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An approach to the didactics of physics for structural engineering from an artistic perspective

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Abstract. The use of physics in structural engineering requires the combination of its logical strength with social sensitivity. Logical strength is provided by mathematics and physics with practical solutions and new thinking relationships. Social sensitivity is achieved by inserting this "hard" knowledge into the solution of community problems. It is desirable that the teaching of physics and its applications prioritize holistic knowledge over mechanicity and that this process be similar to the one followed by the artist when he conceives his work: he dreams it, tries it, feels it, and adjusts and delivers it after having understood it with his whole being. In terms of curriculum, it is advisable to rethink the contents, encourage the use of majeutics, reduce standardization, personalize evaluation, and abolish the belief that there can be useless knowledge.

1. Introduction

Making an analogy with biology and chemistry, it is worth saying that the disciple grows on a substrate that allows him to feed and subsist within an environment that can be hostile or friendly. That substratum is made up of the predecessor masters and the contemporary masters who are not only those who are recognized as having a title but also family members, friends, antagonists and the environment itself [1,2]. Some of them are sowers, others are reapers. The former protects the disciple's opportunities for infinite growth while the latter will try to cut off any sprouts of lateral thinking that go outside the norm. Both are necessary and help maintain the balance if they are given in their natural proportion. The disciple, contrary to what Locke (17th century) maintained, is not a Tabula Rasa, but brings ancestral knowledge that he permanently adapts according to his current experiences. Recognizing this is important if one wants to achieve a naturalized teaching, understanding that this expression refers to the process of awakening in the disciple his capacity to shape his own reality, not a standardized one [3].

As an example, let's think of a classroom where there are two actors called students and teachers. In reality, they are both disciples because they are each being formed from their own experience, but let us accept that the teacher has a socially recognized power over the student and that the student accepts that power because it benefits him in terms of the practical. Let us suppose that the student has grown up in the field and has drunk without reserve from whatever source he finds. When he arrives at school the teacher teaches him that all the water must be treated before it is drunk to avoid illness which induces a doubt in the mind of the student who asks the teacher if he has drunk from a nearby stream. The teacher, who is a citizen, will say that he or she just arrived but that he or she became ill the next day and had to be treated for a digestive tract condition. The doubt arises in the student because from experience he knows that this water does not hurt. Depending on the reason, there would be an endless number of explanations for this difference: that the teacher grew up in a "clean" environment and did not develop

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"defenses" for "dirty" environments; that genetically the teacher is weaker than the student to live in the country environment; that the teacher's digestive condition was caused by something different from the consumption of water from the stream he took as a "scapegoat"; that the teacher is inventing a story to support what he learned theoretically. In short, it is undeniable that the absolute truth that the teacher intends to teach is not infallible.

As in any teaching process, the teaching of physics in structural engineering cannot be detached from the substrate which is composed of the student's previous intuitive and experimental knowledge and his/her availability for the use of exact sciences [4].

2. Being and doing, wisdom and knowledge

There is a general confusion about being and doing [5,6]. Most people identify with what they do and claim that this is what they are. But in reality "being" is essential, while "doing" is circumstantial. Being is like the sea, while doing is more like the waves. It is very important that the disciple does not lose sight of the fact that being is what he does and as such he can adapt that doing to the circumstances that arise. For example, a structural engineer should be able to adapt his knowledge to the real conditions of each community. It is not fair to specify for a house to be built on the top of a mountain the same materials, the same construction techniques, and the same rigor that is the norm in the cities, since doing something like this would impose enormous costs of all kinds on the mountain family. There must be a connection between being and doing. That connection can be sensitivity. The sensitivity of a structural engineer recognizes that the mountain family needs a particular solution based on concepts of stability and resistance of the house to be built. These concepts must involve the materials and labor available in the mountain, the availability of economic resources and above all the tranquility of the family.

The manifestation of being is wisdom, the trace of doing is knowledge. A wise man knows, but not necessarily a man who knows is wise. Wisdom is the sublimation of knowledge; she is sensitive and intelligent. Knowledge itself is circumstantial, it is permanently transformed even by denying itself. Wisdom grows even when it denies itself [3,7]. In the example of the mountain house, the structural engineer may have knowledge, but not necessarily be wise. He or she can become wise if he or she is humble in the face of doubt, but does not humble himself or herself in the face of fear. For example, if the engineer recommends using a type of tree to give structure to the house based on his or her knowledge of the mechanical and physical properties of the tree's dry wood, the homeowners might argue that such a tree is scarce, or that it is very important for the balance of smaller animals and plants, or that it represents the spirit of the forest (it is sacred), thus making it clear that they know not only the structural advantages of the tree, but that they are wise when they accept the uniqueness of that individual within the ecological and emotional balance of the community.

In this writing, the words master and disciple are used to indicate people who "are" and can choose to "do", that is, build themselves up as "wise". In contrast, when the words teacher and student are used, the intention is to indicate that "doing" takes precedence over the idea being presented.

3. The brain hemispheres: east and west

As physical entities we have a command center called the brain which some experts define as "a process rather than an organ" [8]. Beyond the existing discussion about the veracity of the preference of each brain hemisphere for logical or recreational activities, in this section an analogy is made and it is used to raise an important question in the learning of structural engineering. It is said that the right hemisphere of the brain prefers art while the left one prefers mathematics. In the history of the continents, one can see that the East has developed fundamentally on cultures based on the intangible (let's say, from dreaming) while the West has given rise to the civilization of the tangible (which is achieved through logic). However, globalization is permeating both hemispheres of the world map and is fostering a much richer experience than that gained from isolated cultures. It is possible to motivate a similar effect in our teaching work by training ourselves and helping to awaken our disciples from a holistic vision. When we teach, it is necessary to permanently contextualize the knowledge: if we teach how to calculate the resistance of a beam, it is important that we insist that this parameter can save many lives by avoiding the collapse of a structure, not only to settle for calculating the numbers. It is necessary to listen to and respect the emotions of everyone in the classroom and try to understand that consensus does not necessarily imply renunciation, but rather is a social agreement. In order to speak the same language, when defining a structural demand in terms of a range of numerical values, it is accepted that it is a brief representation of the possible threats that the structural element may have rather than an all-encompassing concept.

Physics and metaphysics cannot exist without each other and so the completeness of any knowledge should be considered [9,10]. For example, the teaching of mechanical physics related to the concept of force cannot lose sight of the fact that it is a manifestation of something that has not yet been explained in terms of infallible observations and abstractions. The teacher and his disciple could be justifiably humble in accepting their ignorance of the first source of what we call force. This humility or awe in the face of this manifestation, which, although inexplicable, has measurable effects, can give us an example of how we can integrate (or globalize) the reverie with logic. We could talk about the law and the laws; it would be very convenient to accept the existence of the Law that we cannot understand and its manifestation in what we can explain by means of laws that we deduce with logic, from observation. The principle of uncertainty and quantum mechanics are good examples of the advance of physics within a universe that is more and more alien to reason, but whose effects can be predicted in practical terms as long as we adequately delineate those terms. The fact that we cannot perceive and measure something is not irrefutable proof that it does not exist [3,11].

4. Thinking and learning

Our thinking machine is highly efficient by applying algorithms that are based on loops [12]. The processes of structural analysis and design, being logical, demand in the disciple the formation of more or less stable mental loops that allow to get to propose works that become concrete in the physical world in the form of buildings and bridges. However, this factory of loops can work very well if the head of operations is chosen to think holistically with all his sensitivity and openness. In other words, this is what we have always heard about training professionals in values; this implies helping to awaken sensitivity in the midst of the whole gear of logical loops.

Managing emotions is a key aspect in the training of new professionals because it is necessary that they grow in real environments without forgetting the ideals [13,6]. The observation and acceptance of one's own emotions is perhaps the most important step in such management [14]. The next step is linked to becoming aware of whether that emotion contributes to or hinders the growth that we want to achieve. Finally, we arrive at the adjustment of the emotion. It is curious that the proposed classifications define more negative emotions than positive ones [8,14]. For example, one widely accepted classification speaks of five negative emotions and one positive one. This seems to show that perhaps the most accepted emotion is joy and does not require any subdivisions. Perhaps joy is the ultimate emotion, the one with the most energy and the one that allows for true learning. In contrast, within the negative emotions, fear seems to have the greatest power and be the generator of the other four. Here it is important to emphasize that learning is built on doubt and happy learning based on doubt is possible, but once fear appears the learning tends to stagnate. Being aware of this is very important when establishing teaching strategies.

Modern education is based on standardization [15]. Content, timetables, forms of evaluation and social validation have been standardized. This is justified by the large size of the populations that make up today's societies and by their need to communicate in the same language [10]. However, any excess is harmful and we have fallen into the idolatry of knowledge, forgetting about wisdom. The obsession for perfection, the slavery of the measurable, and the anguish for productivity has taken us away from the enjoyment of knowledge just for the sake of knowing. Today, practically everything a student learns is a function of his immediate functionality, of his possible productivity. For example, in structural engineering education it is rare to find teachers who know the history of art and architecture and their influence on the design of structures. These professors can be highly efficient with their calculations, but they are not always sensitive to what they teach and to whom they teach, resulting in their work being more like that of a machine. Science and paracism seem to admit that we are indeed very refined machines, although the former is based on observation and the latter on flashes of creativity and lateral thinking. The conditions are now in place within the thinking of the disciples to admit a balanced fusion of science and para-science, that is, of the measurable with the dreamable. That is why structural engineering can continue to rely on materials and techniques that have worked for centuries and millennia, but it can also ask itself questions about the possibility of "living" materials that grow and adapt to the immediate demands of the environment: Why not imagine a structure that anticipates its loads and strengthens its elements and connections according to its own prognosis?

Thought is plastic and ductile but typically standardization makes it rigid and fragile [8,9,12]. Thought adapts and can develop without limit if the conditions are present for plasticity and ductility to be allowed in the teaching process. When a student asks the reason for something, the teacher's answer should be totally transparent so that those conditions are met; if the teacher "knows" the answer should accompany his or her answer with the possible origins and shortcomings of that knowledge, it should include a "but" that shows that nothing is totally true or totally false within what we "know"; if the teacher "does not know" the answer, he or she should say so and take advantage of that opportunity so that together with his or her students that knowledge is achieved. Teaching that encourages the plastic and ductile growth of thought can be positively supported by error and the recognition of the limitations of what is admitted to be true. When a structural engineering student asks his teacher why only 7 or 11 bar diameters are used within the design and the teacher answers "because that is the way it is", the opportunity is lost to illustrate during the next minute of class the history and commercial convenience of bar diameter standardization within the steel industry; a discussion could also be proposed on the theoretical and practical possibilities it would have if we could develop procedures with which the bar could be extruded on site according to our most precise design. This way of communicating what is known can allow a natural development of what the student can achieve not only with the knowledge of the state of the art but with his own creativity, with his capacity to dream.

All the manifest, all the diversity, is natural but not necessarily convenient. Convenience is a practical matter, imposing limits to minimize the effort that change and adaptation demand. Particular convenience does not exist, it is only possible if it occurs collectively and that is why it is an eminently practical matter that is linked to the way we communicate. On the other hand, collective peace does not exist because it is an achievement of the individual [5]. The harmony of teaching can only be achieved if these three concepts are reconciled: everything that is manifest is natural, convenience chooses what is accepted from the manifest, peace accepts the totality from the individual's point of view. The recognition of the equality between master and disciple and between disciples is the cornerstone of a free teaching. The teacher who admits to questions and doubt from his students about what he teaches without feeling hurt is surely accepting that equality. On the other hand, the diversity of cultural, gender and religious expressions can bring much richness and encourage reconciliation between nature, convenience and peace if they are properly reconciled.

As a brief reflection on this section, let us think about the familiarity of these words: knowledge = unknowing (without foundation, mobile, not permanent), reason and co-reason (heart, the companion of reason, sensitivity and reason).

5. Results

Physics is a fundamental part of a typical program of the structural engineering line within the civil engineering career that basically includes the following subjects with their respective ramifications: (a) static: it focuses on the relationships between external forces and internal forces in rigid bodies. It studies balance and stability; (b) strength of materials: it studies the relationship between stress and deformation at negligible speed of deformable bodies built with materials of known properties; (c) structural analysis: It combines the concepts of equilibrium and stability with the resistance of materials to predict internal forces and deformations in structures composed of elements from one or several types of materials; (d) structural design: It uses the results of structural analysis to guarantee the resistance and rigidity required in real structures.

The study of the above subjects must be consistent, mutually inclusive. The training of a structural engineer requires an understanding of each of the parts and how they interact: an expert in structural analysis does not necessarily know when a structure is safe and vice versa, someone who knows how to design does not necessarily know how to analyze the structure properly. However, here it is worth to say that the physics, particularly the mechanics, have a paramount importance in the teaching of the structural teaching.

5.1. Some proposals

We propose to train initially from the general to the particular and then encourage expertise from the particular. Before starting the mentioned courses, it is convenient to include a conceptualization course that includes concepts of the relationship between internal and external forces with the most likely numerical ranges to be found in any type of structure studied in an undergraduate program. Therefore, not only will the understanding of the scope of structural engineering be achieved, but also the representative orders of magnitude will be fixed in the results of the analysis and design.

The proposed course will encourage calculation by hand or with basic devices such as scientific calculators and freehand drawing. This will strengthen the relationship between fine motor skills and abstraction. Moreover, it will help students to understand that they do not necessarily need complex devices with inaccessible hardware and software to solve any kind of problem in a responsible way. Accuracy does not necessarily imply efficiency; a student may be very skilled at operating software, but may not necessarily know what the results and data mean [16,17].

The proposed course could be enriched with the abundant use of images and simple scale models that can be felt and observed by the students. This experience helps to fix concepts (form general loops) that can then be "broken down" and structured into smaller, more expert loops. For example, when a student bends a rubber bar, he or she not only feels the restitution force that is generated, but may also observe small changes in texture and some heat in some parts which may induce questions about what effect these developments have on the study of structural analysis.

5.2. Example

We want to understand how the structure of a tree behaves in a zone of the tropics. How could this understanding be induced in a student? It may be helpful to look at an actual tree, a video or photographic image, or a drawing such as the one shown in Figure 1. Channeling questions might be: What are the peculiarities of its movement, and how might the fact that it does not fall apart be described numerically?

Within the answers may appear statements such as: the tree has roots that support it, the tree moves with the wind, there's sound caused by the leaves and by the crunching of some branches, there's leaf loss in the movement, the tree gets constantly wet and dry, the tree doesn't fall apart because it's stronger than the wind, to prevent it from falling to pieces, we should express numerically that the resistance of the tree should always be greater than or equal to what the wind does to it. These answers show that intuitively the student knows about the need for a foundation (roots), the existence of transitory loads (wind), the deformability of the tree materials, the energy transformation that occurs in a system (there is sound and heat), the variability of the load (leaves fall and water can appear and disappear on the branches and trunk), the need for an equation based on resistance and demand forecasts and many other concepts useful in the approach of mathematical models of structural engineering.

To address the problem in numerical terms, it is advisable to take stock of some previous knowledge or concepts: density or unit mass, centroid, center of gravity, lever arm, force, momentum, among others. In this state it can be useful to ask questions to improve the knowledge of orders of magnitude of some physical quantities in the engineering problem being studied: Is the tree heavier or lighter than you, what happens if the tree falls into a nearby lake, can the tree grow taller than a building. It is possible to roughly "scale up" the different parts shown in Figure 1 and get "orders of magnitude" that can serve as a guide for trying some numerical answers. For example, the tree is almost three times the height of an adult man and the diameter of its trunk can be on the order of twice that of the man's body. In other words, the tree may measure about $3 \times 1.70\ \text{m} = 5.10\ \text{m}$ from base to top and its diameter is about $2 \times 0.30\ \text{m} = 0.60\ \text{m}$. If the solid volume of the branches is of the order of one tenth of that occupied by the whole tree, then the approximate volume of the "compressed" tree would be of the order of $5.10 \times 3.14 \times 0.60^2 \times 1.10 = 6.35\ \text{m}^3$. As the wood weighs around $6\ \text{KN/m}^3$ it could be estimated that the weight of the tree is around $6 \times 6.35 = 38.07$ KN (about four tons). If the student observes that due to the wind the tree moves back and forth up to 20 cm in the crown of the tree and if it is accepted that the center of gravity of the tree is $2/3$ of the total height, then it could be said that the center of gravity moves at a rate of approximately $2/3 \times 20 = 13.33$ cm to each side. If these data are used the moment that demands the trunk in its leg is of the order of $38.07\ \text{KN} \times 0.1333\ \text{m} = 5.08\ \text{KNm}$ which allows to anticipate that the resistance of the trunk and the root is at least 5.1 KNm.

The goodness of the calculations can be verified using *e.g.* finite element software. In this case the use of software can be very useful for the teaching process because it is used to check what was deduced mentally [18-22].

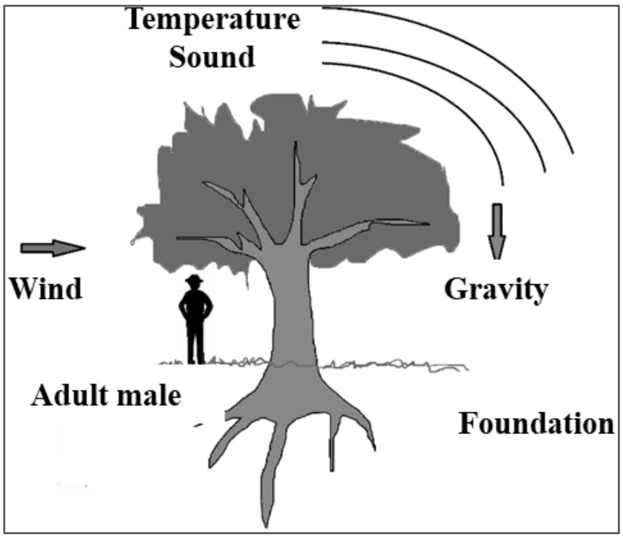

Figure 1. Example of conceptual induction of structural behavior.

6. Conclusions

The harmony of the master-disciple relationship will manifest from the teacher-student relationship if the teaching is holistic. It is necessary to rethink the current value systems based on productivity and standardization to give way to educational processes that allow the plastic and ductile expression of thought.

The formation of loops or logical algorithms in the mind of the structural engineering learner is valuable as long as it serves an open, universal mind. It is not enough to know how to add, it is necessary that it means that sum in each context in which it is applied. It is proposed to create a course of general concepts and orders of magnitude that connect common sense with expert knowledge before exposing students to specific knowledge of the application of physics in structural engineering. This course should be rich in the use of perceptual resources (visual, auditory, tactile) that allow an experience associated with each concept to be set as part of the language of a civil engineer dedicated to structural engineering. It is possible to train professionals with robust concepts that make responsible use of software resources for which it is necessary to insist that the software is at the service of the human, not the contrary.

The proposal allows the teacher to develop from the physics class in their student's skills that strengthen their mathematical physical thinking from the study of balance, stability, deformation and design of structures based on mathematical models inherent in physics.

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