



PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE  
ESCUELA DE INGENIERIA

# **CYBER-PHYSICAL BALL FOR TEACHING PHYSICS TO HIGH SCHOOL STUDENTS**

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Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

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Santiago de Chile, July, 2020

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## RESUMEN

En las últimas dos décadas, el rendimiento promedio en pruebas PISA ha mostrado mejoras insignificantes para la mayoría de los países. Técnicas de aprendizaje activo y métodos que promueven el desarrollo de habilidades del siglo 21, como metacognición y pensamiento creativo, han mostrado resultados positivos a la hora de abordar este problema. Los sistemas ciber-físicos han sido usados para potenciar las interacciones de los usuarios con el mundo físico y pueden ser usados para potenciar la enseñanza de física en colegios. En esta investigación, se construyó una pelota ciber-física para la enseñanza de cinemática a estudiantes de 2<sup>do</sup> medio. La pelota fue diseñada en base a elementos de la vida cotidiana de los estudiantes e incluía una planificación de clases detallada que la usaba. Las pruebas se realizaron con 49 estudiantes de una escuela vulnerable. Después de la intervención, el grupo experimental mostró mejoras significativas versus el grupo de control tanto en rendimiento académico (+10.5%,  $p = 0.05$ ) como en sus puntajes de creatividad para fluencia (+30%,  $p < 0.001$ ) y flexibilidad (+12.5%,  $p < 0.001$ ). En esta, el sistema ciber-físico logro proveer de una experiencia simbólica y tangible al mismo tiempo que se mantuvo transparente para los estudiantes. También, los estudiantes apreciaron como el sistema les permitió entender sus propios conocimientos y construir nuevos a partir de ellos. A partir de este experimento, el sistema ciber-físico mostró ser una efectiva herramienta de aprendizaje activo que empodera a los estudiantes y les permite desarrollar habilidades de pensamiento creativo. Para lograr resultados como estos, es necesario ser consciente del estilo de vida de los estudiantes y adaptarse a él. Esta tesis tuvo el respaldo del proyecto CONICYT / FONDECYT 1180024.

Keywords: [Cyber-physical system](#), [Internet of Things](#), [Active Learning](#), [Education](#), [Physics](#), [Creativity](#),

## ABSTRACT

In the last two decades, the mean performance on PISA tests have shown insignificant improvement in most countries. Active learning techniques and methods that promote the development of 21<sup>st</sup> century skills, like metacognition and creative thinking, have shown positive results addressing this problem. Cyber-physical systems have been used to enhance user interactions with the physical world and they can be used to enhance the teaching of physics in schools. In this research, a cyber-physical ball was constructed to teach kinematics to 10<sup>th</sup> grade students. The ball design was based on elements from the students' daily life and included a detailed course planning that made use of it. The tests were conducted with 49 students from a vulnerable school. After the intervention, the experimental group showed significant improvements versus the control group in both academic performance (+10.5%,  $p = 0.05$ ) and creativity scores in fluency (+30%,  $p < 0.001$ ) and flexibility (+12.5%,  $p < 0.001$ ). In this, the cyber-physical system provided a symbolic and tangible experience simultaneously while remaining transparent to the students. Also, the students appreciated how the system enabled them to understand their own knowledge and build upon it. From this experiment, the cyber-physical system showed to be an effective active learning tool which empowers students and lets them develop creative thinking skills. To achieve results like this, is necessary to be mindful of the students lifestyle and adapt to it. This thesis had the support of the project CONICYT / FONDECYT 1180024.

Keywords: [Cyber-physical system](#), [Internet of Things](#), [Active Learning](#), [Education](#), [Physics](#), [Creativity](#),



# 1 INTRODUCTION

In the last two decades, the mean performance on PISA tests has not changed with more than half of the member countries showing negative or insignificant improvement (OECD, 2019). The call is to personalize the educational experience around students' passions and capabilities (Schleicher, 2019), which requires a holistic approach where multiple strategies are applied simultaneously so they adapt properly for the younger generations (Swanzen, 2018). Nowadays diverse classrooms put double the pressure on individualized learning as standardized techniques show less usefulness, which makes acquiring tools and techniques to adapt faster to each individual the main focus for teachers (OECD, 2020). For the students, this shifting process leaves a general lack of knowledge from different areas that, ultimately, may lead to a serious comprehension barrier (O'Reilly et al., 2019).

Active learning techniques have shown promising results to close this gap, as they can improve student's metacognition of their own thought process and conceptions (Gok, 2018). Multiple studies show a positive correlation between the use of metacognition strategies and academic results in schools (Perry et al., 2019). Also, there is a close relationship between metacognition development and the use of strategies that promote creative thinking (Hargrove and Nietfeld, 2015). Creativity can be defined as the ability to generate novel ideas appropriate to their context (Amabile, 2012). This ability allows students to interpret, recombine and reorganize information creatively so they produce more significant learning and develop a clearer understanding of the concepts studied (Scott et al., 2004).

Mental clarity and proper motivation set a good environment for an engaged classroom, which is necessary to obtain good results when trying to understand abstract and complex ideas (Martin and Bolliger, 2018). The challenge lies in how to motivate the students to reach a high level of engagement. Swanzen (2018), Chiu (2017) and Berge et al. (2020) show the importance of taking into account each individual's motivation when adapting the classroom activity to obtain a desired attitude.

Videogames are a widely used choice to facilitate active engagement in education (Hanghøj, 2013). Even though, there is no evidence that engagement from these kind of tools guarantees better learning results, especially in signatures like physics and mathematics (Young et al., 2012); research on design and implementation of games in science is still limited (Shute et al., 2019). To obtain better learning results, is necessary that players participate actively in the game and develop their own knowledge from it (Ouariachi et al., 2019). Then, the challenges is how to make the engagement from gaming experiences one that has results not only in motivation, but also in the academic result of the students.

Sports engage millions of young people worldwide. Whether motivated by a desire to become stronger, or simply for socializing, sports are mostly viewed as a positive way of achieving these goals (Seippel, 2019). This intrinsic motivation has been used to attract students to other educational areas. Such was the case in Drazan (2020) where biomechanics were used as a bridge to bring STEM education and sport science to young athletes. Similar efforts have been done with Internet of Things to attract students to study STEM subjects as seen in Vakaloudis et al. (2019) and Glaroudis et al. (2019) yet they lack the flexibility shown in Drazan (2020), where technology works as a medium to teach sport science rather than an end in itself. This leaves the challenge to take this further and use sport-related technology to create engaging activities for the classroom and so enhance the student's learning process.

Sport analytics is a field of study where sport-related variables are measured and analyzed to improve the performance of athletes and teams, both from a business and athletic perspective (Dehe et al., 2017). It has seen a major boost with new technologies for real time measurements of physical variables, like the kinematic variables of a racing car, and the implementation of complex models from Big Data and Business Intelligence to identify patterns and make better decisions (Bogo et al., 2019). The tools developed in this area are made so users with no scientific background can easily interpret and use the information from physical events. For example, what happens when a basketball coach analyzes data from an ongoing match and decides to substitute a player to have a stronger presence (Tian et al., 2020). While these tools have not been used for educational purposes, such as school teaching, their ability to simplify concepts make it ideal to create classroom activities.

Cyber-physical systems (CPS) are distinguished for their ability to integrate smart systems that enable interactions between physical and computational components (Radanliev et al., 2019). They have integrated the use of technologies from Internet of Things and Big Data in Industry 4.0 (Xu and Duan, 2019). They are thought to manage the complex dynamic interaction between network systems and physical systems, which involves a series of problems including abstraction of real-time system, system robustness, component service quality and knowledge engineering (Liu et al., 2017). Cyber-physical systems have been developed mostly for the industry, like medical devices (Kurde et al., 2019) and manufacturing (Tilbury, 2019). These have also been used as an active training tool for workers in a factory, where real-time feedback on how workers assemble the pieces result in a highly interactive and active experience (Tao et al., 2019). Also, as virtual reality tools to improve the communication and interactivity between maker and assembler teams in factories (Cecil et al., 2019). Both approaches result in engaging experiences that show the potential of cyber-physical systems as a medium to interact actively in their work.

Therefore, the research questions that drive this work are “How can a cyber-physical system enhance the pedagogical process and its learning?” and “What effects does it have in the creativity of the students?”

With those questions in mind, the objectives of this study are centered around the conceptualization and development of a cyber-physical system that takes the pedagogical needs of the teacher and the student in consideration. Along with the design and implementation of a course planning that fully utilizes it.

## 2 METHODOLOGY

### 2.1 Domain

To answer our first research question it is necessary to determine where to apply the cyber-physical system in a learning experience. The purpose is to create activities where students experience physics concepts via interacting elements from their daily life.

To make use of the interest of youth in sports, subjects from the curriculum related to movement are preferred and those are Newton’s Laws, Energy Conservation and Kinematics. Further selection must be done after taking in consideration constraints from the educational institution, primarily, the time available for the experiment, the location of the class (school yard, classroom, etc) and the student’s lifestyle.

In the 10<sup>th</sup> grade’s curriculum, Kinematics is seen before Newton’s Laws and Energy conservation (Ministerio de Educación, 2016), so enhancing its understanding provides better conceptual grounds for the other two topics. Kinematics is the study of movement itself and, in 10<sup>th</sup> grade, focuses on explaining the concepts of position (1), velocity (2) and acceleration (3) and how they influence each other. While the concepts are connected among themselves, they can be approached with different types of activities so the course planning can be decomposed in 3 sets of independent modules, with one for each concept. In this way, there is flexibility to add extra sessions between modules, like reinforcement of mathematical tools, to align better with the pedagogical needs of the students.

The academic goals for the Kinematics topic (Ministerio de Educación, 2016) emphasize the importance of practical experience and are: A) understanding the difference between absolute and relative positioning based on different reference systems; B) differentiating between displacement and trajectory and how they are calculated; C) understanding how acceleration influences motion; D) discerning rectilinear motion from others based on graphical data. These create a pedagogical need for teachers in how to provide this practical experience in an effective way.

## 2.2 Student Sample

The intervention was made on a group of 10<sup>th</sup> grade students from a Chilean school, the school is characterized by its medium performance in standard national tests (Agencia de Calidad de la Educación, 2019) and its high vulnerability score, where 92% of the students live in socially vulnerable conditions (Junta Nacional de Auxilio Escolar y Becas, 2020). A total of 49 students participated (20 men and 29 women), which were separated in two groups: a control group with 23 students (11 men and 12 women) and an experimental group with 26 students (9 men and 17 women).

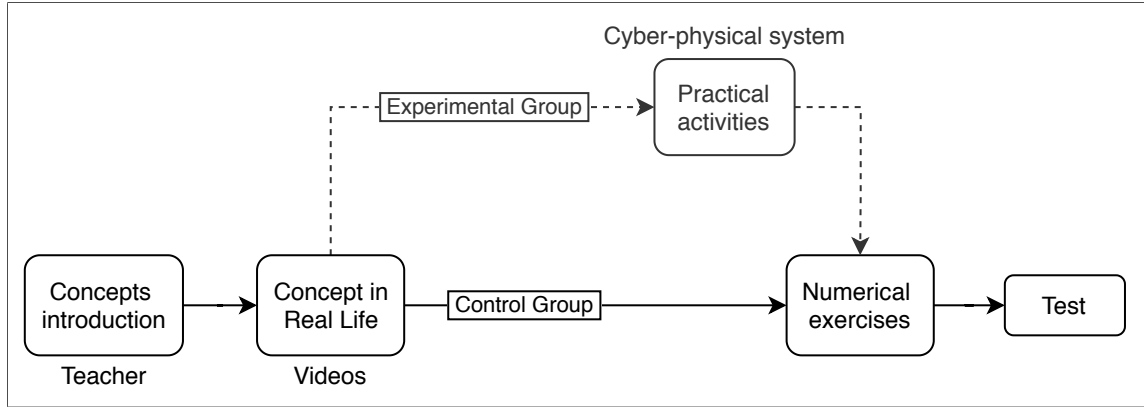
The experience followed a quasi-experimental design, given that both groups were conformed previous to the intervention. However, the assignation between control and experimental group was random. Both groups had students in the range of 15 to 16 years old, and were characterized by a deep lack of motivation towards the signature. This was reflected on their attitudes in the classroom, where they would: stand up, move along the classroom, change seats and talk excessively, all without authorization from the teacher.

## 2.3 Experimental Design

The teacher in charge of the signature programmed 5 sessions to cover the unit "*Movimiento Rectilíneo*" from the curriculum. The students had physics classes 3 times a week, with a duration of 90 minutes each. Both control and experimental group had similar environmental conditions. In both groups, the teacher guided the class and was assisted by at least one member of the research team in all activities.

Classes started with a brief summary of the concepts studied in the previous lecture and introduced the new contents of the current one. Then, the concepts from the current session were reinforced with videos of real life situations, these showed the appearance of the concept in at least three different scenarios that were close to the students' daily life. Next, the teacher guided the class to do numerical exercises related to the concepts seen in the videos. Finally, the students took a quick test of the seen in the class to gauge how much was learned.

The experimental group had an extra step between watching the videos and doing the numerical exercises, where they experimented the concepts in practice through activities with the Cyber-physical System (Figure 2.1). Because of this, they dedicated less time on numerical exercises in comparison to the control group. In Appendix A, there is a summary of the contents of each class, its objectives and the experimental activities planned for it. In Appendix B, the 5 sessions planned for the classroom are detailed.



**Figure 2.1:** Lecture flow for the experimental and control groups.

## 2.4 Cyber-physical systems for teaching kinematics

The hypothesis that drives this work is that a cyber-physical system can significantly enhance the pedagogical process and the learning of physics, by becoming a bridge between the concepts and the students' reality.

Cyber-physical systems are an arrangement of technological devices and communication networks whose purpose are to integrate the interaction between users and the physical world, so their use offers a practical experience by itself. The focus becomes how to design a system that enhances the pedagogical role of the teacher and supports the student play a leading role in the developmet of the required skills (Demirci, 2017). In this aspect, Microcomputer Based Laboratories (MBL) have impulsed the use of electronic tools to support the learning of kinematics with motion and force sensors, in combination with data loggers to study experimental data (Ayop and Ismail, 2019). Generally, these mechanisms are visible to the students and can be interacted with (Redish et al., 1997; Ye et al., 2019) which allows for practical experience. Although the direct presence of the measurement tools help the students' take a leading role in the activity, in many cases, it makes the method of using experimental tools become the main centre of attention rather than the concepts that are trying to be taught (Bernhard, 2018).

Looking back at Tao et al. (2019) and Cecil et al. (2019), the cyber-physical systems they implemented managed to get the user's focus on the task they had to learn rather than the tools they were presented with, and so the system becomes an enabler for the activity. To achieve this, both systems were designed so users could interact with them in an analogous way to what they do normally. The main characteristic of these designs were to construct the cyber-physical systems around manipulable objects from the user's environment so entry barriers were lower and allowed the user to perceive their new labor

as one similar to that of their daily routine.

In Chile, football has the biggest presence among other sports when it comes to young people (Instituto Nacional de Deporte, 2016) and its influence goes beyond just sports (Vilches and Pacheco, 2014) and dates from way back (Santa Cruz, 2003) which makes it an ever present element in society and in school life. In this way a ball is an object related to sports from the students' daily life, that can be used to design activities where it is moved around the classroom to recreate different trajectories and analyze its kinematics variables. Thus, a ball was chosen as the object that meets all the criteria. By being manipulable by hand, it lets each student take control of the exercises so they become the protagonist when they're in hold of it, which also lets them compare what the system measures with what they perceive with their own senses.

The objective with the cyber-physical system was to create a ball that looked like a toy on the outside, so it didn't stand up as a laboratory tool, yet had a microcomputer core with sensors that could process information about its kinematics variables. So, this information could be displayed in the teacher's laptop to get a symbolic visualization of the ball's behaviour.

## **2.5 Measurement Instruments**

### **2.5.1 Grades from the Physics Class**

To determine the effects of the intervention in the academic performance of the students, the studied variables were their grades in the physics class, pre- and post-intervention. These grades are in the range of 1 to 7, which are the lowest and highest grades obtainable in Chile.

The first data record corresponds to the grades previous to the intervention, that is, the grades from the curriculum's unit *"El Universo"*, which is seen before the unit *"Movimiento Rectilíneo"*.

The second record corresponds to the grades from the test that were answered at the end of each class (Figure 2.1). This information was taken from the first four classes of the intervention. Each test had 5 true or false type of questions, and their objective was to evaluate only the concepts seen in that class.

### **2.5.2 Creativity Test**

To determine the effects of the intervention in the students, the studied variable were the scores obtained from the creativity tests. These tests were taken in two occasions, before

and after the intervention.

The creativity test was based in the model of Guilford (1950), which signals that creativity is directly related to divergent thinking, that is, the ability to generate ideas. To measure this, it is recommended to take a test of multiple uses, in which the examinees must describe as many uses as they can that they could give to a specific common object. For the pre-intervention test, a towel was chosen as the common object and for the post-intervention test, it was a bottle. Students received a sheet of instructions which were read aloud by the teacher and, after that, they had 3 minutes to answer the test.

Divergent thinking is measured in four dimensions (Kaufman et al., 2008) and they are scored in the following way:

- Fluency: Capacity to generate many ideas. 1 point is given to the student for each idea generated.
- Flexibility: Capacity to alternate between different domains. 1 point is given to the student for each different category or domain generated.
- Originality: Capacity to generate novel and unusual ideas. 2 points are given to the student if the idea has less than 2% of repetition within the class, only 1 point is given instead if it has less than 5% but more than 2% of repetition. No points are given otherwise.
- Elaboration: Capacity to develop detailed ideas. Not scored, because it is not considered as an essential element of creativity and there isn't a reliable way to achieve satisfactory levels of confidence between examiners' evaluations (Cramond et al., 2005).

To control impartiality in the evaluations, all tests were checked by 3 examiners that had to reach a consensus on each score. Cronbach's Alpha was used to measure the reliability of the data registered from the tests. The pre-intervention test had a value of  $\alpha = 0.9$ , so it is considered to have good reliability. The post-intervention test had a value of  $\alpha = 0.63$ , while this is lower than usual ranges of reliability, the size of the sample ( $n = 49$ ) makes it acceptable to assume a minimum level of reliability (Streiner, 2003).

### 2.5.3 Quantitative Analysis

The quantitative analysis of the grades and creativity tests were made following the recommendations from López et al. (2015). The initial state of the academic performance was determined with an analysis of variance (ANOVA) of the grades obtained in the unit



previous to the intervention (see results in Table 4.1). In the same way, the initial state of the creativity of both groups of students was determined with an ANOVA test. For the creativity analysis, the ANOVA was used to measure significant differences in three dimensions: fluency, flexibility and originality. The assumptions of univariate normality and variance homogeneity were checked for both, the academic performance and creativity dimensions.

To study the effects of the intervention in the academic performance of the students, an ANOVA test was performed with the grades of the tests taken at the end of each class. The analysis measured if there was a significant difference between the control and experimental groups. For this analysis, the studied variable was the arithmetic mean of the four tests (see results in Table 4.3). The assumptions of univariate normality and variance homogeneity were checked previously to these tests.

To study the effects of the intervention in the academic performance of the students, an ANCOVA test was performed to check for significant differences between the control and experimental groups in the three parameters of creativity: fluency, flexibility and originality (see results in Table 4.4). For this case, an analysis of covariances (ANCOVA) was used to minimize the effects of the previous condition of the students, by using the results of the pre-intervention as the covariate. The assumptions of variance homogeneity, normally distributed errors, homogeneity of regression, independence of the independent variable with the covariate and linearity between covariate and dependent variable were checked for all three dimensions of creativity.

For all tests described before, significance was considered when a value of  $p \leq 0.05$  was obtained in the ANOVA and ANCOVA test. Instead, for the checking the assumptions, it was necessary to reject the null hypothesis so the desired value was  $p > 0.05$  in each case.

#### 2.5.4 Qualitative Analysis

For the qualitative analysis, a group of 6 students (1 man and 5 women) were chosen at random from the experimental group.

The analysis was performed with the content analysis methodology (Hsieh and Shannon, 2005) to identify patterns in the students' perception of the activities done in class. This information was gathered through a focus group that lasted about 15 minutes, after the school's schedule. A member of the research team interviewed each students individually, in the absence of the teacher and his companions. The focus group was recorded and transcribed word by word.

The questions that guided the conversation where the following:



- Regarding the disposition to the class: *Did you want to come to classes, knowing there would be videos? Or knowing that you would play with the ball? In classes, did you want to talk about the videos or the activities with the ball?*
- Regarding the contents of the class: *What use did the videos have for you? And the activities with the ball? Did it make sense how the teacher connected the concepts with the videos? Or to the activities with the ball? If you could choose, would you rather have more videos, more ball activities or more exercises in the whiteboard?*
- Regarding the context of the videos and the activities: *Do you remember any of the videos or ball activities done in the classes? Which one? What concepts were related to it and what did you value from it? Did it make sense what you saw in the videos or what you did with the ball?*
- Regarding the transcendence of the concepts in their lives: *Do the concepts that you saw in class have any use to you? Which one?*
- Finally, regarding the activities with the ball in particular: *Would you have wanted to have more experiences with the ball? What would you have done differently?*

The transcription was read line by line and the commentaries from the students were grouped into categories predefined from the objectives of the focus group. After the reading, new categories were created to complement the results found in the records. The results can be seen in section [4.2](#)

## 2.6 Research Ethics

Before intervening the first class, students were provided with information about the objectives of the research, the activities included, risks and benefits of participating. Also, it was highlighted that participating in this study was completely voluntary. The students were asked to sign a document where they accepted or rejected being part of this experiment. Given that the participants were minors at the time of the research, the same procedure was done with their legal tutors so they could sign a document of explicit consent. Only the data from the students that agreed to the research was recollected.

For the qualitative analysis, students received information about the focus group, how long would it last and about its purpose for the research. Students were clarified that the information would be used only for research purposes. Additionally, students were asked to authorize the recording of the session.

Finally, the study also received approval from the Ethics Committee of the University.

## 3 CYBER PHYSICAL SYSTEM

### 3.1 Hardware

For the external structure, a foam ball with a 15cm diameter was used. These types of balls were used for its common presence in volleyball practices and toy stores, so students could quickly recognize it as an element from their daily life. Also they provide good impact resistance to protect the internal electronics and are easy to cut. The ball had an incision from which the surface was preserved to be used as a lid and the foam core was removed to make space for the electronic core (Figure C.4).

The internal structure of the ball consisted of a 3d printed block of [PLA](#) with slots for each electronic component of the system (Figure C.1 & Figure C.3). The block was designed to support the elements and protect them from collisions while the ball is being tossed or hit in the activities.

Most activities from the course planning involve actions with a duration of a couple seconds, like tossing the ball from one student to another, and variables such as velocity and acceleration can change greatly during this short period. To get enough data points for a reliable real-time graph of these variables, a sampling rate of over 10 Hz was sought after. For that, the core of the cyber-physical system was built around [Adafruit's Feather Huzzah](#) development board, which is based on a [ESP8266](#) microprocessor. It has an 80 MHz core and integrated WiFi which offer enough processing power to fulfil the requirements. Live experiments showed that communication times were the bottleneck for the sampling rates, with delays in the ranges of 10 ~ 50 ms. To reduce this impact, a low latency communication protocol was used, the [User Data Protocol \(UDP\)](#), which achieved a stable data rate close to 10 ms. With this, actions like a 2 second throw of the ball could get close to 200 data points for a good resolution in the graphs.

The first module of activities required position tracking along the classroom to analyze reference systems and differences between trajectory and displacement. To be used in different school environments, the system had to work despite factors like availability of power outlets or lack of places to put a camera and get a good angle for image processing. Because of this, [iBeacon technology](#) was used to provide information about spatial positioning for its independence of these factors and easy implementation. iBeacons provide info about proximity from each device through readings of the signal strength (RSSI), so they were used to provide checkpoints inside the classroom so the students would pass through these designated points and create different trajectories for their analysis.

The second module of activities included calculation of velocity versus speed and how two different velocities are added together on the same object. Velocity vs speed values

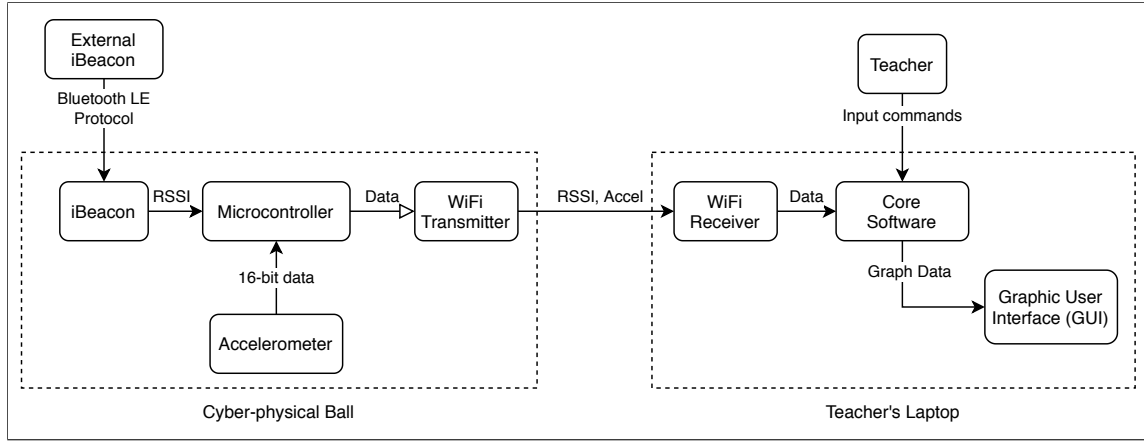
were analyzed by measuring the times and distances traveled from checkpoints in the first module of activities. To provide a practical experience of added velocities on one object, a 2m long conveyor ramp with a constant spinning ratio was built (Figure 3.1), so the ball could experiment 3 different scenarios: free fall, constant speed ascension and both effects at the same time.



**Figure 3.1:** Conveyor Ramp.

The third module of activities required analysis of real time acceleration, how it influences changes in the trajectory and its direct effects on rectilinear motion. For that, a [LSM9DS0 accelerometer](#) was used to provide 3-DOF measurement of acceleration from inside the ball. The sensor has a  $\pm 16G$  measurement range for acceleration values which covers all types of movements planned for the class, some heavy impacts could still saturate the sensor but for pedagogical purposes they could be shown as a peak in the graphs with no repercussion.

Lastly, to have power independence through the class, a 3700 mAh Li-ion battery was used to power the system. With the 3.3V level logic of the board, the system could work for 8 hours with no need for recharging and in case of necessity it could be easily charged with the board's integrated Li-ion battery charger. With all these elements, the cyber-physical system had a total cost of \$75.33 USD (Appendix D) and the final diagram of its components is shown in Figure 3.2.



**Figure 3.2:** Cyber-physical System Diagram.

## 3.2 Teacher's Software

The software was made with Processing 3.X and it implemented UDP communication with the cyber physical ball through the laptop's virtual ports. It consisted of a visual interface with a view for each different type of activity. The program received real time data from the hardware of the ball and updated it's graphic elements according to the activity, so they could be displayed through a projector.

To support the teacher's needs a user-centered design was implemented through user stories (Müter et al., 2019) for defining the requirements of each activity. First, the essential elements were designed based on what the teacher would have to do or show in each lecture. Then, the layouts were designed based on interfaces from sport analytics in professional sport (Sha et al., 2018) and real-time data dashboards (*Mclaren F1 Race Dashboard* n.d.). These designs aim to incorporate recreations of elements present in an activity of the real world, such as diagrams of a classroom or drawings of the objects with measurement values next to them. After that, the design was adapted based on the teacher's feedback and practical testing of the system.

The design of the interface should help in obtaining a quick and effective response on the students' disposition to participate in class. In that regard, Plass et al. (2019) provided empirical confirmation of the large effects of color and expression in the emotional response of teenagers and adults. For that reason, it was decided to use a cartoonish design for the ball and use strong colors, like bright red, in the interface. Also, in regard to usability, information displayed was kept at a minimum at each time, with the option to make specific data visible or not, so students could focus on the concepts to be learned and not get distracted with too much data.

The Graphic User Interface (GUI) was divided into 3 main views, which were the Spatial, Ramp and Data views. These corresponded to the activity modules for iBeacon positioning (Appendix B.1), addition of velocities with the Conveyor Ramp (Appendix B.2) and Acceleration analysis (Appendix B.3) respectively. Each view had the following properties:

### 3.2.1 Spatial View

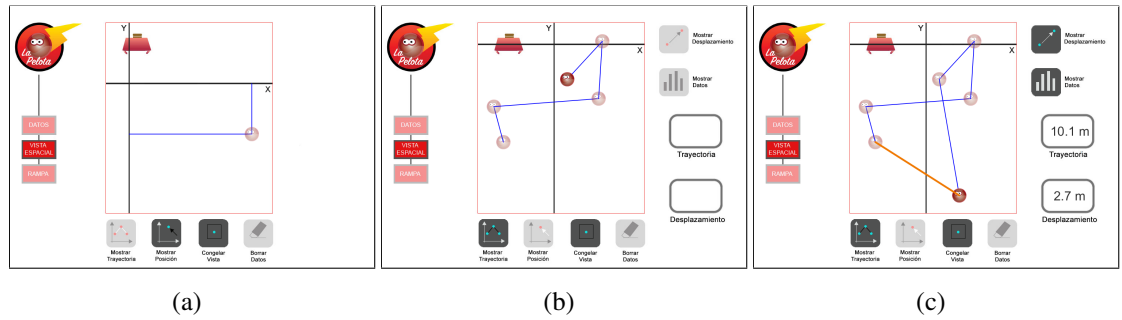
The goal of the Spatial View was to allow students to see where the ball was always located inside the classroom. This interface was used in the first module of activities (Appendix B.1), and it allowed the teacher to do the following actions:

1. Show a vertical representation of the classroom space.
2. Show the ball's position inside the classroom in real time.
3. Show an XY axis that represents the current reference system.
4. Display lines that represent the projection of the ball's current position into the actual reference system.
5. Freeze the screen so no new positions are updated.
6. Plot the trajectory that the ball has traveled around the classroom.
7. Erase the previous positions from the trajectory.
8. Plot the displacement made by the ball and toggle it's visibility when necessary.
9. Display numeric values of the total trajectory and total displacement after the interface has been paused.

This view consisted of a map recreation of the classroom from above, in which the teacher's desk worked as a reference point (Figure 3.3). In this way, students could identify where they should be placed in the map and get a direct transition from physical positions in the classroom to that of the software.

In Figure 3(a), a movable X-Y axis was drawn to represent the presence of an arbitrary reference system that could be placed anywhere inside the classroom. Also a drawing of the ball was always present so students could reflect on how different reference systems changed the relative coordinates of the ball, depending on the origin of the axis.

Previous positions of the ball could be stored, to later show its path around the classroom and let students compare trajectory vs displacement (Figure 3(b)). Additional to this, numerical values for distances could be shown or hidden depending on the activity (Figure 3(c)).



**Figure 3.3:** Spatial View Interface. a) Display of the current position of the ball. b) Display of the ball's trajectory along the classroom. c) Display of the ball's displacement and numeric values

### 3.2.2 Ramp View

The goal of the Ramp View section was to display graphs of the measurements done when using the ball with the conveyor ramp from the second module of activities (Appendix B.1). These activities had 3 major experiments that would be called A, B & C in the graphs. It allowed the following actions:

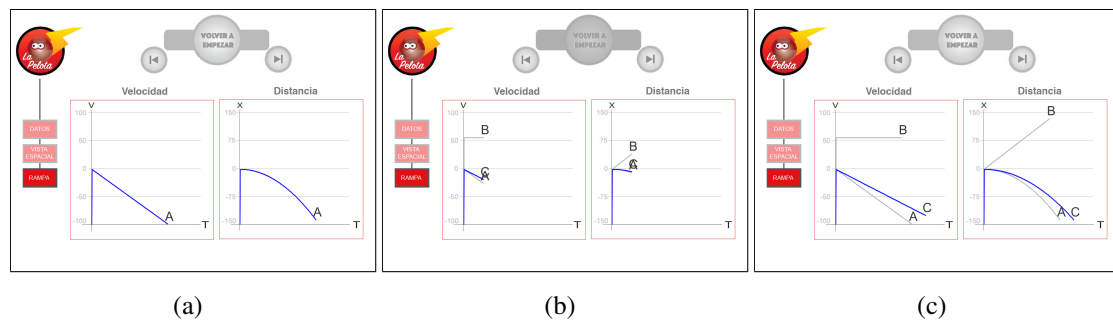
1. Plot data of velocity vs time of the ball for each experiment.
2. Plot of distance vs time for the ball for each experiment.
3. Plots for each experiment in the same graph to compare them easily.
4. Show an animation of each plot being drawn with a duration proportional to the real one.
5. Show the animations of each plot simultaneously.
6. Change which plots are being shown.
7. Restart the saved data to draw the plots from scratch.
8. Show referential values on the Y axis of the plot.

The interface of this section can be seen Figure 3.4. In it, there are two graphs side to side which correspond to the velocity-time plot and the distance-time plot for the scenarios recreated with the conveyor ramp (Figure 4(a)). The plot lines from each scenario were tied to a specific letter (A, B or C) to differentiate them more easily and analyze their characteristics. Detailed information on how the plot data was generated is found in Appendix E.4.

The values chosen for the Y axis were in centimeters per second (cm/s) and truncated for simplicity. On the top side, there are buttons to either add the next of the 3 plots or

remove the last one.

Finally, there is a restart button that allows you to draw all plots again and re-start their animations. If all plots were selected, they would be drawn simultaneously to be compared in real time (Figure 4(b)). Animations, where the lines are drawn point by point, would last longer for experiments with more data in the time axis (Figure 4(c)), this way, students could practice and reinforce their graph reading skills.



**Figure 3.4:** Ramp View Interface. a) Graphs of a velocity-time plot (left) and a distance-time plot (right) of the ball through experiments A and B. b) Display of the plots being drawn simultaneously. c) All plots completely drawn.

### 3.2.3 Data View

Finally, the last section corresponds to the interface to see real time data from accelerometer readings from the ball. This was made for the final module of activities (Appendix B.3) and allowed the following actions:

1. Show plots of the accelerations measured by the ball.
2. Show a plot of the magnitude of the ball's acceleration vs time.
3. Select between viewing the magnitude's plot or the detail from each direction (X,Y,Z).
4. Pause and resume the program to control when it is getting new data.
5. Show a timeline to use as reference for the graphs.
6. Display average values on each interval (A,B,...F) when needed.

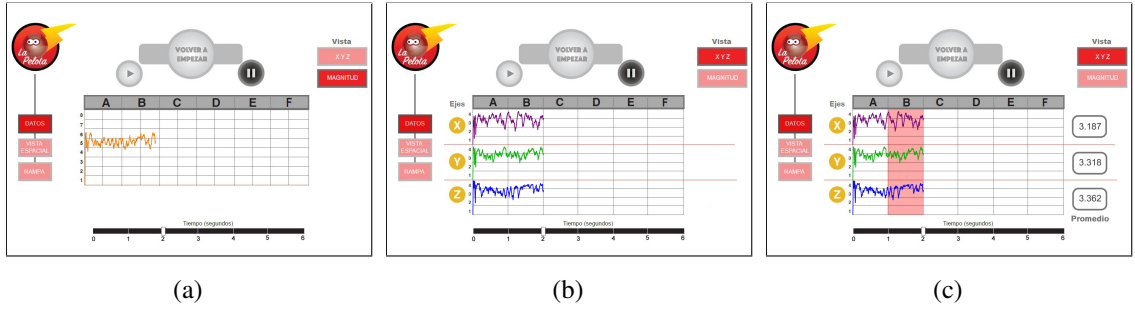
The interface had two different modes of operations, one where the screen showed a graph with the magnitude of the ball's acceleration over time and another where it would be divided in three graphs, one for each direction (XYZ). These can be seen in Figure 3.5.

In the XYZ mode, Figure 5(b), there are 3 parallel subplots each labeled X, Y and Z and they correspond to the acceleration plots of each directional reading received from the

cyber-physical ball. These subplots were divided into 4 levels of strength with no detail about their real values in  $m/s^2$ , so students would focus on the concepts rather than be distracted by the data.

In the magnitude mode, Figure 5(a), the graph covered the whole sections and was divided into 8 levels of strength to be consistent with the division from the XYZ mode, and leave room so the plot would not touch the ceiling. This is because if the maximum reading of each direction is 4, then the maximum magnitude would be  $\sqrt{(4^2 + 4^2 + 4^2)} \approx 6.93$ .

As seen in Figure 5(c), the time axis was divided in sections (A to F) so data from the interval's average values could be shown. This could be done after pausing measurements and clicking the corresponding interval, in order to show the difference between instantaneous acceleration and average acceleration.



**Figure 3.5:** Data View Interface. a) Magnitude Mode. b) XYZ Mode. c) Display of average readings from interval B.

### 3.3 Software Architecture

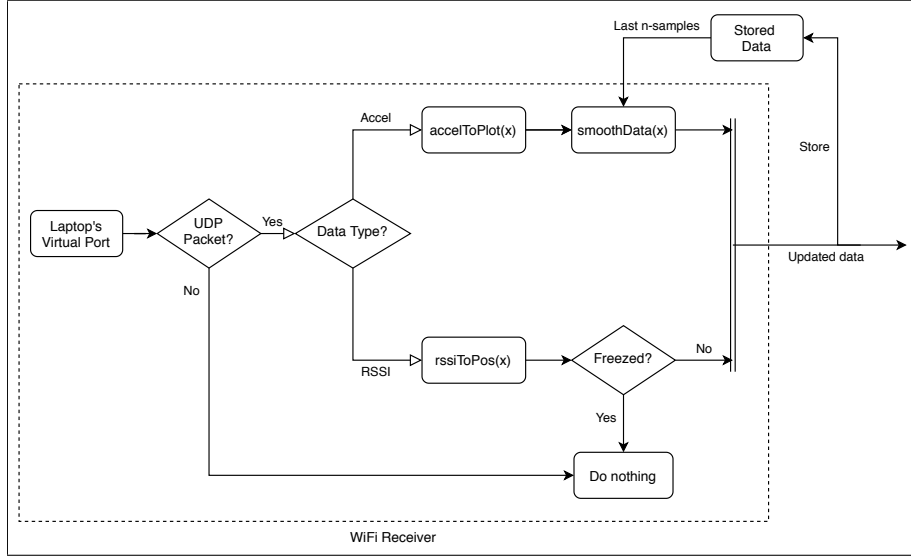
As shown in Figure 3.2, the software consists mainly of an Interface that processes and saves data from the WiFi Receiver to later be used in the Graphic User Interface (GUI). The behaviour of the GUI is controlled by the Interface based on Inputs from the user and the decoded message from the cyber-physical ball. Each module of the software has the following properties:

#### 3.3.1 WiFi Receiver

The ball sends its data as a character sequence with an specific format that is processed as shown in the diagram of Figure 3.6. The specific formats for the character sequences are the following:



- 'AXXXX.XXXXX.ZZZZZ' for acceleration readings. In this, the X, Y and Z values correspond to the respective signed integer read by sensor for each direction.
- 'SAAA.BBB.CCC.DDD.EEE' for RSSI readings. In this, the values from A to E correspond to the individual reading obtained from each iBeacon.



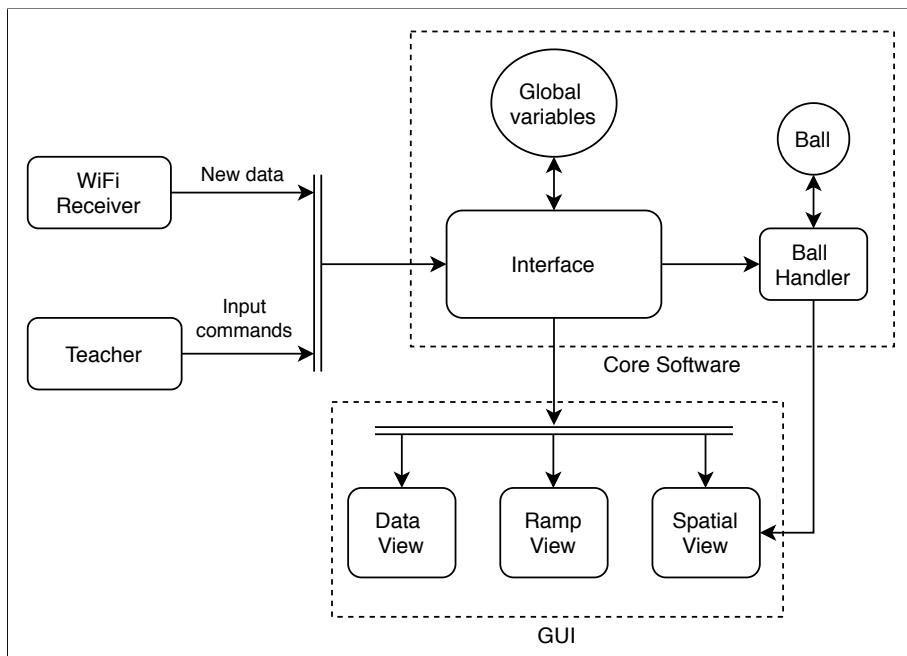
**Figure 3.6:** Processing of data received through WiFi.

The detail about the implementation of each function in Figure 3.6 is as follows:

- `accelToPlot(x)` : This function converts the 16-bit data  $x$  received as the acceleration value into a number  $\hat{X}$  in the range  $[0, H]$  of the subplot window of the interface, where  $H$  is the highest value of the window. The details of the conversion can be seen in Appendix E.1.
- `smoothData(x)` : this function applies a Moving Average Filter with a Weighted Method on a window of 8 samples to reduce noise in the signal  $x$ . The effect and specific filter used for this method is present in Appendix E.2.
- `rssiToPos(x)` : this functions maps the N-RSSI values to the corresponding  $beacon_i$  with coordinates  $(X_i, Y_i)$ . The  $beacon_i$  is determined using a Nearest Neighbor criteria, where a lower absolute value for the  $RSSI_i$  means a higher proximity to the  $beacon_i$ . The representation of this process can be seen in Appendix E.3.

### 3.3.2 Core Software

The data processed by the WiFi Receiver is used along the Teacher's input commands by the core software's Interface to determine how each view from the GUI needs to be updated. Global variables are stored with data from measurements of kinematic variables and the system's current state. The ball's behaviour in the GUI is calculated and drawn by an Ball Handler module which receives input from the software's Interface to proceed. The diagram of this flow is presented in Figure 3.7 and each module is described in the following sections:



**Figure 3.7:** Flow of operations performed in the Teacher's Software.

#### Interface

The interface is in charge of controlling the main flow of the program and performs the following tasks inside of it:

- STORE system's images used in the different views of the GUI.
- ADD Graphic Elements to each view of the GUI.
- SET the parameters at the system's start and when a soft restart is issued.
- DRAW the plot data in the corresponding graphs from the Data and Ramp views.
- HANDLE mouse triggers when the Teacher interacts with the GUI.

- CONTROL the current state of the system and which view is the active one.
- ENABLE the operation of the Ball Handler and the display of the active view.

## **Global Variables**

These following parameters are included in this set:

- Data generated from the outputs of the WiFi Receiver for the plots.
- Static parameters about the classroom dimensions, size of the ball and sampling frequency.
- Parameters about the GUI design dimensions.
- Auxiliary variables for flow control of the program.

## **Ball**

The ball is a Graphic Element object that gets updated with the current coordinates of the ball and changes its visual properties according to the situation. It also has the ability to draw its own projection on the current reference system (see Figure 3(a)).

## **Ball Handler**

This object handles the update and drawing of the current trajectory traveled by the ball in the classroom. It is called by the Interface to perform its tasks and has the following capabilities:

- STORE an array of Ball objects with the current and previous coordinates of the ball's position inside the classroom since the last reset.
- UPDATE the visibility of each ball within the array based on the current program's state.
- DRAW a line with the trajectory traveled by the ball based on the array of coordinates saved previously.
- DRAW a line with the displacement based on the ball's initial position after reset and it's current one.
- DISPLAY numeric data in meters about total distance traveled and displacement.

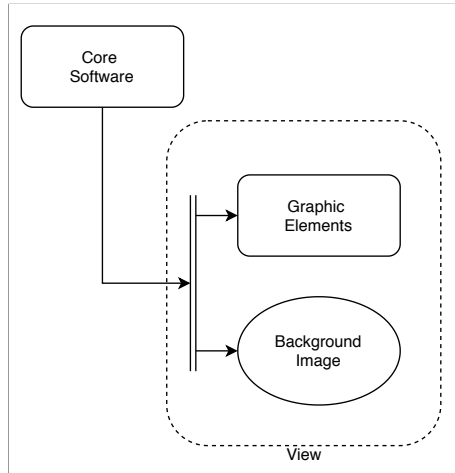
### 3.3.3 Graphic User Interface (GUI)

The GUI is made of the three main views described in Section 3.2. As seen in Figure 3.8, each view is formed of an array of Graphic Elements and a Background Image.

#### Graphic Element

Class of objects that represent all dynamic elements present in the GUI. This includes interactable ones, such as buttons, and moving elements, like the time indicator in the graphs. These have the following main abilities:

- UPDATE its visual properties depending on each subclass behaviour.
- DETECT whether the mouse is currently above them.
- TRIGGER a mouse pressed event for the core software's Interface, if it was clicked.
- DISPLAY or HIDE itself on the GUI if required by the core software's Interface.



**Figure 3.8:** Components of a view from the GUI.

## 4 RESULTS

### 4.1 Quantitative Results

An ANOVA was used to analyze the initial state of the differences in academic performance between the control and experimental group. The results from the [Shapiro-Wilk test](#) ( $W = 0.94; p < 0.05$ ) show that the residuals are not normally distributed, so a

Lavene's test was used for its robustness without normality. The results ( $p = 0.93$ ) show that the null hypothesis is true and there is homogeneity of variance. The ANOVA result were  $F(1, 48) = 0.074; p = 0.78$ , which shows that there were no significant differences between the grades of the students of both groups (Table 4.1). Based on these results, both groups had a similar starting point in terms of academic performance.

**Table 4.1:** Means and standard deviation of the pre-intervention grades

Pre-Intervention Grades	
Control Group ( $n = 23$ )	
Mean ( $\mu$ )	5.34
SD ( $\sigma$ )	1.23
Experimental Group ( $n = 27$ )	
Mean ( $\mu$ )	5.23
SD ( $\sigma$ )	1.25

Regarding the initial state of creativity between the control and experimental group, it was determined that there were no significant differences based on the results of the ANOVAs: fluency with  $F(1, 43) = 0.002; p = 0.96$ , flexibility with  $F(1, 43) = 0.47; p = 0.49$  and originality with  $F(1, 43) = 1.05; p = 0.31$ . This indicates that the groups were comparable in the three dimensions of creativity measured. Also, the assumptions of normally distributed residuals and homogeneity of variances were true for the three parameters.

The three dimensions of creativity were tested for normality and equality of their variances with the Shapiro-Wilk test, Bartlett's test and Levene's test. The results of these tests are in Table 4.2.

**Table 4.2:** Results from normality and homogeneity tests in creativity.

Dimension	Shapiro-Wilk's test		Bartlett's test			Lavene's test
	$W$	$p$	$K$	$gl$	$p$	$p$
Fluency	0.94	0.08	0.33	1	0.56	0.53
Flexibility	0.97	0.37	0.15	1	0.96	
Originality	0.94	0.001				

After the intervention, the result of the ANOVA test on the academic performance of the students were  $F(1, 46) = 3.76; p = 0.05$ . That means that there were significant

differences between both groups, in favor of the experimental group (Table 4.3). This indicates that, after interacting with the cyber-physical system, the students from the experimental group performed significantly better in their conceptual tests from the class. The assumptions of normally distributed residuals (Shapiro's test:  $W = 0.94$ ;  $p = 0.65$ ) and homogeneity of variances (Bartlett's test:  $K = 2.46$ ;  $gl = 1$ ;  $p = 0.11$ ) were true for this analysis.

**Table 4.3:** Means and standard deviation of the post-intervention grades

Exit Tickets (Post)	
Control Group ( $n = 23$ )	
Mean ( $\mu$ )	5.02
SD ( $\sigma$ )	0.85
Experimental Group ( $n = 25$ )	
Mean ( $\mu$ )	5.56
SD ( $\sigma$ )	0.60

After the intervention, the result of the ANCOVA test on the fluency of the students were:  $F(2, 25) = 14.46$ ;  $p \leq 0.001$  with significant differences in favor of the experimental group. The result for flexibility were:  $F(2, 25) = 8.11$ ;  $p \leq 0.001$  with significant differences in favor of the experimental group. And for originality were:  $F(2, 25) = 0.30$ ;  $p = 0.58$  with no significant differences. These indicates that the students from the experimental group had significantly better improvements in both fluency and flexibility versus the control group, but not in regards to originality.

Regarding the assumptions of the ANCOVA test for the fluency, all five were true

**Table 4.4:** Mean and standard deviation of fluency, flexibility and originality

	Fluency		Flexibility		Originality	
	Pre	Post	Pre	Post	Pre	Post
Control Group ( $n = 12$ )						
Mean ( $\mu$ )	4.92	4.33	4.33	3.83	0.17	1.33
SD ( $\sigma$ )	2.75	2.42	2.39	1.64	0.58	1.30
Experimental Group ( $n = 16$ )						
Mean ( $\mu$ )	5.00	5.63	4.19	4.31	0.80	0.67
SD ( $\sigma$ )	2.22	3.73	1.52	2.09	1.47	0.90

based on the following results:

1. Normally distributed residuals: normality assured by Shapiro's test with  $W = 0.93$ ;  $p = 0.1$ .
2. Homogeneity of variances: homogeneity assured by Bartlett's test with  $K = 2.13$ ;  $gl = 1$ ;  $p = 0.14$ .
3. Homogeneity of regression: No significant interaction between the dependent variable and the covariate ( $p = 0.29$ ).
4. Linearity between covariate and dependent variable: Significant correlation with  $p < 0.001$ .
5. Independence of the independent variable with the covariate: No significant dependency ( $p = 0.93$ ).

For flexibility, all the assumptions were also true as shown in the following results:

1. Normally distributed residuals: Assured by Shapiro's test with  $W = 0.94$ ;  $p = 0.94$ .
2. Homogeneity of variances: Assured by Bartlett's test with  $K = 0.68$ ;  $gl = 1$ ;  $p = 0.40$ .
3. Homogeneity of regression: No significant interaction between the dependent variable and the covariate ( $p = 0.06$ ).
4. Linearity between covariate and dependent variable: Significant correlation with  $p < 0.05$ .
5. Independence of the independent variable with the covariate: No significant dependency ( $p = 0.84$ ).

Finally, most assumptions were true for originality too. As seen in the following list:

1. Normally distributed residuals: Not achieved by Shapiro's test with  $W = 0.91$ ;  $p < 0.05$ .
2. Homogeneity of variances: Assured by Lavene's test with  $p = 0.33$ .
3. Homogeneity of regression: No significant interaction between the dependent variable and the covariate ( $p = 0.89$ ).
4. Linearity between covariate and dependent variable: Significant correlation with  $p < 0.05$ .
5. Independence of the independent variable with the covariate: No significant dependency ( $p = 0.17$ ).

## 4.2 Qualitative Results

The commentaries from the focus group were classified under six categories: (1) Valuation of the classes, (2) Valuation of the cyber-physical ball in the classroom, (3) Relationship of the concepts with the activities, (4) Role of the students, (5) Importance of innovation and technology and (6) Perception of the ball in the real world.

As a general consensus, the activities with the cyber-physical system were seen as a positive element that helped students feel part of the class and allowed them to understand the concepts more easily. Also, the students expressed that they would like to see other teachers do activities like the ones they experiences in the physics class with the help of the cyber-physical system. Details about the findings, and a transcription of some commentaries from the students, can be seen in Appendix F.

## 5 DISCUSSION

The experimental group achieved academic results that were significantly better than those of the control group Table 4.3. One of the main reasons for that could be the major improvement on motivation shown by the students because of the new dynamics, as seen when they speak about their impressions of the classes:

*"What I liked the most was that the teacher did dynamic classes"*

-Student 1

*"(the classes) changed the routine"*

-Student 2

Looking more carefully at the students' insight after interacting with the cyber-physical system, they show signs of a higher level of metacognition when addressing their own understanding of the concepts:

*"The ball allowed you to see everything not just in a theoretical way, but also like you see things from another point of view"*

-Student 6

*"The experiments had an impact in our learning process, that is, we learned quicker"*

-Student 5



These results are aligned with the findings from Zepeda et al. (2019), where talks and activities that promote development of metacognition are shown to have a positive effect on conceptual growth. This leads us to state that the Cyber Physical Ball as an effective tool to support metacognition development.

The development of metacognition coincides with the improvements in the dimensions of fluency and flexibility of creativity (Table 4.4). Hargrove and Nietfeld (2015) indicate that promoting creativity also boosts the development of certain cognitive process, like metacognition. One of the reasons that could explain the increase in creativity is because of the practical activities done in class with the cyber-physical ball. One of the benefits of having practical experiences is that they provide the opportunity to think in a creative way (Haigh, 2007). However, practical experience is not enough by itself. It is necessary that teachers plan explicitly how to link the practical focus with the theory (Abrahams and Reiss, 2012). The practical activities not only promote creativity, but are also valued positively by the students who express gladness when doing them:

*"I like it because its kinda more practical"*

-Student 3

*"The ball is more practical than theoretical"*

-Student 4

Further analysis on how the cyber-physical system achieved these outcomes comes from a common pattern present in the students' commentaries, that the ball allowed them to see things in a more clear way. That means that the students could understand what the systems communicated and were open to incorporate it into their own view of the physical world. This acceptance can be addressed to the importance of self-explainability on cyber-physical systems to build a good trust relationship between the end-user and the system (Greenyer et al., 2019). That is, that the system should provide feedback that's easy to understand and is consistent to what can be seen from outside the system, without the help of an expert. This belief is reinforced when student comment about how they see the ball as something alive that could be interacted with:

*"(the ball) had pulse"*

-Student 1

*"You could reanimate it, you could let it die"*

-Student 2

Even though technology had a fundamental role, its also important to note how this is complemented by the pedagogy and a course planning, that allows students to be able to create their own knowledge and take an active role in their learning process (Freeman et al., 2014). Technology must not be alone, as it is demonstrated by interventions that used innovate technologies yet didn't get significant improvements (Shechtman et al., 2019).

The use of technology and how it enables students to become protagonists in their own learning process is appreciated by them, who also say that they usually lack the opportunities to take this role:

*"I find it better for teachers to make us part of their classes, that not just them are talking, that we also have say what we think, what we understand and how hard it is for us"*

-Student 1

*"I think, that maybe all teachers can learn from their colleagues, because there are teachers that are like... like they talk all the time and classes becomes more boring, but if they could... I don't know, if one of them could look to the side and say <I like how she does her classes>... Like, more dynamic, that makes students participate, I think that'd be better"*

-Student 2

Although the cyber-physical system enables the empowerment of the students, it is the teacher who must lean the pedagogy on the side of [constructivism](#) to sustain these opportunities of engagement and participation. Also, it is the teacher's implementation of the lesson plan that sets the flow of the class and determines how the students merge their experiences with the system and their previous knowledge into a consistent concept. While the system provides tools so students can answer questions by themselves, the reach of its capabilities are determined by the teacher's self-efficacy beliefs and knowledge of technology (Taimalu and Luik, 2019). For example, if the teacher doesn't believe in the technology at hand, there won't be an attempt to use it to answer a student's question and thus the benefits of said technology will be forfeited.

Finally, its important to highlight the use of videos as complementary material to the Cyber-Physical System. All videos were chosen by the research team so they would be related to the experimental activity. This coincides with Richtberg and Girwidz (2019), who indicate that videos for learning physics should be interactive. This can be achieved by adding practicals tasks related to the concepts at the end of the videos, therefore, promoting active learning and the students' participation. An example of this is when, in the lecture of additions of velocities (Appendix B.2), the video showed a working mechanic escalator before using the Cyber-Physical Ball with the conveyor ramp, so students would

be able to identify that both situations were similar. This was appreciated by the students when they indicated that everything that happened in class was consistent:

*"With the was ball, it was like, you integrated everything you saw before...  
like you confirm it"*

-Student 1

*"Everything made sense"*

-Student 2

## 6 CONCLUSIONS

Considering the positive results obtained, there are two main benefits to highlight when teaching with a cyber-physical system. Firstly, the results show that a cyber-physical system can have an immediate impact in the students' behaviour by producing high levels of engagements. Secondly, a cyber-physical system can deliver simultaneously a symbolic and a tangible experience to students. Not only does this allow them to attain a more significant understanding of the concepts, it also helps them develop fundamental skills such as creativity.

To achieve results like these, the system must be designed around the students lifestyle so they show a good disposition when interacting with it. For Chilean students in 10<sup>th</sup> grade, this was achieved with their familiarity to ball games, especially football. Which was confirmed when the students commented about how quickly they adopted the system and their appreciation of how it let them take a protagonist role during the class.

The results support the idea found in literature that metacognition is closely related to creativity and how promoting the former develops the latter. In that regard, the experimental group showed clear signs of higher levels of metacognition about their own knowledge and their role in the class. Which latter translated in a better performance in the creativity test, where students were asked to give variate uses for specific objects.

These findings show that systems like the one developed here have the potential to be used as effective tools when developing classroom activities. And not only that, students can view them with such a positive light to go as far as mentioning that other teachers should follow this example.

## 7 LIMITATIONS AND FUTURE WORK

Two improvements can be done to the experimental design to get more robust statistics of the effectiveness of this methodology. First, to expand the sample group to a variety

of classrooms from school's with different socio-economic environments, to measure the relevance of different students' lifestyles and analyze patterns in the data. Second, to make a second course planning where the videos are not included in neither the control group nor the experimental group, so it can be assessed if the cyber-physical systems show its beneficial effects by itself or only as a complement with other complimentary material.

Sport analytics is a field that gives more insight than just visualization techniques for real time data of physical activities, as it was used here. It also provides decision-making tools for athletes to improve their performance (Hughes et al., 2019) based on their activity pattern. Such insights can be used to support the teacher's role and improve how activities are performed in the classroom, based on the behaviour of the students during the class. For example, in the first module of activities of the course planning, where students have to study the differences between trajectory and displacement (Appendix B.1), the system can record the data from all performed trajectories and make suggestions to the teacher on which one to do next for better coverage of the concept, like recreating an specific trajectory that has not been attempted yet and is important to exemplify.

Although the system was quickly accepted by the students, the teacher had more difficulties and needed a member of the team to be always present in class. This was mainly because of the system's need for manual setup at the start of each class, for example when checking its connection to the PC and making sure its position readings were correctly calibrated with the classroom. The overhead from connectivity could be reduced with the automatization of the process by using the ESP8266 Soft Access Point feature and adding a routine in the software that looks for it's specific SSID to set the connection. Calibrations could also be done automatically with the use of extra sensors or a change in technology.

In the future, with progress in the sensor development industry, it could be viable to use GPS Real Time Kinematics modules, like Sparkfun's NEO-M8P-2. These sensors are able to achieve an accuracy of  $0.025m @ 4Hz$  which would greatly improve the cyber-physical system capabilities. With this, spatial tracking could be done in real time and there would be little limitation to all the activities that could be supported for the classroom. From letting the students roam free through the classroom and recording their activity to using it in other topics of the curriculum, like for instance, Energy conservation.

An interesting question related to the curriculum's coverage is where could this be replicated? Different approaches can be taken to answer this, from the object's perspective and from the methodology. In regards to where or how to use a cyber physical ball, in the musical industry there is already a candidate by the name of Oddball (*Oddball - the Drum Machine* n.d.), originally designed to be used as an alternative musical instrument through generations of different sounds depending on impact strength. This ball could be adapted

for teaching, like the ball in this work, with the ability to record and display information about the rhythms produced with it and have an automatic partiture creation feature so students can improve their music creation skills. Another example is Drazan (2020), that can be enhanced with the use of wearable biometric sensors to be a cyber-physical system for the teaching of the nervous system in the biology curriculum.

In this research, the impact of the teacher's expertise and beliefs while using of the cyber-physical system were not measured as the experiments were conducted with the same teacher. Yet, there were signs that building confidence in using technological tools like these would be necessary for large scale implementations, where assistants who know the system would not be always available. To handle this issue it would be necessary for teachers to train in the use of these technological tools, ideally at the educational establishment where they train to become school teachers.

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# **APPENDICES**

## APPENDIX A      SUMMARY OF THE CLASSES AND LEARNING GOALS

**Table A.1:** Contents, goals and activities of the classes (part1).

Contents of the lecture	Learning Goals <sup>(*)</sup>	Experimental Activity
Lecture 1: Reference Systems - Trajectory and Displacement	<ul style="list-style-type: none"> <li>• Demonstrate, with simple experiments, why it is necessary to use a reference systems and coordinates in the description of an object's movement.</li> <li>• Explain concepts of kinematics like position, displacement and traveled distance.</li> </ul>	<ul style="list-style-type: none"> <li>• Analyze how the ball changes its relative coordinates inside the classroom depending on the reference system used.</li> <li>• Observe the displacements and trajectory of the ball in classroom, and identify their differences.</li> </ul>
Lecture 2: Speed and velocity	<ul style="list-style-type: none"> <li>• Explain concepts of kinematics, such as elapsed time, average velocity, instantaneous velocity and speed.</li> </ul>	<ul style="list-style-type: none"> <li>• Determine the differences between speed and velocity based on the movement of the ball in the classroom.</li> </ul>
Lecture 3: Addition of velocities	<ul style="list-style-type: none"> <li>• Use formulas from Galileo to add velocities in simple daily life situations.</li> </ul>	<ul style="list-style-type: none"> <li>• Analyze what happens when there is more than one velocity involved in the movement of the ball.</li> <li>• Identify the differences when velocities have the same direction and when they are opposites.</li> </ul>

<sup>(\*)</sup> A learning goal should be read as "*Students have the ability to <insert goal>*"

**Table A.2:** Contents, goals and activities of the classes (part2).

Contents of the lecture	Learning Goals (*)	Experimental Activity
Lecture 4: Uniform Rectilinear Motion	<ul style="list-style-type: none"><li>• Identify kinematic characteristics of the rectilinear motion, in natural phenomena and daily life situations.</li><li>• Obtain conclusions, related to kinematic concepts, from experimental research on objects with uniform rectilinear motion (zero acceleration).</li></ul>	<ul style="list-style-type: none"><li>• Identify in which situations the ball presents uniform rectilinear motion and what conditions are necessary to satisfy this criteria.</li></ul>
Lecture 5: Accelerated Rectilinear Motion	<ul style="list-style-type: none"><li>• Identify kinematic characteristics of the rectilinear motion, in natural phenomena and daily life situations.</li><li>• Explain the concepts of gravity's acceleration and considered its presence in situations of free fall and vertical throws.</li><li>• Obtain conclusions, related to kinematic concepts, from experimental research on objects with accelerated rectilinear motion (non zero acceleration).</li></ul>	<ul style="list-style-type: none"><li>• Identify in which situations the ball presents accelerated rectilinear motion and what conditions are necessary to satisfy this criteria.</li><li>• Observe that acceleration remains constant in free falls and vertical throws.</li></ul>

## APPENDIX B DETAILED COURSE PLANNING

### B.1 Module 1: Trajectory and Displacement

#### B.1.1 Lecture N°1

##### Lecture N° 1 – Unit 2: Rectilinear Motion

<b>Content</b>	Reference Systems - Trajectory and Displacement		
<b>Class</b>	10 <sup>th</sup> grade	<b>Subject</b>	Physics
<b>Previous Knowledge</b>	Cartesian Plane		
<b>Resources</b>	Cyber-physical ball, projector, computer	<b>Duration</b>	30min

##### Activity N°1:

Objective of the activity: Analyze the changes in the relative position of the ball depending on the reference system.

1. The teacher presents the interface Spatial View (Figure 3.3). Explains that, with this activity, "the position of the ball" will be studied, relative to the reference axes  $X$  and  $Y$  seen in the interface. The teacher asks: *"What reference system is being used here?"*

Expected answer: Cartesian Plane

2. The teacher holds the ball and asks to the students: *"Using the Cartesian axes as reference, where is the ball located? To the right or to the left of the  $Y$  axis? Up or down the  $X$  axis?"*
3. The questions are repeated once again, after letting a student with an iBeacon in his/her seat hold the ball.
4. Finally, the teacher asks while selecting a new origin for the Cartesian plane through the software: *"If we move the axes to this position, where would the ball be located? To the right or to the left of the  $Y$  axis? Up or down the  $X$  axis? Did the ball move? Then, why did its position change?"*

Expected answer: Students are expected to realize that the ball didn't change its absolute position, instead, the reference system used changed and with it the relative position

##### Activity N°2:

Objective of the activity: Observe the displacement and trajectory of the ball inside the classroom.

1. The teacher explains that, with this activity, the movement of the ball will be studied.
2. After selecting to "Display Trajectory" in the software, the teachers shows how the ball leaves a path as it moves in the classroom.
3. The teacher holds the ball and asks to the students: *"In this case, are the displacement and the traveled distance equal?"*

Expected answer: Yes, if the path was a straight line. No, otherwise.

4. The teacher repeats the process with a path that gives the opposite answer to the previous question.
5. The teachers starts at one of the checkpoints and then gives the ball to a 1<sup>st</sup> student in another checkpoint, then asks that the ball is thrown to a 2<sup>nd</sup> student in a third checkpoint (making a change in the direction of the trajectory). After that, the teacher asks: *"Is the distance traveled equal to the displacement? If not what would be the displacement?"*

Expected answer: No, because the trajectory is the line drawn by the ball in the interface, but instead the displacement is an imaginary line between the starting position of the teacher and the current position of the ball.

6. The teacher selects "Display Displacement" in the software and complements the students' answers.
7. Finally, the ball is thrown back to the teacher and he/she asks: *"Is the trajectory equal to the displacement? If the displacement is zero, does that mean that the ball didn't move?"*

Expected answer: No. In this case, the displacement is zero so it cannot be equal to the trajectory done. That displacement is zero doesn't mean that the ball didn't move, but that it returned to its original position

### B.1.2 Lecture N°2

#### Lecture N° 2 – Unit 2: Rectilinear Motion

<b>Content</b>	Speed and velocity	<b>Subject</b>	Physics
<b>Class</b>	10 <sup>th</sup> grade		
<b>Previous Knowledge</b>	Distance, displacement		
<b>Resources</b>	Cyber-physical ball, projector, computer	<b>Duration</b>	20min

#### Activity N°3:

Objective of the activity: Determine the difference between speed and velocity.

1. The teacher presents the interface Spatial View (Figure 3.3) once more. Explains that in this lecture "the differences between speed and velocity" will be studied. The teacher shows that the interface also displays the value (in *m*) of the total distance traveled by the in the drawn trajectory.
2. The teacher holds the ball and throws it to a student with a checkpoint, then asks: *"In this case, is velocity equal to speed?"*  
Expected answer: Yes, because by traveling in a straight line both values are equal.
3. The process is repeated, but this time a 2<sup>nd</sup> student is asked to measure the elapsed time with the chronometer of his/her smartphone. The teachers asks again: *"How much was the velocity and how much the speed?"*  
Expected answer: Both numeric values are expected to be equal.
4. The teachers asks that the ball is thrown to a 3<sup>rd</sup> student with a checkpoint. Then, the teachers asks: *"Are speed and velocity still the same? Which one is higher?"*  
Expected answer: No, because the displacement is different from the trajectory. Given that trajectory is longer than displacement, speed is the higher value.
5. The process is repeated, but this time the 2nd student is asked to measure the elapsed time again. Then, the teacher asks: *"What are the values of velocity and speed?"*  
Expected answer: Its expected that the numeric value of velocity is lower than the value of speed.
6. Finally, the ball goes back to the teacher and he/she asks: *"Are speed and velocity equal? If velocity is zero, does that mean that the ball didn't move?"*  
Expected answer: No, because displacement is zero, so velocity is also zero while speed is different from zero. That the ball had zero velocity doesn't necessarily mean that it didn't move.



## B.2 Module 2: Addition of Velocities

### B.2.1 Lecture N°3

#### Lecture N° 3 – Unit 2: Rectilinear Motion

<b>Content</b>	Addition of velocities	<b>Subject</b>	Physics
<b>Class</b>	10 <sup>th</sup> grade		
<b>Previous Knowledge</b>	Velocity, gravity		
<b>Resources</b>	Cyber-physical ball, projector, computer, conveyor belt	<b>Duration</b>	20min

#### Activity N°4:

Objective of the activity: Analyze what happens when velocities are added together.

1. The teacher presents the interface Ramp View (Figure 3.4). Explains that the topic of study in this lecture will be "what happens when more than one velocity influence the same object". Also explains that in this class they will analyze what happens with the graphs of velocity in three different scenarios involving the ball and the conveyor belt.
2. Case 1: The ball is elevated by the conveyor belt.  
Before seeing the graphs, the teacher asks: *"If the rotation speed of the conveyor belt is constant, how is the ball's velocity? And why?"*  
Expected answer: By being attached to the belt, the ball acquires the same speed of the conveyor belt. Then, if the conveyor has a constant spinning ratio, the ball will have a constant speed.
3. Case 2: The ball falls from the top of the conveyor belt, while it is turned OFF.  
Before seeing the graphs, the teacher asks: *"If the conveyor belt is stopped, how will the ball's velocity be? Will it be constant?"*  
Expected answer: While falling from the slope of the conveyor belt, the ball is affected by gravity's acceleration, therefore, its speed is not constant and will be increasing continuously.
4. Case 3: The ball falls from the top of the conveyor belt, while it is turned ON.  
Before seeing the graphs, the teacher asks: *"If the conveyor belt is ON, how will be the speed of the ball? Will it be constant? Will it be higher than before?"*  
Expected answer: The ball will still be under the effects of gravity, but this time

it will be going against the spin of the machine, so velocities will be subtracted. Because of this, it will take some time before the effect of gravity can surpass the spinning of the belt and the ball will be kept spinning at the top. After that it will fall in a similar way to the last case, but slower.

5. After each case, the answers of the students are complemented with the data shown in the interface.

### B.2.2 Lecture N°4

#### Lecture N° 4 – Unit 2: Rectilinear Motion

<b>Content</b>	Distance traveled	<b>Subject</b>	Physics
<b>Class</b>	10 <sup>th</sup> grade		
<b>Previous Knowledge</b>	Velocity, gravity		
<b>Resources</b>	Cyber-physical ball, projector, computer, conveyor belt	<b>Duration</b>	20min

#### Activity N°5:

Objective of the activity: Analyze how added velocities affect the distance traveled over time.

1. The teacher presents the interface Ramp View (Figure 3.4). Explains that the topic of study in this lecture will be "what happens to the distances traveled when more than one velocity influence the same object". Also explains that in this class they will analyze what happens with the graphs of distance in the same three scenarios from the last class.
2. For this lecture, the activities are a replica of the previous session with the only difference of focusing on what happens with the curve of distance over time. The important part is that students realize the answers to: *"How is the distance traveled when velocity is constant? And when velocity increases over time, as when affected by gravity?"*  
 Expected answer: For constant speed, the distance should be a straight line that increases or decreases over time, depending on the direction of movement. For increasing velocity, the ball travels a longer distance each second, so the plot should look like a rounded curve (technically, a parabola).
3. Once again, after each experiment, the answers of the students are complemented with the data shown in the interface.

## B.3 Module 3: Acceleration

### B.3.1 Lecture N°5

#### Lecture N° 5 – Unit 2: Rectilinear Motion

<b>Content</b>	Accelerated Rectilinear Motion (ARM)	<b>Subject</b>	Physics
<b>Class</b>	10 <sup>th</sup> grade		
<b>Previous Knowledge</b>	Velocity, acceleration		
<b>Resources</b>	Cyber-physical ball, projector, computer	<b>Duration</b>	20min

#### Activity N°6:

Objective of the activity: Identify when uniform rectilinear motion is present..

1. The teacher presents the interface Data View, Magnitude Mode (Figure 5(a)). Explains that in this lecture they will "analyze acceleration in different types of movements". For that, the teacher sets the program to start recording acceleration data.
2. To motivate the students, the teachers asks: *"When you run, is it Uniform Rectilinear Motion (URM)? What do you think?"*  
Expected answer: Students are expected to give different answers that will be partially true, in most cases, as the answer depends on how the process itself is done.
3. To guide the ideas, the teachers asks a student to take the ball and start running in a straight line through the classroom, all this while trying to keep the ball still. After this, recording of data should be paused in the software. Then, the teacher asks: *"In the plot, can you determine when the person was running and when he/she stopped?"*  
Expected answer: The students was running when the graph presents a stable portion with oscillations, and stopped when the graphs became erratic (due to the sudden impulse).
4. The teacher asks: *"Is the acceleration constant while running? Can it be considered a URM? Why?"*  
Expected answer: No, its not constant because when you run yo do little hops which generates a movement that's not a straight line, even though the person seems to run straight, which is confirmed by the oscillations in the graph. Because of this, is not a URM and in general these are very difficult to replicate in real life.

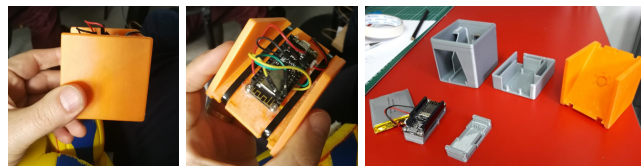
5. After complementing the answers of the students, the teachers asks a new motivation question: *"When I throw the ball upwards, will it be an Uniform Accelerated Rectilinear Motion (UARM)? What do you think?"*  
Expected answer: Like the last time, students are expected to give different answers that will be partially true, as the answer depends on how the process itself is done.
6. The teacher sets the program to start recording again and, to guide the ideas, asks another student to take the ball throw it upwards as straight as possible. After this, recording of data should be paused in the software. Then, the teacher asks: *"In the plot, in which portion the ball was in the air? How does the curve seem like in that moment?"*  
Expected answer: When the curve becomes similar to a straight line, before and after peaks.
7. The teacher asks: *"What does it mean that it is <like a straight line>?"*  
Expected answer: That, in that moment, it is a constant.
8. Then, the teacher asks: *"Do any of you know why it is a constant?"*  
Expected answer: Because when the ball is in the air, no one touches it so it's only affected by gravity, which is constant.
9. Teacher asks: *"Then, is that a UARM?"*  
Expected answer: Yes, because the acceleration is constant and moves in a straight like (mostly).
10. As a final motivation question the teacher asks: *"When you throw an object to another person, is it also an UARM? What do you think?"* Expected answer: As before, mixed answers are expected and will be clarified with the following steps.
11. The teacher sets the program to start recording again and asks two students to throw the ball at each other. The rest look at the graphs shown in the interface. Then, the teacher asks: *"In the plot, in which portion the ball was in the air? How is the curve in that moment?"*  
Expected answer: A somewhat straight line, like in the last experiment.
12. The teacher asks: *"And what does it mean that's like the last time?"*  
Expected answer: That the acceleration is constant, similar to before.
13. Finally, the teachers asks: *"Then, it is a UARM just like it was before, right?"*  
Expected answer: No, because even though the graphs look very similar to the last experiment, the path traveled by the ball is not a straight line so it is not rectilinear.

The information shown corresponds to the **MAGNITUDE** of the acceleration, but not its direction which is crucial for this question.

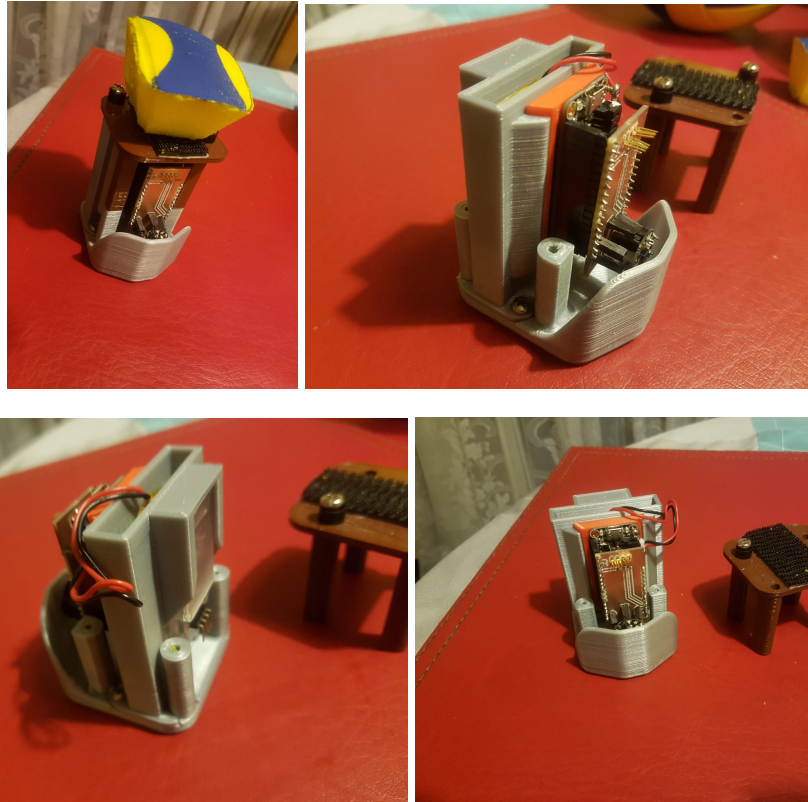
## APPENDIX C      PHOTOS



**Figure C.1:** Electronic core inside the internal support structure of the first ball.



**Figure C.2:** Previous versions of the internal cores.



**Figure C.3:** Electronic core inside the internal support structure of the second ball.



**Figure C.4:** How the balls look when opened.

## APPENDIX D      COMPONENTS USED TO BUILD THE CYBER PHYSICAL BALL

Table [D.1](#) shows the components used to build the Cyber Physical Ball; the price of the components are the one reflected as of April 2020.



**Table D.1:** Components list and their prices

Component		Link	Price (\$USD)
FLORA	Accelerometer	<a href="https://www.adafruit.com/product/2020">https://www.adafruit.com/product/2020</a>	\$ 19.95
LSM9DS0			
Feather Huzzah	ESP8266 (Microcontroller + WiFi)	<a href="https://www.adafruit.com/product/2821">https://www.adafruit.com/product/2821</a>	\$ 16.95
3.7V 3700mAh	Lithium Ion Polymer Battery	<a href="https://www.adafruit.com/product/328">https://www.adafruit.com/product/328</a>	\$ 14.95
HM-10	Bluetooth 4.0	<a href="https://www.amazon.com/HUAZHU-Bluetooth-iBeacon-Module-Arduino/dp/B07XJ74C1W/ref=sr_1_1?dchild=1keywords=dsd+tech+hm-10qid=1588445640sr=8-1">https://www.amazon.com/HUAZHU-Bluetooth-iBeacon-Module-Arduino/dp/B07XJ74C1W/ref=sr_1_1?dchild=1keywords=dsd+tech+hm-10qid=1588445640sr=8-1</a>	\$ 7.99
6"	Foam Ball	<a href="https://www.amazon.com/Dellop-Soccer-Monkey-Playball-Outdoor/dp/B07R2K573D/ref=sr_1_17?dchild=1keywords=6+inch+foam+ballsqid=1588450322sr=8-17">https://www.amazon.com/Dellop-Soccer-Monkey-Playball-Outdoor/dp/B07R2K573D/ref=sr_1_17?dchild=1keywords=6+inch+foam+ballsqid=1588450322sr=8-17</a>	\$ 12.99
100g of PLA	(3D printed block)	<a href="https://www.amazon.com/Printer-Filament-Engine-Dimensional-Accuracy/dp/B01DXWVOPQ/ref=sr_1_2?dchild=1keywords=3D+fuel+plaqid=1588451945sr=8-2">https://www.amazon.com/Printer-Filament-Engine-Dimensional-Accuracy/dp/B01DXWVOPQ/ref=sr_1_2?dchild=1keywords=3D+fuel+plaqid=1588451945sr=8-2</a>	\$ 2.5
Total Cost			\$ 75.33

## APPENDIX E      PHYSICS PROBLEMS AND THEIR SOLUTION IN THE SOFTWARE

To provide a classroom experience that focused on the students' understanding of the concepts, certain variables that were measured by the sensors had to be simplified so as not to distract. More specifically, this included the following:

### E.1      Converting acceleration readings into conceptual levels of strength

For the activities from the third module (Appendix B.3), it was necessary to hide information about real values of acceleration (in  $m/s^2$ ) and display them in a simple scale of natural numbers, so they would be easier to comprehend conceptually. The function `accelToPlot(x)` was used to implement the conversion (Section 3.3.1) with the following formula (see Figure E.1):

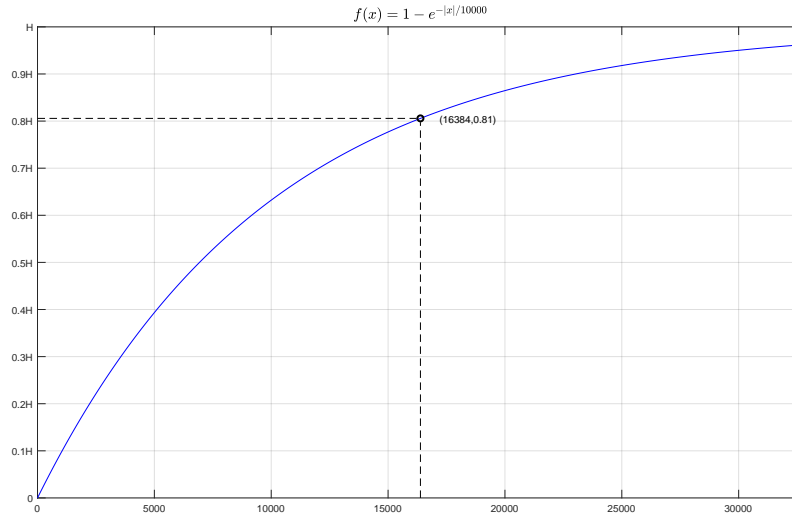
$$\hat{X} = -H(1 - e^{-|x|/10000})$$

Where  $H$  is the height of the subplot window in pixels, and  $x$  is the 16-bit measurement from the sensor.

A decreasing exponential function was used to map the values of  $x$  into the plotting window  $\hat{X}$  to give diminishing returns to higher levels of acceleration in terms of plotting space. This was needed because acceleration values higher than  $3G$ , that is  $x = 16384$ , would correspond to instantaneous impulses and these needed to be shown just as spikes in the graph without further differentiation. This behaviour was decided from a pedagogical viewpoint so students would not be distracted by significant differences in readings of impulses and would retain focus on the concepts to be learned.

With these considerations, the value of  $1/10000$  in the exponential was obtained empirically, as a good factor to represent the desired behaviour of the curves. With this, 81% of the space in the subplot graph was used for accelerations between 0 and  $3G$ . Then, given that the value of  $x$  ranges from 0 to  $2^{15} - 1$ , the output of  $\hat{X}$  is within the  $[0, 0.96H]$  interval which leaves a little room so graphs are never overlapped between each other.





**Figure E.1:** Conversion function for the `acceSToPlot (x)` method.

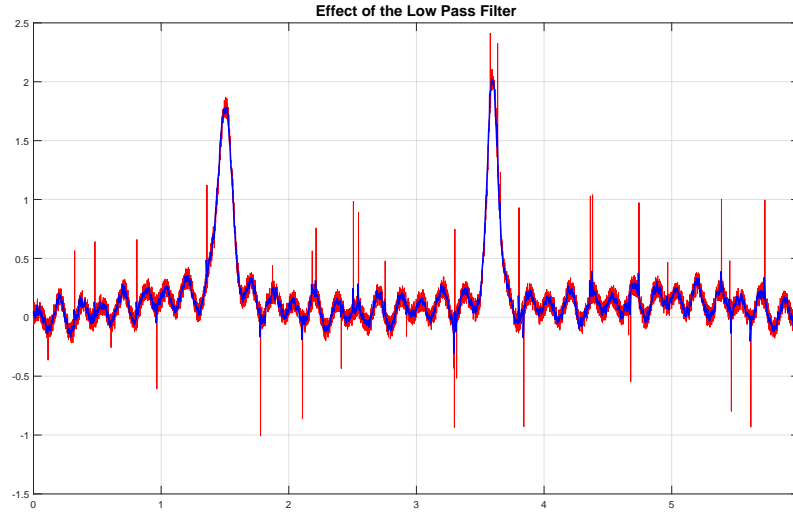
## E.2 Filtering noise from acceleration readings

Acceleration measurements had to retain a certain level of noise from the readings of the sensors, so students realize that real life instruments are not perfect and have margins of error. Yet, the noise present in the readings was higher than acceptable so it required filtering before being plotted for the students.

For that, a weighted moving average filter was used with the following window of 8 samples:

$$H = \frac{1}{36} [8 \ 7 \ 6 \ 5 \ 4 \ 3 \ 2 \ 1]$$

It was selected for its nature as a Low Pass Filter to reduce the effect of noise and its simplicity of implementation. Also, it is not a filter that completely erases high frequency information so impulses, as the ones performed by the students with instantaneous impacts on the ball, can still be plotted. Finally, its effects can be seen in Figure [E.2](#).

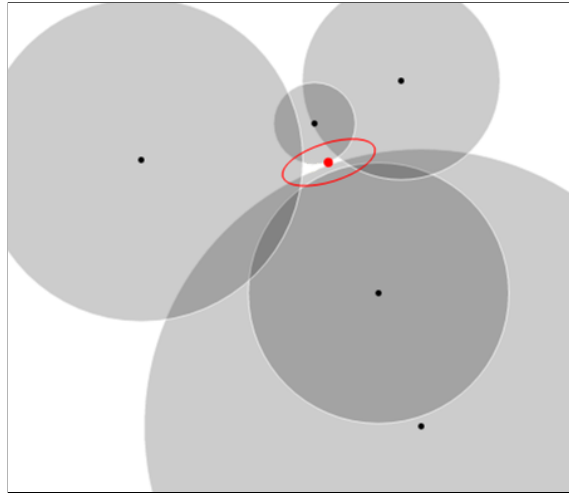


**Figure E.2:** Effect of the filter implemented with `smoothData(x)`.

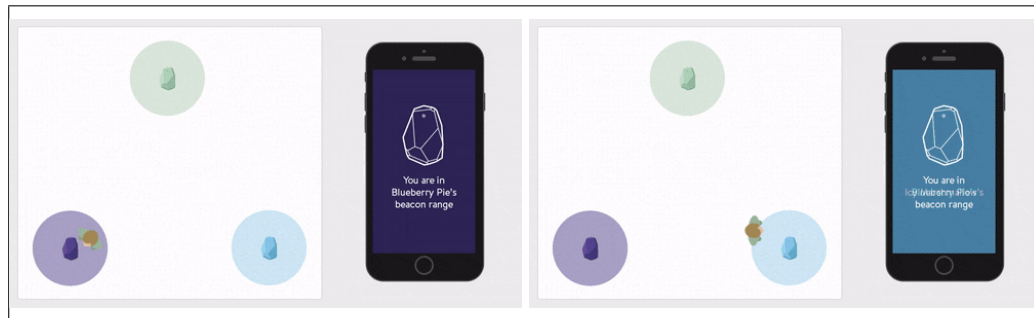
### E.3 Ball localization with iBeacon

Originally positions in the classroom were desired to be calculated with a trilateration scheme like the one shown in Figure E.3. But, as shown by Grzechca et al. (2016), the readings from an iBeacon's RSSI values are highly dependent on factors like orientation, so they are not reliable for high accuracy triangulation inside a classroom.

To handle this situation and still use the benefits of the iBeacon technology, proximity zones were defined around the iBeacons placed in the classroom like in Figure E.4. This way, when the ball was thrown into one of these zones, the software could update its new checkpoint and add a new data position to the trajectory.



**Figure E.3:** Trilateration based on readings from different beacons. Retrieved from [GitHub](#)



**Figure E.4:** iBeacon zones for immediate proximity. Retrieved from [Estimote](#).

## E.4 Drawing of Velocity Curves in the Conveyor Belt

Activities from the second module of the course planning (Appendix [B.2](#)) required to plot the velocity curves of the ball in each experiment, alongside the distance traveled over time. The iBeacon technology has a high latency between each sample so it's not useful for trying to measure the position of fast moving objects, such as the ball falling from a ramp. Despite this complication, the experiments had known constraints and would be replicated in the same way each time, so the outcome would be known beforehand and the plots could be pre-calculated based on the principles shown in Appendix [G](#).

Empirical falling times were measured for each scenario and the following formulas were used to plot each curve (A,B,C) in the interface (Figure [3.4](#)):

$$X_A(t) = -\frac{1}{2} \cdot 35.97t^2 \quad (1)$$

$$X_B(t) = -57.85 t \quad (2)$$

$$X_C(t) = -\frac{1}{2} \cdot 25.71t^2 \quad (3)$$

## APPENDIX F RESULTS FROM THE FOCUS GROUP

**Table F.1:** Findings from the students' commentaries about the classes, their role in the class, the cyber-physical ball, its relevance (part 1).

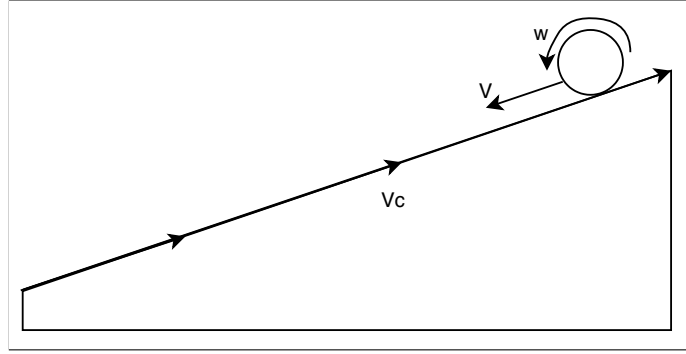
Category	Findings	Quotes
(1) Valuation of the classes	<ul style="list-style-type: none"> <li>Students have a positive valuation when classes are fun and dynamic.</li> </ul>	<p>S1: <i>"What I liked the most was that the teacher did dynamic classes"</i></p> <p>S2: <i>"The classes were fun"</i></p> <p>S3: <i>"(the classes) changed the routine"</i></p>
(2) Valuation of the cyber-physical ball in the classroom	<ul style="list-style-type: none"> <li>Students appreciate when teachers use different resources in class.</li> <li>100% of the students from the focus group prefer the activities with the cyber-physical ball over everything else.</li> </ul>	<p>S1: <i>"(The ball) is something completely different to the classes from the other teachers"</i></p> <p>S2: <i>"(The ball) is kinda different, but at the same time I think it allows for better understanding"</i></p> <p>S3: <i>"I like it because its kinda more practical"</i></p> <p>S4: <i>"The ball is more practical than theoretical"</i></p> <p>S5: <i>"The experiments had an impact in our learning process, that is, we learned quicker"</i></p> <p>S6: <i>"The ball allowed you to see everything not just in a theoretical way, but also like you see things from another point of view"</i></p>

**Table F.2:** Findings from the students' commentaries about the classes, their role in the class, the cyber-physical ball, its relevance (part 2).

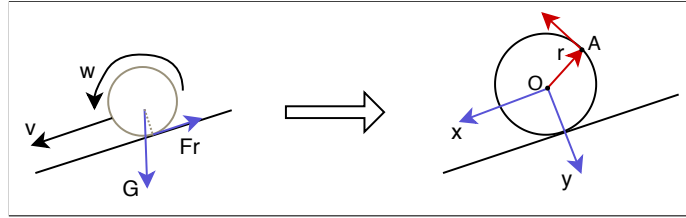
Category	Findings	Quotes
(3) Relationship of the concepts with the activities	<ul style="list-style-type: none"> <li>Students are able to connect the physics concepts with the experimental activities.</li> </ul>	<p>S1: <i>"With the was ball, it was like, you integrated everything you saw before... like you confirm it"</i></p> <p>S2: <i>"Everything made sense"</i></p>
(4) Role of the students	<ul style="list-style-type: none"> <li>Students want to be included by the teachers to have an active role in the classroom.</li> </ul>	<p>S1: <i>"I find it better for teachers to make us part of their classes, that not just them are talking, that we also have say what we think, what we understand and how hard it is for us"</i></p> <p>S2: <i>"I think, that maybe all teachers can learn from their colleagues, because there are teachers that are like... like they talk all the time and classes becomes more boring, but if they could... I don't know, if one of them could look to the side and say &lt;I like how she does her classes&gt;... Like, more dynamic, that makes students participate, I think that'd be better"</i></p>
(5) Importance of innovation and technology	<ul style="list-style-type: none"> <li>Students want that their teacher incorporate technology in the classroom.</li> </ul>	<p>S1: <i>"Because one is more accustomed to technology"</i></p> <p>S2: <i>"With technology its easier to understand"</i></p> <p>S3: <i>"Because you only see the volleyball ball, but it sent signals to other devices through Bluetooth, so it was cool"</i></p>
(6) Perception of the ball in the real world	<ul style="list-style-type: none"> <li>Students recognize the ball as a real object that can be interacted with.</li> </ul>	<p>S1: <i>"(the ball) had pulse"</i></p> <p>S2: <i>"You could reanimate it, you could let it die"</i></p>

## APPENDIX G DERIVATION OF VELOCITY AND ACCELERATION CURVES

In the third scenario of activities related to the conveyor belt (Appendix B.2), the ball is subject to both the effects of gravitational force and an opposing force from the conveyor's spin. This situation is portrayed in Figure G.1 and Figure G.2.



**Figure G.1:** Ball rolling down against the spin of the conveyor belt.



**Figure G.2:** Reference system and external forces over the ball.

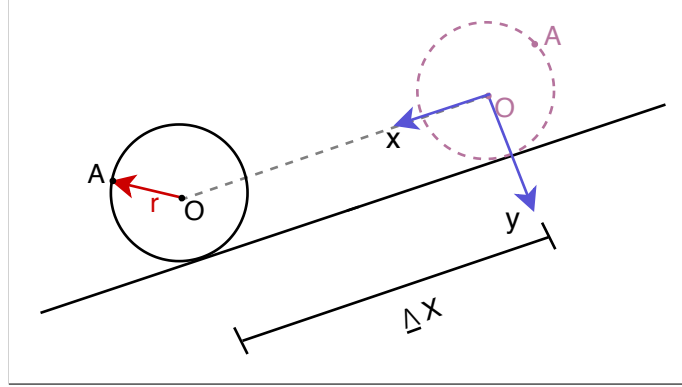
The position of a point  $A$  at the edge of the ball, relative to the origin  $O$  is:

$$\overrightarrow{A_{rel}} = r \hat{\rho} \quad (4)$$

This way, and as shown in Figure G.3, its absolute position in the  $XY$  reference system is given by:

$$\vec{A}_{abs} = r\hat{\rho} + \vec{O} \quad (5)$$

$$\vec{A}_{abs} = r\hat{\rho} + x\hat{x} \quad (6)$$



**Figure G.3:** Position of point  $A$  after the ball travels a distance  $\Delta x$ .

Then, the velocity is calculated as:

$$\frac{d\vec{A}}{dt} = \frac{d(r\hat{\rho})}{dt} + \frac{d(x\hat{x})}{dt} \quad (7)$$

$$\frac{d\vec{A}}{dt} = r\frac{d\hat{\rho}}{dt} + \frac{dx}{dt}\hat{x} \quad (8)$$

$$\frac{d\vec{A}}{dt} = r\frac{d\theta}{dt}\hat{\theta} + \frac{dx}{dt}\hat{x} \quad (9)$$

If we assume that the ball does not slip, then the horizontal displacement must be equal to the distance traveled with each rotation. That is:

$$\Delta x = r\Delta\theta \quad (10)$$

$$\frac{dx}{dt} = r\frac{d\theta}{dt} \quad (11)$$

$$\frac{dx}{dt} = r\omega \quad (12)$$

Then, the velocity of the point  $A$  can be written as:

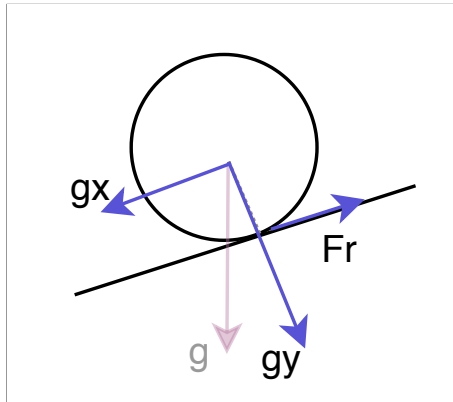
$$\frac{d\vec{A}}{dt} = r \frac{d\theta}{dt} \hat{\theta} + \frac{dx}{dt} \hat{x} \quad (13)$$

$$\vec{V} = r\omega \hat{\theta} + r\omega \hat{x} \quad (14)$$

And the translational velocity, i.e. the component projected on the  $x$  axis, is equal to  $r\omega$ . To get the value of  $\omega$ , we need to analyze the forces that act on the ball shown in Figure G.2. The gravitational force  $g$  can be decomposed on its projections over the  $XY$  axes, as shown in Figure G.4. With this in mind, the only forces acting in the  $x$  axis are  $g_x$  and  $F_r$  which both can be considered constant for the duration of the fall. Then, the situation is similar to a free fall where the velocity grows in a linear way and the curves can be derived from solving:

$$x(t) = x_0 + v_0 t + \frac{1}{2} a_0 t^2 \quad (15)$$

Where parameters  $x_0$ ,  $x(t_f)$ ,  $v_0$ , and  $t$  are known from empirical testing.



**Figure G.4:** Projection of the gravitational force  $g$  on the  $XY$  axes.