The Use of Computational Thinking in Digital Fabrication Projects

A Case Study From the Cognitive Perspective

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***Abstract*—Existing literature presents many cases of computational thinking analysis through the perspective of a skill set for 21st century. However it is important to go deeper and understand how computational thinking activities fosters the cognitive development of the young, especially if we want them to have "a significant advantage in problem solving", becoming innovative thinkers [1]. To be innovative it is necessary that a person use sophisticated cognitive structures to reason over abstractions and deal with hypothesis. These are the characteristics of the formal operational thinking [2]. Therefore, this paper is about the use of formal thinking on computational thinking activities over a digital fabrication project developed in a Brazilian makerspace (POALab FabLab). Using a Case Study we want to show that computational thinking and digital fabrication projects demand the use of formal thinking and, since that, the importance of designing learning activities for makerspaces taking in mind the possibilities of cognitive development.**

Keywords—formal thinking, computational thinking, making, Jean Piaget

I. INTRODUCTION

Computational Thinking definition was set in 2010 by Jeannette Wing as "the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" [3]. Since then the importance of the computational thinking as a skill for 21st century has been widely discussed [1][4][5]. However, in 1980 Seymour Papert has already presented this term, without elaborating on it. Papert considered the computers as "objects-to think-with" [6], or machines that children could learn to manipulate, to extend and to apply to projects, developing new knowledge and a self-confidently image of himself as an intellectual agent.

Thus, Papert's vision is the start point of the discussion about makerspaces as learning spaces. Makerspaces offer access to digital fabrication tools, as 3D printers, robotics, microprocessors, wearable computers, e-textiles, "smart" materials, and new programming languages. These tools enable hands-on learning and give individuals the power to invent. [7].

Through the experience of inventing things using digital fabrication tools, makerspaces offer the opportunity for an active learning experience. This means that the activities developed in such places demand that the learner reflects over the object that they are making, about his actions during the fabrication process and about the knowledge obtained from all that. It is expected that the making activity will bring challenges, and doubts that will put people in an imbalance situation. According to Jean Piaget "the imbalances are the engine of research, because without them, knowledge would remain static" [8]. The equilibrium is restored thanks to an equilibration process made of assimilations and accommodations. Piaget [9] defined assimilation as "the integration of any kind of reality into a structure". Accommodation is responsible for creating or modifying the existing structure according to the assimilated information.

Through this paper we aim to present a case study about using computational thinking in digital fabrication processes. Using the cognitive development approach of Jean Piaget, we intend to show how this kind of experience demands the use of cognitive mechanisms related to the formal operational stage. The case study, data collection and procedures to analysis will be presented at section 4. The findings are localized at section 5. Before that, we will explain what computational thinking is and what its main elements (section 2) and we will present a parallel between computational thinking and formal thought. Conclusions of this work will be presented on section 6.

II. COMPUTATIONAL THINKING

The Royal Society presented in 2012 a more succinct and tractable definition of computational thinking. They defined computational thinking as a "process of recognizing aspects of computation in the world that surround us, and applying tools and techniques from Computer Science to understand and reason about both natural and artificial systems and processes" [10]. As aspects of computational thinking related with the computational world we will consider the following concepts:

- Abstraction: apply different levels of abstraction to understand problems. Through abstraction it is possible to eliminate unnecessary details and choose the right forms of representation, reducing the level of complexity of problems;
- Logical reasoning: is the base of computational thinking. It makes possible the construction of algorithms, the decomposition of problems, generalization, abstraction and evaluation. It allows the elaboration and testing of hypotheses;
- Algorithmic thinking: is the clear and concise definition of the solution of a problem, obtained by describing the necessary steps. It contemplates iterative, recursive, parallel thinking and notions of flow control;
- Decomposition (or modularization): corresponds to the dismemberment of a problem. Its parts can be understood, solved and evaluated separately, thus reducing the complexity of the problem;
- Generalization: it is related to the identification of patterns, similarities and connections. It let us solve problems quickly by using, or adapting, existing solutions to similar problems;
- Data manipulation: systematic processing of information. It contemplates the use of researching tools, filters and organizing the data in tables or data bases ;
- Evaluation: ensures that the solution created is adequate, according to criteria of efficiency, usability and scalability, among others.

All these are very common terms in the Computer Science world. However, according to [3] the computational thinking is not just about Computer Science, as it can be applied in daily life. Through the use of computational thinking everyone can be able to: "understand what aspects of a problem are amenable to computation; Evaluate the match between computational tools and techniques and a problem; Understand the limitations and power of computational tools and techniques; Apply or adapt a computational tool or technique to a new use; Recognize an opportunity to use computation in a new way; Apply computational strategies such divide and conquer in any domain." [3]. In the educational context, computational thinking has been explored in three different ways [5]:

- as computer programming: developing games and simulations using Scratch, Snap, Aris, etc;
- as "computational craft": developing e-textils activities or using kits that allows children to mix electronic and art;
- in robotics projects: programming the behavior of educational robots as Jimu, JabutiEdu, Lego Mindstorms, etc;

We are convinced that is possible to explore the use of computational thinking in activities other than that. Digital fabrication projects can explore computational thinking in automation, design and engineer activities. It seems especially interesting to work with teenagers and adults because digital fabrication technologies can satisfy their interests in solving real problems, creating products with a nice design and making innovations. Besides that, digital fabrication projects promote the acquisition and use of cognitive mechanisms, knowledge and skills that can be useful in the professional life.

III. Computational Thinking and Formal Thinking

Computational thinking is very close to Jean Piaget's theory. It begins with the principle of "learning by doing". Piaget states that the interaction between subject and objects is necessary because it will produce doubts and uncertainties (an imbalance situation), which will trigger a series of mental processes that will lead to the construction of knowledge. It seems to be similar to the "use-modify-create" approach proposed by [5] to develop computational thinking. According to this, subjects begin by performing experiments while using already existing computational models, running a program that controls a robot or just playing. As subjects understand the functioning of these models, games or programs, they begin to modify them, increasing their level of complexity. In the end they have created products with appearance and behavior very different from the original products. It's a demonstration of subjects' cognitive processes and abilities throughout the creative process.

Creativity is another point of intersection of Piaget's theory and computational thinking. For Piaget, creativity is the work of intelligence and the fruit of a construction of knowledge [11]. In computational thinking creativity is explored when subjects use technology to create new systems, processes or products, but also when giving new purposes to existing systems. There is also a connection between Piaget's theory and the concepts of generalization, decomposition, data manipulation, continuous evaluation and algorithms (Fig. 1).

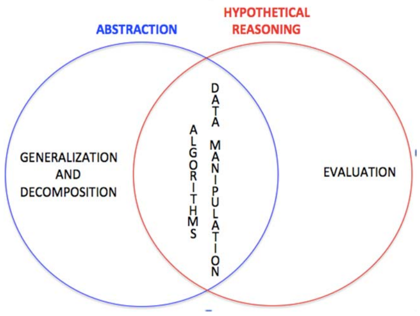

Fig. 1 - Relations between formal thinking and computational thinking

To abstract is the process of taking essential information (characteristics and behaviors) from an object or from an action over an object. In computing, abstraction has a similar concept. It "means reducing something to a very simple set of characteristics, chosen to be most relevant to the problem." [12]. However, Jean Piaget differentiates between simple abstraction, when the data is collected directly by the object manipulation, and reflective abstraction, when there is a reflection over the action realized with the object. In computing the objects are not physically manipulated, but their properties and behaviors can be virtually modified. Through abstraction it is possible to group objects that have the same properties and behaviors and represent them as a class, which is a generic and reusable model of objects. Also through the use of abstraction is possible to manipulate data using data basis and to represent data using generic data types, tables and charts.

The hypothetical reasoning "is a problem-solving approach that explores several different alternative solutions in parallel to determine which approach or series of steps best solves a particular problem" [13]. When elaborating a test script, as part of a continuous evaluation process, the student is dealing with hypothesis that, through the test, can be confirmed or denied. Also the test result can lead to the identification of reciprocities or correlations. This is related to the INRC group of logic operations that, according to [14] "is a structural model designed to account for the complexity of the final stage of logical development."

An algorithm elaboration is based on a mental action that tries to create a solution for a problem through the identification of the necessary steps for such. This also requires a thought organization, which involves grouping operations (for example, when it is identified that certain variables of the problem are of the same type), logical operations (for example, when validating a condition) and generalization (for example, when, from the observation of several similar problems, it is possible to develop a generic solution). These operations demand formal thinking to happen.

IV. 4. Data Collection and Analysis

We conducted a Creativity Workshop at POALab, which is a makerspace situated at Federal Institute of Education, Science and Technology of Rio Grande do Sul State (IFRS), Brazil. The Creativity Workshop was free of charge and any person, older than 14, could apply for it. The activities were conducted by a couple of facilitator: the first author of this paper and a teacher of arts who is also a graduate student of Learning Technologies. The meetings happened once in a week for 15 weeks and they lasted for 3 hours. The challenge presented to the participants was to develop a board game using, as much as possible, the tools available at the makerspace (3D printer, laser cuter, vinyl cutter and Arduino kits).

Participants worked in groups of four people to create a digital portfolio using Google Documents, and shared it with author 1. Then they engaged in a 12-hour training for machine use (vinyl cutter, laser cutter, 3D printer and basic electronics). After that, they had 33 hours to create and test a game.

Initially, we tested their cognitive development using Longeot's Test of Cognitive Development [15] [16]. This test aims to classify the subjects as being in either the concrete-operational or formal-operational stage. It evaluates the operational level in three areas: logic, combinations, and probabilities.

For this case study, we chose John, an 18-year-old mechatronics technician student, because he placed in the formal operational level in all three tests, and he had prior experience with computer programming; therefore, he functions as an illustrative example of how computational thinking is used in a digital fabrication project and how the formal operational level cognitive skills are applied in these situations.

For the purpose of this paper, the data collected and analyzed were pictures, observational notes, and student artifacts, including their individual portfolios. We searched for indications of the use of computational thinking elements into digital fabrication process, according to Table 1:

TABLE I. Computational Thinking Elements Related to Digital Fabrication Activities

Code	Computational thinking elements	Digital fabrication references
CT1	Algorithm thinking	Elaborates an algorithm Elaborates an execution flow for an equipment assembly or to perform a task Elaborates a scalable solution Elaborates a script with instructions for using the solution created
CT2	Abstraction	Elaborates three-dimensional model Elaborates two-dimensional models Elaborates technical drawings, diagrams, mind maps or other models Reduces the complexity of the problem by eliminating unnecessary details
CT3	Decomposition	Identifies parts of the problem and possible solution. Takes advantage of existing solutions to solve project problems
CT4	Generalization	Creates solutions that can be used in different situations or by different users Identifies patterns Transfers ideas between projects
CT5	Evaluation	Identifies the input variables and the possible results to be obtained. Prepares test scripts Applies criteria to evaluate a solution. Compares the performance of similar solutions. Identifies improvements, refine solution and generate new solutions
CT6	Data manipulation	Use of researching tools Systematically collects data Organize data in folders, tables or charts Applies filters or techniques of data mining

The findings that will be presented in the next section reference the computational thinking element identified using the code in the first column of Table 1.

V. Findings

John demonstrated the ability to apply computational thinking and operate in a formal level in many situations during the workshop. We will present the findings of the use of computational thinking and formal thinking using John's creative process during the game design. He and his group decided to make a game, with gears as the principal mechanism to control the dynamic of the game. It looked like a pyramid (Fig. 2 and Fig. 3) with a column of gears at the center. He wrote in his portfolio: "*The gears move every floor. The 1st floor rotates in the clockwise direction, the 2nd counter-clockwise, the 3rd clockwise and the 4th counter-clockwise.*

The pawn moves according to the number that the players get by throwing the dice. So, the player could choose to go up or down a floor or to move on the same floor. When the player stops in a house, he/she activates the effect of that house, for example facing a monster, opening a treasure box to win an item, etc. The goal is to reach the top and fight with the bag guy. The first to kill him, would be considered the winner of the game."

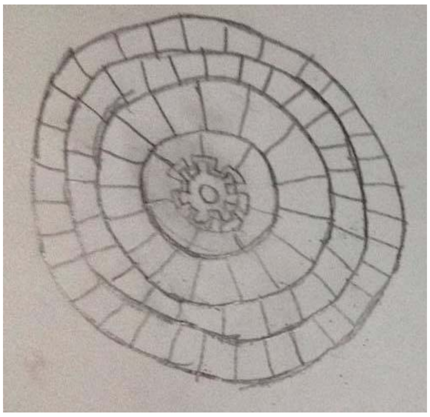

Fig. 2 - Up view of the board

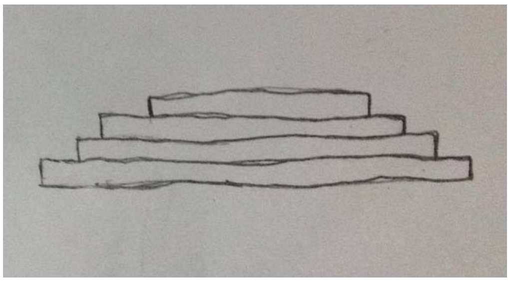

Fig. 3 - Side view of the board

Fig. 4 - Models of gears made with cardboard

Fig. 5 - Prototype of the board

A. Findings of the use of computational thinking

1) Algorithm thinking and Decomposition

The steps that John took to develop his activities indicate the use of an algorithmic thinking (CT1). First he made a drawing as a way to help him to explain his idea for the board game. Then he used a vector graphic design tool to create a 2D model of a gear using cardboard and laser cutter (Fig.4). The purpose was to test if it was possible to use cardboard to create gears with different tooth size. After that he spent some time searching for types of gears and learning how they work and how they could be mixed to make the desired movement for the board. After some weeks studying he made a prototype of the board (Fig. 5).

Just after completing the task related to the board creation, John started working on the pawns prototypes (Fig. 5). This project organization points to the decomposition element of the computational thinking (CT3), which corresponds to the dismemberment of a problem.

Fig. 6 - Prototype of the pawns

2) Abstraction

The computational thinking element related to abstraction (CT2) can be seen when John developed a model of the board using a vector graphic design tool. To do that, John had to focus on the most important details of the board as the kind of gears to be used, their size, their position in relation to each other, etc. That is what to abstract means: making the solution of a problem easier by removing the unnecessary details and focusing in the things that are relevant.

3) Data Manipulation

The type of gears to be used was defined by John after a research through Google. Using the data collected, he developed a table as a way to present to his colleagues the options that could be used in their game. He wrote: "*Below is a table of gears that I generated, we still do not know which ones will be used*". Creating a table is an exercise of data manipulation (CT6) because it demands the use of a research tool and a systematically organization of the collected data. The table 2 is a short version of the original table.

TABLE II. SAMPLE OF THE TABLE CREATED BY JOHN

Kind of gear	Number of teeth	Module
Spur	12	4
Planetary	10	4
Planetary	12	4
Internal	24	4
Internal	36	4

4) Generalization

The participants were asked to identify groups of objects that compound their game. John answered "*pawns, dices, board and gears*" This capacity to identify classes of objects allowed John to search for projects at Thingverse website that could be used as models for his game. This is an example of generalization (CT4), which is a way to solve new problems based on previous problems that have been solved.

5) Evaluation

The model of the board created by John (Fig. 5) was used to evaluate (CT5) the board, the paws and the mechanics of the game. Thanks to the evaluation process, John's group could identify problems with the proportions between the board and the pawns, with the material that he was using to make the pawns, with the power of the engine that would make the gears turn, etc.

B. Findings of the use of formal thinking

The first design action of John was to draw a representation of the board. He represented the up view (Fig. 2) and the side view (Fig. 3) of the board. The notions of invariance, conservation of substance, volume and weight are characteristic of the operative level. However, the manipulation of perspectives is only possible at a more advanced operative level (formal level), when the subject is able to imagine all possible relations between him and the object, without physically manipulating it. Thanks to a high level of abstraction John could imagine, and draw, two different points of view from the subject in relation to the board.

Also in relation to the board, John wrote in his portfolio "*It has been defined that the board will have 4 floors of gears. In the center, there will be a type of a gear that will be coupled to an engine controlled by the Arduino. This central gear will be responsible for the vertical movement of the board. It will be connected to the gears of each level of the board*." This shows how he is able to reason over an abstract idea because he is elaborating a model of the game, with details as the number of floors, the kind of mechanisms will be used, the technology that will help to control the movement, without physically manipulating the object. This is a characteristic to the formal operational stage when adolescents develop "the capacity to reason in terms of verbally stated hypotheses and no longer in terms of concrete objects and their manipulation" [17].

To make the Table 2, John applied the characteristics of a formal operational thinker: abstraction, metacognition and hypothetical reasoning [2]. He used abstraction to generalize and present the relevant data as a table, metacognition to reflect about what he studied, making possible a generalization, and hypothetical reasoning to decide what kind of gears (according to the number of teeth) could be relevant to their game. When asked why the number 4 as module of the gears, he answered: "*it would give a good tooth size which would be less likely to break*". It is an example of the use of logical reasoning because it shows that John could establish a cause-effect relationship between the tooth size and the possibility of breakage.

VI. CONCLUSION

From the presented case study, we concluded that computational thinking can contribute to the development of formal thinking. The computational thinking needs structures and operations that are characteristics of formal thinking to deal with abstractions and generalizations, and to apply algorithmic reasoning to solve problems. We also conclude that digital fabrication projects can provide rich physical and logic-mathematical experiences, which are, according to [9], the essence of human development. The physical experience, through the manipulation of materials as plastic, wood, cardboard, acrylic, electronics, etc., is completed by the use of tools for 2D or 3D design, and computer numerical control machines. The complexity of those materials, tools and machines make the logic-mathematic experience more rich because it demands coordinating actions of the subject on the object in such a way that the subject distance himself more and more from the object, leading to the construction of abstract structures. These structures are the basis of formal operative thinking.

In light of this, and knowing the growing popularity of educational makerspaces, we call attention to the importance of planning maker or tinker activities that provide challenges capable of promoting physical and logical-mathematical experiences that will contribute to the development and exercise of formal thinking.

ACKNOWLEDGMENT

This material is based upon work supported by CAPES (Coordination for the Improvement of Higher Education Personnel). We also wants to thank Federal Institute of Education, Science and Technology of Rio Grande do Sul, campus Porto Alegre and to Dr. Breanne Litts from the Instructional Technology & Learning Science Department, Emma Eccles Jones College of Education and Human Services, at Utah State University.

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