

The T-shaped Engineer

Joe Tranquillo
Bucknell University
jvt002@bucknell.edu
570-577-1758

Abstract: Much buzz has been generated around the concept of T-shaped engineers; those with both technical depth and multi-disciplinary breadth. Unfortunately, most engineering curricula compartmentalize the depth and breadth without connecting the two. This paper highlights a variety of pedagogical techniques for helping students develop a fully formed T. A range of examples are given, from entire courses and semester-long projects to short classroom exercises. A history of the T-shape is provided, ideological and practical barriers to adopting the T-shape are discussed, and opportunities for both faculty and students are highlighted.

Keywords: Liberal Engineering Education, Interdisciplinary Learning, Life-long Learning

Introduction

There is an ongoing movement to educate T-shaped engineers, those with technical depth as well as cross-disciplinary breadth. Most engineering curricula, however, compartmentalize the depth and breadth into different courses. The result is that our graduates are not T-shaped, but are better characterized as two disjointed lines. In this paper I will argue that in order for students to make the connection, environments must be created in which they can practice joining breadth and depth into a T.

Although simple to state, there are at least two barriers that prevent faculty from delivering T-shaped experiences. The first barrier is the perception that technical depth must come first and there is no practical way to introduce breadth into an already packed curriculum. In the first section of the paper, I will highlight two curricular case studies that demonstrate how breadth can in fact strengthen technical depth. The second barrier is ideological - that the T-shape is not important either to an individual or to society. In the second section of the paper, I will review the literature, provide common arguments against the T-shape, and offer a rationale why all engineers should be T-shaped.

Section 1: Practical Barriers

Creating a T-shaped experience comes with many practical hurdles; there is pressure from post-graduate

Joe Tranquillo
Bucknell University
jvt002@bucknell.edu
570-577-1758

needs, ABET requirements, departmental and institutional requirements, and the politics of faculty load allocation. In the spirit of engineering design, constraints are always present and can in fact aid in the development of a T-shaped experience. As examples, I will provide details on two courses that were offered at Bucknell University: a required signals and systems course, driven by the design of biomusical instruments; and a technical elective co-taught with a professor of comparative humanities.

Woven throughout the cases are two categories of observations. First are stories of how students not only formed T-shapes, but began to build genuine interest in and experience with another discipline. The second class of observations are operational and aim to help others implement similar experiences. The section is concluded with ideas for how to introduce a lower case 't' – short experiences that can be embedded within traditional courses or co-curricular activities.

Case study: Building Biomusical Instruments

A traditional signals and systems course will focus on topics such as Laplace transforms, feedback control, data acquisition and signal processing, sometimes paired with labs or long-term projects that challenge students to connect theory to practice. One way to create a T-shaped experience is to challenge students to apply their skills outside of traditional engineering research and design. With that goal, I challenged my signals and system (junior-level, required biomedical engineering course, n=18) students to design and build non-traditional musical instruments.

Each student team (3-4 students per team) designed and constructed an instrument that would record biological signals and transform those signals to Musical Instrument Digital Interface (MIDI) code, a protocol that simulates the sounds of standard instruments. The MIDI code could be streamed through a software library and out to the computer sound card. A requirement was that the system must work in real time and use no prerecorded sounds, enabling a musician to freely improvise. Most importantly, a long-time New York studio musician, turned clinical professor of music, visited the class on several occasions with his improv students. The musicians acted as end users and clients. They made suggestions throughout the semester and pushed the engineering students in new directions, often teaching them a good deal of music theory in the process.

Course Structure and Assignments

Students still learned the topics of a more traditional signals and systems course through readings, homework and weekly quizzes (Tranquillo and Cavanagh, 2007). A series of 12 exercises led student teams through the basics of graphical programming (LabView, National Instruments) and Data Acquisition (DAQ). Several of the labs also built in learning MIDI code. An individual lab practicum, focusing on both hardware and software, was administered toward the end of the term to ensure that individuals on the teams did not specialize too much.

The biomusic project was driven forward by seven project assignments. At the end of the second week, student teams submitted abstracts with ideas for three possible instruments. After the first month they were required to narrow their scope to one instrument and submit a written proposal. Two months into the course, a feasibility demo was required along with a revised proposal. Each of these assignments was followed up with an instructor meeting. Throughout the semester, students were required to document their process on a website that was evaluated at the middle and end of the term. The last assignments were a final demonstration and a final write up. In a typical week, three out of the five classroom hours were used for hands on labs and project time.

At the end of the semester, there were some impressive successes. For example, student teams designed and built instruments such as an instrumented glove to capture and manipulate vocal sounds, an organ that responded to skin conductance, and a series of six-axis force plates that generated sound based upon a combination of forces and moments.

Student Learning and Motivation

All well executed Problem Based Learning (PBL) courses set the stage for deep learning. Technically the biomusic project was driven by what is known as a “wicked” problem – one that, given the students' current skillset, appears nearly impossible to tackle. The biomusic project was wicked in that all devices were driven by biological signals that contained delays, drift, and sensitivity to electrode application. To overcome these problems, students needed to use the theory they were learning in class. They also learned to reframe problems – for example one group made a breakthrough when they redefined their

system as human-instrument, rather than two separate systems.

A key to the course being T-shaped was that real constraints were coming from multiple sources. Some constraints were internal and of a logistical or technical nature (e.g. assignment deadlines, requirement of real-time function, MIDI standard). Other constraints were inherited from another discipline. For example, the students quickly realized that having all percussive, or all high-pitched instruments, would not enable mixing sounds across instruments. This was striking because I placed no requirement that the instruments be played together. They also recognized the need to agree upon a series of notes (a scale). After a short discussion, they invited the improv students to suggest a scale and give input on the instrument voicings. Similarly, students requested workshops on brainstorming (De Bono's Provocation and Six Hats), improvisation (verbal, musical and movement) and a mini-workshop on stage presence (guest speaker from the Theater and Dance Department).

Individual groups reached out to non-engineering experts. The group that worked on the musical glove, worked with the Costume Department, and all members of the team learned to sew. The group that created the galvanic skin organ was in regular contact with faculty in the Psychology Department. One group seriously considered controlling stage lighting with biological signals. Although they abandoned the idea, they had conversations with the lighting director in the Theater Department. Students came back from these meetings amazed by both the breadth and depth of knowledge of the lighting director, and in particular that he spoke a closely related dialect of the systems language they were learning in the course. After that group told the story to the class, the students asked if there was anyone in the theater who worked in audio. The following week the class was given a guided tour of the theater by an audio engineer.

The dynamics of the class encouraged cooperative groups to form. For example, many teams found it most efficient to have one team member focus on the graphical programming in Labview, another on the MIDI standard, and another on the sensors. There were a number of ad-hoc meetings where, for example, the programming experts from different teams would periodically meet to share what they had discovered. In effect, these groups, on their own, reinvented the well known pedagogical technique

known as a Jig Saw.

The class format and project also created some natural bridges to topics that are notoriously uninteresting to students. The importance of industry standards, even in the context of capstone design courses, is certainly one of those topics. In the biomusic project, the MIDI standard naturally fit the scope of the project. But another surprising connection came from a question about how LabView mapped keyboard strokes to numbers, and why it was the same mapping on Macs and PCs. This was a classic case (many that occurred during the course) where I did not know the answer. I mentioned that there was likely a standard keyboard layout mapping that was being exploited by the program. After five minutes of searching, one student found the standard (ISO/IEC 995). This is one of many such stories where a surprise in the project led to students finding their own answers.

Another aspect of the course was that students actively were on the lookout for non-traditional instruments. They initially brought up the Theremin, TalkBox (most popularly used in Bon Jovi's "Livin' on a Prayer"), John Cage's Prepared Piano, and the Drumitar/Zendrum (an electronic percussion instrument played by Future Man of Bela Fleck and the Flecktones). During the course they discovered many more, ranging from Music from Neurons (Lab of Alain Destexhe) to a technical paper on music from biology to the Landfill Orchestra (music created from garbage in Paraguay). Even after the class was over, students have continued to send me information. I recently received two links from a former student - a performance by the classically trained musician turned electronic artist, M4S0N1C, playing two Novation Launchpads and a TED Talk of Bobbi McFerrin "playing the audience."

At the beginning of the class, the intention was for the engineering students to build the instruments and deliver them to the musicians, as in a standard client-engineer relationship. As the semester progressed, the students and musicians formed a real partnership and asked for a public performance/demonstration of the devices at the end of the semester. It turned out that another collaboration was occurring between a dance class and sculpture class, where the sculpture class was creating wearable sculptures that restricted the movements of the dancers. The four classes combined to put on a joint performance in public on Trustee Weekend.

Perhaps most telling, however, was that as the performance date approached, the engineering students asked if they could play their own instruments, as they had become very good at playing them. During the performance, the engineers confidently performed alongside the music students. More information on the performance can be found at: <http://bucknellinnovationgroup.blogs.bucknell.edu/2012/04/20/impulse-group-and-the-dense-network/>

Instructor Observations: Pain and Passion Points

For historical reference, I taught a project-based version of the signals and systems course for six years prior to the biomusic offering, where the project was focused on medical device design (Tranquillo and Cavanagh, 2007). I can confidently say that the music project brought the theoretical concepts alive in a way that the previous medical device project did not. While the medical device design project provided opportunities to apply some of the signals and systems content, the music project generated a more holistic technical experience.

In choosing a theme, I was opportunistic. I had worked with the jazz professor before and had informally polled the students before the course. In fact, I had several possible projects in mind, including training rats to detect landmines (in collaboration with a psychology professor), and athletic rehab equipment (in collaboration with the athletic department). In my polling I found that nearly everyone in the class had some musical training, and a few were nearly at the level of the music students. What the experience highlighted was that it pays to play to the passions of the students. It is from these passions that an instructor cannot only engage students in the material but also help them to internalize why the T-shape matters.

Passion points have built-in hooks to the core subject matter. Many student passions come from the top of the T, which can then be amplified by the stem of the T. For example, the music project naturally highlighted the Fourier Transform, and the connection between delays, eigen values, time constants and poles of a system. In some cases (especially in smaller classes) it is possible to find one project that resonates with nearly everyone. Finding these passions and amplifying them through the learning objectives of the course is one pathway to building a strong T-junction. In other implementations of the course (not discussed here) the themes have included interactive fashion, kids toys and games, military

communications and pet technologies, all in partnership with external advisors. Test questions have remained relatively consistent throughout the years of offering the signals and systems course. Comparing average test score before ($n=84$) and after the change ($n=81$) to more thematic projects, scores have risen nearly 5 points (out of 100).

The course was certainly a joy to teach but was far from straightforward. There were many more logistics to clear the path for student success. As in any PBL courses, I needed to play a role closer to that of a coach – using praise when groups were trying but frustrated, but also honest feedback when groups were coasting or making excuses.

My goal in presenting this case study was to describe a student experience that was unique, and integrated the technical and non-technical. As will be described later in the paper, every two weeks I conducted a short reflection meeting or assignment with the students. The goal was to extract lessons learned. Some were individual, private and more formal, while others were informal public discussions. In course evaluations, students shared that it was during these reflection periods that the light bulbs went off.

Case Study: Brain, Mind and Culture

Engineers typically take courses outside of the sciences to fulfill university and ABET breadth requirements. Unfortunately, many engineering students do not take these courses seriously. They put on their humanities and social science “hats”, but then quickly take them off again once they are back in their engineering courses. Those who do gain some lasting insights all too often keep them compartmentalized.

The Brain, Mind and Culture course (junior/senior technical elective, $n=22$, $n=10$ engineers) was co-taught by a professor of Comparative Humanities and myself. It was cross-listed in the departments of biomedical engineering, neuroscience and comparative humanities, with student enrollment from all divisions of the university. The primary course objective was to provide a venue for an intellectually diverse group of students to compare and contrast their different methods, traditions, communication styles, and contemporary issues.

The course was divided into four units, with each unit focusing on a wider theme; Histories of

[Neuro]Science, The Body and Mind as Open Systems, Transformation of Learning, and Social Interactions. Pedagogically, the course was driven by readings from historical and contemporary philosophy, science, engineering design, film, art and local and international news. Content was chosen to give concrete examples of methodology and tools from a variety of disciplines. When possible, the same topic (e.g. feminist theory;) was approached from multiple viewpoints (e.g. genetic, psychological, sociological, philosophical). Class time was used for semi-structured, students-led discussion on the readings. The first 5-10 minutes of each class were reserved for clarification. It was during this time that definitions, methodologies and discipline-specific history were shared. Often the students took the lead on answering each other's questions.

At the end of each unit, students had the opportunity to add extra content to the unit. In this way, students were co-creators of the course. Sometimes they brought in readings from other courses. Other times they shared stories from extra-curricular activities. The emphasis was placed not on the material but on the active search for connections across disciplines. One of the students proposed for the class to watch the South Park episode, "Fish Sticks" (Season 13, Episode 5), as a follow-up to our discussion on memory. In the episode, the character Cartman replays an incident in his head over and over again, making it more and more outlandish, until at the end of the episode he believes his self-constructed lie so strongly that he is willing to die for it. After some debate between the two faculty, we decided that the student did have a good rationale and that the connection to the course material was strong. The viewing led to a very rich discussion and I realized that if students could see their course material coming alive in an episode of South Park, the course was having the intended impact.

As the course was cross-listed in biomedical engineering and neuroscience, technical content was required. An extra hour was offered during which a number of topics were introduced that do not generally appear in traditional engineering and neuroscience curricula: agent based models, game theory, non-linear dynamics, graph theory, thermodynamically open systems and self-organized criticality. All technical sessions were connected to the main course topics. Many of the humanities students, who were not required to attend the fourth hour, participated anyway.

All students were required to complete an individual, semester-long project inspired by or using the methodology of a discipline other than their own. The bounds of the project were left open, and the instructors worked with each student to find a project that allowed them to practice making their own T-shape. For example, one engineering student analyzed the tension between the administration and the Greek system through the lens of game theory and network science. This particular student came out of the project with a newfound appreciation for the position of the administration. Another student combined her love of bike racing with principles from self-organizing systems. An international engineering student, working with a professor of English, learned how to conduct Grounded Theory research (a flavor of qualitative research). In her final presentation, she expressed how surprised she was to find that a "qualitative method" could be as rigorous, and in many ways more difficult, than her quantitative engineering work.

The focus of the course was for students to see their own discipline as not ending at the boundaries of their curriculum. By being able to compare and discuss different disciplines side-by-side, many students became more aware of why their discipline asks certain questions, the acceptable form of answers, and the assumptions that are hidden inside of these question/answer pairs. Toward the end of the course, many students began to express openly what they thought was missing from their own discipline as well as what their discipline might have to offer to other disciplines. For example, we studied the work of Neri Oxman, a visionary architect and material scientist at the MIT Media Lab, who has advocated for a new type of design using the self-organization of materials. It is design from the bottom up, where the designer creates the rules for how materials will combine, but then lets the materials optimize the structure. This approach was quite a shock to many of the engineers who were currently deep into a formal top down design process in their senior capstone. But, it was clear that the possibilities were not quiet hitting home. So we watched as a 3D printer rendered one of Oxman's designs during a discussion. That discussion was followed up by a second article by Oxman where she predicts that someday entire buildings will be "printed" from simple rules, and that these buildings would not only be optimized to their environment, but also adapt when the environment changed.

Team Teaching

Team teaching can be a powerful way to create a T-shaped experience, but it is not for the faint of heart. Unlike single-instructor courses, joint decisions must be made on a wide range of logistics, including student recruitment, course content and structure, syllabus and website, readings and assignments, grades, office hours, and in-class work. There are also questions about workload distribution among the instructors and the decision-making process for extensions, in-class surprises and other unanticipated challenges. Regardless of the solutions to these challenges, team-taught courses are more work.

The overhead of team teaching is amplified when cultures collide. The waves that are created feel uncomfortable, even to the instructors. How much should ideas be held in tension? Is it better to have a linear or non-linear flow to a course? Will the course focus on knowledge, questions, tools, methodologies or some combination? Students and faculty from different disciplines also carry with them assumptions about the expected rhythm of a semester.

Team teaching across disciplines is certainly not new and most institutions have at least some radically interdisciplinary courses. Perhaps no school has embraced it as fully as Colorado College. The book *Co-Teaching That Works* is a summary of years of expertise. Based upon the findings at Colorado College and my own experiences, there are some best practices. For example, the classroom environment will at times be out of balance. When our class discussed Hume, some felt right at home while others were out of their element. In these situations, as an engineering professor, my role was to ask “silly” but genuine questions. In a class with interdisciplinary topics and students, it is very valuable to have someone playing this role.

In a mixed-discipline class, some explanation of disciplinary grounding will be necessary. In Brain Mind and Culture, students practiced expressing the accepted views of their discipline. Some students found that they held a flawed or incomplete view of some aspect of their own discipline. For most, this was a welcomed experience. A few students expressed the accepted view of their discipline but then followed it up with what they personally thought of that view. Again, these were enlightening experiences that were mined for learning. Lastly, the faculty did their best to be role models – to demonstrate what it looks like to

respectfully disagree, and to provide them with examples of how T-shaped people think and act.

Wandering off topic during a T-shaped experience is all too easy. Students, and even faculty, are vying to get back onto familiar turf. This multi-directional pull can easily lead to parts unknown. It is during these times of tension that deep connections can be made. However, there needs to be some recognized way to get back on track. In the Brain, Mind and Culture course, this simply became eye contact and a nod between the instructors.

Above all, the most important aspect of a multi-disciplinary T-shaped environment is a culture of trust and respect. There will be moments when one discipline will shine. At other times that same discipline will appear terribly shortsighted. It is through trust and respect that the class can paradoxically be both critical and accepting.

Value Beyond the Primary Objectives

In this section I will explore reasons for faculty and students to engage in T-shaped experiences, beyond the course objectives.

Student Rewards

Students enjoy new and unrepeatable experiences. In the internet-age, students know that if they need signals and systems content for their job ten years from now, it will all be online. What they cannot recapture is the experience of the course, such as building a biomusical instrument. Unique experiences builds a sense of urgency that drives forward the desire to engage.

T-shaped experiences create unique stories. They become the response to interview questions, especially the classic “Tell me about a challenge and how you overcame it.” Students can also highlight their ability to do something truly novel. For example, the team working on the biomusical glove had a particularly powerful story. During their research they found a TED talk by the avant-garde pop musician Imogen Heap, who has been working with Virtual Gloves that sample, filter and play back her voice. Their reaction when they discovered her work was “we’ve done that.” While their product was clearly not as sophisticated, they recognized that with more time and better resources they could build something comparable.

T-shaped experiences can help students parse the formal learning objectives of the course. For many years, I posted learning objectives, explained Bloom's Taxonomy, and did my best to map the activities of the course to the objectives. What I heard back from some students, however, was that the learning objectives were still too abstract and they only consulted at them around test time. In the T-shaped experiences described, I challenged students to discover opportunities to prove to me that they had met a learning objective. The result was they not only knew the objectives, but were actively on the lookout for ways to meet them.

Faculty Rewards

There are some very concrete ways in which faculty benefit from providing T-shaped experiences. Although raw teaching scores may not go up, or only slightly upward as they did in the Signals and Systems course, the written comments clearly justify the pedagogical approach. It was noticed by several administrators that students characterized both courses as transformative experiences. Furthermore, alumni enjoy hearing about courses that show that their alma mater is special. For that reason, T-shaped experiences can become great showpieces. Both the biomusic project and Brain Mind Culture course have been featured in university-level publications and campaign talks.

In the process of building a T-shaped experience, faculty may also find others at their institution who wish to collaborate on an unusual project. For example, through our regular contact in the Brain Mind and Culture course, the comparative humanities professor and I co-authored two conference publications and were featured in a CNN Health article. As a result of another course (not discussed here), I collaborated with a professor of Psychology. The outcome was a military grant with a defense contractor, and feature on the Discovery Channel. These unique collaborations have brought me much more publicity than my traditional research program.

Lastly, faculty often must engage in exploratory research projects to remain current in their field. Matching students to these exploratory projects can be challenging. T-shaped courses can provide the right testing ground in which to find students who are willing and able to engage in an exploratory research direction.

Lower-case t

The two case studies show variations in how a fully formed capital T can be encouraged. But it is often not possible to design and offer entire courses in this way. In fact, the Brain, Mind and Culture course was offered after five years of red tape were finally lifted. As an alternative, there are some simple ways that students can be exposed to the top of the T inside of more traditional courses; what I will call the "lower-case t." Many instructors already bring in current events and stories from their own experiences. What can be added to these ad-hoc approaches is more intention. By explaining why and how the stories and experiences extend beyond the classroom material, you can show how cross-disciplinary connections are a valued outcome of an experience. Below are ideas on being more intentional.

I often look at the bubble around my courses and discipline. Reading current events can help, but I have found that lunch with colleagues outside of my discipline to be a deeper source for T-shape content. As I discover connections I bring them into the classroom and share how I discovered them.

In the past, I invited guest speakers who were experts in a sub-field of the course material. For example, I have invited a speech signal processing expert to give a talk in my signals and systems course. Though no fault of the speaker, his research talk added little value. Where I have found invited talks to add value is when the talk brings an unexpected twist to the course. Most often these topics are in the bubble around the discipline. I have found that a meeting with the speaker ahead of time can clarify this objective. A similar type of experience can come from campus or regional talks and events. In this case, it will be up to the students to look for the T-shape in the event.

A combination of readings and discussion can also be very powerful. I have offered a neural signals and systems elective for several years. The traditional classroom time focuses on the biophysics of ion channels, action potentials, propagation and small neural circuits. A discussion period moves to the opposite end of the spectrum, driven by reading from Dennett, Kurzweil, Martin Luther, Erasmus and Ramon y Cajal, as well as many of the sources from the Brain Mind and Culture course. What students gain from this approach is a recognition of the gaps between our scientific understanding of the brain and the philosophical questions surrounding minds.

Section 2: Ideological Barriers

Steve Jobs famously stood beneath a giant street sign showing the intersection of technology and the liberal arts . He explained that this was where innovation happens at Apple. The value of this intersection is not a new idea; the T-shape is simply the latest incarnation.

In this section, I review the history of the T-shape and point out major criticisms of teaching the T-shape to university-level students. I will then provide my own answer to these critiques with the goal of arming the reader with answers to students or administrators who might question the importance of teaching the T-shape.

History of the T-shape

The idea of the T-shape clearly goes back a long way, but it was in the early 1990s that it took on the meaning used throughout this paper. Colin Palmer published research for the British Computer Society discussing the need for “hybrid” managers in the technology world . Palmer acknowledges that the term “hybrid” was coined by Michael Earl at Templeton College, Oxford. The following year David Guest wrote an editorial for *The Independent* (London) , based upon Palmer’s study, where the first mention of the T-shape appears:

This type of rounded personality is also sought in other branches of the same theory, which prizes individuals known as T-shaped People. These are a variation on Renaissance Man, equally comfortable with information systems, modern management techniques and the 12-tone scale.

The T-shape has caught on in a number of fields. High profile thought leaders have advocated hiring T-shaped people, including Tim Brown at IDEO and Jim Spohrer at IBM . The International Society for Service Innovation Professionals (ISSIP) fully supports the T-shape (<http://www.issip.org/tag/t-shaped/>), and has highlighted the concept at their most recent conference. The T-shape has also been adopted by marketing and management , the medical profession and even philanthropy. The United States is certainly not the only country seeking to educate T-shaped professionals , and the T-shape has been publicly acknowledged as part of the DNA of several high profile international companies, including Toyota, Apple and Google.

IBM has been the most visible corporation to champion the T-shape, both internally and externally. Internally they hire and train employees who can engage in a “cognitive build” that enables them to continually reinvent their position. The IBM philosophy is that every skill set and knowledge base has an expiration date; the T-shape is a healthy adaptation to the ever-changing skills and knowledge that are necessary for impact. Externally, Jim Spohrer (IBM) and Phil Gardn (Michigan State) have organized three “T-summits” (<http://tsummit.org/>), highlighting successful T-shaped people, including academic thought leaders (e.g. Rich Miller, President of Olin College of Engineering) industry advocates (e.g. Kathleen DeLaski, CEO and founder of Ed Design Lab) and the US Government (e.g. Susan Singer, NSF Division of Undergraduate Education) and Kathryn Sullivan (US Astronaut).

Driven by industrial and professional hiring, university administrators and educators have begun to adopt the T-shape. In one of the few empirical studies of the T-shape, a wide survey of job descriptions over the last several decades showed a rise in the need for expert thinking combined with cross-functional knowledge and communication skills . Gardner has published on nurturing young T-shaped professionals , and a forthcoming book “Model T – how to create T-shaped professionals,” although written for companies, may provide some valuable insights for college educators. The T-shape movement has also sparked calls for reform – most especially for holistic engineering education . The goal of these reforms is to educate modern-day Renaissance men and women who will continue a golden age of innovation - what has been dubbed the “Medici Effect” . For many engineering programs, the T-shape aligns nicely with their interpretation of the ABET phrase “life-long learner” (Criteria 3i). MIT and Stanford have both published high profile articles , and the US government has funded national centers that facilitate the spread of some key aspects of the T-shape in engineering education (e.g. NSF Engineering Pathways to Innovation based at Stanford).

Arguments Against the T-shape

Perhaps the most common argument against the T-shape is that it will stunt the learning of depth in a discipline. As the case studies above attempt to demonstrate, this need not be the case. I will therefore focus on two deeper arguments against the T-shape. On the level of an individual, perhaps the T-shape

cannot be taught, or maybe it can be taught but the 18-22 year demographic is not the right target. If that is true, should the seeds should be planted earlier in K-12 education? Or perhaps a T-shape can only develop through years of experience after college. These types of questions, especially in the absence of clear answers, can become barriers to adopting the T-shape.

Even if teaching the T-shape to college students is beneficial to an individual, there are some socioeconomic reasons why it may not make sense. A primary rationale for hiring T-shaped employees is that they facilitate the flow of knowledge, processes, and skills throughout the organization, often across traditional boundaries. How many T-shaped people does it take? Is it best for everyone to be T-shaped? Or perhaps is there a saturation point after which adding more T-shaped people does little for, or maybe even impedes, information flow within a company. This idea has in fact been studied through computer simulations and there does appear to be a saturation point. An economic argument can also be made that there may be a small return on educating a T-shaped person, both for universities and the organizations that hire their graduates.

To date, there is no common definition of the T-shape, serving as an additional barrier. To some, the top of the T originates within a very particular discipline, for example marketing, management or entrepreneurship. Here the top is composed of the skills and thought processes from a particular discipline. At the opposite end of the spectrum are those who advocate superimposing a technical background onto liberal arts training. The T-shape also goes by some aliases, including “Generalizing Specialist”, “Hybrids”, and “Versatilist”.

Some question if the T-shape is the right shape. For example, Leonard-Barton discusses “A-shaped” (sometimes also called “-shape” or “Y-shape”) people – those with depth in more than one discipline. They are technically bilingual and can connect two groups together more tightly than a T-shaped person. The “I-shape” (for Innovation) is sometimes used to mean professionals who have their feet planted firmly on the details of their discipline but can from time to time come up to look around. There is also “O-shape” (for well-rounded), “E-shape” (for Entrepreneurial or Execution), “hyphen (-) shape” (a true generalist), and “M-shape” (T-shaped combined with teamwork). Still others advocate the traditional “STEM shape”, as being successful in the majority of work environments

Addressing Arguments Against the T-shape

Based upon my own experiences and what I perceive to be most relevant to engineering educators, I have focused below on addressing the pedagogical rather than the socioeconomic value. To this latter criticism, I would simply respond that it is based principally upon the assumption that depth must come as the expense of breadth.

The question I will respond to is: “What, if any, value is there in T-shaped undergraduate courses and curricula?” Many students have begun to form a T-shape before college and will continue to become more T-shaped over time. It is during the undergraduate years, however, that students will transform their various interests into a mindset that will guide them throughout their career. Teaching the T-shape also brings natural contact with the messiness of the real world, and therefore exercises the capacity for complex and contextual thinking. Lastly, connections across disciplines, the junction of the T-shape, are made through a process of reflection, a life-long skill in and of itself. I will use these three words (mindset, real world, and reflection) to focus the discussion below.

The Growth Mindset

A mindset is a lens through which the world is viewed. It is a complex and individual psychological object that can only be learned through a process of self-discovery. The undergraduate brain is at the near-perfect time for mindset development because it lies at the intersection of two competing phases of development. Neuroscience and psychology have shown that the 20-something brain is still developing. At the same time, years of wrestling with more and more abstract concepts have endowed the brain with the core mental mechanisms needed to handle the complexity of learning a mindset. Undergraduates, with some prompting, are able to take concrete experiences, and not only abstract them, but include them into their views of the world.

One mindset in particular has appeared over and over again as the key to long-term fulfillment and success. Stanford psychologist Carol Dweck has contrasted a fixed mindset with a growth mindset. In the fixed mindset, “an individual believes that their qualities are carved in stone.” This “creates an urgency to prove oneself over and over again.” The important questions for those with the fixed mindset

are: “Will I succeed or fail? Will I look smart or dumb? Will I be accepted or rejected? Will I win or lose?” A person with the growth mindset, however, believes that their “basic qualities are things that they can cultivate through effort.” They ask, “What have I learned? What can I do next? Where can I had an impact?”

Students with either mindset can achieve, but do so for very different reasons. The fixed mindsetters achieve because they have explicit goals that will be either met or not met. Meeting the goal is defined as success, while not meeting the goal is the very definition of failure. The growth mindsetters, on the other hand, are learning focused. For them, failure to meet a goal can still be a success if something was learned. Dweck has extended the idea to everything from business to personal relationships. She argues persuasively that short-term success may be gained through the fixed mindset, but that the pathway to lifetime success, and personal fulfillment, is through the growth mindset. Furthermore, Dweck emphasizes the fact that the growth mindset can be learned through repeated reinforcement. It is like a muscle to be exercised.

Environments can be constructed that encourage students to develop a growth mindset. It is not easy to take the focus off of grades and put it on learning – grades have led students this far and so grades are perceived as the path to future success. But grades reinforce a fixed mindset . Because T-shaped experiences have many pathways to any number of goals (often student-driven goals), they do not come preloaded with black and white wins and losses. Instructors can more easily reward growth rather than getting the right answer, and connect progress toward

A learning Goal to a Numerical Grade.

Adopting a growth mindset appears to be catalyzed in an immersive environment. Based on some well-studied neuroscientific findings , immersive, trial-by-fire experiences bring about intense emotional responses. An emotional response is a powerful evolutionary mechanism for making learning sticky. T-shaped experiences are breeding grounds for emotional responses that lead to sticky learning . For example, the biomusical project was immersive in that it dominated student time both in and out of the classroom. Likewise, the Brain Mind and Culture course was immersive in that students were encouraged to look outside of our classroom for sources of inspiration.

Real-World Challenges

There is a trend in engineering education to bring real-world experiences into the classroom. The typical rationale is that experience with the real world will serve as practice for future careers. Students also seem to agree that real world problems are an exciting taste of what they will encounter when their formal education is complete. There is, however, a deeper philosophical reason that dovetails with the T-shape; encounters with the real world build the capacity to simultaneously hold many interlocking ideas in one's mind.

Complex real-world problems, sometimes called Wicked Problems, are by definition multi-level, multi-discipline problems. To generate a true solution requires addressing the issues at all levels, from the 50,000 meter (potential for impact) to the 5cm (implementation). Engineering educators have historically put a great deal of emphasis on the 5cm view, preparing entry-level engineers for their first job. The T-shaped engineer is often sold as having both the depth to handle the 5cm view and the breadth to understand the social, political and historical context at the 50,000 meter view. What is often missing is the ability to move fluidly from one level to another and one discipline to another.

It is a tall order for an undergraduate to keep all of these levels in their head at once, and that is the point. Exposure to wicked problems increases the capacity to hold complex, and even contradictory, thoughts in one's mind. Jim Collins has studied the difference in leadership at companies that are good and compared them to those companies that become great. A key difference is the capacity to navigate ambiguity, complexity and conflict . T-shaped experiences allow students to grow these capacities and gain confidence in their abilities.

Assigning truly open-ended problems means the faculty member can no longer give simple answers . As students learn that the professor genuinely does not know the answer, they become invested in finding their own answers. To use a business analogy, I encourage students to become their own Chief Learning Officer (CLO). My role is to be the Chief Environmental Officer (CEO) who provides the tools, resources and a culture in which they can succeed. As my students progress, even that support begins fade away, as they learn to seek out their own resources.

Reflection

T-shaped environments provide rich opportunities for reflection. All too often, reflection assignments take the form of a one-page assignment at the end of the course. What students most often produce is a summary of the content they have learned along with a surface level assessment of where they might use the information in the future. T-shaped experiences require deeper reflection to bring to the surface the full richness of the learning opportunities.

I have developed a tool called the Reflection Ladder that is loosely based upon Bloom's Taxonomy, and is used throughout the semester (Tranquillo, 2016). The higher a student climbs on the Ladder, the better they can see where they have been, where they are and where they might go next. The goal is for students to progress in their reflection skills throughout the semester. I also used the ladder to design more targeted reflective propts and exercises (e.g. group/individual, written/verbal/graphical) that helped students practice their reflective abilities.

Conclusions

Plato advocated "cutting nature at its joints, like a good butcher" (Phaedrus). This philosophy has been the driver of our understanding of the world for millennia and has been undeniably successful at taking apart the world. But as the butcher analogy so aptly illustrates, putting the parts back together again cannot proceed by continuing to cut up the world. This is the dilemma faced by the practicing engineer - to put back together, in meaningful ways, the bits that have been taken apart so ably by the scientific method.

Teaching our students to be T-shaped is one way for them to more effectively put science back together in ways that benefit society. The problem is that the butcher analogy has infected the educational system, so much so that even advocates of the T-shape too often assume that depth and breadth can only be learned in separate experiences. But, like the creation of a mechanical 'T', the largest stress - and therefore the most probable point of failure - is at the junction. This paper provides another option; to create T-shaped experiences that focus on strengthening the junction.

Acknowledgements

The author would like to thank John Hunter, Keith Buffinton, Charles Kim, Doug Candland, Jim Baish, Tina Seelig, and Leticia Britos Cavagnaro for their helpful discussions and comments on drafts of this manuscript.

References

Appelo, J. (2011). *Management 3.0: Leading agile*

developers, developing agile leaders Pearson Education.

Arslan, B., Brouse, A., Castet, J., Léhembre, R., Simon, C., Filatriau, J., & Noirhomme, Q. (2006). A real time music synthesis environment driven with biological signals. 2006 IEEE International Conference on Acoustics Speech and Signal Processing Proceedings, 2 II-II.

Bain, K. (2011). *What the best college teachers do* Harvard University Press.

Barton, D. L. (1995). *Wellsprings of knowledge*. Harvard Business School Press, Boston,

Beninghof, A. M. (2011). *Co-teaching that works: Structures and strategies for maximizing student learning* John Wiley & Sons.

Berenbaum, S. A., & Hines, M. (1992). Early androgens are related to childhood sex-typed toy preferences. *Psychological Science*, 3(3), 203-206.

Bordogna, J., Fromm, E., & Ernst, E. W. (1993). Engineering education: Innovation through integration. *Journal of Engineering Education*, 82(1), 3-8.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn*. National Academy of Sciences' National Academies Press.,

Buxton, B. (2009). *Innovation calls for I-shaped People*1.

Cajal, S. R. (1999). *Texture of the nervous system of man and the vertebrates* Springer Science & Business Media.

Cataldo, M., Carley, K. M., & Argote, L. (2000). The effect of personnel selection schemes on knowledge transfer

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis*, 58(1), 7-19.

Collins, J. C. (2001). *Good to great: Why some companies make the leap... and others don't* Random House.

Creswell, J. W. (2013). *Qualitative inquiry and research design: Choosing among five approaches* Sage.

Damasio, A. R. (2006). *Descartes' error* Random House.

Donofrio, N., Sanchez, C., & Spohrer, J. (2010). Collaborative innovation and service systems. *Holistic engineering education* (pp. 243-269) Springer.

Donofrio, N., Spohrer, J., & Zadeh, H. S. (2010). Research-driven medical education and practice: A

- case for T-shaped professionals. MJA Viewpoint, Dweck, C. (2006). *Mindset: The new psychology of success* Random House.
- Edelson, M., Sharot, T., Dolan, R. J., & Dudai, Y. (2011). Following the crowd: Brain substrates of long-term memory conformity. *Science* (New York, N. Y.), 333(6038), 108-111. doi:10.1126/science.1203557 [doi]
- Fine, C. (2010). *Delusions of gender: How our minds, society, and neurosexism create difference* WW Norton & Company.
- Gardner, P. (2011). Challenges in the nurturing the growth of young T-shaped professionals. *Proceedings of the 2nd International Research Symposium in Service Management*,
- Gazzaniga, M. (2012). *Who's in charge?: Free will and the science of the brain* Hachette UK.
- Guest, D. (1991). The hunt is on for the renaissance man of computing. *The Independent* (London), 17
- Hansen, M. T. (2010). IDEO CEO tim brown: T-shaped stars: The backbone of IDEO's collaborative culture. *Chief Executives: CEO Interviews*,
- Hansen, M. T., & von Oetinger, B. (2001). Introducing T-shaped managers. *knowledge management's next generation*. *Harvard Business Review*, 79(3), 106-16, 165.
- Heap, I. TED Global. Retrieved from <http://www.psfk.com/2011/07/tedglobal-imogen-heaps-musical-gloves-manipulate-sound-with-hand-gestures.html>
- Heath, C., & Heath, D. (2007). *Made to stick: Why some ideas survive and others die* Random House.
- Henrich, J., Heine, S. J., & Norenzayan, A. (2010). The weirdest people in the world? *Behavioral and Brain Sciences*, 33(2-3), 61-83.
- Hofstadter, D. R., & Dennett, D. C. (Eds.). (2006). *The mind's I: Fantasies and reflections on self & soul*. New York: Basic Books.
- Hume, D., & Beauchamp, T. L. (2000). *An enquiry concerning human understanding: A critical edition* Oxford University Press.
- Hunter, J., & Tranquillo, J. (2012). *The crowdsourced self*. NeuroHumanities Entanglement,
- Johansson, F. (2004). *The medici effect: Breakthrough insights at the intersection of ideas, concepts, and cultures* Harvard Business Press.
- Kurzweil, R. (2000). *The age of spiritual machines: When computers exceed human intelligence* Penguin.
- Landau, E. (2012). *So you're a cyborg - now what?* Retrieved from
- LeDoux, J. E. (2003). *Synaptic self: How our brains become who we are* Penguin.
- Levy, F., & Murnane, R. J. (2012). *The new division of labor: How computers are creating the next job market* Princeton University Press.
- Levy, N. (2007). *Neuroethics: Challenges for the 21st century* Cambridge University Press.
- Luther, M. (2008). *The bondage of the will* Hendrickson Publishers.
- The headless woman. Martel, L. (Director). (2008). [Video/DVD]
- Matcho, M. (2011). A new start: An experiment in learning from scratch. *Stanford Magazine*,
- McMaster, R. (2012). *The T in STEM - the T-shaped professional*. MIT STEM Pals,
- Morello, D. (2005). *Versatilist: Gartner says technical aptitude no longer enough to secure future for IT professionals*
- Orlan, X. Retrieved from <http://www.orlan.eu>
- Oskam, I. (2009). T-shaped engineers for interdisciplinary innovation: An attractive perspective for young people as well as a must for innovative organizations. 37th Annual Conference-Attracting Students in Engineering, Rotterdam, the Netherlands, , 14
- Oxman, N. (2010). Structuring materiality: Design fabrication of heterogeneous materials. *Architectural Design*, 80(4), 78-85.
- Oxman, R. (2006). Theory and design in the first digital age. *Design Studies*, 27(3), 229-265.
- Palmer, C. (1990). 'Hybrids'-a critical force in the application of information technology in the nineties. *Journal of Information Technology*, 5(4), 232-235.
- Prince, M. (2004). Does active learning work? A review of the research. *Journal of Engineering Education*, 93(3), 223-231.
- Casino royale. Purvis, N. and Wade, R. (Directors). (2006). [Video/DVD]
- Robotic surgery. Retrieved from http://www.youtube.com/watch?v=n37RiY4CZ_Q
- Rust, R. T., Moorman, C., & Bhalla, G. (2010). Rethinking marketing. *Harvard Business Review*, 88(1/2), 94-101.
- Skyrme, D. Brazil: Developing T-shaped professionals to build knowledge clusters. Retrieved from <http://www.entovation.com/gkp/tshaped.htm>
- Snow, C. P. (2012). *The two cultures* Cambridge

University Press.

Stannard-Stockton, S. (2009). T-shaped people & philanthropy. stanford social innovation review. Retrieved from http://ssir.org/articles/entry/t_shaped_people_and_philanthropy

Stelark, X. Retrieved from <http://stelarc.org>

Technology and the liberal arts (website). Retrieved from <http://www.youtube.com/watch?v=KlI1MR-qNt8>

Tracy, J. D., Miller, C. H., & Macardle, P. (2012). Erasmus and luther: The battle over free will Hackett Publishing.

Tranquillo, J. (2016). Mirror mirror: Reflection and the building of mindsets. Proceedings of ASEE.

Tranquillo, J., & Hunter, J. (2011). From the neural to

the social networks of memory; or, 'it's your life crowdsourced'. ThinkArt Conference,

Tranquillo, J. (2015). The faculty ulysses contract. Proceedings of ASEE,

Tranquillo, J. V. (2008). Quantitative neurophysiology. Synthesis Lectures on Biomedical Engineering, 3(1), 1-142.

Tranquillo, J., & Cavanagh, D. (2007). A project-driven approach to biomedical signals and systems. Proceedings of ASEE,

Wesch, M. The machine is us/ing us. Retrieved from http://www.youtube.com/watch?v=NLIgopyXT_g&feature=relmfu

Wu, J., Zou, X., & Kong, H. (2012). Cultivating T-shaped engineers for the 21st century: Experiences in china. Proceedings of ASEE,