



UNIVERSITÀ DEGLI STUDI DI TRENTO
DEPARTMENT OF PHYSICS

Final Thesis submitted to the
DOCTORAL SCHOOL IN PHYSICS - XXX CYCLE

Digital Physics Education

Personal devices, mediated reality, serious gaming



SUPERVISORS

Stefano Oss

Pasquale Onorato

CANDIDATE

Tommaso Rosi

Academic year 2016/2017



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INDEX

INTRODUCTION.....	1
RESEARCH FRAMEWORK.....	3
I.1 Scientific visualization as a teaching tool.....	5
I.1.1 An introduction to visualization.....	6
I.1.2 Educational visualization software.....	19
I.1.3 Students and teachers coding software.....	21
I.2 Personal devices as an educational technology.....	24
I.2.1 Using personal devices for visualizations.....	24
I.2.2 A physics laboratory in your pocket.....	27
I.2.3 Smartphones and tablets cameras as measuring tools in physics laboratories.....	31
I.2.4 Boosting interaction with educational technology: using mobile devices as clickers.....	39
I.3 Mediated reality.....	41
I.3.1 Reality Mediators.....	41
I.3.2 Virtual Reality.....	43
I.3.3 Augmented and Mixed Reality.....	44
I.4 Serious Gaming.....	48
I.4.1 Software.....	48
I.4.2 Hardware.....	54
THE SCIENTIFIC VISUALIZATION WORKSHOP @UNITRENTO.....	57
II.1 Workshop description.....	58
II.2 Contents.....	58
II.3 Response.....	60
II.4 Implementation.....	61
II.5 Results.....	64

II.6	Feedbacks and comments	68
II.7	Survey to non-attendant students	69
II.8	Discussion.....	69
SPECTROSCOPY WITH SMARTPHONES		71
III.1	Introduction.....	71
III.2	Colors and spectra	72
III.2.1	How a PC display works: the RGB additive model	74
III.2.2	How a printer works: the CMYK subtractive model.....	76
III.3	The spectrometers	77
III.3.1	How to make your hand-made spectrometer.....	77
III.3.2	Calibration procedure	78
III.4	Measurements and results.....	81
III.4.1	Light sources	81
III.4.2	Additive mixing: emission from a PC monitor.....	82
III.4.3	Subtractive and additive mixing: transmission spectra of laser printer colored strokes	85
III.5	Using the apparatus with students and teachers	89
III.6	Discussion	91
THE AUGMENTED LABORATORY		93
IV.1	3D reconstructions of physical environments	94
IV.1.1	From depth matrices to 3D reconstructions.....	95
IV.1.2	Computer vision: object recognition and tracking	97
IV.2	Multiple object, three-dimensional motion tracking	99
IV.2.1	Data analysis	100
IV.2.2	Quasi-elastic collisions: center of mass motion and conservation of linear momentum	101
IV.2.3	3D tracking of bolas: center of mass motion and conservation of angular momentum.....	103
IV.3	Augmented reality.....	104
IV.4	Augmented simulations.....	106
IV.4.1	Motion of virtual particles in a physical environment	106

IV.4.2 The augmented ripple tank.....	107
IV.5 Testing the setup	109
IV.5.1 Testing the setup with aspiring teachers	109
IV.5.2 The “Toys and Science” exhibition	113
IV.6 Future developments	116
CONCLUSIONS.....	117
BIBLIOGRAPHY	143

Introduction

The main goal of Physics Education is the development of techniques and pedagogical strategies that may help students understanding physics. Research in this field needs to take into account the entire spectrum of required skills and competencies of good teachers, which is quite rich. In fact, not only they need to master the contents, but also to be prepared from a pedagogical perspective, to have good communication abilities, capability of assessing students learning, and so on. Teachers today also need to face another fundamental challenge: staying in touch with the outside world, and keeping up with the world. Technology is advancing at an impressive and increasing rate, having a profound influence on individuals and society. Both the current and future generations are and will be exposed to these technologies, they will be required to use them, and therefore they will need the right tools to be able to do so in the most constructive and positive way as possible.

How should an educator respond to such demands? Which new equipment should be used in education? Which activities and methodologies need to be redesigned or even replaced by new ones?

These are not simple questions, and there will never be definitive answers because of the continuous introduction of new devices in our lives. What we can be certain of are two different things. On one hand, the use of new technologies in classroom does not automatically translates into better teaching/learning activities. If poorly used, they might even be detrimental. On the other hand, as a large and growing literature has proven, it can be very rewarding and beneficial if correctly used, hence the great importance of carrying on research in this field.

This is certainly most true for physics education, as physics is strongly related to technology: it requires hands-on experiments, measurements, data acquisition, data analysis and visualization; physics research also naturally translates into new technologies, an aspect that may be used to more naturally connect theory with our everyday lives.

In this work we discuss some of the most interesting new doors that the diffusion of low-cost, high-tech devices is opening. It is divided in two main sections.

In the first part, Chapter I, the general research framework in which we are working is presented. Then, in the second, third and fourth chapters several examples of practical applications regarding the presented topics, all designed and realized by the author

(within his research group) are discussed. In particular: a workshop about scientific visualization held at the University of Trento in Chapter II; a teaching/learning sequence based on a low-cost spectrometer in Chapter III; a mediated reality setup for physics education in Chapter IV.

Chapter I

Research framework

The general research framework of this work is the Technological, Pedagogical And Content Knowledge (TPACK) framework specifically applied to physics education. Its basic assumption is that there are three fundamental forms of knowledge that teachers can refer to – Content (CK), Pedagogy (PK), and Technology (TK) – and that educational activities must be designed by considering the complex interplay of these three knowledge bases [1] [2].

Content Knowledge includes theories, concepts, state-of-the-art research and findings, common practices and approaches [3]. Pedagogy Knowledge includes everything regarding teaching and learning processes, such as educational overall goals, students general and specific difficulties, misconceptions, classroom management, planning and evaluation. Technology Knowledge includes everything related to possible uses of technology: knowledge of devices, tools, resources, the pros and cons of using them, the ability of recognizing if technology can help or on the contrary get in the way of reaching a certain achievement, not to mention to continually adapt to evolutions of technology.

Most of all, the TPACK framework recognizes the importance of being aware of all the possible interconnections and intersections of these three forms of knowledge (PCK, TCK, TPK and TPACK), and to emphasize and study them.

“Underlying truly meaningful and deeply skilled teaching with technology, TPACK is different from knowledge of all three concepts individually. Instead, TPACK is the basis of effective teaching with technology, requiring an understanding of the representation of concepts using technologies; pedagogical techniques that use technologies in constructive ways to teach content; knowledge of what makes concepts difficult or easy to learn and how technology can help redress some of the problems that students face; knowledge of students’ prior knowledge and theories of epistemology; and knowledge of how technologies can be used to build on existing knowledge to develop new epistemologies or strengthen old ones” [1]

Research framework

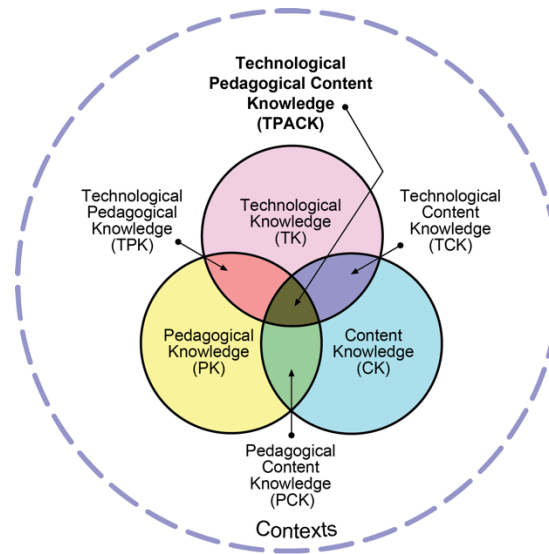


Figure I-1. Scheme of the Technological, Pedagogical and Content Knowledge framework.¹

Moving in this framework, a series of activities, software and setups were designed and developed by the author (within his research group – the Laboratory of Physical Science Communication of Trento, Italy [4]), which will be discussed in following Chapters. Here we will now focus on four different but interconnected topics related to the use of new technologies in physics education which are the basis of those products, which are: scientific visualization, personal devices, mediated reality and serious gaming.

In section I.1 we will present **scientific visualization**, which is the graphical illustration of scientific data. It is used by scientists to both glean insight about phenomena and to better communicate the results of their research, and as it will be seen, it is also a very powerful tool for physics education.

Section I.2 is dedicated to **personal devices**. This general term includes devices such as laptops, which are very common in some contexts such as universities. The emphasis will nonetheless be put on smartphones and tablets. In fact, they feature many points of strength regarding their possible uses in physics lessons and activities, including low-costs, their ongoing diffusion and the number of built-in, high-quality sensors they come with.

¹ Reproduced with permission of the publisher, © 2012 by tpack.org

In I.3 **mediated reality** will be presented. This is a term that is rarely heard outside the research community. Related terms that people are at same extent more familiar with are *virtual reality* and *augmented reality*. *Mediated reality* is a broader term which includes virtual, augmented, mixed and modulated realities. Due to recent technological advancements the devices used in mediated reality setups are becoming more affordable, and tools for related software development have grown. These advancements result in renewed interest of physics education to this topic. In particular, the world of gaming invested a lot in this kind of research, which leads us to the topic of the last section.

In fact, section I.4 is about **serious gaming**. This term today may refer to any activity or product which is strongly based on gaming technology whose purposes are not only entertainment related. This includes the direct use of games themselves, of software used to develop games (game engines), or hardware. In fact, there are many low-cost devices developed for gaming which have many high-quality sensors which may be used in physics activities.

I.1 Scientific visualization as a teaching tool

Images have played a fundamental role in the history of scientific thought. They can synthesize huge amount of information (sometimes an image really is worth a thousand words) and they also help developing new levels of abstraction of problems. In the past centuries, scientists have often been artists too, and their notes and books are rich of sketches and drawings. Illustrations were used to help the understanding of non-expert readers; they were used in private correspondence between scientists themselves; and they were certainly drawn in notebooks and laboratory workbooks.

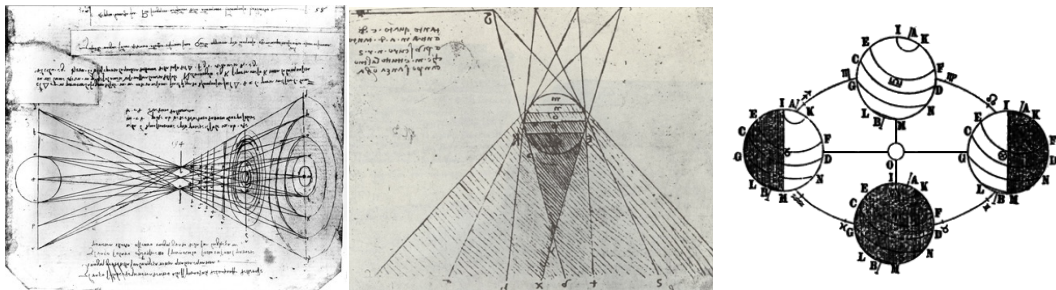


Figure I-2. (Left and center) Optical studies from Leonardo da Vinci's notebooks. (Right) Galileo Galilei – *Dialogo sopra i due massimi sistemi del mondo*.

Research framework

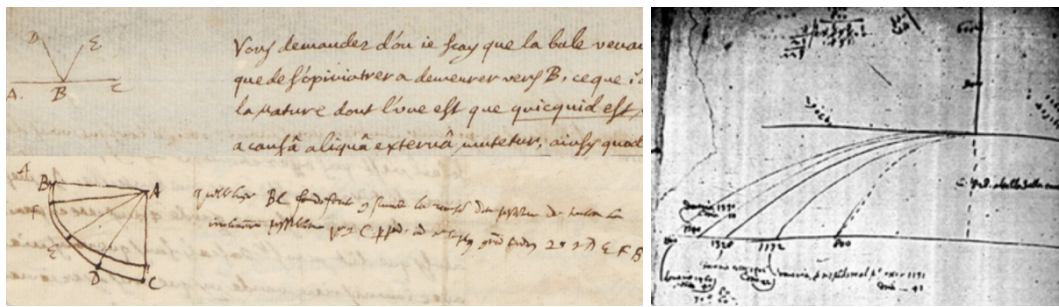


Figure I-3. (Left) René Descartes – Letters to Mersenne. (Right) Galileo Galilei's laboratory sketches.

The role of images in science has not fundamentally changed today. What drastically evolved are the techniques and tools used to create such images. On one hand, the diffusion and the consequent lowering of costs of new technologies makes them more and more part of our everyday life. On the other hand, the advancements in research of new devices and interfaces transform and create new ways of doing and communicate science. Today more than yesterday, images can represent effectively and easily experimental data, mathematical objects, results of simulations and very large amount of information. Digital images allow to see the invisible and the abstract. As a result, scientists, science teachers and communicators need to be more and more familiar with the visual language.

Visualization of scientific data is important for any aspect of digital physics education, whether we are discussing the use of computers, smartphones, mediated reality apparatuses, and so on. We then start this work with the introduction of this topic and its interests from the perspective of physics education. In the first part of this section we give a brief and general introduction to scientific visualization. In the second and third parts we introduce two different aspects of visualization (and software coding in general) in education. Firstly, we discuss the use of software visualization in this context, so we refer to teachers and communicators as users. Secondly, we change point of view and consider teachers and students coding software.

1.1.1 An introduction to visualization

In the first part of this section we intend to familiarize with the concept of digital images and how they are reproduced by digital devices. To do this, a general overview about color models is given first. We then proceed by providing a list of examples of different kinds of visualizations, whose classification is based on the characteristics of the data which needs to be visualized.

COLOR MODELS

A *color model* is an abstract mathematical model which associates to a numerical vector an element of a *color space*, often using three or four values to determine its chromatic components [5]. Note that here the term “color” will be used referring to *perceived colors*, not only to *spectral* ones. A common misconception about color reproduction regards the so-called “primary colors”. In fact, asking a high-school student (or the majority of the population) which are the “primary colors”, she/he will probably answer that they are red, yellow and blue or red, green and blue. This happens because they are thinking about what they studied at the art class in primary school, in the first case, or because they already studied something about the RGB model used for color reproduction of monitors, in the second case. Point is, there are no such things as primary colors in nature. There is, on one hand, a very complex series of phenomena which we can refer to as “**human perception of colors**”² (which also can be very different from an individual to another). And there are, on the other hand, different color models that have been designed and improved (by

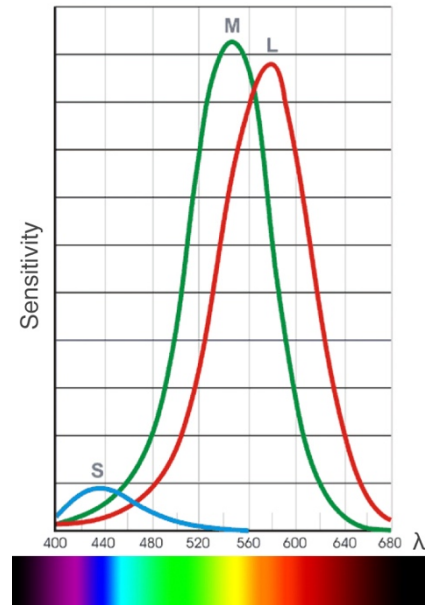


Figure I-4. Spectral sensitivity of cones, one of the two kind of photoreceptor cells in the human retina.

²The **photoreceptor cells** in our retina are a specialized type of neurons which are capable of *phototransduction*, meaning they convert light into electrical signals which stimulate various biochemical processes. There are two main kinds of photoreceptors, rods and cones, which show several functional differences.

Rods are so sensitive they can be triggered by as low as about six photons [9], but in return have a slow response to light and confer an *achromatic vision*: they are responsible for the so-called *scotopic vision*, which means vision under very low light conditions.

The **cones** instead underpin the vision under high light conditions, or *photopic vision*, and are of interest here as they confer color vision to humans (and some animals too). This is made possible by the presence of three different kinds of cones, each one characterized by its own sensitivity to different wavelengths and more sensible to **red**, **green** and **blue** respectively. Any monochromatic visible electromagnetic wave will then result in a different stimulation of the three types of cones which will then determine the resulting perceived color.

Research framework

humans, for humans) in order to allow painters, scribes, printers, computer monitors, projectors, light sources, to reproduce an enormous number of different colors only by mixing a finite number of colors. But it needs to be clear that these are ways of deceiving human perception. Just to make two simple examples: we may perceive a mix of red and green light as the spectral color yellow, but this mixing is fundamentally different from the spectral color even if our perception of them is the same; also, there are perceived colors that do not correspond to any spectral colour at all, such as purple.

It is therefore interesting to investigate color reproduction methods by a quantitative point of view – meaning removing the human perception of colors: of course, this means to do some spectroscopy, from which students (along with everyone else) can understand a lot more on color models. A teaching/learning sequence about the study of colors using a low-cost, home-made spectrometer is discussed in Chapter III.

The two most widely used color models are the RGB and CMYK models. The former is commonly referred to as an additive color model, while the latter as a subtractive one, but notice that (as it will be better discussed in Chapter III) “subtractive color model” is a very misleading term.

The **RGB** (**R**ed, **G**reen, **B**lue) color model is of great interest in digital reproduction of images, as it will be discussed in several sections of this work. It is based on the idea that starting from black, a certain amount of red, green and blue may be added to obtain “any” other color, or let us say the largest variety of different perceived colors as possible. This is of course a consequence of the spectral sensitivities of our cone cells (Figure I-4). An identical value of the three color components will result in a certain shade of grey: when the maximum value is reached, the so-called “white color” is obtained.

The **CMYK** (**C**yan, **M**agenta, **Y**ellow and **B**lac**K**) color model is instead the one used by printers. By laying down the right amount of CMYK pigments on white paper, the printer is able to reproduce a very large amount of different colors. Unlike the RGB color model, which is designed to be used in devices based on light emission such as monitors and projectors, this model is based on studies regarding the reflection of light by pigments and their mixing.

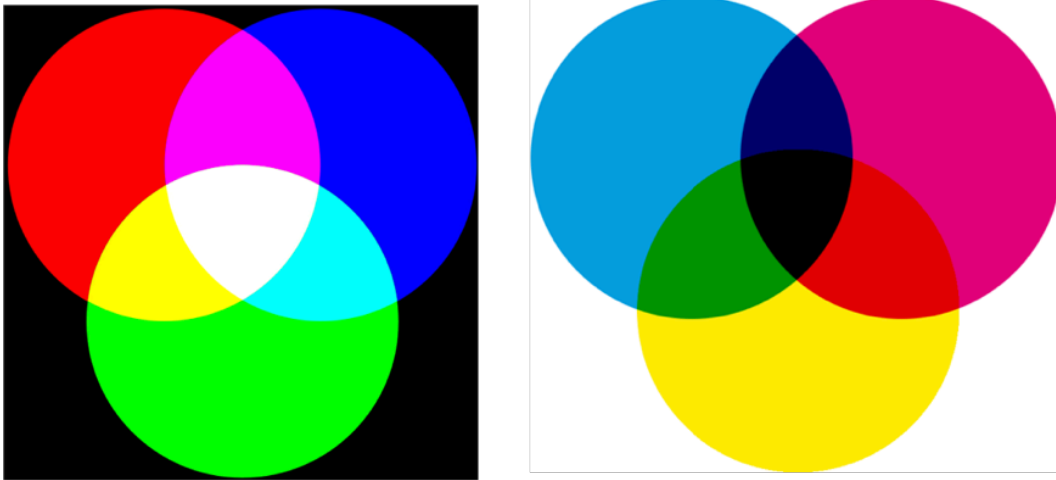


Figure I-5. Simple representations of the RGB and CMYK color models.

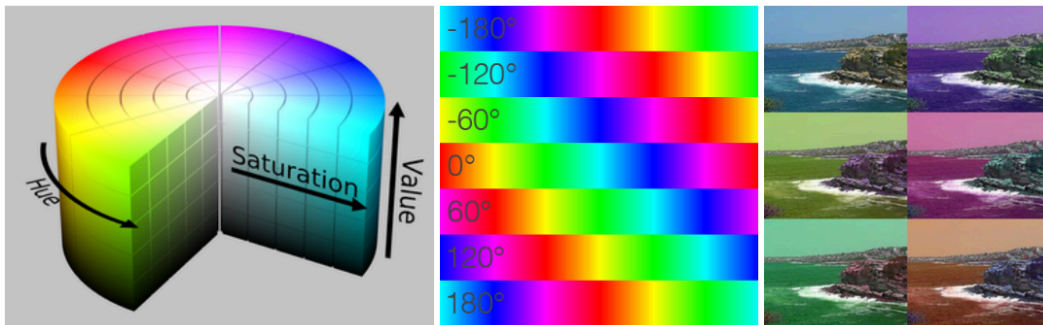


Figure I-6. Another very common color model is the HSV (Hue, Saturation, Value) model. A rotation of the hue coordinate corresponds to a change of colors without affecting the brightness and the saturation of the image.

DIGITAL IMAGES

We shall now introduce the basics of digital reproduction of images. There are two kind of images: bitmaps and vector graphics. The latter is based on mathematical formulas describing the shapes forming the image: this approach has the main advantage of not losing resolution regardless of how much we zoom in it. Vector graphics is for example generally used for fonts. But we are not going into details of vector reproduction of images, as we are more interested in bitmaps. In fact, they are by far the most common type of image, and they are more suitable to be used as an introduction to digital images.

A bitmap image is a 2D matrix whose elements correspond to certain colors. These elements (the image's *pixels*) contain the information which a device, let us say a

Research framework

computer, need to translate to the corresponding colors. As already mentioned, the RGB color model is used by monitors, as we can see using a cheap macro lens on any screen (Figure I-7, and more about this in Chapter III). The term *pixel* refers also to the physical elements of a monitor. Each one of them is composed by a triad of sub-elements: a red, a green and a blue one. The information contained in each *pixel* of the image is then used to determine the corresponding brightness of each of the RGB triad elements of the monitor.



Figure I-7. The *pixel* of an image, and the *pixel* of a monitor.

The term bitmap simply means a “map of *bits*”. A *bit* is the basic unit of information in computing, and it may only have two values: 0 or 1. A typical image (an 8-*bit*, RGB image) uses 24 bits for each pixel, corresponding to 8 *bits* for each of the RGB colors. Why 8? In the binary numeral system used by computers, 8 *bits* correspond to 256 different numbers. In fact:

$$11111111 = 2^0 + 2^1 + 2^2 + 2^3 + 2^4 + 2^5 + 2^6 + 2^7 = 255$$

meaning that using 8 *bits* each color coordinate (red, green, blue) may assume values ranging from 0 to 255. This correspond to $256 \times 256 \times 256 \approx 16,8 \times 10^6$ different colors. It is possible to use more *bits* for each coordinate (such as 16 or 32 instead of 8), but it generally is not useful as the human eye is not able to distinguish more colors. More-than-8-*bits* images are used for other purposes, such as image processing, in order to not lose important information during operations on the *bits*. Another common case in which more *bits* are used (32 instead of 24) is when a fourth coordinate is used, the so-called *alpha-channel*, which stores information about transparency of the corresponding pixels, allowing for example to have images – such as logos – with a transparent background.

A list of perceived colors and the corresponding 24-*bit* representation is given in the following table:

8-bits (R)	8-bits (G)	8-bits (B)	↔	colour
00000000	00000000	00000000	↔	Black
11111111	00000000	00000000	↔	Red
00000000	11111111	00000000	↔	Green
00000000	00000000	11111111	↔	Blue
00000000	11111111	11111111	↔	Cyan
11111111	00000000	11111111	↔	Magenta
11111111	11111111	00000000	↔	Yellow
11111111	11111111	11111111	↔	White

Table 1. 24-bit representation of a list of perceived colors.

3D RENDERING

There are various techniques that may be used to render 3D scenes. A very general and interesting one is the so-called *ray tracing* technique. It takes us back to 2500 years ago when the **emission theory of vision** was being supported by Pythagoras (and later by Euclid and many others): the proposal of this theory was that visual perception is accomplished by rays of light emitted by the eyes, similarly to the use by a blind person of a *white cane*^{3,4}.

The idea behind ray tracing is to set up a virtual three-dimensional world in which there is a *virtual camera* (Figure I-8). Between the camera and the objects to be represented a two-dimensional grid is delimited: the ray tracing technique shall define a specific color for each small area of the grid, which represent the pixels of the final rendered image.

³ This theory was contrasted by Democritus (c. 460 – c. 370 BC) who (besides formulating his famous atomic theory of the universe) proposed the theory of the *eidola*: images constantly being emitted by objects, which eventually encounter an eye and are thus perceived [88].

⁴ Recent statistics show that about 50% of American college students still believe in the emission theory [89].

Research framework

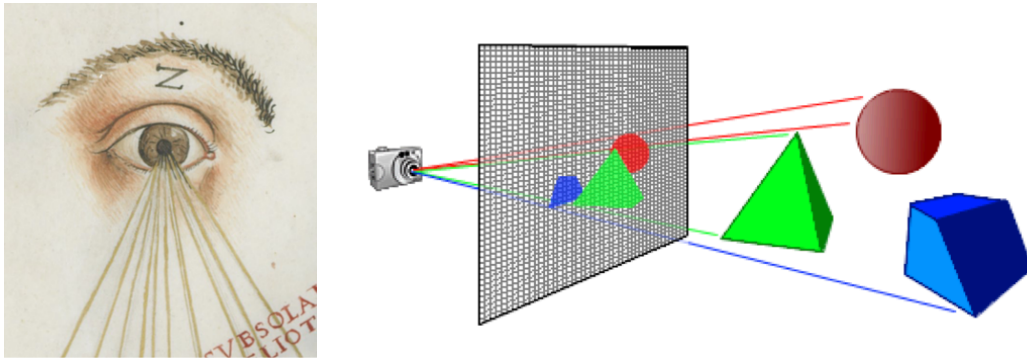


Figure I-8. Digital 3D rendering of images is based on techniques which remind the emission theory of vision.

How is each pixel's color determined? A ray is drawn from the virtual camera (also known as the *ray origin*) through the center of the pixel until it finds an object's surface. Many different calculations may now be made to get the final color. The simplest one just picks the defined object's color in that point, without taking into account lights, shadows, and optical phenomena: this *naïve* technique is usually referred to as *ray casting* (Figure I-9, left).

More advanced ray tracing methods make several other calculations. For example, from the point where the ray (which will now be referred to as the *primary ray*) “hits” a surface, a set of secondary rays called *shadow rays* are traced towards each light source: each of them checks if any opaque object is found before reaching the light, and if that happens the point will not be enlightened by that source. Moreover, other secondary rays may be cast, taking into account reflections and refractions, which may cast other rays and so on. Generally speaking, a good ray tracing algorithm is a recursive one which takes into account absorption, reflection, refraction and fluorescence phenomena. In addition, it may also simulate effects such as the *depth of field* and *aperture shape* (Figure I-9, right).



Figure I-9. (Left) Ray casting in a recent version of the classic *Wolfenstein* video game [153]. (Right) Result of a recursive algorithm in which each ray refracts and reflects multiple times. Caustic phenomenon can also be noticed. Camera effects such as *depth of field* and *aperture shape* are also here simulated.

An example of a technique that may be used to realistically represent 3D objects is the *Phong reflection model*, which is an empirical model for determining the local illumination of points on a surface (Figure I-10).

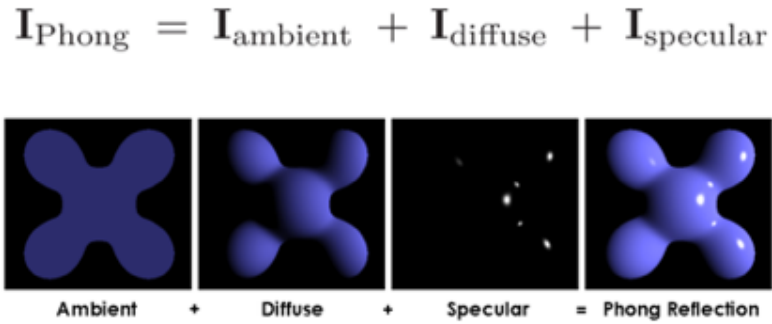


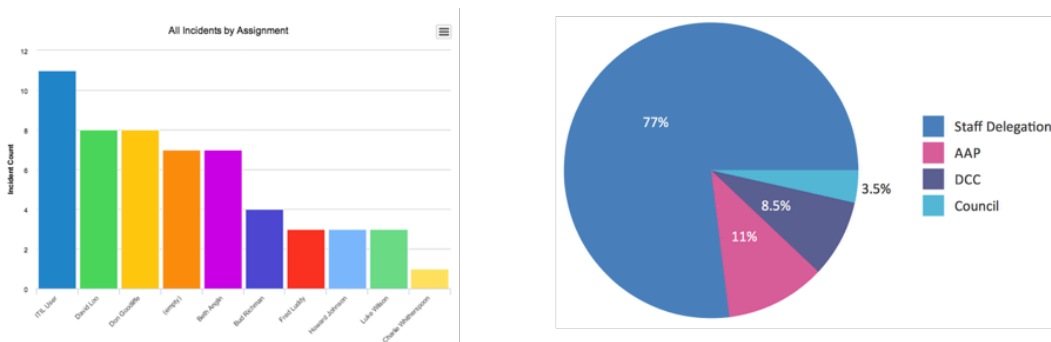
Figure I-10. The Phong reflection model.

EXAMPLES OF VISUALIZATIONS – DATA SPACE & DATA TYPE

We shall now see a small gallery of visualizations that may be used to represent scientific data. They are classified by the characteristics of the data themselves. In fact, in order to choose the most suitable visualization technique, we first of all need to ask ourselves: “where do the data ‘live?’”, and “which is the type of the data?”. The answers to these questions are called *data space* and *data type*. For example, a real-valued function over \mathbb{R}^2 lives in the \mathbb{R}^2 data space and have \mathbb{R} data type ($\mathbb{R}^2 \rightarrow \mathbb{R}^1$).

VALUE SERIES: $\mathbb{N}^1 \rightarrow \mathbb{R}^1$

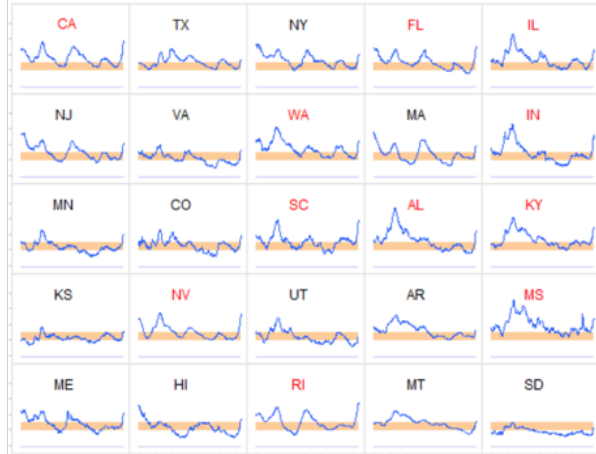
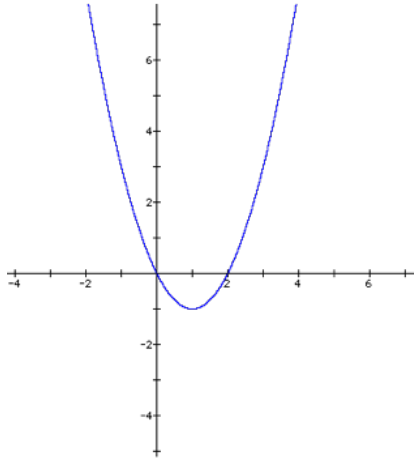
Visualization examples: bar charts, pie charts.



Research framework

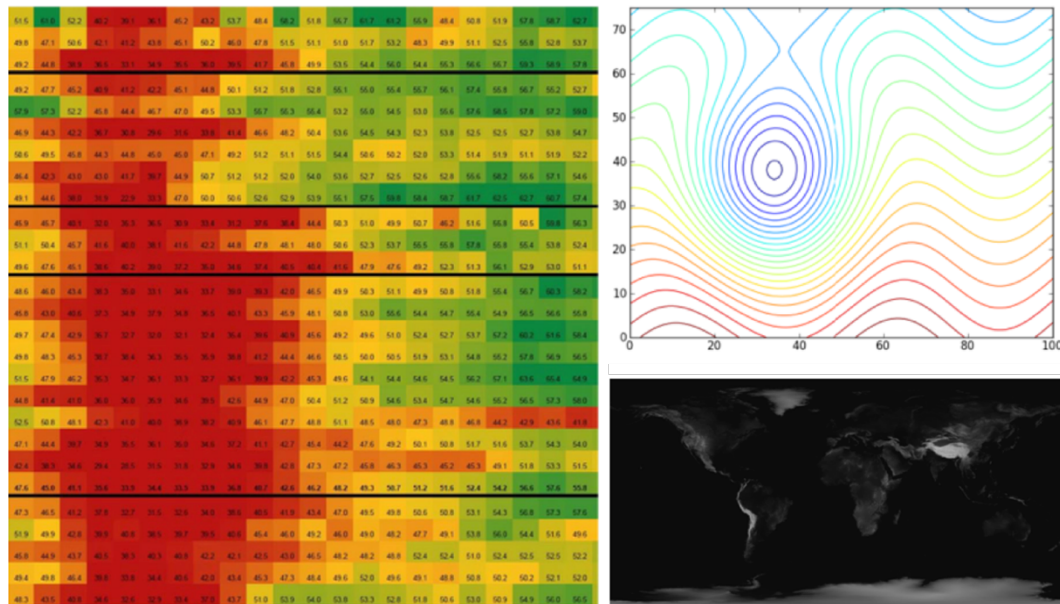
FUNCTIONS OVER \mathbb{R} : $\mathbb{R}^1 \rightarrow \mathbb{R}^1$

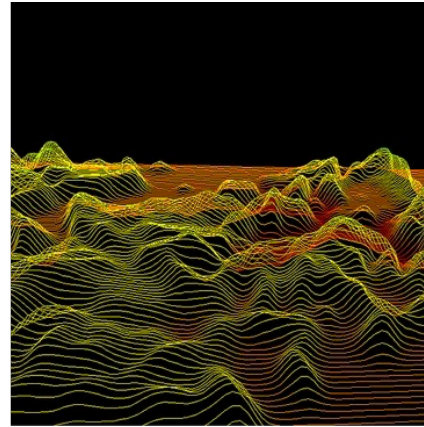
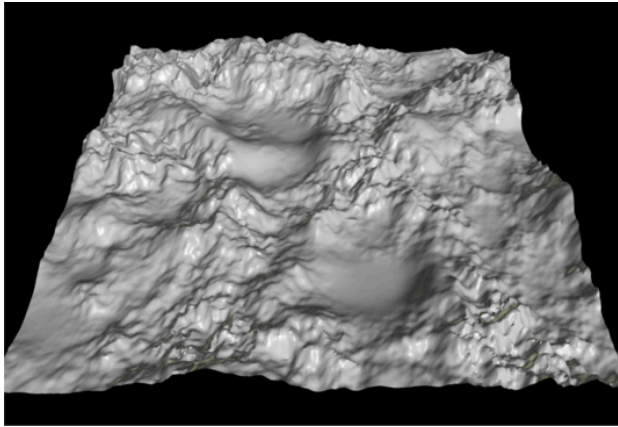
Visualization examples: line graphs, small multiples.



FUNCTIONS OVER \mathbb{R}^2 : $\mathbb{R}^2 \rightarrow \mathbb{R}^1$

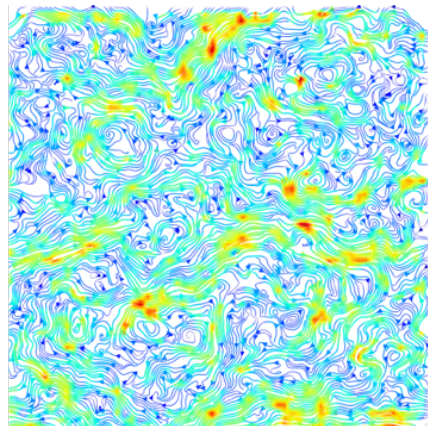
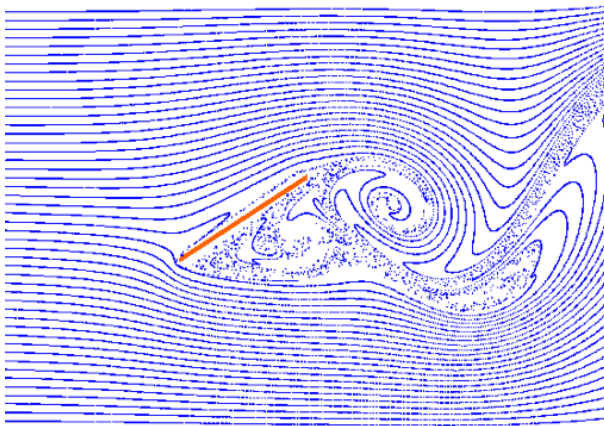
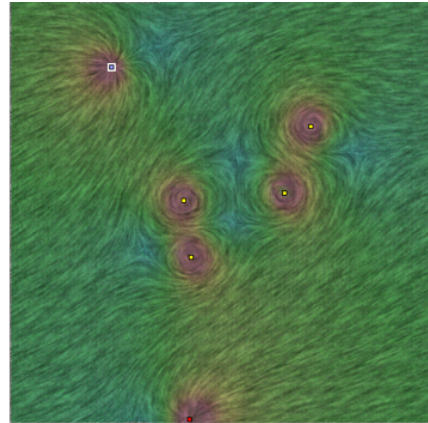
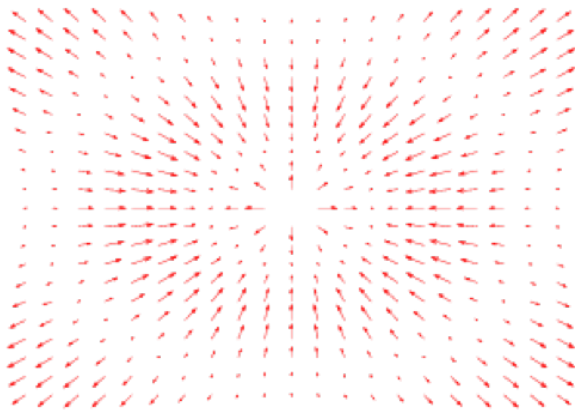
Visualization examples: heatmaps, contour lines, heightmaps (both 2D and 3D representations).





2D VECTOR FIELDS: $\mathbb{R}^2 \rightarrow \mathbb{R}^2$

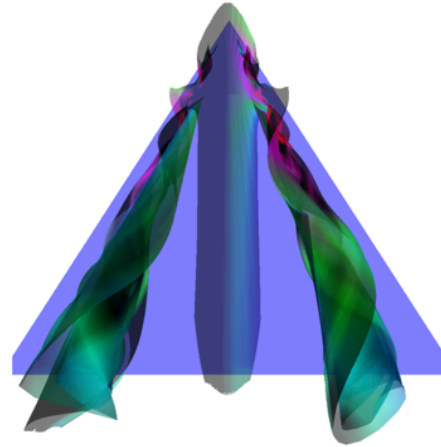
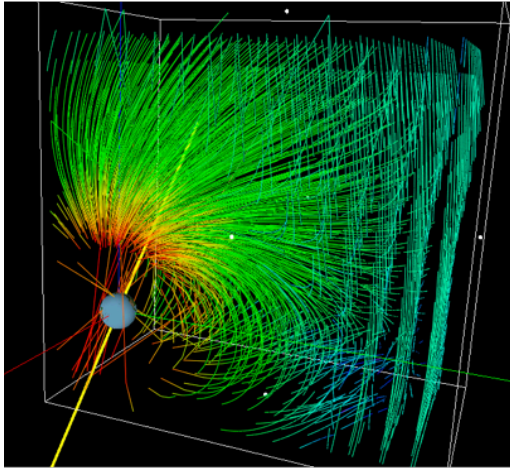
Visualization examples: quiver/hedgehog plots, Line Integral Convolution (LIC), streamlines, streaklines, pathlines, streamlets.



Research framework

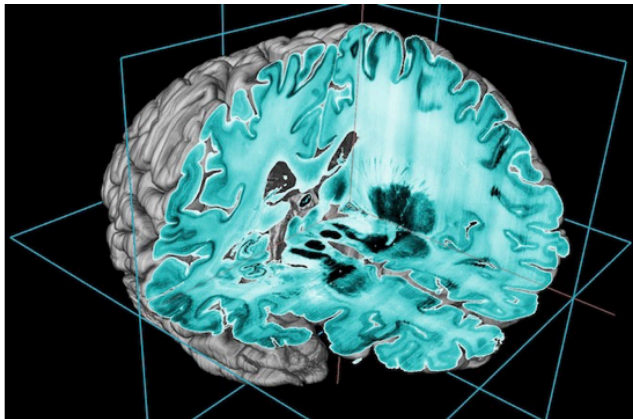
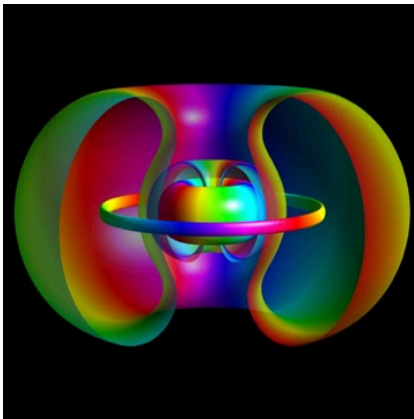
3D VECTOR FIELDS: $\mathbb{R}^3 \rightarrow \mathbb{R}^3$

Visualization examples: quiver/hedgehog plots, streamlines, streaklines, pathlines, streamlets, streamsurfaces.



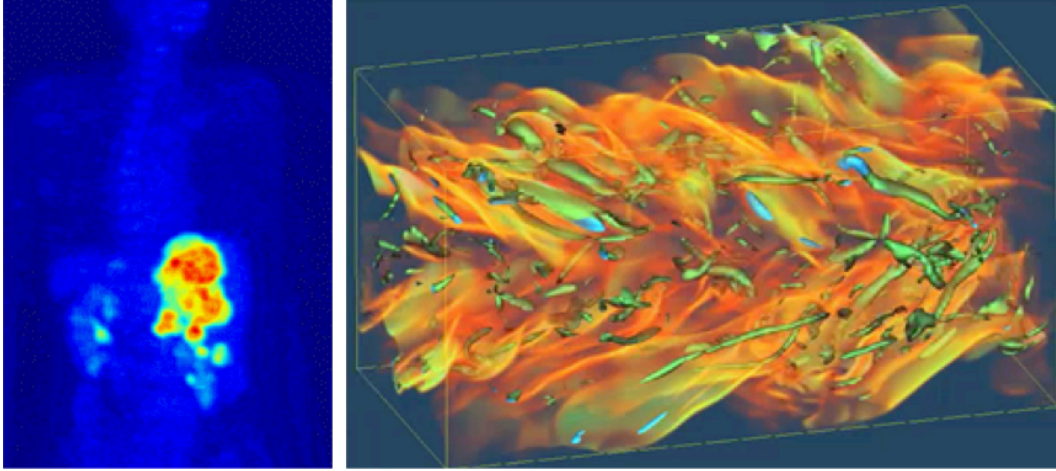
3D DENSITIES: $\mathbb{R}^3 \rightarrow \mathbb{R}^1, \mathbb{C}^1$

Visualization examples: isosurfaces, slicing.



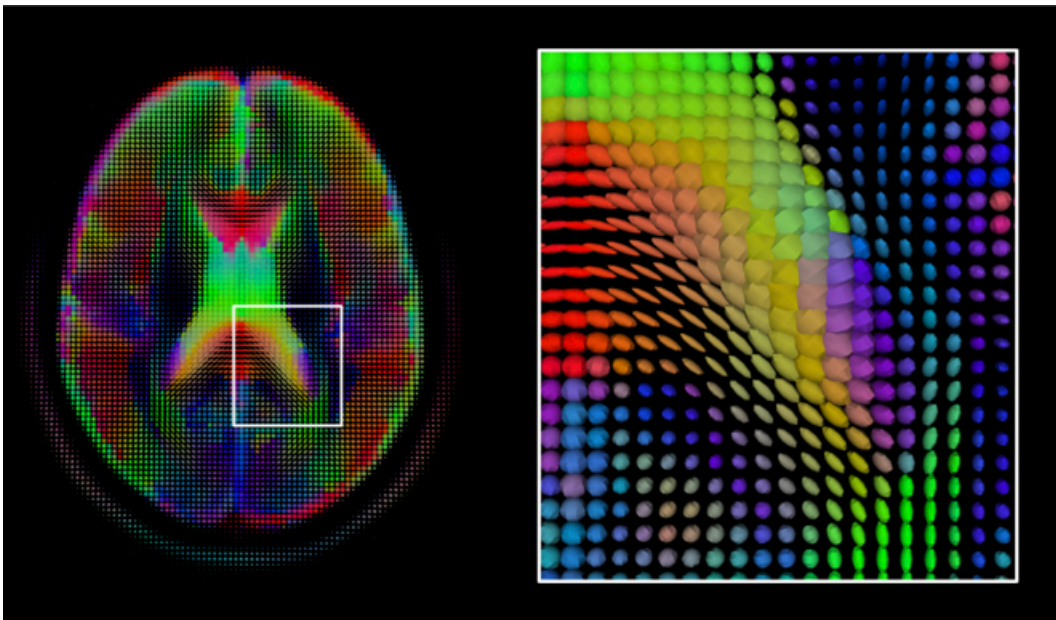
3D DENSITIES: $\mathbb{R}^3 \rightarrow \mathbb{R}^1$

Visualization examples: volume rendering, raytracing.



TENSORS: $\mathbb{R}^2 \rightarrow \mathbb{R}^2$

Visualization examples: hedgehogs, streamline, hyper-streamlines, 3D glyphs.



SIMULATIONS VS VISUALIZATIONS

We shall finish this section with a simple but important clarification. It is very common to hear the terms “simulation” and “visualization” used improperly. There are various explanations for this. First of all, the results of a simulation may be (and often are) visualized. Especially in education and in communication of physical science, whenever a simulation is referred to, a visualization of its results is generally implied. This leads to the improper use of the term “simulation”, used whenever some computer-generated image or animation is implied.

A simulation is an imitation of a mechanism behind a phenomenon. It requires the development of a model, designed to allow us to reproduce the behaviors of interest regarding the studied phenomenon. The results of a simulation are numbers, which may (or may not) be visualized.

A visualization on the other hand, simply refers to the visual representation of data or mathematical objects. The data can be the result of a simulation indeed, but can also be the result of a measurement.

Not every visualization is based on simulation data and not all simulations are visualized. For a physicist (or a scientist more generally speaking) this may sound rather obvious, for example because it is very common to us to be familiar with the field of computational physics, but this is something to keep in mind and be aware of when speaking to a non-specialized audience.

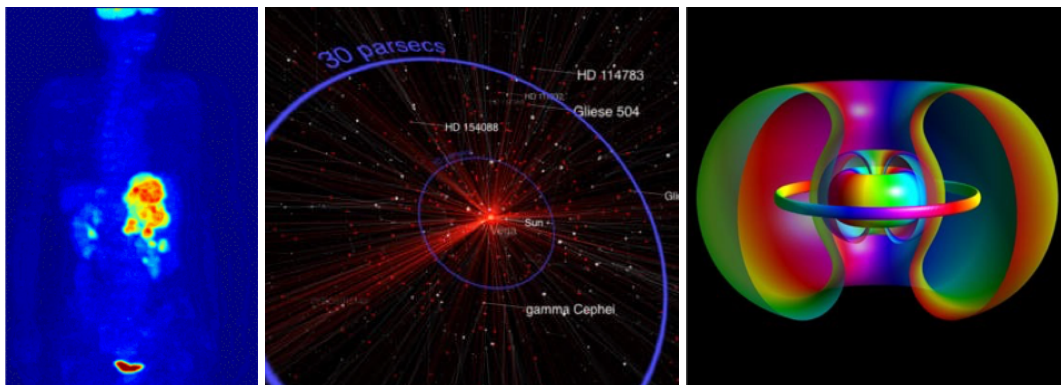


Figure I-11. Examples of visualizations that do not correspond to any kind of simulation. The first two images correspond to measured data, the third to a mathematical object.

I.1.2 Educational visualization software

In the last decades many beautiful projects regarding the use of visualization in science education has been carried on. Visualizations are very effective tools to grab the attention of students, to summarize huge amounts of information, and to present very complex concepts in an intuitive way.

Generally speaking, completeness, precision, visual appeal and simplicity are all important properties of a good visualization software. For physical science communication and education, a good software is often the result of a trade-off between completeness, precision and user-friendliness.

Mobile devices represent a new, fertile media for visualizations designed to be used in education, for various reasons. First of all, the teacher may use apps which can also be downloaded by students in a very straightforward way, so they can reuse them when needed. Additionally, smartphones are particularly interesting for physics education as they are “physics laboratories in your pocket” because of the large number of sensors they come with; and of course, the data they gather needs to be visualized in some way, so scientific visualization plays a central role here too. More about personal devices, in particular mobile devices, will be discussed in I.2.

In the following figures, a small collection of visualization software that is very interesting for physics education is presented. In particular, *Hydrogen!* is an educational app designed and developed by the author. It is an iOS app designed both to introduce and to help foster a deeper understanding of topics of very general interest for the study of quantum physics by using visualizations of the hydrogen atom’s orbitals. In fact, many authors outlined the students’ difficulties in the conceptual understanding of quantum physics, and one of the major problems is that students find the mathematical language used to describe these systems (that cannot be seen) generally too obscure. A lot of research has been done to use computer visualizations of quantum mechanical topics and it proved to be a powerful and flexible tool, allowing to see through the mathematics. A series of fundamental topics can be discussed taking serious advantage of the use of *Hydrogen!*, such as: the concept of a wave function, the correspondence principle, superposition, stationarity and spectroscopy. More about these topics may be found at [6].

Research framework

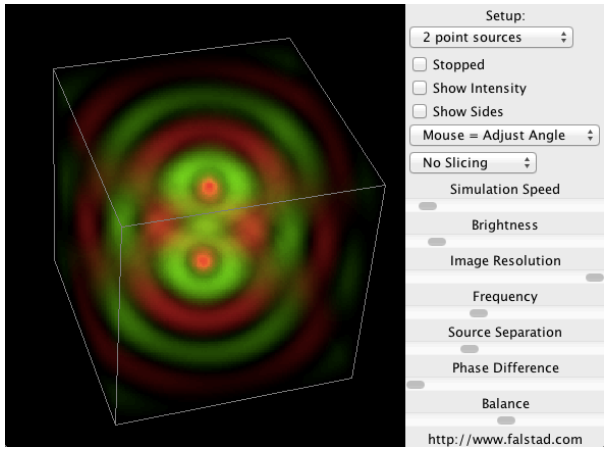


Figure I-12. 3-D Waves Applet by Paul Falstad. [142]

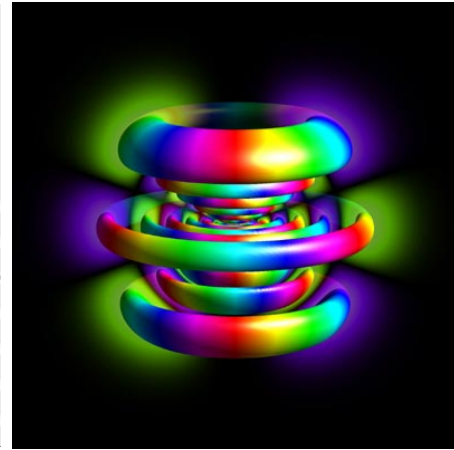


Figure I-13. Visual Quantum Mechanics by Bernd Thaller. [143]

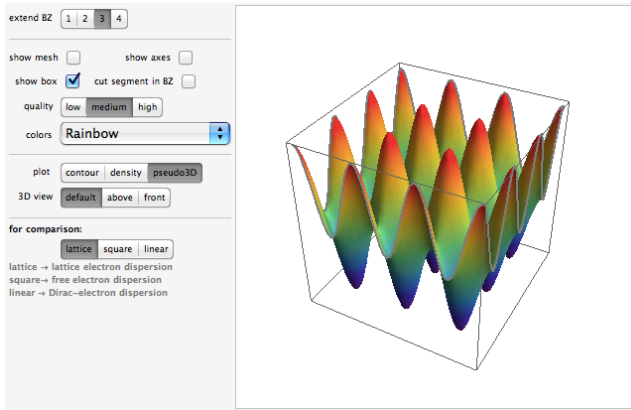


Figure I-14. Brillouin Zone of a 2D Square Lattice: Tight Binding Approximation, part of the applet collection Wolfram Demonstrations Project. [150]

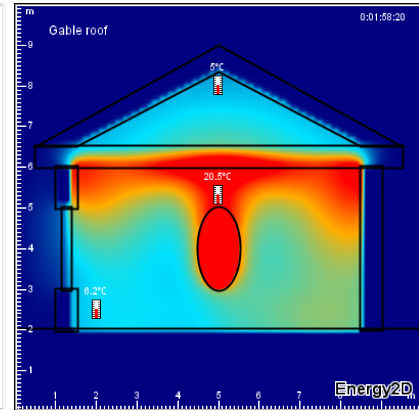


Figure I-15. Energy2D by Charles Xie. [144]

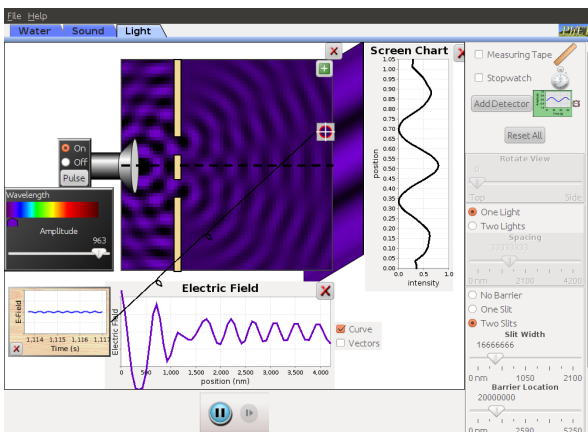


Figure I-16. “Wave Interference” and “Radiating Charge” applets, part of the applet collection PhET – The Physics Education Technology Project. [145]



Figure I-17. "Hydrogen!" by Tommaso Rosi. [146]

I.1.3 Students and teachers coding software

“Computational thinking is the thought processes involved in formulating a problem and expressing its solution(s) in such a way that a computer—human or machine—can effectively carry out.” [7]

Computational thinking is an intellectual framework offered by computer science which all can benefit from. It is an iterative process requiring abstraction of a problem, a formulation of a possible solution, an execution of the solution and an evaluation of the outcomes. Its main focus is on conceptualization, not the execution. Computer science is often thought of as simply computer programming, but it is not.

“Thinking like a computer scientist means more than being able to program a computer. It requires thinking at multiple levels of abstraction.” [8]

For these reasons, computational thinking is more and more widely recognized as a fundamental skill, a skill that everyone should be trained to. Of course, software coding is the natural framework to help anyone develop it. The introduction or enhancement of programming lessons in secondary and even primary schools then is (or should be) a priority.

The first obstacle to promote such activities is of course the lack of preparation of current teachers. Very little can often be done to overcome this problem, even though training courses can certainly help. What needs to be done instead, is to promote activities to introduce computational thinking for all **future teachers and students**.

Much effort has been put into the development of software that could be used to introduce coding and computational thinking. One approach is that of designing programs that allow to remove as many programming knowledge needed (such as

Research framework

syntax-related) as possible in order to focus on content creation. For example, there are multiple software now based on **visual programming languages** (VPLs). A VPL allows users to create their own software by interacting with graphical elements instead of writing textual code. In the last years VPLs have been improved a lot and are nowadays used by advanced software such as gaming engines, media editors and even simulation/modelling/analysis tools (e.g. Simulink). A very good example of software based on VPL designed to be used in education is **Scratch** [9], developed by the Lifelong Kindergarten Group at the MIT Media Lab. As it may be read in the Scratch website, it is designed to allow users “code their own interactive stories, animations, and games. In the process, they learn to think creatively, reason systematically, and work collaboratively — essential skills for everyone in today’s society.” From an educational point of view, the great strength of Scratch, and VPLs in general, is that of allowing students to train their computational thinking skills without requiring them to learn everything about textual coding.

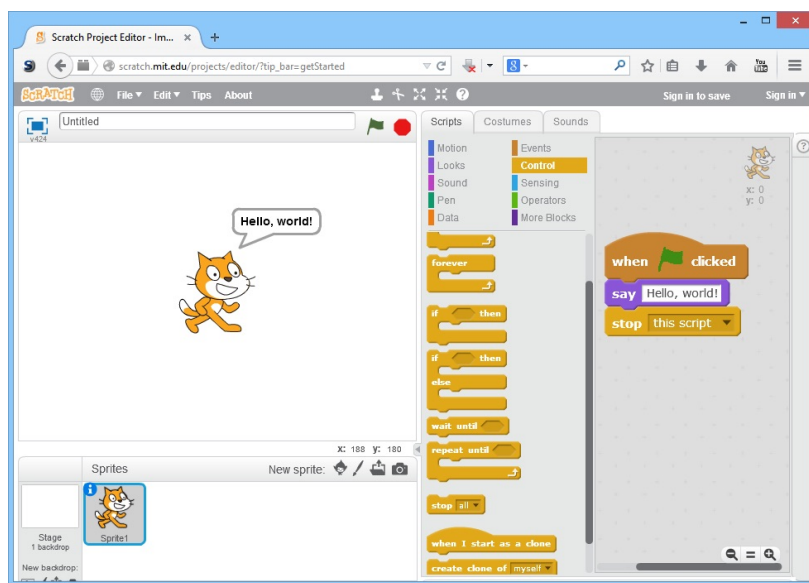


Figure I-18. A screenshot of "Scratch".

Another approach is that of not giving away textual coding completely, but to make things as easy as possible for the user. Of course, depending on the context, this may translate in very different solutions. One of the most important examples of this approach regarding physics education is **Easy Java/Javascript Simulations** (EJS/EJsS), part of the magnificent Open Source Physics project [10]. It is designed to help non-programmers (mainly students and teachers) to code their own interactive simulations by taking away as much burden as possible regarding technical aspects. For example, EJS requires a mix of textual and visual interaction. The creation of a

Graphical User Interface (GUI), for instance, may be a complex part of coding and EJS allows to deal with it using a visual approach. This way, students can focus on using textual coding regarding the simulation, the most important part of the software from the point of view of physics education.

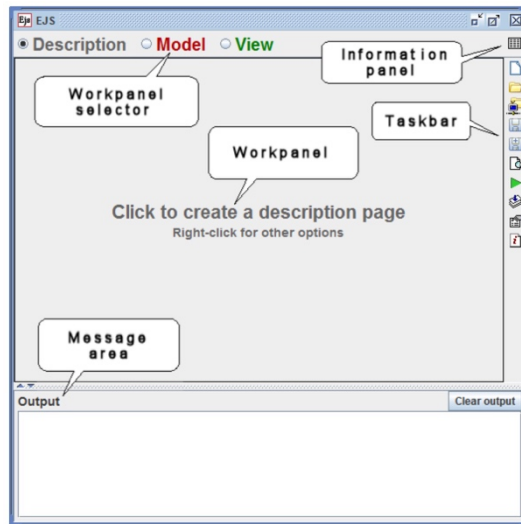


Figure I-19. The “Easy Javascript Simulations” user interface.

Using VPLs to introduce computational thinking is a great starting point, although, as it has been already pointed out [11], a successive transition to textual coding would certainly not be painless at all. A good solution may be the design of learning sequences using a VPL to solve conceptual/modelling problems and then translate the resulting product in a simple, textual language. More about a sequence based both on Scratch and EJS may be found at [12] and [13].

A last approach to introduce coding and computational thinking is that of relying directly on textual languages and integrated development environments (IDEs) that are designed to be the simplest and most effective as possible. Two examples of this are the **Python** language, which is increasingly used and loved by scientists all over the world, and **Processing**, which is both a Java library and an IDE dedicated to help the creation of visual software. The workshop “Scientific Visualization”, created by the author and discussed in Chapter II, is entirely based on Processing.

1.2 Personal devices as an educational technology

The term **personal device** refers to smartphones, tablets, and laptops owned by an individual. The recent proliferation of smartphones and tablets owned by students, and the great appeal they feel towards them, opens new possibilities for physics education. In particular, it affects BYOD (Bring Your Own Device) and JiTT (Just-in-Time Teaching) activities: a lot of research in education using these didactical methods has been done, and much more is needed. Students should learn to use personal devices, in particular smartphones, for learning purposes (investigations, measurements, documentation, communication) [14]. Moreover, students should know about the physics and technology of a smartphone⁵, so using them in classroom might also be the opportunity to learn more about them and teachers should keep this in mind.

There are many educational applets both for computers and smartphones/tablets. Some examples of educational applets regarding visualizations were already presented in I.1, in which we focused on computer software. Smartphones and tablets have several perks regarding their use in education: students generally bring them at school and Universities, they see them as fun to use and, most of all, have many built-in sensors in them, thus effectively becoming “laboratories in your pocket”. In the following sections we discuss different uses of smartphones and tablets in physics education, mainly due to their visualization capabilities, their sensors, and interactions they enable. Probably each of the presented apps is based on scientific or data visualization, so the main distinction between visualization and measuring apps is that the formers do not exploit the device sensors. Even though cameras are sensors indeed, an entire section is dedicated to some of the multiple uses one can make of them, also by adding additional instruments directly on the camera.

1.2.1 Using personal devices for visualizations

In this section we discuss the use of personal devices as tools for visualization in physics education. As already stated, also the apps in the following sections rely on visualizations of some kind, but they are mainly based on the device sensors and measurements. The following apps are not substantially different from those which can be used on computers: their main differences rely on the dissimilarities regarding

⁵ See the UNESCO ICT Competency Framework for Teachers (ICT CFT) [46].

the devices themselves, such as the kinds of interaction, their user-friendliness and accessibility. Of course, the first factor to consider is the educational context. Let us now focus on education at **high-school level**. Most of the following comments might also be valid at primary school level and would probably be less suitable at university level.

In the following, some reasons to prefer visualizations that run on smartphones or tablets over those which run on a computer are given.

Let us suppose a teacher would like to use a visualization software in class. The teacher needs to download the app, to try it and then bring it to the classroom. First of all, smartphones and tablets are designed to be the most user-friendly as possible in the process of finding and downloading apps, and generally feature much less compatibility issues than computer software. Secondly, the teacher needs to bring the app in the classroom. This may either be done by installing software in the computer already present in the classroom (if there is any), or by bringing her/his own device at work. While it is strongly subjective and situational to determine which possibility is “the best”, there are several points of strength in favor of the latter. In fact, once the teacher has installed the desired apps on her/his own device, there is nothing else to worry about other than bringing the device in the classroom. In fact, by relying on devices at school or University, she/he needs to test them before classroom, every time, and for each class. There are multiple things that can compromise the functionality of a software, so testing it the day before is the only way to be (reasonably) sure that everything works. And once again, while it is subjective and situational, it is generally more comfortable for the teacher to just bring her/his own smartphone in the classroom other than to bring there a laptop.

Let us consider the perspective of the students. First of all, smartphones and tablets are the only devices that are never left home by students. As time goes on, it is less and less common that any of them do not own such a device, and those who do, rarely leave them at home unless forced to. Also, activities done with smartphones *are* perceived as more fun and engaging, and as they have the possibility to download the apps used in class, chances are they also could use them at home. At last but not least, the teacher could also decide to ask them to download some apps and use them before lesson for homework, and then use it in the classroom or after the lesson.

The following figures form a small gallery of visualization apps that may be used in physics education.

Research framework

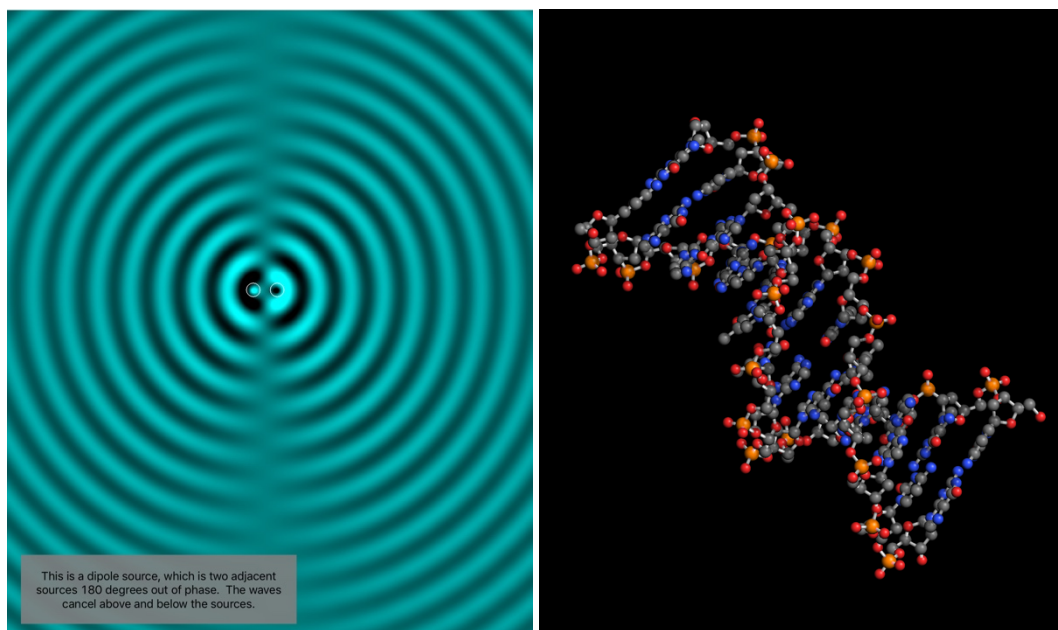


Figure I-20. (Left) *Ripple Tank* by Paul Falstad. (Right) *Molecules* by Sunset Lake Software.

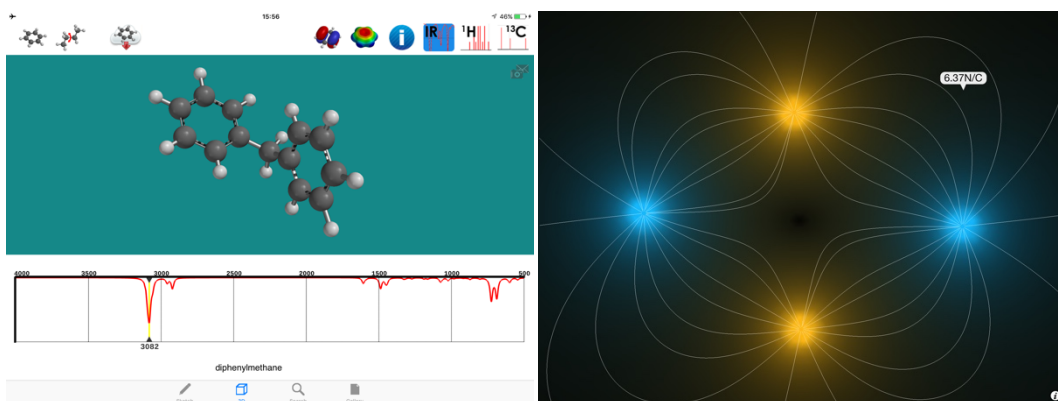


Figure I-21. (Left) *iSpartan* by Wavefunction, Inc. (Right) *Electrostatic Fields* by EnigmoiDesign.

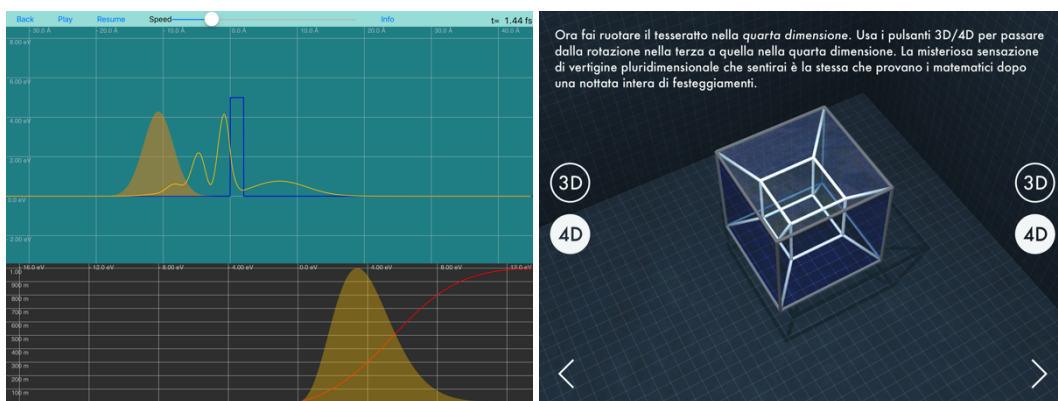


Figure I-22. (Left) *1D Quantum Mechanics: Scattering* by Damon English. (Right) *La quarta dimensione* by Drew Olbrich.

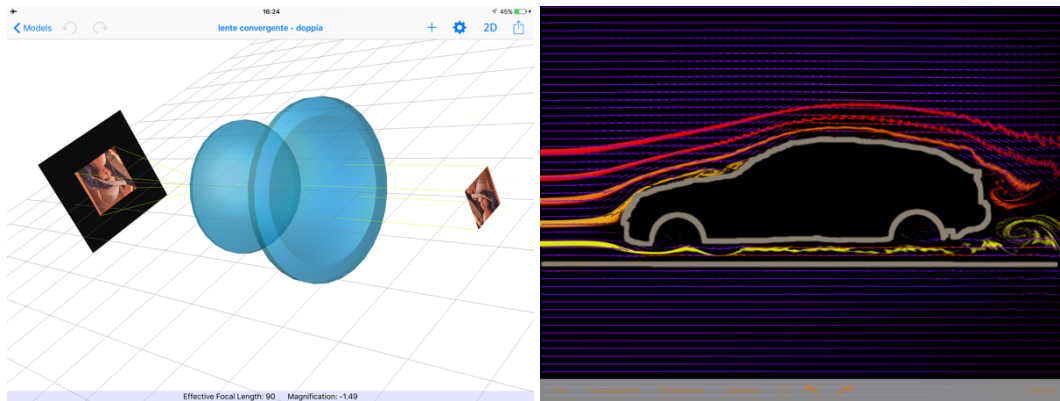


Figure I-23 (Left) RayLab by Kamyar Ghandi. (Right) Wind Tunnel by Algorizk.

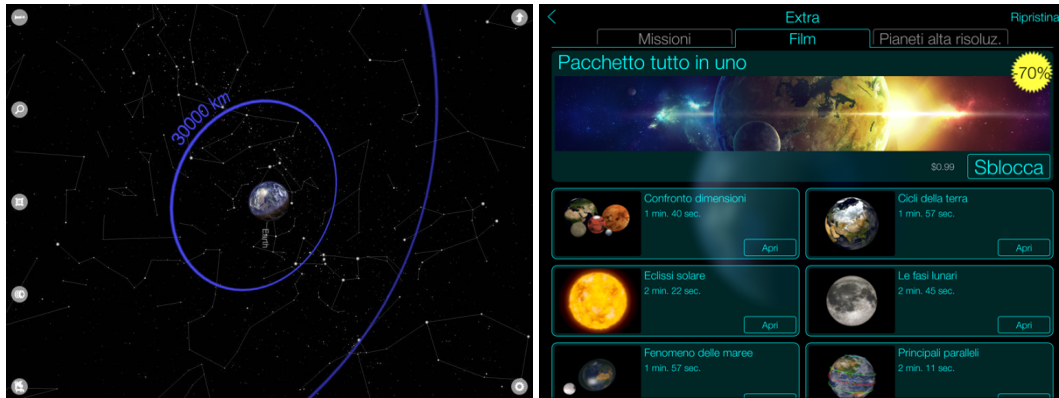


Figure I-24. (Left) Exoplanet by Hanno Rein. (Right) Solar Walk by Vito Technology Inc.

1.2.2 A physics laboratory in your pocket

A smartphone really is a physics laboratory in your pocket: it has many sensors, the computing power for data analysis and visualization, and the software needed (apps that can be easily downloaded). A lot of research has been done regarding the use of smartphones in physics education, based on experiments of mechanics, optics, acoustics, electromagnetism, and more.

There are many apps that can be used for physics experiments. The first one to be used, as it is already present in any smartphone and everyone is familiar with it, is the one for photos and videos: the next section (I.2.3) is dedicated to photo and video acquisition by means of smartphones and tablets, as well as image and video analysis such as motion tracking.

Research framework

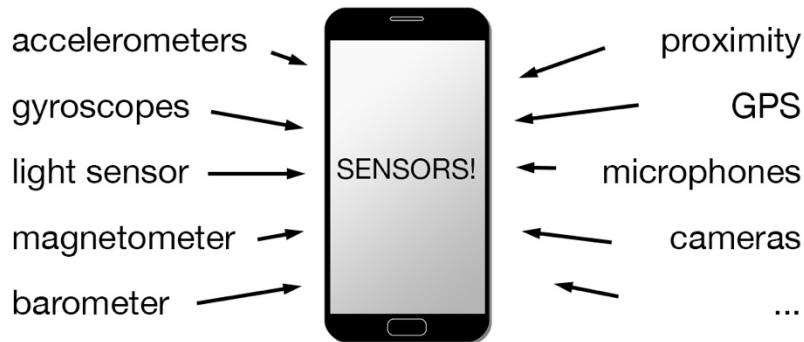


Figure I-25. Smartphone: a physics laboratory in your pocket.

What we found to be the most complete apps for sensor data acquisition, available both for Android and iOS, are *Sensor Kinetics* [15] and *phyphox* [16]. Both of them take inputs from the sensors of the device and are able to create charts, tables, and share data. *Sensor Kinetics* come in two versions: the free and the Pro version. The Pro (paid) version is needed in order to export the data. On the other hand, *phyphox*⁶ is completely free and comes with several options and features, overall being the most promising app for sensors data acquisition at the moment.

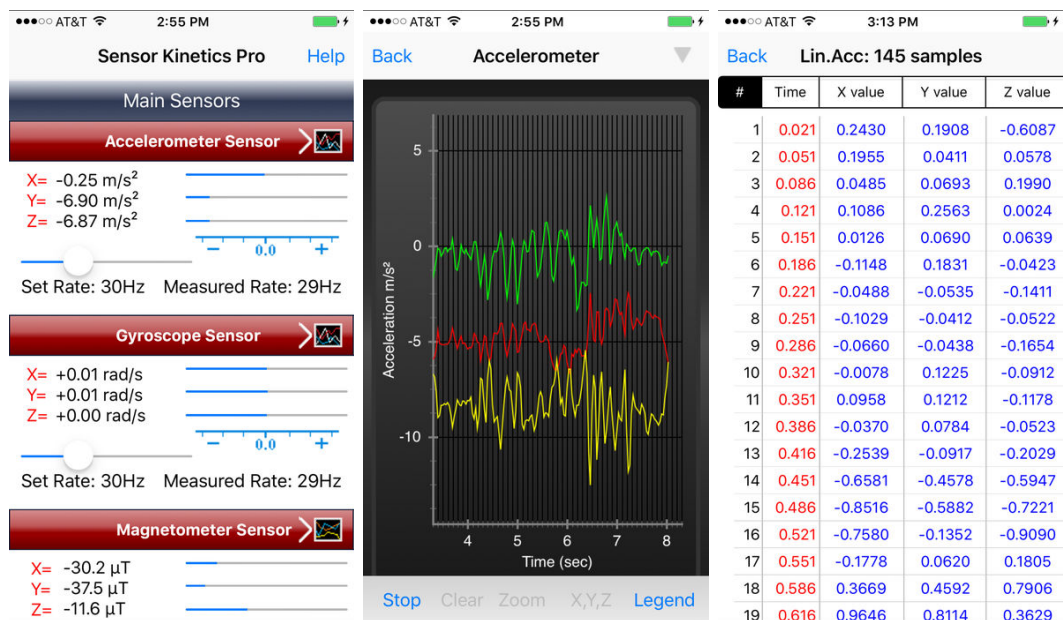


Figure I-26. Three "Sensor Kinetics" app screenshots.

⁶ created at the 2nd Institute of Physics of the RWTH Aachen University by Sebastian Staacks

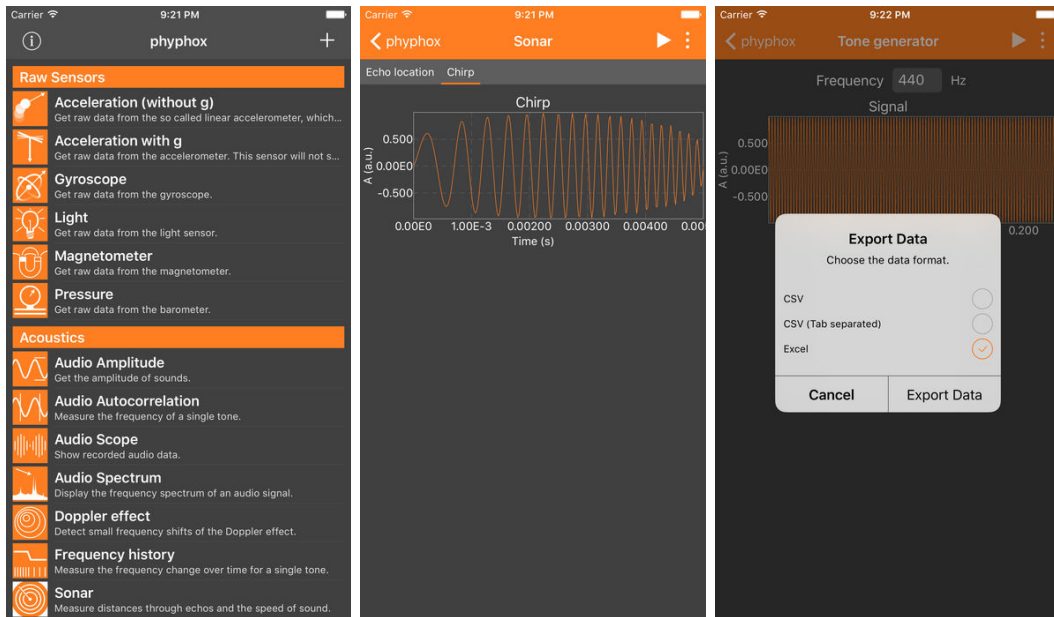


Figure I-27. Three "phyphox" app screenshots.

There already is a rich literature about such experiments (see for example [14] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27] [28]), and it is still growing. In Chapter III, an example regarding low-cost spectroscopy carried out by our research group is discussed [27]. This brings us to a last note regarding sensors and smartphones/tablets, which is the possibility of using external accessories and other sensors to extend their capabilities, as what is done with computers. A very interesting example of this are thermal cameras. FLIR sells relatively low-cost thermal cameras both for iOS and Android smartphones/tablets [29]. There are many experiments that can be done with this kind of camera, for example about thermal phenomena and radiation. Some of the simplest and most fascinating ones are those regarding the dependence of transparency on frequency of radiation. For example, on one hand it may be observed that some materials that we call transparent, such as glass, are actually perfectly opaque to IR radiation. And on the contrary, there are materials such as some plastics or silicon that are opaque for us but are transparent to IRs (see for example Figure I-30 and Figure I-31).

Research framework



Figure I-28. Thermal camera for smartphones and tablets are available at affordable costs and may be good tools to be used in class.

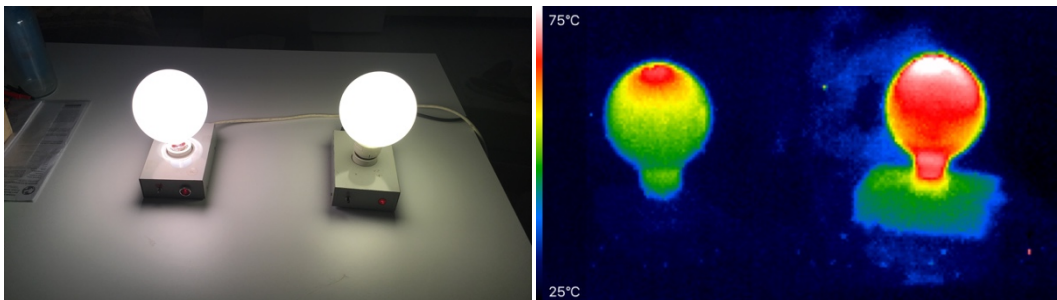


Figure I-29. A LED lamp and an incandescent lamp that look exactly the same (after a few minutes, as the incandescent lamp is warmed up) can be distinguished using a thermal camera. This simple experiment can be very useful to help students understand why a LED lamp consumes less energy than older ones.

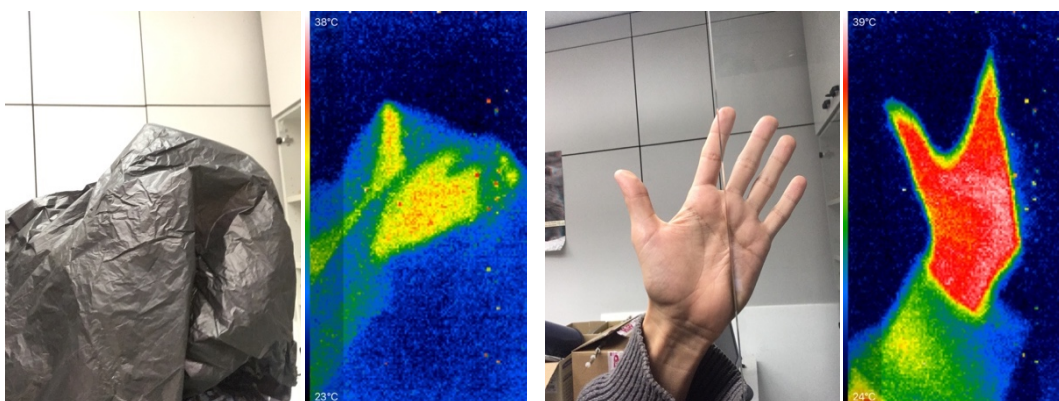


Figure I-30. A material's transmittance of IR radiation may be very different from that of visible radiation. (Left) An example of a "black" plastic which is almost transparent to IR. (Right) The opposite happens with glass, which absorbs most IRs and it is therefore impossible to see through it with a thermal camera.

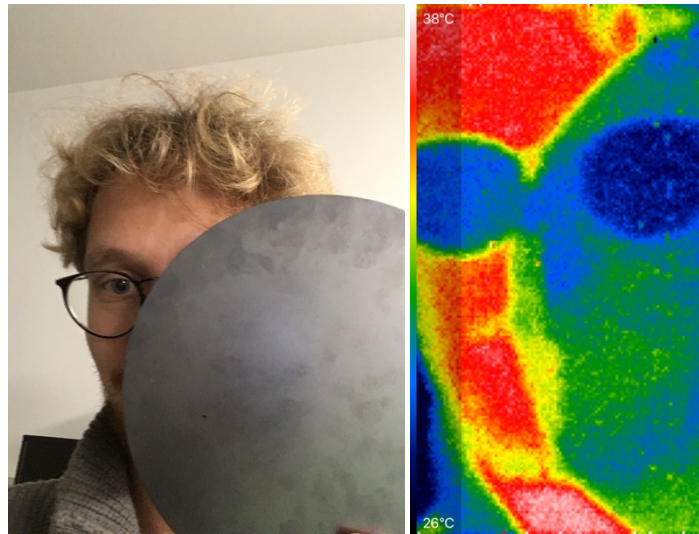


Figure I-31. Silicon is also semi-transparent to IR radiation. In this photo both transparency of silicon and opaqueness of glass are shown.

1.2.3 Smartphones and tablets cameras as measuring tools in physics laboratories

Smartphones and tablets cameras are great instruments for physics education, as the academic literature dedicated to them easily proves. They feature impressive technical specifications which are continuously improving: in fact, the demand of these devices is huge, the competition high, and the quality of the camera may be a crucial factor when coming to models comparison. Both photo and video capturing can be very important for physics measurements. In either cases, the resolution is very good for most educational uses. There are many apps that enable users to get access to the camera and control it as desired. So it is possible to **control parameters** such as ISO, manual focus and exposure time, very much similarly to a DSLR or other professional camera. For both Android and iOS operating systems, it is possible to save pictures in a **raw** format, which can be very important to make quantitative measurements without relying on the so-called *gamma-correction* (more about this in Chapter III). Last but not least, an increasing number of devices features **slow-motion** capture capabilities, of the order of some hundreds of fps⁷, and, on the other hand, time-lapse options.

⁷ For example, the iPhone SE reaches 240 fps

Research framework

Let us now see some examples of possible uses of smartphones/tablets cameras for physics education.

The simplest use we can think of is of course taking photos and videos taking advantage of the features of the device camera (manual control, raw format, slow-motion/time-lapse videos, ...). An example of this is the measurement of the inverse-square law of a light source intensity. Of course, in principle this could be done using the light sensor of the smartphone, but it may not always be possible to do so⁸ or one could simply prefer using photos. In order to do such measurements, it is fundamental to manually set the ISO parameter and exposure time. Also, as already mentioned, one can opt to save using a raw file format: only this way the camera can be used as a linear measurement regarding intensity, otherwise a gamma correction post-processing of the data must be done⁹.

Other experiments can be based on measurements of the dependence of intensity of a light source on time. This may include very fast or very slow intensity variations, as characteristic 50-100 Hz intensity oscillations of lamps or exponential decays of fluorescent lamps on shutdown [25] and of phosphorescent materials. The high-speed or slow-motion camera capabilities of smartphones can also be used to study kinematics, mechanical waves propagation [28] and also temperature changes and response time of thermometers [24].

Another way to exploit the cameras is to add some filters or other objects in front of them. For example diffraction gratings or IR filters can be put just in front of the camera (see Figure I-32 and Figure I-33). Using the two apparently identical lamps of Figure I-29, we can use a diffraction grating to see their different spectra. We may also look at them using an IR filter: the LED lamp would almost look turned off, while looking at the incandescent lamp we are even able to see a very bright emitting filament, meaning the lamp is more transparent to IR radiation than to light. This way, we are able to make the same experiment about the two identical-looking lamps as presented in last paragraph without buying additional accessories (thermal camera). Other very interesting experiments about these topics are those regarding diffraction using the IR LEDs of remote controls [21] (in Figure I-32 an example of IR LEDs seen by digital cameras). Notice that some smartphone cameras have built-in IR-

⁸ For example, as we can read on the *phypbox* website [10]: “Unfortunately, this sensor is not available on iPhones. While these phones have a physical light sensor to automatically adjust the brightness of the display, there is no direct access to this sensor for apps on these devices.”

⁹ More about this will be discussed in Chapter III.

blocking filters, as in the case of iPhones back cameras, so these experiments cannot be done with them. These filters are added to get better photos, so are usually found in good-quality cameras. The iPhones front cameras are of lower quality than that of back cameras, so the formers are to be used for these experiments. Macro photos can also be taken using inexpensive lens kits or even water droplets directly put on the lens (Figure I-34). Polarizing filters may also be used for qualitative and quantitative experiments [30] (Figure I-35).

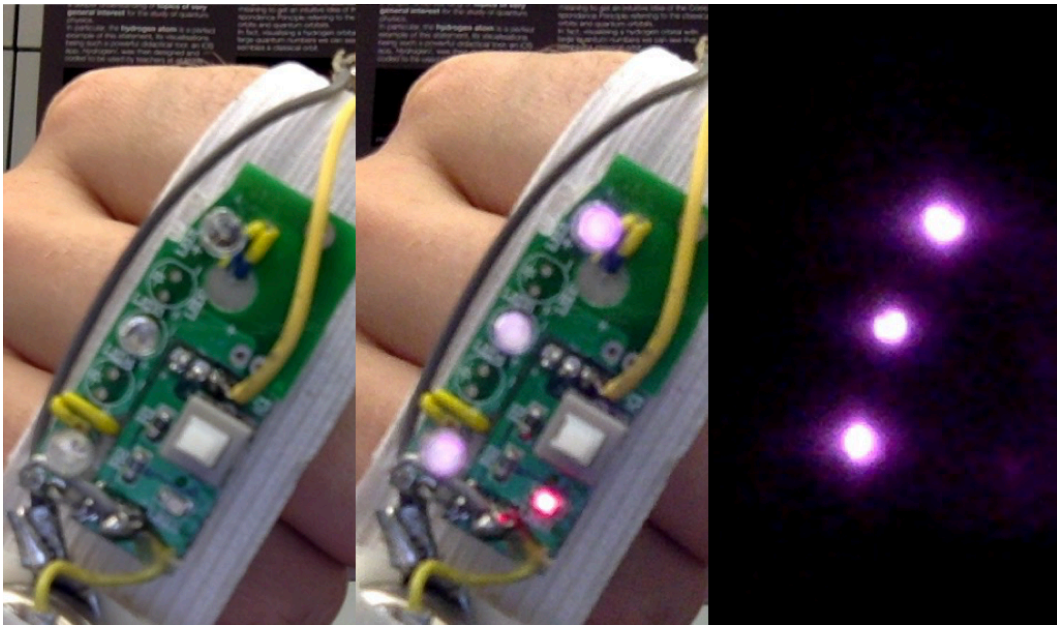


Figure I-32. From left to right: IR LEDs as seen by the naked eye, or by a camera with a built-in IR-blocking filter. IR LEDs as seen by a camera with no IR-blocking filters on it. LEDs seen by a camera with no IR-blocking filters and with a visible-blocking filter on it. Adding a diffraction grating to the setup, it is also possible to determine the frequency of the IR LEDs [21].

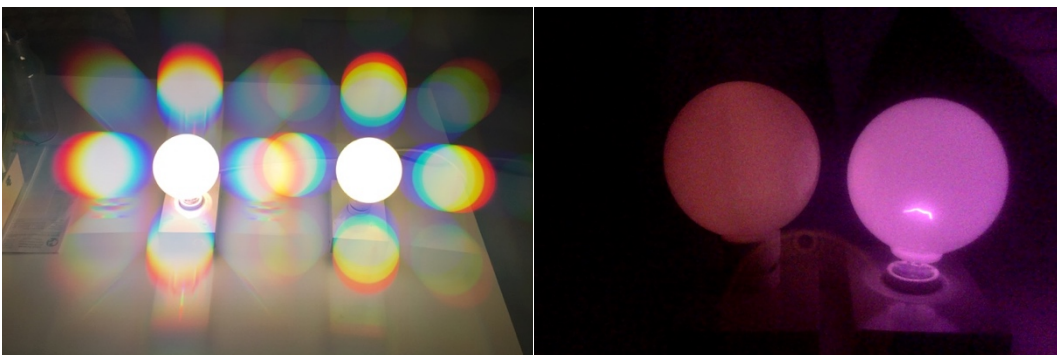


Figure I-33. A LED lamp and an incandescent one seen using a 2D diffraction grating (left) and an IR filter (right).

Research framework



Figure I-34. From left to right: pixels of a monitor seen using an inexpensive macro lens for smartphone; a water droplet on the camera acting as a macro lens; a photo of the pixels taken using the water droplet.

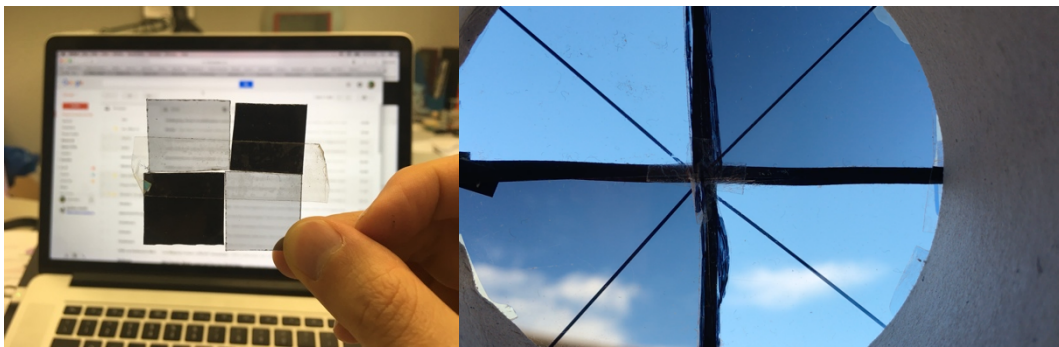


Figure I-35. Qualitative and quantitative experiments may be done using digital cameras and polarizing filters.

A very powerful tool for physics experiments is the analysis of photos and videos. There are several software to choose from, but arguably the most important video analysis and modelling tool for physics education is the software *Tracker* [31]. It is a free, open source java software that is part of the *Open Source Physics project* [10] and hosted by *comPADRE* [32]. The *Tracker* features, regarding its **tracking** capabilities, comprehend¹⁰:

- “Manual and automated object tracking with position, velocity and acceleration overlays and data.
- Center of mass tracks.
- Interactive graphical vectors and vector sums.
- RGB line profiles at any angle, time-dependent RGB regions.”

¹⁰ Directly from the Tracker website [7].

Since its release it has been often used and cited in the literature (e.g. [25] [24] [33] [34] [35] [36] [27] [26] [37] [38]), especially for, but not limited to, experiments regarding kinematics and spectroscopy.

Of course, smartphone cameras can be used to take photos and videos (also in slow-motion and time-lapse) to be used for analysis, but they can also be used to directly do the tracking too. For example, a commercial but low-cost app for video tracking is Vernier Video Physics [39]. It allows to do automatic tracking of objects, creating graphs and data tables that can be exported for additional data analysis and chart creation if needed.

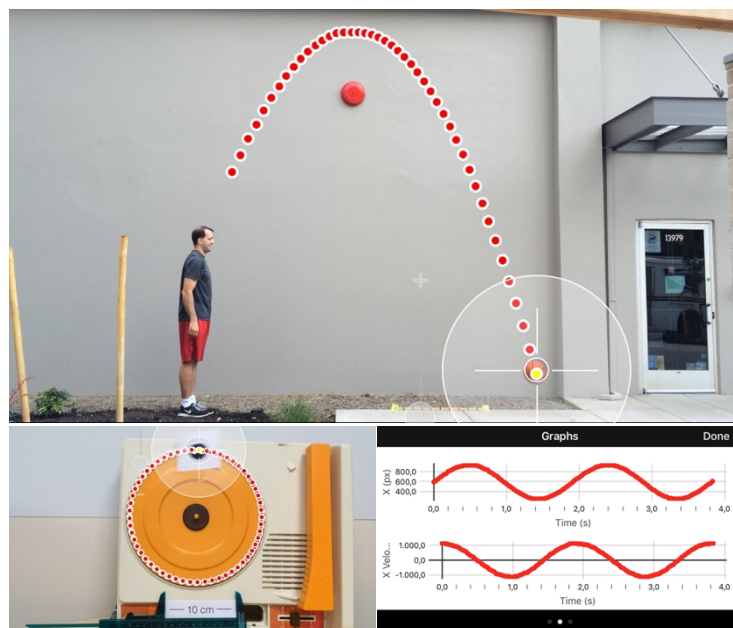


Figure I-36. Screenshots of the Vernier Video Physics app.

It is important to notice that this kind of video analysis tracking only reproduce reasonable results when the motion happens inside a plane which is perpendicular to the direction of the camera. Otherwise, systematic errors would be introduced in the measurements.

For this reason, it would be very interesting to use a setup capable of doing **three-dimensional motion tracking**. Such a low-cost setup based on the Microsoft Kinect will be presented in Chapter IV. Instead, we shall now discuss some possibilities regarding smartphones and 3D motion tracking.

First of all, it is possible to emulate the human stereoscopic vision using two smartphones acting as two eyes. An example of a simple setup for **stereoscopic** photo

Research framework

and video acquisition is shown in Figure I-37, left. Two smartphone cases are glued on a wooden board with two holes, so the smartphones can comfortably be put on and removed from the board. Notice that it is better to use two identical smartphones in order to get images using the same optics. In order to get 3D images that would be the most similar to what we usually see we should use optics with the right field of view and put them at a distance equal to that of our own eyes. Usually, smartphones have so-called wide-angle lenses, meaning they can see a greater solid angle than we can. For this reason, it is better to place the cameras closer together (3-4 cm apart) when looking at objects that are not too far away. This is also the reason why the two smartphones in our setup are rotated 180° one respect to the other, so that their optics could be closer to each other. In Figure I-37, right, a 3D image obtained using this setup is shown (an example of red and cyan **anaglyph**). Using the tools provided by *epipolar geometry* [40] [41] (which describes the relationship between two images of the same scene taken from different points of view) it is possible to reconstruct the 3D position of an object by measuring its positions in the two images. In fact, objects at infinite distances would be exactly in the same position in the two images, while their positions would be more different the closer they are to the camera.

A problem regarding this kind of setup is the **alignment** of the optics. There are various techniques to calibrate the setup and remove systematic errors that would otherwise arise. For example, the MATLAB software [42] provides a 3D scene reconstruction tool based on stereo pair images, and uses a calibration procedure now briefly described (see also [43]). A black & white checker board needs to be made, and various photo pairs need to be taken with the checker board put at different positions and orientations. The software automatically recognizes the checker board in the photo pairs, and provides the automatic calibration of the setup. A simple example of photo pair, also containing a calibration checker board, can be seen in Figure I-38.

Once the calibration procedure is done, any scene may be reconstructed taking a photo pair (no more checker board required in the MATLAB example). The reconstruction is based on the so-called **disparity map**: this map is generally visualized as a greyscale image where the brightness is proportional to the distance of the objects. Its name is related to the fact that the distance, as already discussed, is estimated by measuring the difference of position of the objects in the stereo pair images. An example of disparity map obtained with MATLAB and the two smartphones setup is given in Figure I-38. It is rather a noisy image and better results can certainly be obtained, but we preferred to spend more time focusing on the setup based on the Kinect presented in Chapter IV.

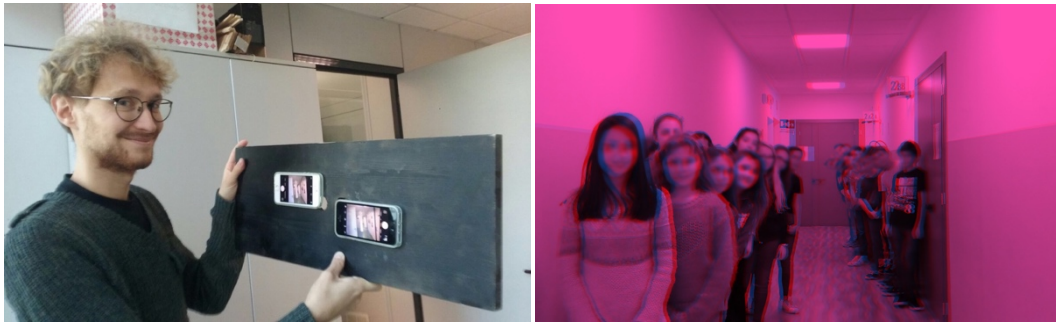


Figure I-37. Left: a simple setup for stereo photo and video acquisition. Right: a red and cyan anaglyph image taken with this setup.



Figure I-38. Two photos taken with two smartphones with a horizontal displacement of a few centimeters and the corresponding disparity map obtained with MATLAB. In this image, lighter objects correspond to smaller distances from the camera.

Research framework

Another problem using two different devices is that regarding **synchronization**: this problem would arise both with photographs that should be taken exactly at the same moment, or with any stereo video. A simple solution to this problem is using some acoustic signal, for example a very spiked one, allowing to synchronize the two videos in post-production, but of course would still require extra work and competences not everybody has.

A very clever, low-cost, and overall simple solution that avoids the synchronization problem and at least diminishes the alignment one, is the setup proposed in [44]. In the paper a common digital camera was used, but of course a smartphone could be used too. The setup is based on the idea of using four mirrors to be able to split the image taken by a camera in two. The result is that on the same device we are able to capture two slightly different images, corresponding to a stereo photo or video. So in one half of the image we acquire information corresponding to one source, and on the other half we acquire information corresponding to the other source. The only trade-off of this setup is the sacrifice of half the image resolution, a problem that is generally of no importance due to the high resolution of current devices. Interestingly enough, for less than 10€ it is easy to find¹¹ smartphone accessories that allow to capture stereo pair images on the device (Figure I-39). In principle, a 3D tracking of objects could be done with any smartphone and such an accessory. Still, the low quality of such objects would require some testing and calibration in order to get accurate results. In Figure I-39 an example of such a stereo accessory and a frame of a video we acquired with it are represented. As a last note, using this setup together with a Google Cardboard (Figure I-40), or equivalent equipment, it would also be possible to directly see the acquired stereo image in 3D.



Figure I-39. A screenshot of a stereo video of a bouncing ball taken with a smartphone and a stereo apparatus. The device is depicted on the right.

¹¹ For example, search “smartphone stereo photo” on eBay



Figure I-40. The “Google Cardboard”, designed to make low-cost head mounted displays using smartphones.

1.2.4 Boosting interaction with educational technology: using mobile devices as clickers

Clickers are devices designed to allow direct interaction between the lecturer and the audience. They have been used in very different contexts, ranging from education to TV shows. The simplest versions simply allow the audience to choose between a set of choices when a question is posed to them, while more recent ones also allows different kinds of interactions. Smartphones are ideal devices to be used as clickers in schools and universities, as all the students have them and there are various apps and websites designed to obtain the most out of them [45] [46].

In the last few decades, evidence on the effectiveness of the use of clickers in education accumulated [47]. Lessons can be entirely designed to make use of them, or they simply can be added to more traditional ones. Their main point of strength is the increase in involvement of the students. Their use “makes the students more responsive in general, so that questions posed to the class as a whole during lecture are much more likely to elicit responses and discussion” [48]. Students commit to their answers, as they are “emotionally” or “psychologically invested” and they are more likely to pay attention in the following discussion [49] [50]. When using clickers, students are more willing to participate and to commit for various reasons, for example because they avoid to directly expose themselves. Also, when they give a wrong answer together with many colleagues, they realize they are not alone in their confusion [51] and they are more open to discussion and to revisit their thinking.

Another very simple reason why clickers can be very effective is that of concentration. In fact, the human capability of concentrating and of information recall drops

Research framework

drastically after 15-20 minutes [52] [53], so a very important part of any lesson is often lost. Periodic brakes and interactive activities help to “restart the attention clock” [54].

From the perspective of the teacher, they are a perfect tool to keep track of the topics that were understood and those which were not, allowing her/him to adjust the lesson accordingly. Also, it has been reported that encouraging discussion between students after they already gave an answer can be very rewarding:

“For me, this was a moment of revelation... or the first time in over 20 years of lecturing I knew. . . that over half the class didn’t ‘get it’... Because I had already explained the phenomenon as clearly as I could, I simply asked the students to debate briefly with their neighbors and see who could convince whom about which answer was correct. The class erupted into animated conversation. After a few minutes, I asked for a revote, and now over 90% gave the correct answer.” [48]

As for any other technological device, a poor usage of clickers can be a useless or even counterproductive. Nonetheless, they have all the potential to improve lessons for many different reasons as it was discussed, and personal devices are perfect devices to be used as clickers.

1.3 Mediated reality

Mediated reality refers to the manipulation of a person's perception of reality. Nowadays, this term generally implies that the manipulation is done by a computer, a smartphone or a similar device, which can add, subtract or alter information regarding the user's perception (generally, the user's *visual* perception). Virtual reality, augmented reality and mixed reality are special cases of mediated reality, all of which can be used in physics education to achieve better learning results. In order to really make useful tools, designers of new hardware/software setups should take into account the mental effort required by the use of new technologies in education [55] [56] [57].

As previously stated, Chapter IV is dedicated to a virtual and augmented reality setup designed by the author to be used in physics education, so this section is intended to provide the reader a general background about these worlds.

1.3.1 Reality Mediators

As already stated, the general purpose of mediated realities is that of alter the perception of reality of the user. The so-called “real” world and a virtual one can be mixed by various extents. The results that can be achieved are strongly influenced by the state-of-the-art of technology and the context in which the setup is going to be used, meaning the first thing to consider is the *reality mediator*. For example, one of the most common reality mediator setup includes a computer and a Head Mounted Display (HMD) along with other devices. As mobile devices have become such widespread devices in the last decade, they also have become some of the most common reality mediators. In fact, they are very flexible devices acting as mediators in very different ways, from being used as HMD (as seen in I.2.3) to mix and augment realities using data coming from cameras, GPS, accelerators and so on. Also, the recent success of the mobile game “Pokémon GO”, helped in increasing people's awareness of the world of mixed reality, augmented reality and virtual reality. In fact, as pointed out in [58], virtual reality (and we could extend the concept to mediated reality in general) is still seen either as fringe technology or a dead technology – either way something that is far away from being a mature and valid usable tool – while this cannot be furthest from truth. Once again, the world of gaming is helping not only the research and development but also the spreading of new technologies, not to mention the people's awareness and understanding of these new tools who are becoming everyday more accepted and familiar.

Before discussing more in detail examples of virtual, augmented and mixed realities we shall now present some examples of the first different experiments done with Head

Research framework

Mounted Displays, as this will help to better understand the world of mediated reality and its possible uses. The following examples are taken from a wonderful research work [59] done by Steve Mann, who has been referred to as the “father of wearable computing” [60] [61].

Any reality mediator needs to somehow synthesize the “real” and the virtual worlds. The starting point to augment reality or to mix realities is that of being able to actually see the physical world. There are various approaches for achieving this goal using HMD. We can use two cameras put as close as possible to both eyes, and display the corresponding image to the corresponding eye. Other approaches include that of using partially transparent visors in order to overlay computer generated information to the usual vision, or to use single-eye visors (Figure I-41) or even a partial-single-eye one. The first one, based on a fully covering visor, is probably the most versatile one, as is the only one which allows to even completely shut down or alter the vision of the physical world if needed. For example, we could entirely remap the acquired images in order to help persons with vision problems: the user could magnify certain areas to be able to read, or the image could be distorted to give more information to persons with scotoma (a blind or dark spot in the visual field). Colors could be enhanced or even removed, brightness adjusted and so on. Or we could even experiment choosing different camera positions and lenses. Two examples are given in Figure I-42, where the cameras were put at a distance larger than usual (“Giant’s eyes”). Citing Mann’s words: “With a 212mm baseline, I could function in most everyday tasks, but would see cross-eyed at close conversational distances” (Figure I-42, left). “With a 1m baseline, I could not function in most situations, but had a greatly enhanced sense of depth for distant objects” (Figure I-42, right).



Figure I-41. Head Mounted Displays for mediated reality. (Left) A double-eyes visor. (Right) Single-eye visor example.

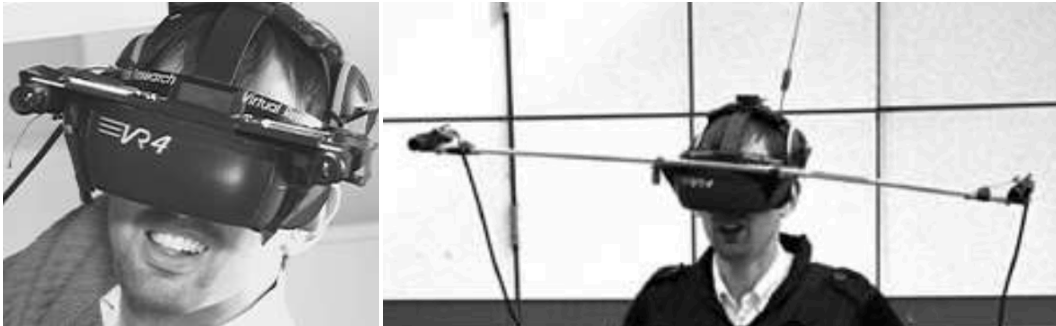


Figure I-42. Experimenting other kinds of vision, for example by placing the “eyes” (the cameras) at larger distances than usual.

1.3.2 Virtual Reality

Virtual reality (VR) is an immersive environment generated by a computer. Two typical setups used to generate such an immersion are the ones based on Head Mounted Displays, or VR goggles, and CAVEs (see below). Sometimes in the literature even simply software visualizations on the computer or mobile devices are addressed as VR. A common feature of VR is real-time interactivity, for example given by the head tracking of the HMD and/or motion-sensing gloves. VR can be very useful for science education in various ways. Its more immersive and interactive way of presenting phenomena can be highly more productive of that of videos, and it is very useful for those students who are more visually oriented. It allows to give experience of dangerous, high-cost, and time-consuming experiments which could not be performed otherwise. Also, if a school or university invests in a VR laboratory, this can be used for multiple disciplines, for example chemistry, physics and engineering, instead of being used for just a single one. Lastly, recent technological developments, also because of impressive investments in the gaming world, reduced the costs of VR gears.

Head Mounted Displays are nowadays generally well-known devices and were briefly presented in the previous section. We shall now present another typical and impressive VR setup, the CAVE. The term CAVE is a recursive acronym standing for CAVE Automatic Virtual Environment, was first developed at the Electronic Visualization Laboratory at the University of Illinois at Chicago. It premiered at the SIGGRAPH 1992 conference, and its name is also “reminiscent of Plato’s allegory of the cave” [62] [63]. A small video showcase of 1992 can be found online at [64]. A CAVE consists of a room whose walls (and sometimes even floor and/or ceiling) are acting as windows on a virtual world, so that the user is completely immersed in it (Figure I-43). The position of the user is tracked so that illusion of perspective can be created. Additionally, 3D projectors can be used. Depending on the setup, various devices and

Research framework

solutions can be added to allow interactions, for example head-tracking to control the camera and motion-detecting gloves (such as those used with goggles). At the moment, such setups are mainly used by researchers for immersive visualizations in universities and research facilities [65] [66] [67] [68], and unfortunately are still too pricy to be bought and maintained by schools.



Figure I-43. Two examples of CAVEs.

1.3.3 Augmented and Mixed Reality

Augmented reality (AR) and mixed reality (MR) are the results of a direct or indirect view of the physical world with the addition of virtual objects and/or information given by computer analysis. Whereas virtual reality replaces the real world with a

computer-generated one, AR and MR bring these worlds together, for example by enhancing the user's perception of reality [69].

Similarly to virtual reality, the most common *reality mediators* for AR are Head Mounted Displays, projector-based setups and mobile devices.

Let us now introduce some examples of mobile devices used for AR.

First of all, it is well-known that they can be used to read QR-codes. To do this, they use some algorithms that allow them to recognize a QR-code and then translate it into something else, generally a URL for a website. The research field which makes this possible is called Computer Vision (CV). There are many different applications of CV for AR, the most common of which is the recognition of markers or images in order to place virtual objects inside a real-world scene captured by the camera (Figure I-44) [70].

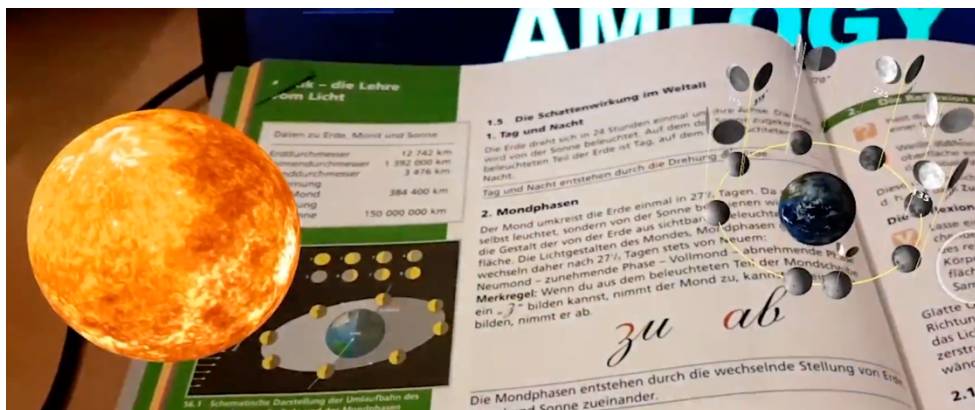


Figure I-44. Books may be designed to be augmented using a smartphone app. In this example, the smartphone app allows to see augmented reality content by recognizing the images of the book. [149]

Another use of smartphones for AR is the exploit of GPS and/or accelerometers data in order to determine the position of virtual objects. An example of this for education is the one described in [71], where it is described how astronomy lessons can be enhanced by the use of an app which allows the students to look around using their devices and to see virtual representations of astronomical objects and related information blended in the image obtained by the camera Figure I-45. In the same paper we read:

“users could see the virtual moon and situated information overlaid on the real scene after finding the moon with their body. By doing so, the degree of reality could be increased because the feature of AR could link the change process of the moon on the daily life

Research framework

environment, instead of a virtual sky. [...] Moon Finder could help students link virtual elements to the real-life environment.”

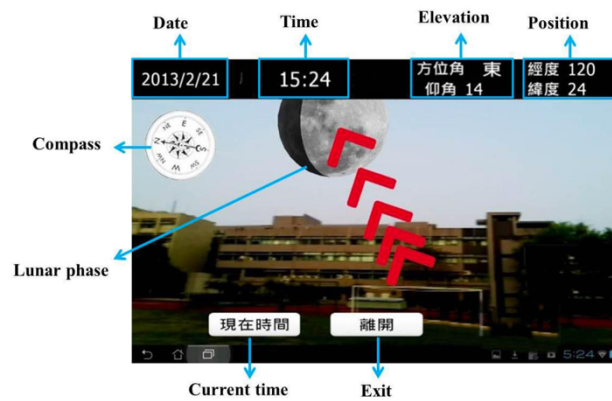


Figure I-45. The interface of the Moon Finder app [71].

Very different kinds of setups are the ones based on projections. In this approach, the digital world is projected onto the real one. In order to obtain an actual augmentation of the real world, and not just projecting unrelated information on it, the *reality mediator* (a computer) needs to rely on some input device. Markers could be used similarly to what it has been introduced before, projecting information influenced by the position and type of markers. A more powerful and flexible approach is that of using depth sensing cameras. As it will be better explained in I.4.2 and Chapter IV, a depth sensing camera is a device which allows the computer to gather 3D data of the world in front of the camera and effectively using it to create 3D virtual reconstructions of the physical world. The idea is then that of projecting information on the objects which are seen by the computer. A fascinating educational application of this kind of setup is that of the so-called “Augmented Reality Sandboxes” (Figure I-46). In this example, a physical sandbox is turned into a real world space in which users can create any kind of landscape simply by moving sand: different heights will be translated into different colors, projected directly onto the sand itself, representing the sea, plains, and even mountains. Simulated water can also be added by hand gestures thus allowing to create rivers, lakes, dams. This setup was successfully used for Geoscience lessons, as with an augmented reality sandbox, many slow, large, and complex Earth processes can become more apparent and tangible [72]. A wonderful open source project was also created allowing hundreds of AR sandboxes to be built around the world [73]. It also inspired the Augmented Laboratory project discussed in Chapter IV.



Figure I-46. Augmented Reality sandboxes.

1.4 Serious Gaming

The terms *serious gaming* and *serious games* refer to any application or activity based on games or gaming technology whose primary purpose is other than pure entertainment. They are employed in a variety of fields, such as education, scientific visualization, health care and architecture. Gaming technology may refer to hardware, e.g. gaming stations, controllers, goggles, and to software, e.g. videogames themselves or game engines.

In literature, those terms may refer to very different scenarios. In fact, a *serious game* originally simply referred to an educational activity based on a game [74], while today it may refer to a broad spectrum of applications [75]. In this section we focus on educational uses of computer, portable devices and gaming stations technology. This field of research includes simulation, visualization, mediated reality, artificial intelligence, collaborative design, and much more.

Enormous amounts of money are spent nowadays in research and development of gaming technology, and scientists can indeed gain great benefit by the use of this technology and have much to learn from the computer games industry [76]. One of the greatest advantage of using this technology is that it is designed to run on commodity hardware, and the related prices are very low compared to specialized workstations or professional visualization/simulation software.

1.4.1 Software

In this section we discuss two topics related to software in serious gaming.

The first one is the most obvious: the use of videogames in education, whether they are designed to be used in this field or not. In fact, some of them are created with the explicit intention of being used as learning tools. Others are not, but may still be used in education or informal contexts because teachers or researchers successfully designed learning activities based on them. This is very likely to happen in physics education, for a very simple reason: a huge variety of videogames is based on physics laws. Just think about the large number of games which include some simulation of the effects of gravity. They could be very simple games, such as 2D platform games, or very advanced 3D, first/third person ones. In either case, the quality of these games is directly related to how realistic they are, meaning how good they simulate reality or even just one aspect of reality (such as gravity). So these games actually *are* based on simulations of physics laws, and therefore can sometimes be used to discuss and even make quantitative analysis of physics phenomena (even if only of simulated ones).

In the second part of this section we introduce gaming engines as a tool for serious games development.

VIDEOGAMES IN EDUCATION

As previously hinted, the relationship between videogames and physics is very strong. Some of most important and influential games since the early history of videogames up to nowadays are based on physics laws simulation. See for example *Spacewar!* (later named to a list of the ten most important video games of all time [77]), *Lunar Lander* and *The Incredible Machine*¹² (Figure I-47 and Figure I-48): all of them were based on simulation of gravity and Newtonian mechanics, and inspired entire generations of new videogames. Today, very realistic-looking videogames incorporate mechanics laws as well as simulating optical phenomena, fluid mechanics and other physical laws and phenomena. Flight simulators are a perfect example of the strong bond of physics simulations and videogames, which can also be used in physics education [78].

Very important research institutes spent much efforts on games development. This is for example the case of the Massachusetts Institute of Technology (MIT), which developed the already cited *Spacewar!* in 1962 and invested in this research field ever since (see for example the *games to teach project* [79], the *MIT Scheller teacher education program / education arcade* [80] and the *MIT game lab* [81]).

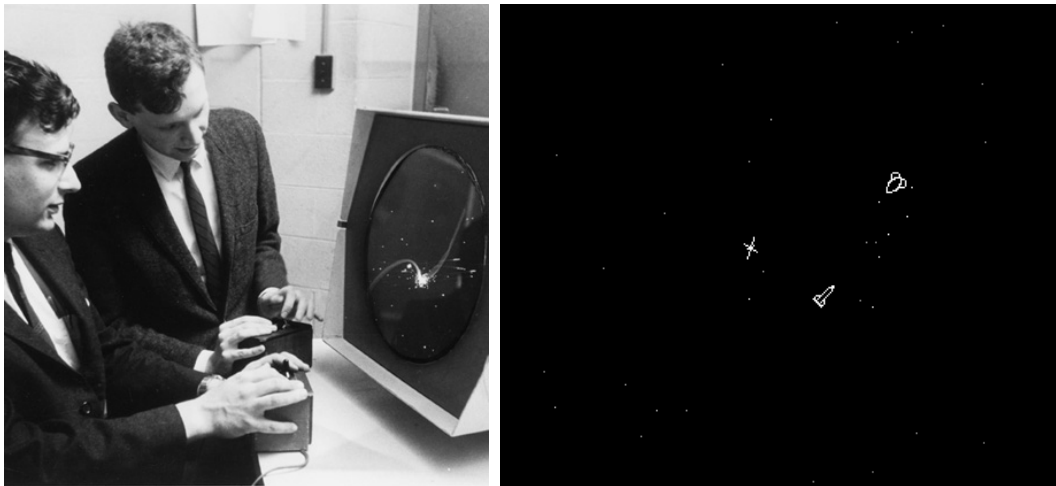


Figure I-47. *Spacewar!*, developed at MIT, was based on Newtonian mechanics simulation.

¹² Free versions of these games may be played through online emulators. See <http://www.masswerk.at/spacewar/index.html> for *Spacewar!*, <http://my.ign.com/atari/lunar-lander> for *Lunar Lander* and <https://www.myabandonware.com/game/the-incredible-machine-1mg/play-1mg> for *The Incredible Machine*.

Research framework



Figure I-48. Two screenshots of the videogames *Lunar Lander* and *The Incredible Machine*.

Two examples of videogames created at MIT for educational purposes are *Lure of the Labyrinth* [82] and *The Radix Endeavor* [83], “designed to augment math and biology instruction” and “engage middle grades students in mathematical thinking and problem-solving”. Other two of their videogames were developed using game engines and will therefore be presented in the next section.

As already mentioned, teaching/learning activities may be designed to use videogames there were not created with an educational purpose. This is somehow easy for physics activities when such games are based on physics laws and phenomena. An interesting example of this is an activity based on the videogame *Angry Birds* [84] (Figure I-49). The idea is that of using video analysis methods to track the motion of the main characters of the game, which are birds shot by the player and which follow simple parabolic motion due to gravity and no air resistance. At the webpage of ref. [85] additional materials provided by the *Open Source Physics* project regarding this activity may be found. Also, as mentioned in the webpage, “this exercise was inspired by Rhett Allain's *Dot Physics*, a physics blog for *Wired*” which may be an interesting resource for physics communication [86].

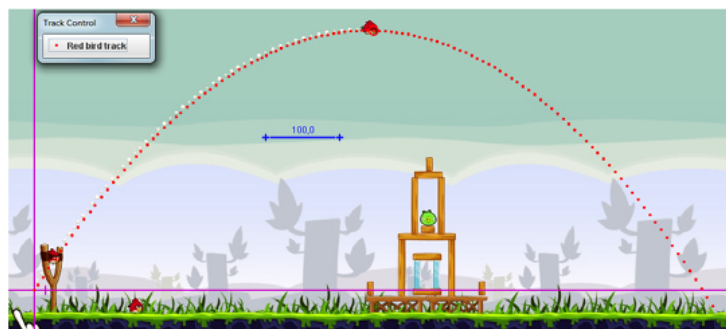


Figure I-49. Video tracking of the main character of *Angry Birds* to study kinematics and dynamics.

GAME ENGINES

A less obvious topic of software in serious gaming is that of game engines.

First of all, let us briefly see what they are and what their history is. As already mentioned, recently the computer gaming industry has grown incredibly fast and is now a very important part of the market. At the very beginning, videogames were implemented starting from zero each time. As the time went by, tools and libraries meant to assist videogame programmers started to be developed and distributed/sold. Nowadays, production costs for modern games can be compared to those of cinema movies production, so a specialization took place dividing game companies into those which design and develop new technologies and those who use them to create new games. A very important example of this process are game engines.

They are software which allow the user to create games with impressive tools at disposal, ranging from graphical engines, to 3D models, to scripts, and so on. As they play such an important role in the game industry, most of new gaming hardware comes with support and libraries to use them with game engines. Very impressive are also the resulting costs of these engines. In fact, a common adopted solution is that of letting them completely free of charge – only for games which will be sold and will result in large incomes (more than tens of thousands of dollars) a percentage of the revenues will be given to the engine's developers.

The idea is then to use this potential for educational purposes. As it turns out, they can be very helpful in the process of creating new educational software. Of course, it all depends on the software characteristics. The greatest benefit will certainly be gained from applications which want to use state-of-the-art 3D graphics. Three examples of visualization projects using game engines can be found at [87]. Immersive VR experience will also be very easy to implement because the most important Head Mounted Displays are fully supported by game engines, so it takes very little effort to take any 3D experience into VR. Also, they provide tools for the creation of 3D landscapes in a straightforward and intuitive – and also very enjoyable – way. Other than creating educational videogames, it is also possible to use these tools to build virtual museums, as suggested in [88]. Also, a project named *CaveUT* was created for the *Unreal Tournament 2004* game engine, which allowed immersive CAVE to be created in that environment [89]. Another very important feature is that of multi-user experiences. In fact, many videogames require to be multi-player, and game engines help to develop this functionality: this may be used in education to create virtual spaces that multiple users can explore together at the same time, such as virtual museums or virtual laboratories.

Research framework

Two examples of videogames developed for physics education with the *Unity* game engines are *A Slower Speed of Light* [90] and *Kirchhoff's Revenge* [91]. The former was created by the *MIT Game Lab* [81] using *OpenRelativity*, an open source tool (also created by some of the authors of the game) for *Unity*, intended to help creating software explorations of special relativity [92]. As we can read from the related webpage [90]:

“A Slower Speed of Light is a first-person game prototype in which players navigate a 3D space while picking up orbs that reduce the speed of light in increments. Custom-built, open-source relativistic graphics code allows the speed of light in the game to approach the player’s own maximum walking speed. Visual effects of special relativity gradually become apparent to the player, increasing the challenge of gameplay. These effects, rendered in realtime to vertex accuracy, include the Doppler effect (red- and blue-shifting of visible light, and the shifting of infrared and ultraviolet light into the visible spectrum); the searchlight effect (increased brightness in the direction of travel); time dilation (differences in the perceived passage of time from the player and the outside world); Lorentz transformation (warping of space at near-light speeds); and the runtime effect (the ability to see objects as they were in the past, due to the travel time of light).”

A collaboration between the authors and the Hayden Planetarium at the Boston Museum of Science also led to event *Einstein's Playground Planetarium Show* [93], in which the distorted world created by the game have been projected on the dome of the planetarium resulting in “an immersive relativistic visualization in full-dome projection” [94].

The second game is a first-person puzzle game and teaches the basic concepts of electrical circuits through a series of levels.



Figure I-50. "A Slower Speed of Light", created with the Unity game engine as an educational tool for general relativity. (Bottom right) A photo of its full-dome projection.



Figure I-51. Kirchhoff's Revenge.

1.4.2 Hardware

The gaming industry is also interesting for physics education from a hardware viewpoint. In fact, many high-tech devices have been developed for gaming and used for *serious gaming* applications. A very important feature they all have in common is their low cost, a characteristic that will always be needed for gaming technologies.

A very simple example of this is the **PlayStation 3 Eye Camera**. Released in 2007, it is capable of 60 Hz framerate acquisition with a resolution of 640×480 pixels and of 120 Hz framerate at a resolution of 320×240 pixels. They were pretty impressive specifics back then, and they actually still are also considering other perks such as its relatively high-performance in low-light conditions and a small manual zoom options. It also features a 4-microphone array that can be used for multi-directional voice location tracking, echo cancellation, and background noise suppression. An example of its use for a *serious gaming* project is an eye tracking setup described in [95]. As we can read in that paper:



Figure I-52. The PlayStation 3 Eye Camera.

“...by using mass-produced video-game hardware, it is possible to produce an ultra-low-cost binocular eye-tracker with comparable performance to commercial systems, yet 800 times cheaper. Our head-mounted system has 30 USD material costs...”

It may still be found online for less than 10€.

The second device we present is the **Wii Remote**. It was released in 2006, featuring 3 orthogonal accelerometers, an infrared sensor capable of multiple-IR-source tracking, various digital buttons, and Bluetooth connectivity that can be used to wirelessly communicate data to a computer. A more recent version also features a gyroscope. It has been used in various physics education activities, often very similarly to how smartphones accelerometers are exploited today [96] [97] [98] [99] [100] [101]. A detailed description of possible uses of the Wiimote as a data acquisition device in physics demonstrations can be found in [102].



Figure I-53. The Wii Remote.

In 2010 Microsoft introduced the first version of the **Xbox Kinect**, designed to allow players to directly interact with games by tracking their bodies and gestures. To do so, the Kinect uses an RGB camera, an IR camera, an IR source and a depth sensor. This last sensor can be very interesting for physics education as it allows to make 3D tracking of objects. A detailed description and analysis of the Kinect as a device for 3D positional data acquisition in physics experiments was proposed in [103]. The Kinect v2 was used in the setup described in Chapter IV. A very well detailed comparison of the first and the second version of the Microsoft Kinect as depth sensing devices (accuracy, precision, linearity, temperature-dependence, objects-colors-dependence, artifacts) is given in [104].



Figure I-54. The Kinect v2.

A last example of hardware that have great potential for serious gaming are Head Mounted displays, which were already presented in I.3. While they have been developed also outside the gaming world, a lot of research have been done for gaming and ultimately their recent diffusion is certainly related to the world of videogames. A very famous HMD is the **Oculus Rift**, and its importance is testified by the fact that compatibility with this device is almost always assured and displayed in new devices that can be related to mediated reality systems.



Figure I-55. (Left) The Oculus Rift device. (Right) An example of a stereo image that can be seen inside a HMD.

Research framework

Chapter II

The Scientific Visualization workshop @UniTrento

The topic of this chapter is the **“Scientific Visualization” workshop**, which was designed and held by the author at the University of Trento in 2016. It involved 40 students coming from 6 different departments, and it was open both to bachelor and master students. The duration of the workshop was 21 hours, corresponding to 3 CFU, and there were no prerequisites for attending the workshop. It is easy to understand the main challenge regarding the design of the workshop: its contents needed to be accessible to students which were completely new about coding, and at the same time it had to be useful and engaging even for the most advanced user. Therefore, in this section the design of the workshop is discussed and its results are shown, which are the final projects of the students (completely designed and coded by them), and also their feedback about the workshop. But most of all, it is argued how this format may be useful not only for students of scientific universities, but more importantly for teachers and students of secondary schools and maybe even primary schools. In fact, with this workshop it has been shown that it is possible even for students with no coding experience to design a scientific visualization app and code it by themselves within a 21-hours workshop. If all future teachers (at least of scientific topics) would have the same opportunity of acquiring these coding skills, they would be able to implement visualizations for their lessons and even be able to design completely different learning experiences for their students.

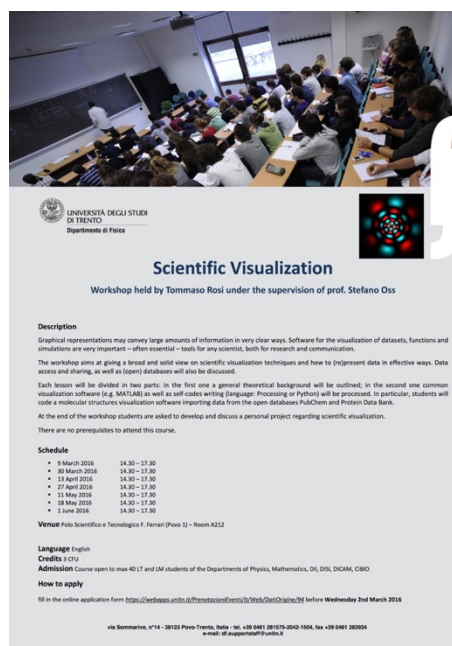


Figure II-1. The poster of the “Scientific Visualization” workshop.

II.1 Workshop description

Let us start by reporting the description of the workshop, directly taken from its syllabus:

“Graphical representations may convey large amounts of information in very clear ways. Software for the visualization of datasets, functions and simulations are very important – often essential – tools for any scientist, both for research and communication.

This course aims to give a broad and solid view on scientific visualization techniques and how to (re)present data in an effective way; we will discuss data access and sharing, meaning also (*open*) *databases*.

Each lesson will be divided in two parts: in the first one we will outline a general theoretical background and in the second one we will put our hands on common visualization software (e.g. MATLAB) and also write our own codes (language: *Processing*). In particular, we will code a molecular structures visualization software importing data from the *open databases PubChem* and *Protein Data Bank*.

At the end of the course students are asked to develop and discuss a personal project regarding scientific visualization.

There are no prerequisites to attend this course.”

II.2 Contents

The following list of contents is also directly taken from the syllabus of the workshop:

“Vision, colors, image processing

- Brief history of scientific visualization
- Colors & vision: physics and physiology
- Visualization of digital images: display technology, *RGB* & *CMYK* color models
- Image processing basics

Information design

- Elementary *plotting* techniques and *information design* basics

- Data visualization design: Edward Tufte's principles
- Languages and tools for data analysis and visualization (e.g. *MATLAB*, *Mathematica*, *R*, *GNUPlot*, *Wolfram|Alpha*)
- How to code graphs from scratch or using *libraries* such as *D3*, *Google Chart API*, *Dygraphs*, *Raphaël*

Functions and scalar fields

- *Visualization* and *simulation*: distinction and software for visualization of simulations (e.g. *VisIT*, *Amira*, *OpenDX*, *COMSOL Multiphysics*)
- 2D/3D functions and scalar fields: *color mapping* (from *heatmaps* to complex numbers representations), *contour lines*, *isosurfaces*
- 3D datasets and functions: surface rendering, (direct) volume rendering, raytracing, slicing, particle systems
- Examples of educational software (*Exoplanets*, *Molecules*, ...) also regarding specific real- and complex-valued functions (*Hydrogen!*)
- Time evolution

Databases & Big Data

- Databases: data access and *open databases*
- Big data
- Data exploration and sharing: common file formats (e.g. CSV, JSON, XML) and tools
- Case studies regarding astronomy (the *Hipparcos* and *Tycho* catalogues, *VizieR*, the *HYG database*) and molecular databases (*PubChem* and *Protein Data Bank*)

Case studies

- *Millennium Run* (or *Millennium Simulation*): N-body simulations with a number of interacting particles $\geq 10^7$ (large particle systems) run by astrophysicists to study the time evolution of matter distribution in the universe
- *Imaging* and *inverse problems*: visualization of data collected by ultrasounds, MRI, PET, TAC
- Other examples: terrain rendering, climate visualization, relativistic effects visualization...

Vectors and tensors

- Vector fields: glyphs, pathlines, streamlines, streaklines, texture advection
- Simple hints on tensor fields
- Rotation and translation matrixes

Laboratory

In the second part of each lesson we will deal with software and coding. We will use the Processing Java library and IDE. We will code a molecular structures visualization software (simple example of *particle system* visualized through *raycasting*) from scratch – molecular structures data imported from the *open databases* discussed in class. In the last session, you will have the opportunity to design and code your own visualization software, regarding any topic you like.”

II.3 Response

It was an interdepartmental workshop which involved:

- the departments of physics (DF)
- the department of mathematics (DM)
- the department of industrial engineering (DII)
- the department of information engineering and computer science (DISI)
- the department of civil, environmental and mechanical engineering (DICAM)
- the center for integrative biology (CIBio)

It involved a total of 40 students. 17 of them were bachelor students (BS) and the remaining 23 were master students (MS). The number of applications was larger than the positions available: the applicants were chosen by the simple “first-come, first-served” rule. Physicists were the most interested in the workshop (21 applications); the number of applications from other departments were comprised between 3 and 9, with an average of about 6,5. The composition of the accepted applications can be seen in Table 2.

Department	BS	MS	Sum
DF	7	11	18
DII	2	5	7
DM	1	4	5
DISI	4	1	5
CIBio	2	1	3
DICAM	1	1	2
TOT	17	23	40

Table 2. Numbers of attending students, divided by departments and study program (bachelor/ master).

II.4 Implementation

As previously mentioned, this workshop was open to a very wide audience (although from inside scientific departments), and for this reason the main challenge in its design was that it needed to be understandable and useful to students from different backgrounds and coding experience. In fact, there were no prerequisites for attending the course. At the beginning of the workshop, they were asked how much experience they had: about 2/3 of them only attended a “General Informatics” course at the first year, and 3 of them claimed to have no previous coding experience at all. We shall now discuss how the workshop was organized to overcome these difficulties.

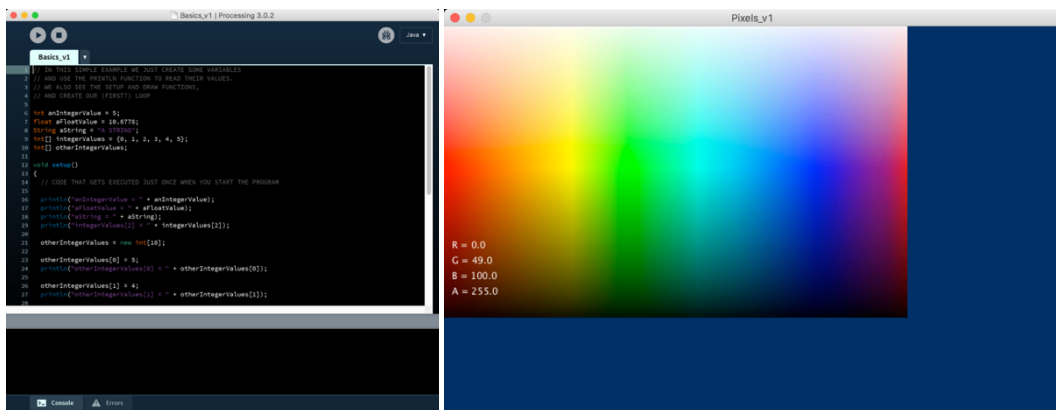
The 21 hours of the workshop were divided in 7 afternoon activities of 3 hours each. Each session was divided in 2 parts: in the first one, some theoretical topics were discussed (see the “contents” section), while in the second one they worked on coding. In this second part, they were followed and helped by both the teacher (the author) and 2 assistants and were asked to reproduce some programs, chosen to give them an understanding of a selection of useful algorithms and general how-tos. At the end of each lesson, the code was given to them in order to allow those who needed more time at home to catch up.

In the last lesson the focus was put into the design and implementation of any kind of visualization they were interested in. Actually, in the end the entire workshop revolved around this **final assignment**: from the beginning it was stressed that this would be the most important assignment and the mean for them to get the credits at the end of the workshop. So every previous coding experience was meant to give them the tools

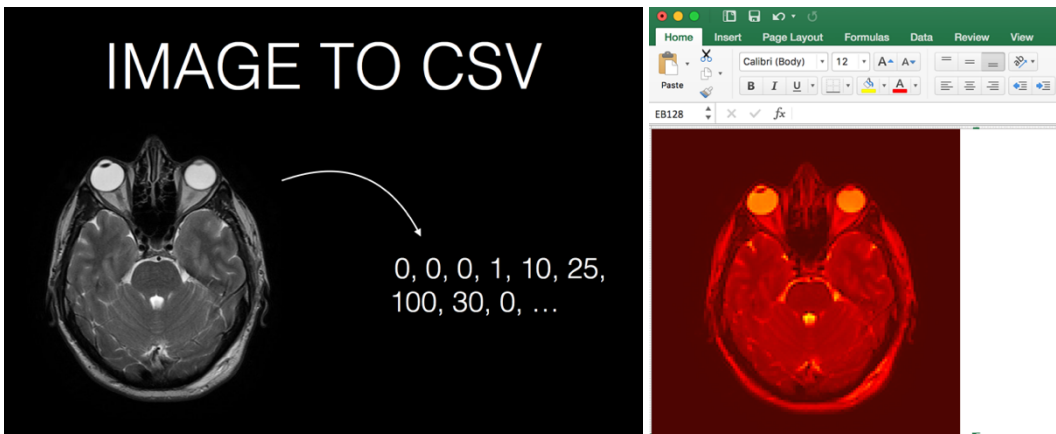
needed to succeed in this final task, and from lesson one they were asked to start thinking about the goal they wanted to aim to with this final assignment and to share their thoughts about it. This way, anyone was able to focus on obtaining a visualization of a topic related to his/her own background, and also the difficulty of this challenge could vary appropriately depending on their own capabilities level.

Let us now briefly see the contents of the coding laboratories.

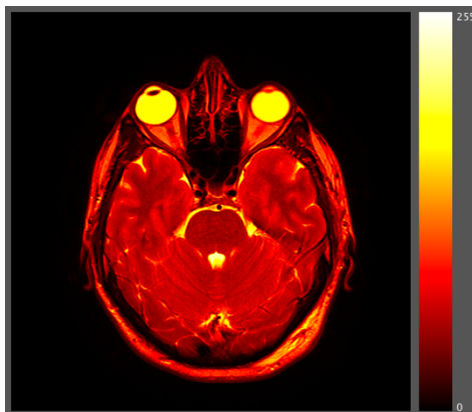
During **laboratory 1** a small introduction of general coding was given. As the topic of the workshop was visualization, the focus was put on: color reproduction through the RGB color model, how to load and display an image, how to get and set the color in a chosen pixel of an image.



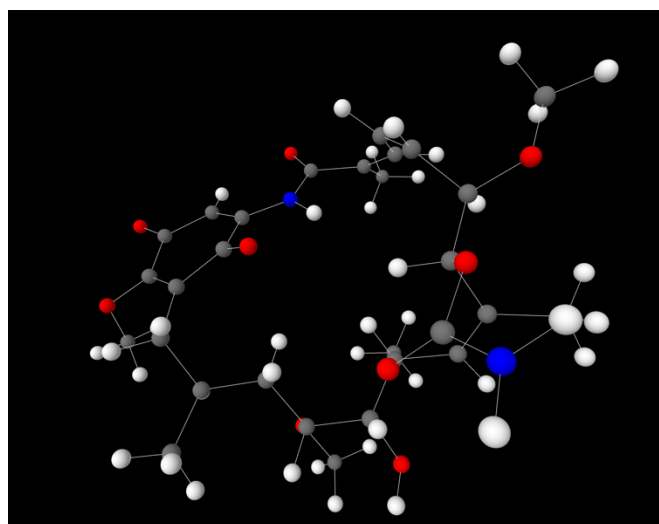
During **laboratory 2**, we accessed the integer value stored in every pixel of an image, see how to process it (for example to change the color scale of the image), and export all the values in the .csv file format, a format which many software are able to import and export. We also have seen how to import such a file in Excel and display the obtained matrix choosing a custom color scale (heatmap).



In **laboratory 3** we coded a more advanced software which allows to represent any image (or any matrix) choosing a custom color scale, introducing the use of *classes* in coding.



During **laboratories 4, 5 and 6** we coded a molecules 3D visualizer. This software was chosen because it features many aspects of coding which are fundamental to create many other visualizations, including: creating a 3D virtual space, being able to move freely in it using the mouse, importing external files of different file formats (downloaded from online open databases), storing the data into arrays, the use of classes.



As already mentioned, the last **laboratory** was entirely dedicated to the final projects.

The website:

<https://scientificvisualization.wordpress.com/>

The Scientific Visualization workshop @UniTrento

was created for sharing contents (slides and codes) and to help the teacher/students interaction, and it is still available as a small online resource.

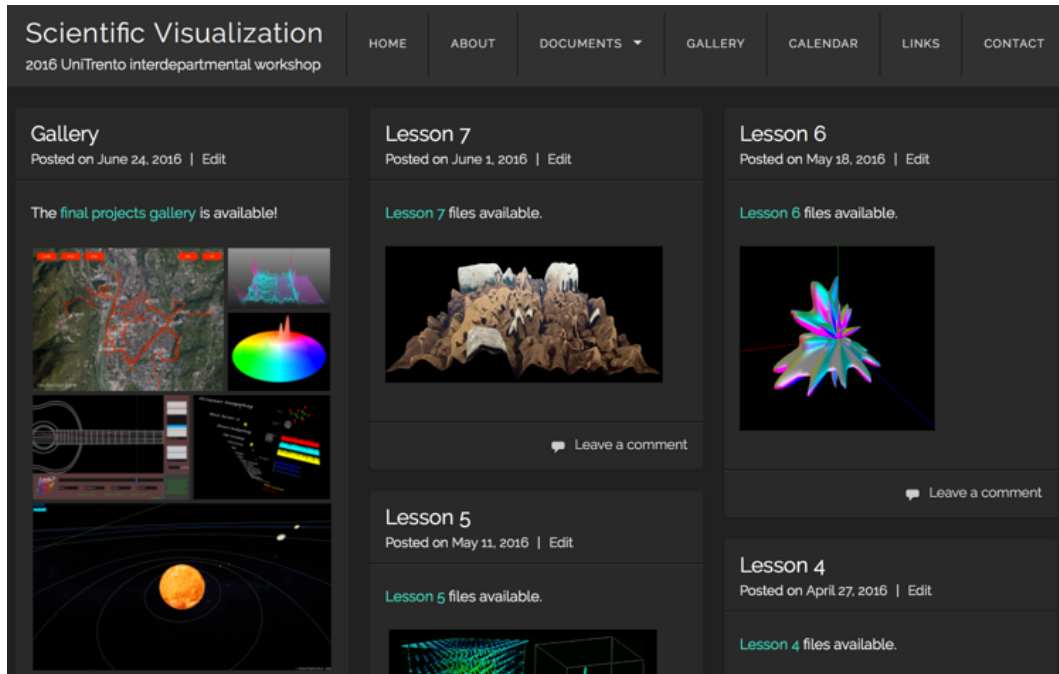


Figure II-2. A screenshot of the workshop website.

II.5 Results

At the end of the workshop, participants were asked to design, implement and present a final project. 30 students attended the entire workshop and only 1 chose not to present a final project. The overall quality of the presented projects was excellent, and it led to the opening of an online gallery on the workshop website:

<https://scientificvisualization.wordpress.com/gallery/>

In the following figures a selection of final projects is presented: in the captions, the name of the authors and of the projects is displayed.

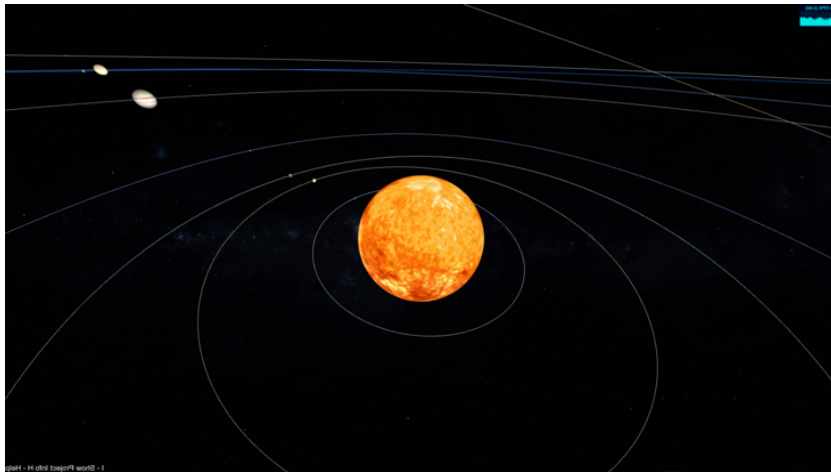


Figure II-3. Daniele Bissoli – Solar System

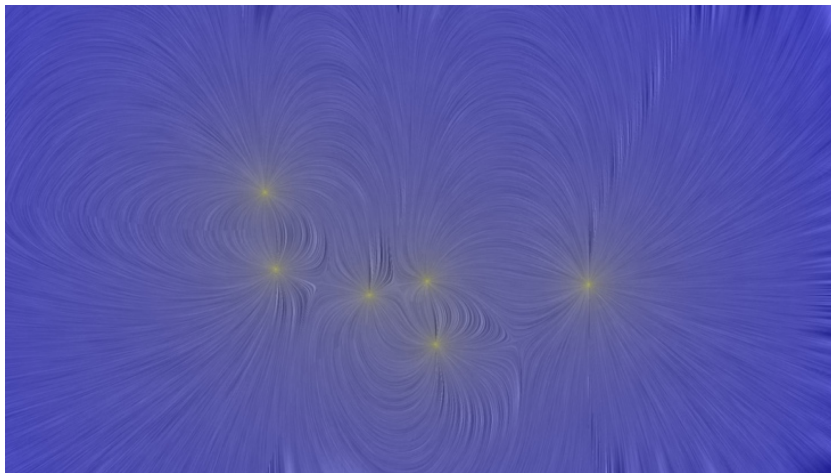


Figure II-4. Davide Marcantonio – Electrostatic LIC

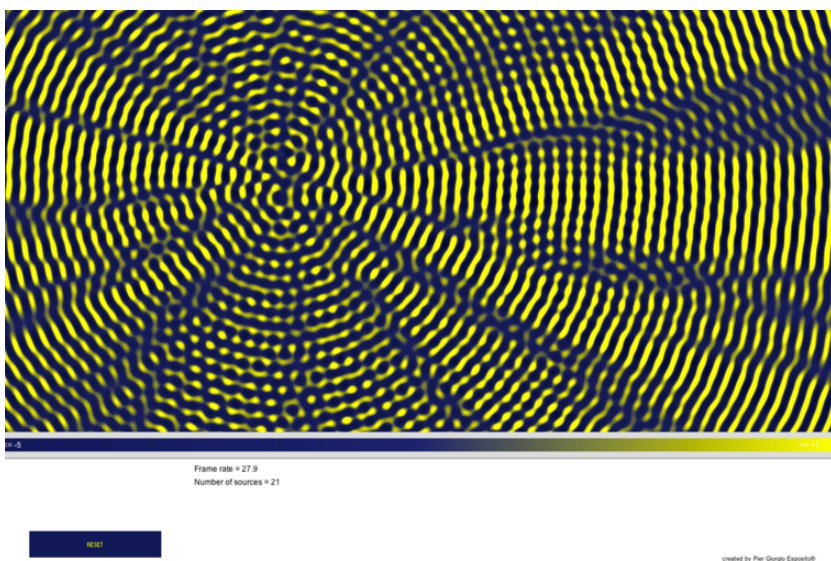


Figure II-5. Piergiorgio Esposito – Onde

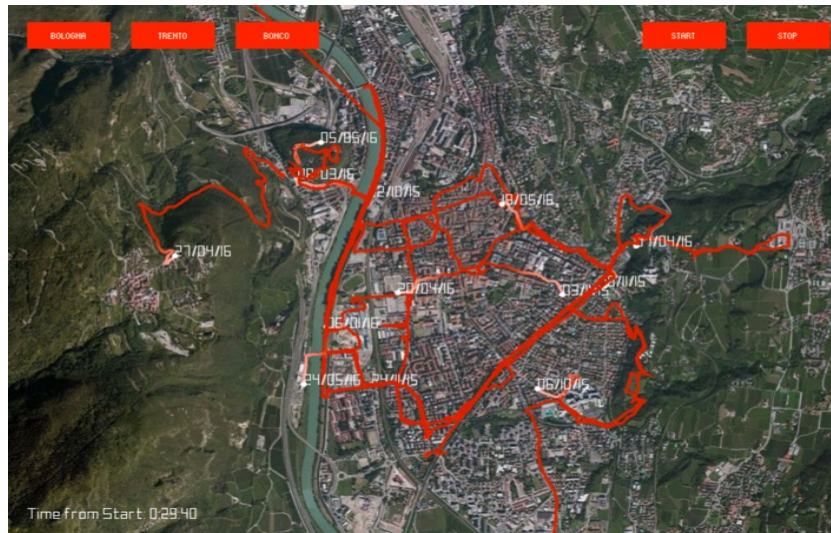


Figure II-6. Arturo Farolfi – BirdviewMap

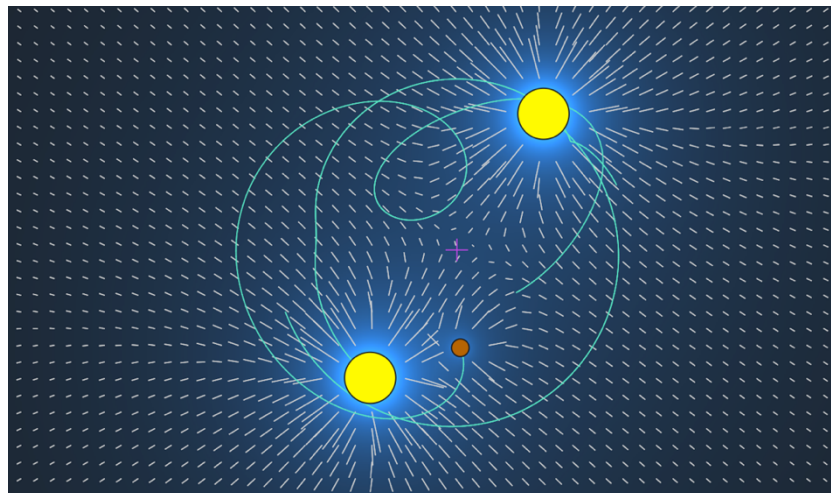


Figure II-7. Fabio Mazzà – Gravity

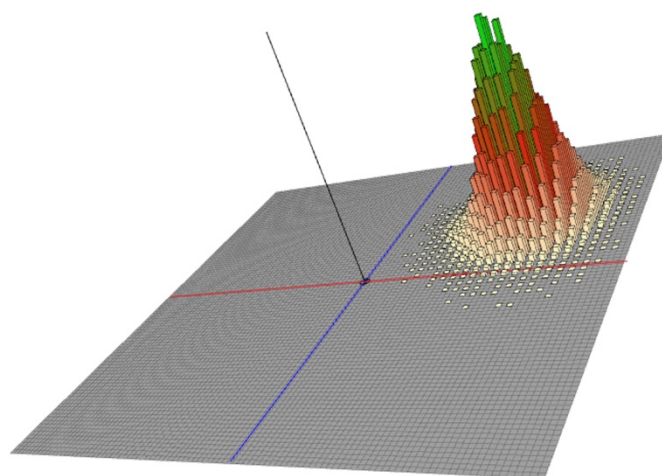


Figure II-8. Andrea Agnora – Random Walk

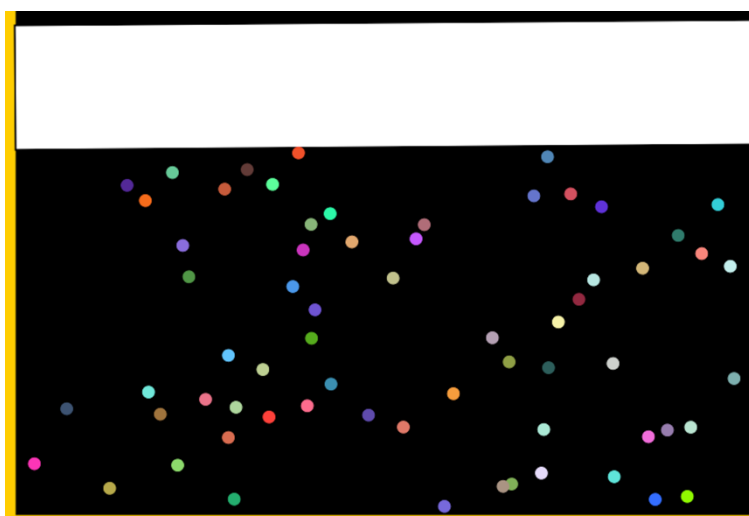


Figure II-9. Luca Lazzerera – Espansione Adiabatica

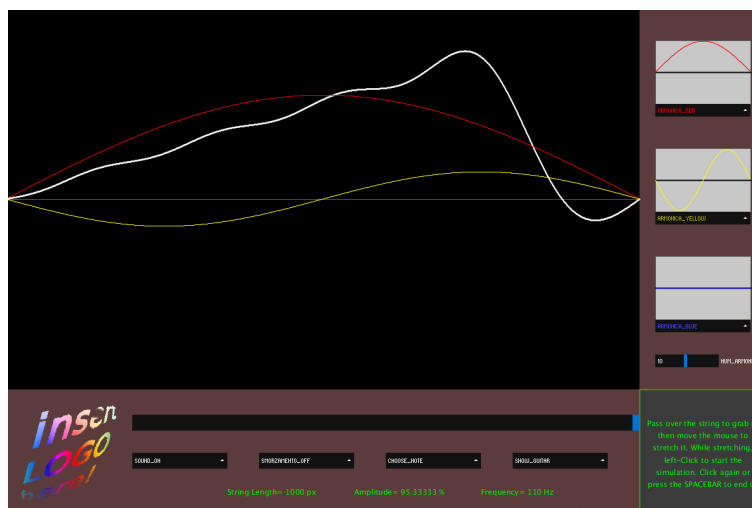


Figure II-10. Mattia Bonesi – Corda Vibrante

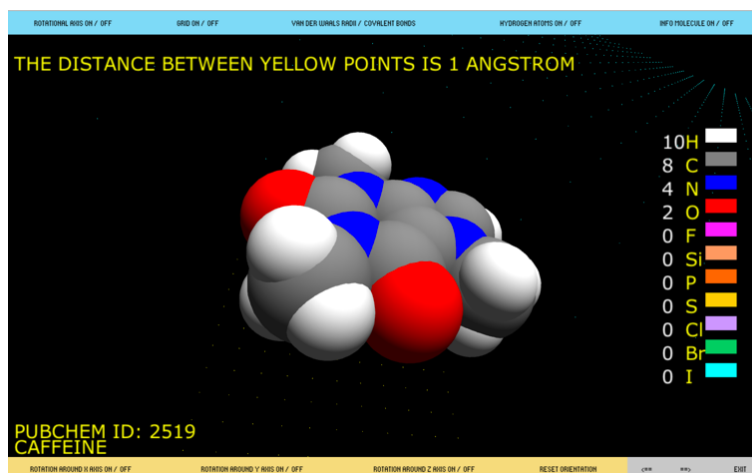


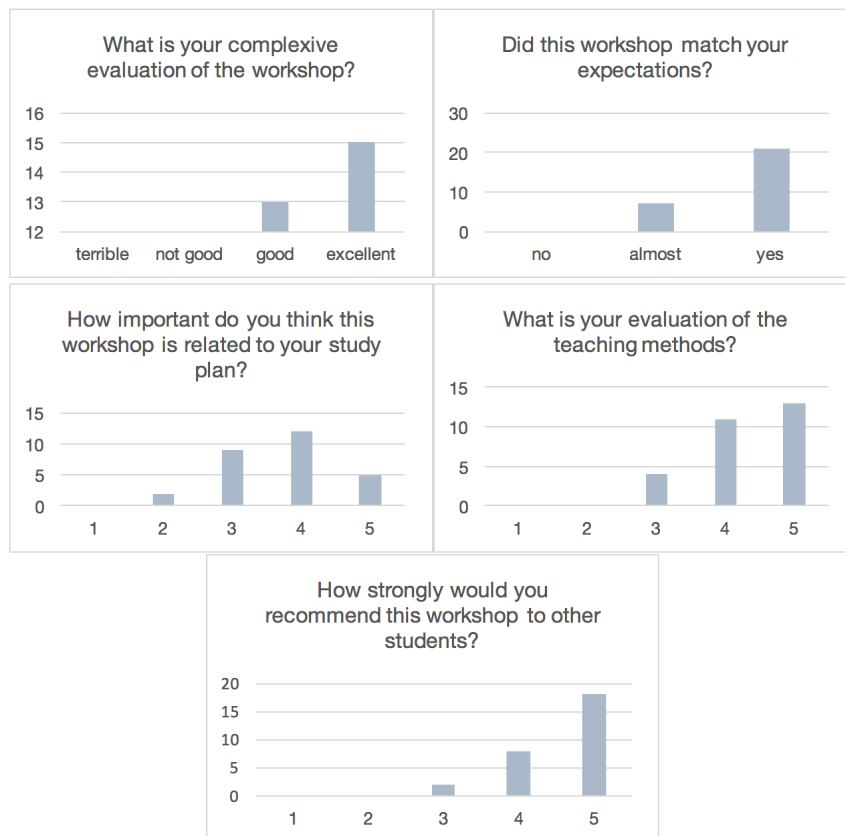
Figure II-11. Marco D'Attis – Molecule 3D

In the online gallery, you may find other projects and also a small description of each one. Also, most of the students agreed, actually very gladly, to add the codes they wrote in the gallery. So for most of the projects, it is possible to download the corresponding code from its dedicated webpage. Most of them also took some time after the approval of their projects to clean their code and to comment it. It has to be noted that this was not asked to them, so they spent some extra time only to help future viewers of the website to use their code. The result of their efforts is the creation of a small online resource that could help other students for their own scientific visualization projects.

II.6 Feedbacks and comments

At the end of the workshop, two surveys were sent to the students. The first one is an evaluation form sent to those who attended the course for its entire duration. The second one was sent to those who didn't, and it aimed to understand their reasons.

The following graphs are a summary of the received answers from the evaluation form – the complete version of the survey and the answers may be found in Appendix A (in Italian), where answers to open questions can be found too.



In the answers to the open questions the satisfaction of writing visualization codes is evident. They are seen as a useful tool for research, for work and communication.

All the participants stated they were satisfied by this experience; 9 of them also would have liked more time to deepen some topics, and 3 explicitly suggested an upgrade of the workshop to a full 6 credits course.

II.7 Survey to non-attendant students

The second survey was sent to non-attendant students, and the complete answers may be found in Appendix B (again in Italian). None of the 6 feedbacks reported a lack of interest or appreciation of the workshop: all of them blamed a lack of time for pressing reasons (thesis writing, exams, work) and most of them explicitly claimed to be very sorry for not being able to attend.

II.8 Discussion

Did this workshop act as a magical wand, turning students with no coding experience into informatics engineers? Of course not. To become good, or even discrete coders it takes hundreds, thousands of hours of study and work, and there is no shortcut for that. But this workshop had two main goals: to give some theoretical and practical background about scientific visualization and, most of all, to give even the most inexperienced student a guideline about how to design and obtain a visualization starting from scratch. They all succeeded in creating their own software importing external data and creating interactive, 3D visualizations from it. Most importantly of all, they gave themselves a goal and were able to reach it. Some of them aimed too high and had to change it, and this gave them more insight about what could they do and what they couldn't, and why.

Overall, it is the author's belief that this kind of experience is something all future teachers should pass through. Of course, not every teacher needs to be a coder, but having at least a chance of trying it is something from which they all would learn a lot from. Also, it has been shown that in a very limited amount of time the students were able to realize very good projects. Potentially, all of them now could take any experimental data gathered in an educational laboratory experience and represent it in an interactive environment. They could use this knowledge to implement their lessons

(or outreach activity more generally speaking) or it could even allow them to design their communications in entirely different manners.

At last, students of all school levels are increasingly involved in coding activities. Nevertheless, these activities rarely are visualization-centered, and this is a mistake. As always, motivation plays a major role in the learning process, and obtaining tangible results is a great motivator. It is easy to imagine that creating interactive, 2D or 3D visualizations would be perceived as obtaining tangible, satisfactory results. And it is also easy to imagine some of the students starting to spend some of their free time tweaking the codes they wrote at school, even if only guided by foolish trials-and-errors, because they are curious to see the results of their tweaks. Something very similar already happens with robotics laboratories which prove to be very attractive to many students, and they are because the results of the coding are tangible. Scientific visualization can be an alternative to robotics, with the benefit of requiring only a computer and nothing else, meaning no additional costs for schools that already have a computer room and, last but not least, that students can literally take home their results. The contents of this workshop could easily be adapted for secondary and even primary school level, and it showed that coding a visually appealing, interactive software can be not so far away as one would generally think.

Chapter III

Spectroscopy with smartphones

A Bring You Own Device (BYOD) laboratory based on smartphones is presented. It has been designed to allow students to create their own spectrometers using low-cost materials and their own smartphones. Spectra of various light sources, including an LCD monitor, and of CMYK colors printed with a common printer are qualitatively and quantitatively analyzed. The basics of additive and the –so improperly called– subtractive color mixing are discussed. Both the monitor and the printed colors can be seen using inexpensive macro lenses for smartphones or, even though it would require a bit more patience, a simple water droplet acting as a lens. The activity was tested with a group of master students (aspirant teachers) and the results are discussed.

III.1 Introduction

Color reproduction and subtractive mixing of artists' pigments are popular and motivating topics in physics education [105] [106] [107] [108] [109]. Recently it was discussed at length how spectroscopy can be an essential tool for a conceptual understanding of colors [110]. In fact, some conceptual steps, based on the spectral composition of light, its intensity, the partial transmission, absorption, and diffusion of light by a pigment, are essential to reconcile classical school knowledge about color (additive/subtractive mixing mechanism) and observation of daily life phenomena.

In recent years several inexpensive educational apparatuses, based on the employment of digital photo cameras (e.g. smartphone cameras), have been used for spectral measurements [111] [112] [113] [114]. We designed standardized variants of low cost spectrometers, where the differences in design depend on the type of grating used. Such spectrometers can be assembled very quickly (about one hour) using inexpensive materials and allow obtaining wavelength and light intensity measurements with good accuracy. By means of these apparatuses students can apply spectroscopic techniques both to the study of different light sources (light bulbs, spectral lamps, LCD monitors),

and to the diffusion/transmission mechanism of color filters or pigments. The question “what is the origin of the perceived colors?” can be addressed in a quantitative manner. In particular, using a smartphone as the detector and a PC monitor as source, students can investigate the main features of RGB additive color synthesis, and how colors are produced on digital displays. Then, using colors reproduced by a printer, they can explore how the CMYK subtractive color model works. The proposed sequence of activities is aimed at both high school and undergraduate students and has been proposed, in the last two years for preliminary testing, both to undergraduate students and to pre-service and on-service high school teachers at Universities of Trento and Pavia.

III.2 Colors and spectra

What are perceived colors and what is their relation with wavelengths of electromagnetic radiation? The problem of understanding the mechanisms underlying the perception of colors has puzzled scientists and philosophers for centuries, and its solution is tied to great names in the history of physics such as those of Young, Helmholtz, and Maxwell [115]. Young [116] was the first to hypothesize that only three kinds of color receptors exist in the human eye, which he identified as red, green and violet; and that all color sensations are produced through a combination of stimuli at these three receptors in different proportions. However, he excluded the possibility that a single “homogeneous color ray” (electromagnetic wavelength) could excite all three kinds of receptors. Helmholtz [117] was the first to clearly distinguish the mechanisms of color production by the direct mixing of light (“additive mixing”) and by the mixing of pigments (“subtractive mixing”). He also was the first to provide a physical explanation for subtractive mixing. Maxwell [118] performed a number of quantitative experiments on additive color mixing, distinguished the colors perceived by the receptors of Young’s theory from the primaries in abstract color space, and he disproved Young’s assertion that no single wavelength could excite all three kinds of receptors through an argument, based on the fact that all colors appear as white when observed at very high intensity, which maintains its force even today.

As already mentioned in I.1.1, a crucial observation based on physiology is that our brain is not capable of uniquely assigning different colors to visible electromagnetic signals with different spectral distributions; in fact, it is possible that all three types of receptors (Figure III-1) respond with identical outputs to some mixing of color signals with different spectral distributions. This is a phenomenon known as *metamerism*, and in fact, constitutes the basis for the possibility of producing the sensation of spectral

colors by additive mixing of other spectral colors, e.g. the reason why yellow can be produced by mixing red and green light.

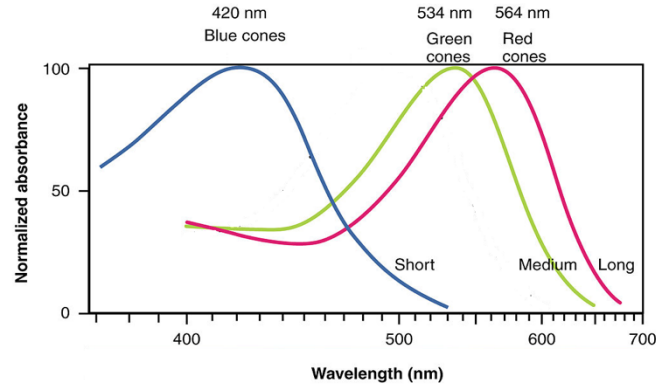


Figure III-1. Normalized spectral sensitivities of human cone cells of short- (S), middle- (M) and long- (L) wavelength types. Adapted from [152].

Starting from the eighteenth century, the trichromatic theory of color representation was developed; at its heart, the theory states that “any” color can be reproduced by mixing appropriate amounts of three primary colors, provided their spectral energy distributions are linearly independent, and cover the whole visible spectrum.

Erwin Schrödinger gave an important contribution to the theory of color. In a 1920 paper [119] he introduced the concept of ideal pigment, whose reflectivity spectrum assumes only the values 0 and 1, and has at most two transitions from 0 to 1 or vice versa. He proved that colors obtained by ideal pigments are optimal, in the sense that they have the maximum possible brightness for a given spectral purity. The concept of ideal pigment has been since used in the analysis of a number of problems related to color, and as we will see is tightly connected to the modern theory of the representation of color in printers. In Figure III-2 we show the ideal transmittance of the ideal pigments associated to the six colors (Red, Green Blue; Cyan, Magenta, and Yellow) commonly used as primaries for additive and subtractive color models. The brightness of a pigment is optimal when the transmission spectrum has only regions with either zero or unity transmission, and the number of 0/1 transitions is as small as possible. We are here using transmittance instead of reflectivity because analyzing the transmittance of printer colors with the spectroscopes is simpler than of using reflectivity.

The mechanism of color perception by the human brain has some curious consequences, the best known of which being the case of magenta. Magenta does not belong to the solar spectrum and cannot be associated to any monochromatic wave;

Spectroscopy with smartphones

however, the color sensation it produces is homologous to the one associated to spectral colors. We can think about magenta as the equal stimulus of red and blue receptors while the stimulus on the green receptors is comparatively negligible. It must be noted that, in the language of Schrödinger's ideal pigments, magenta-type colors result from the only possible kind of ideal pigments which have two separate spectral zones with reflectivity equal to one.

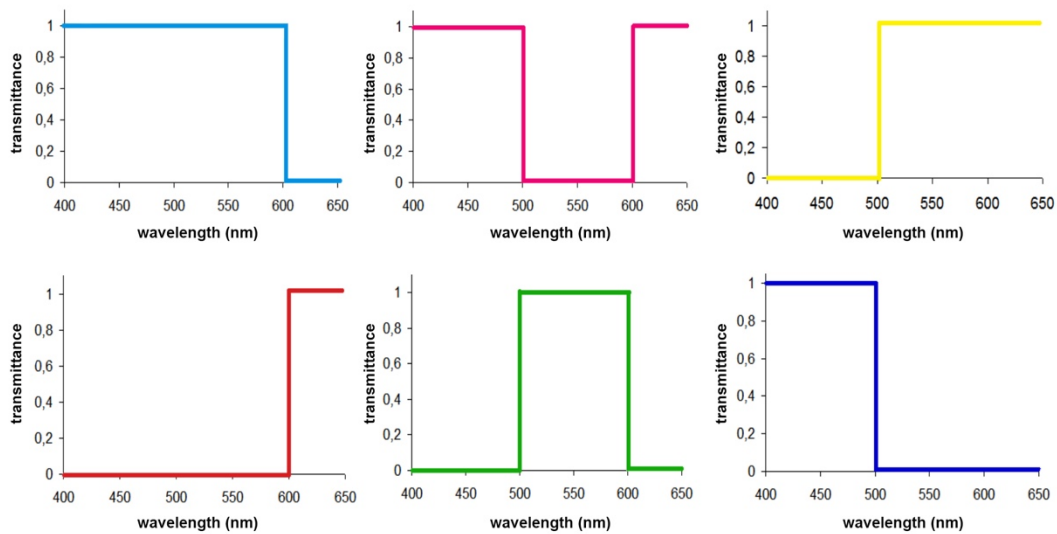


Figure III-2. Spectra of ideal pigments with one or two transitions of transmittance, sketched for six colors used for additive and subtractive mixing. For other colors such as orange or violet–blue, only the spectral locations of the transitions are different.

The theory of colors is nowadays well understood; its foundations have been treated in great detail in monographs [120] [121] [122] [123] and the basic ideas are summarized in several articles [124] [125]. As already mentioned, the understanding of how human color perception works is the basis to create color reproducing devices. In Chapter I we already introduced how monitors and printers work: we shall now summarize what was discussed regarding the former and see in more detail the latter.

III.2.1 How a PC display works: the RGB additive model

Computer monitors and televisions, as well as other devices' displays, create images using the RGB additive color model: starting from a black background, each of the display's pixels may reproduce any color within the RGB gamut by adding a well-defined mixture of red, green and blue. An ideal 8-bit monitor features $2^8 = 256$ different red, green and blue luminosity levels, resulting in more than 16.7 million

different colors. In RGB, the three colors are emitted by physically separated elements (Figure III-3), yet these are so small that our eye cannot typically resolve them and their emitted light overlaps on the retina resulting in a single color impression. Identical values of the three color components result in different shades of grey, with maximum values corresponding to white color.

Note that the observation that light overlaps on the retina and creates a single color impression is by no means sufficient to explain additive mixing. As previously remarked, the physiology of the human eye must be taken into account, at least in broad terms. For example, red and green creates yellow, because the human eye does not have a specific receptor for yellow. If it did, light composed of only red and green wavelengths would create a different impression, made up by the brain, for something that is red and green, but not yellow. In fact, blue and red do not make something like green, or another color intermediate between them. They make magenta instead, which is an impression “constructed” by the brain to define something that is blue and red, not green. We mean constructed, of course, to the same degree that all the sensations associated to colors are “constructed” by the brain.

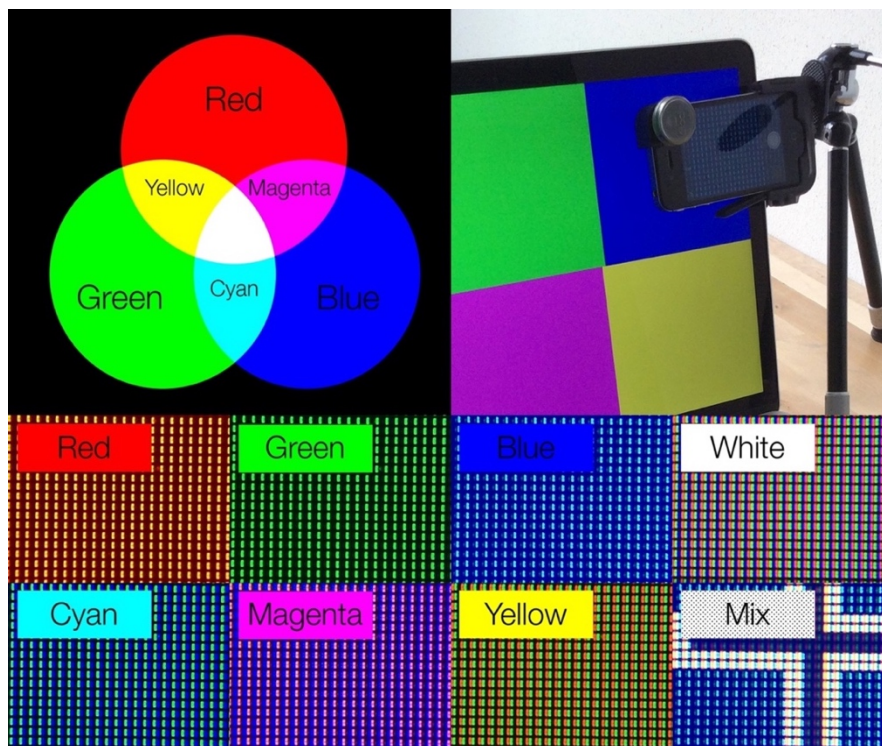


Figure III-3. (top left) The RGB additive color model. (top right) Cheap macro lenses can be used to take photos of the monitor's pixels. (bottom) Photos of some colors reproduced on the monitor: the RGB triads are well seen. Here we used the monitor of a MacBook Pro (Retina, 15-inch, Mid 2015).

III.2.2 How a printer works: the CMYK subtractive model

A printer works by using both subtractive and additive color mixing. The superposition of two or three primary pigments (Cyan, Magenta and Yellow) leads to darker colors; however, pure black cannot be obtained using CMY under standard lighting (a very dark brown is obtained by mixing cyan, magenta and yellow in equal proportions), so usually a black pigment is also used. The printer places ink on the paper sheet in dots which have different dimensions according to the desired intensity for each primary color, and along lines which have different orientation for different primary colors (Figure III-4). As a consequence, the superposition of different primary colors ink is never complete, and the result is a pointillized coloring scheme, with areas of pure CMY colors, areas of colors obtained by superposition (subtraction), and some white spots. These areas are seen by the eye as only one color because of *additive* mixing in space average. Thus, in order to understand how a CMYK printer works, both the subtractive and additive color syntheses must be taken into account.

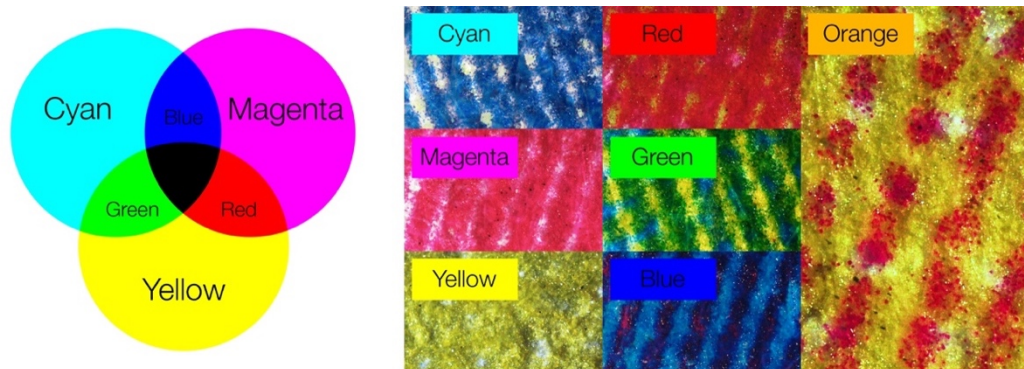


Figure III-4. (left) The CMY subtractive color model. (right) Macro photos of printed colors (on the left, the pure, fully saturated CMY pigments; on the center, the RGB colors obtained as the “addition-subtraction” of two CMY pigments; on the right, an example of the different mixing of CMY pigments to obtain a custom color). Typical widths of the strips are about 0.15 mm. The used laser printer is a Samsung CLX-3305FN.

III.3 The spectrometers

III.3.1 How to make your hand-made spectrometer

First of all, we tested three different kinds of spectrometers: two were based on light transmitted through a diffraction grating and the third one on light reflected by a CD used as a reflection diffraction grating.

The first one, S_{500} (Figure III-5, B), employs a 500 l/mm transmission grating with a direct alignment. The second one, S_{1000} (Figure III-5, C), uses a 1000 l/mm transmission grating with a non-linear geometry. A third kind of spectrometer use a reflection grating, made with a Compact Disk (500 l/mm) with a non-linear geometry configuration. All the spectrometers were assembled using black cardboard. A narrow slit (a bit less than 1 mm of width) is cut at an end of the collimating tube, in order to give us a narrow beam of light. The transmission grating, on the opposite side of the tube, disperse the beam of light with different colors at different angles. The tube, in combination with the slit, acts to ensure that only approximately collimated light is focused by the camera lens on the smartphone.

Since the 1000 lines transmission grating and CD reflection gratings require a well-defined incident angle of the incoming light on the grating, they can be slightly less straightforward to build for inexperienced students. Thus, students in our tests assembled their own spectrometers of the first type, S_{500} , employing a 500 lines/mm transmission grating.

Students captured photos with their own smartphone using the free app *Open Camera* [126] or *Luff* [127] which allows to manually set the camera's focus, ISO and exposition, in order to set them at constant values for different measurements. The images acquired by means of the camera are analyzed with the *Tracker* video analysis software [31] which provides direct measurements of RGB channels and of the brightness of each pixel along a line profile.

Spectroscopy with smartphones

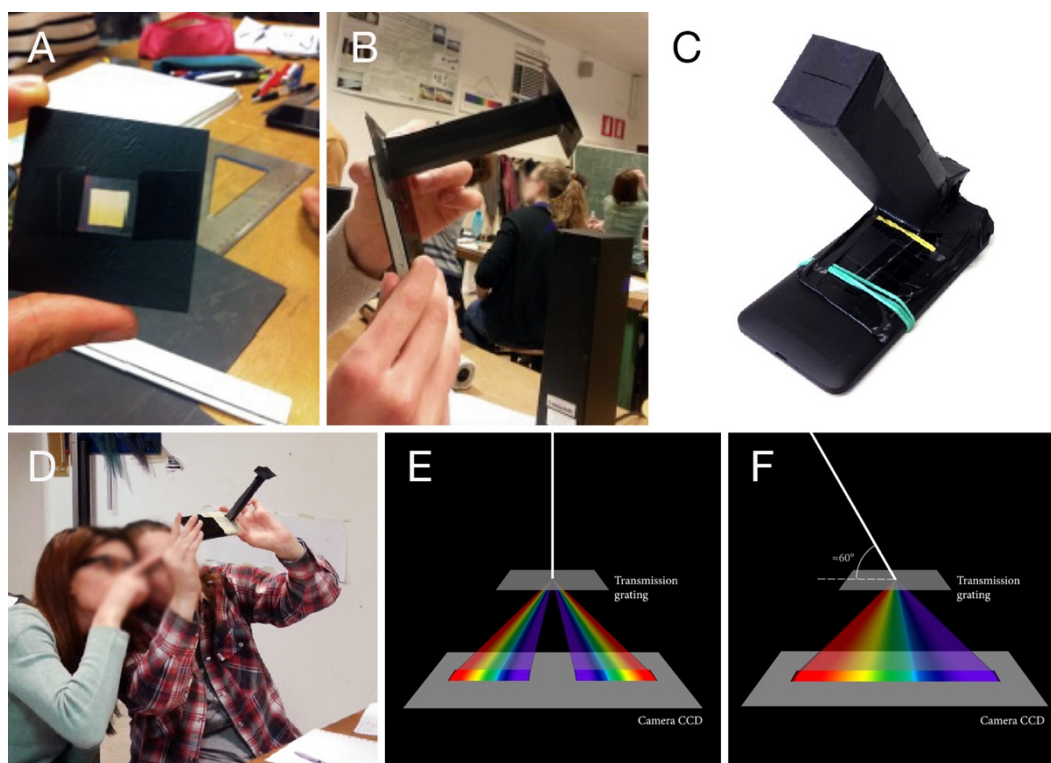


Figure III-5. (A) A diffraction grating used to build the spectrometers. It will be placed near the smartphone's camera. (B) The spectrometer S_{500} , which employs a 500 l/mm transmission grating with direct geometry. (C) The spectrometer S_{1000} , based on a 1000 l/mm transmission grating which needs light to enter with an incident angle of about 60° . (D) Two students using a spectrometer. (E, F) The two schemes representing how the light spectra are impressed on the camera CCD using the two different transmission gratings.

III.3.2 Calibration procedure

The calibration procedure for the spectrometers requires two steps: the wavelength calibration (λ -calibration) and the intensity calibration (I-calibration).

λ -calibration

A commercial fluorescent lamp is used to calibrate the spectrometer. The spectrum of this lamp shows many peaks distributed over the range of wavelengths of visible light. Once students acquire some pictures of the spectral lines (see an example in Figure III-6), they accurately measure the positions (in pixels) of their peaks with *Tracker*. They can then create a plot containing the known wavelengths of the lamps' peaks *vs*

the measured position (see an example in Figure III-7). A linear fit can now be done to obtain a linear relation between wavelengths and position. The uncertainty in the wavelength measurement inferred using this kind of fit is below 3 nm for the S_{500} .

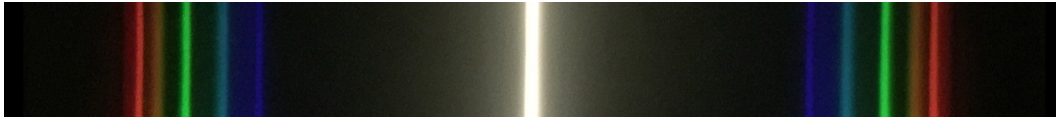


Figure III-6. Example of photo obtained with a S_{500} spectroscope using a fluorescent lamp.

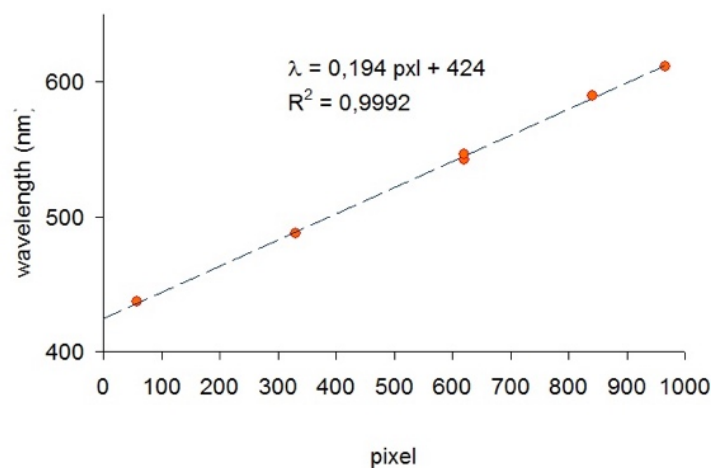


Figure III-7. For the λ -calibration we use a commercial fluorescent lamp. We acquire pictures of the spectral lines, and measure the positions of their peaks using the *Tracker* software. An example of obtained wavelength–pixel calibration values of the spectrometers based on the fluorescent lamp spectrum is plotted.

I-calibration

Tracker can measure the brightness along a line in an image using the “line profile” tool. It has to be noted that a *naïve* use of this tool would lead to measurements with a systematic error in them. See for example Figure III-8, A and B. Here we used a variable transmission filter and summarized the resulting measurements of the corresponding brightness (in luma): we did not obtain a linear dependence between transmission percentage and brightness, as one would expect.

It is possible to obtain correct results in two different ways: to analyze data of pictures taken in a *raw* format or to use the so-called gamma correction. In fact, differently from jpeg images, raw format images conserve the linearity of the acquired

data. But it may be more complicated to use raw images, for example because it might be more difficult or even impossible to save in raw formats with the devices at hand. For this reason, we opted to use gamma correction. To obtain the measure of light intensity from the RGB measured values, we use the formula:

$$Y_{\text{measured}} = 0.2126 R^\gamma + 0.7152 G^\gamma + 0.0722 B^\gamma$$

where Y is a measure of luminance (which is proportional to emitted light intensity per unit area) and $\gamma = 2.2$ is the factor expressing how the luminance on the screen in the image depends on the 8-bits RGB color values [128]. The gamma corrected results of Figure III-8, B can be seen in Figure III-8, C, where linearity is finally preserved.

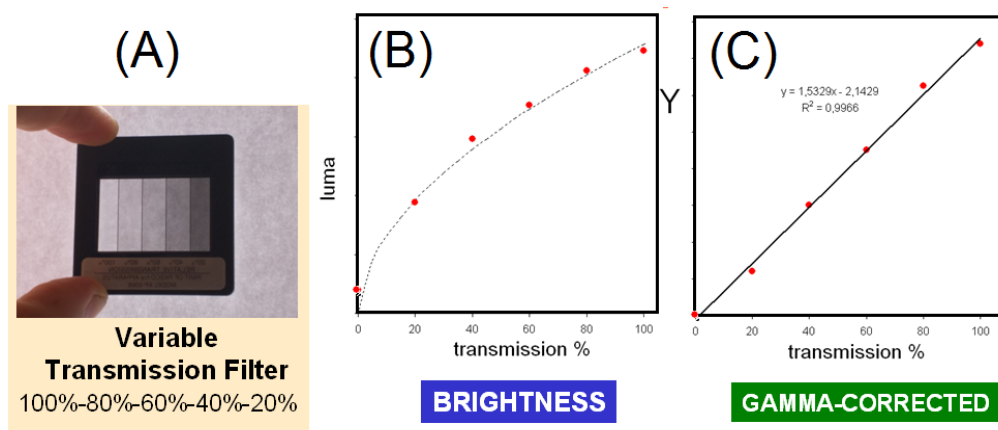


Figure III-8. (A) Jpeg image of light passing the variable transmission filter. (B) Brightness versus transmission as measured without gamma correction. (C) Luminance measured using gamma correction.

The value of luminance obtained also depends on the overall response of the apparatus (CCD camera, lenses and so on). As such, we have to evaluate the relative sensitivity (or ‘spectral response’, see [129]) of the apparatus by measuring the light spectrum from a known source. We use known data for the spectral irradiance, $I_{s_0}(\lambda)$ of a solar disk on Earth’s surface and compare that with our measurements of the solar spectrum, $Y_{s_0}(\lambda)$. Thus we experimentally obtain the relative sensitivity, $R(\lambda) = Y_{s_0}(\lambda) / I_{s_0}(\lambda)$, (as reported in [129]) which converts the measured luminance in the actual intensity, in arbitrary units, for any source: $I(\lambda) = Y(\lambda) / R(\lambda)$. An example of measured relative sensitivity of one of our apparatuses is shown in Figure III-9.

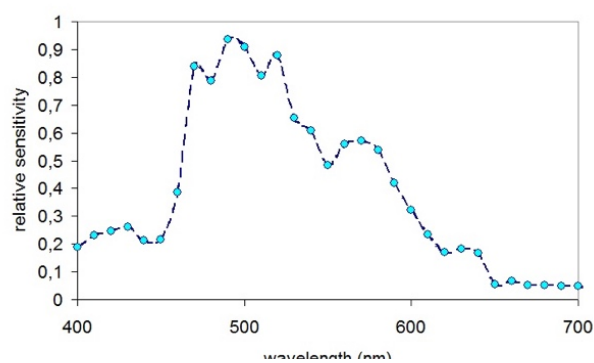


Figure III-9. Measured relative sensitivity for our apparatus.

III.4 Measurements and results

III.4.1 Light sources

Using the home-made spectrometers students were able to investigate different light sources and better understand the physical mechanisms which govern the light emission.

Students, after the construction of their own spectrometers, performed direct spectral measurements of different sources of light. For example, as shown in Figure III-10, A and B, the light emitted by a fluorescent lamp and by an incandescence bulb are compared to show the differences between a continuous and a discrete spectrum. Then they investigated the spectra of many different spectral lamps (H, He, Ne, Ar, Hg) looking for the fingerprints of the emitting substance. Students also measured the quasi-monochromatic light emitted by LEDs and analyzed the broadening of the peaks, for example: a red band in the emission of a green LED; or a cyan band in the emission of a blue LED.

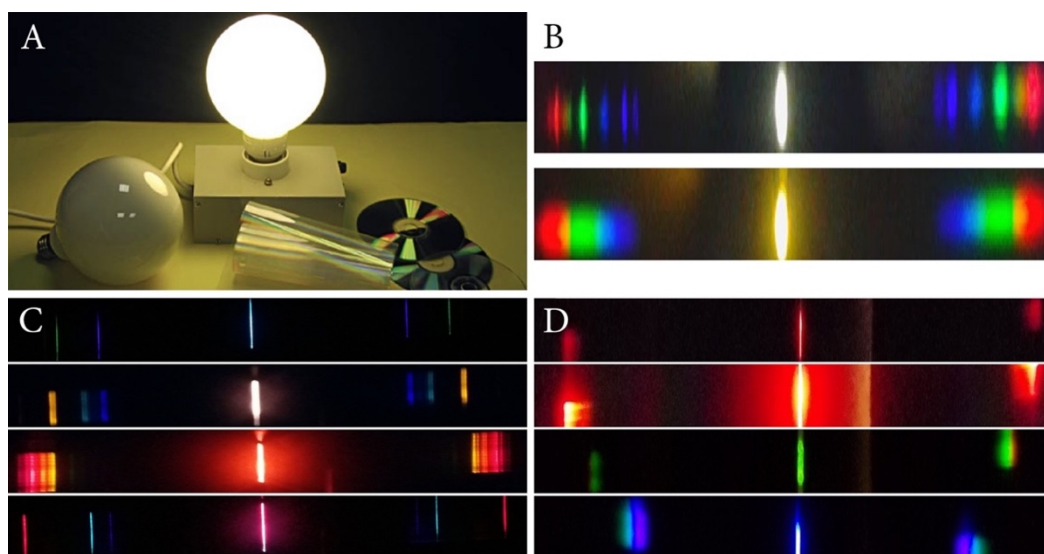


Figure III-10. (A) Two undistinguishable lamps, a fluorescent and a filament bulb. (B) Comparison between the spectra of a commercial fluorescent lamp and an “old” filament light bulb, showing the differences between a continuous and a discrete spectrum. (C) Atomic spectra obtained by students using their home made spectrometers. (D) Spectrum of 4 LEDs, from top to bottom Red, Orange, Green and Blue.

III.4.2 Additive mixing: emission from a PC monitor

In order to detect emission, a PC monitor is used as source and the spectrometer is oriented toward the monitor in a dark environment. The extent to which the monitor produces RGB values significantly depends on its settings. The monitor used in this work is that of a MacBook Pro (Retina Display, 15-inch, Mid 2015) with the “Color LCD” default settings: this is known to adhere reasonably well to the specifics of the standard RGB (sRGB). Figure III-11 shows a collage of the spectra for different colors produced by the monitor and captured by our smartphone-based spectrometer (iPhone 4s).

In the right panel we show the spectra for different colors produced by the screen in agreement with RGB additive mixing of colors.

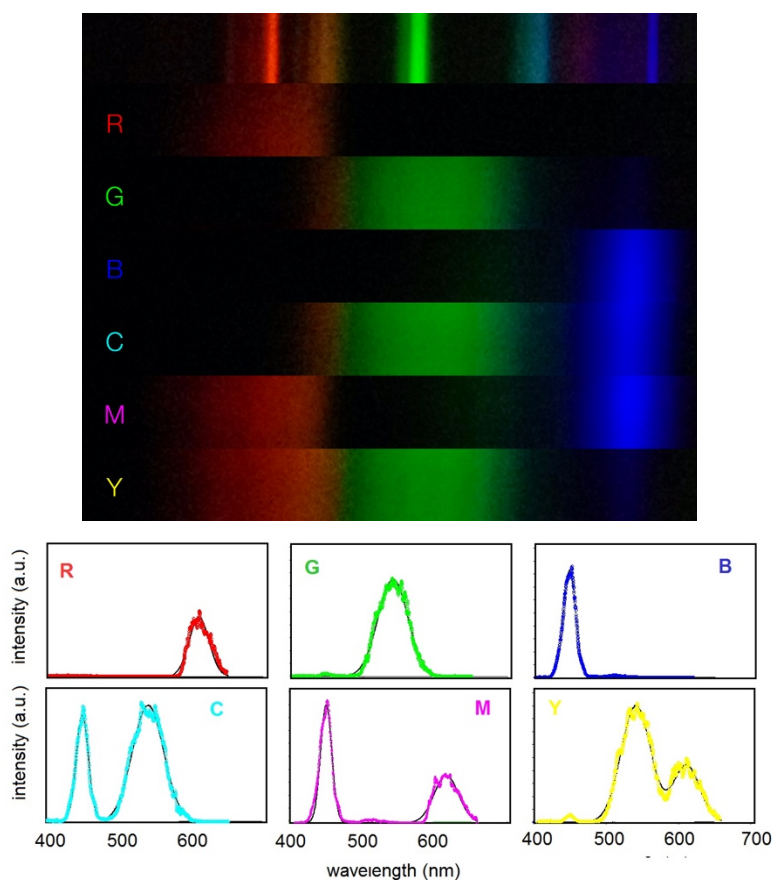


Figure III-11. The intensity of photoemission, $I(\lambda)$, measured with the spectrometer for the different colors on the monitor. (Top) Collage of the acquired photos used for the measurements. On the top the spectrum of the fluorescent lamp used for the wavelength calibration (λ -calibration) is shown. Strips R, G, B, C, M, Y come from photos of the spectra when the screen displays the corresponding color. (Bottom) $I(\lambda)$ is reported in arbitrary units on the same scale of intensity for all the panels.

In order to compare the results of our measurements with theoretically expected values one has to compute the maximum intensities corresponding to the value 255 of R, G and B. The coordinates of the RGB primary colors in terms of the *CIE* $x\bar{y}\bar{z}$ color space primaries are defined as

$$R = (0.64, 0.33, 0.03)$$

$$G = (0.30, 0.60, 0.10)$$

$$B = (0.15, 0.06, 0.79)$$

And the white point D65 recommended by the sRGB specifics, which is an estimation of the white color produced by mid-day sunlight is, again in $x\bar{y}\bar{z}$ coordinates:

$$D65 = (0.3127, 0.3290, 0.3583)$$

Thus, in order to determine the maximum relative intensities of the R, G and B components, the following matrix equation must be solved

$$\begin{pmatrix} 0.64 & 0.30 & 0.15 \\ 0.33 & 0.60 & 0.06 \\ 0.03 & 0.10 & 0.79 \end{pmatrix} \begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} 0.3127 \\ 0.3290 \\ 0.3583 \end{pmatrix}$$

By doing so we find the values $r = 0.213$, $g = 0.392$, $b = 0.396$ for the maximum intensities of linear R, G, B components in arbitrary units.

We shall now see that these computed values agree well with the measured intensity values for pure Red, pure Green and pure Blue colors displayed on the screen.

The spectral line shape function should be described as a Gaussian distribution. Thus we use a multi-Gaussian fit, considering from 1 to 3 peaks,

$$I_p(\lambda) = \sum_n I_n e^{-\frac{(\lambda-\lambda_n)^2}{\delta_n^2}}$$

to evaluate the position of the emission peaks, their intensity and their line-width, δ_n . Quantitative results are reported in Table 3.

Color	Red peak			Green peak			Blue peak		
	λ_R	δ_R	$Y(\lambda)/R(\lambda)$	λ_G	δ_G	$Y(\lambda)/R(\lambda)$	λ_B	δ_B	$Y(\lambda)/R(\lambda)$
Red	611	20	23	-	-	-	-	-	-
Green	-	-	-	541	30	37	-	-	-
Blue	-	-	-	-	-	-	448	12	41
Cyan	-	-	-	541	31	45	450	12	41
Magenta	616	24	22	-	-	-	450	11	50
Yellow	612	26	22	542	29	45	-	-	-
<i>Mean</i>	613	23	22	541	30	42	449	12	44
<i>Deviation</i>	3	3	1	1	1	5	1	1	5

Table 3. Data of the wavelengths of the emission peaks: emission peaks position and values of widths in nm and relative intensity in a.u.

We can compare the ratio for the maximum intensities of linear R, G, B components. For example, two comparisons give us:

$$\frac{I_R}{I_B} = 0.51 \pm 0.05 \text{ versus a theoretical value of } 0.54, \text{ and}$$

$$\frac{I_G}{I_B} = 0.96 \pm 0.05 \text{ versus a theoretical value } 0.99.$$

The peak wavelengths obtained can be compared to the dominant wavelength [130] of the R, G, B primaries of the sRGB specifics, which are 613.8 nm for Red, 542.4 nm for Green, 456.6 nm for Blue. Our measurements give $\lambda_R = 613 \pm 3$ nm, $\lambda_G = 541 \pm 1$ nm and $\lambda_B = 449 \pm 1$ nm.

III.4.3 Subtractive and additive mixing: transmission spectra of laser printer colored strokes

In order to detect light transmission by ink pigments of a laser printer, colored strips are printed on a white paper which is placed on top of the collimating slit and sunlight is used as source. As already mentioned, in our experiments we measure the transmission, and not the reflection spectrum¹³. However, in the diffusion approximation for light propagation in optically turbid media [131], a photon can be said to undergo several, effectively isotropic scattering events before being absorbed, or exiting the material. In this approximation, the transmission and reflection spectra differ at most by a multiplicative constant. Even if the diffusion approximation is not strictly valid, the transmission spectrum should provide a reasonable estimate of the characteristics of the reflection spectrum.

Figure III-12 shows a collage of the spectra for light passing through each one of the colored strips and captured by the spectrometer. The continuous spectrum of sunlight is evident, as are the principal spectral lines from the white fluorescent light source used as wavelength reference. We notice that, when light passes through the colored strips, some colors disappear. For example, yellow pigment absorbs blue and transmits red and green, magenta pigment absorbs green, green pigment absorbs blue and red and so on. The selective absorption/transmission of wavelengths is the basic block of the subtractive color model, which explains how the mixing of a limited set of pigments creates a wider range of colors. As it may be noticed in the same figure (and

¹³ With some modifications to the experimental apparatus it would also be possible to study reflection spectra: see for example the smartphone-based ophthalmoscope of [126].

Spectroscopy with smartphones

more quantitatively in Figure III-13), transmission is very different from the “all or nothing” model of ideal pigments, but it is a smoothly-varying function.

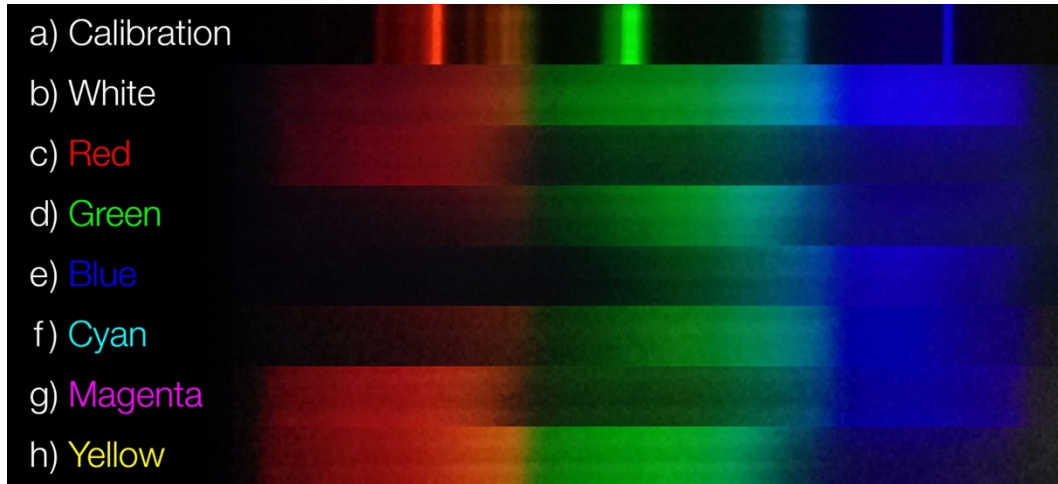


Figure III-12. Strip a shows the spectrum of the fluorescent lamp used for the wavelength calibration (λ -calibration). Strips b, c, d, e, f, g, h come from a single photo of the spectra of sun light passing through the colored ink lines (c-h) and white paper (b). Strip b is also used for the intensity calibration (I-calibration).

Spectral data measurements are obtained by analyzing the photos: light intensity versus the actual position in the photo is obtained by using the *Tracker* software, and the intensity profiles, $I_M(\lambda)$, are constructed by means of the calibration line.

In order to measure the transmittances, we need to compare the spectra of the original and of the transmitted light recorded under identical conditions, thus we use a single photo where both the transmitted and the original spectra (after passing through the white paper) are acquired.

By comparing the intensity measured when sunlight traverses the white sheet only, and the one measured when it passes through the colored lines, we can obtain the transmittance at different λ values. The transmittance $T(\lambda)$ of a sample is defined as its effectiveness in transmitting radiant energy. It is the fraction

$$T(\lambda) = \frac{I_T(\lambda)}{I_0(\lambda)}$$

of incident electromagnetic power that is transmitted through the sample. We identify $I_0(\lambda)$ as the measured intensity through white paper, and $I_T(\lambda)$ as the measured intensity $I_M(\lambda)$. Of course, $I_M(\lambda) < I_0(\lambda)$ when light passes through a colored area.

The measured transmittances for each of the colored printed line samples are reported in Figure III-13 and allow us to quantitatively reinforce the qualitative observations about selective transmission shown in Figure III-12.

The results show an analogy between the printed pigments and the ideal ones (Figure III-2), more evidently for cyan and yellow and a bit less for magenta.

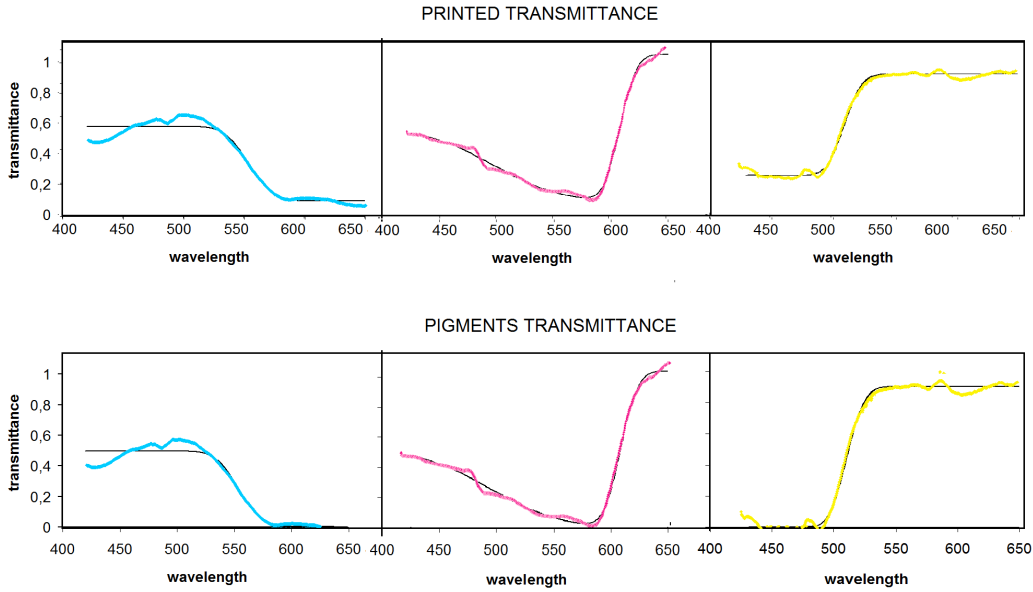


Figure III-13. (Top) Transmittance $T(\lambda)$ as measured with the spectrometer for the different primary CMY color printed lines. (Bottom) Extrapolated transmittance of the corresponding pigments obtained by subtracting the contribution of white unprinted regions. The $T(\lambda)$ for the primary colors are fitted using an *erf* function model. To reduce the noisy appearance of the transmittance curves a moving average smoothing with a 10 nm width was introduced.

We shall analyze in the following the results about the printed CMY colors. We fit the transmission spectra of pigments using the *erf* function to describe transitions from high to low transmittance

$$T_{\text{Pig}}(\lambda) = \sum_n \frac{I_n}{2} \left[1 + (-1)^{i_n} \operatorname{erf} \left(\frac{(\lambda - \lambda_n)}{\delta_n} \right) \right]$$

where *erf* is the normalized error function and (i_n) is even or odd for high pass or low pass transitions respectively; this way we can obtain low pass, high pass, pass band or stop band filters. Depending on the chosen pigment, n can only be either 1 or 2.

Spectroscopy with smartphones

According to the microscope photos some paper areas are white (*Figure III-4*), so they don't have any ink on them. We then suppose a relationship between T_{pig} (the transmittance of the pigments only), the transmittance T_{white} of the paper sheet only, and the resulting measured transmittance T_{measured} as:

$$T_{\text{measured}}(\lambda) = \left(\alpha T_{\text{pig}}(\lambda) T_{\text{white}}(\lambda) + (1 - \alpha) T_{\text{white}}(\lambda) \right) / T_{\text{white}}(\lambda)$$

where α indicates the percentage of the area which is completely covered by the ink. The value $1 - \alpha$ is then proportional to the percentage of the area without ink. From this relation we obtain:

$$T_{\text{pig}}(\lambda) = \frac{T_{\text{measured}}(\lambda) - (1 - \alpha)}{\alpha}$$

We fit the experimental data to evaluate the position of the thresholds of the absorbed bands, their intensity and their width δ_n . Results are described in Table 4 where the approximately evaluated edges of transmission windows are reported.

Color	1-0 threshold		0-1 threshold		White	R^2
	λ_n	δ_n	λ_n	δ_n	$1 - \alpha$	
Cyan	554	29	-	-	0.06	0.979
Magenta	497	62	607	16	0.10	0.997
Yellow	-	-	511	17	0.24	0.994

Table 4. Transmission bands. The correlation coefficients, R^2 , used to evaluate the fit reliability are always greater than 0.97.

Now we can compare the effects of “subtractive” mixing not using a subtraction but calculating the product of transmissions coefficients of the pigments according the formula:

$$T_s(\lambda) = \prod_n [T_n(\lambda)]^{\gamma_n}$$

where γ_n is the effective weight of the given color in the mixing. In our case we consider that the layers of primary CMY colors which are superposed by the printing process to have the same thickness, so $\gamma_n = 1$.

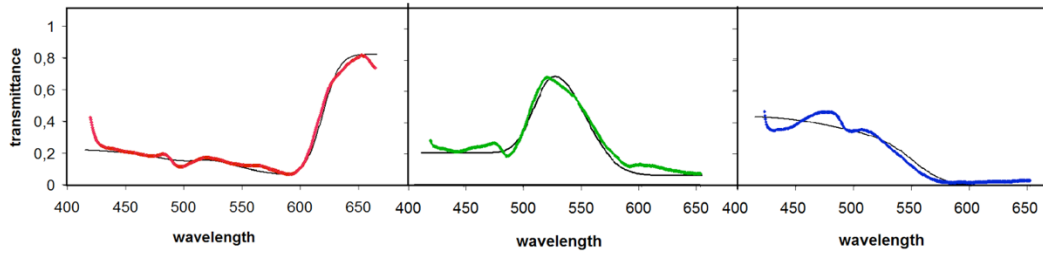


Figure III-14. Transmittance $T(\lambda)$ measured with the spectrometer for the different RGB color printed lines.

We shall now discuss the results shown in Figure III-14 regarding the measured transmittances of the RGB printed colors. First of all, in the close-up photos we don't see any white areas in contrast to what we observed with the printed CMY colors (Figure III-4). Furthermore, we see some areas with single CMY pigments and other areas with two mixed pigments. It follows that for the RGB colors we are expecting mixtures of two CMY pigments, with a resulting transmittance of the form:

$$T_{\text{color}}(\lambda) = \alpha_{\text{product}} T_1(\lambda)T_2(\lambda) + \alpha_1 T_1(\lambda) + \alpha_2 T_2(\lambda)$$

The α_{product} , α_1 and α_2 coefficients correspond to an estimation of the size of the different areas and can be obtained by a fit using the values of Table 4 for the transmittances of the CMY pigments.

The results are:

- $\alpha_{\text{product}} = 43.5\%$, $\alpha_{\text{magenta}} = 49\%$, $\alpha_{\text{yellow}} = 7.5\%$ for red;
- $\alpha_{\text{product}} = 63\%$, $\alpha_{\text{cyan}} = 29\%$, $\alpha_{\text{yellow}} = 8\%$ for green;
- $\alpha_{\text{product}} = 60.5\%$, $\alpha_{\text{cyan}} = 37.5\%$, $\alpha_{\text{magenta}} = 2\%$ for blue.

These results about the ink area coverage (alpha values) could be validated by means of densitometric measurements.

III.5 Using the apparatus with students and teachers

The activities have been proposed, in different sessions, to secondary school students, undergraduate students, pre service teachers and in service teachers of secondary school, in order to study their feasibility and educational potential. A positive influence of the activity in the process of appropriation of experimental methods emerges clearly from the results of our study.

Spectroscopy with smartphones

We report some of the final comments, in which teachers and students highlight the formative role played by these activities. Most comments refer to:

- The relation between light and colors:

“These activities are not aimed to clarify doubts derived from the theory, but rather to invite students to reflect on the nature of light and color and to question what they thought they knew. For example, often when we see two light bulbs, these seem the same, but deepening the study with the use of spectrometers we realize the differences that the naked eye does not notice... we are surrounded by colors but we do not ask ourselves what they really are and how they are formed.”

- The smartphone based spectroscopy, the image analysis and the tools:

“The use of image analysis can be a useful tool to introduce physics to all students... thanks to this experimental approach, while not knowing all the theory that explains these phenomena, students are able to see and understand, from a more quantitative point of view, both wave phenomena of light and colors, since they can measure the spectrum of a light source.”

- The value of the experimental activities in constructing the scientific knowledge:

“The activity is useful because it allows you to experience the difficulties involved in the process of experimental measurement... it provides a good idea of the work of the scientists... it allows you to work effectively on the specific skills of scientific inquiry.”

And finally:

“You explore what the typical steps of an experimental investigation are: identification of a goal, ... the need to calibrate an apparatus, ..., the need to analyze the data collected by assigning the values of the measurements as well as their uncertainties.”



Figure III-15. Some photos of the activity conducted with secondary school students.

III.6 Discussion

In this Chapter we discussed how a low cost handmade spectrometer, based on a smartphone camera, can be assembled and used to obtain quantitative spectra of different sources. The activities allow students to understand the different physical mechanisms underlying colors reproduction. Measurements of emission and transmission spectra allow students to focus on the differences between additive and subtractive models of color formation. For this purpose, the spectra of RGB colors emitted from an LCD screen and the transmission spectra of CMY pigments of a laser printer have been studied, using our low cost spectrometer, and a sequence of experimental activities was designed. This experimental approach to colors was designed for undergraduate and high school courses or interdisciplinary courses/workshops on science and art. The sequence of experiments was tested with secondary school students, undergraduate students, pre service teachers and in service secondary school teachers. When tested with students the activities showed

Spectroscopy with smartphones

effectiveness in raising their interest in the subject, improving their understanding. Teachers, both in service and in training highlighted the formative role played by these activities. A positive influence of the activities in the process of appropriation of experimental methods emerges clearly from the outcomes of our tests.

Chapter IV

The Augmented Laboratory

In this chapter a project which is based on three major topics presented in this work, namely scientific visualization, mediated reality and serious gaming, is presented. The *Augmented Laboratory* project aims to bring innovation in didactic laboratories about scientific topics. It is based on the capability of obtaining 3D reconstructions of the physical world around us. These reconstructions can be visualized both live as they are performed and later as interactive playbacks. The software, entirely designed and coded by the author, simply requires a common computer and a Microsoft Kinect, which acts as a low-cost 3D camera (already presented in I.4.2). The setup can be used to obtain 3D reconstructions of scientific experiments or allows teachers and students to control simulations using physical objects. The complete setup also includes a projector, used to present data in an augmented reality environment.

It is here shown how such reconstructions can be very useful in motion experiments: in fact, following a simple procedure, the software is able to track the trajectories of the objects we are interested in. It is then possible to visualize the measured trajectories as well as all the important information that can be derived from them (energies, linear and angular momentum, the center of mass of the system, and so on). Watching the playbacks, it is possible to analyze these data step by step and to focus on the important moments of the experiments, for instance a collision. All the gathered data can also be exported to be analyzed by external software.

By adding a projector to the setup, we can exploit the full potential of augmented reality, representing all the information about the experiment directly on the objects and the environment. Augmented reality opens new doors for education and communication of science. For example, we can look at the trajectories of the tracked objects and of their center of mass directly on the table on which the objects are moving, or we can project directly on any surface to display its basic properties, such as altitude and level curves, and more advanced data, such as its gradient or divergence.

We also present a new concept, that of *augmented simulations*. An *augmented simulation* is the result of the interaction of a computer simulation with the physical world.

A first example of *augmented simulation* regards mechanics. We can introduce simulated objects whose movement is influenced by the surrounding physical objects and surfaces. This way we can directly see the behavior of an object following the same

The Augmented Laboratory

physical laws that have been presented, and it is also possible to compare the results of measurements and simulations.

A second example of *augmented simulation* is that of the *ripple tank*. It is possible to perform any experiment regarding wave propagation by introducing and moving physical objects. In fact, the objects represent wave sources, obstacles, lenses, and areas of different wave propagation speed, and the software is capable of recognizing and distinguish them. This way, the discussion of topics such as reflection, refraction, diffraction, Doppler effect and the sonic boom can be presented in a very intuitive and straightforward way.

The setup was tested with a group of university students who aspire to become physics and mathematics teachers, and their feedbacks are here analyzed. The system was also used as an installation in the “Toys and Science” exhibition, and various comments about this experience are here discussed.

A dedicated YouTube channel about this project may be found at:

https://www.youtube.com/channel/UCoafVdWnuyc_zzS0pOkbeg

IV.1 3D reconstructions of physical environments

The *Augmented Laboratory* is based on the capability of obtaining 3D reconstructions of the physical world in real time. This can be done using a 3D camera. With this term, we here refer to any device which may provide a *depth image* or *depth matrix*: instead of providing information regarding colors, as a conventional camera, these cameras provide information of the distance of the objects in front of them. See for example Figure IV-1, right: in this figure a depth image is represented, where brighter colors correspond to objects closer to the camera, while darker ones to more distant objects.

For this setup we chose the Microsoft Kinect device (v2), which was already introduced in Chapter I, as a 3D camera. In principle, any 3D camera can be used in the same setup, with only minor changes in the software (although the peculiar characteristics of each different device would require testing and special care).

The Kinect is placed over the environment we would like to reconstruct, for example using a simple setup as in Figure IV-1 (left) or a ceiling mount. A black and white

version of the obtained depth matrix is represented in Figure IV-1 (right). The data acquisition code is based on the open source library OpenKinect [132].



Figure IV-1. (Left) The Kinect is positioned above the environment we would like to reconstruct. (Right) An example of a depth matrix is here visualized as a black and white image, where brighter colors correspond to smaller distances between the sensor and the objects.

IV.1.1 From depth matrices to 3D reconstructions

The simplest 3D visualization of a depth matrix is its *point cloud* representation. The idea is to represent each element of the matrix as a point correctly placed in a 3D space. What is needed is then a transformation from (x, y, z) , the x and y coordinates of the element in the matrix and its depth value z , to (x', y', z') , the coordinates in the 3D space.

The transformation can be imagined this way. Every camera (and also eye) is capable of getting data from objects inside a certain space: this space can be represented as a pyramid. The camera is placed at the apex of that pyramid, looking in the direction of the height connecting the apex to the base (see Figure IV-2, left). The z' value correspond to a plane parallel to the base of the pyramid. The intersection between this plane and the pyramid gives a rectangle, so x' and y' correspond to the coordinates of the element in this rectangle. The greater the *field of view* of the camera, the greater the rectangle corresponding to a certain z' value. Notice that this definition of z' is different from the distance between the element and the camera. If this kind of representation were used, z' would define the intersection between a sphere of radius

z' and the pyramid (Figure IV-2, right). The Kinect outputs depth values as described in the first representation, so that is the coordinate reference we use from now on.

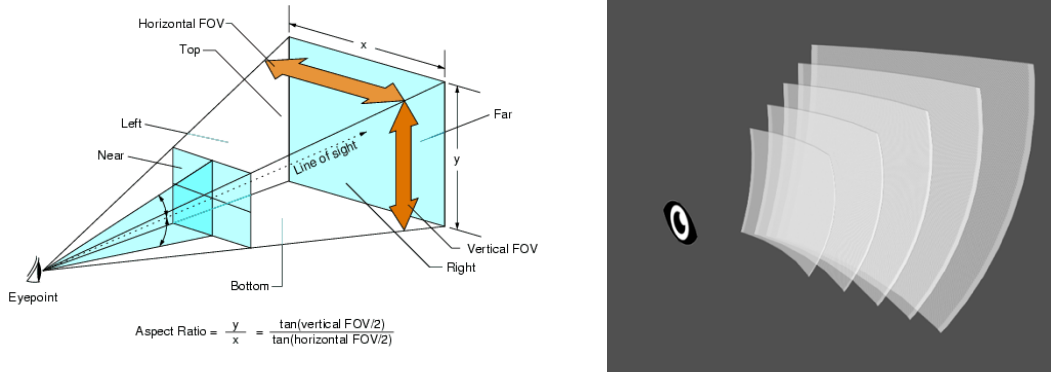


Figure IV-2. (Left) Schematic representation of the field of view. (Right) Intersections between spheres of different radius and the pyramid of the field of view.

The relation between z and z' depends on the linearity of the sensor and on the pre-processing done by the device. For our uses it was enough to trust the declared linearity of the Kinect v2 (giving 500-4500 depth values corresponding to 0.5-4.5 meters) and simply assume $z' = z$. For more accurate measuring tests should be done for each single device used (in principle each Kinect could give slightly different results given by fabrication issues).

Once z' is obtained, x' and y' are given by the following relation:

$$x' = \left(x - \frac{res_x}{2}\right) \tan\left(\frac{fov_x}{2}\right) \frac{z}{2 res_x}$$

$$y' = \left(y - \frac{res_y}{2}\right) \tan\left(\frac{fov_y}{2}\right) \frac{z}{2 res_y}$$

where res_x and res_y are the width and height of the depth matrix respectively, and fov_x and fov_y are the horizontal and vertical field of view (see Figure IV-2, left). Notice that they scale linearly with z , as at double the distance from the camera, double the size of the rectangle in which they are.

For an extensive example of these concepts applied to the case of the Kinect v1, see [133].

With this transformation it is possible to take all the elements of any depth matrix and represent them correctly in a 3D virtual space as a *point cloud* (Figure IV-3, left). It may also be convenient to represent the *point cloud* by filling the space between the points, thus obtaining a more natural look of the visual representation of the data. If the sensor also has a color camera, it is possible to merge the color and the depth streams in a

single visualization (Figure IV-3, right). There are many software and libraries that help creating such visualizations: for this project, the *Processing* Java library was used [134].

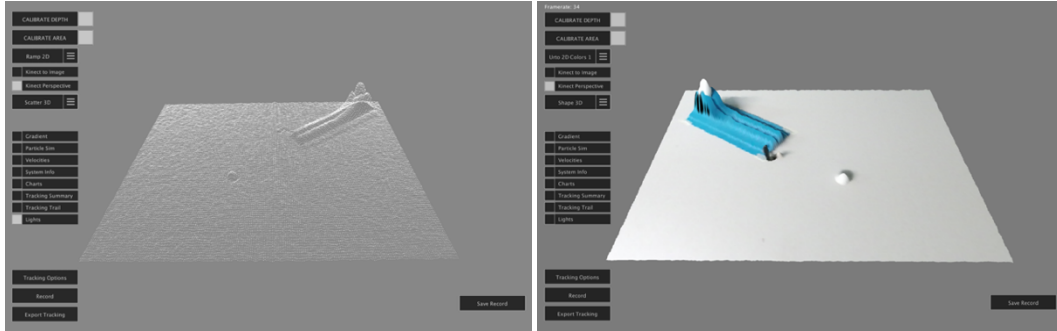


Figure IV-3. (left) Point cloud visualization of a depth matrix. (right) The same data represented using a 2D mesh to connect the points and also with the color information added.

IV.1.2 Computer vision: object recognition and tracking

For this project we are interested in knowing where particular objects are, and what are their shape and size. In order to do so, we need to use the so-called *object recognition*, a technology in the field of computer vision. There are many techniques (appearance-based or feature-based) and algorithms that can be used for finding and identifying objects in an image or a video. The best choice of course depends on the type of recognition needed. A crucial characteristic of the algorithm needed for this project is that it has to be very light computation-wise, as we want to use it live as the acquisition occurs without missing any frame.

The adopted solution is the following. Pressing a single button (or a key on the keyboard) a “base depth calibration” process starts, meaning that for several seconds the software acquires all the depth matrixes and calculates their arithmetic mean: this way, a great deal of noise is suppressed. This result will be used as a reference matrix containing all the information about the background.

From now on, any added object may be identified. In fact, after the calibration process all the subsequent depth matrixes will be compared to the reference matrix, making the system able to recognize all the elements regarding the added objects.

A *naïve* implementation of this recognition algorithm would lead to many false recognitions, because of noise and artefacts. Two filtering processes have been adopted to overcome these difficulties. First of all, matrix elements differing from the reference values for less than a user-defined threshold value are ignored. Secondly,

The Augmented Laboratory

each cluster of adjacent elements (a candidate recognized object) will be ignored unless it contains a number of elements greater than another user-defined threshold value (Figure IV-4).

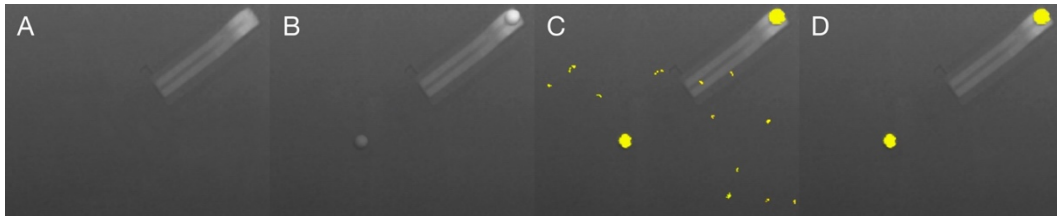


Figure IV-4. Visual summary of the process behind the object recognition procedure. A) The depth matrix without objects (reference matrix). Here the table and a grooved track can be seen. B) The depth matrix with the objects (two spheres). C) Comparison between the two matrixes: any element featuring a difference greater than a threshold value is here highlighted. D) Remaining false objects are filtered by ignoring all the clusters of elements that are too small. After this filtering, only the elements corresponding to the objects we want to track are still highlighted.

At this point, all the information needed to track the objects is known. Any experiment may be performed and the objects we want to track are recognized in real time. Also, as already mentioned, everything may be recorded so that interactive playbacks may later be re-played. A large number of additional information derived from the trajectories may be displayed, such as velocity vectors, the center of mass of the system, plots and values regarding energies, momenta, and so on (both live and in the playbacks).

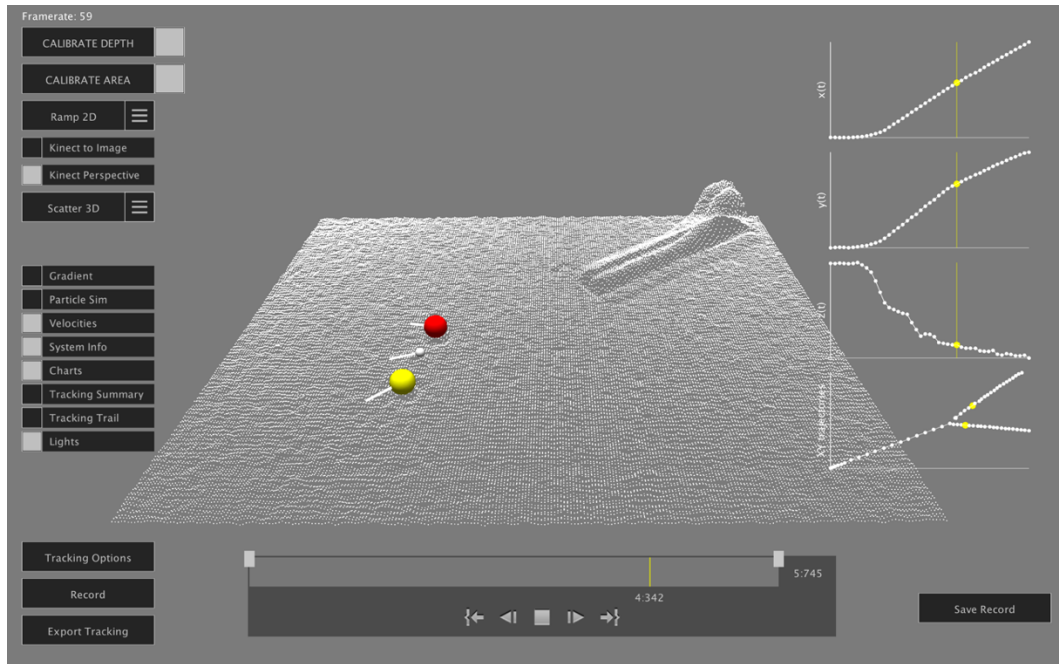


Figure IV-5. A screenshot of an interactive playback of a 3D reconstructed experiment regarding a collision between two spheres. The center of mass of the system is here represented as a small white sphere. Velocity vectors and plots regarding the trajectory of the center of mass are also visualized.

IV.2 Multiple object, three-dimensional motion tracking

We chose two simple experiments to demonstrate the multiple object, 3D tracking capability of our hardware/software setup [135]. These experiments are of interest in an educational context, allowing to discuss quantities such as linear momentum, angular momentum, kinetic and potential energies, and they could not be analyzed by means of traditional 2D video tracking. They are also chosen to be helpful in making students understand how analyzing the motion of the center of mass of a system can be very useful and advantageous.

In the first experiment (Figure IV-6, left), we set up two balls in order to make them collide and then fall under the action of gravity. In the traditional version of this experiment carbon paper is put on the floor to check where the objects fall. Of course, with such a traditional setup a lot of information about the motion is lost. In this experiment, we check the conservation of linear momentum and energy during the collision and track the motion of the center of mass of the system.

The Augmented Laboratory

In the second experiment (Figure IV-6, right), we tie a nylon line to two soft spheres (obtaining a *throwing bolas*) and throw them to track their motion. We are here able to check the conservation of angular momentum referred to the center of mass of the system and the trajectory of the center of mass to test the conservation of energy.

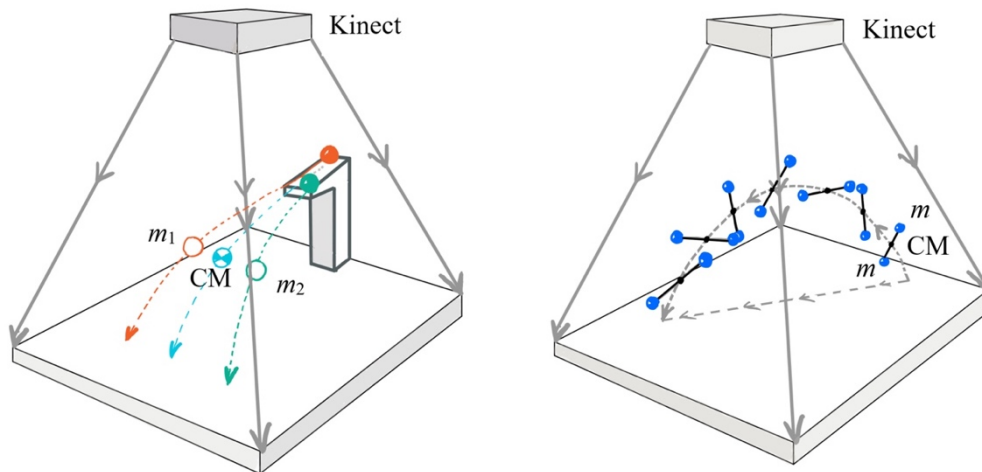


Figure IV-6. Schematic drawing of the experimental setups of the two experiments. In both cases the Kinect was placed at about 2 m from the floor, a position from which it was able to track the objects along their trajectories. Since the Kinect is not capable of acquiring depth data of objects closer than 0.5 m, caution has to be paid in order to have the tracked objects always at larger distances. The diameter of the balls was 3 cm.

IV.2.1 Data analysis

In the following experiments, we are interested in obtaining values for the linear momentum, angular momentum and mechanical energy of the system. These values are obtained from the positions of the objects and the corresponding time stamps at which data is acquired.

There are many sources of uncertainty regarding the positions of the objects. Of course there are those given by the hardware, but there are also others regarding the software, in particular the ones given by the objects recognition and tracking algorithms. Furthermore, the measurements may be slightly influenced by many factors, including the size of the tracked object, its material, the distance from the Kinect, and also its speed. *A posteriori* analysis of the data show that the resulting errors are comparable, if not smaller, to those obtained by using traditional video analysis based on videos with the same frame rate of the Kinect, 30 fps (of course, this strongly depends on the quality of the compared cameras). For example, the data of both experiments allow us

to measure the gravitational acceleration, so we use such measurements to test our setup: the resulting relative errors are of the order of 2-3%. For this reason, we can limit ourselves in using statistical uncertainties given by regressions and averages, being confident that the instrumental errors are below the estimated errors.

IV.2.2 Quasi-elastic collisions: center of mass motion and conservation of linear momentum

The setup consists of a grooved track with two plastic balls on it: the first one (the “incoming” ball) is placed on the highest position of the track and the second one (the “target” ball) on a small support at the end of the track (Figure IV-7, left). The support can be adjusted so that the collision will happen just after the incoming ball left the track and so that the two balls will have the same vertical position during the collision. A proper way to verify such alignment is to check if both balls hit the ground at the same time by listening to the sound they do when they bounce. Also, experiments with different impact parameters may be performed.

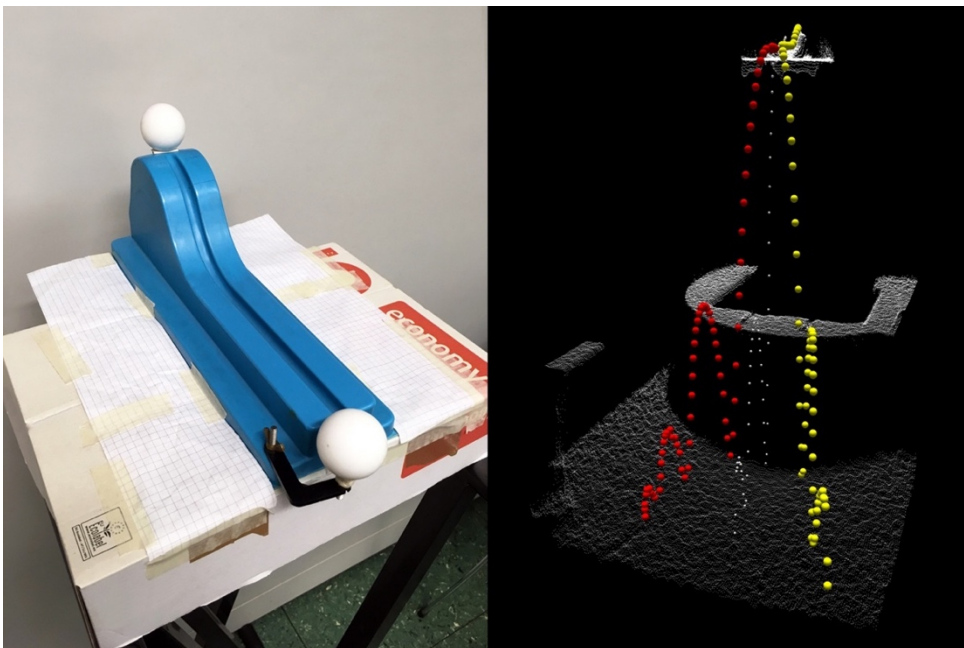


Figure IV-7. (Left) The experimental setup. (Right) Three dimensional visualization of the tracking results. The small white dots in the middle represent the trajectory of the center of mass.

A visualization of the resulting measurements is shown in Figure IV-7, right. The masses of the balls are $m_1 = (18.20 \pm 0.01)$ g, and $m_2 = (18.28 \pm 0.01)$ g. Right after

they leave the track (and before hitting the ground) the only force acting on the system is the gravitational force (of course, not taking into account the friction of air), hence the center of mass is expected to follow a parabolic trajectory. This is well seen in the measurements. First of all, the resulting z positions of the center of mass (choosing the z -axis as normal to the floor) are well fitted by a quadratic time dependence (Figure IV-8, left; regression analysis leads to $g_m = (10.0 \pm 0.3) \text{ m/s}^2$). We can then look at the trajectories of the two balls and of their center of mass on the xy -plane, meaning as seen from the above (Figure IV-8, right). From the positions and time values we are able to calculate the velocities of the center of mass of the system, and therefore the corresponding momentum values. By calculating averages and standard deviations of these values before and after the collision we obtain, respectively, $P_0 = (32 \pm 1) \times 10^{-3} \text{ kg m s}^{-1}$ and $P_f = (31 \pm 2) \times 10^{-3} \text{ kg m s}^{-1}$. The corresponding angles between the direction of \mathbf{P} and of the x -axis are $\alpha_0 = 14^\circ \pm 1^\circ$ and $\alpha_f = 15^\circ \pm 1^\circ$. We can conclude that such measurements are consistent with conservation of momentum.

In the description of this experiment we consider perfectly elastic, friction-less and rotation-less masses: with these hypotheses one expects to obtain a scattering angle of 90° , whilst the observed value is $\theta = 88^\circ \pm 1^\circ$ (see inset of Figure IV-8, right).

From the positions and time values we are able to calculate the averages and standard deviations of the energy of the system both before and after the collision. The resulting loss of energy is below the measurement uncertainty, with initial and final values being $E_0 = (0.63 \pm 0.01) \text{ J}$ and $E_f = (0.64 \pm 0.02) \text{ J}$, respectively.

Experimental values are obtained using: linear regression to compute the trajectories, trigonometry to get the angles from the slopes, and standard propagation of error methods for the uncertainties.

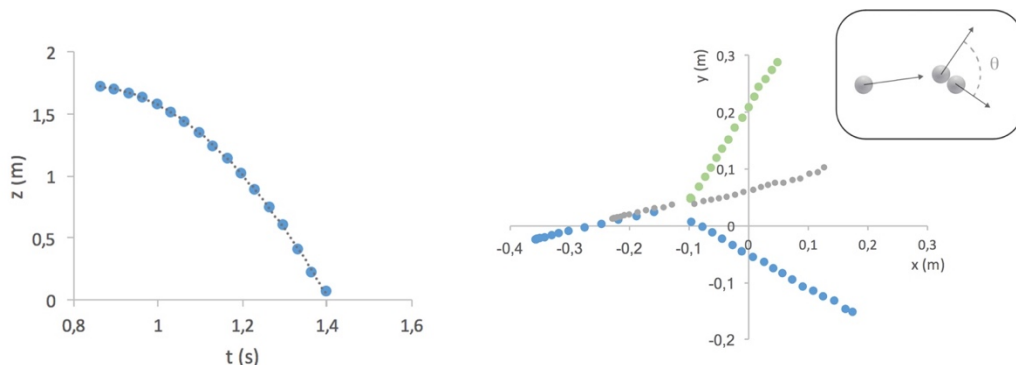


Figure IV-8. (Left) z coordinate of the center of mass after collision and before bouncing. (Right) Trajectories of the two balls and of their center of mass (grey dots) along the xy -plane, meaning as seen from the above.

IV.2.3 3D tracking of bolas: center of mass motion and conservation of angular momentum

A *bolas* (from the Spanish word “bola”, ball) is a throwing weapon made of several balls connected by strings. We built our bolas by tying a nylon line to two soft balls (toys for cats), as shown in Figure IV-9, left. We threw the bolas so that it would fly over a table while spinning, tracked its motion and analyzed it. The balls have masses $m_1 = (9.44 \pm 0.01)$ g, and $m_2 = (9.48 \pm 0.01)$ g. The motion of the system is the superposition of a rotation of the two masses around their center of mass and the motion of the center of mass itself (Figure IV-9, right).

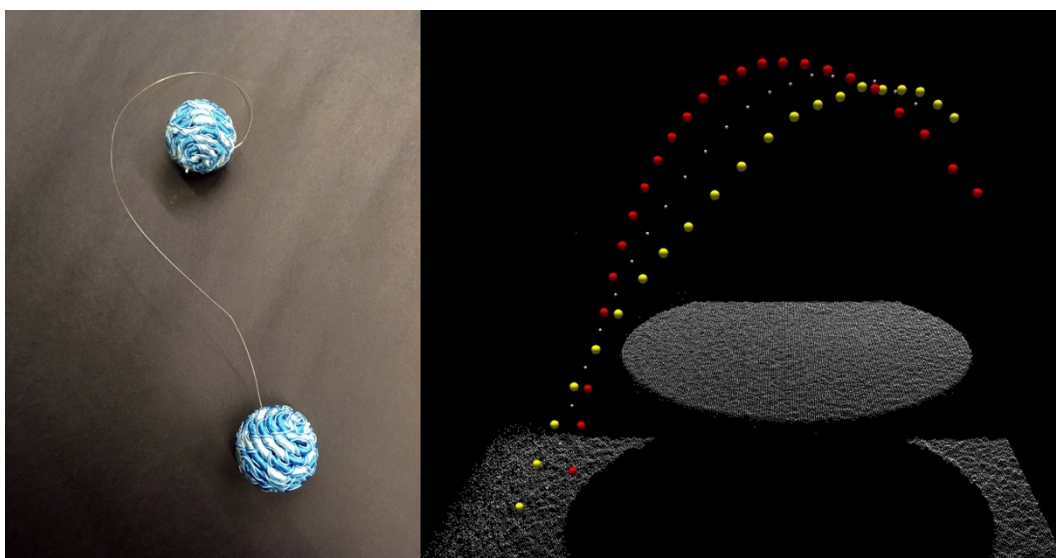


Figure IV-9. (Left) Bolas. (Right) Visualization of the measured positions of the two spheres and of the resulting center of mass (smaller white spheres). The bolas was thrown over a circular table which is also here visualized.

The center of mass follows a parabolic trajectory (Figure IV-10, left); the same data analysis as that of the first experiment leads us to the result $g_m = (9.6 \pm 0.2)$ m/s².

Looking now at the motion relative to the center of mass (Figure IV-10, right), we observe that the two masses follow a circular trajectory: since the only forces acting on the system are directed towards the center of mass (i.e. $\mathbf{r} \times \mathbf{F} = 0$, ignoring air friction) the angular momentum should be conserved. Measurements are consistent with this prediction: while the x and y components of \mathbf{L} are negligible, its z component shows small relative fluctuations (within 10%) around its mean value: $L_z = (1.9 \pm 0.2) \times 10^{-3}$ kg m² s⁻¹. Similarly, we can say that energy is conserved during the whole motion,

The Augmented Laboratory

as we measure only small fluctuations around its mean value: $E = (16.5 \pm 0.5) \text{ J}$. Again, these values derive from the averages and standard deviations of the values calculated for each frame of the recording.

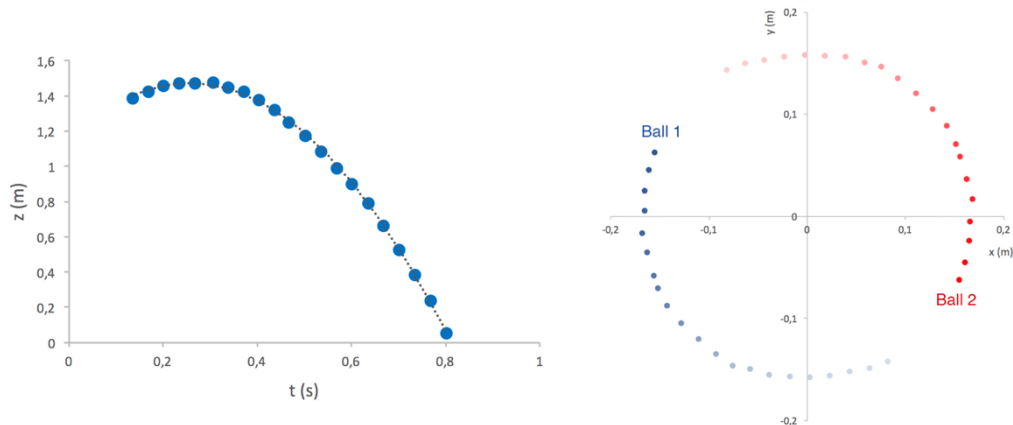


Figure IV-10. (Left) Trajectory of the center of mass. (Right) Trajectories of the two spheres relative to the center of mass of the bolas (clockwise rotation).

IV.3 Augmented reality

By adding a projector to the computer-Kinect setup, we are able to work in an augmented reality environment. To do so, the system needs to be calibrated in such a way that the projection is well-aligned in respect to the physical objects. Once this has been done, we can project information directly on the desired objects or near them.

First of all, we can use this setup to *augment* the tracking measurements of experiments similar to the ones we just discussed. For example, it is possible to follow the tracked objects by projecting their trajectories as they are moving, as shown in Figure IV-11. In this figure, two different colors are used to highlight the trajectories of the two spheres. Any kind of additional information can also be displayed, such as the trajectory of the center of mass of the system (which can be seen in the same figure as a series of white dots), velocity vectors, graphs, values regarding energies, momenta, and so on. Lastly, as we can record any experiment, we are also able to watch the corresponding interactive replays comprehending any additional information we are interested in (**Error! Reference source not found.**).

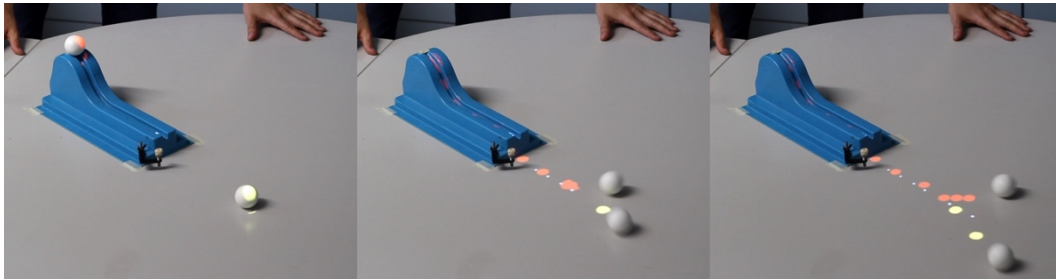


Figure IV-11. Projections of information regarding the tracked objects using augmented reality.

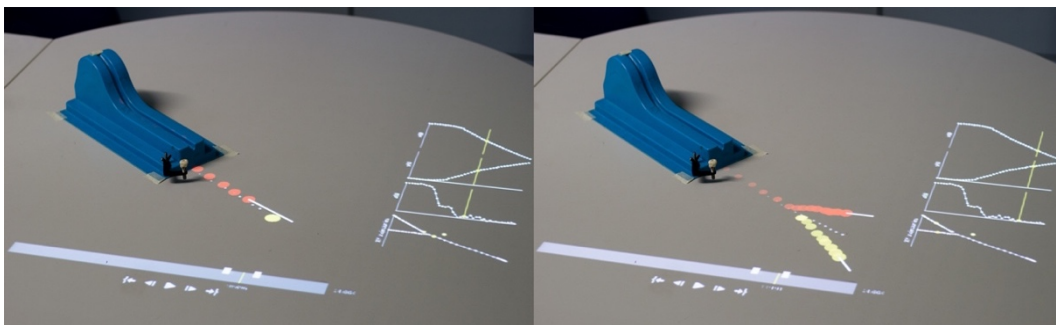


Figure IV-12. Using augmented reality to see the interactive replays of recorded experiments, enriched by any additional information we are interested in.

Another interesting way of using augmented reality is that of projecting information about any surface we use. The idea is that of using the setup similarly to the *Augmented Reality Sandbox* (see I.3.3) but with the addition of mathematical properties regarding the surfaces. In Figure IV-13, left, a visualization of the height of the surface using a custom color scale, as in the *Sandbox* project, can be seen. In the same figure, on the right, a visualization of the gradient of the surface, in the form of a lattice of vectors, can be seen. This kind of visualization can be used when introducing important concepts such as potential surfaces. Any other information regarding the surface, such as level curves or its divergence can, or can in principle, be seen.



Figure IV-13. Surface analysis in augmented reality. (Left) The height of the surface is represented using a custom color scale, as in the *Augmented Reality Sandbox* project. (Right) A visualization of the gradient of the surface using a lattice of vectors.

IV.4 Augmented simulations

We can take a step further in the mixing of virtual and physical realities. In fact, we can investigate new forms of interaction that we can have between simulations and physical objects. We called this kind of interactions *augmented simulations*. As in the example of the 3D tracking, while the use of augmented reality is not required to obtain this kind of interaction, the addition of projections results in a very clear way to present its results, as it will be seen.

We shall now discuss two different types of *augmented simulations*: the motion of virtual particles in a real environment, and a *ripple tank* simulation controlled via real objects.

IV.4.1 Motion of virtual particles in a physical environment

In the first case, we can introduce virtual objects in the physical world, which in turn will determine their motion. For example, in Figure IV-14 a virtual particle is projected on a funnel: the funnel's 3D reconstruction is interpreted as a potential surface, which in this case resembles a 2D gravitational well, determining the motion of the particle.

Also, in principle, the capability of influencing a virtual particle using physical objects may be used to discuss the topic of modeling in physics. In fact, various parameters (such as friction or the elasticity of a collision) could be tweaked, and various models of motion could be simulated in order to see how the particle would behave. The comparison of this behavior with “real” experiments, that can be done in the same environment, may be a useful educational tool.



Figure IV-14. Projection of the trajectory of a simulated object which is moving in a surface potential given by the reconstructed surface of the physical object.

IV.4.2 The augmented ripple tank

The second example of augmented simulation is that of the *ripple tank*. The idea is that of using different physical objects to interact with the simulation. The system is in fact able of distinguish various objects into different categories: point sources, plane wave sources, obstacles and areas of different propagation velocities (refraction indexes).

Everything regarding wave propagation may be discussed using this setup, such as reflection, refraction, total internal reflection, diffraction, interference, and so on. Any kind of lens, prism, and slit experiment may be reproduced (some examples may be seen in Figure IV-15). In particular, since the system is capable of recognizing objects even while they are moving, it may be also used to introduce topics such as the Doppler effect and the sonic boom. For example, a rolling cylinder may simulate a moving point source, resulting in a Doppler effect which may be seen in the upper right of Figure IV-15. Notice also that in this image the cylinder was moving fast enough to result in a sonic-boom-like pattern. In Figure IV-16, another possible way to visualize the Doppler effect is shown: moving a plane wave source using our hands. In fact, while the source is still, the frequencies on both sides of the source will be the same. Instead, while the source is moving, different frequencies will be seen on the two sides of the source.

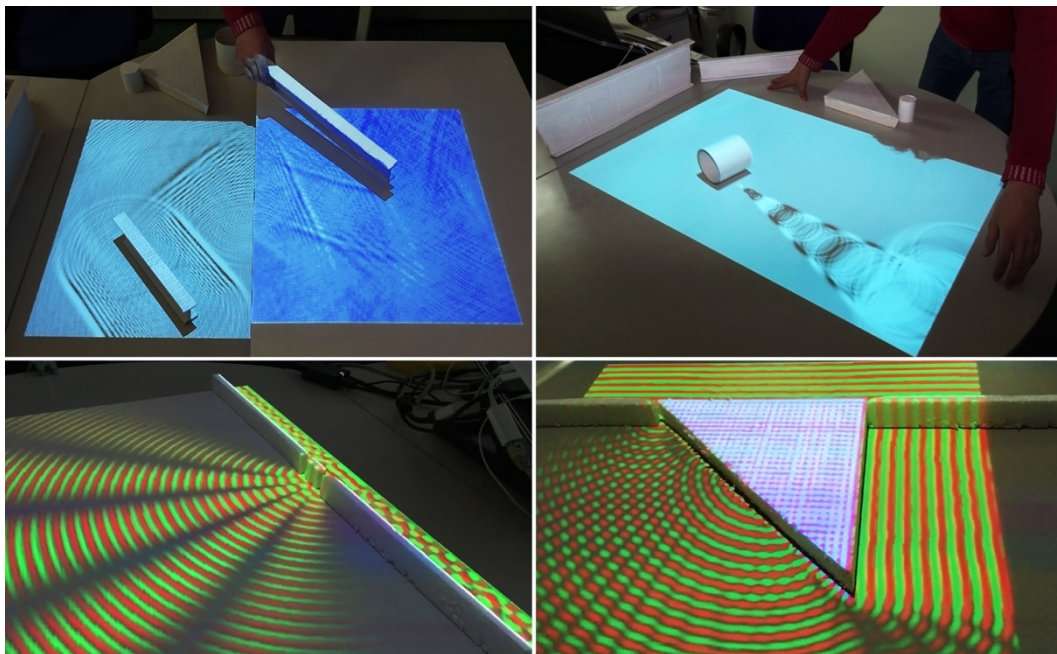


Figure IV-15. Some examples of different experiments that may be reproduced with the augmented ripple tank.

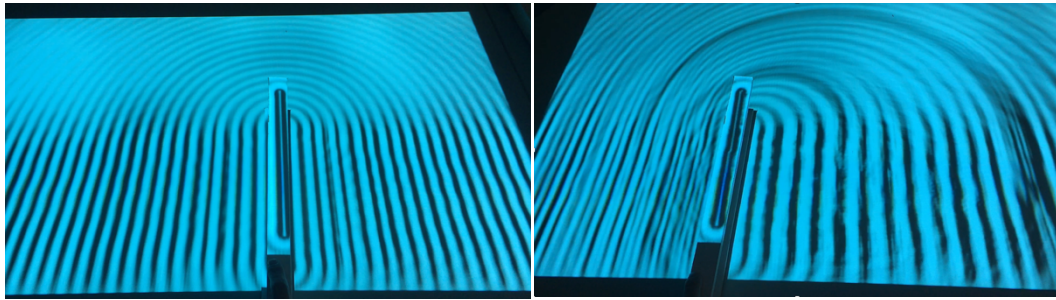


Figure IV-16. A possible way to visualize the Doppler effect: moving a plane wave source. (Left) The plane wave seen while the source is still. The frequencies on both sides of the source are the same. (Right) The resulting waves as the source is moving: two different frequencies may be seen on the two sides of the source.

It has to be noted that the objects themselves are nothing special. For instance, the first set that was built was made of cardboard cut by hand: some of the pieces are represented in Figure IV-17, left. The system mainly needs to check the height of the detected objects, and classify them distinguishing between 3 different ranges of heights: the shortest ones (3-4 cm) are interpreted as areas of larger refraction index (lenses, prisms, ...), the tallest ones (more than 10 cm) are seen as walls, while anything in between will be seen as a source. Notice that these intervals are chosen so that sources might also be put onto areas of different refraction indexes: this way, it is possible for example to put sources inside the water in a water/air interface, say to discuss total internal reflection. The last distinction that needs to be done is between point sources and plane wave sources. This is done by checking the shape of the upper side of the object: circle- and square-shaped ones will be used as point sources, while rectangular ones will be used as plane wave sources.

A second set of objects was then created using a 3D printer, in order to obtain better-looking and more resistant pieces (Figure IV-17, right). The 3D models were designed using the free 3D modeling software *SketchUp Make* [136]. These pieces have also been studied to be modular, using small magnets in order to help the creation of different configurations. For example: the plane wave sources and the walls can be extended using more pieces; two right-angle prisms may be joined together to create a bigger prism (and two of these can create an even bigger one); two convex lenses may be act as a biconvex lens.

This kind of object recognition was chosen in order to obtain a very flexible setup. In fact, this way any shape may be cut using a simple piece of cardboard, so that educators and laboratories would not ever be limited by the pieces at disposal.

The *augmented ripple tank* has been used as an installation in an actual exhibition, as it will be discussed in the next section.



Figure IV-17. Two examples of sets of objects that can be used for the augmented ripple tank. A prism, a lens, a point source, a planar source, and a wall are here represented. (Left) A set made of cardboard. (Right) A 3D-printed set.

IV.5 Testing the setup

The setup was tested in two different situations. In the first one, we showcased it with a group of aspiring teachers of physics and mathematics. They could test it both for 3D tracking and for the use of augmented simulations, and their feedback was collected. Regarding the second one, the setup has been used as an installation of the exhibition “Toys and science”. This experience was interesting at different levels. First of all, it was the first time that the setup had to be completely used by persons other from the author, and the context also needed it to be reliable and stable for days. Secondly, most of the guides were master students, some of which also had previously seen the setup in classroom; a small survey was taken to have their feedback about this experience. And last but not least, very different persons went to the exhibition, ranging from primary school students to teachers to families: in particular, the author had the chance to gather suggestions and comments from university professors and teachers that are interested in physics education.

IV.5.1 Testing the setup with aspiring teachers

We tested the *Augmented Laboratory* with a group of 15 university students who aspire to become physics and mathematics teachers. They previously used video analysis software, in particular *Tracker* [31], to perform traditional 2D tracking, and spent some

The Augmented Laboratory

hours experiencing the use of physics simulation software meant for education such as *Algodo* [137].

At the end of the experience (divided in two afternoons), they were given a survey with three different questions, asking for feedbacks regarding: the use of 2D/3D tracking systems; the use of augmented reality setups; and the use of augmented simulations. The entire survey and corresponding answers can be found in Appendix C.



Figure IV-18. Testing the setup with aspiring teachers.

Overall, they were enthusiastic about the use of **2D/3D tracking systems** (*Tracker* and the *Augmented Laboratory*) and they claim they would certainly use them in class:

“Both Tracker and the 3D apparatus look like very good tools. We can replay the performed experiments as many times as we choose while also looking at the graphs about the physical quantities we are interested in. I would certainly use both in class”

Some of them were particularly impressed by the 3D tracking capabilities, because of the different motion experiments that can be done with it and also for motivational reasons:

“Undoubtedly the capability of performing a 3D tracking allows to get motion data of objects which are not following a planar trajectory”

“Upsides of the 3D tracking: it’s wonderful and allows to get measurements, even for complicated experiments, easily and immediately”

“From an educational point of view the setup which allows 3D tracking may be more interesting and therefore help the students’ involvement”

There are two main concerns about the use of a 3D tracking system over *Tracker*, namely the simplicity of use and the fact that even if 3D motions cannot be acquired with a regular video, 2D motion can simply be enough from an educational point of view:

“Tracker seems simple, since I only need a camera to use it”

“...regarding the 3D tracking instead, I find that, even if it is interesting indeed, it can be difficult to be used”

“The 3D tracking is better than the 2D tracking because of the complexity of the motions that can be studied, but generally speaking, the 2D tracking is enough”

“...the 2D abstraction of the dynamics of a body is generally used in secondary schools, and maybe even universities”

Some of them suggest the use of both systems in order to get the advantages of both, as they are seen as complementary in some tasks:

“I believe that for simple phenomena such as carts collisions and similar, I would prefer to use Tracker [...] But the 3D tracking system can then be used at the end of the course”

In the second question they were asked what they thought about the use of **augmented reality** with this setup. The two main points of strength they address are the help in visualization of abstract concepts (and they often remark “in real time”) and again its capability of grabbing attention.

“Certainly augmented reality would help the need of abstraction in the visualization of physical properties”

“I believe the main benefit is that of clearly see what is happening in real time, being able to interact, to help creating a dialogue and giving answers. I also believe that the setup also would get a “wow” effect on students, something that should not be underestimated”

“I think augmented reality using the Kinect is a very powerful tool for physics education. To be able to see in real time velocities and trajectories of objects allows to explain students physics principles which are the basis of classical mechanics”

Their main concerns regard the possibility of it being a distraction, or even that it would be better to let the students try to use their imagination instead of helping them visualizing these concepts.

The Augmented Laboratory

“I think on one hand students would be attracted from the technology and the possibility of directly experimenting their hypothesis, but on the other hand it could be a distraction”

“...it eliminates the struggle required to imagine them. I fear it may be an attempt to spoon-feed the student”

A very interesting comment is now given. In it we can see the student trying to imagine an integration of this kind of technology in a teaching/learning sequence, in the perfect spirit of the TPACK framework. In fact, as it has been already discussed multiple times, the only way to evaluate the usefulness and effectiveness of a technology in education is trying to imagine what role can it play in the classroom, and if it may or may not help addressing some well-defined issues.

“Augmented reality effectively allow to superimpose theory and experiment. The capability of seeing at the same time a physics phenomenon and its physical-mathematical description, with the use of velocity vectors or the trajectory of the center of mass, would help the students’ understanding, who would have the chance of seeing ‘concretely’ what it has been explained. Nevertheless, I don’t think it should be used instead of experiments or theory, but that it should be used for integration and support. Personally, I would use it after a theoretical lesson to show the physical concepts ‘in action’ [...] Or it could be used at the end of a teaching/ learning sequence to recap and to see once again theory applied to an experiment”

In the last question they were asked what they thought about the **augmented simulations** seen with this setup (in particular, the *ripple tank*) and about the use of simulations in education in general. Overall they find these systems very useful for didactics, because of their connection with theoretical models and because they can replace some experiments that cannot be done for practical reasons. Another point of strength of simulations is that of allowing students to use them on their own, to interact with them:

“Simulations are particularly interesting because as they are built on models, they show exactly the results of these models”

“... they are fundamental to recreate ideal conditions...”

“They help the student to work and seek for answers by himself/ herself”

“...making him reason in a stimulating way as he is using these programs by himself”

About the augmented simulation of the *ripple tank* there are many very positive comments:

“I find this tool very interesting and engaging. With it it is possible to recreate various situations in very short times. It is true that there are similar apps for smartphones, tablets..., but they lack the same impact”

“It may be useful in education, most of all because it could be more practical than applets or other similar tools”

But there are also some who think traditional simulations are better than augmented simulations because of the noise they have seen in the latter. What they refer to is a problem that the first versions of the software had regarding the object recognition. In fact, it could happen to have a noise in the recognition of the shape of the objects that could lead to confused patterns, especially when using multiple sources/reflecting walls. This problem has been greatly reduced in later versions. While some students were not worried about it (as we have seen in the previous comments), others were:

“I think that the system, exactly as we have seen it, it may not be useful as it is too noisy and too different from the ideal case”

“I think that simulations are useful when they show a system completely free of the noise that we have in a real experiment”

Overall, they seemed to agree on the fact that it would be a very interesting setup to be used in museums and other informal contexts, even those who were skeptical of their use with students and that expressed an opinion on the matter:

“The ‘ripple tank’ is certainly suitable for a museum context, in which the public can freely use this tool on their own or with the help of a guide”

“[...] Instead, it could be more interesting to see simulations which visitors can interact with by moving real objects”

IV.5.2 The “Toys and Science” exhibition

The National Congress of the Italian Physics Society 2017 was held in Trento, and for this occasion a series of collateral events named “FisiCittà” have been organized. One of these events was the “Toys and Science” (“I giocattoli e la scienza”, in Italian) exhibition. Its main idea was that of using simple toys in order to discuss (not-so-

The Augmented Laboratory

simple) physics concepts and phenomena. It lasted two weeks, during which most of the schools of Trento brought their students to see it, but it was open to anyone.

The *Augmented Laboratory* was part of the exhibition. In particular, the augmented simulation version of the *ripple tank* was used. As already mentioned, it has been an interesting experience to test the setup and to gather feedbacks from the guides and from visitors.



Figure IV-19. The "Toys and Science" exhibition.

A small survey about the use of the augmented ripple tank was conducted at the end of the exhibition. In Appendix D the entire answers from the six guides may be found. The main feedbacks are here reported.

First of all, they were asked to give a mark regarding two design/technical aspects, the simplicity and stability of the setup, in order to explore the general comfort in using it from the perspective of the narrator. From a design point of view, the system seems to be simple to use, receiving an average score of 9.2/10. Some more effort has to be put in its stability, but overall acted well enough (average score of 7.2/10). They later reported that they didn't give better scores because a couple of times they had to restart the software. Thanks to their feedback, the software has later been improved to fix the experienced issues.

It has then been asked them to make a direct comparison between 3 different systems that could be used in this or similar contexts:

- 1) the real, physical ripple tank
- 2) a simulation
- 3) the augmented simulation

For each of these systems, they were asked to give a mark from 1 to 10 regarding four different aspects:

- their capability of grabbing attention and instilling curiosity
- their help in the presentation and discussion of phenomena
- their capability of instilling willingness of going deeper in the discussed phenomena (what if...?)
- the general suitability of the systems in a museum

For each question, the augmented ripple tank received the best average scores (see Appendix D).

They were also asked general comments/suggestions, and they gave some regarding new features that might be implemented such as a dedicated hardware interface.



Figure IV-20. Some pictures of the Augmented Laboratory at the “Toys and Science” exhibition.

The Augmented Laboratory

The visitors were generally very attracted to this setup. The most interesting feedbacks were given by teachers who claimed they would actually use it in classroom and asked how they could get one for their schools and universities. This has been an important information to gather because it implies that working on the replication and distribution of such a setup could be an important next step.

IV.6 Future developments

There is a variety of possible future developments. First of all, it is not far from being a complete product, at least if used for well-defined tasks, as proved by the experience in the “Toys and Science” exhibition. So the possibility of replicating it and distributing it in some form needs to be considered. From a research point of view, it should be tested in various contexts, from primary schools up to universities. To do so, a profound reasoning about content development needs to be done first. Other *augmented simulations* can also be developed, in order to discuss other important topics of physics. Other hardware may also be tested, such as smartphones and Head Mounted Displays for other forms of augmented and mixed reality visualization.

Conclusions

New teachers should be trained to be as comfortable as possible working inside the TPACK (Technological, Pedagogical And Content Knowledge) framework. They need to be well aware of the benefits that the use of new technologies in the classroom can bring, as well as to not fall in the trap of using it without the required preparation.

In particular, in this work we presented some of the most interesting new doors that the diffusion of low-cost, high-tech devices is opening for physics education. It was given a general background regarding scientific visualization, personal devices, mediated reality and serious gaming from an educational point of view. Then, a series of activities and setups based on these topics, designed and realized by the author within his research group, were discussed.

A workshop about scientific visualization was held at the University of Trento. It involved bachelor and master students of various scientific areas and informatics knowledge level, and lasted 21 hours. Results showed that even the less prepared students have been able to develop their own visualizations. It was argued that a similar experience would be very rewarding for physics education at different levels. The contents of the workshop could easily be adapted for both teachers and students of secondary schools and even of primary schools. As it was discussed in the theoretical framework, a similar experience would lead to the development of computational thinking, so it would be a very important experience that anyone could benefit from.

A teaching/learning sequence based on a low-cost spectrometer was then presented. The apparatus is obtained using a smartphone and almost-zero-cost materials, so students can create their own equipment and bring them home. In this sequence, additive and subtractive color models are introduced and color reproducing devices based on these models (light sources, monitors and printers) are analyzed qualitatively and quantitatively.

In the last chapter we presented a mediated reality setup for physics education, the *Augmented Laboratory*. It is able to distinguish objects from the background and may therefore be used for 3D tracking. It is also capable of using augmented reality in order to project the results of measurements and data analysis directly in the physical environment, on/near the tracked objects. Finally, the concept of *augmented simulations* was introduced, which are simulations influenced by the “real” world, meaning we can interact with them using physical objects.

Conclusions

The last presented setup, the *Augmented Laboratory*, is of particular importance. It is based on some of the most relevant research topics regarding new technologies (not only from an educational point of view), research that is today leading to the development and distribution of devices which are going to be always more present in our everyday life. We are here referring to computer vision, object recognition, human body recognition, mediated realities, personal devices and in particular even smart mobile devices. In fact, even if the current setup is based on a computer and external devices, 3D cameras are now being developed and put in a growing number of new smartphones and tablets. This probably means that in a few years almost everyone could have a small device in her/his pocket that would be able to act as a reality mediator in ways similar to the ones experimented in this work. It therefore seems very strategical and promising to continue the research on these topics from an educational point of view, keeping up with the evolution of technology and being capable of imagining new pathways it may open.

Appendix A

Scientific Visualization workshop – questionario frequentanti

Cosa hai trovato di particolarmente utile in questo corso?

La molteplicità di spunti dati per sviluppare anche in modo autonomo il modo di presentare le proprie ricerche scientifiche.
L'ampio respiro interdisciplinare e la possibilità di cimentarsi nella risoluzione di problemi di visualizzazione grafica in ambiti diversi
parte teorica e utilizzo Processing
Le esercitazioni dirette alternate a parti teoriche introduttive, oltre che una grande disponibilità del docente
Ho appreso un nuovo linguaggio di programmazione, molto utile tra l'altro!
La scoperta di nuovi strumenti per la presentazione efficace di dati
Il tutorato del docente e dei suoi collaboratori.
Rimandi teorici
La possibilità di imparare i metodi migliori per rappresentare dei dati
La presentazione di molti esempi da cui trarre ispirazione per sviluppare una propria idea

Appendix A

L'integrazione tra le nozioni apprese e l'insegnamento a come essere più chiara e comprensibile.
Le idee e gli strumenti di visualizzazione discussi
Gli esempi concreti e l'esperienza del docente
Suggerimenti riguardo alla rappresentazione scientifica che molto probabilmente mi torneranno utili in futuro
Presentare dei dati con cui ci lavoriamo tutti i giorni, ma che non saprei esporre ad un pubblico
La base teorica per una comunicazione scientifica efficace
la parte di scrittura del codice e i vari tipi di grafici
lo studio delle tecniche di visualizzazione e simulazione, gli approfondimenti sulle metodologie e i linguaggi corretti da utilizzare nei vari casi
Riprendere la programmazione
Programmare

Hai trovato qualche cosa di particolarmente poco utile in questo corso?

Non mi viene da segnalare alcun argomento, il corso è stato essenziale.
Troppo concentrato sulla programmazione
no
Forse alcune parti teoriche eccessivamente basilari sarebbero potute essere trattate più superficialmente per dare più spazio ad argomenti approfonditi
Non mi pare.
No

No
No, penso sia ben strutturato
No
no
no
No
La lezioni teorica 5 (pathlines,streamlines,streaklines,streak surfaces...) senza aver fatto dopo una parte di programmazione su questi argomenti

In che modo pensi che il tuo percorso accademico (e la futura vita professionale) possano beneficiare dall'aver seguito questo corso?

La presentazione dei risultati di una ricerca è fondamentale nel mio campo, per cui questo corso è servito a migliorare un aspetto che nei convenzionali corsi di studio non è toccato.
L'aver appreso dei concetti di base di Processing mi aiuterà molto in futuro nella visualizzazione di dati scientifici sperimentali
conoscenza Processing
Il corso insegna a trattare la visualizzazione scientifica come una parte integrante e attiva all' interno di una qualsiasi produzione scientifica, oltre che i fondamentali di un linguaggio di programmazione che possono sempre tornare utili in ambito lavorativo
1. Ho imparato come non fare grafici brutti.
2. Ho conosciuto nuove tecniche di presentazioni dati.
3. Ho imparato come sfruttare quelle tecniche.

Appendix A

Assolutamente si
Siccome penso di andare verso il business/data analysis la visualizzazione dei dati nel modo più appropriato da comprendere per l'occhio e la mente umana è un elemento importante. Questo corso è stato il primo riguardo la visualizzazione in 3D e penso di approfondire più avanti, quindi mi sarà più facile partendo da questa base.
In quanto penso che il mio percorso sarà improntato verso la computazione, questo corso mi ha permesso di fare la conoscenza con un nuovo programma che mi fornirà una marcia in più nella carriera
Mi può aiutare a scegliere il percorso di studi/lavorativo per i prossimi anni
Penso che cercherò di utilizzare quanto imparato per visualizzare meglio e quindi capire meglio i dati che andrò a manipolare.
Positivamente
Saper presentare con maggior successo un progetto
per un insegnante/divulgatore, le nozioni apprese durante questo corso aprono numerose e interessanti nuove strade
nell'espone più chiaramente i dati raccolti
grazie a questo corso avrò nuovi metodi per poter insegnare ai ragazzi i concetti che ho in mente che i tradizionali disegni non sono in grado di spiegare al meglio
Non so se il mio percorso ne beneficerà ma è interessante saper visualizzare oggetti per semplificare concetti e farsi capire meglio dagli interlocutori

Hai idee o suggerimenti per migliorare il corso?

Rinforzare l'interattività già presente, dedicando una piccola parte di lezione a problemi di visualizzazione che provengono dagli studenti stessi.

Penso si potrebbe dedicare più tempo alla spiegazione passo-passo della programmazione in Processing per chi proviene da un background non informatico.
Concentrare la parte di programmazione su qualcosa di utile a tutti non solo molecole
Amplierei ulteriormente gli obiettivi del corso e l'ammontare orario, è un corso interessante e piacevole da seguire e non sarebbe un problema
Usare esercitazioni un po' più guidate per l'introduzione a processing
Una variante 2.0? Anche se immagino sarebbe più complesso da gestire da tanti punti di vista.
Renderlo interdipartimentale?!
Se possibile utilizzare un microfono in aula, in quanto la voce del professore ha un tono piuttosto basso
Sarebbe interessante poter approfondire aspetti legati alla programmazione con processing
estendendolo magari a 6 crediti, potrebbe diventare a tutti gli effetti un corso per gli indirizzi di divulgazione scientifica
no
Più assistenti o meno corsisti perché è molto facile rimanere indietro
Più esercitazioni di programmazione

Parteciperesti a questo corso se venisse offerto di nuovo?

Si, senza dubbio parteciperei.
Certamente sì

Appendix A

Si
probabile
si
Se si intende se lo riseguirei col senno di poi, la risposta è sì. Ad ogni modo mi interesserebbe anche seguire un livello avanzato.
Si
Parteciperei se ci fosse una variante 2.0.
Si
Non credo, non perché non sia stato utile, ma perché credo che avendo posto delle solide basi ora sia mio il compito di approfondire, cosa che per un corso di tre crediti è difficile fare
Si, nei limiti del carico accademico
Ho già partecipato, se venissero aggiornati dei contenuti e il tempo lo consentisse forse sì.
Si
Si
Si parteciperei ancora, dato che per altri impegni non sono riuscito a seguirlo con costanza e profitto.
Si
assolutamente si
si
certamente
Si

Si

Altri commenti generali sul corso:

Lo consiglierei a chi vorrebbe profilarsi nell'analisi di dati, non solo nei campi delle scienze pure, ma anche quelle applicate. Grazie

Ho apprezzato la disponibilità del docente

come orario anticiparlo alle 2 invece che alle 2.30 per i trasporti

ne andrebbe fatto un corso pieno e non un semplice workshop

Appendix A

Appendix B

Scientific Visualization workshop – questionario non frequentanti

Buongiorno, dal registro presenze risulta che abbia superato il massimo di 2 assenze permesse al fine di ottenere il riconoscimento crediti del workshop. Ci sarebbe molto utile avere idea della/e ragione/i per cui questo è avvenuto.

Grazie!

Potrebbe indicare la/e ragione/i per cui ha smesso di frequentare il workshop?

La motivazione per cui purtroppo ho smesso di frequentare il corso è per le troppe attività accademiche in cui ero e sono impegnato (tesi, esami, altro). Avrei frequentato molto volentieri Il corso di cui sono rimasto subito positivamente impressionato per l'impostazione, i contenuti e per la disponibilità di voi tutor.

Rimango molto interessato al tema in quanto troverebbe ampio spazio non solo nella tesi ma nella disciplina architettonica-urbanistica. Spero ci sarà un'altra possibilità, magari il semestre prossimo.

Ti ringrazio

La prima assenza l'ho fatta perché mi vergognavo a entrare in ritardo e sono entrata alla seconda ora, un'altra per problemi personali e la terza assenza è stata perché pensavo che la lezione sarebbe stata la settimana successiva, perché in genere erano ogni 2 settimane.

Esami

Buongiorno, ho smesso di frequentare il workshop per motivi di lavoro. Causa vari imprevisti e molteplici attività in corso, purtroppo non sono riuscito ad organizzarmi come volevo. Mi dispiace, perché penso che fosse interessante e ben organizzato. Siccome, al momento, non sono uno studente, avevo deciso di seguire il workshop nel tempo libero, per passione e perché al momento mi occupo anche di data visualization. Se verrà riproposto l'anno prossimo lo prenderò certamente in considerazione. Grazie.

Gentile Tommaso,

sfortunatamente per un sommarsi di impegni non mi è stato possibile frequentare il corso. Mi ero iscritto in quanto trovavo molto interessanti gli argomenti proposti non ch'è utili e coerenti con il mio attuale lavoro di tesi. Proprio in concomitanza con il corso, ho avuto diverse deadline da rispettare, e questo mi ha reso difficile la presenza.

Grazie mille per la disponibilità.

Si sono aggiunti altri impegni, principalmente lavoro e la preparazione di un esame durante il semestre e in mezzo alle altre lezioni.

Altri commenti

Le slide rimangono delle fonti eccezionali!

E' stato un corso interessante, mi dispiace molto di aver perso delle lezioni.

Corso estremamente interessante, soprattutto la parte teorica, purtroppo per impegni accademici non sono riuscito a terminare il corso. Credo sia però necessaria più chiarezza nei contenuti del corso, per esempio che le esercitazioni riguardano esclusivamente processing.

Appendix C

The Augmented Laboratory – questionario studenti

DOMANDA 1

Durante il corso abbiamo utilizzato il software *Tracker* per eseguire la video-analisi al fine di effettuare misure e analizzare moti di oggetti in uno spazio bidimensionale. Abbiamo successivamente visto come opera un sistema in grado di eseguire un tracking 3D. Dal punto di vista didattico, quali pensi siano i principali vantaggi e svantaggi dei due tipi di acquisizione e analisi dati confrontandoli tra loro e rispetto ad un laboratorio tradizionale? In quali casi, nella pratica didattica, utilizzeresti l'uno o l'altro?

RISPOSTE

Sia Tracker che il sistema 3D mi sembrano ottimi strumenti. Possiamo vedere l'esperimento registrato quante volte vogliamo e contemporaneamente leggere i grafici delle quantità che ci interessano per ogni istante dell'esperimento. Sicuramente li utilizzerai entrambi.

Da un punto di vista didattico il sistema che permette di eseguire un tracking 3D può portare ad un maggiore interesse e dunque coinvolgimento degli studenti. Dal punto di vista pratico i vantaggi sono praticamente gli stessi rispetto ad una normale attività laboratoriale senza l'utilizzo di tali strumenti. Infatti entrambi permettono di risparmiare tempo nell'acquisizione dati e nella loro elaborazione. Tali strumenti sono complementari nell'utilizzo e li userei per tutte le lezioni riguardanti lo studio dei moti.

Tracker mi sembra facilmente utilizzabile, dato che, avendo una telecamera a disposizione, dovrei essere in grado di utilizzarlo fin da subito. L'unico inconveniente che ho riscontrato nell'utilizzare questo software è dato dal fallimento dell'autotracking, questo piccolo inconveniente mi è risultato abbastanza fastidioso... Tale problema però può essere evitato provando

precedentemente l'esperimento e prestando attenzione all'illuminazione e all'ambiente circostante.

Forse avendo a disposizione uno strumento che lavora in 3-D lo userei, ma non so dire altro.

Ritengo che l'utilizzo di Tracker sia stato molto utile, soprattutto perché c'è un lavoro totalmente svolto dallo studente: dal fare i video e acquisire dati al risultato finale visualizzato sui grafici è tutto nelle sue mani. E credo che mettendo le mani in pasta si capiscano meglio le cose. Per quanto riguarda il tracking 3D credo che sia molto utile dal punto di vista qualitativo, un po' meno efficace dal punto di vista quantitativo. Chiaramente, didatticamente parlando, sarebbe interessante poter utilizzare entrambi gli apparati anche perché il secondo fornisce una visione più globale della situazione. Sicuramente Tracker è un apparato che utilizzerei in classe per le ragioni sopra dette, per quanto riguarda il tracking 3D, invece, trovo che, per quanto interessante, possa essere di difficile utilizzo.

A parer mio, con Tracker si riesce a far lavorare gli studenti in piccoli gruppi. In questo modo c'è un maggiore attività del singolo studente nello studio dell'esperimento. Tuttavia col tracking 3D, sebbene fare quanto detto è in pratica impossibile, si potrebbero far osservare più fenomeni contemporaneamente, come il caso ideale e quello reale.

Credo che per fenomeni semplici come scontro tra carrelli et simili preferirei usare Tracker in quanto fa ragionare di più il singolo studente. Però si potrebbe anche completare rivedendo l'esperimento col tracking 3D a fine modulo.

Penso che il software tracker che abbiamo usato durante il corso sia molto utile e semplice da usare a scuola dato che permette di comprendere bene i moti dei corpi. Utilizzerei tracker per studiare i moti più complicate più difficili da interpretare.

Vantaggi del tracking 2D: è gratuito, abbastanza facile da usare e permette di lavorare su dei video senza necessariamente dover fare l'esperienza in laboratorio (questo è anche uno svantaggio però), comodo per esperimenti di difficile realizzazione. Vantaggi del tracking 3D: è fantastico e permette di eseguire esperimenti anche difficili con semplicità e immediatezza, però è ancora in fase di costruzione e non disponibile in prezzi e quantità ragionevoli.

Utilizzerei volentieri il tracking 2D abbinato all'esperimento in laboratorio (come fatto a lezione per intenderci), in modo che gli studenti abbiano

effettivamente svolto l'esperienza ma con la soddisfazione di analizzare dati con una precisione maggiore e un minor dispendio di tempo.

Tracker è un ottimo strumento da utilizzare in una classe in quanto lo studente, lavorando sui dati reali, riesce a capire la differenza tra teoria e pratica. Inoltre studia le traiettorie e i moti, disegnando grafici ed errori. Lo utilizzerei soprattutto per gli urti, il piano inclinato e la relatività.

Il sistema del tracking è molto utile per trattare i problemi di meccanica classica, specialmente la cinematica. Il tracking 3D ha dei vantaggi rispetto al tracking in 2D per la complessità dei problemi che si possono studiare, ma nella maggior parte dei casi il tracking 2D è sufficiente. Con Tracker, inoltre, ogni studente può analizzare il video e ricavare le leggi fisiche. Nei laboratori tradizionali gli studenti devono prendere confidenza con un maggior numero di strumenti rispetto a Tracker, ma spesso risulta più difficile misurare accuratamente i dati sperimentali.

Indubbiamente la possibilità di eseguire un tracking 3D permette di ottenere una migliore analisi dei dati quando il moto di un corpo non può essere approssimato a bidimensionale o planare (trampolino di Galileo). Tuttavia, l'astrazione bidimensionale della dinamica di un corpo è ricorrente durante tutto il percorso scolastico liceale, se non addirittura universitario, pertanto ritengo sia più utile sfruttare un tracking 2D per l'acquisizione e l'analisi dati. Il tracking, rispetto ad un laboratorio tradizionale è indubbiamente più versatile, in quanto permette di analizzare simulazioni più complesse e varie, inoltre è possibile svolgere un'analisi dati quasi istantanea e dunque di rapportarsi immediatamente con la teoria avendo la possibilità di effettuare dei fit, scoprendo subito se la teoria studiata approssima correttamente la realtà.

Onestamente non credo ci siano particolari svantaggi nell'usare tracker al posto di un normale laboratorio, l'esperienza verrebbe comunque svolta dagli studenti, quando possibile, come pure l'analisi dei dati.

DOMANDA

2

Durante il corso abbiamo utilizzato il Kinect in combinazione con un videoproiettore per costruire un ambiente di realtà aumentata in cui si possono visualizzare sia gli oggetti reali che variabili fisiche significative (vettori velocità, traiettoria del centro di massa...) anche simultaneamente. Dal punto di vista didattico, quali pensi siano i principali vantaggi e svantaggi di utilizzare la realtà aumentata nella didattica della fisica? In quali casi e come, nella pratica didattica, utilizzeresti questo strumento?

RISPOSTE

Penso che la realtà aumentata abbia del potenziale che però mi sembra ancora in buona parte inespresso. La visualizzazione in tempo reale dei vettori mi sembra fuorviante (sono vettori 3D proiettati su due dimensioni) e elimina lo sforzo di immaginarseli. Per quello che ho visto ho la sensazione che si riveli un tentativo di dare la "pappa pronta" allo studente.

Il principale vantaggio è quello di poter simulare virtualmente delle attività laboratoriali senza perdere troppo tempo, di visualizzarle più volte e di poter così analizzare molteplici casi in minor tempo. Utilizzerei questo strumento sempre per lo studio dei moti.

Sicuramente un ambiente di realtà aumentata faciliterebbe lo sforzo nell'astrazione richiesto per poter visualizzare alcune proprietà fisiche.

Ritengo che il vantaggio principale sia poter vedere chiaramente quello che succede in tempo reale, potendovi partecipare in maniera interattiva favorendo il dialogo e fornendo risposte immediate. Inoltre credo che lo strumento possa avere un effetto "wow" sugli studenti, cosa che non è da sottovalutare. Come scritto sopra, però, credo che sia meglio metterci le mani e utilizzare strumenti della quotidianità piuttosto che vedere come vanno le cose su uno schermo. Molto probabilmente non utilizzerei lo strumento a favore di lavori di gruppo che sviluppino idee su come fare le cose senza che ci sia già qualcosa che le fa al posto nostro.

Penso che gli studenti da una parte sarebbero attirati dall'aspetto tecnologico e di possibilità di sperimentare al momento le loro ipotesi, ma dall'altra sarebbe una distrazione, che renderebbe più difficile agli insegnanti tenere un discorso approfondito. Inoltre renderebbe il tutto più un lavoro di classe, facendo lavorare di meno i più lavativi.

Credo che la realtà aumentata possa esser utile nella fase di ricapitolazione finale al termine di un modulo, così che gli alunni possano rivedere gli esperimenti e notare che le leggi studiate approssimano bene le condizioni reali.

Utilizzerei questo strumento quando diventa difficile rappresentare i fenomeni con gli esperimenti classici in laboratorio.

Il vantaggio è che è più chiara e aiuta l'insegnante a spiegare e far intuire concetti sulla realtà 3D, che è difficile rappresentare su un libro/lavagna. Forse lo svantaggio è che perde in termini di contatto con la realtà, ma mi sembra uno svantaggio minimo. Io lo utilizzerei lo stesso, se fosse disponibile, per chiarezza in alcuni ambiti.

Lo svantaggio principale del Kinect è quello di non poter lasciare gli studenti lavorare da soli dopo aver fatto un esperimento. Su alcune cose è molto simile ad un programma come Algodoo. Mentre per altri aspetti è molto innovativo, ad esempio è possibile vedere vettori, coefficienti angolari e campi di forza.

La realtà aumentata tramite il Kinect è uno strumento potentissimo, secondo me, per la didattica della fisica. Il poter vedere in tempo reale le velocità e le traiettorie degli oggetti permette di far capire agli studenti i principi fisici alla base della meccanica classica. Il suo utilizzo ottimale credo sia a livello di scuole superiori, dove gli studenti devono capire non solo i concetti fisici, ma anche saperli applicare tramite formule e vettori.

La realtà aumentata permette effettivamente di sovrapporre teoria e pratica. La possibilità di vedere contemporaneamente un fenomeno fisico e la sua descrizione fisica-matematica attraverso i vettori velocità o traiettoria del CM faciliterebbe l'apprendimento da parte degli studenti, che avrebbero la possibilità di vedere "materialmente" quello che gli è stato spiegato. Tuttavia non credo debba essere sostituita agli esperimenti o alla teoria, ma debba essere usata come un mezzo integrativo, di supporto. Personalmente la utilizzerei o in seguito ad una lezione teorica per mostrare "in azione" i concetti fisici appena esposti analizzando un'esperienza che i ragazzi dovranno svolgere fornendo quindi un aiuto visivo alla fisica che verrà analizzata. Oppure si potrebbe usare alla fine del percorso didattico per ricapitolare e rivedere in una sola volta la teoria applicata all'esperimento.

DOMANDA 3

Lo stesso setup può essere utilizzato anche per controllare delle simulazioni, come abbiamo visto nel caso del "Ripple Tank", in cui gli elementi della simulazione erano introdotti manipolando oggetti reali. In quale contesto (laboratorio scolastico, esposizione museale, ...), se ritieni che ve ne sia alcuno, pensi che questo tipo di strumento potrebbe avere una utilità didattica? In generale cosa pensi degli ambienti di simulazione (tipo algodoo, applet, etc.) e quale ritieni possa essere la loro utilità nella pratica didattica?

RISPOSTE

Penso che un ambiente di simulazione sia utile quando permette di mostrare un sistema totalmente privo del rumore che si otterrebbe in un esperimento reale. Algodoo e gli applet (tipo quelli di PhET) sono ottimi in questo senso. La ripple tank, per quanto in un primo momento mi abbia affascinato, mostra forse più rumore di un esperimento reale. Per ciò che ho visto non mi sembra che il gioco (l'interazione attraverso oggetti fisici) valga la candela (veramente troppo rumore).

Ritengo questo strumento molto interessante e coinvolgente. Permette di ricreare varie situazioni in tempi brevi. E' vero che esistono già delle applicazioni simili per tablet, smatphone,..., ma non hanno lo stesso impatto visivo dello strumento visto nello studio del dott. Rosi. Tale strumento permette infatti agli studenti di apprezzare al massimo l'esperienza e di acquisire conoscenze in modo attivo e divertente. Ritengo infine che programmi come Algodoo ed altre applet siano davvero utili nel contesto didattico e che quindi debbano essere inserite come supporto alle attività scolastiche al fine di migliorare l'apprendimento della fisica.

Gli ambienti di simulazione sono particolarmente interessanti, perché essendo costruiti sulla base dei modelli, mostrano esattamente i risultati di tali modelli.

Il "Ripple Tank" è sicuramente adatto ad un ambiente museale, in cui il pubblico può liberamente avvicinarsi con questo strumento oppure farlo con l'aiuto di una guida.

Nella pratica didattica potrebbe avere la sua utilità, e soprattutto potrebbe rivelarsi molto più pratico di applet od altri strumenti fisici analoghi.

Ritengo che, così come l'abbiamo visto, possa non essere utile perché troppo rumoroso e troppo lontano dal caso ideale. A mio parere porterebbe a creare ancora più confusione allo studente. Inoltre esistono moltissime applicazioni in cui si possono ricreare le stesse situazioni evitando rumori quindi non la utilizzerei di sicuro. Potrebbe essere invece interessante un utilizzo dell'apparato nei musei, ma comunque solo dopo aver risolto i problemi visti. Per quanto riguarda gli ambienti di simulazione, ritengo che siano fondamentali per ricreare la situazione ideale che in alcuni casi non riesce dagli esperimenti "a mano". Credo però che debba essere l'ultimo passo e che non debba essere una sostituzione dell'esperimento stesso. Ho apprezzato particolarmente Algodoo perché permette di metterci del tuo e

quindi non è solo una visualizzazione di come vanno le cose ma è comunque una progettazione.

A parer mio, sono più adatte a livello museale che scolastico: ritengo che uno studente comprenda meglio aspetti teorici se li vede in esperimenti reali. Ad esempio gli esperimenti con le onde sono, credo, di abbastanza facile esecuzione nelle scuole. A livello museale invece potrebbe essere già più interessante far vedere delle simulazioni in cui la gente può variare la simulazione manipolando oggetti reali.

Per quanto riguarda gli ambienti di simulazione, credo che siano in parte utili: in parte per il ragionamento sugli esperimenti reali e dall'altra perché consente più facilmente ad uno studente di lavorare singolarmente facendosi domande e rispondendosi da solo.

Ritengo che i software di simulazione siano molto utili al fine di comprendere a pieno i moti dei corpi e in generale i fenomeni fisici.

Questo strumento (il Ripple Tank) ha un'utilità secondo me limitata, in quanto può essere comodamente sostituito da altri strumenti che si trovano in rete e anche da Algodoo stesso. Per quest'ultimo, lo ritengo fondamentale per far capire i concetti fisici agli studenti tramite simulazioni, e adatto a riprodurre i casi "ideali" che la fisica propone e confrontarli con casi reali (es. moto parabolico con/senza attrito dell'aria). Tuttavia, è uno strumento che abbinerei alle lezioni frontali quando necessario, più che a un'esperienza di laboratorio.

Strumenti come Algodoo, Tracker e altri citati sono utili in ambito scolastico perché permettono allo studente di vedere e capire tramite simulazioni della realtà gli effetti fisici, facendolo ragionare in modo stimolante in quanto è lui stesso a lavorare con tali programmi. Permettono di trasformare la realtà in modelli fisici e di conseguenza in "numeri", formule e grafici. In ambito didattico è però più facile utilizzare programmi al computer che manipolare oggetti reali (a meno che la scuola sia attrezzata con laboratori e strumenti che permettano di fare esperimenti più complessi).

Le simulazioni possono essere molto utili per far prendere confidenza con i principi fisici agli studenti, ma probabilmente un programma di trucking è più utile per far capire il metodo scientifico, in cui l'osservazione del fenomeno risulta fondamentale. Ritengo che le simulazioni (come il Ripple Tank) possano essere molto più utili in ottica museale, in cui non è importante che gli osservatori ricavino le leggi fisiche partendo dalle

osservazioni, l'importante è che capiscano alcuni concetti fisici anche senza passare dalle formule che li formalizzano.

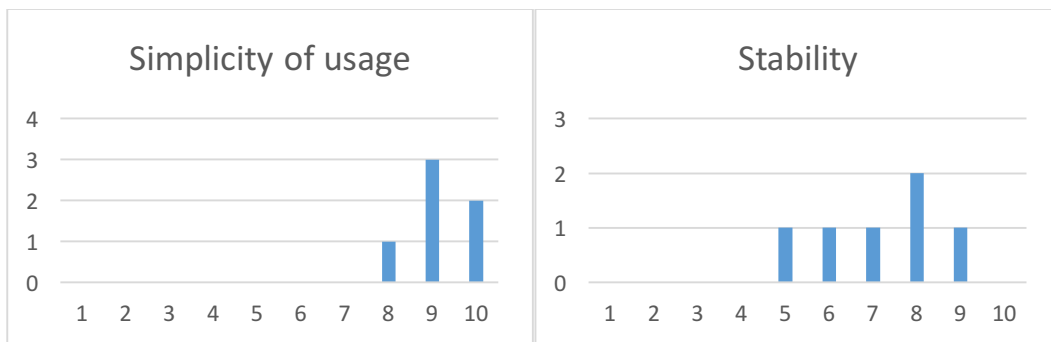
Questo genere di strumento penso che sarebbe adatto sia per scuole che per musei tuttavia credo che debbano essere usati o per solidificare delle conoscenze già acquisite dagli studenti o dal pubblico o per permettere a chi possieda già un minimo di nozioni in materia (es: simulazioni propagazioni ondose) di simulare casi più complessi o di interesse difficilmente riproducibili in laboratorio. Pertanto gli ambienti di simulazione ritengo siano più indicati come approfondimenti ai temi trattati a lezione e non da sostituirsi alle classiche esperienze didattiche.

Appendix D

The Augmented Laboratory

– guides survey

First of all, please give two evaluations regarding the general comfort of using the system from the perspective of the narrator:



Comments/thoughts about what can be improved and what worked well:

Suggerisco di introdurre un pulsante per bloccare l'immagine una volta osservato il pattern scelto oppure un disabilita kinect in modo da poter mettere le mani sopra la proiezione e poter indicare liberamente con le mani. Suggerirei inoltre una pulsantiera o equivalente per la calibrazione e azzeramento. Efficace nella rapidità di utilizzo e nella realizzazione di configurazioni non comuni in ottica ondulatoria e realizzabili con il classico ondoscopio. Un aspetto critico è l'illuminazione, a volte a schermo del pc si vedeva meglio della proiezione e quindi i ragazzi osservavano lo schermo laptop. O si toglie il laptop per nn distrarre o si riduce la luminosità ambientale.

Sarebbe bello poter cambiare frequenza dell'onda emessa interattivamente

Serve un tasto di "reset" vicino al narratore. Sarebbe più comodo e immediato che cercare il tasto "R" sul PC.

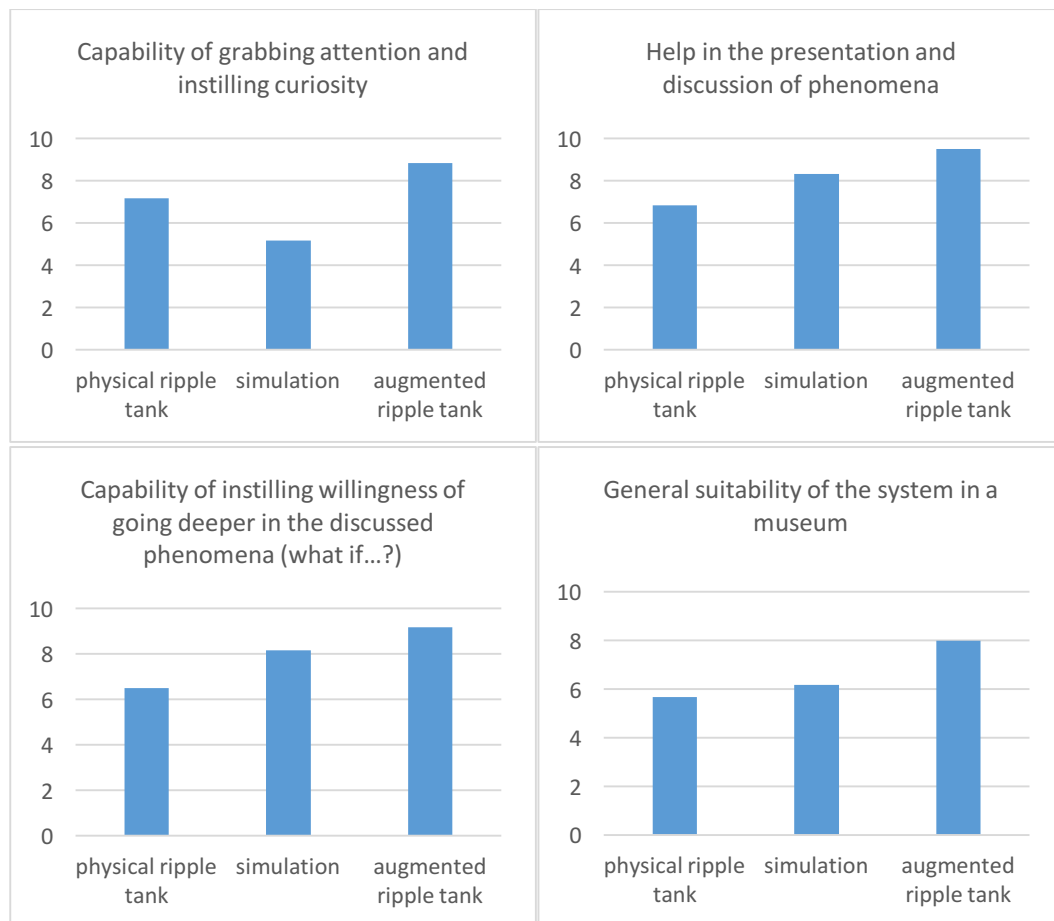
Appendix D

Sarebbe bello avere una bacchetta “trasparente” al Kinect per indicare le cose sul tavolo.

Let us now continue by making a direct comparison between 3 different systems that could be used in this or similar contexts:

- 4) the real, physical ripple tank
- 5) a simulation
- 6) the augmented simulation

For each of these systems, give a mark from 1 to 10 regarding their:



Any other comments/thoughts about using the Augmented Ripple Tank:

Well done! Rilancio l'idea di cercare un influencer e impostare una campagna di crowdfunding

Una visitatrice (dopo aver proposto un confronto tra il comportamento corpuscolare e quello ondulatorio) ha chiesto se non è possibile inserire una "modalità corpuscolare" creando una sorgente che emette particelle.

Serve un operatore che spieghi come si usa lo strumento e come si evita il rumore. I visitatori tendono a disporre gli oggetti in posizioni insignificanti (i "prismi" messi in verticale col vertice in alto ad esempio, oppure pasticciano con le mani e si lamentano che non si vede nulla).

Appendix D

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