A cognitive approach to the museography of an interactive science museum: a worked example

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Abstract. Exhibits in interactive science museums (science centers) achieve their learning objectives as the interaction of visitors produces the inferences that are expected. We present here a methodology to assess communicational effectiveness of interactive exhibits. The methodology is developed by following Vergnaud’s conceptual fields theory and permits us to determine the cognitive processes that exhibits demand from the visitors. We applied this methodology to a particular exhibit on electromagnetic induction at the Museo Interactivo Mirador (MIM), in Santiago, Chile. The necessary data were obtained from the audiovisually recorded visit of a group of secondary students, whose knowledge on the subject was previously analyzed and contrasted with their behavior during the visit.

Keywords: Informal learning, science centers, interactive exhibits, museography

1. Introduction
Evidence shows that interactive museums (science centers, in Anglo-Saxon countries) are an important resource for complementing formal education in science. A global survey conducted in 2013 by the Association of Scientific and Technological Centers (ASTC) shows that no less than 17% of visitors come from scheduled school visits [1]. This number is larger in Chile, where the Mirador Interactive Museum (MIM) reports that school visits account for a third of the
total [2]. Evidence also demonstrates that in general terms most informal learning in science topics occurs in science museums [3, 4]. This highlights the importance of research in the area of informal education, particularly in the effectiveness of interactive exhibits and museography of science centers to produce the expected learning [5]–[10].

The design of interactive exhibits with the purpose of producing learning of ideas and concepts only through the visitors’ autonomous interaction poses a significant challenge [11]. Without the orientation or sistematicity provided by a formal environment, visitors may interpret exhibits differently than expected. In addition, the visitor’s prior knowledge can only be vaguely assumed and may exist at a wide variety of levels. In order to get visitors to infer the concepts and relationships relevant to the exhibits’ goals, it is crucial to ensure the communicational effectiveness of the exhibits and the entire museography. In prior studies regarding this topic, we find some approaches that have been used to study effective communication for learning in an informal environment [12]–[15].

When the visitors’ experience results in an increase in their knowledge, regardless of the level of that knowledge, it is an outcome of the cognitive processes they develop when engaging with the interactive exhibits. Consequently, every museological strategy should consider these processes. However, previous studies regarding these subjects are scarce and most do not incorporate a cognitive approach [16, 17]. In fact, exhibit design is primarily guided by intuition and classroom/laboratory experience or based on certain technical guidance that is learned when exhibit developers share their experiences [18, 19]. Notwithstanding, if the objective is to enhance visitors’ learning, exhibit design could greatly benefit from a better understanding of how cognitive processes are developed.

In this article, we address the communicational ability of exhibits to transmit their contents by introducing a methodology that is based on determining the cognitive processes that are displayed. This report is based on an investigation that we conducted in the electromagnetism area of the Mirador Interactive Museum (MIM) in Santiago, Chile. To date, no systematic studies have been developed at MIM regarding the impact of a visit on the visitors’ knowledge and understanding of the corresponding scientific concepts. We observed a group of 15 high school students during their visit to the Electromagnetism area of the museum. The main goal of our research was to examine how students’ thinking evolves by analyzing the cognitive processes that they developed as a result of their interaction with the different exhibits on electromagnetism. Two full reports on those primary goals will be published elsewhere [20, 21]. However, a necessary and complementary byproduct of the prior study is the observation of elements to ensure the exhibits achieve their purposes. Another study with a similar purpose was published [22]; however, that analysis did not include cognitive processes.

The communicational abilities of exhibits are also strongly limited by visitors’ prior knowledge. Exhibits are effective if the pertinent concepts-in-action and theorems-in action are recognized by visitors. Therefore, an in-depth analysis of the importance of prior knowledge and experiences must precede the museography and exhibit design. In our approach we focus
on cognitive processes underlying visitors’ interaction with exhibits. Following Vergnaud, the cornerstone of cognition is conceptualization, in whose construction participate implicit ideas and categories which Vergnaud describes under the concepts of concepts-in-action and theorems-in-action: a close relationship between reality—situations—and its representation—operational invariants and linguistic-symbolic codes. In order to elucidate the cognitive processes involved, we present a methodology based on the identification of the operational invariants put in action by the visitor and, from them, we derive his/her evolving thinking as a result of experience. As a corollary, we derive a methodology useful for designing exhibits and museography.

2. Theoretical foundations

Learning is a transformational process, as purported by Piaget, who highlighted the adaptive function of cognition [23, 24]. Piaget defined the building blocks of cognition as schemas, or to clarify, “a cohesive, repeatable action sequence possessing component actions that are tightly interconnected and governed by a core meaning” ([23], p. 7). In alignment with the same constructivist approach, Vygostky emphasizes the importance of social and cultural elements in learning [25, 26]. Vygostky introduces the concept of the Zone of Proximal Development (ZPD) as “the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers” (in [25], p. 86). Vygotsky has inspired designers of interactive experiences because the concept of the ZPD suggests that designers provide “scaffolding” to enable learners to participate in a more complex discourse than they could experience on their own [27].

A visitor’s experience when interacting with an exhibit cannot be described thoroughly in terms of the intended ultimate goal. In general, one exhibit poses multiple problems to visitors. Then, a variety of schemas are necessary for visitors to display. A more elaborate theory is needed to analyze visitor-exhibit interactions in a science museum. These interactions are not solely a psychological issue but also epistemological. The contents of the subject to be learned through the interaction with an exhibit play a fundamental role. G. Vergnaud, a psychologist and Piaget’s disciple, devoted much of his work to understanding how mathematics and science are learned [28, 29]. In Vergnaud’s theory of conceptual fields, he recognizes that cognition must be referred to the specific content and complexities related to the topic that is being learned [30–32]). He also agrees with Vygotsky that “constructivism concerns not only the development of individuals, but also of culture, especially of scientific culture” (free translation of the original text in [33]).

For Vergnaud [28, 29], the cornerstone of cognition is conceptualization, which refers to “the identification of objects, of their properties and relationships” [34]. Vergnaud asserts that our thinking includes implicit ideas and categories by referring to the concept of knowledge-in-action or the operational invariant. These concepts are the building blocks of conceptualization and have a close relationship between reality (situations) and representation (operational invariants...
and linguistic-symbolic representations). In Vergnaud’s theory of conceptual fields, a different non-classical perspective is assumed and it is established that a concept cannot be described without a reference to a specific situation (we follow hereafter Ref. [35]). Therefore, the relevance of situations is important in a psychological context through the difficulties that students must manage. It is also epistemologically relevant because the problem that situations involve is a source of knowledge. In this manner, Vergnaud developed a concept C as the triplet $C = (S, I, R)$ where $S$, the reference of the concept, is the set of situations that ensures that the concept is significant and useful, $I$ represents the meaning of the concept and is the set of operational invariants that assign the meaning and contents to make the concept operate, and $R$ represents the signifier of the concept and is the set of linguistic and symbolic representations used to display the invariants and situations. To study the development of a concept during the learning process or to analyze how it is used, it is necessary to consider the triplet as a whole.

Because situations give meaning to a concept, a situation makes sense because of the schemas. A schema is the invariant organization of behavior for a certain class of situations. Vergnaud developed a different conception of schema than Piaget and established a subject-in-situation relationship rather than using the subject-object interaction of Piaget. The primary components of a schema are the operational invariants, which represent the knowledge contained in the schemes. These invariants constitute the implicit or explicit basis for obtaining the relevant information for the objective to be achieved and to develop appropriate standards for action. The operational invariants may be referred to either as concepts-in-action, which are concepts that may or may not be relevant, or theorems-in-action, which are propositions related to concepts that may be either true or false. Theorems-in-action involve concepts-in-action. The concepts-in-action relate to each other through theorems-in-action.

From the theoretical perspective, the concept of schema provides a link between behavior and representation. The relationship between situations and schemas is the primary source of representation and therefore conceptualization. Conversely, operational invariants ensure the essential articulation between theory and practice because perception, search and the selection of information are based entirely on the system of concepts-in-action that is available to an individual (objects, attributes, relationships, and conditions) and the theorems-in-action that underlie his/her behavior.

For every situation, the data to be analyzed and the inferences that result depend on theorems-in-action and the identification of different types of relevant elements. Most concepts and theorems-in-action remain entirely implicit, but they can also become explicit. From this perspective, concepts-in-action and action-theorems can progressively become true scientific concepts and theorems. The goal to be achieved by a set of exhibits regarding a specific topic is to help the visitor to make the corresponding concepts and theorems explicit and scientifically accepted from the implicit knowledge the visitor displays. Although the entire process can take longer than one visit to the museum, the goal for every museum experience is that there is sufficient correlation between the visitor’s prior knowledge, displayed as concepts and theorems-
in action, and the interactions that are made available by the exhibit.

Vergnaud’s approach provides us with adequate tools to analyze visitor-exhibit interactions. First, the various ways that an exhibit can be manipulated must be considered. They include different situations where students can display their knowledge-in-action (operational invariants). In this manner, prior knowledge is more pertinent to the situation and can be revealed as implicit concepts and relationships. Because we focus on determining the operational invariants and their representations, we are able to examine whether the expected inferences are possible.

Learning is based on prior knowledge. To reliably evaluate the success of the museography and exhibits, the theoretical framework of our methodology focuses on clarifying the prior knowledge of visitors in regard to the specific topic of the exhibits. The goal is to determine how the problems that are posed to the visitor by the exhibits fit that prior knowledge.

3. The conceptual field
Vergnaud purported that a conceptual field is a set of problems and situations, and the solution of those problems requires concepts, procedures and representations of different but closely related types [28]. In the research we partially report here, we consider museum exhibits on electromagnetism. An example we will develop below is focused on electromagnetic induction. A variety of concepts are involved, from electric charges to currents, from currents to magnetism, etc. A thorough review of the concepts that are involved in the exhibits and the museography of the area is necessary to approach the complexity of the topic. In particular, regarding the subject of electromagnetic induction, almost every concept in electromagnetism must be considered.

Among other general physics concepts, magnetic field, electric current, conductivity, magnetic force, magnetization, voltage, energy are relevant in the subject fo electromagnetic induction. In addition, more elaborate concepts that are derived from electromagnetic theory, such as magnetic flux and electromotive force (emf), could appear. But also mathematical concepts such as the rate of change in time and vectors are essential. Experiences that demonstrate how a current is produced, when a material becomes magnetized and attracted by a magnet, or how an electromagnet works could be crucial to understand the concepts involved in electromagnetic induction phenomena.

Historically, electromagnetic induction is an outcome of nineteenth-century science which, along with deep theoretical consequences, has been the scientific basic for electric power production technologies. The phenomenon is based on the generation of an electric current that is caused by the action of a time-varying magnetic field over a conductor. This variable magnetic field can be generated in various manners that include the relative motion of a magnetic field source (for example, a magnet) and a conductor. The conductor is typically a closed electrical circuit where the current is induced (induced electrical current). The effect is not perceptible by human senses but can be detected using instruments, such as an ammeter. The exposure to a phenomenon that cannot be seen “by naked eye” is clearly a challenge for exhibit designers.
The standard instruments that are used to detect the effect must also be understood through a complementary conceptualization of a related subject.

Classical electromagnetism is widely understood through Maxwell’s theory, and its concepts and relationships can be described accurately through mathematical relationships. However, museography regarding this topic cannot be based on the mathematical Maxwell’s theory if it is addressed to general public, or even secondary school students. Instead, approaches recurring to partial descriptions, such as Faraday’s Law, could be in principle more accessible. However, as Zuza et al. stated, “interpreting Faraday’s law has been a challenge in the physics community and most students experience learning difficulties when attempting to understand electromagnetic induction phenomena and Faraday’s law” [36]. Therefore, it becomes apparent that the topic of electromagnetism poses a significant challenge for museographers and exhibit designers.

Following Vergnaud, conceptualization is achieved through the situations the learner faces. These situations are provided by the exhibit, in a variety that depends on the exhibit’s design. In the following section, we present an interesting example of an exhibit on electromagnetic induction. We also describe the different, possible situations this exhibit could pose to the visitor.

4. An exhibit on electromagnetic induction phenomena
In this section, we illustrate with an example the methodology we exposed above. ”The Electromagnetic Pendulum” is an exhibit of MIM’s electromagnetism area, which we describe in detail below.

This exhibit features a metallic swinging bar, that includes a permanent magnet in its moving end, that oscillates when released from a higher position. Under the trajectory of this pendulum, a cart that carries a plate in a vertical position and is composed of various materials can move on a semicircular track. The horseshoe-shaped magnet produces a magnetic field that is perpendicular to the plane of oscillation, and when the pendulum meets the cart, the plate passes through the gap in the magnet. A photograph of the exhibit is provided in Fig. 1, with details about the cart where the plates are mounted. Depending on the plate material and geometry, there will be an interaction between the magnet and the plate when both are in relative motion.

Six plates are available: three copper plates (one full solid, one with a circular hole in its center, and one comb-shaped with slits), one solid aluminum plate, one solid acrylic plate, and one acrylic plate with a solenoid embedded and including two LEDs in the circuit of the solenoid). Fig. 2 provides a photograph of the plates.

None of the plates are ferromagnetic, and the plates are only attracted by the magnet because of the electrical current that is induced by the magnet. Once the cart is placed with the plate in the bottom of the rail at rest and the pendulum swings, a force can be produced between the plate and the magnet of the pendulum. This force is due to the action of the magnetic field on the electric current that is induced on the plate. This process causes the cart to move by the
rail, following the pendulum.

![Image of the exhibit "Electromagnetic Pendulum".](image1)

Figure 1: The exhibit “Electromagnetic Pendulum”. In the lower right corner of the figure a detail of the cart where the plates are mounted is shown.

![Image of the exhibit plates.](image2)

Figure 2: The plates of the exhibit. The plates at the top of the figure are solid and constructed of copper, aluminum and acrylic. At the bottom, the first two plates are constructed of copper. The latter has a solenoid embedded with a pair of LEDs on its upper edge (not seen in the picture), which are connected to the solenoid.
The goal of the exhibit is to ensure that the visitor notices the distinctive behavior of the cart for the various mounted plates and to deduce certain hypotheses to explain what is observed. Although the exhibition was designed for autonomous operation by the visitor, for safety reasons, the MIM has provided a guide for conducting the experience.

5. The exhibit as a set of situations
Every interactive exhibit poses a problem to visitors, requiring actions and then conceptualization. The exhibit becomes a situation that encourages the development of concepts. Therefore, it is necessary to accurately describe the exhibition as a situation and, in cognitive terms, beyond the specific aspects that arise from a scientific perspective or the exhibit instructions. In alignment with Vergnaud, it is not sufficient to conceive situations solely in terms of the operations that are demanded of visitors (sensorimotor, cognitive) because these are concatenated with more generic thinking [28]. To better analyze the museum exhibits, we define three fundamental elements to describe situations: objects, variables and unknowns [21].

Objects include the interacting elements and building blocks that are included in the situations. Objects are characterized by consistent properties that are independent from the context. In the case analyzed in this study, objects include magnets, solenoids, conductors, circuits, ammeters, and voltmeters. A magnet is recognized according to the concept of magnetism, and a circuit is related to the concept of electric current.

Variables are descriptions that relate objects to their mutual interactions and define the dynamic context of the problem. In this study, the magnets and conductors are in relative motion, and LED bulbs light up when an electric current is induced. In addition, variables define the degree of complexity; using cognitive processing to solve a problem depends on dynamics that are exposed by those variables. An example of this process is when electromagnetic induction results from a time-varying magnetic field that acts on a conductive material. This process poses various levels of difficulty for conceptualization if the variation of the magnetic field is produced by a magnet’s movement relative to the conductor or when an AC voltage source powers a solenoid.

Unknowns define the framework for responding to the problem and correspond to the domain of searching for the visitor’s explanations. Unknowns can be quantitative or qualitative. For this study, an unknown could be, for example, why the ammeter detects an electrical current in a closed circuit when a magnet is moving near it.

The three components described above permit us to classify situations in different domains that are specific to the contents of the exhibits and also to account for the different degrees of freedom that the situations represent for the visitors. For example, because a magnetic field can be generated by a magnet as a solenoid with an electric current (electromagnet), the respective effect on each object will have a different epistemological characteristic if the field comes from one source or another. To clarify, the concept of magnetic field cannot be considered devoid of the object that constitutes its source. Although in scientific terms the source of the magnetic
field is indistinguishable in the phenomenon of induction, this will not be the case for every visitor.

We use this methodology to characterize the exhibit we described previously. The various possible situations that could result from operating this exhibit are described in Fig. 3.

| Objects | Pendulum, magnet, cart, plates (solid copper, copper with hole, copper with slits, solid aluminum, solid acrylic, and solenoid with LEDs), and a semicircular rail for the cart. |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Variables | The pendulum with the magnet oscillates; the cart with the plate (of copper, aluminum, acrylic, etc.) moves along the track; the cart is initially located at the lower section of the track; the magnet and the plate interact; the pendulum and the cart oscillate synchronously; the cart with the aluminum plate moves while interacting with the magnet of the pendulum; the pendulum oscillates and the LEDs light up; the cart is released from the higher section of the track; etc. |
| Unknowns | Why does the car move when the pendulum oscillates although they are not in contact? Why does the cart move sometimes and other times it does not move? Why are the aluminum or copper plates attracted to the magnet although they do not become magnetized? Why does the plate with a solenoid not move when the pendulum swings, but rather, the LEDs light up? Etc. |

Figure 3: The situations the exhibit “Electromagnetic Pendulum” provides are composed of the objects, variables and unknowns listed in the table.

6. Discussion

The exhibit described in this report was designed to provide a number of situations that permit, in principle, the conceptualization of electromagnetic induction phenomena. The primary concepts involved include magnetic field, relative motion, magnetization properties of materials, conductivity, induced electric current, magnetic force, and energy transfer. Depending on the specific situation (objects, variables, unknowns), it is expected that visitors put into action certain related concepts and manage the corresponding theorems-in-action, that is, the corresponding relationships between the concepts.

This article describes various situations that the exhibit “Electromagnetic Pendulum” provides for visitors. Our analysis allows us to determine if the concepts and relationships
the students use allow them to explain what they observe and ultimately complement what they know about electromagnetic induction. In this study we applied a methodology to evaluate the exhibit’s effectiveness.

An examination of the dialogues that were held between the students indicates the operational invariants, that is, the concepts-in-action and theorems-in-action for each situation. Generally, we observed that students were influenced by the exhibit to deduce relevant features that characterize electromagnetic induction. Two primary conclusions that the students inferred are that non-ferromagnetic metals, such as aluminum and copper plates, are attracted by the magnet because of their conductive nature and the induced currents in those metallic plates are due to the relative motion between the magnet and the cart with the plate. Although these two conclusions, which appear as strong signals of what is occurring, are not necessarily understood as they are described in formal electromagnetic theory.

The exhibit was designed to establish certain crucial facts about electromagnetic induction. One fact is not to use ferromagnetic metals to avoid the well-known magnet-iron interaction. Another fact involves a coil circuit model for the induced current inside the metal. In this model, a copper plate with a large central hole provides an approach that is similar to the model. Furthermore, this plate is similar to the solenoid, which was previously described (see Fig. 2). In addition, the slotted plate provides a situation that emphasizes the coil model for induced current, since for that plate, no significant interaction is observed when the magnet moves relative to the cart. In spite of all that, It is remarkable that the students in this study were unable to infer any conclusion that reliably supported the model. The mechanism that was proposed by students to explain the absence of a force between the magnet and the slotted plate or even why the LEDs in the solenoid light up differed from the intentions of the exhibit designers. Additional exhibits exploring these aspects could be useful if the model, which is important to be able to understand the phenomenon occurring in the solenoid, is a relevant issue.

The exhibit is effective in revealing certain primary aspects of the phenomenon, such as the relevance of the conductive nature of the material that interacts with the magnet and the need for relative motion between the conducting plate and the magnet (incorporated in the pendulum). These are important aspects to understand what produces the basic phenomenon; however, it is not enough to develop adequate explanations and infer other forms to produce the phenomenon. The ultimate reasons of why the plates are attracted by the magnet and why the magnetic force affects the current remain hidden. This latter issue is important if we pursue a simple explanation of what the visitors observe in the exhibit operation beyond the physics of electromagnetic induction. The exhibit is not successful in this aspect, and the reasons for this lack of success may be found in other elements of the entire museography. By examining the other exhibits in the area, we do not find an exhibit showing explicitly the action of a magnetic field on an electric current, in the same terms of the force that acts on a permanent magnet.

Conversely, to infer a modern scientific explanation of the induction phenomenon, it is
essential to understand the concept of a varying magnetic field. Although the mechanistic approach that results from highlighting the relative motion between the parts could be considered relevant, the success of Maxwell’s electromagnetic theory is derived from focusing on fields. This must not be considered an advanced topic, because a comprehensive understanding of this concept is the cornerstone of modern physics. In principle, the exhibit provides examples of this and allows a comparison of the results that are obtained by first oscillating the pendulum or initiating the experience by releasing the cart from its highest position in the track with the pendulum at rest. Why does this exhibit not work in the aspect we discuss? One specific exhibit cannot provide all the elements. It is a matter that concerns the entire museography. Unless the guide helped visitors understand that from the perspective of the cart, we have a varying magnetic field (in both situations that are mentioned above), it is unlikely for visitors to infer this aspect of the exhibit.

Two primary questions arise here. One question is whether the students have learned more about electromagnetic induction because of the visit to the museum, which is a matter for a different report [21]. The other question is whether the visitors that we considered in this research are representative of the public that visits the museum. The answer to this question is no. The students are part of a privileged group in the sense that they have previously studied the subject as a part of their formal education. However, their experiences in the museum are representative of how effective the exhibit is in conveying ideas and facts to produce scientific inferences regarding electromagnetic induction. The discussion above demonstrates that the exhibit partially accomplishes this task. However, we believe that this is a matter related to the entire museography, and we do not place any blame on one exhibit.

7. Conclusions

The issue we analyze in this article is how an interactive exhibits can lead visitors to infer the relationships that are involved in its contents. These inferences refer to the understanding of facts and ideas through the organization, comparison and interpretation based on the visitors’ prior knowledge. We developed a methodology that permits us to determine the cognitive processes through the identification of the operational invariants that are put in action during the experience. We are aware that we cannot completely describe the relevant cognitive operations because the invariants are possible representations of those processes. However, the determination of the operational invariants provides more information regarding the most basic elements of visitors’ thoughts that are related to what we seek to understand, or rather, the evolution of the visitor’s thinking as a result of the experience.

A proper conceptualization requires a variety of situations, and this affects the design of the museography. In informal contexts, distributed learning becomes relevant, particularly in relation to educational communication [37]. In regard to the design of an exhibition on electromagnetic induction, a set of exhibits will provide different situations that allow visitors to experience and learn all the concepts that are needed for the expected inferences. The exhibit
we discuss here provides, in principle, a diversity of situations. However, the learning process varies for different people. Museum exhibition planning provides the possibility of considering this issue by introducing parallel experiences for visitors’ interactions.

A practical corollary is relevant here in relation to the objective of complementing the methodologies involved in the design of interactive exhibits. The method of analysis we utilized in this article is suitable for use in the conceptual design of both museography and exhibits. Fig. 4 illustrates the steps.

![Diagram of methodology for conceptual design of museography and interactive exhibits]

**Figure 4:** Scheme of a methodology for the conceptual design of museography and interactive exhibits.

The primary goal of a science museum is to inform the public of the phenomena, concepts, methods and ideas of science. In this manner, learning goals must be understood according to different levels. Although this study focused on examining the understanding of concepts and relationships at a level compared to what is expected in formal education, we consider that the methodology and conclusions are also valid for lower levels of learning. In addition, we emphasize that interactive science museums have become an important resource for science teachers, whose expectations certainly highlight the interactive experiences as an important complement to formal classes. We believe that the conclusions of this article could lead to
improvements that would not be difficult to achieve in the design of museography and exhibits.

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