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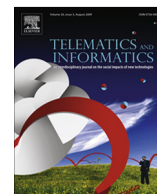
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Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece

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ABSTRACT

This research project attempts to examine to what extent the technological capabilities of open source 3D printing could serve as a means of learning and communication. The learning theory of constructionism is used as a theoretical framework in creating an experimental educational scenario focused on 3D design and printing. In this paper, we document our experience and discuss our findings from a three-month project run in two high schools in Ioannina, Greece. 33 students were tasked to collaboratively design and produce, with the aid of an open source 3D printer and a 3D design platform, creative artifacts. Most of these artifacts carry messages in the Braille language. Our next goal, which defined this project's context, is to send the products to blind children inaugurating a novel way of communication and collaboration amongst blind and non-blind students. Our experience, so far, is positive arguing that 3D printing and design can electrify various literacies and creative capacities of children in accordance with the spirit of the interconnected, information-based world.

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1. Introduction

Three-dimensional (3D) printing – actually a subset of additive manufacturing – is, in short, the process of joining material, layer-by-layer, to make objects from 3D model data (usually created by a computer-aided design software or a scan of an existing object), in contrast to subtractive manufacturing technologies (ASTM, 2010). This technological capability has been around for more than three decades and has been known as the “rapid prototyping machine” (Bradshaw et al., 2010; Campbell et al., 2011). It was called “rapid” because one-offs could be made more easily and quickly than by the conventional numerically-controlled machines and it was called “prototyping” because it was too slow and expensive to be used for production (Bradshaw et al., 2010). For example, an architect could print in 3D the design of a building or an automobile engineer could print a prototype of a part from the car for further refinement of the design. However, lately 3D printers have been adopted, especially by aerospace and health care industries (Bullis, 2011), to make functional products as well, whereas the rise of relatively low-cost (€500–1300), open source desktop 3D printers, such as RepRap or Ultimaker

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(Kalish, 2011) have given the chance to hobbyists and adopters of the do-it-yourself culture to experiment, design and produce things moving gradually from “prototyping” to “manufacturing”. Moreover, it becomes evident that this Commons-oriented, open source, collaborative experimentation with 3D printing has arguably dropped the costs and improved the user-friendliness of 3D printing hardware and software making this technology more accessible than ever, even to schools and young students.

This article is part of an ongoing research project that tries to tentatively examine to what extent and degree the technological capabilities of 3D printing could serve as a means of learning as well as a way of meaningful communication amongst blind and non-blind students. This paper, which describes the first phase of this project, focuses on open source 3D printing, within the context of two high schools based in Ioannina, Greece, with particular reference to possible applications for learning. In total 33 students from one public and one private high school were called to collaboratively design and produce, with the aid of an open source 3D printer and a 3D design platform, functional artifacts of their own choice. Students were told that those artifacts, from stamps, cups and sharpeners to sophisticated toys, carrying messages in Braille language, would be sent to blind fellow students.

Within the framework of constructionism we attempted to run our experimental project, document our experience, discuss our findings and create an educational scenario in a narrative format that could be used, tested, criticized, enriched and, hopefully, improved further. This paper begins with the formulation of our research questions as well as a brief review of the relevant theoretical background. The methodological part follows with a description of our educational scenario as well as some information on the schools where the project took place. We, then, discuss our experience through students’ creations concluding with recommendations for future research.

2. Research questions and theoretical framework

Nowadays students have grown up in a framework of constant connectivity and interactive culture and, thus, may have different attitudes and understandings of concepts such as creativity, collaboration, communication and sharing (see only Prensky, 2001, 2007; Rushkoff, 1996; and for a critical approach to the “digital native” concept see Bennett et al., 2008; Bennett and Maton, 2010). This behavior should have arguably led to reforming the institutions of learning and education. Since the 1980s, Seymour Papert (1980a,b, 1993, 1997), father of the LOGO programming language and key developer of constructionism, has been arguing that the social penetration of information and communication technologies (ICT) provides individuals or communities with the means to develop and to implement new educational ideas. However, as Papert (1997) points out discussing the penetration of computers in schools, learning institutions resist the reform by appropriating or assimilating it to their own structures.

The main research question that guides our inquiry could be formulated as follows: What role could 3D printing and design, along with the modern ICT, play in developing and implementing new educational ideas based on the principles of constructionism? Therefore, from the aforementioned question a few sub-questions emerge: What kind of educational environments could be created, fused with the values of collaboration and meaningful communication which are pillars of the Commons-oriented, open source movement (as it is explained later)? Could these scenarios and environments be considered as “objects-to-think-with” (Papert, 1993, p. 182), which would contribute to the social process of constructing the education of the future? And last but not least –actually this was the main concern of the teachers, Christos Bitsis and Loukianos Xaxiris, who participated in this first phase of our project– could such a media-based knowledge acquisition contribute to the solution of problems observed in these high schools, i.e., lack of students engagement (personal communication with Bitsis and Xaxiris, April, 2013); theoretical teaching and textbook based instruction (personal communication with Bitsis, Xaxiris, April, 2013); poor demonstration infrastructure available (personal communication with Bitsis, Xaxiris, April, 2013); and students’ misconceptions about project-based learning (personal communication with Bitsis, Xaxiris, April, 2013). Regarding the latter point, it would be interesting to mention that although students were unanimously for a hands-on, practical mode of learning they seem to highly underestimate the project-based courses held so far in their schools (questionnaires and personal communication, 2013).

To tackle these questions we choose to develop our educational scenario based on the learning theory of constructionism developed by Papert (1980a,b, 1993, 1997), Papert and Harel, (1991) and informed by Ackermann (2001), which emphasizes the personalized production of knowledge artifacts as well as the social nature of the learning process:

constructionism – the N word as opposed to the V word – shares constructivism’s connotation of learning as “building knowledge structures” irrespective of the circumstances of the learning. It then adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it is a sand castle on the beach or a theory of the universe (Papert and Harel, 1991, p. 3).

Similar to many prominent scholars in the philosophy of education (for example Jean Piaget, Lev Vygotsky, Paulo Freire or John Dewey) constructionism maintains that students’ intellectual growth must be rooted in their experience (Papert, 1980b). Knowledge is not seen as a commodity to be transmitted but as a personal experience that has to be constructed

(Ackermann, 2001). Our constructionist approach is informed, though, by Ackermann's, (2001, p. 10) discussion on Papert and Piaget where she argues for both "dwelling in" and "stepping back" in "getting such a cognitive dance going". Echoing Kegan (1982), Ackermann (2001) highlights not only the need to become embedded but also to emerge from embeddedness for a deeper understanding of oneself and others. However, our approach remains constructionist in essence, since it focuses more on the art of "learning to learn" and highlights the importance of media, conversations with artifacts and context in learning (Ackermann, 2001; Papert, 1993). In our project students get the opportunity to engage in hands-on explorations that fuel the constructive process (Ackermann, 2001; Papert, 1993) and, thus, constructionism offers us the appropriate context.

Further, the ethics of the open source or Commons-oriented movement (see only Bauwens, 2005; Benkler, 2006, 2011; Bruns, 2008; Kostakis, 2012; Lakhani and Wolf, 2005; Levy, 2001; Wark, 2004), which has created several media technologies of educational value (from free/open source software, say Moodle or Sugar, to free encyclopedia Wikipedia to open hardware such as the Arduino micro-controller or low-cost 3D printers), could arguably provide a context for experimentation, communication, collaboration, sharing and learning. Based on constructionism; inspired by the general values (i.e., free collaboration, autonomy, openness, learning by doing and peer learning, sharing of resources, producing use value for society etc.) of open source/Commons-based communities' production processes; and using open source tools (such as the 3D printer Ultimaker) whose internal structure can be easily studied, we attempt to create open educational environments.

With substantive, indeed massive techno-economic changes appearing in our life world, almost anything eventually changes with them or adapts at least somehow (Perez, 2002) and this open source movement could be regarded as a manifestation of a creative culture emerged from constant connectivity and interaction (Bauwens, 2005; Benkler, 2006, 2011; Kostakis, 2012, 2013; Lessig, 2005, 2009). It has been stated that the open source movement shows "how cooperation trumps self-interest – maybe not all the time, for everyone, but far more consistently than we have long thought" (Benkler, 2011, p. 249). Therefore, in addition to the technical knowledge which may be gained, through such an environment students could arguably have a chance to realize that there are also possibilities for societal development based on intrinsic positive incentives and voluntary efforts beyond competition and self-interest.

3. Educational scenario and methodology

The current paper tries to document the first of the three phases of our ongoing research project. Specifically, the first phase includes a tentative effort to examine the educational sides of 3D printing and design in a small sample of high school students. At the second phase, we try to create a network of collaborators, i.e., teachers and scholars from other schools (both primary and secondary) and institutions (such as public centers of creative development) inside and outside the Greek borders who are willing to apply, test, criticize, enrich and improve further first phase's educational scenario. In that way, hopefully, we will gain more experience, knowledge and insights increasing our sample, enhancing the educational scenarios and building an open collaboration network. The third phase will contain the investigation of the communicational potential of 3D printing amongst blind and non-blind students.

Therefore, in this first, pilot phase we decided to approach two high schools, one public and one private. The main reason we chose high schools was because of the "project course" that students of first and second class in Greece have. That is to say, for two hours per week in students' official curriculum there is a special course in which they are supposed to run collaborative and/or individually two research-based projects in a school year. Exemplary topics could include the documentation of old, forgotten professions or a discussion of social media technologies. According to the learning theory of constructionism, when having children do their work using ICT, duration is key for students to become personally – intellectually and emotionally – involved (Papert, 1980b). So, the existence of the project course gave us enough time to implement our scenario but also covered for our inexperience with primary school students. Moreover, personal acquaintance with both the directors of the schools allowed full consensus easily as well as the appropriate cooperative environment for such a project to run smoothly. We approached several other schools of the region, whose directors, unfortunately, seemed unable to comprehend our goals and unwilling to cooperate.

The project began, on January the 23rd, 2013, with the private high school Dodonaia, based in Ioannina (a relatively small city in north-western Greece), particularly with its second year class, consisted of 15 16-years-old students. The second school was the 7th General Lyceum, a public high school, and the project took place in its first year class consisted of 18 15-years-old students. The collaborator teachers respectively were the physicist Loukianos Xaxiris and the ICT teacher Christos Bitsis responsible, amongst others, for the "project course". In total we were in class approximately for 700 min in each school while many students worked beyond school time as well. In addition, three open 3D printing days (April Saturdays' mornings from 11:00 to 17:00) took place in our lab where students were present, discussing about necessary adjustments and changes in their designs while watching theirs or others fellow students' artifacts printing.

To begin with, the main learning goal was that students grasp the concept of 3D design using simplified software (there are both very good, user-friendly free/open source and proprietary software available) and the basics of 3D printing as part of a living experience (Dewey, 1997; Mooney, 2000; Papert, 1993). This concerns the application and further development of skills from various fields such as engineering, design, linguistic (the software was in English and much information on the web was in English as well) or artistic skills. Bearing in mind that students learn better if they are in charge of their own learning processes (Freire, 2000, 2005; Papert, 1993), we let them explore the research procedures themselves performing

their efforts, though within the framework of organized teaching. Another skill was that students should be able to use web tools (such as email, office suites, browser-based software etc.) efficiently to present and support what they have learned and share with others, as conversation plays a vital role in learning (Mooney, 2000; Papert, 1993). Therefore, students were expected to be able to explore the process through trial-and-error; to learn to function in group collaboration and decision making; and to engage in a creative way of thinking creating 3D objects.

To achieve these goals the learning activities that took place begun with an introduction of the concept of open source 3D printing along with the idea of learning and improving through experiment, re-use and sharing. In more detail, through lecture- and video-based classes students were introduced in the 3D printing technology and in the open source movement. We attempted to demonstrate how through collaboration people can achieve certain goals as well as that self-interest is not the sole purpose of society and economy. People can produce collaboratively (in contrast to competition) while satisfying their inner needs for communication and learning (in contrast to considering money as a key motivating factor). The objectives of this stage (duration 60–90 min) was students to pay attention; understand; respond; think critically; and participate in a discussion on what humans can achieve when they cooperate with each other. The necessary hardware ideally includes computers, a video-projector and a 3D printer. If available, it is desirable to download (there is a plethora of 3D models available under Commons-based licenses) and 3D print a functional object in the class for demonstration, empowering children's motivation for the project.

Afterwards, students had to get familiar with their working environment, i.e., to learn designing (and thinking) in 3D using specified, browser-based software. They had the choice to either learn the design software through special lessons the platform offers or by a learning-by-doing process. Therefore, the students, once having been introduced in the context of an open source 3D printer and got familiar with the software, were free to propose objects. On this basis, later, they formed tentative working teams (from 2 to 4 persons, and two students worked on their own). In their decision to form groups and take a final decision on the selected objects we asked them to take into consideration four points and try to cover at least three of them (the first one was mandatory). Their object should be possible to be 3D printed on a low cost 3D printer like ours (this predicates that they have understood its capabilities and limits); it should be novel, functional, and/or usable by blind children.

Monitoring how students used the software, 80% opted to learn the software experimenting and tinkering, without following the lessons (almost 70% of this 80% took at least one lesson, though, but quit afterwards). Then, most of the students who decided to design objects aimed for use by blind fellow students had to learn writing in the Braille language in order to implement it on the design of their artifacts. As was mentioned above, the students were free to choose whether they would design an object to be sent to the blind or not: 13 of the 16 objects, finally designed, were meant for use by blind people and 8 of them would carry messages in Braille, even though this was an optional condition. In this stage (400–500 min), the children were expected to think creatively; experiment; adapt and perform creatively in small-groups, pairs or even individually. It should be emphasized that since they found that there was not enough time in class, most of them continued their work at home, which, in our opinion indicates their commitment to the project.

The next learning activity contained the engagement of students in the printing process in which students had the chance to see the flaws of their design and make the necessary adjustments for it to be printable. Because of the several shortcomings the designs had, it took us more than 120 min, on average, to deal with each artifact. The 3D printing took place in our lab and three persons had to be present to address students' questions, to help them with suggestions while making the appropriate adjustments for printing a functional object as well as using the 3D printer. This process could not be facilitated at school, since it is very time consuming to print one object with our printer, let alone plenty. However most of the students (28/33) were present, spending more of their personal time to help materialize their design.

In the last learning activity students would write reports on their artifacts (for instance why they chose such an object or problems in designing and printing phases etc.) as well as provide some information on open source 3D printing (some would investigate the mechanics, others the software, the used materials or the socio-economic impact) and take part in an official school ceremony presenting in public their efforts. A general flowchart with basic steps of the project ensues (Fig. 1).

The teacher (in every class at least one of the authors was present cooperating with the teacher) was the catalyst and orchestrator of the learning process (Papert, 1980a,b, 1993). In the introductory, lecture-based classes the teacher explained the concept of open source and the operation of 3D printing and 3D design, making the relation of these particular ICT tools to general and course concepts, and triggered discussions with the whole class. Afterwards, the teacher was responsible to facilitate and monitor interaction amongst students and courseware, and direct students learning by clarifying misconceptions; providing vocabulary for concepts; giving examples of skills; modifying behaviors; suggesting further learning experiences; providing an occasion for students to cooperate on activities; discussing their current understanding; and helping them present their efforts publicly.

In the beginning of this project's phase we gave students short, anonymous questionnaires of 18 questions (see Appendix). This process took place in order to help us conceptualize the context and, therefore, transform the project into something more suitable for the students, rather than to exclude any assumptions about the research question. For that reason there was no validation required. The aim was to get an idea of how familiar and dependent students were with and on ICT (i.e., computers, Internet, social media, open source projects, 3D printing), how much they liked the way lessons are taught in school and whether they knew what the Braille language was. 73% had heard of the Braille language and the same amount had already had an idea about what profession would like to study (almost half was for technical studies).

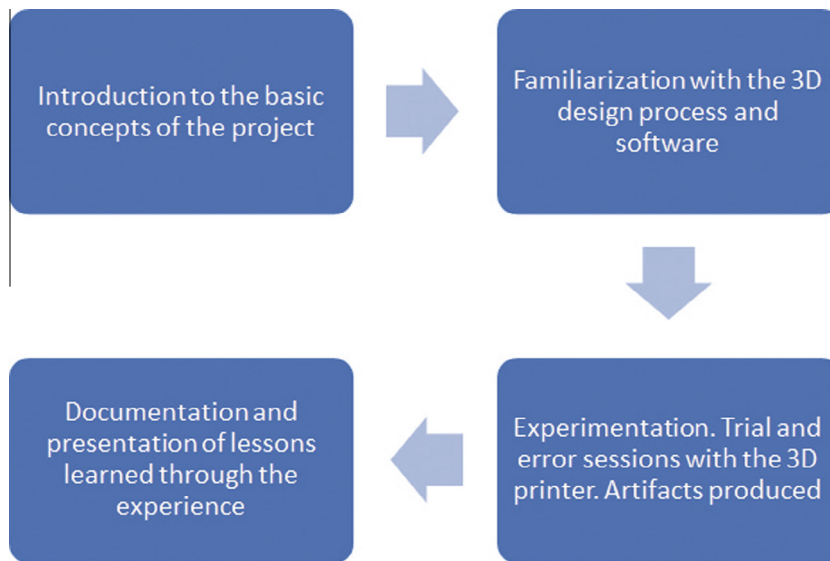


Fig. 1. Basic steps of the project at schools.

All 33 students were for a more practical, hands-on learning approach. Their favorite courses are physics and math (64% did not find bland the way these lessons are taught) but not the project course which comes last in students' preferences (2 out of 33 voted for the project course as one of their two favorites lessons). Regarding familiarity with ICT, 82% of the students had an account in, at least, one social media platform, 94% were using Wikipedia and 48% had heard, watched or read something about 3D printing. It would be interesting to note that in the private school all students owned a smart-phone or a tablet whereas in the public a 45% had one. Another discrepancy in their answers was that in the public school 95% did not consider school as a burden while in Dodonaia the respective percentage was 40%. In the long, semi-structured interviews and discussions we had – and still have – with teachers of both schools before and during the project, the crucial problems, from which the educational systems in Greece has been suffering (and recently with the deep socio-economic crisis and the cuts in education the situation has deteriorated), came to the fore as documented in the previous section.

To sum up, the process used to create and study our educational scenario and its implementation is rooted in the qualitative research methodologies, namely the case study approach informed by both primary (i.e., questionnaires to students; semi-structured interviews with teachers and students; and in situ observation) and secondary (i.e., literature review) research. It should be emphasized that on the one hand our engagement and involvement into the development and the application of the educational scenario in the two high schools might breed the possibility for biased interpretation of the

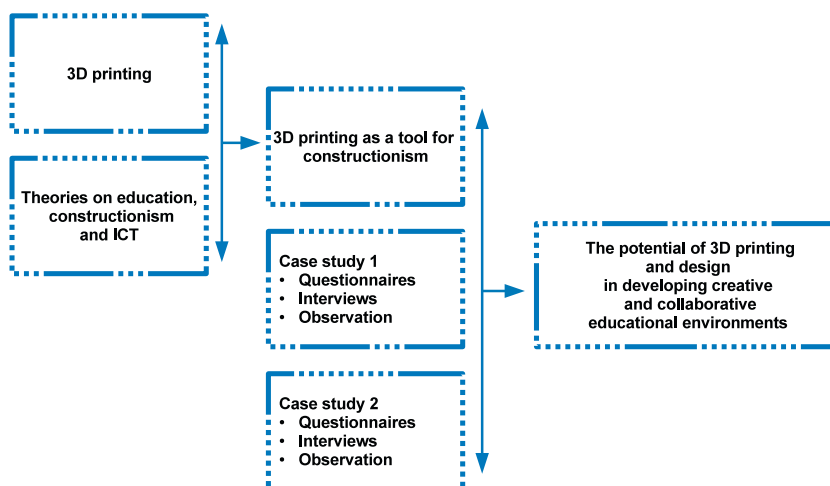


Fig. 2. Schematic representation of the research framework. The vertical arrows stand for the “confrontation” of some particular issues, from which a conclusion can be drawn (the horizontal ones).

results. On the other, as insiders we had the chance to experience the complex relations with students and the educational processes in class and, thus, arguably gain a sharpened understanding of why the instance happened as it did (Flyvbjerg, 2006). Based on Verschuren and Doorewaard (2005), a schematic representation (Fig. 2) of this paper's research framework follows so to gain a general understanding of the various steps towards the realization of our goal. Our research project is a case study and, hence, what should be expected from such a study is to develop our partial answers to the research questions, which would be “input to the ongoing social dialogue about the problems and risks we face and how things may be done differently” (Flyvbjerg, 2001, p. 61).

4. Artifacts and results

We assumed that 3D printing and design would motivate students express their ideas making them tangible and shareable (Ackermann, 2001) via processes that stimulate students to make various connections related to the under creation artifacts. Selected examples of such processes are listed below:

- Learning to design and think in 3D.
- Researching material in Greek and in English about the Braille language.
- Exploring the mechanics of the objects to be designed or the open source 3D printers.
- Studying designs of similar objects made with conventional manufacturing techniques and understanding the engineering process behind them.
- Envisioning what blind people would need that 3D printing could deliver.
- Combining ordinary hardware with their 3D printed artifacts.
- Applying knowledge from different disciplines such as geometry, physics, architecture or the arts.
- Sharing their creations with the world under Commons-based licenses.

And as Papert (1993, p. 103) maintains ‘the more connections... made the more likely to be long-lasting’.

According to the teachers (personal communication with Bitsis, Xaxiris, April, 2013), who have been coordinating the project course since its introduction in 2011, greater engagement by students along with a reduced need of discipline and less disruption were observed. “My class consisted of generally uncooperative, especially concerning the project course, students who, surprisingly enough, were very willing to engage in this particular project”, Xaxiris (personal communication, April, 2013) notes. “There were some fellow students that even surprised me”, a Dodonaia student (personal communication, April, 2013) emphasized echoing not only his teacher but also students from both schools. As Bitsis (personal communication, April, 2013) told us, “this change is a result of children's increased connection with the world (new ideas, literacies, technologies)... followed by an increase in their self-esteem”. Both teachers claimed for an increase in their esteem as well and noticed an increased involvement by parents, since many of the latter showed a great interest for the project course. In addition, through the use of open source technologies, working approaches and licenses it was stated that “a sharing culture is developed, i.e., child to child and school to society” (personal communication with Bitsis, April, 2013).

It would be arguably better to let the children's creations speak for themselves. In total 16 + 1 artifacts were designed; the plus one designed by a public high school's third-class student, G., who upon hearing about the project asked to participate despite his “hectic time and heavy workload” (G., who is dyslectic, designed a H₂O molecule, calculating the right angles, that can be studied and understood by the blind as he put Braille letters on the oxygen's and hydrogen's molecules) (Fig. 3).

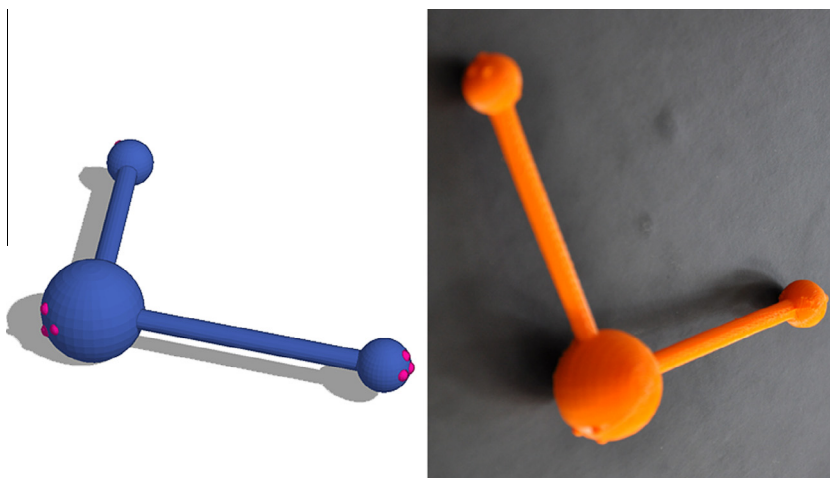


Fig. 3. The molecule was ergonomically designed specifically for the blind by the student.

As mentioned, 13 of the 16 objects were specifically designated for use by the blind although children were free to design almost whatever they want (the remaining three are an airplane, an electric guitar and a sophisticated i-phone case). It could be argued that every single artifact has a story to tell, therefore, we refer to all the 13 designs with a short description enlivening our discussion. A few figures are provided for those objects whose design or function is difficult to be effectively explained in words (all figures can be found on-line in our project's blog).

The first object, designed by two students, is a 3D comic where the hero exclaims “save the world!”, written in the Braille language. The forms are on purpose kept simple because, as students found out after some research, “blind people are unable to understand complicated shapes such as windows, doors etc.; however, hopefully they can imagine the stars” (personal communication, March, 2013). Three other students discovered on-line a 3D model depicting the Parthenon of the classical ages and decided that blind fellow students need to know how Parthenon looks today. Hence, since this particular model was distributed under a Creative Commons license, they were free to build on that after studying Parthenon's current condition (and through that its history), carefully dismantling classical times' magnificent temple. Another object is a cup with the message “drink me” in the Braille on it “to make drinking more fun for the blind”, as our young designers said (personal communication, February, 2013). Moreover, small-scale 3D models, which could “help the blind understand the forms of their surroundings”, to put it in students' words (personal communication, March, 2013), of three, complementary touristic sites of Ioannina (a mosque and a museum which are situated in the old castle of Ioannina) as well as the largest bridge in Greece were made by three different groups. In addition, a group of four students came up with a stamp on which one can read in Braille the text “7 ΓΕΛ” (the name of their school in Greek) which is found underneath. In other words, this is an analogue “way of translating the Braille language”, as one of the four highlighted (personal communication, March, 2013). In this artifact students had to make several adjustments for it to be functional since our 3D printer creates the object layer-by-layer and the design's geometry had to take into consideration the necessary support infrastructure (Fig. 4).

Furthermore, some novel ways of combining conventional hardware with 3D printing modules are manifested through the sharpener and the Rubik's cube projects. To begin with, the sharpener (Fig. 5) was created by two students with the aim to offer the blind the possibility, with special symbols, to understand sharpener's geometry and, thus, easily sharpen a pencil and make efficient management of the waste. Therefore, after 3D printing the three modules, a typical razor had to be added. Two other students attempted, and to our surprise succeeded, to create a working Rubik's cube using Braille language's letters instead of colors. They managed to set functional the printed object with synthetic rubber by carefully adding small holes diagonally in each part of the design (Fig. 6).

An informed version of the old sand-timers for use by the blind was another object produced by a group of two students. Instead of sand they used marbles to produce sound while counting the time. Their design has a few small holes scattered on its surface so as to not trap the sound (Fig. 7). Moreover, two students noticing a lack of board games for the blind decided to create a Braille-based Sudoku board. They came up with a novel way of playing the Sudoku game creating extra tiles with numbers in Braille that offer replay value (Fig. 8). And last but not least, the solar system (Fig. 9) was one of the most intriguing objects made by a student “who although extremely talented and clever – a national chess champion in his age –, never cared much about school” (personal communication with Xaxiris, April, 2013). Still we are unable to functionally 3D print it because of its complexity which seems to seriously challenge our knowledge in 3D design and printing. The student had to realistically adjust his model in scale, therefore, various complex calculations had to be made. Then, he wrote on each planet the first letter in the Braille language in order to allow the blind to experience the solar system's structure.

Most of the objects have already been 3D printed and are functional. However, even for those (like the solar system) which remain in pixels (but we are trying to turn its bits into atoms), the design phase itself was of great interest for all the participants (personal communication with Bitsis, Xaxiris, April, 2013). More important than to successfully 3D print students' creations was to have them present during the process to discuss the problems and make necessary adjustments directly and in real time. We had the chance to experience this creative interaction with most of them, and see in their eyes the disappointment, when 3D printing proved devastating, but also the exhilaration and satisfaction when, after several adjustments and much (co-)calibration, we managed to get functional objects. Overall, all have shown great engagement



Fig. 4. The stamp went through several modifications to reach its final form.

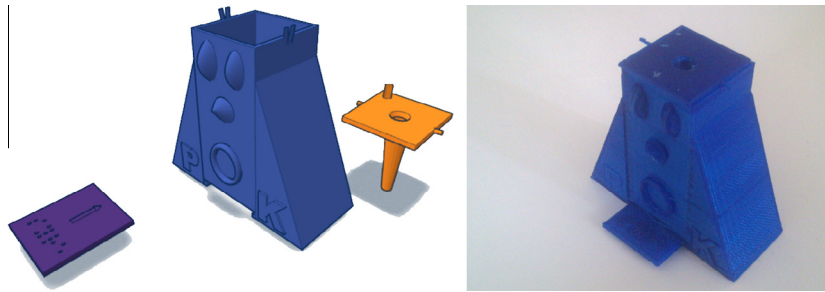


Fig. 5. A razor and some glue were needed for the sharpener to be complete.

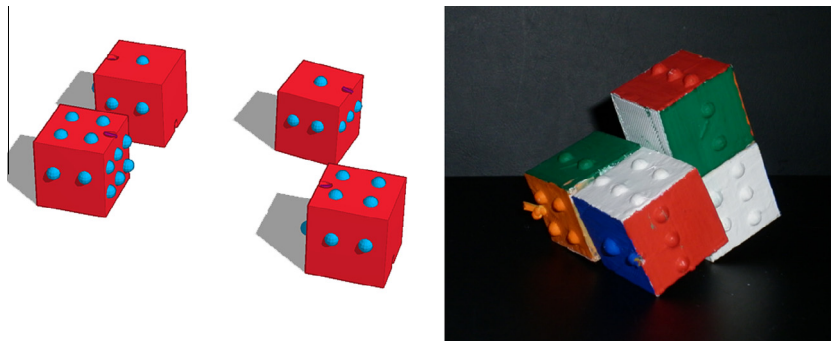


Fig. 6. The students painted the sides of the cube to make it functional for non-blind people.



Fig. 7. Instead of sand several materials were tested to reach the desired sound effect.

and care for their design and many have contacted us or appeared on our lab after the project's end to inquire the printing processes and other future projects. This has provided us with a clear indication that 3D printing, and other open source technologies, can have a meaningful impact in a classroom by allowing students to tap in their creativity while exploring communities whose goal is the sharing of information and knowledge. Of course, this remains a subjective interpretation which was shared, at least, with students' teachers with whom we will collaborate during the next school year.

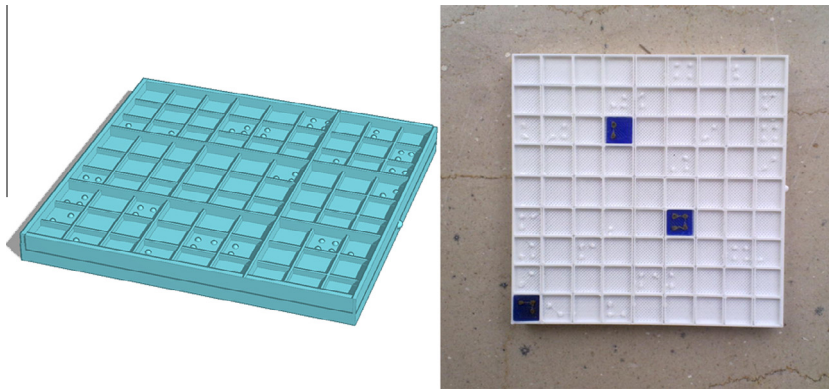


Fig. 8. This artifact required a lot of math skills both for the game itself but also for the appropriate sizes of the parts.

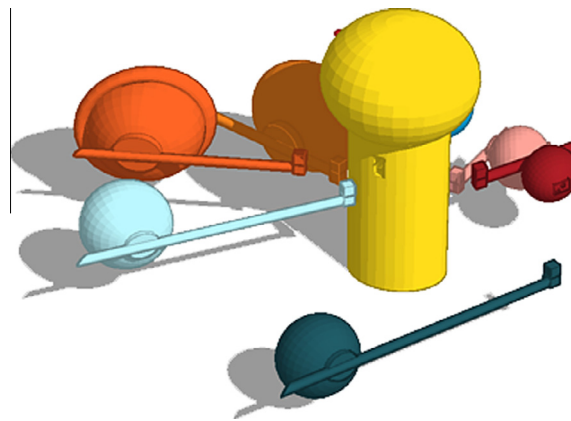


Fig. 9. This design incorporated knowledge from several principles.

5. Conclusions

Echoing Papert (1993, p. 216), this research project does not, and cannot, single-handedly invent mega-change but seeks to participate in its emergence. The case studies of the first phase were realistically modest in scale and were offered not “as exact pictures of the future but rather as an intimation of the rich potential that the future might hold” (Papert, 1993, p. 6). Through this three-month educational experiment we attempted to shed light on the effects 3D printing could have as a learning tool, helping students to become literate, i.e., to think differently than they did previously and, thus, see the world differently (Freire, 2000, 2005; Papert, 1993).

This was not a process without challenges. First of all, there are differences at the level of technological literacy among students. Despite the fact that most possess basic skills in ICT, some are more “engaged” than others, creating an uneven field in the classroom. To tackle such a challenge the teacher needs to distribute his focus accordingly so that all students achieve the same level of understanding and knowledge gained. This was further evident in our case study, since the equipment used exceeds that of standard ICT classes. It demanded first the familiarization of the teachers with the 3D printer and extra caution in the explanation of key concepts and principles, so that all students could proceed without falling behind. In addition, allowing the students to create an artifact with very few restrictions, resulted in a wide variety of objects that made it challenging to provide proper consultation on the various obstacles that occasionally appeared. However, through dialog and experimentation, but also information available on the Internet, these obstacles were overcome. Further, the cost of such equipment (3D printer) currently limits the possibility of acquiring several units for the convenience of students. Even in our case where an open source 3D printer was used, whose cost is significantly lower than the proprietary ones, the schools found it difficult to apprehend one. Also, technical issues demand further familiarization of the teachers with the hardware and their keeping up with advances in technology. These advances will eventually allow for cheaper, faster and more accurate 3D printers to find their way into schools.

Our overall experience was certainly positive arguing that 3D printing and design can electrify various literacies and creative capacities of children in accordance with the spirit of the networked, interconnected, information-based world.

We have seen that students, who were otherwise indifferent (according to them and their teachers) about their project class, when given proper stimulation and the necessary tools can choose what to learn themselves through exploration. Thus, addressing our initial question, modern ICT can help in creating a lively environment in a classroom where, as in our case, students may truly engage in the whole process by materializing an artifact out of a mere idea. Then proudly share their results with others while they acquire knowledge instead of dry information out of textbooks.

Of course, more research needs to be done in different frameworks and contexts than ours focusing not only on open source 3D printing but also on other open source hardware such as the Arduino micro-controllers. And there are three main reasons for that: first, open hardware is cheap and hi-tech; second, it is open and, thus, can be easily studied and modified to serve certain educational purposes; and third, it is a product that celebrates the power of human cooperation. In addition, as already stated in this article, the communicational aspect of 3D printing (especially in the context of the blind and non-blind) along with the global, Commons-oriented information production (for example, the ability to design globally but produce locally) will be one of our next research pathways. We would be happy to see other efforts in that or even alternative directions, sharing, however, the goal to educate children so they can creatively face a future that we may never see.

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Appendix A

Descriptive table of students' answers.

Question	Dodonaia School				7th General Lyceum				Total							
1. How much time do you spend on the computer every day?	0–1 h	1–2 h	2–3 h	>3 h	0–1 h	1–2 h	2–3 h	>3 h	0–1 h	1–2 h	2–3 h	>3 h				
	1	5	5	4	4	6	6	2	5	15%	11	33%	11	33%	6	19%
2. How much of this time do you spend for something related to school?	0 h	1/2 h	1 h	> 1 h	0 h	1/2 h	1 h	>1 h	0 h		1/2 h	1 h	>1 h			
	9	1	4	1	8	4	6	0	17	52%	5	15%	10	30%	1	3%
	Yes		No		Yes		No		Yes		No					
3. Do you think that the way these two courses are taught is tedious?	6	40%	9	60%	6	33%	12	67%	12	36%	21	64%				
4. Do you consider school as a burden?	9	60%	6	40%	1	5%	17	95%	10	30%	23	70%				
5. Have you decided what kind of academic career you will follow?	10	67%	5	33%	14	78%	4	22%	24	73%	9	27%				
6. If yes, is it something related to technology?	9	60%	6	40.0%	9	50%	9	50%	18	55%	15	45%				
7. Would you prefer a more practical, hands-on learning approach?	15	100%	0	0%	18	100%	0	0%	33	100%	0	0%				
8. Do you own a smart phone or tablet?	15	100%	0	0%	8	45%	10	55%	23	70%	10	30%				
9. Do you use any social network (e.g. facebook, twitter)?	14	93%	1	7%	13	72%	5	28%	27	82%	6	18%				
10. Do you use Wikipedia?	15	100%	0	0%	16	89%	2	11%	31	94%	2	6%				

Appendix A (continued)

Question	Dodonaia School				7th General Lyceum				Total			
11. Did you know that Wikipedia is an encyclopedia created by volunteers?	13	87%	2	3%	15	83%	3	17%	28	85%	5	15%
12. Do you know what is the free software/open source software?	5	33%	10	67%	6	33%	12	67%	11	67%	22	33%
13. Have you ever used any application of the free software/open source software?	2	13%	13	87%	3	17%	15	83%	5	15%	28	85%
14. Have you ever heard of 3D printing?	9	60%	6	40%	7	39%	11	61%	16	48%	17	52%
15. Do you enjoy sharing things?	13	87%	2	3%	14	78%	4	22%	27	82%	6	18%
16. Have you ever heard of the Braille language?	12	80%	3	20%	12	67%	6	33%	24	73%	9	27%

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