The Power of Differentiated Learning in Higher Education STEM

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Dr. Jeffrey Vitter’s inauguration as the 17th Chancellor of The University of Mississippi on 11th November, 2016, provided an opportunity to spread an important message and theme: “the power of higher education to transform lives, communities and the world”. In his inauguration speech, Dr. Vitter described higher education as the “…great enabler that helps people lift themselves above their circumstances and disadvantages” (Vitter, 2016). He also quoted Nelson Mandela’s belief that “education is the most powerful weapon you can use to change the world.”

These inspirational words are certainly true when you consider global economic performance of various countries (The Global Competitiveness Report 2015-2016). Using 2015-2016 data, Switzerland ranked first in the global competitive index (GCI), with the higher education and training pillar ranking at 6.0 out of 7. Singapore ranked second (GCI), with an education ranking of 6.2, while the United States of America was third (GCI) and with an education ranking of 5.9. Compare these rankings with Nigeria for example, which was ranked 124 out of 140 (GCI), with an education rank of 2.8 out of 7.0, or Guinea, with the lowest GCI and an education rank of 2.2. The GCI is based on 12 different pillars or identifiers such as health, financial market performance and technological readiness, but here it is compared with the higher education pillar to demonstrate its strong positive correlation with global performance. There is no question that the power of higher education does indeed transform lives, the community and the world.

Vitter also said at his inauguration (Vitter, 2016): “What does it take…to go from great to greater?”, and it is within this context that I focus on the actual nature or quality of “the power of higher education” in STEM professions in order to have long-lasting and far-reaching effects within our world. Despite high freshmen retention rates of our students (86.5% based on the 2014 cohort), and overall graduation rates slightly higher than the national average (The University of Mississippi, 2016), I
see the daily struggles of my students learning new content as they ‘master the art’ of their newly chosen profession, and hear about their many struggles in other classes as well. A small part of me is pleased about this, because these struggles enable students to develop grit and determination to overcome their obstacles. But another, much larger part of me is very displeased to see the demoralizing and negative effects of these struggles on students who had left high school with a positive opinion of their capabilities and potential. Several pedagogies practiced in K-12 settings are designed to enhance engagement and understanding through differentiated learning, experiential learning, team work, active learning, and project-based learning amongst others. Although students still face many struggles as they grapple with new concepts, the learning is structured in such a way to give them the best possible opportunities to progress. Why should these pedagogical techniques suddenly no longer be applicable in higher education? Scaffolded instruction should not stop simply because students ‘come of age’ and move to a higher educational institution. Pedagogical techniques are still a necessary requirement in higher education settings, and despite Piaget’s theory that children by age 16 should have mastered formal operational cognitive thinking, studies have shown that over half of students entering higher education are still at concrete operational thinking (Tomlinson-Keasey, 1978). This study, while now dated, still rings true at least anecdotally for many Professors today. Many of us have been – and will continue to be – educated via traditional lecture-style deliveries in higher education, but if the power of higher education can transform lives, communities and the world, imagine the phenomenal transformational power of an excellent education! At the University of Mississippi, we pride ourselves on offering a ‘great education’, but what can we do to make it greater? I take this opportunity to review and compare a) teaching in the higher education sector; b) the shift from simply ‘getting an education’ to ‘getting an excellent education’; and finally c) the interconnectedness of different disciplines necessary to deliver personalized or differentiated learning to all students, to truly participate in the transformative power of an ‘excellent’ education.

For many of us fortunate to have gained a Bachelor’s Degree or beyond, we will recall the tedious task of sitting through lectures driven entirely by the Professor, while participating in passive learning. We may have experienced a particularly engaging Professor who could keep us fully engrossed for an hour with ‘just words’. This is not necessarily a bad thing … if you’re a verbal learner who learns well by listening to content and making sense of your notes madly scribbled down in the rush to get the most from the lecture. Too bad for the much larger majority of the class who prefers to be actively participating with the content as they learn. Most of today’s Professors learned via passive learning, and do not see a problem in copying these teaching methods in their own classes. This method after all has been around since Universities first began, in the 11th century (Brockliss, 1996). It is well-known by educators in K-12 education settings that passive learning does not provide sufficient engagement and successful learning outcomes for many, although this knowledge has been slow to filter through to higher education. In a 2014 study by Freeman et al (2014), active learning strategies vs lecturing were compared via a meta-analysis of 225 STEM education studies in the literature. It was concluded that examination performance by students taught via active learning methods increased by almost half a standard deviation, meaning that a student could score up to 18% better than other students in the class if they were actively, rather than passively, taught. Additionally it was found that the risk of failure by students taught passively increased 55% compared with the failure risk of students participating in active learning strategies. In the 67 lecturing studies analyzed by Freeman et al (2014), they calculated that over 3,500 students would not have failed a STEM-based course, if taught actively. Pardon? How many students might this represent at a national level if all STEM-based courses delivered via traditional means were included? How many newly qualified STEM professionals might have
entered the workforce to transform lives, communities and the world?

Thankfully in more recent times, Engineering Education particularly is trending towards a more modern image. There are for example, several conferences specifically aimed at engineering education, such as the American Society for Engineering Education (ASEE) and the First Year Engineering Education (FYEE) conference, both well attended annually. These conferences allow for discussion on many active learning strategies within engineering, most of which have been adapted from K-12 pedagogies. They include experiential learning, project-based or design-based learning (PBL or DBL), peer-mentoring and independent studies of ethical issues, to name a few. Engineering by its very nature is a practical profession, whether it is designing new plants or experimenting with new concepts. Hence it is well-suited to experiential, project-based or design-based learning, where many of the theoretical concepts are more adequately mastered by use of such methods.

Farrell & Cavanagh (2014) discussed an experiential learning program devised for students in an introductory engineering course, where they participated in several laboratory trials to characterize biodiesel. Students worked in teams, learned various aspects of biodiesel production, purification and quality control, and were able to apply mathematics, science and engineering principles in their experimental design and analysis. This program was based on a pedagogical framework known as “How People Learn” (HPL), covering four main criteria of knowledge, learner, assessment, and community centeredness. This course addressed outcomes a, b, c, and e from the Accreditation Board for Engineering and Technology (ABET); and pre- and post-assessment tests indicated a highly effective study in achieving the stated learning objectives. Mantri (2014), reported results of a detailed study in India, designed to assess the effectiveness of PBL with large numbers of students in three courses from electronics and communication Engineering. PBL incorporates theoretical input from experiential learning and constructivist theory. Results demonstrated significant improvements in student engagement and knowledge/skill progression as a result of more interactive pedagogies compared with traditional means. Boylan-Ashraf, Freeman & Shelley (2015) performed a statistical study of structured or scaffolded learning in Introductory Engineering Courses, and found significant advancements in learning of students who participated in the active / student-centered delivery compared with the lecture-based delivery. In the Introduction to Chemical Engineering course (ChE101) at the University of Mississippi, I have implemented a freshman design project where students explore the scale-up opportunities of preparing chocolate bars into a full-scale process. This experiential project, while challenging, showed quantum leaps in learning by many students, and an enhanced confidence and ability in knowledge, as judged by subsequent assessments. All of these examples show high engagement by the students and a depth of learning that is difficult to replicate by passively listening to lectures. While these examples demonstrate we are offering a great education, what can we do to make it greater?

Personalized learning is one of the grand challenges for engineers in the 21st century (NAE Grand Challenges for Engineering, 2016) from a technological point of view. As an educational strategy, it is known as differentiated learning or targeted learning, and is essentially a framework within which student need is identified early into a course. Armed with this information, educators carefully choose activities that best meet the needs of their learners to enhance the outcomes of every student. The framework at the K-12 level consists of five principles (Rock, Gregg, Ellis & Gable, 2008; Tomlinson, 1999; Prager, 2013): 1) Understand student need and preferred learning modes; 2) Focus on key concepts and provide multiple approaches to learning; 3) Provide challenging learning experiences within each student’s Zone of Proximal Development (ZPD); 4) Foster collaboration between students and 5) Create independent learners and student ownership of learning. This framework is well-practiced throughout the world in many K-12 settings (eg Valiandes, 2015; Wu, 2013; Bullock, 2016), but is sadly lacking in most higher education settings. I am presently
adapting these principles into this arena, focusing mainly on the later-acquired cognitive thinking appropriate at this level, however the key ingredients are still relevant.

Implementing such a framework into a higher-education class does appear onerous to a Professor, particularly given the academic pressures of research performance in addition to teaching. And granted, this is of genuine concern, however, going from ‘great’ to ‘greater’ takes work, dedication, and perhaps short-term modified work priorities in order to successfully implement such an important program. Mantri (2014) also noted the ‘non-trivial’ nature of suitably training faculty to improve their capabilities within the classroom in delivering student-centered learning, and others also mention time constraints as a barrier to effective implementation (e.g. Lavis et al, 2016). A typical differentiated classroom would start with the Professor collecting initial data on the students to find out their present academic abilities and their preferred modes of learning. ‘Teaching content’ would be replaced with identifying the main concepts of a topic, and also teaching these concepts in multiple ways. Several of the active learning strategies outlined above (e.g. experiential learning, PBL) would be employed in accordance with the students’ preferred learning modes. Depth to this learning would proceed with additional activities designed to extend the students’ current understanding to the next level. Clearly students would be at a range of different levels of understanding, and addressing these needs would require provision for beginning, intermediate and advanced tasks. Collaborative tasks would be added to promote further depth to the learning, and provide additional means for students to construct their knowledge from each other. Throughout the concept development, depth of learning, and collaborative tasks, the Professor would check in with the knowledge growth, (i.e. attending to student needs) and review content and support learning as required. Finally, armed with the mastery of concepts and depth of knowledge, students would eventually progress towards taking ownership of their learning and creativity. With this type of framework, one can see that a great education employing active learning strategies can be made greater by directly attending to student needs and providing support for all students in their chosen course of study. If active learning strategies can reduce failure rates (compared with passive learning) by 55%, how much more could be achieved with differentiated learning, where strategies to address personal needs are accomplished?

This question is in-part answered by a small body of differentiated learning studies attempted at the university level, with some excellent results. Chamberlin and Powers (2010) implemented a differentiated curriculum for first year mathematics students in the Rocky Mountain region, USA, in two regional centers. Both institutions ran the course: number and operations, and taught five sections at each college with a total of 224 student participants. One institution served as the control while the other was the treatment group, where differentiated instruction was implemented between one and two times per unit, and overall approximately one-third of the course. ‘Differentiated instruction’ for this study included an initial gathering of data to assess students’ readiness, interests and learning profiles, followed by a range of activities based on their needs. These included tiered activities in class to either improve or extend understanding; whole class discussions; student work groups within class; choice of activities catering for different learning modes; pro-active instructional modification based on students’ needs; homework sheets with differentiated tasks; and finally, formative and summative testing. Analysis of the pre- and post-testing from both student groups revealed that the treatment group scored an average 1.7 times higher than they did on the pre-test; while the control group scored only 0.3 times higher. Konstantinou-Katzi, Tsolaki, Meletiou-Mavrotheris, & Koutselini (2013) also created a differentiated program for 27 first year engineering mathematics students. These students had come from diverse secondary-schooling backgrounds, namely from ‘science-direction’ learning; ‘non-science-direction’
learning; and ‘technical-direction’ learning. Consequently, a pre-test of concepts ranging from basic to advanced knowledge for Calculus I revealed a normal distribution with most students scoring a C (66 – 75%). Differentiated instruction was implemented into this class for the semester, using activities ranging from direct instruction; interactive and collaborative learning; revisiting concepts requiring additional attention; teacher intervention; and back-up materials provided for additional individual learning. In all cases, activities were prepared for three levels covering pre-requisite, essential and transformational knowledge and skills. In the post-assessment test, 13 more A-grades and 15 less ‘C-or-below’ grades were recorded, demonstrating improvements by most students as opposed to improvements only from the ‘average student’. These results complement the many studies done on differentiated learning in K-12 settings, and confirm the overall success of utilizing the key differentiation principles in the classroom.

Intentional implementation of personalized learning requires an interconnectedness amongst different disciplines: engineering and computer science; education; behavioral psychology; and neuroscience or brain-based research. Universities are well-positioned to draw these various disciplines together, where the ‘best of the best’ can synergestically come up with a multi-disciplinary solution. A brief review of educational literature in recent years does in fact show evolvement of this multi-disciplined approach, and results are fostering a far more targeted approach to enhance learning outcomes of all students. While this has generated much excitement and interest within the respective research areas, there is still work to be done in fully realizing and implementing personalized learning at all educational levels (K-16).

Activation patterns in the brain can be imaged using fMRI, and several studies have reported working memory being served by frontal areas of the brain, specifically the fronto-parietal areas and the basal ganglia (cited in Ischebeck, Zamarian, Egger, Schoke, & Delazer, 2007). However, studies with adults previously trained in arithmetic operations showed different regions of brain activation, specifically in the left angular gyrus, representing the brain retrieving information from long-term memory rather than from working memory (or short-term memory) (Ischebeck et al, 2007). This shift in brain activity demonstrates to the educator that learning has been successful, and has resulted in long-term knowledge for the individual. Ischebeck et al (2007) presented complex multiplication problems to healthy adults on a repeated basis and novel problems less frequently, and demonstrated that repetition after eight times showed a significant change in brain activation patterns with higher input from the left angular gyrus (linked with long-term memory). This valuable insight contradicts common perceptions in higher education, where a new topic or concept need be taught only once, rapidly disseminated to students, followed immediately by another. The onus on students to continually review the material is vital for the brain to receive the necessary repetition (preferably in different modes) for learning. Ceuvas (2016), a cognitive psychologist, discusses three types of memory storage – episodic, semantic and procedural – identifying episodic memory as that most likely to fade or reduce with time. He cites episodic memory as the form initially established within a classroom, and that in order for students to genuinely learn and gain long-term knowledge, that episodic memory must be converted to procedural memory. This is much like the shift in brain patterns observed from fronto-parietal areas to the angular gyrus. Ceuvas (2016) argues that while higher-order thinking as per Bloom’s taxonomy is paramount in developing challenging processing of thought that can promote procedural memory, practice and reinforcement (and hence repetition) of these processes is required to fully engrain the long-term memory. Therefore repetition, not to be confused with rote learning of mundane facts, is a necessary key in activating the long-term memory storage of the brain, as identified by the brain imaging described earlier (Ischebeck et al, 2007).
Neurologist and educator Willis (2007) explains the brain functioning using a different analogy. The brain stores information in neurons, and additional knowledge is gained when neurons communicate with each other by forming dendrites. The more skills, information and experience; the more dendrites that form and the larger they become. However, these connections can also decrease if the information is not regularly used or practiced. The more different ways a particular concept is learned by students; the thicker the dendrite branching becomes and hence the greater chance of shifting short-term memory into long-term memory. Additionally, the more engaging ways the brain is stimulated with new concepts; the greater the long-term memory that is built. Building relationship and creating experience for learners with their learning content also assists the brain in building multiple pathways to the same storage centers of information.

The active learning strategies (eg HPL, PBL, scaffolded learning) practiced in some Engineering Education Centers described earlier certainly promote relationship with the content and create experience for the students, and therefore their positive learning outcomes make sense based on the improved multiple pathways within the brain created. However, differentiated learning takes these positive effects further. Using the five differentiation principles enables educators to shape the learning based on learner need and present information in multiple ways (i.e., build the repetition to shift from working- to long-term memory). Depth and higher-order thinking can be added to the learning process to foster long-term memory and capabilities. Collaborative activities enable additional ways of learning the same content, creating a different relationship with the learning material and allowing learners to construct new knowledge from their peers, in accordance with Vygotsky’s constructivist theory. Frequent formative assessment of students to identify their current struggles and subsequently addressing these issues correlates well with brain-based research that identifies repetition and practice for long-term memory to be established. It is also clear that students require different amounts of repetition depending on their prior knowledge, and different types of stimulation depending on their many individual factors, and hence the learning experience becomes individualized or differentiated to cater for each of their needs. The differentiation framework essentially provides an avenue which supports the current findings of brain-based research, and an educator can become highly creative within these boundaries while keeping in mind the implications of student-centered activities on brain activity. With a new generation of students equipped with longer-term knowledge in their chosen profession, imagine the power of utilizing in-depth knowledge to transform the lives of individuals, communities and beyond?

In addition to implementing such techniques into Engineering Education, engineers themselves have an important role to play in the development of personalized education from a technological viewpoint. In a technology-driven era, it is tempting to take up the challenges of automating processes, even education. Personalized learning tools are in fact available in some instances, such as drill-based mathematics or language software programs that adapt to the learner’s responses by gradually increasing or decreasing the level of difficulty as required. Several textbooks are being rewritten as interactive online texts with similar capabilities and prompts along the way for students to access when learning new concepts. The challenges for engineers and computer scientists is to produce this type of
learning on a mass-scale – for example, there are few textbooks written for specialized subjects in Chemical engineering designed in this way. But is automation of personalized learning the right way to go? Certainly as a tool within a toolkit of many possible options for differentiated learning, this technique could indeed be useful, but caution is to be practiced in relying too heavily on any one technique. Levinson, Weaver, Garside, McGinn & Norman (2007) investigated computer-aided instruction in medical education, using simulations and multiple view of various anatomical structures. Students with poor spatial ability had a reduced performance of almost 30%, which was quite significant. This result was matched with other studies that also showed, for some students, a significant drop in performance via the use of e-learning of complex structures. Online textbooks, and links to you-tube clips or other multimedia isn’t necessarily the answer to higher engagement and long-term knowledge gain, and it is important for the educator to understand and experiment with each class which activities contribute to angular gyrus brain activation. Any potential downside to activities that may not be as effective can be minimized by keeping in mind the need for multiple approaches to learning and the use of multiple stimulations.

To recap, I have described the typical experiences of students in higher STEM education; the significant advancements possible for students with the implementation of differentiated teaching and learning techniques; and finally the role that interdisciplinary research has and can continue to play in the widespread introduction of personalized learning in higher education. Dr. Vitter is right to focus this university on the transformational possibilities available through the power of higher education. While the power of higher education does indeed transform lives, communities and the world, I argue that the power of an excellent education, uniquely directed to the needs of each learner, is significantly more transformative. Differentiated learning is a concept that must be embraced by our university in order to make our ‘great education even greater’.

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