systematic approach for implementation of STEAM education in schools

STATE OF THE ART OF STEM TECHNOLOGIES WITH APPLICATIONS IN THE CLASROOM

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INTRODUCTION

The main goal of the sySTEAM Project is to increase the educational use of STEAM (science, technology, engineering, art and mathematics), ensuring quality and the smooth implementation of inquiry-based, project-based, problem-based and transdisciplinary learning. This report, on the state of the art of existing and emerging technologies for classroom use, is the first step to achieving that goal.

The technologies featured in the present report span a sufficiently wide range of possibilities so that each school can identify the applications that best suit their needs. Technologies have been classified according to their degrees of maturity and development worldwide as either 'consolidated' or 'emerging', but all have been selected based on their capacity to mobilise transversal STEM projects.

For each technology, diverse aspects have been analysed: working principle, historical background, practical applications, educational connection and real-world examples. Our aim is to provide science teachers with a general outline on how to prepare pupils to be more creative, problem-solving and critical in the future.

This report will be followed by another presenting a set of guidelines to implement such technologies in the classroom.

CONSOLIDATED TECHNOLOGIES

PROGRAMMING

> ***Programming skills have an impact on several key areas of citizenship development, such as ethics and critical thinking, problem-solving orientation, bridging the digital divide and improving labour market prospects.***

With the participation of Jordi Losantos (Computer Engineer, Technical University of Catalonia (UPC); MBA, ESADE Business School; and secondary school teacher) and Joan Alemany (Graduate in Mathematics, UPC; cofounder, eSeeCode; and high school teacher).

Underlying principle

In computer science, *programming* refers to the action of translating a series of previously designed instructions (algorithms) into computer language in order to process a dataset for a specific purpose.

Any programming strategy requires prior modelling of the problem to be resolved from a perspective of applied informatics. This requires an in-depth analysis of the problem and a top-down design process that separates possible resolutions through automation.

Programming a computer application is based on logic, knowledge of sequential processes and the correct use of programming language syntax. Therefore, it is possible to write a programme without in-depth familiarity of the hardware used.

Historical background

Programming was first developed in the 20th century in Europe and especially in the United States, with applications in the large electronic calculation machines of World War II (such as the large computer ENIAC). By the end of 20th century, microelectronics and the first high-level programming languages had emerged.

BASIC, Fortran and Pascal provide a reasonable interface, between a pseudo-human language and machine code. Today, the most commonly used programming languages – C++, JavaScript, Phython and PHP – include many functionalities that make it easy to write comprehensive computer programmes with few lines of code.

The latest trend in programming languages design is the minimisation of rigid syntax in the code, with very visual proposals generally based on interactive blocks that place more emphasis on the logical structure of the programme than on correct syntax. Scratch, Swift Playgrounds and GPblocks are good examples of this. Although they are widely use as teaching models, they are truly high-level languages that can be used to programme high-performance applications.

Practical applications in everyday life

Programming skills go far beyond the knowledge of some languages. Experts agree the most important idea is just the inherent adoption of computational logic, knowledge of technology and problem-solving analysis.

In a world where people are increasingly (and more intimately) interacting with all types of technological elements, from machines to software, programming knowledge provides the tools to effectively understand and use mobile devices, professional computing applications, social media, and even smart appliances, among other applications.

This last point is very important, as the current trend is to connect all types of devices, shaping a phenomenon known as the Internet of Things (IoT), which will pose great challenges for privacy and processing of personal data. Accordingly, it will also allow the development of technologies based on the analysis of large datasets, or Big Data, probably by means of artificial intelligence.

Thus, programming skills have an impact on several key areas of citizenship development, such as ethics and critical thinking, problem-solving orientation, bridging the digital divide and improving labour market prospects.

Educational connection

In the educational field, the need to teach the basics of computer programming to young people is as old as programming itself. One of the first systems adopted by schools was the Logo educational tool (designed in 1967), which has maintained its iconic turtle through various updates. However, some experts admit that under-investment in school computers due to the recession in the 1990s in Europe has kept programming skills from being integrated into the basic academic curriculum. It was not until the turn of the century, which coincided with a period of economic growth in Europe in 2004-2008, did computer programming return with force to the early stages of education. Lower hardware costs and good graphic performance have popularised Scratch (developed in 2015 and partially inspired by Logo) as the standard visual programming language. This programming system, based on manipulating interactive blocks rather than writing lines of code, avoids the frustration of having to write in syntax-dominated language and allows students to monitor the results of their programmes in any situation. In this paradigm, other languages (Swift, GPblocks, eSeeCode or Tynker) have emerged to improve some features that have not yet been completely perfected in Scratch.

At present, programming is included in the academic curriculum as a part of computer skills and new technologies at all stages of education in most EU Member States, and it is considered a key skill in the training of the future citizens. In particular, programming at the primary and secondary school level employs a series of cross-disciplinary skills in the educational development of children and young people, such as:

- critical and logical thinking;
- problem solving;
- implementation of strategies;
- analysis and evaluation of algorithms;
- abstract thinking;
- creative approach to reality; and
- teamwork (in large projects).

Practical examples

Experts agree that there is no single way to learn programming skills, and students develop them as the tools and task require. Therefore, creation-based approaches are fundamental. The concept would be ‘programming to learn’ rather than ‘learning to programme’.

CREATION OF SIMPLE GAMES

Programming games, from simple ones like Domino or Solitaire to more complex ones like platform games, presents students with multiple challenges to address by applying programming strategies based on problem analysis. These small games allow students not only to develop the programming part, but also artistic aspects (graphic design) and literary features (writing instructions for the player).

MAINTENANCE OF A WEBSITE

Many teachers in the STEM areas encourage students to maintain a joint class website, including a variety of information about the academic course. This can use various languages associated with the web, such as HTML, CSS, PHP or JavaScript, to integrate them into the site and provide it with a customised look. Of course, these activities also tackle aspects such as design, content writing and communication.

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ROBOTICS

> ***Robotics applications in the classroom allow us to work on aspects that can hardly be addressed only by purely theoretical schemes.***

With the participation of Jordi Losantos (Computer Engineer, UPC; MBA, ESADE Business School; and secondary school teacher) and Joan Alemany (Graduate in Mathematics, UPC; cofounder, eSeeCode; and high school teacher) and Frank Sabaté (specialised STEM teacher).

Underlying principle

Robotics is a transversal discipline that deals with the study, design, construction and application of robots. The terms robot and robotics have the same conceptual origin, although their adoption has a peculiar history.

Due to its multidisciplinary nature, robotics draws on many principles. On the one hand, it is based on programming, in the sense of coding the processes and actions for a robot. All information detected via sensor is processed from a computational point of view. On the other hand, since the robot is a physical device, its construction is focused on the basic principles of engineering, electronics and mechanics.

Historical background

Currently there is no unified definition of what a robot is. However, experts agree that a robot would be any engineering device, programmable by a computer, capable of collecting information from its environment via sensors and responding to it thanks to a set of automated actuators. It is, therefore, necessary to distinguish an authentic robot from automated software (popularly called bots) that would not be considered as robots even though it can be very sophisticated.

From a historical perspective, we can look back to legends from classical Greece or ancient China about the animated mechanical models of various animals, the golems from the Jewish tradition and even automatons: recreational pieces that were very popular in Europe in the 19th century. But these constructions lack an adaptive response to their environment.

The term *robot* as associated with artificial creatures first appeared in 1920, in the play R.U.R. (an abbreviation of Rossumovi Univerzální Roboti) by Czech author Karel Čapek. In this play, the roboti (deriving from the Slavonic word robota: forced labour) are humans' artificial servants, who end up rebelling and extinguishing humanity. Although in Čapek's play those servants are not mechanical beings (today we would call them androids or clones), this moment marked the turning point when 'robot' was finally adopted as a modern version of the classic automaton.

Two decades later, the American novelist and professor of biochemistry, Isaac Asimov, coined the term *robotics*, first mentioning the neologism in the short story entitled 'Liar!' (published in the Astounding Science Fiction magazine in 1941), and using it widely in all his later literature, dedicated to exploring the limits of artificial intelligence and its impact on future human society.

Practical applications in everyday life

The EU report on robotics argues that developing robotics would have a positive impact in several areas:

- **Health**, with the development of assistive surgical devices and aid devices for elderly and/or functionally diverse people.
- **Agriculture and bioeconomy**, in automated sowing, harvesting and crop monitoring.
- **Energy savings**, developing more efficient and less polluting production systems.
- **Transport and retail management**, developing self-driving vehicles and automated warehouses.
- **Security**, in assisting and protecting citizens in risky situations such as rescues or assistance in extreme conditions.

Educational connection

In the educational field, turtle robots associated with the Logo programming language were first developed in the 1980s. Towards the end of the 1990s, the Lego company presented the Cybermaster robots, developed for use in schools, which were upgraded to Mindstorms NXT in 2006 and Mindstorms EV3 in 2013. As the need for electronic components has decreased, multiple options using all types of sensors with Arduino or Raspberry Pi technology have become available.

From an educational point of view, classroom robotics applications allow educators to work on aspects that can hardly be addressed by purely theoretical schemes. In this sense, translating formal concepts into reality is a major challenge for students because the robot's interactions with the real world force the programmer to deal with inaccurate data, variable stimuli and imperfect elements. That is why it is necessary to learn to design strong solutions for real problems in multidisciplinary projects.

Other positive aspects of using robotics in the classroom are more transversal, such as students' motivation, because they can perceive the practical and experimental approach as a game. Sometimes, students' interaction with the robot can be used to reinforce social aspects and skills. Robotics in the classroom help to bring technology closer to students, especially at a time when they are developing their strengths for the future.

Practical examples

ROBOT THEATRE

Robots ready to simulate human expressions, like Aisoy (https://www.aisoy.es/), allow students to organise small plays with robotic actors. These would be designed to work with multiple skills such as the robot's programming, plastic expressions (clothing and props), performing arts, literature and human relationships.

PRECISION GAMES

Precision games have to do with programming a robot to cover a certain distance and be as close as possible to a mark or a wall. Students must give orders to the engine systems and optical or proximity sensors to decide when to stop the robot. This exercise shows students that reality poses more complex challenges than a theoretical treatment can solve, such as the uncertainty margin of sensors or loss of traction of the impeller device.

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VIRTUAL AND REMOTE LABS

> ***In these simulated spaces, students can operate sophisticated and/or dangerous tools in safe conditions, facing the challenges of lab experimentation in a controlled environment.***

With the participation of Sílvia Zurita (PhD in Chemistry, University of Barcelona; teacher, Polytechnic University of Catalonia; secondary school teacher).

Underlying principle

The scientific paradigm is largely based on the principle of empirical knowledge, so science education must include experimental elements. Many of these practical activities can be done in daily spheres, such as classroom demonstrations or field trips, but all educational establishments should have a properly equipped lab, dedicated exclusively to experimental sciences.

Equipping a lab is no easy task: scientific instruments are often expensive and fragile, and they may be toxic or dangerous if mishandled. Thus, well-trained teachers, flexible class arrangements that enable working with small teams, and adequate funding are needed for setting up and running school science labs. Even with these conditions in place, many concepts cannot be tested due to obvious limitations, such as the study of nuclear reactions, explosive combustions or molecular genetics. But lab competence is a growing demand in the EU labour market, which is increasingly focused on research and innovation.

Fortunately, technological developments have enabled the creation of interactive and often sophisticated simulations, as an authentic virtual lab. In these simulated spaces, students can operate sophisticated and/or dangerous tools in safe conditions, facing the challenges of lab experimentation in a controlled environment.

In addition to virtual lab realities, there are also remote labs: physical premises that can be remotely operated to obtain real experimental data. Remote labs have the advantage of showing all the imperfections of real life, something difficult to programme on a simulation, but there are very few and their activities are quite limited.

In order for a virtual or remote lab to be effective in an educational context, they must appeal to students. That is why the current trend is to use elements of virtual and augmented reality as well as gamification. The aim is to transform a static activity in front of a screen into an immersive experience that pursues a stimulating objective.

Historical background

Virtual Labs

It is not easy to trace the history of simulation as an educational tool. However, we do know the first simulations were made using physical elements, for instance the dolls used in the 1960s in medical schools for lung resuscitation practices.

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The popularisation of computers in the 1980s, together with the appearance of high-level programming languages, allowed the first simulations of virtual reality, especially for the flight simulators widely used in the flying schools. Those simulations reached the general public through games such as Microsoft's pioneering Flight Simulator (1982). In 1989, Maxis launched the first edition of Sim City, an urban simulator, followed by Sim Earth (1990), a planetary simulator with a rudimentary system of climate and ecological control. Universities also developed virtual applications to complement their studies, usually free of charge, but their specificity, high level and the impossibility of mass distribution limited their application elsewhere.

The year 2004 marked the advent of the so-called Internet 2.0, characterised by greater social interaction and the popularisation of broadband. Internet became much more accessible, and applications developed in university environments could be more easily disseminated online. Many of those applications transcend the university environment and have an impact on simple concepts covered in primary and secondary school. Given the continuous updating of these virtual spaces, it is difficult to establish timing. Thus, a (non-comprehensive) review of the current accessible virtual labs will be carried out in the following sections.

Remote Labs

As in the case of virtual labs, the history of remote labs is also opaque. The fact that many of these initiatives are limited to the university sphere make them difficult to find and, in many cases, difficult for novices to operate.

Research into remote labs did not uncover platforms dedicated to their dissemination or broad repositories.

Practical applications in everyday life

Virtual labs are designed as an educational complement, so everyday applications in people's lives derive from their contact with such applications at school and/or university. Thus, the direct benefits of this technology would be the same as those of the physical lab, namely:

- Implementing research methodologies in daily life. A paradigmatic case is the emergence of a new cuisine, greatly influenced by laboratory-based techniques.
- Enabling outreach activities. While many such activities are designed for formal education, they open the door to science teachers using them in all kind of activities, such as conferences or workshops.
- Encouraging critical thinking. The opportunity to undertake realistic activities in a research environment, even if it is a simulated environment, allows us to understand the complexity of scientific methodology and to combat the proliferation of simplistic, pseudo-scientific ideas.

Educational connection

In the classroom, virtual labs provide a great opportunity to work on various aspects of the academic curriculum as well as cross-cutting skills. In many cases, the resources used in these systems allow people to mentally visualise processes that would be difficult to transmit otherwise. However, consulted experts stressed the need for highly specialised and trained teachers to give these tools real educational meaning.

In the curriculum section, we have already mentioned that virtual labs enable experiments that cannot be carried out in a school lab due to hazard or cost (nuclear exploration or genomic techniques, for example).

But we can also find some very remarkable elements in the cross-cutting skills area:

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- Students' motivation. Gamification and 3D immersion strategies used in modern virtual labs enhance the attention and retention of students who may be less receptive to traditional scientific practice. This trend is increasing because of the development of new systems of sensory interaction with virtual reality, such as touch or smell.
- Socialisation and interaction. Groups of students should soon be able to interact in the context of virtual labs, assuming different roles and working together to carry out research.
- Familiarisation of digital environments. Performing an activity in a virtual environment can attract students to these technologies and inspire future developments in the field of virtual or augmented reality.

In any case, and without underestimating the utility that these tools can have in an educational centre, it is important to stress that these tools complement school labs, which cannot be abandoned.

Practical examples

Virtual Labs

There are a number of virtual labs online. Many are simple, open-access simulations or interactive animations on a specific topic. Others are genuine labs, designed with virtual reality technology, which replicate fully equipped professional facilities. In line with the criterion of Lynch & Ghergulescu (2017), here are a few examples:

2D labs based on web technology (HTML5 or JavaScript):

- **Go-Lab Project** (https://www.golabz.eu/), now known as NextLab, is a web portal funded by the EU under the scope of the Horizon 2020 programme, dedicated to inquiry based science education (IBSE). Their school labs feature numerous interactive activities focused on different aspects of science, as well as a tool for teachers to design and share their own virtual labs, adapted to their context.
- **ChemCollective** (http://chemcollective.org/home) is a repository of virtual labs in the field of chemistry, which are programmed in HTML5 and can be used in nearly all current browsers.
- **NMSU Virtual Labs** (http://virtuallabs.nmsu.edu/) is a web portal of the New Mexico State University. Users can work several aspects of food science and technology on their virtual labs.

3D virtual labs based on virtual reality systems:

- **3D Labs UPM** (https://3dlabs.upm.es/) is a project of the Technical University of Madrid that has several virtual labs. Experiments are focused on engineering, physics and chemistry. Activities are performed in 3D virtual reality environments and designed using open-source software called OpenSim.
- **Virtual Engineering Sciences Learning Lab** is a virtual space created in the SecondLife platform, where users can perform activities in an environment designed as a science museum. Users' interaction provide an extra layer of social skills, which is less visible in other virtual labs.
- **Labster** (https://www.labster.com/) offers a fully equipped 3D virtual lab for all kinds of experiments in molecular biology and chemistry. As it is a private initiative, its services are subject to user charges.

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Remote Labs

Faulkes Telescopes (http://www.faulkes-telescope.com/) is a network of robotic telescopes, used by students and teachers for free. Anyone can book a time to operate one of the many telescopes throughout the world to obtain real astronomical images and use them in the classroom. The fact that there are telescopes in many locations allows teachers and students to observe the night sky during class time.

VISIR (http://ohm.ieec.uned.es/portal/?page_id=76) is an automated breadboard where electronics student can remotely test the result of a real wiring.

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EDUCATIONAL VIDEO GAMES

> ***… games may activate important social mechanisms, such as problem solving, empathy and teamwork …***

With the kind participation of Víctor López (physicist, PhD in science teaching; researcher, CRECIM-Universitat Autònoma de Barcelona (UAB); associate lecturer, UAB) and Cristina Simarro (researcher, CRECIM; industrial engineer; associate lecturer, UAB).

Underlying principle

A major trend in education nowadays is gamification, or the use of game strategies such as earning badges, points or other rewards after completing particular tasks in the classroom, as a means to motivate and engage with students in their learning process.

Game-based learning (GBL) is another, slightly different concept, wherein board games, card games, video games or other game formats are used to actually learn and practice the subject material, not just to motivate students.

Both strategies can improve classroom dynamics and be implemented both on- and offline in different ways. However, this report focuses on the technological side of gaming and reviews only educational video games.

The main principle behind gamification and GBL is based on the stimulation of a dopamine rush. Dopamine is the neurotransmitter used by the brain for motivational purposes (in a very simplified way). Every action with a sense of purpose, especially those with an expected positive reward, are driven by dopamine and result in the activation of the pleasure centres of the brain once the action is accomplished.

Thus, as long as the challenges and the rewards offered are meaningful to students, gamification and GBL can improve their concentration and increase the time spent on the subject. And this is a key point in the success of any of these strategies, since the game by itself cannot force children to learn. A well-planned, teacher-driven educational process behind gamification and GBL is paramount.

Historical background

Although some argue that Pac-Man was the first educational video game, its intention was purely entertainment. However, Pac-Man applied many characteristics of an educational game, such as simple rules, obvious rewards, a sense of excitement and puzzle solving.

Many regards the first educational video game to be the Logo programming environment (1967). While it may not have been intended as a game, the act of moving the tiny turtle around by coding instructions on the console was indeed entertaining. And many schools used it (and still do) to teach the fundamentals of computer thinking and mathematical concepts in a fun way.

With the popularisation of home computers came the emergence of the video games industry, and the educational area was just another market to be exploited. 'Lemonade Stand' (economics), 'Oregon Trail'

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(History), 'Reader Rabbit' (Language) and 'Where in the world is Carmen San Diego?' (Geography) were some of the first video games created for educational purposes in the 1980s. Some became very popular, especially in the United States.

As computer performance increased in the 1990s, video games became more interactive and complex. Many games simulated realistic environments, like Sim City, Sim Earth, Civilization and several kind of flight simulators, exploiting the basics of virtual reality. However, in time, a number of these evolved into arcade games, and their original educational aims were lost.

In the late 1990s and the 2000s, home consoles overtook personal computers as the device of choice for most video games. PlayStation, Xbox and Wii released educational games like Brain Academy or MineCraft as a means to attract a family audience, not just the usual teenage gamers.

Since 2007, with the introduction of the iPhone and the popularisation of mobile devices, most educational games have been transformed into Apps. Today, thousands of educational games can be found on iTunes and Google Play, and many are used daily at schools all over the world.

Practical applications in everyday life

A game can be described as an artificial conflict between players that must be solved by using a set of predefined tools and rules, agreed on by everyone. Thus, depending on the game, important social mechanisms can be activated, including problem solving, empathy and teamwork.

In 1786, Benjamin Franklin published an essay entitled 'The morals of chess', comparing chess game with real life. In the text, he outlined how a chess player learned important social values, such as perseverance, foresight and caution, through the game playing.

What Franklin stated for chess is true for video games as well. In 2013, a team of Dutch researchers published a review of research on the benefits of playing video games, reporting evidence to support the idea that modern video games develop a set of important skills, from spatial recognition to social interaction.

On the other hand, playing video games at school might put people in contact with computers from an unexpected perspective. Kids who are not especially attracted to technology might develop computer skills and become familiar with virtual or augmented reality, whereas they wouldn't otherwise.

Educational connection

Most of the educational connections described for virtual labs also apply to video games.

In the field of STEM-based video games, however, experts agree on the importance of engaging students in activities showcasing scientific practice. In this regard, gamified virtual labs, embedded into a virtual reality environment, would be the best approach from the educational perspective.

Quiz games have become quite popular in recent years, especially since the introduction of mobile platforms. Many are tagged as 'educational apps' in Google Play or App Store, but they lack a relevant educational impact since their focus is content that the player already knows, with no opportunity to practice new skills.

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This notion is consistent with the idea of 'learning by doing', and one must keep in mind that indeed, video games can help people practice and acquire some basic concepts, but interaction with a teacher is still necessary to fully understand the details of the subject material.

Thus, provided there is a teacher with a well-defined plan, gamification and GBL can help with the motivational side of learning in the classroom and can be used as a means to practice and consolidate some lessons.

Practical examples

LEARN SCIENCE

Platform Nintendo DS. In this game for handheld Nintendo devices, the gamer can play minigames based on diverse aspects of science. The progress is mainly practical, with demonstrations and puzzles to be solved, and the player can obtain rewards. There is a social side too, since players can challenge their friends online for better scores.

FOOD FIGHT

Any platform https://www.brainpop.com/games/foodfight/. Food Fight is a simulation of an ecological web chain for two players. Each gamer takes the role of a species and tries to increase its population, while jeopardizing their opponent's success.

SPORE

PC, Mac and Nintendo platforms. Design a creature and develop it through different evolutionary stages, from cell phase to full civilisation and space exploration. Each stage lets players explore and modify the fundamentals of the universe at their will.

MANGA HIGH

Any platform: https://www.mangahigh.com/en/. Somewhere in between gamification and game-based learning, this programme offers teachers several minigames in the field of mathematics and geometry, with the possibility to assign and schedule tasks to the students.

BLOOD TYPING GAME

Any platform: https://www.nobelprize.org/educational/medicine/bloodtypinggame/. Simple web-based game to practice the basis of blood types and blood compatibility between people. There is some resemblance with clinical practice, with needles and tests and transfusions into patients. The player must possess some previous knowledge on blood types.

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LOW-COST EXPERIMENTATION

> ***… the idea that anyone, anywhere, can perform the experiment encourages students to try it at home with their families. The thrill of experimentation may awaken new vocations for science.***

Underlying principle

The basic grounds for low-cost experimentation is to make science popular. The idea that science is an activity, rather than a set of facts or concepts, implies that anyone, anywhere, should be allowed to experiment with the rules of nature.

The downside of this challenging idea is that expensive lab materials are sometimes needed to see an effect. Thus, low-cost experimentation refers to any procedure by which anyone can test fundamental aspects of science at virtually no cost by using common materials.

Historical background

Low-cost experimentation might be considered an evolution of the do-it-yourself (DIY) movement that arose in the United States in the early 20th century. This concept reached maturity in the 1960s Bay Area punk scene. The original DIY movement wasn't about explaining the science behind natural phenomena but rather using a countercultural approach to reject consumer society. However, as the projects grew in complexity, engineers from various fields started sharing their technical knowledge with the rest of the DIY community.

The popularisation of science, as we know it today, began in the mass media. Its peak can be considered the broadcast of the mythical series *Cosmos, a Personal Journey* during the fall of 1980. The show, created and presented by Carl Sagan, reviewed the history of the universe, the evolution of species on Earth and the success of mankind in the search for knowledge. But *Cosmos* was a story *about* science, not science itself.

One of the first science shows on TV with hands-on activities was the 1992 *Beakman's World*. Inspired by a 1991 comic strip by Jok Church and targeted to a fairly young audience of pre-teens and adolescents, Paul Zaloom played the role of an extravagant scientist demonstrating various physical and chemical curiosities. Most of the experiments were designed in such a way that anyone could repeat them at home with basic raw materials. In fact, do-it-at-home was actively encouraged.

Since then, many science shows have been produced all over the world with similar formats.

Practical applications in everyday life

The idea that anyone can test the basic rules of the natural world is challenging by itself. The empirical knowledge of how things behave may make a difference to anyone and promote basic science literacy to non-scientists.

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Thus, the design and development of low-cost experiments (and their proper dissemination) can contribute to promoting more rational, less superstitious and more critical societies.

Educational connection

those found in a school or a local hardware store is very welcome. Besides, the idea that anyone, anywhere, can perform the experiment encourages students to try it at home with their families. The thrill of experimentation may awaken new vocations in science.

On the other hand, experimentation tends to be multidisciplinary, and many of the experiments that can be done with common materials develop concepts from many subjects, such as physics, chemistry, biology, mathematics and technology. Building bridges across disciplines at school makes classes more dynamic and appealing, boosting motivation.

Moreover, most of the materials used for experimentation are recycled or reused, such as empty plastic bottles or used straws, so engaging the students in planning and performing these kinds of experiments reinforces their sense of sustainability.

Practical examples

REACTION CAR

Using a plastic bottle, a balloon and a straw (and a couple more things), anyone can build a car that moves using Newton's 3rd law of kinematics. Access: https://explorable.com/balloon-rocket-car-experiment.

PLANTS SEE THE LIGHT

Plant some seeds in a box with a small opening in one side and wait for them to sprout. In a few days you will see how the seedlings reached the opening regardless of any obstacle in their path. This experiment might show you one of the properties of any plant: phototropism. Access: http://www.untamedscience.com/biology/plants/phototropism/.

MENTOS GEYSER

If you drop a Mentos candy into a soda, the tiny pits on the surface of the candy will serve as nucleation points for the dissolved CO_2. The rapid formation of bubbles at these points makes the whole bottle burst with a powerful stream. This is an adaptation of the classic experiment with baking soda and vinegar, but the principle behind it is much different. Access: https://www.stevespanglerscience.com/lab/experiments/original-mentos-diet-coke-geyser/.

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EMERGING TECHNOLOGIES

3D PRINTING

> ***3D printing should be considered a productive tool for all subjects related to design.***

With the participation of Joan Alemany (graduate in maths, Politechnical University of Catalonia; co-founder of eSeeCode; secondary school teacher) and Frank Sabaté (schoolteacher specialising in STEM).

Underlying principle

3D printing is the group of processes allowing the manufacture of physical objects from a computer model, using computer-aided design (CAD) or a 3D scanner.

This kind of printing can be classified under the additive construction paradigm, whereby the piece is the result of positioning the modelling material, layer by layer, until the final product is complete (like in the construction of a building). In contrast, subtractive construction implies casting an initial piece and then cutting away excess material until achieving the final product (like in classical sculpture).

To achieve this additive effect, 3D printers must be automatic and programmable tools that use semi-solid or solid materials to work with volume, not only on surfaces like a traditional printer.

Therefore, 3D printing draws on computing and programming principles that allow the development of 3D, computer-aided design, as well as on mechanical and engineering elements that enable the manufacture of 3D printers themselves.

Historical background

The main 3D printing systems were first developed in the 1980s by Dr Hideo Kodama, from the Industrial Research Municipal Institute of Nagoya, in Japan. Kodama developed the precursor to the current stereolithography system (SLA). The first patent for this system was granted to the American inventor Charles Hull in 1984; Hull brought the first 3D printer based on the SLA-1 3D system to the market in 1987.

A year later, in 1988, Carl Deckard filed a patent for the SLS, a new way of 3D printing based on the fusion of dust particles. In 1992 the Stratasys firm marketed the first printer based on fused deposition modelling (FDM), which became the standard for the most popular 3D printers for amateurs because of its low cost.

Nowadays many firms are testing the limits of these basic technologies with new systems to work and combine different materials, like metals, and to increase printing speed.

Practical applications in everyday life

Professionals and experts generally agree that 3D printing will shake up the productive sector at an international scale. Logically it will also transform the global economy.

Although it is difficult to say with certainty what the future holds, the potential for manufacturing practically any object, using a broad range of materials, could culminate in a situation whereby consumers would be able to print most daily products at home rather than buying them in physical shops. The end user of a product would purchase the design directly from big online shops and load the design onto their own printer.

From this point of view, the practical applications of 3D printing in daily life would be endless.

Educational connection

The above-mentioned implications in daily life depend on consumers' capacity to produce most basic consumables locally. There is thus no need to learn but only to choose from the diverse models on the market.

From an educational perspective, however, 3D printing poses an interesting challenge. The consulted experts are worried about the current trend of avoiding the use of 3D printing capacities as learning tools in favour of using them solely as demonstration. As a consequence, downloading pre-designed models of the most popular repositories like OpenSCAD (www.openscad.org), Tinkercad (www.tinkercad.com) or Beettle blocks (beetleblocks.com) is not regarded as an authentic educational application of these technologies. Hence it is essential to establish clear teaching objectives before starting 3D printing activities in the classroom.

3D printing should be considered a productive tool for all subjects related to design, for instance:

- Engineering and technology: production of objects and construction of models or mechanical or electronic devices previously designed in the classroom.
- Mathematics and geometry: spatial visualisation of shapes and abstract figures obtained from theoretical processes.
- Plastic and artistic expression: design and production of theatre props and three-dimensional art objects.

Practical examples

There are diverse 3D printing technologies, each with its own strengths and weaknesses, depending on the intended use of the printed object. The most common examples are:

STEREOLITHOGRAPHY (SLA)

The original material is a viscous liquid that solidifies when exposed to intense ultraviolet radiation. The model is constructed inside a container filled with this material and with a motorised platform. A laser emits a beam of ultraviolet light with the shape of the first (interior) layer of the figure, thus fixing the first sheet. The platform goes down to dip the model in the material again and afterwards the second layer is radiated and joined to the first, and so on until the model is completed.
The main advantage of SLA is its speed and the level of detail that can be achieved. Nonetheless, the models are fragile and sensitive to direct sunlight.

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SELECTIVE LASER SINTERING (SLS)

From a mechanical point of view, SLS is similar to SLA, but the original material in SLS is a powder, usually made of nylon (though it also can be from other materials like polystyrene or ceramic). The laser heats up the first layer of the powder, fusing the particles. The motor platform immediately lowers again, and a fine powder is brushed onto the model, constituting the second layer. When the model is complete, the remaining nylon power is extracted with pressurised air.

The main advantage is that the fused nylon is very resistant, so the pieces made using this technique can be functional. Besides, since nylon powder is solid, there is no need for printing support structures in the model.

MODELLING THROUGH FUSED DEPOSITION MODELLING (FDM)

There are different ways to apply FDM, but in general, the initial material is a solid plastic thread which is heated up until the fusion point and settled in layers by an extruder capable of moving in space. The process usually proceeds from the bottom up.

Since all the components are basically mechanic, without lasers or sophisticated elements, FDM is the least expensive solution and thus more accessible to non-professional users. However, the quality of the models is inferior to those produced by the SLS and SLA systems because the thickness of the thread determines the resolution and the maximum detail that can be achieved.

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OPTICS AND PHOTONICS

> ***… there is no easy way to teach the nature of light and its properties … understanding light is non-intuitive, so it must be taught with very carefully and with an educational plan in mind.***

With the kind participation of Víctor Grau (PhD in physics; Professor, Arts and Sciences Teaching Department, Universitat de Vic).

Underlying principle

Optics and photonics are closely related branches of physics that study light and its behaviour. Optics can be considered the traditional framework from which photonics emerged upon discovery of the quantum nature of light.

Briefly, light can be understood as an electromagnetic wave and a beam of tiny particles called photons. From the perspective of a wave, light moves through space in the form of a wavefront that can show classical properties such as reflection, refraction, diffraction and interference. Its wavelength (the length between peaks expressed in nanometers) accounts for its colour.

However, light is much more complex than that and should not be represented as a typical mechanical wave, as it appears in many textbooks. Physical and geometrical optics explain and predict many of the classical properties of light in great detail.

From the perspective of a beam of photons, light shows properties not seen in classical waves, such as a photoelectric effect, accounting for individual impacts of photons on a detector, or the light produced in an LED device, where electrons release a photon when falling into lower energy states. This new perspective led to the emergence of quantum optics and related fields.

Historical background

There is some controversy about when optics became a field of study. A 3000-year-old lens-like object was found in Nimrud (today's Iraq), suggesting that optics were first studied in the Assyrian culture. However, there is no consensus on whether it was actually used as a lens or if it was just a piece of furniture.

We know for sure that the ancient Greek and Roman cultures used glass spheres filled with water as lenses and developed some theories on the propagation of light. In fact, the term *optics* comes from the ancient Greek *optikē*, meaning *appearance*. After the fall of the Greek and Roman civilisations, the development of optics continued in the Arab and Indian worlds, with key documents on the field capturing the knowledge gained.

It is noteworthy that the earlier theories did not represent light appropriately, and while they described properties like reflection or refraction with some detail, they failed to understand what could emit light and how images were formed in our mind. In this regard, the initial development of physical optics was grounded on a deficient understanding of the fundamentals of light itself.

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As an example of this misunderstanding, the 17th century saw bitter discussions between Newton and Hooke, two of the most renowned physicists of all time, on the nature of light as either a bundle of particles (according to Newton) or as a wave (according to Hook). Both interpretations were based on Kepler's earlier works on geometric optics. Needless to say, both were partly right in their assumptions.

The 19th century saw the first steps in the resolution of the conflict, with Young's and Fresnel's experiments definitively establishing the nature of light as a wave, and later, with the Maxwell equations showing light from the electromagnetic point of view.

In the 20th century, Planck, Einstein and Bohr completed the theory of light as both a wave and particle, planting the seed for a new field: quantum optics. The invention of the laser in 1960 is regarded as the starting point of photonics, dealing mainly with the study of photons, its physical properties, its production and its interactions with matter.

Practical applications in everyday life

Humans are diurnal creatures, so light is all around us most of the time. We often make decisions based on optics, for instance painting a room with light colours to maximise illumination or considering the position of the windows when installing a TV in a living room to avoid reflections. However, many of these decisions are based on an intuitive understanding of basic optical phenomena. And optics can be tricky sometimes.

A solid understanding of light and its properties might be of use in our daily life in many aspects:

- Photography and video, especially considering the widespread use of smartphones and photo/video sharing apps.
- Use of light-based devices, such as remote controls, motion detectors and proximity sensors.
- Identification of optical effects, such as mirages or other distortions due to reflection and refraction of light.

Educational connection

According to experts, there is no easy way to teach the nature of light and its properties. Introducing it in the school curriculum would require starting with the particle-like model in primary school (6–12-year-olds) and proceed to the wave model during secondary school (12–18-year-olds).

The obvious connections between optics and photonics are rooted in mathematics, physics and technology, the core STEM disciplines. However, there are other connections:

- **Biology**: optics and photonics help explain the basis of photosynthesis in plants, the colour of flowers and the physiology of the eye.
- **Philosophy**: the very idea of *seeing* may raise some philosophical questions, such as the subjectivity of beauty.
- **Arts and humanities**: many artistic expressions depend on light, including photography, painting, architecture and performing arts.

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Practical examples

One of the most important issues raised by the experts when it comes to teaching optics and photonics is the notion that understanding light is non-intuitive, so it must be taught very carefully and with an educational plan in mind.

No simple practical example or analogy can explain light, so teachers are strongly recommended to first build up a solid knowledge of the fundamentals of classical optics:

- **Light propagation**: the idea that light travels from point A to point B in a straight line. This might be obvious to an adult, but a child just cannot see the point since there is no way to see it actually move.
- **Basic properties**: reflection and refraction of light, which is easy to introduce from the perspective of a beam of particles.
- **Detection and vision**: light is not emitted by our eyes, but rather reflected from objects in the path of a light source.

After this foundation has been established, advanced concepts can be introduced during preparation for university:

- **Wave model of light**: diffraction/interference and colour as wave-related properties of light.
- **Polarisation**: the angle of rotation of the electromagnetic wave and how it can be modified or constrained.
- **Quantum theory of light**: the basic notion that photons are an energy package that can be absorbed or emitted during energy transformations.

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NANOTECHNOLOGY

> ***Since nanotechnology lies somewhere between physics, chemistry and technology, its study could build bridges among the various STEM disciplines.***

With the kind participation of Jordi Diaz (PhD in chemistry and material sciences; founder, Nanoeduca and Nanoinventum school activities; researcher, Universitat de Barcelona).

Underlying principle

Nanotechnology refers to any technological activity conducted at scales around 1 to 100 nanometers (1 m = 1,000,000,000 nm). This is the scale of atoms themselves, as the diameter of helium is about 0.1 nm.

Thus, nanotechnology applications provide extreme miniaturisation, using and rearranging individual atoms at will. Engineers are finding impressive new properties of materials at the nanoscale, such as enhanced strength, reduced weight and colour variations related to size. Similarly, many properties of known materials, such as conductivity or magnetism, show unexpected behaviours when broken down to their fundamental molecules.

To perform these processes, specialised tools have been developed, such as high resolution transmission electron microscopes (TEM) or scanning tunnelling microscopes (STM), powerful devices to actually *see* the atoms. For their part, atomic force microscopes (AFM) are capable not only to see but to actually move atoms around.

Nowadays, the applications developed at the nanoscale are widely used across disciplines, such as chemistry, biology, medicine, material science and engineering.

Historical background

Practical effects of the nanoscale have been observed – if not understood – throughout history. The colour of many pigments relate to the nanoparticles that compose them. The strength and flexibility of Damascus steel blades are thought to be related to the formation of carbon nanotubes during forging. However, these observations remained largely unexplained for centuries.

It was Richard Feynman, in his inspiring lecture at Caltech in 1959, 'There is plenty of room at the bottom', who first raised the possibility that experiments could take place at the nanoscale and that atoms could be rearranged at will. This conference is regarded as the origin of today's nanotechnology, a term coined in 1974 by Norio Taniguchi.

Despite the lack of technology to really develop applications at the nanoscale at the time, Prof Feynman dismissed any theoretical limitations and predicted the development of some of the applications we see today.

The development of nanotechnology has been very dependent on the ability to see and manipulate things at a tiny scale. Thus, the milestones for its implementation correlate with the invention of the STM and ATM in the early 1980s.

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This new technology, capable of rearranging individual atoms, was put to work for the first time in 1989, when IBM, the developer of the STM, used this device in a stunning demonstration, signing their company initials on a nickel surface with 35 xenon atoms.

The potential uses of atomic rearrangement, like nano-engineering and nano-robotics, have been discussed at length. However, few applications exist in this still-nascent field.

Most of the current advances in nanotechnology have to do with nano-coating surfaces with metal ions, such as silver or gold, to enhance the properties of existing materials, or designing new molecules with self-assembly capabilities to build structures from the bottom up, similarly to biological structures.

Despite the promise of huge benefits, recent concerns have arisen around the use of nanotechnology. Heavy metals, such as silver or gold, are known to be carcinogenic when ingested or inhaled. Likewise, some evidence suggests that carbon nanotubes might be as harmful as asbestos to our lungs.

Practical applications in everyday life

Current nanotechnology applications are mostly being used in mass production and industry, such as in the miniaturisation of electronic components or catalysts to capture harmful molecules and reduce pollution. The average citizen is not familiar with these applications, so knowledge of the nano world may seem a bit irrelevant to everyday life.

However, some insight on what happens at these tiny scales might open minds to new realities, new paradigms and lateral thinking. Citizens fully aware of the complex nature of our world might be more creative and critical.

Educational connection

Since nanotechnology lies somewhere between physics, chemistry and technology, its study could build bridges among the various STEM disciplines. For example, when the approach is practical, children can experiment on magnetism by using ferrofluids (and see the magnetic field in 3D) or consider the daily applications of superhydrophobic materials in the classroom.

In this regard, some efforts have been made to deliver nanotechnology activities to schools. The NanoEduca toolkit for secondary school (available internationally upon request) is a good example of these efforts, providing all the necessary materials and instructions, as well as a full educational plan to integrate activities in the classroom.

The experts contacted agree that both students and teachers are very receptive to activities focusing on the nano world, giving positive feedback on related activities. For teachers, the chance to approach classical concepts from another perspective proves highly engaging. Many teachers feel disconnected from the advances of contemporary science and technology and working on the basics of an emerging field like nanotechnology boosts their motivation.

Nanotechnology applications also go far beyond the STEM paradigm, sometimes touching philosophy, social sciences and, ultimately, ethics. Consider, for instance, the claims that some nanoparticles might be harmful for us or for the environment. Can this issue be sorted out? How? Recycling of nanoparticles has proven to be quite difficult. Are the benefits worth the risks?

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Other issues around nanotechnology that can be considered at the classroom level are those concerning the rationalisation of its use. Is it really necessary to use nanocomponents everywhere? Could this increase technological inequalities in the world?

Practical examples

PROTECTION AND CONSERVATION

Nanomaterials have been developed to help in the conservation of ancient works of art, such as paintings. Not only can these materials merge more naturally with the original objects, they can prevent future deterioration better than traditional methods.

CHARACTERISATION OF MATERIALS

The imaging techniques developed to study nanomaterials have applications in other fields, such as the identification of materials found at a crime scene or attributing a work of art to a particular artist.

NEW PIGMENTS

Some nanoparticles change colour depending on their size. This has led to the development of nano-dyes, with many applications. Quantum dots, for instance, are used in molecular biology to tag proteins and other molecules into the cells and study their location.

NANOCIRCUITS

Still under development, the ability to miniaturise circuits would allow their integration with any material, such as clothes. Once the technology is ready, a new era of wearable devices is expected.

NANOROBOTICS

Molecular machines that are fully programmable and controllable are envisioned, with enormous potential applications, such as medical robots operating inside our body.

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ANNEX 1

DIFFERENCES BETWEEN PROGRAMMING LANGUAGE BASED ON SYNTAX AND LANGUAGES BASED ON BLOCKS

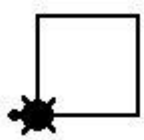
Use **Logo** to draw a square measuring 50 pixels per side using a repetition loop. The language is simpler, and there is little syntax.

to square

repeat 4 (forward 50 right 90)

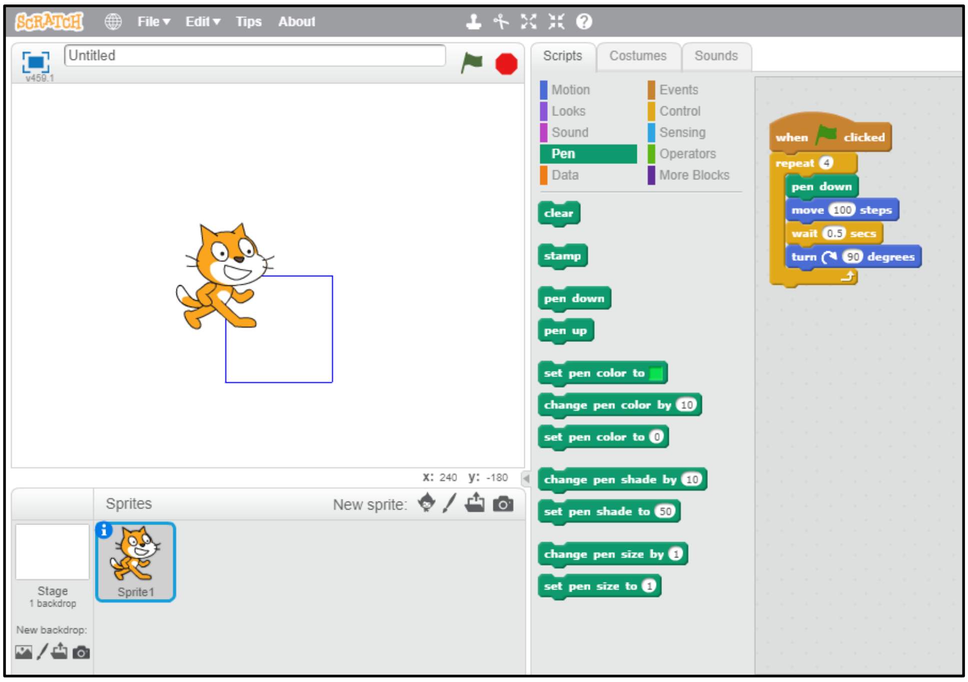
end

forward 50



4x right 90

Use **Scratch** to draw a square measuring 100 pixels per side using a repetition loop. As shown, there is no code with syntax and thus there are no possible coding errors, only logical programming errors.



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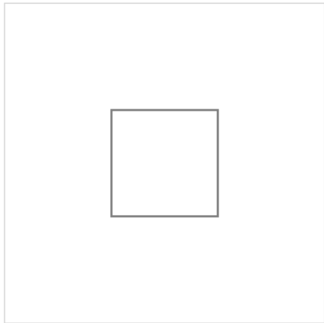
Use **JavaScript** (in combination with HTML5) to draw a square measuring 100 pixels per side. In this case no loop is used since the rectangle is directly defined. As shown, the language is much more complex, with a non-intuitive syntax and integrated functions (like *document* or *var*).

```
<!DOCTYPE html>
<html>
<body>

<canvas id="myCanvas" width="300" height="300" style="border:1px solid
#d3d3d3;">
Your browser does not support the HTML5 canvas tag.</canvas>

<script>

var c = document.getElementById("myCanvas");
var ctx = c.getContext("2d");
ctx.rect(100, 100, 100, 100);
ctx.stroke();

</script>

</body>
</html>
```



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