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From Learning to Talk to Learning Engineering; Drawing Connections Across the Disciplines

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ABSTRACT: This paper introduces eight so-called *conditions of learning* (immersion, demonstration, engagement, expectations, responsibility, approximation, employment and response), which have been previously established for the learning of literacy. It is stipulated that these conditions are universal in nature; in other words, they must be present for any learning to occur. When these conditions are met, students learn more efficiently and are able to enjoy and appreciate their subject matter. The article discusses briefly how these conditions were established and their relevance in the study of engineering. More importantly, the article also presents examples of how these conditions can be satisfied in those learning environments that are commonly found in engineering.

INTRODUCTION

Cambourne, in his efforts to find an educationally relevant theory of learning, conducted research with young children for a period over 20 years: from the early 1970s through to the 1990s [1][2]. His research focused on children learning literacy, and the result was the establishment of eight so-called *conditions of learning*. These conditions are naturally met when children learn how to speak the language of the culture into which they are born. As a result, the learning of one's native language is almost universally successful, extremely rapid, usually effortless, painless and extremely durable, despite the incredible complexity of the process.

Upon understanding these conditions, one cannot help but see their relevance in the learning of any skill or subject matter. After all, the cognitive process of learning does not distinguish one set of skills from another. In other words, it is stipulated here that these conditions are universal and must be satisfied for learning any subject matter or skill. This article attempts to prove that this is certainly true for learning in engineering.

This article delivers a brief explanation of each condition as established by Cambourne, followed by a discussion on how each condition applies in engineering settings.

IMMERSION

Cambourne observed that from the moment of birth, young language learners are constantly bathed in oral language. Before babies are even aware of what is going on around them, they are being exposed to the sounds, rhythms and cadences of what they must ultimately learn. Parents, relatives and friends talk to them or are talking around them before even the young learners have any concept of words. As a matter of fact, recent research has shown that babies benefit from listening to their mother's voice while still in the womb. This observation led him to establish *immersion* as a necessary condition for the learning of language.

But what exactly do we mean by immersion and how does this apply in engineering? According to Cambourne, immersion is the state of being saturated by, enveloped in, flooded by, steeped in, or constantly bathed in that which is to be learned [2]. In simpler terms, immersion is a very high level of exposure to the subject being studied, not necessarily within a formal educational setting. This exposure helps the learner see connections between concepts and ways to apply these concepts. When the level of immersion of young children to oral language is considered, it is obvious that it is very much above and beyond the level of immersion of engineering students in any course.

While it is unrealistic to expect the same level of immersion in engineering settings, certain activities may increase the exposure of students to their field of study and result in improved learning. For example, the author has often observed that students usually perform better if they exhibit one or more of the following characteristics:

- Have double majors in related fields (eg aerospace engineering and aviation);
- Spend time on hobbies related to their fields (eg fly airplanes or radio-controlled models);
- Work in aerospace engineering-related jobs.

Students engaged in any of these activities seem to have a better-developed schema than their classmates. They are able to relate concepts studied in class to something they have seen or experienced in the real world. They also seem to have less difficulty with design. The reason behind their improved performance does not seem to relate to intelligence or any other factors, but rather to the fact that their level of immersion in their field outside the classroom is greater than that of their classmates.

For example, students with double majors not only take twice as many courses on each core subject, they learn to approach each subject from different perspectives, something which in itself enhances learning. In the aviation propulsion class, students learn how to take an engine apart and put it back together. They learn how to troubleshoot and maintain an engine. On the other hand, in the aerospace engineering propulsion class, students learn how to analyse the performance of an engine and design a propulsion system. The double major students are able to make connections between the two worlds (maintenance on the one hand and analysis/design on the other), and draw upon countless images from their experience in the former to help them with the latter. The other students are struggling to visualise the various components of an engine, which they may never have seen before, while at the same time trying to understand thermodynamic cycles, compressible flow and chemistry.

Students who are pilots understand *stall* better than anyone else. They exhibit much higher interest in boundary layers and flow separation – traditional topics in aerodynamics and fluid mechanics – because they have a vested interest in it. Occasionally, the author has had students who have flown fighters. These students can relate to flight mechanics in unique ways because they have experienced each topic of the subject in actual flight. Similarly, radio-controlled model airplane buffs can size the tail of an airplane using their intuition and experience, unlike a student without such experience, who tries to do it for the first time in a senior level aircraft design class.

Lastly, students who hold engineering jobs seem to cope better with the stresses and rigour of engineering classes. The connection they enjoy with the real world of engineering makes them better conditioned for studying engineering.

These examples show that any exposure to the subject of study outside the engineering classroom tends to improve academic performance. It seems that this exposure increases the immersion of the learner to engineering and helps with the development of engineering intuition and skills. Sadly, the level of immersion in engineering seems to be much lower these days among incoming freshmen, primarily because of societal changes that have taken away many opportunities for young learners to observe and interact with professionals in technical fields. Moreover, a large number of engineering students in many campuses spend many hours working on jobs that have very little, if anything, to do with engineering.

But what can be done to increase the level of immersion of students? While we will never be able to reach the levels of immersion in oral language, the ideas below may still help:

- Encourage students to become active in hobbies related to their field of study.
- Take students on field trips to sites linked to their study field.
- Decorate laboratories and classrooms with pictures and models of state-of-the-art engineering products (visual immersion).
- Encourage, even require, students to take internships or perform community service in areas related to their field of study.

DEMONSTRATION

Cambourne found that all learning begins with opportunity and the ability to observe, see, hear, witness, experience, feel, study and explore some action or artefact. Young learners receive countless demonstrations of oral language. However, there is a key element that makes these demonstrations effective: they are usually *whole* demonstrations. When parents speak to their infants or toddlers, they use whole sentences with a specific purpose in mind. Thus, the demonstration provides enough information about the various systems and subsystems of the language so that the learner will eventually be able to work out how all the pieces fit together and interact with each other. On the contrary, demonstrations that emphasise only one or two of the language subsystems and de-emphasise or ignore others that typically accompany them, make learning less comprehensible and therefore more complex [1][2].

Demonstrations in engineering classrooms usually follow the latter example. Quite often, entire lectures are consumed with derivations and discussions on theory with no examples or applications in sight. Even in the best cases, when demonstrations are performed, often they are not *whole*. Information is usually cut into pieces and spoon-fed to students. Just like with oral language, a *whole* demonstration in engineering would provide enough information about the various systems and subsystems so that the student will have the data available to work out how all of the pieces fit together and interact with each other. This principle is extremely important in engineering design.

One way to perform *whole* demonstrations in design is through case studies. In aircraft design, for example, students need to see a complete analysis of the configuration of a particular airplane, discussing the various decisions/choices a designer had to make. This process helps students establish the connection between the various features of a configuration and the mission specification for which the airplane was designed. While a design class lends itself easily to *whole* demonstrations, students also need to see the big picture while discussing specific topics in more specialised courses. This approach has also been proposed as necessary to engage students with certain learning styles, such as global learners [3].

In order to clarify the difference between a traditional versus a *whole* demonstration, an example is discussed from aerodynamics. The topic is boundary layers and the skill to be demonstrated is the calculation of skin friction drag. The traditional approach presented in many textbooks uses a flat plate as an example [4]. The calculation is straightforward. However, many students tend to miss the connection between the calculation on a flat plate, presented in the text, and the calculation (of the skin friction drag) on the surface of an airplane wing – or even that of a high-speed train. A better approach to teach this skill is to use a *whole demonstration* by utilising the surface of an actual airplane for the calculation. Figure 1 shows the Piaggio P-180 Avanti, which the author has used for this purpose. While the calculation does not differ from that of a flat plate, students immediately realise that even curved surfaces can be approximated as flat plates for the purpose of calculating skin friction drag. Most importantly, this *whole* demonstration offers the following advantages:

- The topic (skin friction drag) is now much more relevant.

- The picture allows for other design aspects of this airplane (ie front fuselage shape, propellers' location behind the wing, wing sweep angle, etc), to be discussed in relation to boundary layers.
- The discussion can be further expanded to include other aspects of aerodynamic design (wing thickness, three-surface configuration, etc).
- Connections can be made to topics outside aerodynamics, such as stability and control, propulsion, etc. These connections make it easier for students to understand these topics later on in other classes.

Figure 1: The Piaggio P-180 Avanti.

The main idea in all of this is to present the *aerodynamics* piece of the puzzle as part of a bigger picture and not as something that is isolated.

Integrating the curriculum, as many schools have already done, is another way to facilitate *whole* demonstrations in engineering [5][6].

ENGAGEMENT

While immersion and demonstration are necessary conditions for learning to occur, they are not in themselves sufficient. What may be missing from the learning equation is engagement. Just like the engine of a car can be revved up unproductively without any movement of the vehicle when the clutch is not engaged, so can students be immersed in their subject and exposed to many demonstrations without any learning as a result.

Engagement is attention, which comes as a result of a perceived need or purpose for learning in the first place. Engagement is evident when the learner actively participates in the proposed activities, which, in turn, may involve some risk taking.

So what does it take to get the students engaged? According to Cambourne,

> *Students must be convinced that they are potential doers of the demonstrations. For example, parents always convey to their children implicitly or explicitly the message that they will eventually learn to talk. This is in sharp contrast with the way many engineering freshmen have been welcomed to their fields in large auditoriums: Look to your right, look to your left. Only one of you will be here for graduation four years from now!* [1][2].

Messages that explicitly or implicitly convey that what is about to be demonstrated is so difficult that some of the students may not be able to perform it, will serve no other purpose but to discourage at least some of the students. Cambourne commented that:

> *Students must be convinced that by mastering the skills being demonstrated, they will improve the quality of their lives. An illustration of this principle is the difference in efficiency with which adults and children learn a new language when they migrate to another country. Granted there may be other contributing factors, such as difference in learning ability due to age. However, kids in general feel more compelled to learn this new language so they can communicate with their friends at school. On the other hand, adults sometimes manage to fulfil all their basic needs using their native language at home, when with friends, and sometimes even at work. As a result, they do not always master the language of their new country as quickly as their children* [1][2].

The situation is very similar when learning engineering. Often students enrol in an engineering programme for reasons that do not provide for strong engagement. For example, many students want to become engineers because an engineering degree will help them find a well-paying job. Is this a strong motivator to help students persevere through an engineering curriculum, especially when things get tough? As Csikszentmihaly found in his research with students of painting:

> *Painters must want to paint above all else. If the artist in front of the canvas begins to wonder how much he will sell it for, or what the critics will think of it, he won't be able to pursue original avenues. Creative achievements depend on single-minded immersion* [7].

Csikszentmihaly found that it was those students who savoured the sheer joy of painting itself, who later became serious painters. Those who had been motivated in art school by dreams of fame and wealth, for the most part drifted away from art after graduation.

So how does this relate to the teaching and learning of engineering? Some students are extremely motivated and interested in their field; these students have discovered engineering on their own, often through a hobby. There is no obstacle high enough to cause these students to drop out of engineering. The challenge, on the other hand, is to inspire, engage and motivate the rest of the students who may be more ambivalent about engineering. This is no trivial task. One way to achieve this, is by consistently taking the time to show students how the various engineering products have impacted the quality of our lives. Only by inspiring students can we hope to engage them in the subject matter. Two importantly factors that need to be considered are:

- Students must be convinced that the risks involved, if they become engaged, both physical and emotional, are liveable. Asking questions during class is one form of engagement. When students ask a question, our response to them may have a strong impact on whether they will engage with our subject or not.

- The probability of engagement increases dramatically if the person who demonstrates has bonded with students. If students think highly of us and believe that we like them and care about them, they will be much more likely engaged with our demonstrations. Needless to say, if we are often grumpy, remote, sarcastic, threatening, punitive, or in general negative, it is natural to expect students to be discouraged and lose their desire to engage in our subject matter.

EXPECTATIONS

High expectations are often linked with excellence. As mentioned earlier, one of the reasons children learn to talk so easily is because they are expected to be able to talk by a certain age.

Communicating high expectations to students has been established as the 6th principle for good practice in higher education [8]. One way to communicate high expectations is through a consistent display of confidence in students' ability to succeed, in whatever they try to master. The trick is to convince students that we are genuine about our expectations, our positive feelings and attitude towards them, as well as our subject. But in order to be genuine about our expectations, we must first get to know our students and their abilities.

As Goleman pointed out, in order to achieve a state of *flow* in learning, the activities must challenge the student to the fullest of his capacity [9]. If the assigned task is too simple, it will be boring. If too challenging, the result will be anxiety rather than flow. Being enthusiastic, and the degree to which we manage to make this enthusiasm contagious, also affects student attitudes towards the subject. Some examples where high expectations have made a difference in students' performance in the author's courses are highlighted below:

- Students are given strict guidelines on technical report preparation in design and laboratory courses. At first, students will test the waters and submit reports that do not meet all of the guidelines. Whenever these ill-prepared reports were accepted and graded, a large percentage of students ignored the guidelines altogether in subsequent reports. On the other hand, when reports are returned to students ungraded and it is made clear that reports will not be accepted unless they follow the guidelines, eventually all students conform to the requirements.
- In the aircraft design course, students design, construct and test a remotely controlled model airplane for participation in the Society of Automotive Engineering (SAE) Aero-Design Competition [10]. In the early years of the course, students were graded based on their overall effort and not their outcomes. As a result, most of the early airplanes produced did not fly at all or, if they flew, were not capable of lifting the minimum weight required to qualify for the final round of competition. In recent years, students' grades have been linked to the amount of payload their airplane can lift and how well they perform in the SAE competition. As such, over the last several years, all of the airplanes produced have qualified for the final competition, with many placed in the top six in a very competitive field of approximately 30 participating teams from universities across the USA, Canada and Mexico.
- Students are expected to come to class prepared to solve problems. Usually, if there are no consequences, most students will not make the time to read the assigned material beforehand. In order to raise expectations, students are often given unannounced quizzes at the beginning of class on the material they were supposed to study. Not only do most of the students now take the time to read, their performance in problem-solving sessions has significantly improved.

RESPONSIBILITY

Cambourne observed that it is the young learners who decide at which point in their lives, having seen enough demonstrations of oral language from parents and others, they will engage in simple conversations and start talking, some of them using isolated words, others waiting longer until they feel comfortable to use more complete sentences.

The condition of *responsibility* is an important one in the context of life-long learning [11]. The need to stay current is becoming more and more pressing as new technological advances continue to transform the workplace at a very rapid pace [12]. In the mid-1980s, the *half-life* of an engineer's technical skills (ie how long it takes for half of everything an engineer knew about his/her field to become obsolete) was estimated to vary from 7.5 years for mechanical, to 2.5 years for software engineers [13]. These numbers are probably smaller today.

Thus, unless our students learn how to search for, process, digest, understand and apply information on their own, they will find themselves in difficulty trying to cope with engineering jobs of the future. This is the reason behind ABET EC 2000, criterion 3, outcome (i), which states the expectation that engineering graduates should have *a recognition of the need for, and an ability to engage in lifelong learning* [14]. In order to acquire all of these skills, students must be given opportunities on a regular basis to make decisions about their learning independent of us. Two distinct ways that this can be accomplished is by giving students the responsibility to:

- Study a particular topic on their own and demonstrate their knowledge by solving assigned problems. Interaction with the instructor, as well as with other students, is encouraged, but no lectures are given on this topic.
- Design any experiment they must perform in the laboratory. For example, in the aerodynamics laboratory, one of the experiments involves testing an airfoil in the wind tunnel, measuring its aerodynamic characteristics and comparing them with published data. Under the old paradigm, an extensive manual would specify exactly what angles of attack and airspeeds to use, what kinds of measurements to take, and so on. But if everything they need to do is spelled out in the manual, students do not really have to think about the experiment until they get home and start processing the data. This approach does not satisfy ABET EC 2000 criterion 3, outcome (b), which states the expectation that engineering graduates should *be able to design and conduct experiments, as well as analyse and interpret data* [14]. Under the new paradigm, students search for and study beforehand the published data on the airfoil to be tested. Then they design the experiment to measure whatever data they think they need in order to verify the performance of this airfoil.

APPROXIMATION

When toddlers learn to talk, they are always encouraged to try out new words and new expressions. Their attempts, no matter how imperfect, are always welcome. Likewise, engineering students should not be expected to wait until they have completely mastered a skill before they are allowed to use it. Rather, they should be given many opportunities to emulate what is being demonstrated.

Approximations – which often include errors – have always been important in engineering. Many inventions that changed the course of our lives came after repeated failures. The Wright brothers' Flyer is one such example (see Figure 2). After repeated crashes in 1901, a discouraged Wilbur Wright was quoted saying, *nobody will fly for a thousand years!* Fortunately, his discouragement did not last very long, for it was only a couple of years later that the brothers made history by flying successfully the first manned, controlled airplane.

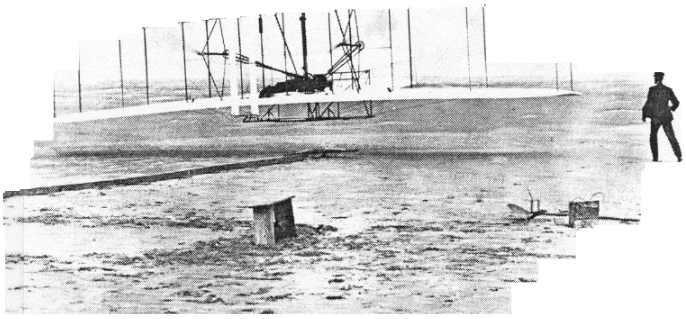

Figure 2: The 1903 Wright brothers' Flyer.

Yet, sometimes educators seem to be obsessed with the idea that students must get things right the first time, whether it is a homework problem, a laboratory report, a design project, or even an examination problem. Students then become reluctant to take risks, prefer to stay within the framework of what they already know and progress through refinement becomes impossible. This is in sharp contrast with the real engineering world where iteration is a standard procedure in any new design.

Allowing students to attempt problems during class (active learning) offers opportunities for them to approximate what is being taught. If this is done in small groups (cooperative learning), it also gives them a chance to see how others approximate the same concept [15]. Incidentally, active and cooperative learning have been established as the 3rd and 2nd principles, respectively, for good practice in higher education [8]. But even in formal assignments, such as homework problems, laboratory or design reports, learning is enhanced if students go back, given some feedback, and redo the assignment. Making corrections on reports and writing comments gives students valuable feedback, but unless they are encouraged and even rewarded for fixing what they do wrong, there is no guarantee they will get the message we try to give them with our feedback.

EMPLOYMENT

Young learners of oral language always employ their newly acquired skills in situations that are meaningful to them. For example, they use language to ask for something they want or to communicate with friends when playing a game. You will never hear a toddler practicing irregular verbs in the past tense.

Engineering students usually get many opportunities to employ each new concept they learn. Homework problems, paper reviews, laboratory experiments, design projects, and all kinds of assignments have been invented just for this purpose. While all of these assignments are helpful, sometimes they miss a key element. There is no meaningful purpose for them other than to learn a particular skill.

For example, consider an aerodynamics problem where the students are asked to calculate the induced velocity at a point in the flow field of a semi-infinite vortex using the Biot-Savart law [16]. This is certainly an opportunity for the employment of a new concept. However, students cannot immediately see the value of this problem because the connection with the real world or with something that is important to them is not obvious. Problems of this nature are often perceived as necessary but irrelevant and fail to engage students.

Imagine instead the same concepts applied to a Boeing 747 taking off from San Francisco International (Figure 3). The weight of the 747 is given, so that the strength of its tip vortices can be calculated (Figure 4). Imagine further a student pilot flying a Cessna 152 caught in the wake of the 747. The students are asked to ponder what will happen to the Cessna depending on its relative position with respect to the 747. For example, they may calculate its rate of descent (if caught in the downwash directly behind the 747), or its rate of roll (if caught directly behind one of the tip vortices of the 747).

Figure 3: A Boeing 747 during takeoff.

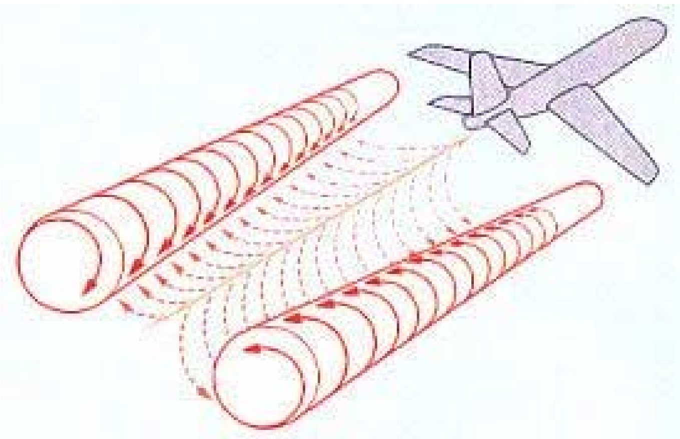

Figure 4: A schematic of the wingtip vortices behind an airplane in flight.

Although the calculations for the two problems are very similar, what is different in the 747 problem is the perceived importance to students. Pilots are eager to find out whether they have a chance of surviving such an incident. Frequent air travellers want to know what is a safe distance for jet transports to follow each other on takeoff or on final approach. In other words, the perceived purpose for solving this problem is not to acquire some abstract skill but rather to answer students' own curiosity about something important to them. In the process, of course, the skill of calculating induced velocities in the flow field of a vortex is acquired.

Another important aspect of employment is the opportunity (or lack thereof) to employ concepts discussed in class to something related to the students' personal lives. For example, after a class discussion on boundary layers, a student once wrote in her reflection journal that she went home wondering why her homebuilt airplane was experiencing a pronounced nose-down pitching moment every time she flew in rain. As she reflected upon this, she was able to apply what she had learned in class and come up with a reasonable explanation of what was happening. Unsolicited opportunities of this kind to employ engineering concepts help reinforce the learning at a much higher level. To encourage this kind of employment, students may be asked to maintain a reflection journal and discuss on a weekly basis what they think they learn in the course, how they learn it, what are their strengths and weaknesses, what are the challenges and highlights for them in the course and most importantly, how they think the material applies to the real world, and in particular, how it relates to their own personal experience. One should be sceptical about students who, although they managed to do well on homework and test problems, cannot come up with any connections of this kind.

RESPONSE

Response (feedback) refers to exchanges between the learner and *significant others* for the purpose of sharing information about both the subject being learned, as well as the degree of control that the learner has over it at any one time. Young children always receive such feedback from parents and others close to them.

Cambourne states that for feedback to be effective and contribute to the learning process it must be:

- Readily available and frequently given;
- Timely, relevant and appropriate;
- Non-threatening and with no-strings attached.

Giving students prompt feedback has been established as the 4th principle for good practice in higher education [8]. In engineering classes, feedback may be given to students by:

- Their classmates – assuming cooperative learning is used extensively in the course. This feedback is very valuable because students are often more sensitive to criticism from their peers than to criticism from their teachers.
- The instructor – through written or oral comments on various assignments. Again, a student will be much more open to instructor feedback when there is a good rapport between the two.
- Engineers from industry, which is available to students working on industry-sponsored projects or when engineers from industry are invited to judge student projects (eg student design competitions [9]).

When combined with opportunities for approximation as mentioned above, it is easy to see why feedback is an essential element for learning.

CONCLUSION

The preceding discussion makes the case for the universality of the eight conditions and, as a consequence, for their relevance in engineering. Based on the author's own experience as a learner and teacher, an understanding of these conditions, along with a conscious effort to satisfy them, always results in enhanced learning experiences for the students.

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