to a small air drag) while the vertical component of its velocity changes linearly; just like the ones discussed in the example I in this article.

Other experiments that could benefit from a digital recording are Atwood's machine (for study of Newton's second law), conservation of linear momentum during collisions between two carts on a friction-less track and centripetal force [9]. In conclusion, mobility and ubiquity of iPads and tablet computers offer an easy way to engage students in learning and acquiring discipline-based knowledge, both in and outside a classroom, and promote lifelong learning.



Figure 11. Positions of the right heel of a person pushing a cart.

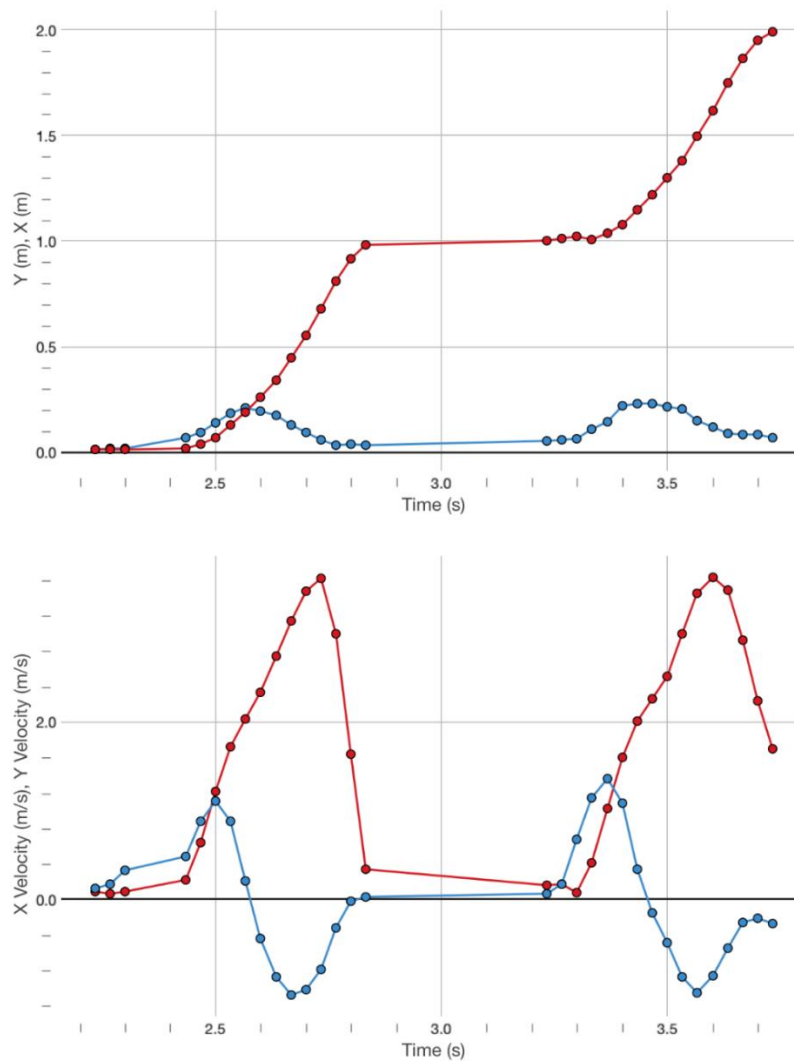


Figure 12. x and y positions and velocities of a heel as the foot moves up, down and forward. Red curve is x component and blue curve is the y component.

**Acknowledgments**

The author would like to thank University of the Sciences (USciences) for a grant of an iPad; and Rich Cosgriff, Rod Murray and Andrew Esposito, Phyllis Blumberg and Elia Eschenazi for useful discussions.

**References:**

[1] Klein P, Grober S, Kuhn J and Miller A 2014 Video analysis of projectile motion using tablet computer as experimental tools. *Phys. Ed.* **49** (1) 37

[2] Streepey J January 2013 Using iPads to illustrate the impulse-momentum relationship, *Phys. Teach.* **51**, 54-55

[3] Vernier Software & Technology, 13979 SW Millikan Way, Beaverton, OR 97005.

[4] Pasco scientific, 10101 Foothills Blvd, Roseville, California USA 95747.

[5] Sargent Welch, P.O. Box 92912, Rochester, NY USA 14692.

[6] Griffin and George Ltd. Great Britain.

[7] Aurora T and Brunner B 1991 Phase Relations in a Simple Harmonic Motion, *Phys. Ed.* **26** 382

[8] Winter D, Greenlaw R and Hobson D 1972 Television-Computer Analysis of Kinematics of Human Gait, *Computers and Biomedical Research* **5**, 498-504.

[9] Wilson J and Hernandez C, 2005 *Physics Laboratory Experiments*, Sixth Edition, ISBN: 0-618-38259-3. Houghton - Mifflin Company, New York