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# *Two 2-mm Shifts with CLT, in Preparation for VR*

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**Motivation**. The *engineering sense* is a widely accepted notion. It suggests the existence of a latent sense that, when developed in students would enable them, as clever practitioners of engineering, to recognize the kinds of solutions that might be successfully applied to problems in their fields.

Often, an associated tacit assumption is made. As with any of the *senses*, the student should possess the engineering sense in some form a priori, if he or she is to pursue the study of engineering. An educator then need not create and instill such a sense, but only help awaken it in proper context and guide its development, usually aided by suitable textbooks. As such, textbooks most often exert only a meager effort toward building reader intuition with their subject matter, counting on the insightful educators, and the experiences previously lived by students, to fill in that gap on behalf of the authors. Textbooks instead focus on supplying a specific body of necessary knowledge, a standardization of methods, and offering a plurality of examples that help illustrate the scope of the various methods, and help contextualize their utility.

Frequently, however, textbooks take center stage in course design, and the pitfall of closely following the book when explaining the material is not evaded. This could all be well and good, if the assumption of a pre-existing sense stands true, and students can really see into the subject matter at the time they are exposed to it. However, it is perhaps also a way to sustain a vicious cycle in education: students of a particular talent and mindset become educators in a well-matched field. They then write and follow books that target like-minded students, rather than capable students in general. The like-minded students are then poised to repeat the cycle.

In fact, any student who does not possess such a pre-existing sense, might find that typical curricula do not really teach them engineering, but rather inchoate information that is only opaquely related to it. It may not matter how many examples such a student sees and solves; the underlying mental attitude instantiated in those examples might never arise in his or her mind. While educators hope that their best efforts will indeed awaken and sharpen some latent sense of their subjects in *all* their students, they will recognize that only a small subset will respond to those efforts, however carefully designed and intently made. While this phenomenon renders grading easier (because it is easier to differentiate an A student from a B or C student), it does not speak to a widely successful educational system.

One might therefore ask, what if there is really no underlying sense to awaken in the average student, but instead only a set of thought-rules to be transferred? What are our curricula now doing to bring those unspoken rules out into the open for such a one to learn?

Consider for a start this elementary example from a 1000-level course:

> Let us study two cylindrical bars, each pinned at one end to, and inclined ±30º from, the ceiling. *Together* the bars carry a downward pointing load of 10-N that is applied to a pinned joint which connects their lower ends. How much load does *each* bar carry in this scenario?

The correct, but perhaps unintuitive, answer is also 10-N. Intuitively, one would think that the 10-N applied should be *shared* between the bars, so that each would carry less than 10-N. Perhaps, persuaded by the symmetric arrangement of the bars and applied load, one could even jump to the conclusion that each bar would carry half the applied load. While these intuitive thoughts are by no means unreasonable, they are wrong. When Newton's law and vector algebra are considered, which are not innate thought-rules, one then comes to the correct conclusion.

Now, no textbook (that I know of) will after such a problem openly state the unspoken rule that: the load one applies to a structure is *not* shared between its elements; instead, each of its elements could well be burdened by a *larger* load than what was applied to the structure on the whole. This conclusion is supported by a correct solution to the above problem, considering angles of less than 30º (not part of the question), and then generalizing the finding made in the problem (without guidance) to those engineering structures said to obey the laws of statics (and later, also dynamics). Clearly then, solving the problem correctly would only on rare occasions awaken such a realization in a student. What is actually required is that the student be in the habit of independently exploring sister problems in search of similar buried insights that will serve to build his or her engineering sense. Even if one morphs the example above into a multitude of different problems (abstract or practical), there is really no guarantee that an average student would come independently to the desired realization, which will be key to solving more advanced problems in mechanics (e.g. those involving *stress concentration*) in post-requisite courses.

Similar reliance on independent, insightful student reflection on problems is the norm for engineering studies, so that dedicating part of our educational effort to fostering such reflectiveness seems in order, or else it may not happen naturally for students without coaching.

**The First 2-mm Shift**. Early in the Spring of 2019, discussions with CLT drew my attention to *thought-process modeling* (TPM), whose aim is to articulate in-class some of what was habitually unspoken, i.e. to recognize that a matter traditionally considered to be commonsense is often not so commonly sensed by the broad swath of students. Implementation of TPM is attractively simple and uncostly. Basically: (a) Narrate your thinking out loud about a problem at hand and its expected answer, rephrasing the problem jargon-free when possible to better assess student expectations of the answer. (b) List with the class the knowledge structures constructed in the course (or in its prerequisites) that can be tried to solve that problem. (c) Ask students to share some of their thoughts on how to map (b) to (a), and discuss those thoughts with an eye to dispelling common misconceptions. It is helpful to personally identify with at least some of those misconceptions, to legitimize their evolving thought processes. (d) Latch onto the pivotal ideas that were raised, and which seem closest to correctness, and describe why and how you deem they could solve the problem. It is then useful to critique the solution's limitations, in light of the preceding thought processes, to contextualize its suitability and emphasize its non-universality.

Consider again the example of the two bars: (a) one could first ask the class: "clearly, each bar will carry less than the 10-N applied, right?". After a pause, "how can we find out for sure?". Most students will resort to silence, while others will bravely declare that "it is obviously true; no need to show it". (b) We then agree to turn to Newton's laws to settle the matter (whose authority is beyond question for us). (c) Some students will creatively blend Newton's law with their own personal expectations, to wring out of them their pre-chosen outcomes, often with catastrophic consequences. For instance, summing force magnitudes irrespective of direction, to confirm the preconceived answer of "half the applied load" as the solution to the problem. In such circumstances, a re-visit of the fundamental laws would not appear to fall beneath the educator's dignity, nor outside of the scope of the course. For instance, one could clarify that the vertical components of the forces do indeed align with the student expectations, but that horizontal components must also appear in the bars to alter the final outcome. (d) After the problem is correctly solved and its message summarized, one could discuss related ideas, e.g. the role of the pins in the problem, their non-universality across engineering applications, and how their change (to fixed supports, e.g.) might alter the details of the method and the findings.

Despite having tried a number of similar TPM instances in class, I only noticed mild classwide improvements to the key performance metrics of my 3000-level course. It appeared to me that the modeled thought processes only took root in those students that had the prior knowledge and mental attitude to foster them. Hence, my assumption of an existing a priori sense in my students had not been quite addressed by TPM.

**The Second 2-mm shift**. Subsequent discussions with CLT drew my attention to an interesting study (Perkins & Salomon, 1992) , whose very subject is the *transfer of knowledge* and its known difficulties in education. In that study, the authors skillfully contrast two types of knowledge transfer: *low-road* (i.e. to familiar real-life circumstances) versus *high-road* (i.e. to unfamiliar real-life circumstances). From an engineering perspective, it would seem helpful to map these two notions (respectively) to *interpolation* and *extrapolation*. Student application of thought processes modeled in-class to familiar problems is akin to interpolation. Their application of the same thought processes to less familiar settings is akin to extrapolation. We know well the perils of extrapolation, especially when contrasted to the well-behavedness of typical interpolation. The coveted engineering sense is thus that *intuitional* stand-in for unaffordable *analytical rigor*, on which one may rely to effectively tackle problems that are not familiar, as they arise in an engineering context. Its development thus greatly facilitates the extrapolative activities that are generally anticipated in the engineering profession.

It seems manageable to create such an intuition in our students, if we ask them to approach problem solving in standardized ways that openly recognize and embrace the frequent unaffordability of full rigor; ways that apply across the curriculum to ensure their proper internalization. As an example, one finds guidance in the notions of Validation, Verification and Uncertainty Quantification (VVUQ), which govern *predictive modeling* (and its known extrapolative activities). Namely, (a) a mathematical model that approximates a real system is developed, (b) an algorithm that approximates a solution to the mathematical model is written, (c) the solution is then verified to eliminate bugs and to quantify numerical error, (d) uncertain model parameters are then inferred based on the available data, (e) the accuracy and fitness of the model for its intended use are then validated, (f) the model is used to predict certain quantities of interest (QoI) in a new but related setting, and finally (g) the ranges of values for the QoI in that setting are assessed. These VVUQ notions could help students recognize the potential role for their intuition in problem solving, and help them make better guesstimates when required. Ideas (a) – (d) are typically covered in any good curriculum. However, ideas (e) – (g) often remain unspoken, especially in the earlier courses, or are lumped under the vague instruction to "check your work".

In my 3000-level course, it was not difficult to try (e) – (g) explicitly in a project. By the end of the semester average class performance on a holistic rubric that measures student ability to "examine multiple problem-solving approaches" leaped on Bloom's cognitive scale from 2.75/6 to 4.75/6. That came as a very pleasant surprise to me, given that the content I delivered and the method by which I delivered it were not altered much during the semester, just my problems were geared more explicitly toward the notions of VVUQ.

Even for the simple example of the two bars, VVUQ ideas could be brought up. For instance, for (e) one could ask students to describe their thoughts on whether their consideration of the bars as axial members is accurate and fit for their intended use. For (f) they could be asked to outline how the internal loads would change if the pinned joints are transformed to welds. For (g) they could discuss if the welds could in practice introduce further uncertainties, and how dramatic those uncertainties might be with respect to the load bearing capacity of the structure.

If general notions as those of VVUQ are spelled out across the curriculum, they could serve to instill and develop some of the desired thought-habits in many of our students. TPM would then only need to supplement these general notions, in the context of one's own subject.

**What next**? We are setting up a virtual reality (VR) lab that serves as a unifying exploration ground of key engineering applications, to help foster higher-order thought habits in students, e.g. VVUQ. In the VR lab students from across the program can explore real-life engineering applications, solution strategies and thought habits, in a less abstract setting (i.e. one of *enhanced ecological validity*), as well as provide them with a better opportunity to exchange knowledge across course boundaries (i.e., rendering curricula *soft boundaried*).