Using Information Theory to Develop Modern Educational Methodologies

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***Abstract*—The field of research in educational methodologies has been offering during the last decade a series of innovative and promising new initiatives. These initiatives have tried to apply to the educational environment the fruits of current psychology research. Ideas such as student motivation, gaming, multiple intelligences, project-based learning, flipping the classroom, makerspaces, and others, abound in the field of educational methodologies. These new initiatives are evaluated with traditional procedures grouped under the umbrella of the scientific method. This paper first discusses the limitations of these evaluations. Second, it describes learning and teaching as a computational process. Finally, it proposes the use of principles of Information Theory as the foundation for the design of modern educational methodologies.**

***Index Terms*—education, methodologies, learning and teaching, information theory, computation and cognition**

I. Introduction

There is a marked interest in modern society for the developments, discoveries and innovations in the area of education. This is particularly noticeable in primary and secondary education. Regular reports in the news media create and maintain the interest of society in these discoveries and innovations. Parents, teachers, school administrators, students, and citizens in general, are periodically presented by the news media with exciting news in the area of education. These new ideas, procedures and paradigms come generally from the academic world. In the last years, some of these ideas are experiencing a successful reception in school systems. They include theories such as motivation teaching and learning, multiple intelligences, gaming in teaching, project-based learning, flipping the classroom, or the makerspace movement [1]-[17].

But it is a common occurrence that the promising futures advocated by these innovations rapidly fade into obscurity. In fact, the proliferation of these paradigms is due to the fact that new paradigms substitute others that have proved to be inefficient. The promise of project-based learning, once it has disappeared, it is substituted by the promises of flipping the classroom, or the makerspace movement.

This paper, first, analyzes why the researched-based studies of these educational initiatives often fail to predict accurately the results in the classroom.

Second, it describes the processes of teaching and learning as having a fundamentally computational nature. Unlike other systems in the human body, such as the circulatory, respiratory, or digestive systems, the nervous system operates under very different principles. The former systems manipulate atoms and molecules, the later operates bits. For this fundamental reason, it requires its own research paradigm.

Finally, this paper proposes the use of principles of Information Theory as a platform for the study of the cognitive processes in teaching and learning, and for the development of modern educational methodologies.

II. The Role of the Scientific Method in Computation

The scientific method is one of the greatest achievements in human history. It has changed the evolution of humanity in the last three centuries. But it is not the solution to all problems. It has its capabilities, but also its limitations [18]-[20]. It is, for the moment, the best and only solution for the study of complex systems for which their nature is not yet completely understood. Pharmacology and immunology are two examples of this. Other areas, however, such as computation, are ruled by sets of simple rules.

Research in the computational model of the brain, from very small animals, such as the c-elegans, to the human

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brain, it is opening the doors to the application of computational theories to the study of animal computational systems [21]-[26].

A. The Need for Replication in Research

The opening of new avenues in research, such as the use of computational techniques in the study of how the mind learns, it is not the complete solution to the current problems. For those cases where it is appropriate the use of the statistically based research method, it is important to address the problem of reproducibility [27]-[30]. Often, new teaching methodologies are presented to the school community with small samples of tested research. It is the intrinsic appeal of the new methods, such as flipping the classroom, or multiple intelligences, and not the demonstrated reproducibility of their results that attracts new adopters. An important cause in this lack of reproducibility is the difficulty to compare experiments, since cognitive processes are only abstractly defined. For example, it is important to have a formal definition of intelligence in order to perform quantitative experiments in multiple intelligences.

B. The Deterministic Nature of Computational Processes

The computation processes which are the object of teaching and learning in school are deterministic in nature. This is made evident by the fact that the main methods of evaluating school achievement use tests for which the answer to the question is already known. Probably the most widely used school test in the world is the PISA test [31], [32]. Every three years, over half a million students, of age 15, from over 80 countries take this test to evaluate their performance in language, science and mathematics.

Fig. 1 shows one of the problems of the mathematics PISA test. This problem was selected randomly. The analysis of other problems of the PISA test, and similar tests, can be read in [33]-[35].

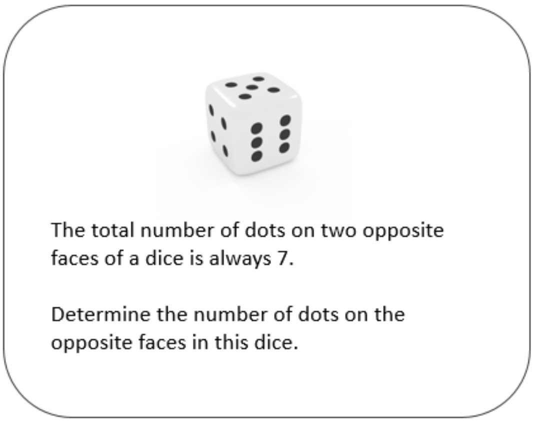

Figure 1. Example of a problem of the PISA test.

This example illustrates the determinism of the problem. The correct answer to the number of dots on the face opposite to the six dots, is one dot. Any other answer is incorrect. Fig. 2 represents the PISA scale of mathematics difficulty of this problem. The difficulty of this problem is 516 points. A total of 58% of students of the OECD countries answered correctly.

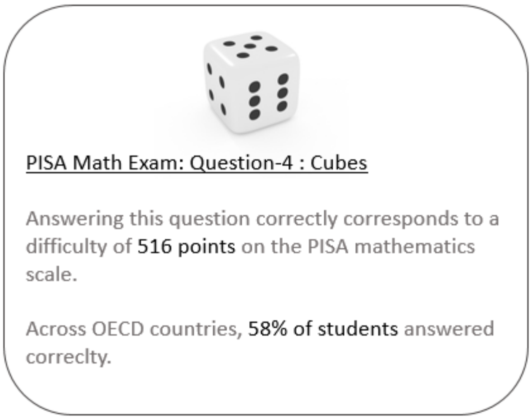

Figure 2. PISA mathematics scale of difficulty.

C. Revealing the Internal Nature of Cognitive Processes

According to the statistical requirements of the scientific method, the PISA mathematics scale of difficulty is valid since it was obtained with the results of over half a million students. However, it is evident that there is a great gap between the results of the scientific experiment and the expectations of performance of healthy, 15 year old students, with over nine years of schooling.

What are the conclusions to be derived from this experiment? Is it reasonable to deduce that 42% of the world students lack the cognitive capability to solve this problem? Is it reasonable to deduce that the educational systems of the world are incapable, after 9 years of schooling, to train 42% of their students to solve this problem? If the problem of the dice ranks with a difficulty of 516, is it reasonable to have total average performance of 500 points in the scale of PISA across OECD countries, with a standard deviation of 100 points, points?

These and other important educational and administrative questions cannot find appropriate answer in the PISA test because it does not reveal any information on three important areas:

- Problem complexity: is the problem intrinsically complex in its computation?
- Human cognitive capabilities: is the problem beyond the cognitive computational capabilities of many students?
- Human cognitive scope: is it possible for the human mind to solve problems that are computationally many orders of magnitude more complex that the problem of the dice?

It is this lack of information in these fundamental areas of cognition that requires the formulation of the test in terms of information theory: the computational complexity of a problem, and the human cognitive capabilities.

D. Confounding and Hiding Larger Problems

It it is apparent that the PISA test, and all the other standard tests, create scales of difficulty unrelated to the problems. This is because they evaluate the difficulty of a problem not in its intrinsically computational complexity, but rather in the percentage of students that solve it correctly.

Similarly, these tests rank the cognitive capabilities of students, and the countries that they represent, based on the percentage of questions they answer correctly. This also, is incorrect.

These tests reflect indeed the responses of the students, and therefore their performance and that of their school systems. But they confound other problems that are not related to the complexity of the problems or the cognitive capabilities of the students.

Today, the educational systems of the world, and the general research in new teaching methodologies focus on improving by changing the teaching and learning process without formally addressing these fundamental questions of computational complexity and cognitive capabilities.

III. Teaching and Learning as Computational Processes

The Raven Advanced Progressive Matrices Test is considered as the intelligence test with greatest correlation to the general cognitive abilities [36]-[39]. This characteristic explains the centrality of this test when assessing intelligence. It consists of 36 questions with increasing complexity. A detailed analysis of these questions shows that they are designed as simple combinations of five logic rules: Constant in a row, Quantitative pairwise progression, Addition/subtraction, Distribution of three values, and Distribution of two values [37]. The first questions of the test include only a few tokens of the simple rules. For example, question 1 includes only two tokens, corresponding to the constant and pairwise rules. The most difficult question, question 36, includes 5 tokens of rules, including Distribution of two values.

A. Teaching and Information Theory

The Raven test is a prime example of how Information Theory [40], [41] can systematically be used in evaluating the complexity of a problem and the cognitive capability of students. Each question on the test has an intrinsic level of difficulty which is the determined by the number and type of the token rules included.

Assessing students with the Raven test provides a detailed map of the types and number of rules they are able to decode.

Similarly, in primary and secondary education, all questions appearing on tests, especially those appearing on multiple-choice tests, can be described in terms of data and rules to be applied to the data.

For example, all quantitative problems in the areas of mathematics and science in primary and secondary education respond to a, common, three-step, simple process of resolution [42]. Therefore, if all these problems respond to the same computational structure, the structure itself needs to be part of the learning process. Therefore, the study of the taxonomy of computational rules in science and mathematics needs to be a fundamental part of education.

B. Formalizing Teaching in Terms of Information Theory

The process to formalize teaching and learning in terms of Information theory begins by describing each problem in computational terms. This formal description is called the Minimal Set or Ontology [43]. The Minimal Set includes all the data, but only the necessary data, and all the rules, but only the necessary rules involved in processing the data. Experiments show that making the Minimal Set explicit, and focusing the teaching process in the study of the Minimal Set changes substantially the performance of students [35].

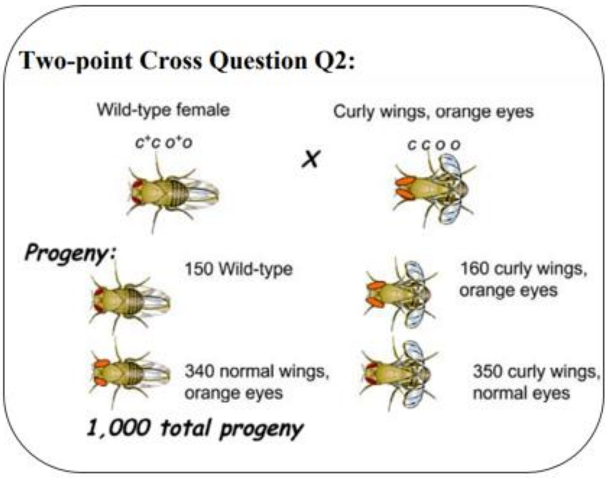

Figure 3. Minimal Set in a Biology Problem.
(image from: https://science.sciencemag.org/content/sci/suppl/2008/12/31/323.5910.122.DC1/Smith1165919.SOM.pdf)

Fig. 3 shows a problem in a Biology test [44] where the question is: *"What is the recombination frequency between curly and orange?"* with the following choices for the answer: A)0.16; B) 0.31; C) 0.49; D) 0.50; E) 0.69.

The two-point cross question is typical in biology exams. A two-point testcross is done to determine the recombinant frequency between 2 linked genes (in this problem the genes for eyes and wings of the fly.)

The Minimal Set of this type of problem is simple: of the four values obtained in the test, we discard the two larger values. The result is obtained by adding the two smaller values. In this case 150 plus 160 is 310. With 1000 total progeny, that leads to answer B) 0.31.

The computational complexity of this Minimal Set is very low. The identification of the relevant data is simple: select the two smallest values. The processing of the data is simple as well: add these two small values, and normalize by dividing by the total number of samples.

At this point, it is important to note the difference between competence and comprehension. To be competent in solving correctly this problem does not guarantee comprehension. Comprehension requires to know the biological processes involved and why the Minimal set requires adding the two smallest values. But the question of the test only evaluates competence. To evaluate comprehension a different set of questions is required. Comprehensive tests need to address both competence and comprehension.

It is also clear that lack of competence implies lack of comprehension. The fact that qualified students are unable to solve problem such as this, with very simple Minimal Sets, indicates that the teaching methodologies fail to teach these Minimal Sets.

C. Study of Native Human Cognition Capabilities

Through evolutionary time, the human brain has developed a large set of cognitive capabilities. These include image recognition, motion control, language, and many more. These capabilities are layered hierarchically. Low level computations are used by higher level processes. For example, the optical recognition of lines provides information that helps us recognize letters, and then words and full paragraphs. Also, processes involved in face recognition use resources shared by other optical processes such as text recognition.

Since reading is a late arrival to the tasks in human live (only a few thousand years), it is evident that we have adapted old cognitive processes in the resolution of new tasks. We call this model of adapted computing Virtual Machines [45]. A Virtual Machine is an existing cognitive process that has been adapted to solve a similar buy new task. For example, a line recognition process can be adapted to recognize symbols, such as letters (of varied alphabets), digits, mathematical operators, etc.

A formal exploration of the human cognition capabilities is essential in the design of a modern educational system. If, for example, the human mind does not have existing primitives for the implementation of multi-digit arithmetic [46] it would be ill advised to emphasize mental arithmetic in detriment of other higher cognitive tasks such as classification or pattern recognition.

The study of the cognitive capabilities of humans and their adaptation to the resolution to modern problems is a field of research generally unexplored, and with great dividends to offer.

D. Design of Cognitive Techniques Adapted to the Human Mind

In this final section we illustrate some concepts of Virtual Machines and their application to teaching and learning with a simple example designed for young children.

Some of the obvious sets of cognitive capabilities of humans include those related to language. Children, from very early ages, are able to understand, memorize and repeat simple stories. Also, they are able to identify protagonists, conflicts, narratives, secrets, goals and strategies.

The story includes a good Queen that wants to invite her friends to her birthday party. For that, she issues a secret number, a password, for those invited to the party.

Because she wants to prevent her enemies from accessing the secret password, she devises a scheme that only her friends know.

She will send her friends bags with four sticks of various lengths. In order to obtain the number of the passwords, her friends will select the two smallest sticks in the bag. When connected, the total length represents the secret number.

The purpose of the two larger sticks in the bag is to confuse her enemies in case they steal one of the bags.

When asked a young child to repeat the story, she will be able to do it with great detail. It will recognize the role of the Queen, her friends, her enemies, the party, the bag, the sticks and the secret password. This knowledge represents her comprehension of the problem. The child will also be able to open the bag with the four sticks, discard the two larger ones (for very obvious reasons) and connect them to calculate the secret number. According with the four sticks in Fig. 4, the two smallest sticks connected produce the secret number 3.

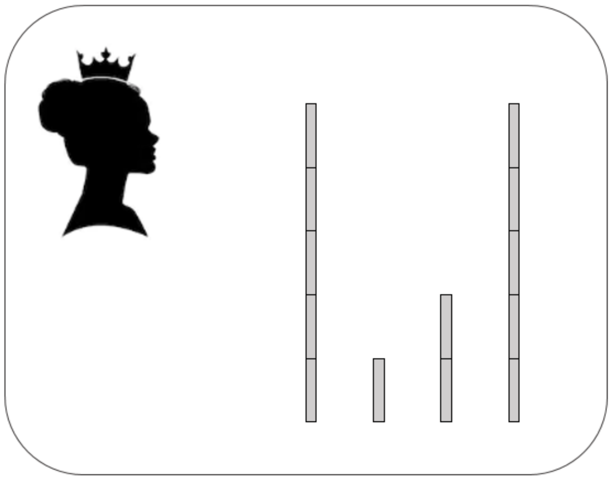

Figure 4. A Virtual Machine for the Two-Point Crossing Problem.

The Minimal Sets of the story of the Queen and the biology problem of the Two-Point Crossing illustrated in Fig. 3 are identical. These two problems are isomorph; they share the same Minimal Set [33]. The data sets in both cases, and the relationship with the solution of the problem are identical. A computing system implementing this Virtual Machine is capable of solving both problems.

This simple example of two apparently different problems, let's call them A and B, illustrates the need to research teaching and learning with computational tools. How do we answer these questions: Is A computationally more complex than B? Are the cognitive capabilities of students solving problems A and B different? Are the cognitive capabilities of student able to solve problems that are more complex than A and B?

Because the answers to these questions are different if we use Information Theory or simple statistics of correct responses, it becomes evident the need to adopt formal computational methodologies in the design of modern educational methodologies.

IV. Conclusion

Current educational systems are closely linked to the national and international testing systems that are used to evaluate them. In general, the complexity of the problems and the cognitive capabilities of the students are measured using traditional scientific-based methods of testing using the probability of correctly answering a question.

Information Theory provides the tools to develop new methods of teaching and learning, and new methods of evaluation. These methods of evaluation directly measure the computational complexity of the problems and the cognitive capabilities of students.

Concepts such Minimal Sets, Virtual Machines, and Isomorph problems illustrate the use of Information Theory in education.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

JC, X and MA conducted the research; JC and X wrote the paper; JC, X and MA participated in the Design of Virtual Machines; JC and MA participated to Identify Cognitive Primitives; JC and X participated to Develop the Model Software; all authors had approved the final version.

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