Educational Makerspaces and Conceptual Art Projects Supporting STEAM Education

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ABSTRACT

The integration of STEAM (Science, Technology, Engineering, Arts and Mathematics) in K-12 education has been a priority for most countries around the world for the last decade. However, the intrinsic difficulty of mathematics and the sciences has limited the success of this integration. Educational Makerspaces have recently been identified as ideal environments for the successful integration of STEAM in the classroom. Educational Makerspaces promote learning as a group activity. This learning involves constructionism: designing and building artifacts. In addition, the inspiration and emotional support derived from working in a group provides the motivation to overcome the traditional obstacles found in STEAM projects. In this paper we present two workshops that are part of a research project to integrate STEAM and Educational Makerspaces in the university environment. The curriculum of the workshops is defined by the implementation of STEAM ideas derived from museum-quality Conceptual artworks. The design of these workshops is intended to be integrated in high schools and the education activities of art museums and libraries. This will have the effect of reinforcing the ties between these institutions.

CCS CONCEPTS

• **Applied Computing**; • **Education**; • **Collaborative learning**;

KEYWORDS

Educational Makerspaces, STEAM Education, Conceptual Art, Computational Theory of the Mind, Data Representation, Mathematical Languages

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1 INTRODUCTION

STEAM education is currently receiving great attention on the part of public and private school administrations around the world [1–3]. There is great interest on the part of researchers, teachers, and school administrators in finding tools and techniques that would allow a successful integration of STEAM in the curriculum. However, the majority of the attempts to expand the interest in STEAM among students has found very little success [4–8]. These initial setbacks have prompted researches to explore new educational methods to address the traditional challenges of mathematics and science in school. Educational Makerspaces (EM) have been proposed, among others, as viable methodologies for this endeavor [9–12]. Our research team has been granted a three-year project for the design and evaluation of EM experiences in the teaching-learning process at the university level [13]. As a result of this project, a MakerSpace will be created in our university. It will host a set of workshops designed for the advancement of STEAM initiatives among the student body, as well as other EM activities proposed by other teams in the university. This project has been granted the use a large laboratory-style space equipped with basic equipment and furniture. The impact of the integration of this EM in the university will be assessed with a set of tests designed to evaluate the scientific knowledge acquired by the students participating in the project's workshops. In addition, a set of surveys will be implemented to assess the affective response of students and the emotional impact of makerspaces in education. One research question is: do students learn seriality and symmetry concepts as a result of their participation in these workshops in the environment of EM?

In this paper we describe the first steps of this project, in particular, the development of a set of workshops integrated in the environment of EM. These workshops are designed specifically to increase STEAM activities in the classroom.

A primary goal of the research project is to evaluate the option of offering the workshops outside the university environment. One scenario involves the implementation of the workshops as after-school activities in local high schools. A second scenario involves the collaboration with local museums and libraries in their outreach educational activities where students and citizens participate in artistic activities.

The project has created a website to foster partnerships with local institutions (schools, museums, and libraries) for the collaborative implementation of these and similar workshops. This site will include information on the structure, design, logistics, participation, etc., in these events [13].

The following sections of the paper present the design of the STEAM curriculum intended for the students. Also, they describe the educational methodology selected to teach STEAM concepts based on Educational MakerSpaces.

2 CURRICULUM DESIGN

Every phase in a complex project has significant implications in its overall success. In the type of workshops described in this paper, the definition of the curriculum determines their lasting value. The curriculum summarizes the new set of ideas that will be acquired by the students. For this reason, these ideas need to be specified with scientific detail. The workshops will provide the participants with memorable experiences, but they, by themselves, are only the road to a higher objective: the mastery of fundamental STEAM knowledge.

The curriculum selected for the workshops described here are designed to explore two fundamental concepts of the world around us: seriality and symmetry. The concept of seriality, in the context of these workshops, is defined as the exploration of the many possibilities generated as the result of some rules and constraints. In the first workshop, we will explore all the possible cases in which four colors could be combined. In the second workshop, we will determine how many structures related to an empty cube could be found following some simple rules. The concept of symmetry, in the context of these workshops, will refer to invariance under some basic transformation, and also to harmony and beauty.

The exploration of seriality and symmetry is in itself a valid and a stirring objective. If we add the circumstance that these two concepts permeate many processes in nature, the workshops provide a complementary benefit in the education of our students. These concepts will allow them to recognize in their environment a set of patterns unseen before.

If we define intelligence as the "ability to create models" [14], the curriculum of these workshops is designed to provide students with the tools to recognize in nature patterns that they will be able to model. In this way, by understanding and describing nature, we provide seeds of progress.

2.1 Historical Art Connections

Symmetry has been, and continues to be, an essential element in the arts, including painting, sculpture, dance, music and architecture [15, 16]. Patterns, rhythms and replications with modifications are intrinsically meshed with human psychology. Our brains identify as pleasant, harmonious, beautiful or desired patterns that present elements of symmetry [17, 18].

The exploration of seriality in the arts is more limited, and it appears with greater prevalence in music, often with the label of serialism [19].

For purposes of illustration, we will highlight the geometric patterns of Islamic art as the systematic study of two-dimensional symmetry in the arts. Figure 1 shows an example of Islamic art with multiple symmetries.

The study of symmetries in Islamic art is remarkable. It was only in the late 19th century, that a mathematical proof identified that there were only 17 groups of two-dimensional symmetries [20, 21]. Several centuries earlier, Islamic artists managed to discover and introduced into their artwork all, or almost all, 17 groups of symmetries [22, 23].

Figure 1: Geometric Pattern, Victoria & Albert Museum, London. Digital image, accessed 20 August 2020. (https://patterninislamicart.com/archive/museums/6/victoria-albert/va070.)

The formal study of these discoveries, both in the arts and in mathematics is, in general, outside the curriculum of students. One of the goals of these workshops is to reclaim as valid areas of study those spaces that historically have been of great interest to humanity, but that in the last decades have been relegated by more ordinary tasks such as arithmetic.

The example of geometry in Islamic art illustrates some of the foundational principles of STEAM. There is a clear integration of arts and mathematics in the study of the 17 groups of symmetry. Mathematics provides the grounds for the difficult exploration of a complex world. The arts provide a meaningful valuation of abstract concepts that have an important role in everyday life, and that are reflected in artworks and architecture that can be appreciated by all.

2.2 Reference Artwork

Two world-class artworks were selected for these workshops, Wall Drawing 413, and Incomplete Open Cubes, both by conceptual artist Sol Lewitt. Figure 2 shows a fragment of Wall Drawing 413 in a recent implementation in the Botin Foundation. This artwork explores the combinations of four basic colors (grey, yellow, red, and blue) and clusters of these combinations based on simple symmetries.

Figure 3 shows a segment of the artwork Incomplete Open Cubes exhibited in the San Francisco Museum of Modern Art. This artwork explores the ways in which it is possible to construct an open cube (only edges) with fewer than the required 12 edges. Two added requirements establish that no edge may be unconnected to the others, and all three dimensions need to be occupied.

These two artworks were selected to define the curriculum of the first two workshops for two reasons. First, the artworks needed to be museum-quality pieces. This world-class status guarantees the existence and availability of a large body of research and literature around them. This includes books, museum catalogs, art reviews, etc.

Figure 2: Wall Drawing 413, Art Madrid. Digital image, accessed 20 August 2020. (https://www.art-madrid.com/en/post/Sol-LeWitt-Botin-Foundation-Santander.)

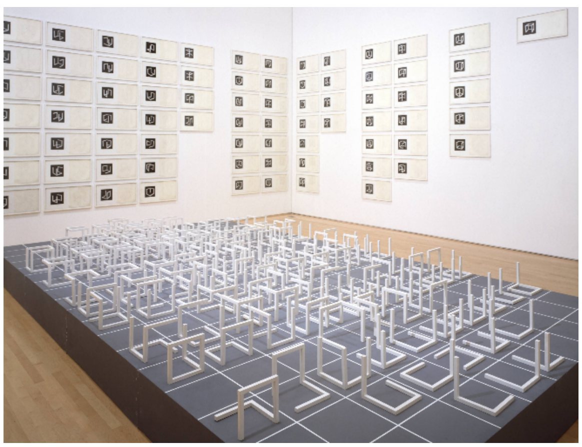

Figure 3: Incomplete Open Cubes, San Francisco Museum of Modern Art. Digital image, accessed 20 August 2020. (https://www.sfmoma.org/artwork/97.516.A-KKKKKKKKKK/.)

The second reason for selecting these artworks is that they belong to an art movement known as Conceptual Art. The artist Sol Lewitt famously wrote [24]:

"I will refer to the kind of art in which I am involved as conceptual art. In conceptual art the idea or concept is the most important aspect of the work. When an artist uses a conceptual form of art, it means that all of the planning and decisions are made beforehand and the execution is a perfunctory affair. The idea becomes a machine that makes the art."

The selection of conceptual artwork is important for these workshops because the artist specifies in concrete terms the idea that makes the art. This allows a link between the sciences and the arts where often only subjective criterium was used in its analysis. More importantly, art criticism has been characterized during the last decades as being obscure, ambiguous, and uninformative. The scientific method is based on the fundamental idea that a hypothesis must be falsifiable or refutable, that is, the capacity to be contradicted by evidence.

Conceptual art offers a bridge of communication to the sciences by formalizing its ideas in refutable terms. If the progress of science in the last three centuries could serve as a guide, the integration of fields proposed by STEAM predicts a renaissance of the arts after the long winter lamented by many [25].

The first section of the curriculum is obtained directly from the existing literature regarding the two artworks. This includes the definition of the problems, the process followed by the artist in the exploration of solutions and the final implementation. It includes also the formal review of art critics and the descriptions in museum catalogs and existing books.

These curricular materials, as well as those described in the rest of this paper form the academic materials used in the workshops. These materials, and others related to the workshops are collected on the website dedicated to the research project described earlier [13].

2.3 Development of New Languages

In the process of creating the first phase of the curriculum, as described in the previous section, several cognitive limitations were identified. These limitations are evident with a formal analysis of the implementation of the artwork and the interpretation of the results.

This analysis indicates that the full geometric exploration set at the onset of the project were not completely realized. The discovery of these cognitive barriers opens new areas of investigation. In this section we describe the most relevant barriers identified; we implement two mathematical languages to overcome them; and we develop the academic materials to implement them in the workshops.

2.3.1 A Two-Dimensional New Language for Wall Drawing 413: Irregularity. The first cognitive concept that we will study refers to the 'irregularity' of the patters formed in Wall Drawing 413. According to the description of the artwork by the Massachusetts Museum of Contemporary Art: *"In Drawing Series IV, LeWitt used the Cross Reverse method of change, in which the parts of each of the original units are crossed and reversed. When drawn on the wall in ink, the irregular, colorful patterns made by these permutations become boldly evident* "[26]. This description of "irregular patterns" appears in other catalogs as well [27].

The methods used for the combination of colors were labeled with ambiguous names, such as cross and reversed. Figure 4 shows the numeric definition of two of the methods used by the artist: III Cross & Reverse Mirror, IIII Cross Reverse.

Because the process behind the artwork ("the idea becomes a machine that makes the art") is simple and deterministic, it is obvious that the artwork is very regular. To define its patterns as 'irregular' is to miss its true nature and to confuse it by its opposite.

It is possible that a naïve viewer of Wall Drawing 413 (Figure 2) may initially perceive its patterns as irregular. One can easily identify in the following sequence (0, 5, 10, 15, 20, 25,. . .) a clear pattern: the multiples of five. The sequence (0, 3, 6, 9, 12, 15, 18, 21,. . .) is also a sequence with a pattern: the multiples of three. However, not seeing the pattern in the second sequence ("not seeing the idea, the machine behind the artwork") will make the viewer perceive an irregular series of digits. To see the artwork in Figure 2

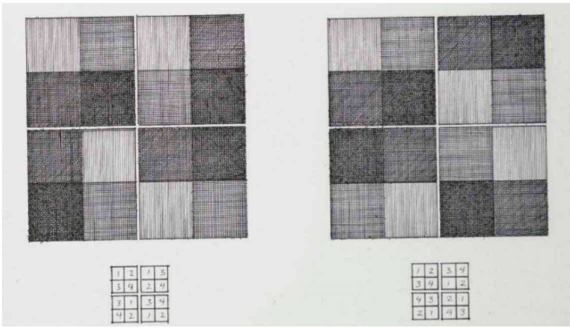

Figure 4: Symmetry patterns III Cross & Reverse Mirror (left), IIII Cross Reverse (right). The Museum of Modern Art. Digital image, accessed 20 August 2020. https://monoskop.org/images/a/a1/Sol_LeWitt_MoMA_1978.pdf.

as 'irregular patterns' implies not to see the regular idea in which it is based.

To convey the participants of the workshop the regular nature of the idea, we developed a formal language to describe the symmetries used in the process, abandoning the ambiguous and incomplete labels of Cross and Reversed. The language includes three main components. First, the twenty-four permutations of the four colors is obtained by following a method that is familiar to all participants: how to count small amounts of money. The second part consists in defining the symmetry of each cell of four by four squares in terms that are familiar to all participants: the use of simple words (papa, bebe.) The final part consists in recreating from memory the complete artwork using its minimal set of colors: six domino-like tiles.

In a small test of this language, (N=6), 100% of participants have been successful in recreating from memory Wall Drawing 413 after being introduced to this new language. The workshops scheduled to be implemented as part of the project will be the environments where the efficiency of this language will be formally evaluated.

One implication of this experiment is that the artwork is indeed very regular. This regularity is what allows participants to reproduce it from memory. A second implication is that these participants, if asked, could identified many additional symmetries and regularities that appear throughout the artwork. In other words, their understanding of the true nature of the artwork goes beyond what has been traditionally reported in the literature.

2.3.2 A Three-Dimensional New Language for Incomplete Open Cubes: Paleontology and Taxonomy. In the previous section we studied the concept of "Irregularity" in the context of STEAM and two-dimensional Conceptual Art, Wall Drawing 413. Here we will study two additional concepts in the context of STEAM and three-dimensional Conceptual Art, Incomplete Open Cubes (IOC). In order to make these concepts easier to remember, we will use the metaphors of "paleontology" and "taxonomy."

On the first task of IOC, we will imagine the artist as a "paleontologist." Instead of searching dinosaur fossils in the vast desert of Gobi, the artist is searching for "all possible open cubes." We are interested in the quality of the technique used to search, and the likelihood that it will provide optimal results.

On the second task of IOC we will imagine the artist as a "taxonomist". Instead of naming, describing, and classifying plants or animals, the artist will name, describe and classify the incomplete cubes that have been discovered. We are interested in a taxonomy that is based on essential attributes of the structures, in order to provide a deeper understanding of their nature. We do not classify fossil bones by their length or weight, but by the animal to which they belong, their part in the body, and the function they perform.

In this section we propose the idea that to perform satisfactorily the tasks of "paleontologist" and "taxonomist" of the IOC it is necessary an appropriate language. Because such a language was not developed for the original IOC, the analysis identifies important deficiencies in both tasks. To overcome these deficiencies, we develop a mathematical language.

IOC explores the construction of open cubes (only edges) that are incomplete. Incomplete cubes are those with fewer that the twelve required edges of the complete cube. The minimum number of edges is set to three in order to accommodate the rule that all three dimensions need to be represented in the structure. The maximum number of edges will obviously be eleven. Also, no structure is allowed to have unconnected edges.

If in the Wall Drawing 413, the permutations of four colors (24 unique permutations) represented a numerically simple task, the challenge of IOC (which includes combinations of 3, 4,. . .11 edges) presents a much more complex task. Twelve bits (each representing the presence, 1, or the absence, 0, of an edge) suggest a search field of around four thousand potential structures ($2^{12} = 4096$.) A complex problem requires a powerful language to describe and manipulate its data.

The search of the artist for these structures, according to his notes [28], reveals the difficulties he encountered. Figure 5 shows some of the notes in the search of the structures with seven segments. This problem of systematic search in a large field is sufficiently complex that it even escaped the editors of a book exclusively dedicated to the artwork IOC. On page 24 of [28], the essayist remarks, referencing the notes shown in Figure 5 "Lewitt initially identified 39 seven-part variations, when in fact there are 32."

It is correct that there are only 32 seven-part variations, but the essayist fails to mention that although Lewitt found 39 variations, three of the correct variations were never found in this list. Eight variations were included twice, under different names, and one variation was included three times, under different names. The problem was too complex to be addressed with the simple language of naming the edges with letters and doing an alphabetic search.

To provide the participants of the workshop with the tools needed to solve the complex problems presented by IOC, we developed a new three-dimensional mathematical language. This language was designed to be used by students without any formal education in topology or advanced mathematics. It was designed to be used by a typical high school student, or by a typical museum visitor interested in conceptual art such as IOC.

The language takes advantage of human cognitive primitives: the innate abilities to perform data manipulations, such as image recognition or three-dimensional location [29]. It is based on the

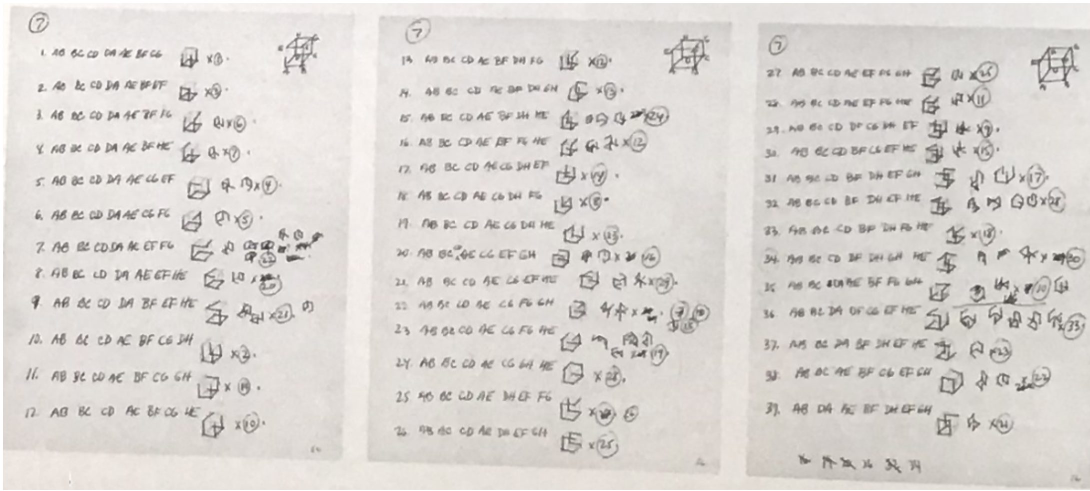

Figure 5: IOC. Thirty-nine structures with seven segments. Artist notes. LeWitt, S., Flatley, J., & Lee, P. M. (2001). Sol LeWitt: incomplete open cubes. MIT Press.

recognition of three fundamental shapes: a complete square, represented by the symbol O, a square where a side has been removed, represented by the symbol U, and a square where two adjacent sides have been removed, represented by the symbol L.

An IOC structure is represented in these languages a building with a floor and a ceiling, connected by one or more columns. With this vocabulary, the search consists on the systematic exploration of structures or buildings, where the floor and ceiling are, in general, described by the sub-structures O, U, and L.

In a small test of this language, (N=4), 100% of participants have successfully discover the 122 structures of IOC. This is the task that in our metaphor is implemented by the "paleontologist." As noted earlier, the workshops scheduled to be implemented as part of the project will be the environments where the efficiency of this language will be formally evaluated.

The need to eliminate duplicate structures and to group into families the correct structures is the object of the second part of the workshop. We call this task in our metaphor the task of the "taxonomist." As was noted earlier, the artist and art critics had great difficulty in identifying equivalent structures where one could be obtained by rotating its equivalent. Figure 5 shows that candidate structures were named by the letters representing their edges. Then, and alphabetic comparison was implemented to order them. But it is obvious that this system of naming structures with letters cannot identify rotational symmetries.

The artist eventually required that two mathematicians would confirm that 122 was the correct number of existing structures [28]. The number of 122 existing structures is indeed correct, however, the final implementation of IOC offers only 121 distinct solutions, repeating one solution, and missing another. Figure 6, shows photographs of the 122 pieces created in wood. The last two structures of 10-edges are identical. It is surprising that even with the structures implemented in a way that could be manipulated and rotated at will, the artist, art critics, and museum visitors apparently failed to see the error.

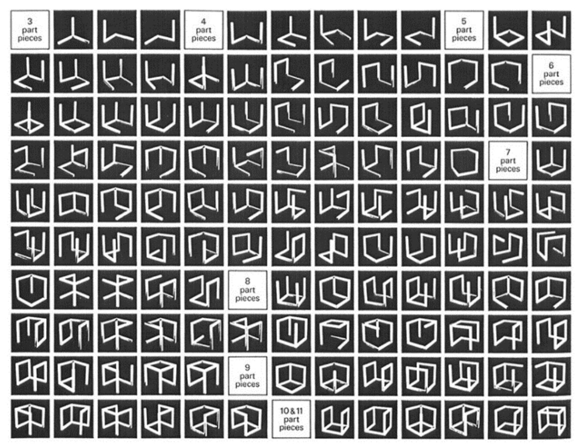

Figure 6: Poster with the classification of the 122 structures of IOC. The Museum of Modern Art. Digital image, accessed 20 August 2020. (https://monoskop.org/images/a/a1/Sol_LeWitt_MoMA_1978.pdf)

The three-dimensional new language developed for IOC is used also for the task of duplicate elimination. Each structure receives a name base on the shape of their floor and ceiling, and the number and location of its columns. This makes the operation of duplicate elimination almost trivial.

In a small test of this language, (N=4), 100% of participants have been successful in naming a set of 25 randomly selected structures. This is the task that in our metaphor is implemented by the "taxonomist." As noted earlier, formal evaluations of these procedures are schedule to take place as part of the workshops.

Finally, and important artistic aspect of IOC is the classification of the 122 structures and how they are presented to the viewer. Figure 2 shows how the structures are grouped and displayed in the museum environment. The three-dimensional wood structures are placed on a platform, grouped by number of edges. The same grouping criteria is used for the photographs on the walls, or on the posters announcing the exhibitions. Figure 6 shows how the 122 structures are grouped by the number pieces required in each one. The effect on art critics and museum visitors of this grouping of structures is what they often describe as 'chaos.' Even the way in which each piece is placed on the floor is cause of confusion. According to the artist, there is not preferred orientation in placing a piece on the floor.

However, a great multitude of symmetries is missed by this arrangement. Using the three-dimensional language created, a surprising number of families of structures appears based on the shape of their floors, their ceilings, and their columns. All this occurs regardless of the number of pieces of the structures, indicating that their classification based on number of pieces is limited and limiting, and precludes the viewer from exploring the real nature of this three-dimensional world.

As part of the workshop, the students classify the 122 structures based on three dimensional symmetries, opening a new field of collaboration between the sciences and art. In this collaboration, the use of scientific tools allows participants to elevate artistic questions of harmony, symmetry, and aesthetics to levels until now unanswered, even unquestioned, in the analysis of IOC.

3 EDUCATIONAL MAKERSPACES

The educational methodology selected to teach the STEAM concepts described in earlier sections is known as EM, Educational MakerSpaces. It is based on the process of gathering all the participants, students and teachers, in a physical space that has been especially designed for the construction of artifacts. This construction takes place in groups, where all collaborate towards a common goal: sharing the learning experience by creating together.

This educational methodology is based on three principles. The first is collaboration. By working in groups, the participants form part of a greater entity that allows them to overcome obstacles beyond their individual potentials. The second is construction. By physically creating an artifact, the participants engage cognitive abilities that go beyond those used in the classroom with pencil and paper. The experience of the construction improves the individual knowledge of the participants in a way that is more profound and permanent in their memories. The third is emotional synergy. The affective disposition of the participants created by the first two principles, working together, and constructing an artifact, creates an emotional environment that acts as a catalyst to overcome obstacles, and fosters deep learning.

The learning experiences scheduled in the project described in this paper are designed around the concept of workshops. The structure of each workshop begins with the definition of the curriculum. The description of the curriculum has been the objective of previous sections.

The curriculum, in turn, is formalized into a set of academic materials. These materials are used in three phases of the workshop. The first phase introduces the concepts to the participants. For example, Figure 7 shows a diagram that represents the regular pattern of Wall Drawing 413. It represents, based on the words PAPA-PAPA, and BEBE-BEBE, the structure of each cell of 16 squares, that repeats again and again.

The academic materials in phase 2 are used for the hands-on practice to assess 'concept understanding.' For example, Figure 8 shows a template of all possible structures with a floor with a pattern in U (green color) and all possible distributions of columns (yellow color.) The participants use these templates to complete the missing ceiling structures (which they draw in red color) and identify those structures that are new; define their names (according to the rules created earlier); and list all the symmetries discovered.

The academic materials in phase 3 are used for the main activity of the workshop: the creation of a large size, collaborative artwork, that reflects the fundamental cognitive ideas explored. Figure 9 shows a set of open cubes build in aluminum in a garden environment. This image illustrates how the artifacts created in the workshop could become installation in the gardens of the university or other public places.

Because the construction of artifacts is one of the three pillars of EM, these workshops need to dedicate special attention to the selection of materials and construction tools. The materials are determined by the object of the project: paint for the Wall Drawing 413, and wood or aluminum for the IOC.

The research project has designed workshops of different durations, to accommodate the time constraints of the participants. The phase of construction is the most important and therefore the most time-consuming part of the workshops. For this reason, the materials for construction need to be selected according to the time available, and the physical size of the artwork created. In general, a workshop lasts 10-20 hours. This time allows for several meetings and the use of more sophisticated materials, such as paint and metal. For shorter versions of these workshops it is still possible to recreate the artworks, but the material selections are different. For example, the Wall Drawing 413 is replicated in a relative short period of time when the participants, instead of painting, tape sheets of colored paper to the walls. In the case of IOC, using balsa wood and glue, the participants create smaller versions of the metal structures.

Finally, the workshops have being designed to test and optimize the use of EM for the integration of STEAM activities, both in the classroom environment, and other public environments such as the educational activities of museums and libraries. For this reason, each workshop includes two sets of formal evaluations. First, we include the STEAM related evaluations, where we assess, through the work of the participants, the depth of the scientific ideas acquired by them. Second, we survey the affective experience of the participants when they worked collaboratively in the construction of meaningful artworks. The workshops are planned to be held during the 2020-21 academic year as long as the health situation due to COVID-19 allows it with total safety for the participants.

4 CONCLUSIONS

A formal study of two museum-class artworks reveals that their reported artistic analysis offers subjective interpretations that directly contradict the geometric properties in which they are based. A mural is considered irregular because its overwhelming regularity has not been recognized. A large family of structures is considered chaotic because its internal symmetries have not been discovered.

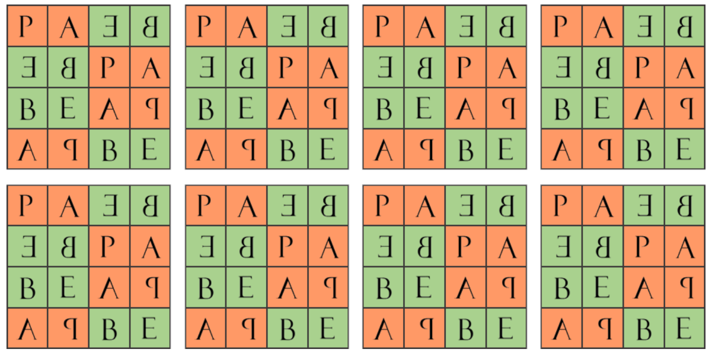

Figure 7: Regular symmetry pattern of Wall Drawing 413.

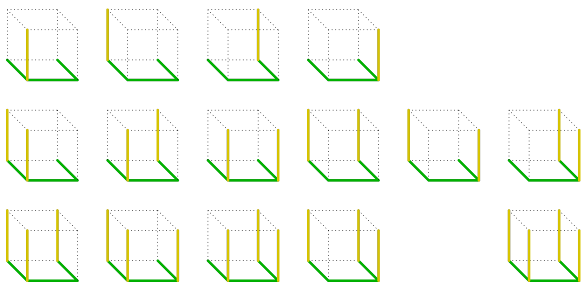

Figure 8: Incomplete structures with U-pattern base, 15 column distributions, and empty ceiling structures (to be completed by the participants in the workshop.)

Figure 9: Installation of IOC aluminum structures. Art Hag. Digital image, accessed 20 August 2020. (https://arthag.typepad.com/arthag/2011/07/sol-lewitt-city-hall-park.html)

The paradoxes offered by these two examples are used to probe into the deep nature of conceptual art, the formulation of artistic ideas, and their relationships with STEAM.

Two initial workshops, in a series of EM experiences of a research project, show promising initial results. The hypothesis that complex artistic ideas require mathematical languages for their development, study and communication is tested. Two mathematical languages were developed to overcome the intrinsic difficulties reported in the creation and exhibition of these two world-class artworks.

The human capacities to explore the nature of conceptual art is limited when it is approached with no scientific tools. At the same time, students are capable of easily acquiring ad-hoc mathematical languages. Equipped with these languages, workshop participants implement with ease tasks that seemed extremely difficult, such as reconstruct from memory a complex wall drawing, or discover and classify all 122 structures of incomplete cubes.

These initial results support a formal study of this hypothesis via multiple workshops, and the exploration of their implementation in non-academic environments such as educational activities in museums and libraries.

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