2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
ASEE
Paper ID #37315

Teaching or Learning? A Framework for Shaping Good Old Fashioned Engineering Students

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Abstract

Engineering educators are struggling more and more with underprepared students. The typical approach has been to engage in teaching innovations with the goal of educating innovative engineers. But what if the issue is not the teaching, but the learning? To create a framework for educating innovative engineers, this paper seeks to catalogue how innovative engineers were educated. A framework for shaping self-directed, lifelong learners, developed by reviewing the learning strategies, activities, and mindsets of self-directed lifelong learners, can usefully evaluate learning activities developed for engineering students. Starting with the current need as identified by engineering societies and continuing through living expert learners, engineering giants, great American autodidacts, Renaissance and Reformation learners, the commonalities of lifelong learners clearly illustrate the features of the framework. Innovative engineers are committed to self-directed lifelong learning (typically through reading, notetaking, and practice), are curious about the outside world, and desire to shape that world according to its creation order. Lifelong learners also benefit from camaraderie between fellow learners and sympathy from faculty and mentors. From this understanding, engineering educators can develop activities and assignments that foster these attitudes and enforce practice in the activities of lifelong learners.

Introduction

In the West, the educational system shows signs of an imminent failure. Whether by design, negligence, or ignorance, graduates from American high schools lack critical thinking and mastery of basic knowledge to be successful in life, higher education, or engineering [1]–[5]. In many ways, the current educational moment has forgotten its two-fold aim: "the systematic development and cultivation of powers of mind and body" and "the systematic inculcation of knowledge" [6]. Engineering educators may no longer assume their students are trained in how to learn or have internalized "such knowledge as may be useful in gaining other knowledge, … the love of learning, [or] … the habits of independent study" [6]. Rather, a growing number of incoming engineering students lack basic math and science literacy and the skills required to learn new content as expected and required for success in engineering programs. At the same time, established practitioners, engineering societies and accrediting bodies demand engineers be lifelong, self-directed learners [7], [8]. This places engineering educators in a difficult position: taking under-prepared incoming students and creating self-directed lifelong learners capable of mastering themselves against external manipulation [9], of mastering inherited knowledge from previous generations [10], and of expanding their mastery to solve the problems of the future [11]. Ultimately, the goal of every educator should be to see students increase in true understanding. "A disciple is not above his teacher, but everyone when he is fully trained will be like his teacher" [12] requiring the teacher to be "the kind of person the students want to become like" [6].

So how can engineering educators respond to this challenge? Far too often, the first step is to complain: students are unmotivated, fellow faculty are focused on research, COVID has made everything worse, etc. Alternatively, engineer educators seek to make their teaching more engaging through active learning, flipped classrooms, adaptive homework, AI-powered personal learning, and more! “Yet even in the most advanced classrooms, many students seem to fail to grasp and retain information beyond simple short-term recall. In many cases, students are left without any meaningful increase in their understanding, understanding that is frequently assumed in future courses [13]. The result is students who either retake courses, change majors, dropout or painfully scrap by” getting through courses often on the pity of instructors [14].

Education has experienced nearly 100 years of focus on teaching pedagogy. John Dewey lead educators down Rousseau’s satirical take on education [2], [10] inspiring newspaper writers to argue the easy fix for public education is “burning the buildings and hanging the professors” [15]. From its inception, ASEE has been advocating for the same basic teaching reforms of the Rousseau/Dewey pedogeological ideology, yet “there is nothing new under the sun” [16]. When engineering educators are tempted to blame to K-12 education, in a confused exercise of Hegelian synthesis, more and more of ASEE’s policy recommendations reflect the failing pedagogical and sociological ideologies adopted by that same K-12 system [17].

Perhaps, the educational reforms of the last century have inverted the problem. More and more emphasis has been placed on the teaching innovation. Western culture since the world wars has valued Rousseau’s “noble savage” and Wordsworth’s “Idiot Boy” idealization of youth while devaluing the wisdom of age [18]–[20]. Rather than promoting flourishing in learning, by neglect of the universal laws of teaching, technological innovations in education may hamstring future student development as “man’s power over nature turns out to be power exercised by some men over other men with nature as it’s instrument” [21]. Yet, ill-prepared modern engineering students are the products of a system not of their choosing.

How can engineering educators lead students toward lifelong learning and self-mastery despite their often deficient educational and social development? Older traditions might hold the key for “tradition means giving a vote to the most obscure of all classes, our ancestors. It is the democracy of the dead” [22]. To support engineering educators seeking to educate innovative engineers [23]–[25], a learning (rather than teaching) framework will emerge from an investigation of the education of innovative engineers. The challenge might not be in the skill of the teacher to teach but the skill of the learner to learn. A framework of mindsets, practices, and skills gleaned from the histories of self-directed lifelong learners should help educators know what attitudes, emphasizes, and skills to develop in themselves and their students. With such a framework, educators should design activities that both allow students to master course content and develop the skills and attitudes of the lifelong learner. Like all good engineers, educators should begin with end in mind.

The Education of Innovators

Engineering Accreditors and Professional Societies

Lifelong learning is a skill to practice in both the cognitive and affective domains [8]. Every accrediting body and professional society advocates for the development of lifelong learners [26]. As one example, the American Society of Civil Engineers *Body of Knowledge* argues for lifelong learning skills to develop through “undergraduate education and mentoring experiences” [7]. During college, students should engage in “independent study projects and open-ended problems” with the goal of pushing beyond the presentations of their instructors [7]. As professionals, engineers should engage with “continuing education, professional practice experience, and active involvement in professional societies, community service, coaching, mentoring, and other learning and growth activities” [7]. Though the goal of lifelong learning is laudable, the advocated means may reflect an underdeveloped understanding of the nature of self-directed lifelong learning; many of these activities are little more than extensions of the instructor-centric college experience. By an anemic understanding of the full nature of lifelong learning, “in a sort of ghastly simplicity we remove the organ and demand the function. We make men without chests and expect of them virtue and enterprise. We laugh at honor and are shocked to find traitors in our midst. We castrate and bid the geldings be fruitful” [21]. We spoon feed our students and demand they feed themselves.

That said, professional societies have an important role to play; lifelong learners depend on a network of fellow lifelong learners. C.S. Lewis and J.R.R. Tolkien’s think tank the Inklings produced stupendous cultural creation and critical thinking [27]. Ben Franklin’s Junto similarly shaped the American founding [28]. Engineering companies are frequently named for a team of principle professional engineers that shared common goals. Professional societies house the knowledge of previous generations and make it available to future generations. In so many ways, professional societies provide lifelong learners the opportunities to engage with other lifelong learners both living and past.

Living Expert Learners

A living generation of self-directed, lifelong learners fill the ranks of industry and academia. The successful engineers of this generation either had or rapidly developed self-directed learning traits to survive the gauntlet of the weed-out engineering programs that dominated higher education from the 1970s to the 2010s. The most respected universities built their reputations by only accepting the most qualified students, those students who already possessed considerable skill in learning [29]. An anecdotal survey of doctorate-holding engineering faculty tells a clear story. In the largest engineering programs, unprepared teaching assistants or distracted research-minded faculty were the least helpful learning resource. What these college courses did provide were tools for learning and practice (textbooks, homework, projects, etc.) and evaluations of mastery (midterms and finals). Though ineffective teachers were undesirable, successful students knew how to learn for themselves by reading the textbook, by notetaking from both book and lecture, by practice on homework and projects, and by mutual sharpening through work with other students. Their undergraduate professors provided the “intervention of a single coherent and personal authority to direct the [student’s] will at its beginning … for it to be self-directing afterword” [10]. The authority of the “sage on the stage” provided the influence and the will to obey that motivated developing engineers toward graduation and future careers. These learners continued to develop through academic reading, practical design, and dissertation writing to perform the highest levels of idea synthesis and experimental innovation [30].

Engineering Giants

The truly great engineers had a curiosity about the world around them and a deep desire to shape that world. Two skills frequently marked the truly great engineers: visual-spatial mastery of the mathematics and physics that describe the world, and a commitment to observation of the particulars in their practice. William F. Baker (1953-) epitomizes the visual-spatial mastery of physics and mathematics. While designing his many projects including the Burj Khalifa, he worked in two-dimensional projections to trace load paths and identify the reactions required for static equilibrium. This ability allowed him to develop preliminary designs for complex structures before turning to computer modeling [31]. Ralph Peck (1912-2008) argued for all engineers to commit to daily notetaking of field observations. The practice of learning in the field required more than looking at construction activities; the engineer has to really see what is happening [32]. Peck's mentor and the father of modern geotechnical engineering, Karl Terzaghi (1883-1963) drafted his foundational soil texts on the job site. Terzaghi would bring a writing desk to the site and meticulously record every observation. He was then able to apply his spatial understanding and mastery of mathematics to create foundation capacity models still in use today [33]. Christian Otto Mohr (1835-1918) developed his now universally taught Mohr's Circle through synthesis of his experience building railway bridges, his teaching, and his love for graphical presentations of complex mathematical models [34]. Each of these engineering innovators and many others practiced the lifelong learning skills of notetaking and observation combined with a deep understanding of visually represented mathematical models.

Great American Autodidacts

America has a long history of exceptional engineering innovators. Each of these innovators depended on self-directed lifelong learning. Many were homeschooled or without formal education. Henry Ford (1864-1947) learned through observation and tinkering [35]. Thomas Edison (1847-1931) voraciously read technical and scientific books in his early teens [36]. Michael Faraday (1791-1867) structured his self-education on Isaac Watts' (1674-1748) *Improvement of the Mind* devouring books during his seven year apprenticeship [37]. Benjamin Franklin (1706-1790) sought out new vocational opportunities at every turn in the pursuit of his self-directed education [28]. Though, any one of these innovators and many more would be worthy of a deeper dive into to the makings of their education, a less well-known American innovator, Nathaniel Bowditch (1773-1838), provides an excellent example of a self-directed, lifelong learner.

Nathaniel Bowditch revolutionized naval navigation and helped establish American sailing dominance at the dawn of the 19^{th} century by developing a method for determining longitude without a chronometer. He shared his knowledge of astronomy and mathematics in the *American Practical Navigator*, a book in continuous revision and publication since 1802. During Bowditch's lifetime, the *American Practical Navigator* was known as the "Seaman's Bible"; today's U.S. Navy simply refers to the book as *Bowditch*. At various times, he was extended and then rejected invitations to serve as mathematics chair at Harvard, University of Virginia, and West Point. His labor of love was to translate, expand, and publish Laplace's (1749-1827) *Mecanique Celeste* [38]. What education equipped Nathaniel Bowditch to innovatively change the world so profoundly?

Born at the same time as his nation, Bowditch experienced only the most basic schooling, before his mother's death and his father's alcoholism forced him into indentured servitude from the age of 12 to 23. Entering indentured servitude with only the fundamentals of reading and arithmetic, he worked through the small library of his master, John Ropes, son of Judge Nathaniel Ropes. Later two mentors, Reverend John Prince and Reverend William Bentley, secured the young Nathanial Bowditch access to the inventory of the Kirwan Library (captured by Yankee privateers in 1780 and stewarded by the Philosophical Library Company of Salem, Massachusetts). “Bowditch’s method of study was direct and thorough. He sat down to the books and – with interruption for working, eating, and sleeping – read straight through them” [39]. He kept Commonplace Books, containing copied book sections and notes on many topics. He practiced problem solving using chalk and slate. As navigator, supercargo, and captain, Bowditch taught his crews, uneducated men before the mast, how to calculate longitude from lunars with an unaffected sincerity and unbridled enthusiasm. With nothing more than lexicon and Bible, Nathaniel taught himself Latin and French so that he could read (and correct) Isaac Newton’s *Principia* and Laplace’s *Mecanique Celeste* in their original languages [40].

Observation, curiosity, and logical thinking undergirded every aspect of the education of American innovators. The basics practices of a lifelong learner can be catalogued from their biographies: mentoring established scaffolding and resources, reading provided content, notetaking, practice, and peer-instruction solidified learning. These practices are the practices of every lifelong learner.

Autobiographical Aside

The life of Nathaniel Bowditch deeply shaped the author in his childhood. When first exposed to the Newberry Award winning, *Carry on Mr. Bowditch* [40] in fourth grade, the world transformed: a barely literate child of ten discovered that knowledge on almost everything could be found in books. By the age of twelve, his exuberant love for reading resulted in a birthday celebration held at the Central Branch of the Dallas Library to see where his favorite books lived, at least when not checked out. A passion for learning, ready access to a plethora of books, and a home education that encouraged scientific exploration, critical thinking, and writing to explore new ideas established the author for success at any college. His ability to excel academically regardless of instructor skill in teaching allowed him to secure a fulltime research aid position while still working on his master’s degree. This path makes him distinctly different from his current students but eager to inspire the same enthusiasm and learning skills that have empowered his career and learning.

Renaissance

Moving back even farther, the innovators of the Renaissance and Reformation era provide yet another perspective on education. The Renaissance learners, from Leonardo da Vinci (1452-1519) to Galileo Galilei (1564-1642) to Johannes Kepler (1571-1630) to Rene Descartes (1592-1650), each benefited from two emphasizes often neglected by modern engineering educators: a coherent Christian worldview and a classical education. Isaac Newton (1642-1726) is an exceptional example of an innovator who both embraced a healthy worldview and classical training. His formal education in Greek, Latin and mathematics equipped him to read the innovators before him: Descartes, Galileo, and Kepler. From this grammar and dialectic, Newton developed theories of motion and differential calculus that still informs much engineering today.

Renaissance era learners were shaped by a classical education. Before attempting to innovate, each of these learners submitted to the ideas of the generations that came before them. The Renaissance and Reformation were powered by a deep literacy in the knowledge of previous generations, be it the works of Greco-Roman antiquity for the Renaissance or the Bible in its original languages for the Reformation. This made each learner deeply aware of his dependence on previous generations. To contribute meaningfully to the future, a learner must be taught the non-obvious: the history of knowledge that came before. This applies equally to the foundations of western civilization as well as scientific thought [10] and stands in strong opposition to the anti-historicism of the neo-Marxists, inheritors of the Frankfort School, and activists in the "long-march through the institutions" [41]. To lean into a Rousseau/Dewey constructivist ideology where the instructor acts as a "guide on the side" may delude students into thinking they, unaided, have discovered how the world works and can evoke an unhinged narcissism [10].

Instead, a rapidly growing body of reformist (not progressivist) educators argue, primarily within the homeschool and private school movements, for a return to the classical model of education [14], [42], [43]. The classical model that empowered the early modern European universities used the Trivium of grammar, dialectic, and rhetoric to scaffold student learning and so fulfill the law that "the truth to be taught must be learned through truth already known" [6]. In the grammar stage, students learn the building blocks of the topic at hand. For engineering, math and experimental sciences provide foundational knowledge. Frequently, the grammar stage is best learned by Locke's "rules and rote"; until a student knows *something* they cannot be expected to meaningfully create *anything* [10]. The dialectic stage teaches students to compare, contrast, differentiate, and discriminate between various arguments and facts. The dialectic stage is primarily based on thesis-antithesis logic grounded in the law of non-contradiction [44] and by necessity rejects the Hegelian dialectic that dominates postmodern cultural decline. In engineering mechanics courses (Statics, Dynamics, Fluids, Thermodynamics, Circuits, Materials, etc.), students develop their dialectic skills. The final stage of rhetoric equips students to take their base knowledge (grammar) and their logical thinking (dialectic) and to generate new ideas, new arguments, new solutions, and new designs. An explicitly classical model of education grants students an awareness of what they are learning and where their education is taking them. Students then make connections between and across courses as opposed to previous educational experiences that rewarded performing on a final exam rather than internalizing knowledge.

Reformation

Renaissance and Reformation era learners also benefited from a common Christian worldview. The dominate current scientific and engineering epistemology embraces a materialistic and random evolutionary model of the world that asserts "the uniformity of natural causes in a closed system" [45]. This sadly, places man as a cog in the machine of an impersonal universe and leaves him "below the line of despair" in a meaningless world and without purpose [46]. The learners of the Renaissance and Reformation labored with far more hope. They confidently pursued the underlying truths in the world through an epistemology built on "the uniformity of natural causes in a limited system, open to reordering by God and by man [as God's image bearer]" [45]. Even those who were not themselves orthodox Christians believed that a personal and immutable Creator made the universe, giving these lifelong learners the confidence needed to observe the particulars and search out the universal laws that governed those particulars.

Likewise, these learners believed that their developing knowledge could make a difference in the world and benefit mankind, allowing them to "be fruitful and multiply and fill the earth and subdue it" [47]. By contrast, the Enlightenment aimed to make man his own "integration point" [48] and eventually culminated in the current unrivaled idolatry of the atomistic individual and the demand for unrestrained self-expression [20]. Arguably, to the degree that engineers and scientists have embraced such a God-denying outlook, innovation has reduced to iterative technological advances, rather than true developments in fundamental understanding achieved by the likes of Newton and Faraday. Even later innovators like Alfred North Whitehead (1861-1947), Albert Einstein (1879-1955), and J. Robert Oppenheimer (1904-1967) recognized that the Christian worldview, alone among rival worldviews, gave rise to modern science [49].

Some may argue that these distinctly western forms of education and worldview belittle the great engineering achievements of cultures throughout the Africa, the Middle East, and Asia. Though common grace resulted in many great engineering feats, the shape of modern engineering and engineering education is distinctly Western. The Renaissance and Reformation gave rise to the modern university in Europe, the theological founding of the ivy league colleges in North America, and the subsequent exporting of the bachelor, master, and doctorate structures of higher education across the globe. These educational structures, where they have taken deepest root, have resulted in human flourishing and engineering success in the modern era.

The coherent Christian worldview keeps engineering students from the ditches on both sides: they are neither "entirely ineffectual" in their ability to shape the world to their will or "omnipotent" in every situation [10]. Rather than the unhindered self-expression of a generation given to despair, depression, and anxiety, current engineering students could experience hope, meaning, and purpose through the knowledge of the Creator and reconciliation through His Son, Jesus Christ. Engineering students should be taught to "conform their will and judgement to certain external facts of physics that remain non-negotiable… To practice the craft is to enter into a relationship with a world that exists independently of oneself" [50]. Engineering students may learn the appropriate relationship between reality, their mental models, and the engineering models taught in the classroom [51]. A recovery of such a worldview should equip and inspire engineering students to truly understand creation and advance human flourishing.

These last two characteristics may cause the greatest cultural dissonance of all the ideas presented in this paper. The decadent west is committed to atomistic individualism and autonomy [52]. Yet, effective, self-directed lifelong learners must submit to the wisdom of those who preceded them and embrace that in their creatureliness they may know "truly" even as they will never know "exhaustively" [46]. In these two truths, there is exceptional liberty.

The Framework

If engineering educators desire to educate innovative engineers, this review of the education of innovative engineers may guide the development of learning practices and pathways. Consider the commonalities seen in the innovative engineers and autodidactic learners of the past:

Commitment to Self-Directed Learning

Self-directed lifelong learners collect and organize information for themselves. They read hard books and take notes. They attend lectures and take notes. They use their notes to write, synthesize ideas, and make connections across levels of learning. They are supported when learning is scaffolded through a classical model of education and training on reading [30] and notetaking [53], [54].

> "Blessed is the one who finds wisdom,
> and the one who gets understanding." [55]

Curious Engagement with the Outside World

Self-directed lifelong learners are marked by intrinsic curiosity leading to exploration, observation, and experimentation. In lifelong learners these activities often take place on their own or through conscientious engagement with vocational opportunities. Such curiosity is most hopeful when empowered by a worldview that aims to align the engineer's mental model with the objective external reality of creation. The world is a truly magical place and worthy of independent study in which the learner takes personal responsibility [56].

> "When I look at your heavens, the work of your fingers,
> the moon and the stars, which you have set in place,
> what is man that you are mindful of him,
> and the son of man that you care for him?"[57]

Desire to Communicate and Apply Understanding

Self-directed lifelong learners desire to shape the world. They aim to develop the logic, visual-spatial reasoning and critical thinking required to fulfill their purpose. They practice problem solving in familiar and unfamiliar contexts [58]. They want to develop the communication skills of writing, mathematics, and sketching to "paint in another's mind the mental picture in one's own" [6]. Working with others, they engage in exercising dominion and transforming creation.

> "So God created man in his own image,
> in the image of God he created him;
> male and female he created them.
> And God blessed them. And God said to them,
> 'Be fruitful and multiply and fill the earth and subdue it, and have dominion over the fish of the sea and over the birds of the heavens and over every living thing that moves on the earth.'" [47]

Camaraderie Between Students

Self-directed lifelong learners engage with fellow learners through professional societies, peer-instruction, and service to developing learners in their midst. They solve problems together and help others solve problems as well.

> "Iron sharpens iron,
> and one man sharpens another." [59]

Sympathy Between Faculty and Students

Self-directed lifelong learners require mentorship and authority figures. Mentors illuminate learning pathways and provide resources and experience. Proper authority inspires emulation (rather than demanding obedience) in the mastery of content [10]. Submission to the wisdom of previous generations enables learners to build on the success of others.

> "Wisdom is with the aged,
> and understanding in length of days" [60]

Presuppositions

This framework assumes that students will learn to create the new on their own, but what they need is instruction in historical knowledge, instruction in that which is not obvious. The framework presumes that wisdom is learning, not only by personal experience, but also by the experience of others. The framework argues that self-directed, lifelong learners working as engineers must understand, describe, and work with an objective reality (neither infinitely malleable, nor deterministically material) toward human flourishing. The framework also requires that human language (both mathematic and linguistic) is representative, and not a self-referential construct [46]. The framework embraces that humans can know truly and objectively (thereby rejecting post-modernism) though not comprehensively or exhaustively (thereby rejecting modernism).

Applying the Framework

How can engineering educators educate innovative engineers? First, they must not pull back from their role as an authority in their students' lives [9]. Engineering educators are responsible for providing the scaffolding and resources required to support student learning. They must provide good learning resources that mirror the types of resources (*i.e.*, books and codes) that will be used in their professional lives rather than tethering them to novel indoctrination methods shaped as much by the medium as the intended message [61], [62]. As engineering educators consider the impact of the Internet, YouTube, and artificial intelligence on the access and formation of knowledge, this framework can provide a grounding standard to guide interactions, assignments, and assessment in the engineering curriculum.

Engineering educators can facilitate the inter-student camaraderie of a strong learning environment. They can provide peer-instruction opportunities, discussions, and group projects to facilitate this engagement. In many cases, this is already accepted best practice in the engineering education community [63]–[66].

Engineering educators have the unique opportunity to encourage the mindsets and practices of self-directed lifelong learners and engineers [25], [67]. Engineering educators can give students the opportunity to practice presenting their ideas to others. They can establish opportunities to solve problems and learn from their mistakes. Effective homework methodologies can support this kind of learning [67]–[73]. Other methodologies may undermine lifelong learning practices though an overemphasis on the appearance of initial accuracy rather than the development of understanding [13], [74]–[76].

Engineering educators have a unique opportunity to inspire students to engage with the outside world. They should encourage students to work in laborer, technician, co-op, internship and research positions and document their experiences [77]–[79]. They can be eager to answer questions about how the world works and be honest when they do not know.

Engineering educators can help students develop their reading, listening, observing and notetaking skills through various assignments. Discussion boards, after-action reports, notetaking assignments, and reflections can engage students in this kind of learning. In any given assignment, the goal of this framework is to help engineering educators design activities that support the skills of lifelong learners, rather than undermining learning through an overemphasis on summative assessment or a dependence on teachers and/or trendy teaching methods.

Finally, engineering educators can inspire students with a coherent worldview. By establishing their narrative location in history and culture, engineering educators have an opportunity to help students make sense of the world, develop their vocational calling, and inspire them to shape the world as God's image bearers, reconciled to their Creator and seeking to push back the effects of the curse upon creation. In a world of hopelessness and father-hunger [80], [81], engineering educators have to opportunity to inspire engineering students toward a career of purpose empowered by a mental models submitted to and aligned with reality and able to leverage the work of previous generations of engineers and scientists [51].

Conclusion

In a pursuit of teaching innovation powered by various technologies, engineering educators can easily be distracted or overwhelmed by the new, faddish, or novel. Good teaching requires relatively little; a stick in the sand can be sufficient [82]. Learning may be even more straightforward. Students need to read. Students need to take notes. Students need to work and solve problems. Students need to develop and apply knowledge outside the classroom. Students need to appreciate, understand, and internalize the work of those who came before them. It is not all that complicated. By considering the practices of self-directed lifelong learners, engineering educators can evaluate and re-evaluate their teaching practices and learning activities. Ideally, every engineering student would develop not only technical competence within their disciplines, but also the self-directed lifelong learning skills and attitudes required for success in the future, regardless of their initial level of preparation for the collegiate learning environment.

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