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Applying Piaget's Equilibration Theory to Understand Conceptual Learning in Engineering Education*

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Conceptual learning bridges the novice-expert gap, enabling transfer of structured knowledge to develop skills for new situations in engineering for both technical and humanistic domains. Though substantial information about expertise development is already available to support teaching in engineering, it is directed largely ascertaining characteristics or status of novices and experts and lacks emphasis on cognitive mechanisms responsible for bridging or transposing from one behavior status to another. Thus, this article explores the cognitive mechanisms stimulating engineering students' conceptual learning under Piaget's equilibration theory, which addresses the main problem of knowledge construction. In order to discuss Piaget's equilibration theory usefulness for the conceptual learning process, we present a case study where we tracked the progress of 18 Brazilian engineering students enrolled in 'Introduction to Engineering', over two semesters. In this humanistically-oriented course, freshmen are challenged to theoretically connect Science, Art, Technology, and Engineering concepts in order to stimulate critical thinking skills. We gathered data through semi-structured interviews, applying Bardin's content analysis techniques. The discussion of the results provides an interesting view of the utility of Piaget's theory in engineering education in humanistically-oriented courses as an alternative to focusing on transformations in conceptual learning.

Keywords: genetic epistemology; equilibration theory; conceptual learning; engineering education; higher education

1. Introduction

Concepts are "elementary units of reason" [1, p. 455] that explain our world and influence our actions [2]. Conceptual learning bridges the novice-expert gap, enabling transfer of structured knowledge to develop skills for new situations [3, 4].

In engineering, critical thinking skills, more specifically, are very important features to achieve, because they are one of the building blocks of the competences that the engineering student shall acquire in order to respond to professional issues effectively [5–7]. Critical thinking skills are "metacognitive processes consisting of subskills (e.g. analysis, evaluation and inference) that, when used appropriately, increase the chances of producing a logical solution to a problem or a valid conclusion to an argument" [8, p. 48]. Their use implies an *intrinsic cognitive load* [9, 10] related to the situation's uncertainty and complexity (the number of variables involved; relations, interactions, and regulations among them). This is a common situation in engineering, requiring strong higher-order thinking ability [4, 6]. To stimulate such thinking, teachers should engage students in a deep approach to learning [11] to develop adequate understanding of and meaning-making around key concepts and principles (or *big ideas*) and devise a solution [3].

Streveler et al. [2] claim that research on conceptual learning among engineering students is scarce and that this scarcity characterizes a *technical domain*, involving misconceptions of key concepts such as force, heat, or electricity in circuits. Their claim extends to a *humanist domain* [12], integrating a liberal arts perspective [4], and to misconceptions of the connection between the 'big idea' of Engineering and the concepts of Science, Technology, Art, Law, Public Policy, Management, etc., which are essential to thinking critically and to understand complex interdisciplinary systems. According to Adams et al. [12, p. 66], the humanist domain "sees engineers not only as technologists, but also as social experts, managers, and businesspeople who recognize the social complexity of the world and markets they act upon and of the teams they belong to". Determining the connections between the concepts mentioned is challenging in terms of (high) intrinsic cognitive load, since understanding each concept requires deep understanding of its evolving idiosyncrasies based in the practices and reflections of researchers and practitioners. Using

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the Structure of Observed Learning Outcomes Taxonomy (SOLO) (see http://www.learningandteaching.info/learning/solo.htm; [11]) to qualitatively evaluate engineering learning situations in relation to those involving complex professional issues—by predicting major actions needed to reach an effective solution, such as 'explain', 'debate', 'relate', 'define', 'evaluate', 'reflect', 'create', 'analyze', 'compare', etc.—, it is reasonable to suppose that they are approximately equivalent in intrinsic cognitive load. Therefore, engaging engineering students in such activities is essential [6, 12].

Bransford, Brown, and Cocking [3] claimed that substantial information about expertise development was already available to support teaching. Though Litzinger et al. [4] agree, the information they mention seems much more about characteristics or status of novices and experts and less about cognitive mechanisms responsible for bridging or transposing from one behavior status to another. This statement holds for Redish and Smith's [13] article outlining some components of cognition (such as *activation*, *association*, *compilation*, and *control*) to assert the desirability of adopting a theoretical framework for student thinking and learning in support of teaching practices to foster it. Moreover, Streveler et al. [2, p. 290–291] raise questions like "how does conceptual knowledge evolve as a learner moves from novice toward expert performance?" and "what makes some concepts so difficult to learn and some misconceptions so difficult to repair?" Utilizing information about these cognitive mechanisms is important to clarify these questions and to help teachers comprehend what is occurring (cognitively) in their students while learning is taking place—thus supporting more effective interventions, especially when applying student-centered methodologies [14]. A possible approach to such achievements is the use of Piaget's *genetic epistemology* [15–17] and especially his *equilibration theory* [18–23], because they offer important insights about knowledge construction in early adulthood and beyond. The equilibration theory belongs to one of his major theoretical thrusts, namely, *constructivism*, which stood the test of time [24].

Piaget's great ambition was to formulate a general theory of how knowledge evolves in human beings—a theory of the *epistemological subject* [16, 17, 25–27]. Because he focused much effort on researching childhood in order to understand the essential cognitive mechanisms in this process of knowledge construction from neonatality to youth, the main contributions of his extensive work unfortunately still remain strictly associated in the scholarly imagination with child development [18, 19, 25]. This view is captured, for example, in the criticisms to his work usually related to the theoretical thrust of *stages* in cognitive development—ranging from methodological issues (such as sample size and participant features, the naturalistic strategy of inquiry adopted, the kind of tasks proposed etc.) to the expected ages that would characterize each stage [28]. On the other hand, constructivism has been supported by research [3, 24, 29] so far; besides, it has been used to design *active* methodologies for instruction and applied in engineering education [30–32]. If constructivism, proposed by Piaget, provides guidance to design instructional methodologies in Engineering Education, it is a justifiable reason to consider the cognitive mechanisms that Piaget theorized in order to better understand the knowledge construction in the student.

Thus, we aim to explore the cognitive mechanisms stimulating engineering students' conceptual learning from the standpoint of Piaget's genetic epistemology. The research questions adopted are: (a) How effectively does the subject function during the conceptual learning process for the humanist domain when applying critical thinking skills in a specific situation that presupposes a high intrinsic cognitive load, such as that existing in relation to complex professional issues? and (b) How do the cognitive mechanisms identified by Piaget's equilibration theory help explain this process in the engineering student?

To investigate these questions, we present a case study [33] tracking the progress of 18 freshmen volunteers in a textile engineering program at a university in southern Brazil, enrolled in the course 'Introduction to Engineering' during the first and second semesters of the 2014 school year. To stimulate conceptual learning in the *humanist domain*, we simulated a situation with high intrinsic cognitive load, approximately equivalent to that required to apply critical thinking skills to deal with complex professional issues—with the support of SOLO Taxonomy [11]. In it, students explain from a theoretical perspective the relations between Science, Art, Technology, and Engineering concepts; we designed this activity using the constructive alignment method, proposed by Biggs and Tang [11], to promote a deep approach to the learning process.

Applying a qualitative approach [33], we gathered data through three semi-structured interviews. Next, we applied the content analysis method [34, 35], more specifically the *categorical* technique, to *quantify* [36] the qualitative data, and the *enunciation* technique to track improvements in students' conceptual learning through their explanations [34]. We added the Wilcoxon signed-rank statistical test to support the *credibility* [34] of the results, and to help us more freely discuss them.

2. Knowledge construction in Piaget

Piaget [22, p. 7] centered his theory on the *equilibration process* once he came to see it as the main problem of knowledge construction, which would not proceed integrally "either from the unique experience of the objects or a preformed innate programming in the subject, but from successive constructions with constant elaborations of new structures". In this *equilibration process*, Piaget [15, 22] claimed, *regulations* were the cognitive mechanisms responsible for these constructions or changes in knowledge. These regulations consist of three general elements—*internal cognitive structures*, *assimilation*, and *accommodation*—and the features of the specific environment.

Internal cognitive structures are those (neurologically, physiologically) intrinsic to the body (system) [26]. Piaget [15, p. 16] conceptualized these dynamic structures in terms of *schemes*, or patterns presented in actions that are "transferable, generalized, or differentiable from one situation to another". *Assimilation* denotes the body's tendency to attract external content that is supported by its schemes, whereas *accommodation* denotes the body's tendency to adjust its schemes to the content at hand [37].

We associate cognition with higher-order thinking, but forget that the brain is part of a whole (structured) system called the 'body'—and, consequently, underestimate this system's role in the knowledge construction experience [26]. Though the brain is the home of thinking, the body is what *interacts* with/in the environment [1, 38]. Thus, just as homeostasis comprises a core set of innate organic mechanisms of regulation that the body maintains to guarantee its own integrity, the reflexes of the newborn (innate *schemes* such as 'sucking', 'touching' and 'looking') and the surrounding objects of knowledge comprise the very first set of cognitive mechanisms of regulation [22, 37].

Exercise of reflexes by repetition in occasional situations precedes the acquisition of elementary actions (or habits), leading to generalizing these actions, followed by the introduction of new, more structured actions [25, 37]. Thus, according to Piaget [37], the child initially constructs her knowledge about the world by practically interacting with it. This pattern of knowledge construction centered in practical actions, Piaget [23, 37] called *sensorimotor*. Although sensorimotor knowledge is especially crucial in the child's first years, it persists throughout life and becomes automated for most situations (allowing us to walk, identify objects, play sports, listen to music, type on the computer, play a musical instrument, drive a car, etc.) [22, 26, 37].

Sensorimotor regulations are the earliest source of knowledge construction, placed by Piaget [23] under the aegis of the *empirical abstraction* process (*empirique* in French), which relies on the manipulation of physical objects (their shapes, features, spacing, timing, causality, etc.) or on the material aspects of action itself (moving, grasping, walking, seeing, hearing, pulling, etc.). Empirical abstraction perpetuates the *permeation* of (practical) knowledge in the body—meaning there is not yet any meaning-making or deep understanding associated with it [23, 26].

Consider a young college student taking her very first driving class. She first acquaints herself with the panel buttons, the levers next to the steering wheel, the side and rearview mirrors, the pedals, etc. merely by looking at them (recognizing them vaguely from her parent's car), and then follows the instructor's directions, touching, pressing, pulling, pushing, and/or adjusting them. Then, following the instructor again, she starts the engine and puts the car in gear.

This is a good example[1] of a situation involving empirical abstraction. After considerable time practicing driving, the student is expected to acquire habits and broaden the earlier *schemes* applied (by combination, differentiation, etc.), and thus to learn to perform the activity of driving a car properly. According to Piaget's theory [15, 22, 23, 27], the several primary actions undertaken by the student in that specific situation would bring her solely practical knowledge, because they would allow her to know *how to drive the car* but not yet to *understand the car or its motion.*

According to Piaget [23], *empirical abstraction* gives a person the foundation to engage in conceptual knowledge construction, where representation—through imitation, language, images, intuition, perception etc.—increasingly plays a major role. The improvement and diversification of the earlier cognitive mechanisms of regulation by the *interaction* between the body and environment assumes two main, complementary new features for this new knowledge construction: the process of *taking-of-consciousness* (*réfléchissement*) [18, p. 257] and the process of *comprehension* (*réflexion*) [22, 23]. Piaget [23] said these regulations comprise the process of *reflective* (*réfléchissante*) *abstraction.*

The cognitive mechanism of taking-of-consciousness initiates a cycle of *internalization* involving meaning-making or deep understanding through representation [22, 23]. It supports the conceptualization of assimilated content, due to the necessity of construction at the conscious level [36, 40] of what earlier *permeated* the learner's thinking through

[1] Though we elaborated our examples for a didactic purpose here—thus extrapolating what Piaget himself researched—, they were based on evidences gathered in the literature that uses Piaget's constructivism in contexts beyond childhood [see 39–41].

practical knowledge [22, 23]. Piaget [27, p. 119] understood taking-of-consciousness to be "fragmentary and deforming". Therefore, the cognitive mechanism of comprehension closes a cycle in order to reorganize new content vis-à-vis previous knowledge (within internal cognitive structures) so as to change it (by additions, corrections, or differentiations) [22, 23].

The *reflective abstraction* process, with its mechanisms of *taking-of-consciousness* and *comprehension*, encompasses two different, both important, coexisting modalities: one that arises earlier to bridge *permeation* and *internalization*, called *pseudo-empirical abstraction* (or *pseudo-empirique*), and another that arises later to bridge *internalization* and *pure abstraction*, called *reflexive* (*réflexive*) *abstraction* [23]. *Pseudo-empirical abstraction* comprises the manipulation of physical objects' intrinsic features, but (and this is its main difference from empirical abstraction) the characteristics extracted from these manipulations are coordinated by the subject's actions [23]. Examples of these characteristics are ranks, counts, classifications, differentiations, commonalities, equivalences, and inferences [26, 43, 44]. In turn, in *reflexive abstraction*, physical objects' intrinsic features (or content) are gradually synthesized into general features/patterns/structures/extensions due to the manipulation of the characteristics of coordination inserted by the subject's actions [22, 23, 27].

Consider again the young college student referred to above. Now she is attending an introductory physics course and learning Newton's Laws. On her way to class, based what she has learned so far and exercises she has completed, she attempts to make sense of Newton's Laws with reference to her driving. She begins:

> *I am in the car parked, so that means that the forces acting on it are in equilibrium. Now, we are moving; I step on the accelerator and the car's velocity increases, but this does not mean that the force applied on it is increasing if acceleration is steady. . . Now, velocity is steady, so I suppose, or my acceleration is null, or there are other external forces acting contrarily, creating friction. . . Well, as I still feel my foot stepping on the accelerator to control the velocity and keep it steady, the resulting forces must be in equilibrium again. . . this looks just like when I was parked!*

This simple example shows how pseudo-empirical abstraction works. Although the student's practical knowledge of driving is insufficient to deepen her understanding of Newton's Laws, it gives her grounds to make sense of them. As she drives the car, she extracts not just the physical features of its motion (e.g., *still*, *steady*, *varying*), but also characteristics such as *velocity increasing/decreasing*, *forces in equilibrium*, *applied force* or *acceleration*—assimilated previously in the classroom and reinforced from the exercises in the books—by coordinating actions of 'analyzing', 'comparing', 'describing' and 'making inferences' about motion statuses. According to Piaget [15, 22, 23, 26], the student is *internalizing* or getting 'deeper' understanding of Newton's Laws. After a considerable number of cycles of internalization (with corrections, ratifications, and/or differentiations that she will discover and use to refine her thinking), her conceptual knowledge will evolve and allow her to realize (the *big idea*) that Newton's Laws depict motion for many other possible situations in real life that she has never experienced. This expands her scope for purer abstraction, wherein particular content is replaced by its extension (or generalization) and formalization is manipulated extensively, as for example in the manipulation of mathematical models.

3. Methodology

The qualitative research undertaken adopts a *constructivist* philosophical worldview, wherein "meanings are constructed by human beings as they engage with the world they are interpreting", and a *case study* strategy of inquiry per Creswell [33, p. 21, 38], in which a researcher engaged in inquiry "explores in depth a program, event, activity, process, or one or more individuals"; cases are "bounded by time and activity" and detailed information is collected by a "variety of procedures over a sustained period of time".

The final sample consisted of 18 people, 10 (56%) female and 8 (44%) male, with a mean age of 20.4 ± 3.1 years. All participants signed the informed consent document, which was submitted to and approved by the ethics and research committee of the site university and meets the requirements of the Declaration of Helsinki.

We collected data through three semi-structured interviews (lasting up to 50 minutes) conducted in reserved rooms onsite. These interviews occurred in parallel to the period that the students were undertaking a course activity requiring them to explain, based on a firm theoretical foundation, the relations between Science, Art, Technology, and Engineering concepts. Interviews took place before the activity; during the activity (two or three weeks after the first interviews); and after the delivery of students' final written reports, as part of assessment (again two or three weeks later). We filmed the interviews (with permission) and transcribed the content to a digital text editor.

We chose to work with the course Introduction to Engineering and this specific section because one of the authors was teaching it, allowing us to follow students' progress more closely. One of the course goals is to introduce to some basic historical notions and key concepts related to Science, Art, Technology, and Engineering. Explaining the relations among these concepts based on a firm theoretical foundation seems to us crucial to give students a broad view of the engineering profession and open their minds to the *humanist domain*. Moreover, this teaching task is very challenging, since the literature that deepens the theoretical discussions about these relations is very fragmented. Students then need to create a conceptual system in which parts remain imprecise and unclear, just as happens with many complex professional issues. At a minimum, we expect them to engage in critical thinking to respond to the situation effectively. To promote a deep approach to learning for the proposed activity, we used the Constructive Alignment Method [11], planning five lessons involving small group discussion and whole class discussion (one lesson for each concept—Science, Art, Technology, and Engineering—and a last one dedicated to discussing the relations between the four concepts).

For interviews, we elaborated a protocol based on Carraher [45], Inhelder and Piaget [21], Schmid-Kitsikis [46] and Piaget [23]. The protocol splits into three parts, with respective main questions as summarized in Table 1. Additionally, we applied internal controls [46] in the form of interview questions to confirm answers given (for example, *What do you mean by... ?*; *Could you be more specific about... ?*; or *Are you sure about it?*).

In order to analyze the data collected through the interviews, we applied guidelines developed by Bardin [32], Creswell [31], and Krippendorff [33] to proceed in an interactive process through preparation, organization, and coding of the material. After thorough consideration of the data and adjustments, the final coding led us to three main *themes* or *context units* [34]: *Definitions*, *Explanations*, and *Tasks*.

Each main theme was broken down into *thematic units* [34]. For the main theme *Definitions*, we had the following thematic units: Definitions with previous knowledge about Science, Art, Technology, and Engineering (this thematic unit was subdivided again for each definition); and Definitions supported with a theoretical foundation about Science, Art, Technology, and Engineering (similarly subdivided). For the main theme *Explanations*, we had the following thematic units: first explanation about the relationship between the four concepts, based on previous knowledge; second and third explanations about the relationship between the four concepts, supported with a theoretical foundation. For the main theme *Tasks*, we had the following thematic units: Tasks planned and Tasks performed by the participants.

Each thematic unit resulted from what we called *emergent categories* [34], to denote their differences from the thematic units. For the thematic units from *Definition*, we identified the following emergent categories: *Predicates*, *Purposes*, *Outcomes*, and *Spontaneous exemplification*. For the thematic units from *Explanation*, we found the same three emergent categories mentioned above for *Definitions* and a fourth named *General relation predicates* (in reference to the relationship between the concepts as a whole). For the thematic units from *Task*, we found the following emergent categories: *Means* and *Outcomes*.

Each emergent category resulted from the grouping of the elementary content of the speeches—words (such as nouns, adjectives, verbs) and phrases. We referred to this approach as grouping by *registry units* or *indexes* [34].

In order to track improvements in the knowledge of the students through their explanations, we used the *enunciation* technique [34], based on a structure using the following parameters to evaluate their *discursive coherence* [47]: Noncontradiction, Nontautology, Information Relevance, Thematic Continuity, and Semantic Progression. We considered all parameters equally for score integration. Table 2 presents the evaluation structure.

In order to support the credibility of the inter-

Table 1. Interview protocol

Interview	Questions
1st	• Based on your previous knowledge, could you please try to give a definition of. . . (Science, Art, Technology, Engineering)? • How do you think these four concepts are related? • In order to successfully accomplish our activity, which tasks do you plan to undertake?
2nd	• Could you tell what were the tasks carried out so far in order to be successful in our first activity? Could you please give details on each task? • Based on the theoretical foundation you've developed so far, could you please define. . . • How do you think these four concepts are related?
3rd	• Now that you've finished your final report, how do you think these four concepts are related? • Is there anything else you'd like to mention about the activity (new tasks carried out, the meaning of this experience to you in terms of your learning, etc.)?

Table 2. Evaluation structure for discursive coherence of the explanations

Subject:	**(_)1st(_)2nd(_)3rd Interview**	**(_)1st(_)2nd(_)3rd Explanation**
	Parameters	
Noncontradiction	(_).0-There are contradictions that make the message uncomprehending to the receiver. (_).2-There are contradictions, but not enough to compromise the understanding. (_).5-No contradictions.	
Nontautology	(_).0-There are redundancies that compromise any kind of understanding to the message receiver. (_).2-There are redundancies, but not enough to compromise the understanding. (_).5-No redundancies.	
Information Relevance	(_).0-There is no relevant or potentially relevant information to clarify the understanding of the receiver. (_).2-Partially relevant or potentially relevant information. (_).5-Fully relevant or potentially relevant information.	
Thematic Continuity	(_).0-Presents thematic breaks that compromise the understanding of the receiver. (_).2-Presents thematic breaks, but not enough to compromise the understanding. (_).5-No thematic breaks.	
Semantic Progression	(_).0-Does not contain new ideas. (_).2-Contains new ideas but doesn't explain conceptual elements, merely stating them. (_).5-Has new ideas, which are explained fully.	
Score	**Accumulated grade:**	**Normalized grade:**

pretations in the Discussion section, we also quantified the indexes of the three main themes. We applied to the main themes *Definitions* and *Explanations* the Wilcoxon signed-rank statistical test with a 95% confidence level (using the Action tool in Microsoft Excel) to detect random variations in these indexes [48]. We also applied this test to the scores of the participants' explanations to support the results regarding their improvement.

4. Results

4.1 Tasks

This main theme consists of the tasks the participants informed us of, both planning and execution, to determine the concepts' definitions and find information to support them by outlining the relations between them. We present a few excerpts here to show the variety of tasks conducted. Most participants used books (dictionaries, scientific methodology texts, art compendia, etc.) from the universities' library and sources from the Internet (blogs, scientific articles, websites from universities, etc.).

FDG: I **researched** topics [in books] that could include what I was looking for [the concepts] and then I went to the Internet. I **browsed** Google and universities' websites. *How did you proceed?* Instead of straightforward definitions, I **sought** examples to **understand** the meaning through them.

GAP: I **researched** two books and took the rest from the internet [browsing]. *How did you proceed?* I **copied** the concepts I found. Then I **read** them.. . I tried to **join** part of one [concept], then the other... to **compare**. . .

From these excerpts for this main theme, we extracted indexes (in bold) for the tasks performed and organized in Fig. 1, showing their types. Of the 138 indexes found, 45 were found redundant in an intra-individual analysis. The remaining 93 indexes, discounting inter-individual repetitions, ultimately showed 32 task types.

Of the 32 types of tasks, those with the highest number of indexes (representing 56% of the total) were as follows: 'search', 'browse', 'seek', 'ask', 'read', and 'change'. It is important to emphasize that these types of tasks cannot be considered more important than others per se; but the frequency of their occurrence in the speech of students suggests that there is a tendency for types of tasks that are more practical or tangible (except for 'change') oriented to content *assimilation* in the specific context of attempting to explain relationships between concepts. However, the variety of more abstract actions pertaining to content *accommodation* (such as 'change', 'analyze', 'resume', 'synthesize', 'formulate', 'order', 'connect', 'relate', 'compare', 'conclude', 'deepen' or 'reflect') is greater.

4.2 Definitions

This main theme consists of information provided by the participants about their understanding of the definitions of Science, Art, Technology, and Engineering considering two distinct moments: initially, based on their previous knowledge from their personal experiences (school, reading in magazines and on websites, opinions of friends and relatives, etc.); and later, with a theoretical foundation. We took up one excerpt from each concept to illustrate the changes in participants' conceptual knowledge.

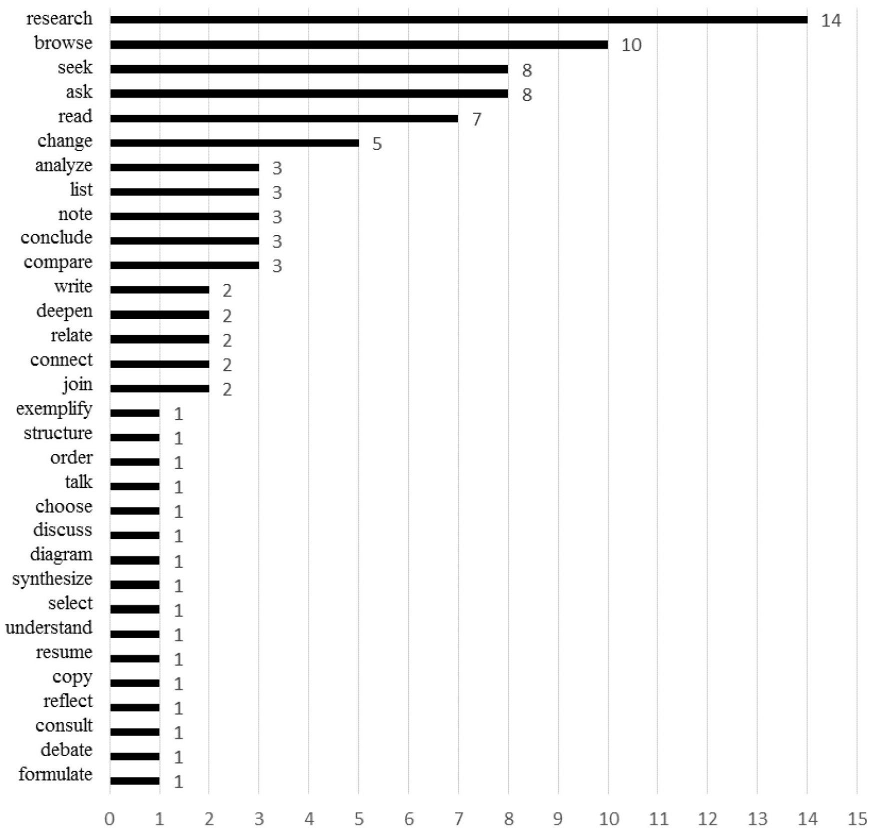

Fig. 1. Types of tasks performed by the students.

Science definition attempt using previous knowledge

AFF: It has to do with **scientific knowledge**, more **rational**, hmm. . . a **kind of knowledge** more **tested**, **experimented**, that is. . . quite **solid**. . .

Science definition attempt supported by theoretical foundation

AFF: Science is an **effort** to **produce** a **true description of nature**. So, it can **rationalize**, **construct logically**, and it also **rejects subjectivity**. It's... based in **concrete elements**, **observable** and **experimented facts**.

Art definition attempt using previous knowledge

GAP: There is the art of **painting**, from **drawing**, but I don't know what Art is for sure.

Art definition attempt supported by theoretical foundation

GAP: Art is... it has that **sensitive side of man**, to look at, to observe, and to **make it visible to others what he's feeling**.. . .. **Externalize his opinion**. . . through **dance**, **theatre**, and **painting**.

Technology definition attempt using previous knowledge

FDG: It's the **process** that made us **get where we're now** [progress], using Science to **put** [it] **into practice** and **develop**.

Technology definition attempt supported by theoretical foundation

FDG: It's. . . the **practical part**. While Science seeks only to understand and test hypotheses, Technology **makes an idea come true** [through technique].

Engineering definition attempt using previous knowledge

MFP: It's **planning** for you **to do something**. For example, you have a **problem** and then, with Engineering, you try **to solve** that with **planning**.

Engineering definition attempt supported by theoretical foundation

MFP: Engineering is the **profession** that **facilitates techniques**. It **creates technologies**, the **techniques** that **facilitate the service to other people**. Or, to **create something** to **facilitate something to someone else** . . . It can be to **facilitate production**. To **help economically**, to **be more viable**, to **produce efficiently**.

To ascertain if the variation in the amount of information—measured through the indexes grouped in the emergent categories (*Predicates,*

Table 3. Variation of the definition indexes

Wilcoxon Test	
Pairs	T^{+}
Definition Indexes	
S1–S2	6.5*
A1–A2	9*
T1–T2	29.5
E1–E2	42

* P-value ≤ 0.05.

Purposes, Outcomes, and *Spontaneous exemplification*)—reported by the participants in these distinct moments could be by chance, we applied the Wilcoxon signed-rank paired test. Table 3 shows the test results.

The results show that the variations (in general) are significant only for the concepts of Science and Art. According to (most) participants, the material they found about the concepts of Science and Art had more variety of views and definitions, while that on Technology, despite the amount of information available, did not exhibit great novelty, and the material about Engineering (concept) was little and repetitive (besides being closely fused to that on Technology).

4.3 Explanations

This main theme consists of information provided by the participants about their understanding of the relations between Science, Art, Technology, and Engineering, in three distinct moments.

Initially, based on their previous knowledge from their personal experiences, most of the participants' first attempts at speeches were confused and vague. Although they intuitively supposed relations between concepts, most could not articulate them, even when urged to define each concept more specifically or carefully. Only a few ultimately articulated the relations.

First explanation attempt (previous knowledge)

GAP: I. . . thinking about it, **Engineering depends on Technology**, **Technology depends on Science** and **these three are Art**. I believe that everything. . . **they're an art**.

LSR: Engineering is the **intersection** or the **connection** between. . . Art, Science and Technology. Science I won't know how to tell you. But Art. . . we can use the example of a project, that you have the **idea** to **create a project**, to **turn it into something tangible** through Technology and Science. Science is [related] through **scientific research**. . . Then with the support of Technology to provide **favorable instruments**. . . *Could you be more specific?* A civil engineer that designs a bridge. You'll have **creativity** from Art. . . to create, to have an idea about the bridge. With Technology, you'll have the **instruments to build the bridge**.

FDG: I think to **give foundation** [Science, Technology and Art related to Engineering]. . . Science. . . by what is known in **Physics**, **Mechanics**, **Chemistry**, it **enables something**, in the **real sense** . . . like a **project** I worked out. It **can be built indeed**. Art, to **think of one thing that no one has done yet**. And, the technology to run. . . a more **practical part**. The **theory of Science**, **innovation of Art,** and **execution by Technology**.

In their second attempt to explain (second interview), participants articulated relations between concepts better; some also brought definitions from the literature for discussion (they had been invited to bring their notes). Most persisted in their initial intuition about each concept's main characteristics and consequently about relations between concepts, with some elaboration and variation; as they indicated, this was because arguments for other definitions were not strong enough for them to abandon their beliefs. Some explanations were still vague, and participants reported doubts about them because of ambiguous and contradictory information between sources. When we supported their cognition with questions, they articulated clearer explanations, and their discursive coherence improved in general (see Table 5).

Second explanation attempt (with theoretical foundation)

LSR: I related Technology to Science and Engineering, which involves the **methods and techniques to solve a problem**. With the **support of Science and Engineering**, you'll have Technology. There is a relation to **develop methods to solve human beings' daily problems**. And Science depends on Technology. . . because the great breakthroughs in Science are reached through the **development of new technologies**. And Art is related to Engineering through **creativity**. . . with **innovation**. For me, Art is about **creativity, ideas to create something new.**

FDG: I believe that. . . Art comes with the **inspiration** to make a perfect **project** [Engineering] in what is possible to **supply all humankind's necessities**, using Technology to **have things done** and the

Table 4. Variation of the explanation indexes

Wilcoxon Test	
Pairs	T^{+}
Exp.lanation Indexes	
1^{st}Exp.–2^{nd}Exp.	63
2^{nd}Exp.–3^{rd}Exp.	23
1^{st}Exp.–3^{rd}Exp.	37.5*

* P-value ≤ 0.05.

Table 5. Variation of discursive coherence scores

Wilcoxon Test		**Discursive Coherence Scores**		
Pairs	T^{+}		M	SD
Discursive Coherence Scores				
DC.1stExp.–DC.2ndExp.	3*	DC.1st Exp.	6.36	1.65
DC.2nd Exp.–DC.3rdExp.	19.5	DC.2nd Exp.	7.57	1.89
DC.1stExp.–DC.3rdExp.	1*	DC.3rd Exp.	8.67	1.81

* P-value ≤ 0.05.

Science to **understand how to do it**, both the **best way** and with **less resources**, **natural** or **economic**.

In their third attempt to explain (third interview), most participants articulated very similar reasoning to one another, focusing on the main characteristics of each concept as a basis to establish their relations (see Table 6). Their discursive coherence again improved (see Table 5). Some even moved beyond establishing the main characteristics to manipulating and extending the concepts. However, a few participants reverted to confused, vague speech content similar to their first explanations.

Third explanation attempt (with theoretical foundation)

GAP: Engineering is related to **creation** (Art), in other words it's an **artistic process**. In order to **perform functions with quality** it's necessary that [the engineer] masters **scientific knowledge** (Science) related to a specific area. . . to **develop new technologies** that will be **used by society** [Technology]. Relating [Art] to Engineering,. . . an engineer, he **creates things**, then he has to be an 'artist'. He has to be **creative**, . . . **intuitive**, he must have **sensibility** at the moment of. . . he has to look around at society and **understand what is needed** to **create things**, such as **new products**, **technologies**, **goods**, **services**.

LSR: Science relates to Engineering through the **studies** and **knowledge**. . . based on **theoretical principles**. Technology is the **practice of Science**. Through the **development** or **elaboration** of **new equipment and machines, computers, robots**, whatever. . . to **improve productivity**, to **improve the quality of a product** or even to **solve a problem**. . . whatever the engineering field is. [. . .] these solutions will be related to Art. Art has. . . it's **created by human beings**, having this **sensitive dimension**, where each person has a **different point of view**. However, in Engineering, it applies through **creativity** [Art]. We can exemplify with the development of a **project** [Engineering]. **Science brings the studies**, **Technology brings the practice,** and **Art brings creativity**, with the **ideas**. To **solve** a **problem**.

FDG: **Engineering has relations of dependence with Science, Art, and Technology**. **Sometimes not with all those three, but always with two of them**. At least, there are two [concepts] that need to be in connection in order to. . . undertake a **project** in Engineering. Therefore, Engineering necessitates Art, Science, and Technology. **From the Technology 'to make' something; from the Art 'to create' something; and from Science, 'to know' something**. *How did you conclude that?* Because. . . just as to define each one [concept], we use this word 'to know' for Science, 'to create' for Art, and 'to make' for Technology. The definitions of each one of them didn't alter for these words.

To verify if the change in the amount of information across interviews—measured through indexes grouped in the emergent categories (*General relation predicates, Predicates, Purposes, Outcomes*, and *Spontaneous exemplification*)—was a chance variation, we applied the Wilcoxon signed-rank paired test. Table 4 shows the results.

The results show that the variations (in general) are significant only between the first and third explanations, possibly because three participants declined to give explanations in the second interview, requesting to leave this to the final interview.

To track improvements in participants' conceptual knowledge, we evaluated their speeches using the structure in Table 2 and applied the Wilcoxon test to verify if variation in scores was significant. Table 5 presents the results.

The results show that variations in the scores (in general) are significant between first and second and between first and third explanations. This means that they likely reflect improvements in students' knowledge.

We found similarities in configuration of speeches, possibly due to a shared *modus operandi* shaping students' reasoning in a given situation. Table 6 presents these configurations.

Looking first at participant GAP, his *modus operandi* was initially confusing. As seen in Table 6, his reasoning had the following configuration:

$$R = (S \rightarrow T \rightarrow E) : (S \leftrightarrow A), (T \leftrightarrow A), (E \leftrightarrow A).$$

That is, GAP saw the relation between the three concepts as a dependency chain but also saw them as equivalent to a single concept simultaneously, which is incoherent. In his third explanation,

Table 6. Configurations found in the participants' explanations of the relations between the concepts of Science, Art, Technology, and Engineering

Part.	1stExp.	2ndExp.	3rdExp.
ACS	$R = (A \to S \to T \to E)$	$R = (A \to S \to T) \Rightarrow E$	$R = (A \to S \to T) \Rightarrow E$
AFF	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E$
CPU	$R = (S \cup T \cup A \cup E): (S \to T \to A \to E)$	$R = (S \cup T \cup A \cup E): (S \to T \to A \to E)$	$R = (S \cup T \cup A \cup E): (S \to T \to A \to E)$
FDG	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E$	$R = (p \vee q \vee r \vee s) \Rightarrow E: p = (A \cup T), q = (A \cup S), r = (T \cup S), s = (\mathrm{A} \cup \mathrm{S} \cup \mathrm{T})$
GBR	$R = (A \to S \to T \to E)$	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup E \cup A) \Rightarrow P$
IDE	$R = (S \cup T \cup A) \Rightarrow E: (S \to A \to T)$	$R = -$	$R = (S \cup T \cup A \cup E)$
LHM	$R = (S \to T \to E) \cup A$	$R = -$	$R = (A \to S \to T \to E)$
LSR	$R = (S \cup A \cup T \cup E): (S \to A \to T)$	$R = \big((S \cup E) \Rightarrow T\big) \cup A: (T \leftrightarrow S)$	$R = (S \cup T \cup A) \Rightarrow E$
MSR	$R = N \Rightarrow (S \cup T \cup A \cup E): (S \to T \to A \to E)$	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E$
PGC	$R = \emptyset$	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E$
TLS	$R = (S \cup T \cup A \cup E): (S \to A \to T)$	$R = \emptyset$	$R = (S \cup T \cup A \cup E)$
CAC	$R = (S \cup T \cup A) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E: \mathrm{T} = \mathrm{A} = \mathrm{S} = \mathrm{E}$	$R = E = (S \cup T \cup A): (A \to S \to T)$
CAF	$R = (T \cup S) \leftrightarrow A \Rightarrow E: S \leftrightarrow A,\ T \leftrightarrow A, E \leftrightarrow A$	$R = \emptyset$	$R = (S \cup T \cup A) \Rightarrow E$
GAP	$R = (S \to T \to E): (S \leftrightarrow A), (T \leftrightarrow A), (E \leftrightarrow A)$	$R = -$	$R = (S \cup T \cup A) \Rightarrow E$
GML	$R = (S \cup T \cup A \cup E)$	$R = (S \cup T \cup A \cup E)$	$R = (S \cup T \cup A) \Rightarrow E$
MBA	$R = (A \supset S \supset T) \cup (A \supset E)$	$R = (A \supset S \supset T \supset E)$	$R = (A \supset S \supset T \supset E): A \leftrightarrow E$
MFP	$R = N \Rightarrow (S \cup T \cup A \cup E)$	$R = (p \vee q \vee r \vee s \vee t \vee u \vee v): p = (A \cup S \cup T \cup E), q = (S \cup T \cup E), r = (T \cup A \cup E), s = (S \cup A \cup E), t = (\mathrm{S} \cup E), u = (\mathrm{A} \cup E), v = (\mathrm{T} \cup E)$	$R = (p \vee q \vee r \vee s \vee t \vee u \vee v): p = (A \cup S \cup T \cup E), q = (S \cup T \cup E), r = (T \cup A \cup E), s = (S \cup A \cup E), t = (\mathrm{S} \cup E), u = (\mathrm{A} \cup E), v = (\mathrm{T} \cup E)$
MHS	$R = (S \cup T \cup A \cup E)$	$R = (S \cup T) \Rightarrow E$	$R = (S \cup T \cup A) \Rightarrow E$

GAP's reasoning changed to the following configuration:

$$R = (S \cup T \cup A) \Rightarrow E,$$

indicating a relation of logical addition (or union) between Science, Technology, and Art, resulting in Engineering.

Participant FDG's *modus operandi* was initially equivalent to the one GAP ultimately achieved, but his third explanation achieved the following more sophisticated configuration:

$$\begin{aligned} R &= (p \vee q \vee r \vee s) \Rightarrow E: \\ p &= (A \cup T), q = (A \cup S), \\ r &= (T \cup S), s = (A \cup S \cup T). \end{aligned}$$

That is, he said relations among the concepts were based on the requirement that at least two of Science, Technology, and Art be present, to result in Engineering. He justified this reasoning by noting that each concept was represented by a fixed element (or verb).

5. Discussion

The results (summarized in Table 5) revealed that most participants 'made the grade' in conceptual learning for the *humanist domain* when applying critical thinking skills in a situation presupposing high intrinsic cognitive load, like situations involving complex professional issues. Participants showed increasingly organized and articulated reasoning, moving from fragmented, confusing, vague arguments to consistent, connected, and clarifying ones, homing in on the *big idea* of the relation between concepts via *big ideas* about each concept. According to Bransford, Brown, and Cocking [3], this kind of conceptual knowledge enables an expert status.

The definitions seemed to work like building blocks for participants' conceptual learning, and were instrumental in improving their explanations. However, the acquisition of definitions alone was not enough to formulate improved explanations. Even participants who brought notes with definitions for each concept did not reproduce them *ipsis litteris*, only the main ideas or gist that mattered to them. They only turned to their notes to justify their position with details. That is, not the presence of definitions alone but participants' *interaction* with them enabled the extraction, manipulation, and coordination of their perceived features.

Indeed, these features or characteristics were not fully represented in any of the participants' definitions, but instead emerged from elaborations undertaken by the students. Even when proximity between definition seemed implied—for example, it was common to find in dictionaries puzzling sentences declaring that Science, Technology, or Engineering was the 'art' of something—the inferences still came from the person, as observed during the interviews. The *modi operandi* that shaped students' reasoning determined their inference and elaboration processes.

Returning to Piaget's knowledge construction theory, the 'something else' in the learning process is partially revealed by these students' actions. From among tasks performed by participants, in Fig. 1, we identified those oriented to both *assimilation* and *accommodation* of new content, and observed that the frequency of the former but the variety of the latter were greater. This implies that participants dedicated more effort to assimilating new content, perhaps due to intrinsic cognitive load associated with its novelty. Thus, a teaching strategy that could achieve more balanced frequency and variety of tasks vis-à-vis assimilation-/accommodation-orientation would help students achieve better conceptual learning.

Piaget's mechanisms of knowledge construction [22, 23] and a focus on the *reflective abstraction* process show us how students' actions to change their knowledge in the attempt to improve it unfold. All participants initially functioned within a *pseudo-empirical abstraction* modality, first grouping features of concepts and then extracting characteristics of their coordination in operations such as 'ordering', 'classifying', 'comparing', 'analyzing', 'inferring', and 'evaluating', to build arguments about the relation between the concepts. This *modus operandi* was universal in the first explanation (Table 6), and was maintained by most students until the end, with slight variations until reaching an equilibration that improved their reasoning (that is, after several cycles of internalization leading to corrections, additions, differentiations, etc., in their understanding). However, from the second explanation onward, we identified some participants (FDG and MFP, as seen in Table 6) beginning to employ a more sophisticated *modus operandi* in which, after considerable cycles of internalization, they began to operate within the modality of reflexive abstraction. This happened only when participants could reduce the variability of definitions for a given concept by realizing common core features, and opening the possibility for their continued cycles of internalization to abdicate from manipulating the qualities of the concepts and instead manipulate their extensions to achieve better explanations of their relations.

Finally, some readers may not agree with what we investigated could be considered as concepts (Science, Technology, Art and Engineering) but, for example, fields of practice instead. Our position is based on important literature from cognitive and educational psychology [1–3, 29, 49] which consider concepts as units of mental representation that people use to make sense of the world. Of course, some concepts are simpler (such as 'table', 'cat', 'object' etc.) and others far more complex (such as those investigated here). We understand that even if we consider Science, Art, Technology and Engineering like fields of practice, when we try to make sense of any of them—'what is it for?', 'what are its features?', etc.—, we carry out their meaning into concepts. Moreover, this *concept* position relates to an intended *interdisciplinary* view [12, 50], which we sought to stimulate the students during the activity we proposed in the course. Thus, considering interdisciplinarity as *combination* or *convergence of viewpoints* from different knowledge areas [50], any attempt of meaning making we wanted from our students about the relationships between those fields of practice would have to go through the students' conceptualization.

6. Conclusions

Our investigation aimed to explore the cognitive mechanisms stimulating engineering students' conceptual learning from the standpoint of Piaget's genetic epistemology. One major implication of our findings is the possibility of using Piaget's theory of knowledge construction into conceptual learning in engineering education for both investigation and in teaching.

Related to investigations, we think Piaget's theory may support the focus on *transformations* leading from one behavior to another instead of static statuses. In Piaget's equilibration process, both empirical, pseudo-empirical and reflective abstraction will form an integrative mechanism of cognitive regulation until adulthood. Each modality of functioning coexists and reflects specific features of the thought; we wonder if their stimulation could help predict deep/surface learning outcomes in the student, and what is the kind of balance that this stimulation should have. As our data showed, when students were faced with a new situation, they functioned initially within a pseudo-empirical abstraction modality, and not within the reflective one (even though this modality being naturally available to all them). We wonder when this would be the rule in the learning process. Thus, such investigations could be extended to other courses and with freshmen, sophomores, juniors, and seniors, over longer periods and using different intrinsic cognitive loads, in relation to not only the humanist but also the technical domain.

Related to teaching, we think that Piaget's theory by now, according to our findings, brings the message that we should care about the orientation *from concrete to abstract* for the interventions in the classroom. In other words, teachers who expect their students to learn about complex (and usually more abstract) issues should set this complexity as an intended learning outcome (in terms of actions such as 'defining', 'explaining', 'creating', 'relating', 'hypothesizing', etc.). Moreover, in order to support the transformations that enable knowledge construction, they should urge their students to move from simpler (and usually more concrete) actions ('identifying', 'describing', 'copying' etc.) to more abstract ones. Another point is that this orientation must allow the students participate or interact with the teacher and their peers during this process.

Undoubtedly, we recognize the limitations from our investigation. An important limitation refers to the fact that we could not fully capture the *empirical abstraction* process, the very beginning of knowledge construction in Piaget, because of insufficiently close tracking of specific actions performed by learners (perhaps, designing think-aloud tasks using specific consulting sources such as books and websites could help). We believe that empirical abstraction could help us explore transformations in more practical situations (in both humanist and technical domains), where contact with tangible principles of knowledge and practice in specific fields is key to conceptual learning. Another limitation refers more specifically to the applicability of Piaget's theory to conceptual learning in Engineering Education. We understand that its core principles—which are shared by constructivism and, consequently, most of the active methodologies already in use in Engineering Education—captures the picture of the epistemological subject solely. Thus, it captures a general view about regulations in metacognition. It does not address affective issues and the variability in students' cognition that teachers may face in the classroom that influence the learning process.

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