Florida Tech July, 2022 KEEN Maker Education Interim Report Executive Summary

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For way too long, education in making environments ranging from ideation and conceptualization (visualization studios) to fabrication (makerspaces, student design centers, and machine shops) has remained relatively informal. Faculty and staff operating making spaces are strained to keep up with the high demand from students and colleagues who seek to maximize their potential through enhancement of their making skills. Moreover, the wide range of experience levels in individual skills makes it much more challenging to teach these skills in mass production mode than is typical of other laboratory courses.

The goals for the maker education grant are as follows:

2019 - Providing evidence for entrepreneurially-minded learning (EML) integration into making

- Connecting to the Making World

2020 - How should EML be integrated into making? - Contributing to the Making World

2021 - How may we enable faculty/staff to integrate EML into making?

- Disseminating to the Making World

A major motivation for us in writing this proposal was that we were tired of training students on individual skills only to find out soon thereafter that a different skill was limiting their success in our research labs, especially when faculty thought that students should already have such prerequisite skills. Part of the problem is that there are so many different skills to learn that very few people have all of them. *Formalization of the maker skill set training process would address the primary* ***pain point*** *of dampened enthusiasm associated with* ***deficiencies in the skill set*** *heretofore resulting in a* ***lack of persistence*** *toward students' and faculty members' professional goals.*

Together, we will establish best (and worst) practices to create value for education in all types of learning environments where making takes place. In the process, we will make connections, both in terms of ideas and personal contacts, within the entire Kern Entrepreneurial Engineering Network (KEEN) so that no one has to re-invent the wheel and so that aspiring engineers can satisfy their curiosity and create value through persistence toward their goals through prototype construction.

Thus far, we have a) organized an outline for a literature review on education in making environments, b) screened KEEN cards and obtained results from preliminary surveys to see who in the network is interested in maker education and its prerequisite and postrequisite design experiences, c) developed a comprehensive survey of EML in making environments to be distributed shortly to KEEN partners, d) developed a coding rubric to convert the survey results into EML enhancements, e) begun site visits to KEEN universities toward identifying three schools with whom to partner to co-develop modules during 2020 and beta those modules in 2021, f) used a), b) and e) to identify which modules should be developed.

We also have defined KEEN's "postdisciplinary" engineer as an engineer who, if given enough time, is capable of solving all types of engineering problems. Finally we outline curricula for developing both a "maker minor" and a double major of "maker engineering" and either chemical or biomedical engineering.

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1. What is a Postdisciplinary Engineer?

Thor Misko of the Kern Family Foundation (KFF), during a visit to Florida Tech in Nov. of 2018, said that what KFF is trying to develop through the Kern Entrepreneurial Engineering Network (KEEN) are postdisciplinary engineers ([1](#Ref1)). Unlike a multidisciplinary engineer who is a jack of many trades and a master of the discipline in which he/she received a B.S. degree, a postdisciplinary engineer is capable of completing all aspects of all engineering problems. This is exactly the opposite of the way that most engineers are educated at most institutions of higher learning.

Prof. Jim Brenner has said for years that chemical engineers make the most money because they are the most versatile of engineers because they are the only discipline that places enough emphasis on conservation of mass, in addition to conservation of energy and momentum, to be able to tackle any engineering problem. Moreover, chemical engineering is largely based on how to scale up process to make a product to mass production quantities.

Some of the second most versatile and second highest paid of engineers are biomedical engineers, who are able to build the prototypes that the chemical engineers cannot. By contrast to chemical engineers, biomedical engineering focuses much more on personalized product solutions, creating value for customers by enabling longer, better quality of life. Dr. Brenner was the founder of Florida Tech's Nanotechnology Minor Program and a co-founder of its Biomedical Engineering Program. Nanotechnology practitioners use their curiosity to discover scientific principles that form the basis for engineers to maximize surface area to volume ratio to create value for customers. Nanotechnology applications in biomedical engineering include development of the tools to assess success such as electron microscopes and confocal laser scanning microscopes, DNA sequencers, and biomedical imaging contrast agents. The chemistry, physics, and biology associated with anchoring of cells to polymers, metals, and ceramics, whether it be via traditional implants or more advanced methods like bioprinting, will ultimately create value by increasing probability of success (better), doing so more quickly (faster), and doing so at much lower cost (cheaper).

How does one define creation of value? Better, faster, and cheaper

2. A Double Major in Making and in Either Biomedical or Chemical Engineering - How to

Build a Postdisciplinary Engineer (i.e. How does one make a postdisciplinary engineer?)

In response to Misko's challenge of developing postdisciplinary engineers, Dr. Brenner is proposing that the postdisciplinary engineer is a hybrid chemical/biomedical engineer who is also capable of building prototypes, and consequently later in this document, he outlines a KEEN-focused curriculum (Appendix 2.1) that is suitable for a double major in chemical or biomedical engineering AND a new field he will dub as "maker engineering". This adds roughly only 15 credits to graduation beyond the "non-maker" B.S. degree for chemical (ChE) and biomedical (BME) engineers.

In order to be capable of completing all aspects of all engineering problems, students should have the following experiences to develop both skill sets and mindset.

a) CAD drawings of parts and assembled subsystems related to design experiences;

b) PowerPoint skills necessary to present their work in oral and poster presentation forms;

c) use of PowerPoint or Visio to design a process flowsheet or a flowchart for a computer program algorithm (Making the connection between process flowsheets and such computer flowcharts is an absolutely necessary connection for students to make.);

d) a three-credit computer programming class that contains some C++ and all of the common components of computer programs (IF statements, WHILE loops, etc.), but preferably first in a format that combines object-oriented and textual formats like LabView, before also including some exposure to Arduino (mostly C++), Python (for some sensors and controls for which Arduino code does not exist and for which Python code does), and G code (for 3D printing);

e) the ability to construct a circuit wiring diagram;

f) confidence in working with at least of all of the following machine shop and makerspace tools including mills, CNC's, lathes, saws, sanders and polishers, 3D printers, laser cutters, and water jets;

g) confidence with a wide range of instrumentation, including both sensors and controls (servo, stepper, and preferably piezoelectric);

h) the ability to go from concept to hand drawing to CAD drawing to fully working prototype;

i) the merging of a)-h) into course-level and spiraling projects, with at least a freshman- and a senior-level design experience in at least their own major;

j) introduction of entrepreneurially minded learning (EML) concepts as first semester freshmen, with incorporation of such concepts regularly throughout the curriculum;

k) incentives for students with experience with one skill or type of knowledge to help other students succeed (in contrast to the reward system in traditional classes);

l) proper consideration (i.e. critical thinking) of both technical and non-technical issues related to a project, as outlined in a questions and issues sheet (ref. [39](#Ref39));

m) the experience to do a thorough analysis of the patent and journal literature to better define the value of the project opportunity;

n) a thorough grounding in each of the following topics beyond the freshman engineering and computer science classes in a)-e), with the number of semesters in parentheses on the left side of

the semicolon and the numbers of semesters with lab on the right side of the semicolon: physics (2; 2); biology (1-3; 0-3); chemistry (3-5; 2); calculus (4); mass and energy balances (1-2); materials science and engineering (1;1); statics/dynamics/biomechanics (1-2; 0-1); transport

phenomena (2-3); thermodynamics (1); advanced computational methods (1); nanotechnology and

materials characterization lab (3; 2); The Basics of Making (1); signal processing (1; 0-1); and

reactor design (1).

Preferably, a sufficient background in senior chemical engineering design or mechanical engineering manufacturing design so that the student understands what will be necessary for mass production should also be included. Among the more controversial inclusions in n) above are the following, along with explanations as to why they should be included for the postdisciplinary engineer:

Table 2.1 - Controversial Inclusions for Inclusion in Postdisciplinary Engineer Curriculum

Topic Reason for Inclusion

Nanotech & Biology Innovations in bioprinting resolution & cell/scaffold interfaces

Materials Characterization To assess the effects of the nanotech innovations

Statics, Dynamics & The biomechanics of cell attachment to scaffolding is very

Biomechanics for ChE's sensitive to the diameter of the porous fibrous substrate

(Yang ([2](#Ref2)), Tomadakis ([3](#Ref3)), and Bashur ([4](#Ref4)))

Thermodynamics for BME's Self-assembly of fibers into porous structures (i.e. tissues) is

dictated by surfactant (soap) thermodynamics and is an emerging

area in nanotechnology (particularly for mis-assembled proteins like those

associated with Alzheimer's or Parkinson's diseases).

Reactor Design for BME's This is the area that distinguishes ChE's from everyone else. Tissue

"engineering" will not truly be engineering until BME's master reactor

design.

A complaint common to almost all engineers is "Why do I have to take so many humanities, social science, and business/economics courses?" Their point is that the amount of reading necessary in such courses is high relative compared to the amount of time that they have. Engineers in particular and society in general now want authors to get to the point. For example, they want to either read or listen to a summary of Sun Tzu's "The Art of War" ([5](#Ref5)) rather than read the entire book. Consequently, we are recommending the following changes to the non-STEM courses:

1) A re-design of the humanities sequence to include more emphasis on economic systems and philosophies, and the implications that they have on entrepreneurship;

2) Required viewing of The Men Who Built America ([6a](#Ref6a)) and The Food That Built America ([6b](#Ref6b)) video

series to illustrate the effects of economic and social impact considerations on inventions; and

3) A set of movie, TV, audio, and text clips that will a) inspire imagination, creativity, and curiosity; b) enable students to make mental connections between the technology of today (cell phones, laptops, etc.) and tomorrow (tricorders, customized replacement organs, food replicators, space travel, transporter technology, etc.) and their science fiction predecessors; and

c) the ethical and social implications of the technology they will eventually develop.

Florida Tech has an Honors Program under development, and Prof. Brenner's existing nanotechnology minor program will be the prototype for the Honors Program. The first course in the Honors Program is HON 2000 Honors Seminar. The content for HON 2000 reflects the previous list's recommended changes and will be taken in the final semester as a "capstone humanities" class for the entrepreneurially-minded making program. In addition, an alternate to FYE 1000 First Year Experience geared toward Honors Program students (HON 1000 Entrepreneurially Minded Learning) and KEEN goals is under consideration. Florida Tech would like permission to, with no further funding, name the newly proposed Maker Engineering program as the Kern Family Foundation Honors Program in Maker Engineering. ([Appendix 2.1](#Appendix2point1)).

3. Maker Minor Requirements - What does it mean for someone to be called a "maker"?

One type of postdisciplinary engineer is a maker. Making is often referred to as "rapid prototyping". As the development and refinement of prototypes is critical to the development of an entrepreneurially-minded engineer, it is worthwhile to list the steps in the development of a salable product below.

1) identification of an opportunity in terms of customer needs, wants, and/or wishes;

2) assessment of the impact that such an opportunity might present;

3) definition of the problem;

4) a brainstorming process to identify the questions and issues for a product and/or process (Brenner, ref. [39](#Ref32));

5) categorization of the questions and issues into technical/engineering, economic, environmental, safety, health, legal, regulatory, quality, and social impact (Brenner, ref. [39](#Ref32));

6) conversion of 4) and 5) into a set of design constraints;

7) one or more sketches as part of the initial ideation of a solution;

8) definition of the sketch to include all process and product variables in a familiar engineering notation;

9) listing all process and product knowns and unknowns so that the engineer knows how many equations must be written;

10) application of the conservation laws of mass, energy, and momentum;

11) definition of initial and boundary conditions;

12) development of a prototype as a first-generation solution;

13) preliminary testing of the first-generation prototype;

14) re-working of the prototype to better meet design constraints and/or create more value;

15) filing of a provisional patent;

16) preliminary testing of the second generation prototype;

17) marketing of the prototype to generate a future customer base;

18) further refinement and more rigorous testing of the prototype;

19) design and construction of a pilot plant to mass produce the refined prototype;

20) solicitation of further improvements via customer beta testing;

21) incorporation of improvements from 19) before starting construction of a production-scale plant;

21) construction of the full scale production plant;

22) assess whether the full production plant scale product is a) within acceptable tolerances and b) consistent with the pilot and prototype scale versions;

23) an aggressive marketing campaign;

24) full scale production of a v.1 product;

25) incorporation of customer feedback toward a v.2 product; etc.

A maker identifies unmet needs or wants (i.e. opportunities), translates customer wants into product or process characteristics, specifies design requirements and constraints, converts the product characteristics into a hand-drawn sketch, then into a computer-aided drawing (CAD) or set of drawings, determines what the necessary parts are and how the parts should be assembled, and uses whatever means are available and/or necessary to construct a prototype. In the words of Willy Wonka, "We are the makers, and we are the dreamers of dreams." ([7](#Ref7)) Every inventor is a maker. Although not all makers are inventors, a much higher percentage of makers are either inventors or innovators than is found amongst engineers, let alone the general population. As engineer B'Elanna Torres said during an episode of Star Trek Voyager, "It may be the warriors who get the glory. But it's the engineers who build societies. Don't forget that." ([8](#Ref8))

For engineers who wish to be makers but do not find it necessary to be completely independent to solve every engineering problem, Dr. Brenner proposes a minor in making [Appendix 3.1](#Appendix3point1)). The number of additional credits necessary to convert mechanical (MEE), aerospace (AEE), and electrical/computer (ECE) engineers into engineers "capable of completing all aspects of all engineering problems" is between 25 and 30.

So what are the things that a “maker” must be able to do?

1) Makers must be able to draw a design and convert it into a computer-aided drawing (CAD).

2) Makers should be able to draw a flowchart, both as a basis for writing a computer program and as a tool for conceptual process design typical of chemical and systems engineering.

3) Makers need to be able to write a computer program in at least one programming language.

4) Makers must to be able to build circuits containing resistors and capacitors and interface sensors and controls with Arduino or Raspberry Pi microcontrollers;

5) Makers should have experience with a range of tools, including 3D printers, laser cutters, water jets, mills (including CNC’s), lathes, band saws, drills, belt sanders, sewing machines, and simple tools like screwdrivers, wiring tools, and soldering equipment.

6) All makers should have design/build experiences at least at the freshman and senior levels.

7) Makers should have a broad enough science background to be able to tackle all engineering problems and at least four semesters of calculus and differential equations.

8) Makers should have basic skills in visualization, signal processing, instrumentation, and robotics and an advanced skill in at least one of those areas.

9) Makers should be exposed to the entrepreneurial mindset concepts described elsewhere in KEEN EML documents.

10) The humanities and social science required courses should include much more emphasis on the science fiction that has served as inspiration for prior and future inventions, as well as philosophy, logic, ethics/bioethics, and economics classes that emphasize prerequisites for entrepreneurship.

11) Recommended electives include marketing and/or management principles, project management, and systems engineering.

4. History and Reasons Why the Content Is Laid Out the Way That It Is

Wearable sensors have been a popular topic for chemical engineering first year students. In 2011, Julia Worrell and Athela Frandsen, two of the earliest nanotechnology minor students chose that topic and performed a conceptual design of a wearable sensor-embedded space suit. Julia (left of Figure 4.1 below) also launched rockets and experienced weightlessness before graduating and designing a wearable sensor-embedded space suit launched by SpaceX in February of 2018. Athela (right in Figure 4.1) was also one of the students in Florida Tech's 3D printer camp in 2014. Back then, the students actually built an entire 3D printer as part of the camp. Originally intended as an outreach program to high school students, we attracted over 20 students who had already taken at least one year of college at Florida Tech to that camp. When both students graduated as chemical engineers, they regretted not having a prototype-building experience as part of their senior design like all other engineering majors. At that time, Florida Tech started its push toward adding more prototyping options for chemical engineers. After Dr. Brenner attended a KEEN National Conference in Jan., 2018 and participated in the "Quantified Self" workshop put on by Eric Meyer and Mansoor Nasir of Lawrence Tech ([23](#Ref23)), he decided to put together a proposal to Florida Tech's College of Engineering for a class described to KFF staff in November of 2018 and now to be offered for the first time in Fall of 2019 called "The Basics of Making". Discussions of Prof. Brenner's bioprinting and tissue engineering test bed research projects with Ms. Worrell and Ms. Frandsen upon their return to campus for the Feb. 2018 SpaceX launch were critical in getting internal support for "The Basics of Making" course and ultimately the makerspace education proposal that KFF funded in November of 2018.

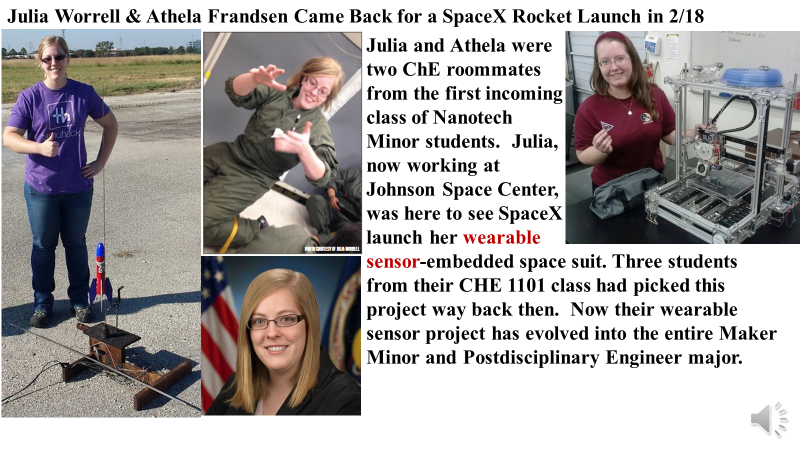


Figure 4.1 - Wearable sensor and 3D printing serve as inspiration for maker minor

Why are bioprinting & tissue engineering test beds excellent examples of creating value?

The most common tool used for rapid prototyping is the 3D printer. 3D printers consist of motors (electrical engineering) mounted on rails into a sturdy framework (structural engineering) with Arduino control (computer engineering) of a polymer being extruded through a nozzle (chemical engineering). While there certainly is value in 3D printing, there is much more value in bioprinting of cells dispersed in hydrogels into candidate organs (the subfield of biomedical engineering known as tissue engineering). While some researchers have learned how to grow and differentiate one's own stem cells into a candidate replacement organ with minimal immune rejection, the term "tissue engineering" is a misnomer. Unless one can reproducibly control something, it cannot truly be called engineering. At this point, most papers in tissue engineering talk about the relatively small percentage of tissues that developed properly and neglect to discuss the many samples that did not turn out correctly.

Over the past several years, Dr. Brenner has moved toward tissue engineering test beds because he recognized an opportunity to inexpensively automate cell culturing and thus accelerate the tissue engineering development process. In 2017, two of the best research students in separate research groups at Florida Tech for whom Dr. Brenner was a secondary advisor complained to him about how mundane cell culturing is. They compared it to feeding and changing diapers for 25-30 Petri dishes of cells on scaffolds every two days. One of the students left Florida Tech after her M.S. degree only to come back on a visit several months later to say that, while her current employer had automated the feeding and waste removal, she still had to take the growing cells out of their native environment and expose them to cytotoxic dyes meant to enhance contrast of cellular features just so that they could perform optical microscopy to see whether the cells were proliferating and morphing into the desired organ type. The only group to have automated the microscopy is a group led by Wikswo and Cliffel at Vanderbilt ([9](#Ref9)); moreover, their microscopy methodology was not particularly scalable to large numbers of bioreactors with full mass balance accounting. This was the identification of an opportunity in terms of customer needs, wants, and/or wishes that KEEN seeks.

Since then, Dr. Brenner realized or observed the following:

1) The reason why chemical engineers have such an easy transition into biomedical engineering is that they have a much better grasp on mass balances, particularly unsteady state mass balances covered in their reactor engineering course, than do biomedical engineers.

2) There is a desire amongst almost all engineering majors to be able to build things.

3) A common complaint amongst chemical and civil engineering students at Florida Tech's senior design showcase is that they can't win because their projects are largely, if not completely, done on computers because the cost of construction is often thousands, if not millions, of times beyond the budgets of senior design experiences. The chemical and civil engineers would like to be able to build prototypes like their counterparts in other engineering disciplines, but certainly for chemical engineers, there is just no room in the traditional curriculum for prototype construction.

4) Wikswo and Cliffel's tissue engineering test bed research ([9](#Ref9)) was being developed into a microfluidic kit by LabSmith, which was looking for beta testers of their kit as part of an NSF SBIR grant ([10](#Ref10)).

5) A surprisingly large amount of content necessary for the construction and operation of 3D printers and all necessary parts for all sensors and controls for a tissue engineering test bed could be purchased new, but unbranded were available from China for about 1/10th of what they had cost ten years before. Moreover, Arduino-based software and wiring diagrams for any of these sensors and controls were even available through sites like Atlas Scientific ([11](#Ref11)), Libelium's Open Aquarium ([12](#Ref12)), and GitHub ([13](#Ref13)). the author determined that he could buy the components that LabSmith was selling for 10-20% of what LabSmith was selling them for, and at that price, he could self-fund the construction of a tissue engineering test bed that could serve as the basis for Ph.D. research projects for the remainder of his career and never have to beg governmental funding agencies again.

6) The "maker" movement is full of very wealthy entrepreneurs who either donate equipment themselves and/or find others who donate equipment. For example, at Florida Tech and at George Fox University, the first university Dr. Brenner visited as part of the 2019-2021 KFF grant, approximately 90% of the machine shop equipment was donated by regional industry. Dr. Brenner has put ~$100 K over the years into equipment some of which his students have resurrected for his nanotechnology minor program. Mr. Martin Gallagher made so much money selling GBotz 3D printers several years ago that he decided to "partially retire" and become the director of Florida Tech's Evans Library Digital Scholarship Laboratory (a visualization and 3D printing/scanning lab). Florida Tech's Mr. David Beavers has donated approximately $100 K for either Florida Tech's MakerSpace or, since KFF's grant, to a class that Dr. Brenner will teach for the first time in Fall of 2019 called "The Basics of Making". Based in part on the "Quantified Self" project led by Eric Meyer and Mansoor Nasir ([14](#Ref14), [15](#Ref15), [16](#Ref16), [17](#Ref17), [18](#Ref18), [19](#Ref19), [20](#Ref20), [21](#Ref21), [22](#Ref22), [23](#Ref23)) at Lawrence Tech previously funded by KFF and described at the 2018 KEEN National Conference ([23](#Ref23)), "The Basics of Making" class will be described in more detail in a later section of this report and will be the first of the "co-developed tools" for Florida Tech's 2019-2021 KFF grant. One thing that is definitely clear about "maker" culture is that many of its practitioners have a different concept of entrepreneurship than what most people consider to be entrepreneurship. Their mindset is based on the most memorable line from the 1989 Kevin Costner baseball movie "Field of Dreams": "If you build it, they will come. They will most definitely come" ([24](#Ref24)).

7) Dr. Brenner has trained lots of multidisciplinary engineers, but not nearly as many postdisciplinary engineers. In fact, "The Basics of Making" class was developed because Dr. Brenner was tired of training research students on one skill like soldering only to find out two weeks later that they hadn't completed their tasks because they lacked computer programming skills, for example.

5. Literature Review of Entrepreneurially Minded Learning (EML) in Making Environments

The Kern Entrepreneurial Engineering Network (KEEN) has funded ~50 universities with the goal of establishing an entrepreneurial mindset in graduating engineers. KEEN has an emphasis on the demonstration of curiosity, the integration of mental connections obtained from a variety of sources to gain insight, and the creation of extraordinary value from the obtained insight via the identification of unexpected opportunities and via the persistence to succeed after having learned from failure. Persistence may be the most importance component of success in the makerspace movement. However, only 14 of the 768 KEEN cards published by 7/31/2019 that target "creating value" generated hits for "persistence" ([31](#Ref31)), although many quote the "persist through and learn from failure" bullet item.

In this document, we will examine all aspects of making from ideation to fabrication in the following types of environments, ranging from visualization to fabrication:

1) Digital scholarship labs with virtual and/or augmented reality (VR/AR);

2) On-campus makerspaces;

3) Off-campus makerspaces;

4) Community outreach / training environments;

5) Student design centers; and

6) Machine shops.

The purpose of this article is to comprehensively review the literature of surveys on the following topics:

1) What are the benefits, implications, and challenges of 3D printing?

2) What are the effects of makerspace education on creative thinking?

3) How do makers think and what motivates them?

4) How do making environments influence the conversion of thought into design?

5) What should be in each type of making environment?

6) What are the business aspects of and financial sustainability for each type of making environment?

7) How can courses, summer camps, and workshops be used for training of student makers?

A subsequent article will contain results from the most comprehensive survey of faculty, staff, and students on each of the making environments mentioned above. The numbers in parentheses correspond to reference numbers that will be renumbered after completion of this graduate project but before article submission.

What follows is an outline for the literature review.

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Initially, this review article began as a request by the Kern Family Foundation (KFF), sponsor of the Kern Entrepreneurial Engineering Network (KEEN), to conduct as a review of the status of maker education both inside and outside of KEEN, with emphasis on how KEEN's entrepreneurial mindset and its 3C's of curiosity, connections, and creating value affect making and vice versa. Those reading this who are unfamiliar with KEEN are encouraged to click on the following hyperlinks:

<https://engineeringunleashed.com>

<https://engineeringunleashed.com/curiosity>

<https://engineeringunleashed.com/connections>

<https://engineeringunleashed.com/creating-value>

<https://engineeringunleashed.com/Mindset>

Embellishment Upon KEEN's 3 C's:

John Estell of Ohio Northern University co-led a workshop on alignment of ABET and KEEN student outcomes at the 2019 KEEN National Conference (ref. [186](#Ref186a)) in which he expanded KEEN's 3 C's to include the additional C's of character, collaboration, and communication. Estell's work appears to build on Bers *et al*. ([34375](#Ref34375))'s work on positive youth development's (PYD's) 6 C's: caring, connections, contribution, competence, confidence, and character. Bers' own 6 C's of positive technology development (PTD) are as follows: collaboration, communication, community-building, content creation, creativity, and choices of conduct.

Of these the only new C is competence, which should be considered as an addition to Estell’s 6 C’s. Selection of a frontal auxiliary's views and hidden lines, as well as proper dimensioning are among the CAD drawing fundamentals that one must evaluate when assessing the technical benefits of AM training ([105c](#Ref105C)) in first year design ([105c](#Ref105C)) and in finite element modeling courses ([106c](#Ref106C)).

By contrast, while competence is not directly a mindset issue, it is the primary author's experience and that of his students that often gaps in one's skill set limits what one is willing to envision and pursue. This anecdotal conclusion was recently confirmed by Neumayer and Santos ([140c](#Ref140C)), whose most important conclusion was the link between prototyping competence and entrepreneurial performance is the most important outcome, especially for management students who lack experience with the technical aspects of their products.

Furthermore, collaboration and communication are the human portion of what enables one to make the connections within one's mind necessary for innovation and invention. When combined with experience in practicing one's craft (i.e. exhibiting curiosity), one becomes competent, seeks further collaboration and communication to become more skilled, and ultimately creates valuable content.

Search Criteria

Articles summarized in this review paper were part of at least one of the following Web of Science searches:

TOPIC: (((("maker" OR "makerspace") OR "maker space") OR "fab lab") OR "fablabs") AND TOPIC: (survey)) resulted in 515 results, of which only 14 were deemed relevant.

TOPIC: ("fablab" OR "maker fair" OR "maker faire" OR "makerfaire" OR "makerfair") AND TOPIC: (survey) resulted in 2 hits, both relevant.

TOPIC: ("maker movement" OR "maker culture") AND TOPIC: (survey) resulted in 7 hits, all of which had already been found.

TOPIC: ("hackerspace" OR ("3D" AND prin\*) OR "additive manufacturing" AND TOPIC: (survey) resulted in 356 results, raised the total from the first four searches up to 30 relevant articles.

TOPIC: (("makerspace" OR "makerspaces") AND "education") resulted in 20 hits, all of which were relevant, but five of which had already been found.

TITLE = (mak\* OR additive) AND (cours\* OR educat\*) AND All Fields = (prin\* OR laser).

Of the resulting 160 hits, 19 were deemed relevant.

TOPIC = (cours\* OR educat\*) AND TITLE = (maker OR makerspace OR makerspaces OR "additive manufacturing"). Of the resulting 623 hits, 146 were deemed relevant.

To ensure thoroughness of coverage of all maker education efforts within the KEEN network, every single one of the now over 3000 KEEN cards was examined and compiled into what is now the [One CardDeck to Rule Them All](https://engineeringunleashed.com/card/2167) and cards linked to therein.

5.I. Review Articles

The creation and engineering of projects involving physical objects involving electronics, robotics, 3D printing, laser cutting, sewing, and/or arts and crafts, in conjunction with software or control tools, is what comprises the maker movement ([34317](#Ref34317)). Papavlasopoulou *et al*. ([34317](#Ref34317)) reported that the highest number of papers of any category within the makerspace education field is geared toward improving computer programming skills ([34317](#Ref34317)) via data acquisition and control with Scratch (10 papers), LilyPad Arduino (9 papers), or Arduino (6 papers). At that time, only seven papers included university students ([34317](#Ref34317)), only two papers each focused on Raspberry Pi or 3D printing ([34317](#Ref34317)), and very few studies focused on gender issues ([34317](#Ref34317)). The primary emphasis of the three most cited review papers is K-12 education pedagogy ([1c](#Ref1C), [34317](#Ref34317)), with establishment of a maker culture also being discussed in detail by Papavlasopoulou *et al*. ([34317](#Ref34317)) and the motivational factors for K-12 makers being the focus of Vongkulluksn ([21c](#Ref21C)). Maker culture is a community-based philosophy in which users work together to improve each other’s skills and reduce cost in resulting projects; it is the 21st century evolution of the do-it-yourself (DIY) movement.

The most comprehensive review of physical university makerspaces has been conducted by Barrett *et al*. ([34394](#Ref34394)), including several KEEN members from James Madison and Georgia Tech. This review classifies makerspaces in terms of form of administrative responsibility (faculty-run, student-run, staff-run, or a combination thereof), location (on or off campus), whether they campus wide or departmentally-run, and who is permitted to be a member of such makerspaces, and lists their web sites ([34394](#Ref34394)). Student-run makerspaces are less common except at very large public universities ([34394](#Ref34394), [103c](#Ref103C)). Barrett *et al*. also listed what equipment is available at each of those campus makerspaces ([34394](#Ref34394)). In order of frequency of use: 3D printer, laser cutter, woodworking or metalworking capabilities electronics, and soldering capabilities ([34394](#Ref34394)). Very common pieces of equipment included: CNC routers, CNC mills, CAD/CAM stations, printed circuit board (PCB) mills, plasma cutters, vinyl cutters, 3D scanners, and welders ([34394](#Ref34394)). All but five of the makerspaces listed in the 2014 report were restricted to campus users ([34394](#Ref34394)). Vanderbilt's Mobile Makerspace shares many similarities to Stanford's "d.school", but is for patients at its children's hospital rather than its students ([34394](#Ref34394)). Wichita State completed a makerspace that is open to dues-paying public members ([34394](#Ref34394)).

Chen and Wu ([34334](#Ref34334)) have performed a survey of maker literature, rather than just literature on maker education. Two of the three most cited articles in their review are by Sheridan *et al*. involving a case study of three makerspaces ([34395](#Ref34395)) and on the maker movement in education ([34396](#Ref34396)). Sheridan *et al*. ([34395](#Ref34395)) shows how "makerspaces help individuals identify problems, build models, learn and apply skills, revise ideas, and share new knowledge with others." Another oft-cited article is Dougherty's article describing the history of the maker movement ([34397](#Ref34397)).

Chen and Wu ([34334](#Ref34334)) report that the most popular books amongst makers are by Anderson ([34398](#Ref34398)) and Dougherty ([34399](#Ref34399)). Harel and Papert's ([34400](#Ref34400)) book entitled "Constructionism" explains the most popular theory for measuring the scholarly benefits of making and is quoted by many of the articles in the maker education literature. A book that might become popular in the KEEN community is "Making Is Connecting" by Gauntlett ([34401](#Ref34401)).

Most schools integrated making sessions into either a whole semester curricular elective ([34402](#Ref34402), [34403](#Ref34403), [34404](#Ref34404), [34405](#Ref34405), [131c](#Ref131C)) or at least for a few weeks ([34406](#Ref34406)). Camps ([34407](#Ref34407), [142c](#Ref142C), [77c](#Ref77C)) and workshops ([34408](#Ref34408), [142c](#Ref142C), [9c](#Ref9C)) are also common. Of the integrated making sessions, the studies by Hartnett *et al*. ([34404](#Ref34404)) and Delle Monache *et al*. ([34405](#Ref34405)) are probably the most relevant, as they were open to engineers of many majors at the university level. Sewable sensors and actuators similar to those used by Eric Meyer of Lawrence Tech in the Quantified Self curriculum ([14](#Ref14), [15](#Ref15), [16](#Ref16), [17](#Ref17), [18](#Ref18), [19](#Ref19), [20](#Ref20), [21](#Ref21), [22](#Ref22), [23](#Ref23)) have been successfully implemented by Searle and Kafai ([34402](#Ref34402), [34403](#Ref34403), and [34406](#Ref34406)) and were part of a course [first offered by Brenner in 2019](https://fit.instructure.com/courses/604044/assignments/5079709). Most studies had as their main subject computer programming or a combination of programming and math ([34409](#Ref34409)). Mellis, Qi, Buechley, and Resnick ([34410](#Ref34410), [34411](#Ref34411), [34412](#Ref34412), [34413](#Ref34413), and [34414](#Ref34414)) have successfully implemented multiple workshop series involving Arduino-based electronics, 3D printing, laser cutting, and circuit board prototyping for both university students and adults in the surrounding community.

In a review paper, Davis ([34358](#Ref34358)) examines implementation of making environments at libraries in New England, including a table listing which university uses which types of equipment. Most noteworthy about Davis' contribution is a ranking of the relative importance of the funding mechanisms for library making spaces as follows: the library's capital projects budget, surpluses in the library's annual operating budget, internal funding from campus constituents, donations and gifts, external grants, and small user fees.

5.II. Benefits, Implications, & Challenges

5.II.A. Benefits, Implications, & Challenges of Makerspaces

Instructors

Despite considerable effort by some faculty as noted by Lenhart *et al*. ([61c](#Ref61C)), makerspaces still are not well integrated into engineering curricula ([60c](#Ref60C)) because faculty have not adequately re-designed how they teach to reflect the opportunities afforded by the makerspaces ([61c](#Ref61C), [69c](#Ref69C)). The biggest challenge of learning in additive manufacturing environments is summarized by Roldan *et al*. ([34376](#Ref34376)). While the apprenticeship process has a long historical precedent and is an effective means of learning, "it is not scalable for the instructors as it requires extended one-on-one interactions with experts. This is particularly difficult in university makerspaces where leaders must be able to support hundreds of students. ([34376](#Ref34376))". Blikstein ([34415](#Ref34415) and [34416](#Ref34416)) warns that the exact opposite of a KEEN maker activity can result if EML is not the primary focus: “Because the machines can produce beautiful objects with very little effort, the teachers should avoid quick demonstration projects and push students in more complex directions", calling this the “keychain syndrome”.

Students

Bosqué and Kohtala ([34323](#Ref34323)) asked users “How familiar are you with 3D printing?” and “What do you use 3D printing for?”. The primary difference between “good enough” or “expert” makers compared to “beginners” in demonstrating proficiency are the ability to print parts to solve a problem, the ability to adjust printer settings to improve the quality of a printed object, and to repair their own printer. Bosqué and Kohtala ([34323](#Ref34323)) then asked "Do you make your files yourself?". There was an obvious trend towards “homemade” files with increasing making experience. This illustrates just how critical it is for makers to have CAD drawing experience. While mechanical, aerospace, and civil engineers have such CAD background, at universities that do not have a common general engineering freshman requirement, chemical, electrical, computer and sometimes even biomedical engineering students do not get such experience. Moreover, most engineers other than electrical or computer engineers do not learn how to draw a wiring diagram unless they learn their computer programming via National Instruments LabView. *Consequently, it is critical to the success of any making curriculum that students learn CAD drawing, wiring diagrams, and computer programming as prerequisites to either Arduino-based data acquisition and control or to 3D printing.*

Libraries

Libraries have increasingly become a hub for visualization and making environments in order to increase access. Consequently, they are "experiencing a shift from providing resources for the passive consumption of knowledge such as books and periodicals to the cultivation of active knowledge creation across various media, both analog and digital" ([34391](#Ref34391)). In order to keep their customers on the cutting edge, librarians face many students and faculty who have a wide variety of experience levels and a wide variety of needs, wishes, and wants. Moreover, librarians were classically not trained to provide such services in school.

Industry

Most business users do not know how to properly use the new maker technology either. Conner *et al*. ([34319](#Ref34319)) examined how entry-level 3D printers are used at four businesses chosen to represent the following uses: 1) education and services; 2) system-level products; 3) final parts; and 4) tooling, with the goal of identifying benefits, implications and challenges associated with 3D printing. In general, entry-level printers did not meet expectations or requirements of the companies, but did help them educate their workforce for use of production-grade systems. Connor notes that one company used a CNC laser cutter to process its automotive materials, but didn't realize until two years later that the CNC laser cutter couldn't properly process half of the materials used in their production and consequently supplemented their laser cutter with a water jet cutter ([34319](#Ref34319)).

Bowyer ([34417](#Ref34417), [34418](#Ref34418)) and Bosqué ([34323](#Ref34323)) call the major benefit of the development of open source 3D printers "Darwinian Marxism"; it allows the average person to have ownership of the means of production.

Katterfeldt *et al*. ([34386](#Ref34386)) show how that maker workshop participants’ self-efficacy (or competence) leads to "confidence, enjoyment, and interest in programming and technology". Benefits of makerspaces regarding university and corporate staff workforce development include a) how to overcome doubt to complete a project and ultimately build confidence, b) hands-on engagement and creation in makerspace professional development, and c) development of different methods for presentation and collaboration ([34351](#Ref34351)).

5.II.B. Effect on Creative Thinking

Weiner, Lande ([220](#Ref220)), and Jordan ([221](#Ref221)) from Arizona State capture the formative aspects of how one becomes a maker quite well in "The Engineer of 2020, in the Making: Understanding how Young Adults Develop Maker Identities and the Implications for Education Reform" ([34377](#Ref34377)). This group "terms the iterative process by which makers share knowledge and improve upon each other’s works as *additive innovation*" ([34377](#Ref34377)).” Jordan and Lande reference Gee’s identity lens framework ([157c](#Ref157C)) as having four independent analytical lenses: nature, institutional, discourse, and affinity ([34377](#Ref34377)), with discourses being further broken down into material discourse and social discourse. The initial "pre-maker" phase is one in which they connect with mentors via maker-based competitions, summer camps, and/or MakerFaires. The development of material and social discourses were highly iterative. It begins with making, then reflection via discussion, then revision, and then reflection, much like the prototyping process itself ([34377](#Ref34377)). At the core of one’s identity, Weiner *et al*. ([34377](#Ref34377)) places relational identity and nature identity, surrounded by a material discourse identity, surrounded in turn by a social discourse identity, and finally surrounded by an outer shell called an affinity identity. Other articles discussing how a maker’s identity is formed that are not discussed elsewhere include [128c](#Ref128C), [125c](#Ref125C), [117c](#Ref117C), [29c](#Ref29C), and [46c](#Ref46C).

It is a common practice for professors during oral graduate student exams to ask questions that will help the professors delineate the edges of their knowledge. As scary as this process is for most graduate students, it should be no surprise that if the learning curve for a design or research project seems too steep, many students will not take that journey ([34382](#Ref34382)). In maker spaces, the inquiry process is often inverted when makers start by creating and then end with understanding ([34382](#Ref34382)). Most critically, "failing, to the teens, equates to not learning, while for the mentors it epitomizes learning". Consequently, teens generally choose smaller projects rather than ones that require significant planning ([34382](#Ref34382)).

When describing deep and sustainable learning (or in German, *Bildung*) of digital fabrication technologies such as Arduinos and versions of Arduinos more suitable to school children, Katterfeldt *et al*. ([34386](#Ref34386)) states that the concepts must be graspable, involve imagineering, and lead to self-efficacy (independence). The term "imagineers" is a Disney concept that summarizes what makerspace educators want to generate as a final product.

Jeng *et al*. ([100c](#Ref100C)) examines relationships between maker education and computer thinking in an Internet of Things (IoT) maker course. While maker education improves both students' attitudes toward computer thinking and programming competency, they are not motivated by the maker education, indicating that the challenge of having to learn both software and hardware skills as well as integrate them into a large whole challenges their confidence. This is similar to South Korean and Japanese children having low self-esteem about their excellent math skills, whereas American children are quite confident despite their lower achievement ([158c](#Ref158C)). Chen *et al*. ([101c](#Ref101C)) observed only benefits in their IoT maker course and then developed a model called "Propose, Guide, Design, Comment, Implement, Display and Evaluate (PGDCIDE)" for a model of their students' learning.

Kim *et al*. ([114c](#Ref114C)) formulate a thorough learning model consisting of exploration, empathy, iterative project problem selection and sharing, ideation, iterative solution selection and sharing, fabrication, testing, looping all the way back to the exploration and empathy stages, and finally formulating the story into a poster and then a paper. This iterative process ultimately forms a maker's mindset. Anis' model is quite similar ([73c](#Ref73C), [149c](#Ref149C), [152c](#Ref152C)).

Other articles describing development of an environmentally-oriented mindset through making ([7b](#Ref7B)), student learning models, teacher pre-service and inservice learning models, and pedagogy include several additional references ([102c](#Ref102C), [98c](#Ref98C), [92c](#Ref92C), [3b](#Ref3B), [16b](#Ref16B), [11c](#Ref11C), and [130c](#Ref130C)) as well as four K-12 review articles ([1c](#Ref1C), [3c](#Ref3C), 21c, 114c). Several articles ([1c](#Ref1C), [11c](#Ref11C), [16b](#Ref16B), and [11b](#Ref11B)) discuss the tension that arises from the dichotomy of a maker-based education and more formal education. Further insight into the effect of maker environments on creative thinking will be described later in [Section 5.IV.D](#Section5IVD) (ref. [34390](#Ref34390)). While several other papers could be included in this section, they focus more on design for additive manufacturing (DfAM) and are, therefore, included in [Section 5.IV.C](#Section5IVC).

5.II.C. MakerSpace Startup Requirements & Options

Hynes and Hynes, in "If You Build It, Will They Come? Student preferences for makerspace environments in higher education" ([34331](#Ref34331)), presented photos of eight making environments to university students and then coded their responses according to four predictors of environmental preference: coherence, complexity, legibility, and mystery. They concluded that people want to experience the liveliness of an open making environment that has an industrial aesthetic with patina, with bar level seating that could be moved around, and with storage units with either transparent doors or no doors. Female students expressed more interest in tidiness and mystery and are more intense in their opinions ([34331](#Ref34331)). Artifacts in the space stimulate community building by allowing users to explore new ideas and express themselves using novel tools and media ([34375](#Ref34375)).

Safety and environmental issues must be addressed up front, as they have a measurable effect on K-12 edcuators' perceptions, particularly those of female instructors ([116c](#Ref116C)). significant concern is appropriate ventilation. The two most commonly used 3D printing filaments are poly(lactic acid) (or PLA) and acrylonitrile-butadiene-styrene (ABS) copolymer. Both PLA and ABS emit ultrafine particles (UFPs) of 20-1000 nm in diameter at approximately 36-60x baseline levels during printing; absent appropriate ventilation, this level does not drop to the expected baseline even after 24 hours of no printer use ([34363](#Ref34363)). Even with appropriate ventilation, the particulate emissions after both 3D printing and laser cutting take tens of minutes to return to baseline ([112c](#Ref112C)). The vast majority of laser engraver particulate emissions happen during the post-operation steps ([112c](#Ref112C)). The amount of volatile organic compound (VOC) emissions is certainly non-trivial ([112c](#Ref112C)). Each K40 generic [laser engraver](https://www.ebay.com/itm/253313831369?epid=16045484765&hash=item3afaae51c9:g:ofkAAOSwwTph2587) should have a small air compressor ([159c](#Ref159C)), a water chiller ([160c](#Ref160C)), and a dryer duct connecting to a particle collection unit ([161c](#Ref161C)) before being ducted outside the building. 3D printers should be inside a common ducted frame like a walk-in fume hood and mounted on Unistrut, Superstrut, or equivalent to minimize the effects of vibration from one printer affecting the print quality on other printers. As very few people have experience at upgrading the laser engravers and then configuring arrays of laser engravers and 3D printers for safe operation, we recommend the following instructions and video.

Sweden's nationwide Makerskola program has designed standardized maker kits and has addressed teachers’ lack of professional knowledge related to digital technology and design thinking via separate training of teachers and school leaders, for both to gain some confidence in this area ([34384](#Ref34384)). Critical support is handled via a website for more static information, a digital archive, and two separate Facebook groups ([34384](#Ref34384)).

What should be in each kit obviously depends on the educational level. At a minimum for secondary and university students, each student should have the [Elegoo Uno R3 Project Most Complete Starter Kit w/Tutorial Compatible with Arduino IDE](https://www.amazon.com/EL-KIT-001-Project-Complete-Starter-Tutorial/dp/B01CZTLHGE/ref=sr_1_5?crid=2BP25O2KUIL14&keywords=Elegoo+Uno+kit&qid=1652448405&sprefix=elegoo+uno+%2Caps%2C121&sr=8-5) ($60 + S/H). The instructor should have at least one of the [Smart Robot Car V4 kits in this link](https://www.amazon.com/ELEGOO-Tracking-Ultrasonic-Intelligent-Educational/dp/B07KPZ8RSZ/ref=sr_1_4?crid=2BP25O2KUIL14&keywords=Elegoo%2BUno%2Bkit&qid=1652448791&sprefix=elegoo%2Buno%2B%2Caps%2C121&sr=8-4&th=1) for every ten students. The author supplements what is in these kits with items from [YourDuino.com](http://www.yourduino.com), [DFRobot.com](https://www.dfrobot.com/), [Keyestudio.com](https://www.keyestudio.com/), and several other sources as summarized in [this link](https://fit.instructure.com/courses/604044/files/45147539?wrap=1), plus a slightly [downsized $80 version](https://fit.instructure.com/courses/604044/files/45147537?wrap=1) of the [Bucknell University SpeakerBox](https://bucknellmakers.dozuki.com/Guide/Speaker+Assembly+2019/92?lang=en). When $50 is added for items specific to students' end-of-semester group project, the cost per student is $250, in lieu of a textbook.

5.II.D. Open Source vs. Distinction in Sharing Economies

This concept refers to the decision as to whether a content or product producer should publish much of its content on the Internet, versus protection of that content so that it maintains a competitive distinction. The makerspace movement is largely based on 3D printing technology. Stratasys owned the original patent ([33](#Ref33)) on 3D printing technology, but 3D printing did not become widespread until that patent expired, after which the RepRap Prusa ([34](#Ref34)) was developed and put on a web site with a full parts list, computer-aided drawings (CADs) for each part and assembled subsystems, a bill of materials and vendors, and detailed construction instructions all available for free download. Subsequently, modern makers have come to expect that they should be able to learn, and now build, almost anything through access to web sites like Thingiverse ([35](#Ref35)) for CAD drawings or GitHub ([13](#Ref13)) for Arduino code for almost any device.

Despite the apparent relevance of its title, "Paradoxes of Openness and Distinction in the Sharing Economy", the section on makerspaces focuses more on sociological issues rather than logical paradoxes inherent in a "sharing economy" ([34360](#Ref34360)). On the other hand, Langley *et al*. ([34387](#Ref34387)) in "Trajectories to Reconcile Sharing and Commercialization in the Maker Movement" lists several possible paths for makers to pursue, as follows:

1) Hobbyist;

2) Commercial enterprise;

3) A non-profit model dependent on volunteers, subsidies, and donations;

4) Conversion from a commercial enterprise to a non-profit model, relying on sharing to build a

large community of users (ex. [Arduino's history](https://www.arduino.cc/)) as a path toward business success;

5) Conversion from a non-profit model to a commercial enterprise such as when [MakerBot](https://www.makerbot.com/) went from its

open source [RepRap](https://reprap.org/wiki/RepRap) roots to being [purchased](https://investors.stratasys.com/news-events/press-releases/detail/186/stratasys-and-makerbot-complete-merger) by [Stratasys](https://www.stratasys.com/en/resources/resource-guides/3d-printing-buyers-guide/?utm_source=google&utm_medium=cpc&utm_campaign=Stratasys-Masterbrand-Brand&utm_term=stratasys&gclid=Cj0KCQjwg_iTBhDrARIsAD3Ib5jlm9Z04JJiNfyjRASFXRVD6oovv5T1q4ixcu3Uch7rp8yWhcEIYhoaAoAvEALw_wcB), the original patent holder on 3D printers ([U.S. Patent #5121329A](https://patents.google.com/patent/US5121329A/en));

6) Social enterprise makers begin as nonprofits that try to share both technological and social capital before becoming dependent on grants and eventually developing into commercial enterprises; and/or

7) Social entrepreneurs start by developing commercial products or services that later use some of their profits to further a social mission, often increasing accessibility to their own products and services in the process.

The [Gathering for Open Source Hardware (GOSH)](https://forum.openhardware.science/) ([164c](#Ref164C)) community forum is a hybrid of [GitHub](file:///C:\Users\Kristen\Downloads\GitHub.com) and LinkedIn. The wonderful opportunities that making connections via GOSH enable are exemplified via the following story. Recently the author was asked to review a proposal to the GOSH forum on Flexi-TEER ([165c](#Ref165C)), an open source version of an epithelial volt-ohm meter (EVOM; [166c](#Ref166C)). After discussing the topic with the proposal author, we realized that we were both upgrading a nanoparticle tracking analyzer ([167c](#Ref167C)) with independent electric and magnetic field control for assessing permeation of ions through tight junctions in growing or healing or cancerous skin and other tissues. Both of us needed the partners that heretofore we did not have. Now with Zoom, such professional networking is far easier than going to in person conferences.

One GOSH forum leader is Urs Gaudenz, founder of [Gaudi Labs](http://www.gaudi.ch/GaudiLabs/?page_id=19) and its [accompanying shop](https://gaudishop.ch/index.php/product/3d-printed-fiber-spectrometer-kit/). Gaudi's business model is a classic example of one of the hybrid business models listed above. Gaudi disseminates his research by publishing his CAD drawings, computer code, and .stl files publicly available via his web sites and via GitHub. This review paper's primary author has used Gaudi's [70 euro spectrometer](https://gaudishop.ch/index.php/product/3d-printed-fiber-spectrometer-kit/) and [99 euro PocketPCR thermocycler](https://gaudishop.ch/index.php/product-category/pocketpcr/) to help build a polymerase chain reaction (PCR) system for the cytokine detection system portion of his self-funded tissue engineering test bed research. This is an example of an end-of-semester project for his Basics of Making course described in [Chapter 7](#Section8TheBasicsofMakingCourse); such a course prepares juniors, seniors, and graduate students both for senior design and for engineering research. The equipment cost for this project was just over $ 1K, but of course, that does not include the labor cost to develop and test such a PCR system. For comparison, [ChaiBio](http://www.chaibio.com) sells an open source PCR for $ 5800, whereas commercial PCRs typically cost more than an order of magnitude more. Whereas most makers are familiar with GitHub, very few are familiar with [Metafluidics.org](http://metafluidics.org), a site where researchers can download all necessary items for fabricating many microfluidic devices.

Makers use the Internet often both for inspiration and for advice. Most makers are aware of [GitHub](file:///C:\Users\jbrenner\Downloads\GitHub.com) as a repository for open source maker projects and [Hackaday](https://hackaday.com) for its daily recommendations of maker projects. According to Shan and Wang ([124c](#Ref124C)), topic initiators in asynchronous online communities like Hackaday or GOSH either share their original ideas and provide resources or advice. If such online community discussions require more than that, participants take their higher level discussions offline for privacy reasons ([124c](#Ref124C)).

Among the goals of The Kern Family Foundation (KFF; ref. [36](#Ref36)) and its offspring, the Kern Entrepreneurial Engineering Network (KEEN; ref. [37](#Ref37) = [engineeringunleashed.com](http://engineeringunleashed.com)), is the dissemination of entrepreneurially-minded engineering education content amongst the KEEN partner institutions ([38](#Ref38)) to such an extent that the word entrepreneurial is implied when someone says engineering. Entrepreneurial engineering inventors should ask whether they want the National Science Foundation (NSF), the National Institute of Health (NIH), some other government entity, or even a private organization like KFF as a funding agency/business partner. The benefits of such funding for faculty include validation of one's ideas, likelihood of promotion and/or tenure, tuition and stipend for students and postdocs, etc. While it is possible to obtain patents for newly developed technology made possible through government funding, unless one develops such technology without ever having submitted an application for government funding, those on a governmental review panel (i.e. the people other than the applicant most capable of developing the applicant's ideas into a prototype) see the idea in its infancy. Moreover, once a paper on the subject comes out in print, presumably after a patent is filed, there is nothing to keep those who do not respect intellectual property rights, or even come from countries that do not respect intellectual property rights, from reverse engineering an invention. In essence, without an inventor "going it alone", it may not be possible to pursue the trade secret intellectual property path now; in an era where 3D scanning makes reverse engineering relatively straightforward, it may not be worth trying to invent via the trade secret path.

5.II.E. Importance of Community, Psychological Benefits, and Inclusion

"What Makes a Maker: The Motivation for the Maker Movement in Information and Communication Technology (ICT)" demonstrated a) the positive influence of community participation on both the amount and the quality of one's making, b) status motivation, opportunity motivation, and extrinsic motivation all positively influenced making, and c) that use-value motivation positively influenced makerspace community participation ([34336](#Ref34336)). Several KEEN makerspace coordinators identify community participation as critically important to the success of a makerspace. However, what was most interesting in ref. [34336](#Ref34336) was that the maker's intrinsic, extrinsic, and use-value motivation did NOT positively influence their making.

Issues regarding inclusion and equity for women, minorities, those in rural areas, those in urban areas, and for shy people are the subject of numerous papers ([142](#Ref142C)c, [125c](#Ref125C), [117c](#Ref117C), [116c](#Ref116C), [115c](#Ref115C), [108c](#Ref108C), [105c](#Ref105C), [93c](#Ref93C). [86c](#Ref86C), [34376](#Ref34376), [22c](#Ref22C), [21c](#Ref21C), [2c](#Ref2C), [4b](#Ref4B), [1b](#Ref1B), [45c](#Ref45C), [42c](#Ref42C), [37c](#Ref37C), [29c](#Ref29C)). Those with particularly noteworthy observations or conclusions are delineated further below.

Deruelle and Metzger ([34345](#Ref34345)), in "Preventing Isolation by Collaborative Innovation", show significant psychological benefits associated with maker environment communities, particularly for intelligent but shy students.

Roldan *et al*. in "University Makerspaces: Opportunities to Support Equitable Participation for Women in Engineering" share numerous insights regarding how to improve female engineer retention via making environments ([34376](#Ref34376)). Self-efficacy of female engineering students declines during their first year of college and never recovers. ([168c](#Ref168C)). One problem is that high-powered tools commonly found in university makerspaces may make newcomers unwelcome due to lack of experience ([169c](#Ref169C)).

Roldan *et al*. ([34376](#Ref34376)) "identified six mechanisms inspired by McMillan and Chavis’s framework ([170c](#Ref170C)) through which female engineering students evaluate their sense of community in university makerspaces: 1) project assessment; 2) member assessment; 3) perspective taking; 4) signals of approachability, 5) structured help-seeking, and 6) credentialing." Useful recommendations to improve the experience for females in making environments are as follows (ref. [34376](#Ref34376)), with similar results from Tomko *et al*. ([135c](#Ref135C) and [94c](#Ref94C)):

1) Make sure that gender diversity and female safety are taken seriously.

2) Have smocks and hair ties available.

3) A sewing machine should be part of makerspaces and student design centers.

4) Staff should signal "Ask me for help." rather than "Does he mind being disturbed?".

5) Training for perspective taking is time well spent.

6) Credentialing will allow female engineers to gain the respect of their male counterparts.

Providing an opportunity for peer respect is not the only benefit to credentialing. Credentialing via a learning management system such as Canvas or [Dozuki](https://bucknellmakers.dozuki.com/) allows makerspace management to set up online training prior to students earning the privilege of being trained. Such a system also can be used to control which users have access to what spaces and which equipment within those spaces. At the 2019 [Bucknell BFAB Summer Camp for Faculty](https://bucknellmakers.dozuki.com/Guide/Speaker+Assembly+2019/92?lang=en), Alan Cheville of Bucknell announced that he has a very simple and [inexpensive swipe card credentialing device and software](https://bucknellmakers.dozuki.com/c/7th_Street_Studio) that his university uses effectively to permit more equipment usage during off hours with less staff intervention.

Students experience a mixture of excitement and frustration with regard to making activities ([21](#Ref21)). In particular, much of the frustration of K-12 students with the need for iteration is much more tolerable as a maker matures ([21](#Ref21)). Weibert *et al*. ([34419](#Ref34419)) list the following sources of positive and negative effects on fun associated with making, along with several that are specific only to adults as noted by Tanenbaum *et al*. ([34420](#Ref34420)) and Chu *et al*. ([34383](#Ref34383)). Concern over breaking, lack of tool knowledge, visualization challenges, finding creative inspiration, a need for personalization, self-imposed quality standards, and too high a focus on product (particularly among children) are the major negative effects of making on fun ([34419](#Ref34419), [34420](#Ref34420), and [34383](#Ref34383)). Positive effects include achievement in successful material and tool usage, moments of discovery, sharing of creation, and competence ([34419](#Ref34419), [34420](#Ref34420), and [34383](#Ref34383)). Pleasure, expressiveness, and a focus on process appear to be positive effects of making on fun that are experienced only by adults ([34419](#Ref34419), [34420](#Ref34420), and [34383](#Ref34383)).

More attention is merited to the benefits of making to those diagnosed with Asperger's syndrome. To that point, Collier and Wayment ([34357](#Ref34357)) in "Psychological Benefits of the ‘Maker’ or Do-It-Yourself Movement in Young Adults: A Pathway Towards Subjective Well-Being" demonstrated that makers of university age experience mild, positive arousal, a quieted ego, and substantially less rumination after stressful events after making as a hobby, rather than for a class project. Yan also reports anxiety alleviation following making ([132c](#Ref132C)).

Gillespie and Nossoni ([148c](#Ref148C)) report that students in makerspace sections of 1st year engineering courses were more likely to "identify skills such as teamwork, problem solving abilities, and communication as being the most important part of being an engineer as opposed to characteristics related to personality traits like determination and the ability to adapt". The emphasis on teamwork seems to be one that is far more important at the university level ([6c](#Ref6C), [10c](#Ref10C), [148c](#Ref148C)) than at the K-12 level. Gillespie and Nossoni ([148c](#Ref148C)) also observed that introducing students to makerspace via classroom experiences significantly decreased students feeling like outsiders, but that feeling of belonging often takes two months.

Given the community and psychological benefits just covered, it should not be surprising that establishing a narrative and remaining consistent with that narrative are important. For a summary of this subject as related to maker education and makerspaces, the reader is directed to a review article ([21c](#Ref21C)) and papers therein.

5.III. How Makers Think & What Inspires Them

5.III.A. Importance of Community & Psychological Benefits - summarized in [Section 5.II.E](#Section5IIE).

5.III.B. Motivations and Character Traits of Early MakerSpace Adopters

Some of this content was or will be covered in other sections (refs. [34323](#Ref34323) in [Section 5.II.A](#Section5IIA) and [34330](#Ref34330) in [Section 5.VII.F](#Section5VIIF)). Also covered in other sections is a reference rich in KEEN connections ([34377](#Ref34377)) in [Section 5.II.B](#Section5IIB).

Persistence through failure is the most critical element to success for engineering students during the fabrication process. Maltese *et al*. ([34388](#Ref34388)) defines failure as ranging from everything from a failure of an LED to light up because the wires are reversed to the failure of an entire project. They claim that failure is often personalized through how it is identified and responded to. For instance, it is more likely to be negatively personalized by women and persons of color, and has a cumulative effect ([34388](#Ref34388)). Maltese comprehensively reviews others' articles on failure's potential to be risky, detrimental, an opportunity to learn from one's own and others' mistakes, and a critical part of the design cycle ([34388](#Ref34388)). Maltese then solicited survey results on the [Association of Science and Technology Centers](https://www.astc.org/)’ Making & Tinkering Community of Practice listserv and to makerspace contacts listed at [TheConnectory.org](https://theconnectory.org/) and [MakerEd.org](https://makered.org/) web sites regarding the following two questions:

1) How do maker educators view failure in the context of making?

2) How do maker educators describe their response, and students’ response, to failure in the context of making?

Experienced makers consistently reported that failure was a learning opportunity ([34388](#Ref34388)). 58% of respondents viewed failure positively, with persistence (39%) and learning from mistakes (42%) being most common, followed by a sense of accomplishment (18%), self-confidence (14%), creativity and innovation (only 4%), curiosity (3%), and patience (1%) ([34388](#Ref34388)). When goals were not met, respondents reported quitting (32%), frustration, and disappointment most frequently, but 6% were due to materials and tools and 14% reported challenges associated with instructors finding the correct balance between sufficient structure to succeed vs. so much structure that creativity and innovation were stifled ([34388](#Ref34388)). Twelve percent thought that the pace of instruction was too fast, and 26% reported prototyping failures as leading to negative outcomes ([34388](#Ref34388)). Frustration was common for woodworking, particularly with glue, for wiring and soldering, for 3D printing, for construction of wearable sensors, and for computer programming ([34388](#Ref34388)). Twenty-eight percent of respondents said that time to work on the project, meeting deadlines for a public display or competition, and/or limited resources led to further frustration ([34388](#Ref34388)).

Maker educators most commonly asked students to reflect on their work and outline their next revision (39%), and 20% even celebrated the students' failures ([34388](#Ref34388)). When students asked for help, 63% of maker educators posed questions back to the students ([34388](#Ref34388)).

Maltese *et al*. ([34388](#Ref34388)) then made the following recommendations: 1) modeling of troubleshooting; 2) minimization of any strong emotional responses; 3) minimization of stress-inducing deadlines; 4) resisting the urge to just fix the problem; 5) minimization of handling of the students' projects; and 6) usage of questions to guide the student to solve the problem himself or herself.

Wang *et al*. ([34322](#Ref34322)) used innovation diffusion theory and a technology acceptance model to analyze the willingness of Chinese people to adopt 3D printers for home use. Perceived ease of use, perceived usefulness, perceived enjoyment, and perceived compatibility all were correlated with intent to use ([34322](#Ref34322)), with ease of use being more important for older adopters and female adopters. As expected, designers were more likely to adopt 3D printers for home use than the general public ([34322](#Ref34322)).

In addition to the benefits of the art-focused makerspace at Bucknell and the art-inspired showcase at George Fox University described in [Section 5.III.G](#Section5IIIG), given what motivates makers, establishing a maker culture is a high priority, particularly with regard to [MakerFaires](http://www.makerfaire.com), showcases, and competitions. Penn State faculty demonstrated quantitatively the benefits of showcases and design competitions ([70c](#Ref70C)). Texas A&M sees similar benefits from a mini-Maker Faire ([96c](#Ref96C)), particularly with regard to establishment of a maker culture. Beavers *et al*. ([75c](#Ref75C)) describe some of the challenges in establishing a maker culture in library makerspaces at a liberal arts university.

Other university maker cultures topic were discussed previously in [Section 5.II.E](#Section5IIE).

Tabares and Boni ([110](#Ref110C)c) emphasize "establishing an open and collaborative learning ecosystem (OCLE) between different educators, students and external stakeholders". Sharma *et al*. ([47c](#Ref47C)) seek to develop an ecosystem of Learners, Users, Manufacturers, Innovators, Operators, and Servicemen (LUMINOS). Chung *et al*. ([101c](#Ref101C)) directly assess “maker spirit” as a measure of their success in establishing a maker culture.

5.III.C. STEM Literacy Practices of Experienced Makers

An article rich with regard to persistence and the view of failure ([34388](#Ref34388)) was just described in [Section 5.III.B](#Section5IIIB). Tucker-Raymond *et al*. ([172c](#Ref172C)) "identified eight goal-driven purposeful processes from interviews with experienced makers: ideating, designing, tinkering, fabricating, sharing, managing, teaching, and socializing". The same group then went further on to address the following three questions to further narrow which of the eight processes were most important ([34374](#Ref34374)):

"1) What are makers’ sources of information?

2) How do makers source materials and information?

3) How do they integrate that information into ongoing projects?"

Sources of information included a wide range of Internet sites, particularly Instructables.com and YouTube videos. Also included were popular culture, product specification sheets and brochures, CAD drawings, wiring diagrams, compiled .stl files for 3D printing of objects. Standard sources such as textbooks, lecture notes, patents, journal articles, certain magazines, catalogs (most notably McMaster-Carr), their own and others' previously designed objects, and conversations with peers and mentors both in person and online ([34374](#Ref34374)) were also considered. Gravel *et al*.'s ([34374](#Ref34374)) show that makers integrate their information via a series of ideation, design, tinkering, and fabrication.

5.III.D. Open Source vs. Distinction in Sharing Economies - summarized in [Section 5.II.D](#Section5IID).

5.III.E. Effect on Creative Thinking - summarized in [Section 5.II.B](#Section5IIB).

5.III.F. Entrepreneurial Mindset

Among K-12 educators, Kim *et al*. ([114c](#Ref114C)) most thoroughly analyzed and incorporated lessons learned from others to not only develop effective pedagogy within budgetary constraints, but also the comprehensive view of a maker's mindset of any K-12 paper. After examining the previously developed frameworks of mindset development, they listed the steps of what they term "novel engineering" as a) selection and reading of an appropriate book, b) identification and review of the problem, c) conceptualization, design, prototyping, and testing the solution, d) presentation and feedback, e) improvement of the solution, f) sharing, and g) restructuring the story ([114c](#Ref114C)). They also compared a variety of design thinking models ([114c](#Ref114C)). After listing which literature articles fit their novel engineering instructional model, they solicited experts' opinions and improvements before coming up with a revised model to include the following: a) tinkering; b) exploration and empathy; c) ideation; d) creation, e) testing; f) sharing; and g) story rewriting, with journal reflection at each step ([114c](#Ref114C)). They then developed a curriculum for teaching a graphically-oriented computer programming language and assessed maker mindset development using the following categories: a) asset and growth orientation; b) willingness to tinker; c) collaboration; d) viewing failure as positive (persistence); e) and playfulness ([114c](#Ref114C)). Pre-testing and post-testing was conducted on experimental (maker-focused) and control (traditional instruction) groups. The only mindset improvement for the control group was with regard to persistence. By contrast, the maker-focused instruction resulted in improvements in all mindset categories ([114c](#Ref114C)).

Regarding fostering entrepreneurship, Bergman, Jr. and McMullen ([51c](#Ref51C)) distill the makerspace startup process down to six questions:

1) Open vs. closed membership ([51c](#Ref51C))

Are we open to all applicants regardless of maker experience, or will we require an application for membership? Choosing the more exclusive route requires a higher buy-in from more well- qualified applicants and results in a more predictable pool and more cohesive community of users at the expense of diversity, inclusivity, and number of users to defray equipment costs.

2) Identifying opportunities ([51c](#Ref51C))

Does the makerspace ownership want to act as a broker for users and/or companies?

3) Supporting opportunities ([51c](#Ref51C))

Do we want to support entrepreneurs at the ideation stage, the prototyping stage, the early manufacturing stage, the mass production stage, and/or some or all of these stages? A single user or company may dominate space, equipment, and/or makerspace coordinator time, to the detriment of other users.

4) Diversification vs. specialization ([51c](#Ref51C))

Tailoring to an already existing, highly specialized user community reinforces a lower volume of deeper collaborations. A diverse user community will make it more difficult to have universal training and programming, but a makerspace ownership that wants to create value for users and companies by connecting them can be an effective business model.

5) Onboarding and socializing new membership ([51c](#Ref51C))

How much handholding is leadership capable of providing? Or willing to provide?

6) Designing the physical space ([51c](#Ref51C))

Do we want to be a factory, a store, or both?

Van Holm ([8c](#Ref8C)) lists makerspaces' four principal contributions to economic development as follows: "(a) creating a cultural change by encouraging entrepreneurship in the community, (b) supporting small business growth through the provision of services, (c) providing workforce training, and (d) increasing workforce retention." Gartner *et al*. ([19c](#Ref19C)) has conducted a technology assessment of the benefits of additive manufacturing that is suitable for policymaker decisionmaking.

The low percentage of Chinese university engineering students (6.1%) being in favor of innovative entrepreneurship was attributed to the lack of emphasis on developing a maker mindset by Chinese instructors ([42c](#Ref42C)). Chinese engineering students scored average among university students in innovation and creativity ([57c](#Ref57C)). As in athletics, makers learn via modeling example moreso than with regard to more traditional classroom subject matter. Confidence in one's competence is important in communicating a proper maker's mindset; thus, faculty need to dedicate the necessary time to establishing such competence ([131c](#Ref131C)). If faculty are uncomfortable with learning alongside their students, the students will pick up on that discomfort. Neumeyer and Santos ([140c](#Ref140C)) demonstrated that the following variables enhanced entrepreneurial performance: female gender, teammates communicating with each other to enhance the group's prototyping quality, and past experience in both entrepreneurship and prototyping. Faculty need to view themselves as fellow learners to properly model the teamwork aspects necessary for a proper maker's mindset.

5.III.G. Art Aspects of Design

Makers are more inspired by the artful aspects of design than typical engineering students and find fulfillment when they are able to manufacture what they envision. Within the KEEN community, Chris Sharp of George Fox University is particularly noteworthy in this respect. Along with Daniel Castaneda of James Madison and Heather Dillon of The University of Washington at Tacoma, Sharp chaired a session entitled "[Leonardo da Vinci 2.0: Re-Discovering Artistic Expressions of Engineering to Foster an Entrepreneurial Mindset](https://engineeringunleashed.com/card/2402)". Da Vinci was far more of an engineer than most people think, including his understanding of the golden mean as the limit obtained when two consecutive Fibonacci numbers are divided by each other as being a critical concept anatomical design and his impact on powered human flight. Along with Chad Stillinger, Sharp also organizes an [ArtDuino Make-A-Thon](https://engineeringunleashed.com/card/1152), combining the benefits of art, engineering, making, and competition into both a training event and an inspiring community building opportunity.

During the author’s visits to other universities, Bucknell University clearly had the most pervasive maker culture amongst faculty, students, and staff. Sabrina Shankar, in a presentation titled “[EMphasizing Making from a Student Affairs Perspective](https://engineeringunleashed.com/card/1643)” ([153c](#Ref153C)) and a 2020 KEEN National Conference session named [EMphasizing Making](https://engineeringunleashed.com/card/311) ([154c](#Ref154C)) in slides 25-29 of EMphasizing Making\_Full Slides.pdf, highlighted pottery, glass making, painting, mosaics, jewelry, screen printing, and soap making workshops, in addition to the expected technically-focused workshop content in order to get buy-in from the entire campus community.

Clapp and Jimenez ([12c](#Ref12C)) claim that the A in STEAM education is not all that clear in general and even less so with regard to maker-centered learning experiences. At this point, at the K-12 level, incorporation of maker-center learning experiences is largely a missed opportunity, although Jordan *et al*. ([17b](#Ref17B), [133c](#Ref133C)) have shown that it can be properly integrated via a mobile makerspace program coordinated with a school district's art program.

5.IV. Conversion of Thought to Design

Although there is considerable discussion of the conversion of thought into design, particularly regarding conceptual mapping, there is not very much quantitative evidence regarding how one's mind translates a thought into part of a sketch. One notable exception to that is from Chiradeep Sen's group at Florida Tech ([173c](#Ref173C)), whose group has developed their own artificial intelligence code for grouping all of the strokes in a cluster to draw a single named object on a tablet computer. Features measured to collect such data include the number of pen strokes, the number of pen stroke clusters, the number of pauses, the clustering threshold (set to 1 s at first), the number of pen strokes per cluster, the duration of pauses, and the features, components, assemblies, and labeling of the sketched solution ([173c](#Ref173C)).

5.IV.A. Collection & Integration of Information from Many Sources to Gain Insight

This subject is covered in other sections, particularly in Sections 5.II.E, 5.III.B, and particularly 5.II.D, 5.III.C, 5.III.F, and 5.IV.D.

5.IV.B. Effect on Creative Thinking - [summarized previously in Section 5.II.B](#Section5IIB).

5.IV.C. Design for Additive Manufacturing

"Design for Additive Manufacturing (DfAM) aims to take advantage of the unique capabilities of AM to 1) design and optimize components according to the functions of the product/component and the requirements of the selected AM process for production; and 2) rethink, redesign, and refine an existing product/component, utilizing the characteristics of AM to improve the functionality ([34333](#Ref34333), [34421](#Ref34421))."

A group of faculty at Penn State University led by Rohan Prabhu has published a series of papers on how to teach DfAM courses ([92c](#Ref92C), [120c](#Ref120C), [6c](#Ref6C), [48c](#Ref48C), [41c](#Ref41C), [30c](#Ref30C), [13b](#Ref13B), [70c](#Ref70C)). Prabhu *et al*. ([92c](#Ref92C)) encourages design students to adopt a design mindset that both capitalizes on the opportunities that AM presents that would be impractical when parts are manufactured using conventional methods, but also maintain a sense of realism with what they call restrictive DfAM regarding feasibility of conventional designs. When judged with regard to uniqueness, usefulness, technical quality, and overall creativity, They concluded that only teams taught via restrictive DfAM and a blend of opportunistic DfAM followed by restrictive DfAM selected more unique and creative designs. Students only trained in opportunistic DfAM emphasized minimization of build material. Finally, those trained only in restrictive DfAM emphasized minimizing build time. The same Penn State faculty then formulated and evaluated strategies for design interventions ([13b](#Ref13B)). Finally, the group demonstrated quantitatively the benefits of showcases and design competitions ([70c](#Ref70C)). Texas A&M sees similar benefits from a mini-Maker Faire ([96c](#Ref96C)), particularly with regard to establishment of a maker culture.

Campbell and DeBeer have led a group analyzing capabilities of makers throughout South Africa ([14c](#Ref14C), [150c](#Ref150C)). Then they both reviewed others' frameworks for rapid prototyping (RP) university education and improved on them via a comprehensive set of surveys ([54c](#Ref54C)). The resulting educational framework ([54c](#Ref54C)) consists of AM technology, research and development, in-house facilities, educational curricula, and technology transfer.

The Politecnico di Torino in Italy ([34320](#Ref34320); [24c](#Ref24C)) has an additive manufacturing (AM) M.S. program that integrates a computer-aided environment for design, engineering, and manufacturing (CAD/CAE/CAM). Within their program, students are required to take courses in computer-aided production (CAP), numerical methods for product/process design, and molds and forming processes ([34320](#Ref34320)). Students select a plastic product, redesign it using AM principles, perform CAD modeling of a fully working assembly, and then do all aspects of modeling and manufacturing of parts from their design including mold re-design ([34320](#Ref34320)). This is an excellent model for an M.S. program; most, if not all, aspects could be incorporated into an honors mechanical engineering undergraduate program. Student surveys assessed motivation, understanding, interest, teamwork, impact, geometry, assembly, functionality, process, education, lab practice, and modifications. Of these categories, results were > 80% positive for all but teamwork and modifications, with lack of attendance and participation in these two most challenging categories leading to most of the negative reviews.

Blosch-Paidasch and Shea ([68c](#Ref68C)) have tested a set of 25 questions and objects to accompany a set of design heuristics for AM. They found that both individuals and teams included more AM concepts and modifications, exhibited more creativity, and generated more concept that capitalized on the unique capabilities of AM. When teaching AM, Mantelet *et al*. ([6b](#Ref6b)) and Stern *et al*. ([4b](#Ref4B)) show that interspersing a set of creativity tools results in term of more original and feasible designs, as well as higher student satisfaction, than a more traditional approach where AM and creativity are not taught together.

Muir and Haddad ([34332](#Ref34332)) have studied the impact that AM should have on just-in-time inventory management, particularly regarding customer satisfaction, sensitivity to price, and delivery lead time with regard to the spare parts supply chain of manufacturing organizations.

Pradel *et al*. ([34333](#Ref34333)) conducted a thorough study on AM practices of design engineers with the goal of exploring design engineers' knowledge acquisition practices, selection criteria, and experiences. There appears to be a consensus that AM methods will always be overly expensive for mass production and that AM will be used for rapid prototyping and spare parts manufacturing primarily ([34333](#Ref34333)). Moreover, design engineers tend to lump together all AM methods rather than design for the specific advantages of a particular method, whereas it is common for them to design specifically for injection molding, for instance ([34333](#Ref34333)).

Budinoff and McMains ([85c](#Ref85C)) observed that AM training had no effect on the likelihood of common manufacturability issues during team prototyping did not significantly decrease the occurrence of common manufacturability problems during team prototyping. Moreover, there was only a 20% increase in the prototyping participation rate for those with DfAM training vs. those without such training ([85c](#Ref85C)).

Not suprisingly, all but one of the papers that focused on technical competence as a measured outcome were the DfAM papers discussed previously in this section ([12c](#Ref12C), [32c](#Ref32C), [48c](#Ref48C), [85c](#Ref85C)) or for a sophomore cornerstone design course (149c). The only K-12 paper that focused on competence is by Yeh *et al*. ([145c](#Ref145C)). Yeh assessed three aspects of elementary school maker competence (making, collaboration, and sharing of knowledge), and seven other factors (exhibition of a maker's mindset, motivation for sharing, means of sharing, level of participation, team interaction, theoretical knowledge, and practical application). That list is almost sufficient for an ABET or KEEN outcome assessment plan for university students!

5.IV.D. Library Spaces, Augmented Reality (AR), Virtual Reality (VR), and Visualization Courses

At Florida Tech, in addition to the expected 3D printing services and training courses, Martin Gallagher's makerspace features a wide range of 3D scanning and AR/VR capabilities.

**INSERT several items featured on draft card**

By far, the most comprehensive study on the benefits of VR for design for additive manufacturing (DfAM) is by Ostrander *et al*. at Penn State ([58c](#Ref58C)); not only does VR dramatically improve students' grasp of spatial relationships, but the students appreciate their enhanced understanding ([58c](#Ref58C)). Shu and Huang's findings ([127c](#Ref127C)) regarding VR-based instruction's superiority over PowerPoint slides were particularly noteworthy when used as part of online pre-activity instruction. Especially as a result of the COVID pandemic, training requirements shifted much moreso toward the online version of driver education written test pre-training prior to in person equipment training; this is perhaps the area that VR-based instruction, delivered online, can have the greatest utility. Taking this one step further, students being trained in pre-event disaster preparedness struggle to think sufficiently creatively to respond appropriately unless confronted with real scenes from a disaster ([72c](#Ref72C)).

A librarian's perspective on maker environments within libraries is the subject of review papers by Moorefield-Lang ([5c](#Ref5C)) and Roldan *et al*. ([34376](#Ref34376)), along with multiple other papers ([34329](#Ref34329), [34358](#Ref34358), [62c](#Ref62C), and [34361](#Ref34361) (discussed later in [Section 5.VII.B](#Section5VIIB))), including aspects such as assessment of makerspace effectiveness ([27c](#Ref27C)), creating a maker culture ([74c](#Ref74C)), elementary school library makerspaces ([39c](#Ref39C)), mobile library makerspaces in [Section 5.V.E](#Section5VE) ([34361](#Ref34361)), inclusion ([34376](#Ref34376)) discussed in [Section 5.II.E](#Section5IIE), financial sustainability ([34358](#Ref34358)) discussed previously in Section [5.I](#Section5I), and environmental considerations ([34363](#Ref34363)) in Section [5.II.C](#Section5IIC).

Cun *et al*. ([27c](#Ref27C)) have developed an assessment protocol for library makerspaces consisting of activities, assessment tools for librarians, assessment tools for patron purposes, and potential assessment tools. Activities offered are categorized as workshops/courses, games, 3D printing, recording studio experiences, virtual reality, home media, and activities for non-English speakers. Assessment for patron purposes include basic mastery of technology, mastery of course specific skills, additional course availability, and assessment of technology proficiency specific to younger audiences. Assessment for librarian purpsoes include evidence of attendance, level of interest, willingness to come back, willingness to engage in other library programs, changes in library use, course specific learning progress, and extent of self-driven use. Potential assessment tools include paper or digital surveys, librarian self-assessments, librarian observations, visitor logs, one-on-one interviews with patrons, and competition for resources.

Based on a review of the entrepreneurial literature, Bieraugel *et al*. ([34390](#Ref34390)) identified five behaviors that makerspace users exhibit.

1. Makers are highly observant of both ordinary and novel features.

2. Makers question assumptions, often ask "What If?", "Why?", and "Why Not?", and exhibit KEEN's

contrarian point of view.

3. Makers experiment "with ideas with a hypothesis-testing mindset—learning by doing as a way of

gaining insight into the workings of things and imagined possibilities".

4. Makers network with people and use a wide variety of sources to gain perspective.

5. Makers reflect often to make the intellectual connections that KEEN wants its entrepreneurial engineers

to exhibit.

Bieraugel *et al*. ([34390](#Ref34390)) then examined the suitability of five spaces in the university library, including an atrium, a computer lab, a collaboration room, an open area with large tables, and a quiet study zone, as well as three spaces outside the library including a “green space”, a student union, and a makerspace for the following behaviors: exploration of ideas, exploitation of ideas, observation, questioning, experimenting, networking, and reflection. A plurality of liberal arts students preferred the quiet study space, while the makerspace was by far the most popular among engineering students (82%). First-year students spent most of their time in the student union, while upperclassmen preferred the computer lab. Based on a set of librarian inservice activities, Bowler *et al*. ([143c](#Ref143C)) emphasize that the focus for librarian "professional development should not be a packaged, one-size-fits-all training program but rather, a methodology that allows library staff to design a set of reflective activities". Allowing both students and library staff to check out Arduino microcontrollers allows such reflection in the form of tinkering to make their projects and makerspaces better ([113c](#Ref113C)).

An advanced visualization course ought to be a requirement for makers, but students should be able to select from topics ranging from game design to computer-aided engineering to ANSYS or COMSOL simulations to docking of molecules or proteins to biological or chemical surfaces or even computational chemistry programs like Gaussian. A comment by several civil engineers from multiple KEEN universities was that civil engineers have less to gain from a maker education program. These civil engineers regained enthusiasm for this maker education initiative when it was suggested that they should focus on "walkthroughs" of their building designs, visualization of water flow through soils and traffic flow through intersections. Wang *et al*. ([34340](#Ref34340)), in "Topographical Survey Engineering Education Retrofitted by Computer-Aided 3D-Printing" demonstrate a series of procedures, details, methods, and experiments about printing 3D structures from 2D drawings using SketchUp software with a CADSpan plug-in. The printing of what otherwise would be contour maps dramatically enhanced the students' grasp of topographical maps, particularly amongst the female students ([34340](#Ref34340)).

Jankowski and Hachet ([34318](#Ref34318)) is an outstanding review article on non-immersive techniques for navigation, selection and manipulation, and system control using either mouse or touch-based methods. Topics covered include rotation, panning, and dollying. Dollying is not the same as zooming ([34318](#Ref34318)); rather the camera is translated along its line of sight. Walking/driving/flying refers to how a game player, photo tourist, or prospective home buyer would view his/her environment. Point-of-interest movement by x-y-z point selection, query, hyperlink, and landmarks are all included within the navigation section ([34318](#Ref34318)). This reference should form the basis of an advanced visualization course offered through a computer science program and would be taken by many students in a maker program.

Yang *et al.* ([34326](#Ref34326)) reviews methods for making 3D movies into stereoscopic, auto-stereoscopic, volumetric display, and holographic projections, including a thorough analysis of the advantages and disadvantages of each manufacturer's technologies; of these, holographic projection is the only one that does not require additional equipment on the body.

5.V. What Should Be in Each Type of Making Environment

5.V.A. MakerSpace Startup Requirements & Options - summarized in [Section 5.II.C](#Section5IIC).

5.V.B. AR/VR Library Spaces - summarized in [Section 5.IV.D](#Section5IVC).

5.V.C. Pre-College

This content was either previously discussed in [Section 5.II.D](#Section5IID) regarding references [34375](#Ref34375) and [34384](#Ref34384) and in [Section 5.II.E](#Section5IIE) in reference [34383](#Ref34383) or will be discussed in [Section 5.VII.A](#Section5VIIA) regarding [Michigan Tech's summer camp in reference 34315](#Ref34315), in [Section 5.VII.F](#Section5VIIF) regarding reference [34330](#Ref34330), or in [Section 5.VI.G](#Section5VIIG) in reference [34362](#Ref34362).

5.V.D. FabLab Business Models

Makerspaces can be classified as educational, design, or production, with the vast majority of makerspaces being geared toward the former two ([34c](#Ref34C)). Traditional business models focus on efficiency, but the value created for a makerspace usually is more about its effect on creativity ([67c](#Ref67C)).

In "Makerspaces and Contributions to Entrepreneurship", van Holm states that the maker movement will "influence entrepreneurship by 1) attracting more individuals into product design, 2) generating dense but diverse networks, 3) creating new ideas and innovative thinking, and 4) by lowering the costs for prototyping, making early sales and acquiring outside funding more realistic." ([34366](#Ref34366)) Like health clubs, makerspaces typically have > $100 K in shared tools and thus contain far more than what an individual maker could have in his/her own home, yet only require a fee of $50-100 per month ([34366](#Ref34366)). FabLabs are distinguished from other makerspaces by following the original [Gershenfeld/MIT plan](http://fab.cba.mit.edu/about/charter/) that resulted in the FabLab Charter ([34423](#Ref34423), [34365](#Ref34365), <https://fabfoundation.org/getting-started/#fablabs-full>/):

"(1) be regarded as a “community resource” and consequently, open to the public for some of the week;

(2) respect open source ideas;

(3) consider commercial activities as possible activities, as long they are only incubated in the lab and develop further outside of it;

(4) have a common set of tools, capabilities and processes to allow an effortless sharing of projects and people between labs; and

(5) think about yourself to be part of the wider network".

The standardization of a common set of tools, capabilities, and processes enables the training to be standardized and ultimately creates value by minimizing the cost of the training and the tools. However, FabLabs are currently funded mainly by government agencies, universities, or private companies and have not yet demonstrated complete economic self-sufficiency ([34344](#Ref34344)).

That being said, in 2010/2011 John Boeck and Peter Troxler conducted a Fab Business Study that resulted in eight business models for FabLabs and for the Fab the Library program ([34423](#Ref34423), [34365](#Ref34365)). Of these, the most often used models are 1) to be constantly seeking grants, 2) to embed the FabLab into an educational institution, and/or 3) to constantly be offering workshops. DeBoer ([34365](#Ref34365)) describes the advantages and disadvantages of Boeck and Troxler's business model approaches and adds pointers to each one.

A member of the Kern Family Foundation that funded this study noted that Make, the company that organizes MakerFaires, went bankrupt in July of 2019 before re-emerging recently ([171c](#Ref171C)). While some effort has been made to reduce cost, only those authors' works described above, and a paper by Motwani and Gupta ([119c](#Ref119C)) have looked at return on investment and particularly the revenue side of financial sustainability in any meaningful detail.

Santos *et al*. ([34344](#Ref34344)) have done the most comprehensive study of customer satisfaction for frequently used maker tools, services provided within makerspaces, and the proficiencies of makers' skills. American makers are noticeably deficient in Arduino programming, software programming, Internet of Things (IOT), and digital manufacturing skills (mostly CAD; [34344](#Ref34344)). Most makerspaces do not have 3D scanning, vinyl cutting, or lathes. 3D scanning until very recently was prohibitively expensive. Lathes are typically part of machine shops ([34344](#Ref34344)). Vinyl cutting is surprisingly inexpensive and can be useful for community-building craft activities. CNC milling is common in the USA and Europe, but not in poorer countries. US makerspaces have significantly fewer limitations on equipment access via control cards than their European counterparts ([34344](#Ref34344)). A noticeable deficiency is found among all countries for support in finding the right kind of 3D printer for the job. Spanish, German, and American courses and training are viewed better than those in other countries ([34344](#Ref34344)). Overall, Germans were more satisfied with their makerspace services than those from other countries ([34344](#Ref34344)).

5.V.E. Mobile and Virtual Platforms

A less flattering term for a maker is a "hacker", and "consequently, mythologies surrounding the hacker stereotype have made an impartial consideration of hacking difficult" ([38c](#Ref38C)). In “Hacker Values ≈ Library Values”, Schiller ([155c](#Ref155C)) says that hackers and librarians share key values regarding public openness, freedom, and sharing. Mobile FabLabs can be set up to attract new audiences or to bring the library to the public. The FryskLab ([34365](#Ref34365)) in The Netherlands is the most well-known example of such a mobile FabLab evolving out of a library. After initial rejection of a government grant because it was deemed to not be consistent with library services, the librarians estimate that 80% of the effort of starting the FryskLab came from the staff volunteering their time. Mobile makerspaces run by librarians can be effectively rotated between schools within a school district (Craddock, [156c](#Ref156C)), particularly when coordinated through the school district's art program ([17b](#Ref17B), [133c](#Ref133C)). Moorefield-Lang ([34361](#Ref34361)) delineates how to overcome the challenges associated with library-run mobile makerspace programs.

The FryskLab van contains 10 3D printers, 10 MacBook Air and 15 Dell laptop computers, 3D scanning and doodling, numerous Arduino kits, assorted hand tools, a wide variety of CAD software, [Repetier](https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjFmNek8uH3AhWltTEKHUVxCGsQFnoECBQQAQ&url=https%3A%2F%2Fwww.repetier.com%2Fdownload-software%2F&usg=AOvVaw0Umo7-eapb70uMoEv9qSJK) for conversion of CAD drawings into .stl files, [Cura](https://ultimaker.com/software/ultimaker-cura) (for slicing), and a wireless router. Katterfeldt *et al*. have conducted approximately 40 TechKreativ mobile workshops using a similar set of hardware; they emphasize that the principles must be graspable and involve imagineering to promote self-efficacy ([34386](#Ref34386)). Katterfeldt *et al*. also claim that student produced artifacts become reflective conversation starters for both makers and visitors to a making environment ([34386](#Ref34386)).

Long prior to COVID, the idea of a mobile making platform was a robot. Phogo ([65c](#Ref65C)) is a recent Python incarnation of the original Logo robots, which later evolved into [Parallax's Scribbler](https://www.parallax.com/product/scribbler-3-s3-robot/) based on [Basic Stamp](https://www.parallax.com/product-category/basic-stamp/), the California Board of Education (BoE) [BoEBot](https://www.parallax.com/product-category/boe-bot/), Lego Mindstorms, and finally into the [Arduino-based Elegoo contemporary robots](https://www.amazon.com/ELEGOO-Tracking-Ultrasonic-Intelligent-Educational/dp/B07KPZ8RSZ/ref=sr_1_1_sspa?keywords=Elegoo+robot&qid=1652554208&sr=8-1-spons&psc=1&spLa=ZW5jcnlwdGVkUXVhbGlmaWVyPUExOTNLTlVIQkNIVExZJmVuY3J5cHRlZElkPUEwNDUzNzg2UjRYR00zMzhWS0RRJmVuY3J5cHRlZEFkSWQ9QTA3NTEyMDgyV0tZRTE4SlNYNjFYJndpZGdldE5hbWU9c3BfYXRmJmFjdGlvbj1jbGlja1JlZGlyZWN0JmRvTm90TG9nQ2xpY2s9dHJ1ZQ==). In 2013, the author had 3D printing experience but no robotics background when his daughter took a Python programming class via the Florida Virtual (High) School; the final exam for that virtual class was to use one's phone to video the successful programming of a Scribbler that would be shipped via mail to/from students. Tucker Balch at Georgia Tech ([701](#Ref701)) had recently developed a robotics-focused Python curriculum that was later extended to C++ by a group from The University of Tennessee ([702](#Ref702)), and simplified for use by the Florida Virtual School ([703](#Ref703)). A shortened form of that high school programming activity is now integrated into a [Python programming activity](https://fit.instructure.com/courses/604044/assignments/5079707) and a [robotics programming activity](https://fit.instructure.com/courses/604044/assignments/5079639) in the author's [Basics of Making class in Chapter 7.](#Section8TheBasicsofMakingCourse) Mehrotra *et al*. ([131c](#Ref131C)) report on the successful implementation of an in-person mobile robotics summer school for high schoolers and for in-service teachers attending a professional development course via Zoom. Mobile robotics is one of the easier-to-implement, low cost opportunities for implementation of maker education at the K-12 level, especially if one's community has a Lego Robotics or Lego Mindstorms club to partner with.

The COVID-19 pandemic forced all of us to come up with alternative methodologies for communicating content to our students, particularly to makerspace education, to makerspaces, and to cornerstone (freshman) and capstone senior design courses as summarized in CardDeck: Teaching in a Virtual World. Of particular importance to this review paper are the Making and Make-A-Thons - Adaptations to Virtual Learning and the Capstone Design and Cornerstone (1st Year) Design in a Virtual World links. Among these, Kuhn, Peña, and Stine of Arizona State University illustrate how one can run a [remote design challenge](https://engineeringunleashed.com/card/390). Gurian and Casale of Drexel University, Kuhn of Arizona State, Somasse of Worcester Polytechnic Institute, and the primary author each presented [pandemic-induced adaptations to maker education at the 2021 KEEN National Conference](https://www.engineeringunleashed.com/card/2420). KEEN fora and groups that helped with regard to the COVID transition are as follows, as coordinated by Margot Vigeant of Bucknell: a) [The Virtual/Online Learning group](https://engineeringunleashed.com/group/19); b) [Hands-on learning in the context of social distancing](https://engineeringunleashed.com/forum/75/topic/6219); and c) [Teaching Online: COVID-19.](https://engineeringunleashed.com/forum/86/topic/5695)

Making can indeed be done remotely. Opportunities afforded, challenges experienced, lessons learned, and technology used to manufacture a robot are reported by members of the International Maker Educator Network ([84c](#Ref84C)).

5.V.F. Small Business's Opinions Regarding Makerspaces

Small business's opinions regarding makerspaces were covered in ref. [34319](#Ref34319) in [Section 5.II.A](#Section5IIA), in ref. [34332](#Ref34332) and [34344](#Ref34344) in Section [5.IV.C](#Section5IVC), and in ref. [34344](#Ref34344) in Section [5.V.D](#Section5VD).

In the prior section, the subject of hacking was discussed. Chinese maker culture views hacking quite differently. The Chinese view hacking as a way to found open source hardware (i.e. not patented) businesses, in stark contrast to the Western view of hacking as the approach for students and hobbyists ([7c](#Ref7C)).

As not only a faculty member who has been part of three startups, the last of which the author is currently the primary inventor and 20% owner, there are several aspects of startups that are quite different from larger employers. Firstly, turnover is much higher because in a startup, ownership must keep the capital investment cost as low as possible so that when sales eventually come, the company will appear more attractive to future investors. Secondly, recognizing possible opportunities for new business development is paramount to the creation of value for the company. Thirdly, each employee has to wear many hats, ranging from someone who has all of the maker skill set tools, a maker mindset, the ability to be a corporate evangelist who also is aware of the bottom line, and the ability to manage entire projects. In other words, an employee and/or owner of a very small business must be the proverbial jack of all trades, but also must be a master at several as well. Consequently, this faculty/employer values independence higher than any other characteristic. Assessment of independence has not been given enough attention by previous authors. A notable exception is a makerspace run by engineering management graduate students; in that space, students prefer just being equipped with teacher guides as opposed to being instructed using traditional curricula ([102c](#Ref102C)).

5.VI. Business Aspects

5.VI.A. Entrepreneurship - summarized previously in [Section 5.III.F](#Section5IIIF).

5.VI.B. Openness vs. Distinction in Sharing Economies - summarized in [Section 5.II.D](#Section5IID).

5.VI.C. FabLab Business Models & Return on Investment - summarized in [Section 5.V.D](#Section5VD).

5.VI.D. Leveraging Makerspace Development via Research Training & Inexpensive Equipment

According to Erik van Holm ([8c](#Ref8C)), makerspaces' small membership will not result in numerous entrepreneurs, and thus "governments should avoid making excessive commitments to makerspaces before they provide greater evidence of tangible contributions, but allowing them an expanded role in formal education can enhance their ability to incubate a maker mind-set." As one of the goals of this grant was to dramatically reduce the cost of makerspace education, we have moved toward use of multiple $300 Creality Ender Pro 3 printers and multiple $500 generic laser engravers, rather than spending lots of money (typically $25 K) on laser cutters or Stratasys 3D printers. Having multiple copies of the same equipment permits the makerspace to always be up and running without a high capital investment cost.

Measuring the value on a university makerspace is far more challenging than determining its capital and operating costs. How does one measure the amount of additional research productivity that is generated because of the makerspace's presence and usefulness? When starting a research project, typically the faculty member's proposal is rejected multiple times before achieving success. Especially during that time, it is critical to get some preliminary experiments done that demonstrate the project's feasibility. Often the project's requirements are sufficiently multi-faceted that research students lack one or more skill set necessary to achieve the faculty member's objective, resulting in frustration for all involved. Bundling all of the necessary mindset and skill set tools into a single three credit course is the subject of [Chapter 7](#Section8TheBasicsofMakingCourse) of this document. After completing such a course, the professor and students should look toward GitHub and to Joshua Pearce's book entitled Open Source Lab: How to Build Your Own Hardware and Reduce Research Costs (ref.).

Whereas most makers are familiar with GitHub, very few are familiar with [Metafluidics.org](http://metafluidics.org), a site where researchers can download all necessary items for fabricating many microfluidic devices.

5.VI.E. Small Business's Opinions Regarding Makerspaces - summarized in [Section 5.V.F](#Section5VE).

5.VI.F. The Future of Additive Manufacturing and Its Impact

Jiang *et al*. ([34316](#Ref34316)) conducted a set of Delphi interviews with a panel of numerous experts from a variety of different fields including economics, politics, venture capitalism, and engineering to predict the future of additive manufacturing (AM). What the experts saw as the most intriguing also generated the most dissent ([34316](#Ref34316)). Jiang ([34316](#Ref34316)) predicted that the most likely scenario involves the constant updating of products leading to a business model where AM's biggest role is in the area of spare parts and/or will contain multiple materials with embedded electronics. Jiang ([34316](#Ref34316)) then predicted that consumers will turn to online design database platforms, both open source and proprietary, that companies will push for legislation to regulate such design database platforms, but that such companies will ultimately not be able to defend their intellectual property. Jiang summarized their work in terms of four possible scenarios for AM, including those of a) market explorer; b) content provider (database of CAD drawings, printed circuit board (PCB) files, etc.); c) service provider; and d) mass customizer ([34316](#Ref34316)).

Perez-Perez *et al*. ([18c](#Ref18C)) also conducted a study of 21 Delphi scenarios, but this study focused on manufacturing professionals only, consisting of the following types of questions:

a) three questions regarding whether the business model would be domestic or international, whether objects would be manufactured at highly specialized stores, and whether a majority of factory manufacturing would be via AM;

b) four questions addressing AM-induced market changes in manufacturing of prototypes, tools, and

products, and use of lathes;

c) one question on real-time part inspection-based quality assurance (QA);

d) four questions on supply chain and distribution (pre-COVID)

e) three questions on AM process standardization, personnel qualification, and certifications/warranties

for personalized parts;

f) one question on sustainability;

g) two questions on the relative importance of different AM processing methods; and

h) two questions addressing the importance of AM benefits and current weaknesses.

Perez-Perez *et al*.'s Delphi study yielded the following conclusions ([18c](#Ref18C)):

1) Experts thought that AM would be a factor, but not dominant, in industrial manufacturing in 2030.

2) In the 1990's, printing jobs were often to taken to Kinko's (now FedEx Office) to be printed by specialists. This is the least likely business model for AM in 2030.

3) The vast majority of experts (90%) concur that real-time quality assurance will be reality by 2030.

4) There will be two separate markets: one for digital designs, and one for manufactured items.

5) Fused deposition modeling (FDM), selective laser sintering (SLS), and selected laser modelling (SLM) will be prevalent technologies with some direct metal depositions, limited stereolithography (SLS), and almost no laminated object modeling or other new technologies being significant.

6) There are many reasons to use AM, most notably flexibility for design changes, personalization, shorter production runs, and time to market.

7) AM's primary weaknesses are end product properties, manufacturing speed, and part/product certification.

When one hears the term "smart" applied to a device, this implies some level of WiFi-enabled data acquisition and control (for which the prototypes typically involve Arduinos or Raspberry Pi's), now referred to as the Internet of Things (IoT). Most people are familiar with the touchscreen for their home air conditioning system as an example when one gets notified of an error in the system's performance or gets reminded that it is time to change a filter. The field describing such devices is embedded systems engineering, which combines electrical/computer engineering with one or more other engineering disciplines. Not only does this provide convenience for the user, but the manufacturer can get notified of problems so that they can be remedied quickly and often without a home visit.

Obviously there are privacy and cybersecurity issues associated with IoT technology. Many people are rightfully concerned that their Alexa or Siri virtual assistant smart speakers might be spying on them or be combined with other tracking technology by Google and other big tech firms. Now that the major potential drawbacks to such smart device technology have been discussed, it is time to examine the many benefits that smart devices have enabled.

The author has wanted to teach a course on data acquisition and control involving all of the typical chemical engineering equipment since 1998, but until 2019, the cost was so prohibitive that there was no way that each student, or even student group, would be able to configure their own. In 1998, the cost of a pressure transducer was $1000-1500, and that price hasn't changed much since ... unless you get a generic equivalent. One can buy generic load cells and the accompanying Arduino shields, which use the same technology as pressure transducers, for about $10 now, including shipping, when bought in bulk for an entire class. Now it is possible to not only perform data acquisition and control inexpensively for simple numerical signals, it is not hard to do for streamed audio and video as well. There is an app for almost everything now, and you can download it and control it from your smartphone.

To make money off of smart technology, one must make enough money on either the device, or a kit or app that makes it function as desired, in a short enough period of time to make the invention worthwhile. Engineering economics analysis started in the oil refining field, where plant lives were designed to be 20 years and are often much longer because the technology is not evolving rapidly, the markets for each of the products from oil refining are so well established, and the fact that there is a market for virtually everything exiting the refinery (i.e. very little waste). For new chemical engineering plants that are not as big or as well established as oil refineries are, if there is the breakeven time is greater than the typical plant life of 10 years, then that project is not pursued. In the more rapidly evolving fields such as those enabled by maker education, a breakeven time of two years is probably more realistic. Either you or your competition will come out with a better product by then. When computing capital investment costs, it is assumed that

Capital Investment Cost = a\*(Plant Capacity or # of Units Manufactured)b,

where a and b are experimentally determined constants and b is the economy of scale exponent. If there is no economy of scale, then b equals one. In well-established industries like most chemical engineering plants, typically b equals 0.6, and goes down from 1.0 to 0.6 as the technology matures. However, in maker eduation-enabled technologies, rarely does one see that exponent go down much, and consequently, inventors are even more susceptible to generic copying.

Among the fields that are currently or will be dramatically impacted by cost reductions associated with developments in additive manufacturing (AM) and laser cutting are sensors, Internet of Things (IoT) devices, microfluidic lab-on-a-chip and organ-on-a-chip devices, the proteomics, genomics, and metabolomics fields, and ultimately the field of tissue/organ engineering. For those trying to communicate the value of electronic textile (E-Textile) LilyPad Arduino-based wearable sensor projects ([137c](#Ref137C), [129c](#Ref129C), [74c](#Ref74C), [31c](#Ref31C), [28c](#Ref28C), [2c](#Ref2C)) to their students, the authors recommend a review paper by Padash *et al*. ([31c](#Ref31C)) on the use of AM and microfluidics to make wearable sensors that quantify the metabolites of human sweat as an introduction.

To make preclinical evaluation of the efficacy and/or toxicity of pharmaceutical formulations, genetically modified organisms (GMOs), and/or chemicals possible, one needs to generate models of organs and prepare arrays of identical cellular environments such that one can later evaluate the effects of concentrations of what the cells will view as disturbances systematically. This is the approach of Harvard professor and founder of [Emulate](https://emulatebio.com) [Donald Ingber](https://wyss.harvard.edu/team/core-faculty/donald-ingber/) ([US8647861B2](https://patents.google.com/patent/US8647861B2/en)) and many subsequent patents derived from it). Emulate has generated models of a wide range of human organs and even demonstrated the interactions between them, as described in a range of [publications at Emulate’s web site](https://emulatebio.com/resources/#publications). Toxicological studies will finance early versions of such prototypical organs, followed by willing volunteers in need of organ replacements.

Sometimes it is challenging to directly measure the effects of chemical disturbances with sufficient specificity and sensitivity. A possible alternative would be to develop a biosensing system consisting of genetically modified *Escherichia coli* contained within a 3D-printed device to detect a chemical quorum signal of *Pseudomonas aeruginosa* ([88c](#Ref88C)).

Whereas reproducibility of such organs will need to be emphasized before large numbers of patients are willing to undergo such organ replacements, in the short term, the variability during the toxicological testing phase is not a major issue. Most biomedical engineers are focusing on developing the science that is specific to certain organs. The review paper's primary author is developing tissue engineering test bed arrays, with the goal of dramatically driving down the cost of development for researchers before scaling up the lessons learned for organ manufacturing for specific patients.

While neural tissue engineering has certainly advanced substantially in the past 20 years, this field will almost certainly be the last to be fully developed because of the unusually high sensitivity of neural cells. The use of microfluidic channels as conduits for nerve cells to grow along toward a source of neural growth factors is a common motif in many papers (reviewed in ref. [44c](#Ref44C)). Most early tissue engineering research involves NIH 3T3 mouse fibroblast cells, which are much hardier than other cell lines.

To make the instruction of such additive manufacturing with a biomedical or chemical content emphasis possible, one should start with some hybrid of the [Bucknell SpeakerBox](https://bucknellmakers.dozuki.com/Guide/Speaker+Assembly+2019/92?lang=en), Lawrence Tech's [Eric Meyer's Quantified Self](https://engineeringunleashed.com/card/1715), and my [Basics of Making](https://fit.instructure.com/courses/604044/assignments) course. Then one is ready for an advanced course in additive manufacturing technologies such as the [biomedical engineering-focused microfluidics course](https://engineeringunleashed.com/card/2705) developed by [Youngbok (Abraham) Kang](https://engineeringunleashed.com/profile/view/3099) at George Fox University.

5.VI.G. Pre-College "Silicon" Schools

Williamson ([34362](#Ref34362)) describes four high school models based that emphasize making, particularly focusing on computer programming, Arduino-based data acquisition and control systems, and 3D printing. IBM's P-TECH is part of its Smarter Cities program. The Kahn Lab School is a supplement to the online Kahn Academy. The XQ Super School Project is crowdsourced by the wife of Apple founder Steve Jobs. Most interesting, however, is a chain of makerspace-focused schools named AltSchool based on founded by a former Google executive.

5.VII. How to Teach the Content

5.VII.A. Summer Short Courses

Bucknell University (ref. [26](#Ref26a) and KEEN card [102](#Ref102)) has the most well-known camp within the KEEN network, with separate week-long camps for students and faculty. In addition to a biomedical engineering-specific curriculum called the Quantified Self ([14](#Ref14), [15](#Ref15), [16](#Ref16), [17](#Ref17), [18](#Ref18), [19](#Ref19), [20](#Ref20), [21](#Ref21), [22](#Ref22), [23](#Ref23)), Eric Meyer of Lawrence Tech has developed a camp geared toward attracting prospective students. In addition, all resources are already available for the camp via a KEEN card (ref. to KEEN card [18](#Ref18)).

Several faculty at Michigan Tech led by Joshua Pearce organized and ran three day 3D printer camps. There were supplemental online instructional and visual tools for middle and high school teachers that participated in surveys after their workshops and again after one year in the classroom. Of note, this has become the second most cited article in the makerspace education literature ([34315](#Ref34315)). "The Michigan Tech Open Sustainability Technology (MOST) Laboratory RepRap 3D printers cost $550 in parts, of which about half are printed on the printers themselves" and were built by teams of two high/middle school teachers in three days. YouTube videos, including one from Appropredia.com on wire braiding to improve wire management, were used to supplement simple images during the printer construction ([34315](#Ref34315)).

Florida Tech's Martin Gallagher and David Beavers led a camp in 2014 ([28](#Ref28)) in which students built their own version of Gallagher's GBotz brand 3D printers ([28](#Ref28)); while there was considerable value for the students in assembling such a complex device, the time associated with maintenance support for those printers was sufficiently high ([252](#Ref252)) that Gallagher built the printers himself for the 2015 camp and focused much more on teaching the students how to use the printers. The 2014 camp was scheduled as a 40-hour camp, but turned into a 70-hour camp for some students and workshop coordinators. Perhaps part of the problem was that students were expected to build their own printers, instead of in pairs, or that images alone, instead of videos, were used to aid students in the assembly. Beavers then conducted a study of the reliability of numerous commercial 3D printers before settling on the Sindoh 3DWOX ([252](#Ref252)). Other "build a printer" progams have been conducted by Joshua Pearce's Michigan Tech ([34315](#Ref34315)) and Sharma *et al*. ([47c](#Ref47C)).

The Michigan Tech team also teaches the basics of a free 3-D solid modeling software named OpenSCAD in 30 minutes, although more complex functions that build upon the parametric design capabilities of most CAD drawing programs have a steep learning curve ([34315](#Ref34315)). Many librarians report the same steep learning curve that 3D modeling presents for those who do not have prior training ([34425](#Ref34425), [34426](#Ref34426), [34427](#Ref34427), [34337](#Ref34337)) and illustrate how critical such training is for a 3D printing service to be successful in a multidisciplinary facility ([34337](#Ref34337), [34428](#Ref34428)). 301 unique student users at The University of Nevada-Reno participated in 85 different online 3D modeling short courses using 15 different 3D modeling software programs (primarily SolidWorks, AutoCAD, Blender, Rhino, and OnShape) a total of 4740 hours; however, users only completed 30 courses fully ([34337](#Ref34337)). This illustrates the impatience of both today's students in general and makers in particular regarding learning necessary skills.

Students prefer informal settings such as summer camps, after school programs, and workshops over graded assignments when learning making ([34377](#Ref34377), [34383](#Ref34383)). A Bots For Tots workshop where 9–10-year-old children were tasked with constructing ‘‘dream toys’’ for 4-year old students in their school was shown to enhance female participation ([34385](#Ref34385)). A significant percentage of undergraduate students are highly motivated to make toys. In the author's classes, retractable lightsabers and fully functional remote-operated garbage trucks have been popular. These same students are motivated when they know that their projects might get used at a children's museum ([34382](#Ref34382), [43c](#Ref43C)). The [Lewisburg Children's Museum](https://www.lewisburgchildrensmuseum.org/) has been the focus of Bucknell's outreach program, especially during its faculty maker education workshops ([26](#Ref26a)).

5.VII.B. Workshops

In-person library workshops generally have low attendance but high satisfaction ([34337](#Ref34337)), especially if there are two workshop leaders with one for the advanced students and one for the beginners, or if there are prerequisites based on previous courses or workshops. In discussions with staff at numerous universities, Florida Tech faculty have observed that the knowledge and experience differences between users is the biggest challenge in conducting workshops. This subject should be addressed through co-developed content in 2020 and 2021.

Students can self-organize the critical mass interest for a given topic, and then reach out to qualified instructors to teach workshops ([34424](#Ref34424), [34327](#Ref34327)). More often, such workshops are offered as part of an ongoing series of continuing education workshops that can be geared toward advertising services to faculty, non-library staff, library staff, and/or students. Such workshops can be either within a permanent making environment or a mobile (or pop-up) environment ([34329](#Ref34329), [34361](#Ref34361), [34365](#Ref34365)). The mobile workshops are often set up to either introduce making technologies to an audience that is either too remote or not wealthy enough to have its own makerspace; among these, the most successful is the FryskLab ([34365](#Ref34365)).

5.VII.C. Maker Education by Educational Level

K-12 maker education is not the primary focus of this review paper as it has been reviewed somewhat by others ([1c](#Ref1C), [3c](#Ref3C)). Table 5.VII.C.1 list K-12 maker education articles. As the effects of motivation for making, the effects of making on mindset and creativity, and the effects of creativity and mindset on making are often, but not always, the same for K-12 as for university students, these subjects have been addressed elsewhere in prior sections. Table 5.VII.C.1 also lists maker education articles that are not library-focused at the undergraduate and graduate levels as well.

Table 5.VII.C.1 - Summary of Prior Work on K-12 Maker Education

Educational Level References

Elementary [1c](#Ref1C), [2c](#Ref2C), [3c](#Ref3C), [11c](#Ref11C), [12c](#Ref12C), [14b](#Ref14b), [19c](#Ref19C), [20c](#Ref20C), [21c](#Ref21C), [22c](#Ref22C), [23c](#Ref23C), [34c](#Ref34C), [65c](#Ref65C), [77c](#Ref77C),

[78c](#Ref78C), [79c](#Ref79C), [114c](#Ref114C), [115c](#Ref115C), [125c](#Ref125C), [130c](#Ref130C), [134c](#Ref134C), [145c](#Ref145C), [16b](#Ref16B)

Junior High [1c](#Ref1C), [2c](#Ref2C), [3c](#Ref3C), [11c](#Ref11C), [12c](#Ref12C), [22c](#Ref22C), [23c](#Ref23C), [38c](#Ref38C), [39c](#Ref39C), [43c](#Ref43C), [45c](#Ref45C), [50c](#Ref50C), [109c](#Ref109C), [125c](#Ref125C), [130c](#Ref130C), [138c](#Ref138C), [16b](#Ref16B)

High School [1c](#Ref1C), [2c](#Ref2C), [3c](#Ref3C), [11c](#Ref11C), [12c](#Ref12C), [22c](#Ref22C), [23c](#Ref23C), [38c](#Ref38C), [46c](#Ref46C), [52c](#Ref52C), [64c](#Ref64C), [74c](#Ref74C), [101c](#Ref101C), [117c](#Ref117C), [125c](#Ref125C), [129c](#Ref129C), [130c](#Ref130C),

[138c](#Ref138C), [141c](#Ref141C), [16b](#Ref16B)

Undergraduate [4b](#Ref4B), [5b](#Ref5B), [17c](#Ref17C), [25c](#Ref25C), [42c](#Ref42C), [48c](#Ref48C), [49c](#Ref49C), [54c](#Ref54C), [60c](#Ref60C), [61c](#Ref61C), [148c](#Ref148C), [149c](#Ref149C), [69c](#Ref69C), [70c](#Ref70C), [72c](#Ref72C), [142c](#Ref142C),

[73c](#Ref73C), [85c](#Ref85C), [97c](#Ref97C), [99c](#Ref99C), [100c](#Ref100C), [105c](#Ref105C), [106c](#Ref106C), [110c](#Ref110C), [111c](#Ref111C), [135c](#Ref135C), [137c](#Ref137C), [144c](#Ref144C), [146c](#Ref146C), [93c](#Ref93C),

[151c](#Ref151C), [120c](#Ref120C), [6c](#Ref6C), [48c](#Ref48C), [41c](#Ref41C), [30c](#Ref30C), [13b](#Ref13B), [70c](#Ref70C)

Graduate [9c](#Ref9C), [4b](#Ref4B), [6b](#Ref6b), [16c](#Ref16C), [24c](#Ref24C), [54c](#Ref54C), [123c](#Ref123C) (dental school)

Continuing Education [107c](#Ref107C) (Naval employees returning to civilian life)

Most notable among these are the work by professors at Penn State, in South Africa, and at Torino discussed in [Section 5.IV.C](#Section5IVC). Among the articles at the undergraduate or graduate level, all of the articles in the undergraduate row of Table 5.VII.C.1 are summarized in other sections. Noteworthy was a special issue of International Journal of Engineering Education entitled Maker Spaces in Engineering Education ([147c](#Ref147C)).

5.VII.D. Teacher and/or Librarian Pre-Service and Inservice Training

Pre-service and inservice training for K-12 maker educators and librarians is also not the primary focus of this review paper. The most cited such paper is by Joshua Pearce of Michigan Tech ([34315](#Ref34315); [2b](#Ref2B)). Within the KEEN network, Weiner and Jordan of Arizona State and Lande of South Dakota School of Mines ([105c](#Ref105C)) observe that trained pre-service K-12 teachers develop more active student-centered lessons than they would normally develop, but even so, they lack reflection or iteration, and are thus comparable to those of novice designers. Review papers on this subject include refs. [1c](#Ref1C), [3c](#Ref3C), and [21c](#Ref21C). Other articles on this subject of K-12 teacher instruction include refs. [8b](#Ref8B), [15c](#Ref15C), [58c](#Ref58C), [63c](#Ref63C), [53c](#Ref53C), [81c](#Ref81C), [96c](#Ref96C), [98c](#Ref98C), [97c](#Ref97C), [103c](#Ref103C), [115c](#Ref115C), [116c](#Ref116C), [126c](#Ref126C), [128c](#Ref128C), [130c](#Ref130C), and [131c](#Ref131C). Maceli ([35c](#Ref35C)) and Horton ([55c](#Ref55C)) have thoroughly summarized the benefits, best practices, and challenges associated with pre-service and inservice training for librarians. Chen and Cao address the challenges specific to implementation of virtual inservices for librarian maker education ([92c](#Ref92C)).

5.VII.E. Incorporating Making Activities into University Courses

The vast majority of work that has been done regarding incorporation of making activities, particularly those with an entrepreneurial mindset (EM) flavor, was done by members of the KEEN network. This work was first summarized in Tables 6.1 - 6.7 of [Chapter 6](#Section6ConnectionsandKEENCards). This was later compiled into a [KEEN card named CardDeck: EM Resources for Makers](https://engineeringunleashed.com/card/1737) and several KEEN card decks within Section C of [The One CardDeck to Rule Them All](https://engineeringunleashed.com/card/2167). The purpose of this was to create value for faculty by making the necessary connections to create a one stop shop to direct faculty to a wide range of making activities, organized into the following four categories:

1) EML Integration into & Mindset Developed in Making Courses;

2) Mindset Developed & Skills Learned in Maker Courses;

3) Incorporation of Making Content into Classes That Are Not Maker-Focused;

4) Community Building Co-Curricular EML; and

5) Toy Making.

Papers by members meeting the search criteria are summarized in Table 5.VII.E.1. It is worth noting that conference papers presented at the American Society of Engineering Education do not get indexed by Web of Science. There are also a number of papers not listed here that were generated by Penn State authors and are in [Section 5.IV.C](#Section5IVC) on Design for Additive Manufacturing.

Table 5.VII.E.1 - Full Papers on Incorporation of Making into University and High School STEM Courses

Anatomy/Biomedical Imaging [108c](#Ref108C), [88c](#Ref88C), [16c](#Ref16C), [12b](#Ref12B), Patient education ([15b](#Ref15B))

Chemistry Thermal Imaging ([72c](#Ref72C)), [63c](#Ref63C), [18b](#Ref18B)

Computer Science & IoT [100c](#Ref100C), [99c](#Ref99C), [78c](#Ref78C), [76c](#Ref76C), [71c](#Ref71C), [66c](#Ref66C), [65c](#Ref65C)

Electrical/Computer Engineering Waveguides ([146c](#Ref146C)), Controls ([97c](#Ref97C)), [19b](#Ref19B)

LilyPad Arduino [137c](#Ref137C), [129c](#Ref129C), [73c](#Ref73C), [152c](#Ref152C), [31c](#Ref31C), [28c](#Ref28C), [2c](#Ref2C)

Physics Speed of Sound ([144c](#Ref144C)), Electrical Potential ([129c](#Ref129C))

MEE 1st Year CAD/Cornerstone Design [105c](#Ref105C), [104c](#Ref104C), [73c](#Ref73C), [152c](#Ref152C), [148c](#Ref148C), [149c](#Ref149C)

MEE Structural Dynamics [32c](#Ref32C)

MEE Robotics [131c](#Ref131C), Phogo ([65c](#Ref65C))

MEE Senior Capstone Design [73c](#Ref73C)

MEE Finite Element Modeling [106c](#Ref106C)

Ocean Engineering & Marine Sciences Coral Studies ([90c](#Ref90C))

5.VII.F. Three-Credit Semester-Long University Courses Focused on Making

The primary author teaches a [KEEN-focused three credit junior/senior lab course](https://fit.instructure.com/courses/604044/assignments/5079639) that includes computer programming, CAD, wiring/soldering, circuits, Arduino-based sensors and controls, robotics, 3D printing, and wearable sensors. This [course](https://engineeringunleashed.com/card/1823) concludes with an [end-of-semester group project poster and performance competition (gallery walk)](https://engineeringunleashed.com/card/821) where students and professors will assess the curiosity exhibited by, the connections made by, and the value created by each team. After learning the full gamut of making skills, culminating in the fabrication of the Bucknell SpeakerBox, student groups choose from a highly multidisciplinary selection of junior/senior design projects, existing or student-initiated research projects, or toys.

Because of the higher prerequisite expectation, Go and Hart of MIT ([9c](#Ref9C))'s syllabus includes a thorough analysis of AM processes and machine technologies, design methods, machine controls, industrial examples, and emerging processes and materials ([9c](#Ref9C)). In lab sessions, students not only operate but also characterize desktop AM machines, and work in teams to design and fabricate a bridge of maximum strength-to-weight ratio. The end-of-semester project selections are quite interdisciplinary and have led to research projects and patent applications ([9c](#Ref9C)). Go and Hart ([9c](#Ref9C)) have made this course the focus of a manufacturing-focused master's degree program and a one-week professional short program.

Grinschek *et al*. ([111c](#Ref111C)) have developed a 3D printing and design for additive manufacturing course for chemical engineers that goes into the depth of AM that would one expect in a graduate mechanical engineering (MEE) course and that preceded my Basics of Making course. Not surprisingly, they admitted struggling with a lack of computer-aided drawing (CAD) background for the vast majority of their students. At the suggestion of [Margot Vigeant of Bucknell University](https://engineeringunleashed.com/card/1751), we address that through an [assignment](https://fit.instructure.com/courses/604044/assignments/5079709) using [OnShape](https://cad.onshape.com) tutorials, recommended to the students prior to the semester. Also interestingly, Grinschek *et al*. ([111c](#Ref111C)) had no laser cutting or Arduino component. In Table 5.VII.E.1, if further specification within a field is necessary, it is next to a given article on the right side of the table.

A group from The University of Arizona ([34330](#Ref34330)) developed a set of biosensor experiments as part of an outreach program to middle and high school students. They classified biosensor design and development

into seven categories: genetic engineering, nanotechnology, circuit building, microfabrication, 3D printing, smartphone utilization, and computer programming. Applications included food safety, medical applications, environmental applications, and biosecurity. Middle school students were more interested in food safety, whereas high school students preferred medical applications and biosecurity, most likely because they had taken high school biology. Interest switched from 3D printing, circuit building, and smartphone applications by middle schoolers toward genetic engineering and nanotechnology amongst high schoolers. Microfabrication methods such as soft lithography are completely foreign to students prior to college and were not of interest to the middle and high school students ([34330](#Ref34330)). These trends can generally be attributed to the bias of students toward subjects they have knowledge of.

The Arizona researchers ([34330](#Ref34330)) describe in enough detail a colorimetric biosensor circuit construction that could be a project for an average group in a junior/senior university making course. A sweat biosensor project described in sufficient chemical detail by Kwon *et al*. ([34335](#Ref34335)), but without a detailed circuit diagram, would be more challenging. The best students should be able to do microfluidic lab-on-a-chip sensors like the protein immunoassay sensor described by Rusling ([34324](#Ref34324)). For a group of excellent students who are truly adventuresome, "3D Printing, Ink Casting and Micromachined Lamination (3D PICLM): A Makerspace Approach to the Fabrication of Biological Microdevices" might be a reasonable senior design project ([34392](#Ref34392)).

5.VII.G. Entire Curricula, Interdisciplinary Programs, and Now a Postdisciplinary Engineering Program

Examples of entire curricula at the K-12 level are in refs. [11c](#Ref11C), [16b](#Ref16B), [23c](#Ref23C), [47c](#Ref47C), [114c](#Ref114C), [122c](#Ref122C), and [130c](#Ref130C). Of these, Kim *et al*. ([114c](#Ref114C)) thoroughly analyzed and incorporated lessons learned from others to not only develop effective pedagogy within budgetary constraints, but also a comprehensive view of a maker's mindset; this paper is discussed in detail in [Section 5.III.F](#Section5IIIF).

[The additive manufacturing M.S. program at the Politecnico di Torino in Italy](#Torino) and the [South African curricula](#South_Africa), and the Penn State group have already been discussed in [Section 5.IV.C](#Section5IVC) on design for additive manufacturing (DfAM). In addition, a National Science Foundation workshop of DfAM curricula led Simpson of Penn State ([6c](#Ref6C)) concluded that that DfAM should focus on AM synthesis/structure/material/function relationships, engineering fundamentals, problem solving, teamwork, ideation, and critical thinking skills, and finally, design practices that take advantage of the design freedom made possible by AM. Probably the weakest area is with regard to the thermodynamics, transport phenomena, and, in some cases, reaction kinetics associated with the additive manufacturing ([111c](#Ref111C)) and laser-assisted deposition and engraving ([4c](#Ref4C)) processes.

One topic that should be emphasized at the graduate level and hinted toward at the undergraduate level is the concept of a digital twin ([94c](#Ref94C), [251](#Ref251)). A digital twin is a virtual representation, often now as an app, of an object or system that uses a combination of simulation and artificial intelligence (AI)-based learning from real-time data to enhance the performance of both the real object/system and its digital twin. This digital twin concept is central to many of the new electrical/computer engineering and science – focused applications described by Liu *et al*. ([118c](#Ref118C)) in what they call transdisciplinary engineering and most people call interdisciplinary engineering. Stanford has a similar research track called the Leifer NeuroDesign Research Program ([neurodesign.stanford.edu](https://neurodesign.stanford.edu/); ref. [118c](#Ref118C)). The Torino group ([24c](#Ref24C)) has a multidisciplinary DfAM program. While quite exciting, such programs do not encompass all aspects of the more complicated engineering problems of the future. For problems also involving all aspects of science and engineering, what is needed is a postdisciplinary engineer.

Chapters 1 through 4 laid out the definitions of a postdisciplinary engineer and of a maker, as well as what the expectations ought to be for each of them. Florida Tech’s nanotechnology minor program spawned its biomedical engineering program, was the inspiration of its honors college. Now discussions are underway to implement a maker minor and a postdisciplinary engineering major curriculum, with the goal of properly preparing students for the many expectations associated with this maker field proposed in Figure 5.VII.G.1 below.



Figure 5.VII.G.1 - Postdisciplinary engineer curriculum

Some faculty may argue that this could be described as “general engineering” or engineering. However, the postdisciplinary engineering program has far more chemistry, biology, and materials science, and of their corresponding engineering disciplines than a typical general engineering program. The postdisciplinary engineering program also has enough project management and systems engineering, and business/entrepreneurship courses to prepare an engineering student for almost anything. For many years, chemical engineers have touted that they are the most versatile of engineers and thus deserving of their higher salaries. To continue that branding, chemical engineering programs need to adopt the changes outlined in Figure 5.VII.G.1.

Both Tabares and Boni ([110c](#Ref110C)) and Shively *et al*. ([16b](#Ref16B)) emphasize that there will be considerable resistance and organizational challenges to implementing multidisciplinary programs. This will be true within an institution from the traditionally silo-like curricular and organizational structures of discipline-specific programs and departments, as well as from external hierarchies. The biggest challenge to getting the postdisciplinary curriculum approved is with regard to how to accredit it through the Accreditation Board for Engineering and Technology (ABET). Until there is an ABET standard for accreditation of postdisciplinary engineers, we have chosen to have the degrees be accredited as a dual degree program of a B.S. in a traditional engineering discipline with an M.S. in systems engineering.

5.VII.H. Honors Programs, Co-Curricular Programs, After School Programs, & Research Preparation

After school programs at the K-12 level or clubs like a Lego Robotics or Lego Mindstorms club were the proper avenue for such students at that level ([59c](#Ref59C)). An effective after school maker education program could also involve a mobile makerspace traveling around a school district on a rotating basis ([17c](#Ref17C)). One of the pillars of KEEN’s entrepreneurial mindset is curiosity. The better students, regardless of education level, will be looking for something more to challenge them. Most top prospective engineering students have taken numerous AP or dual enrollment courses. Either they want to graduate in three years, take a minor, get a dual BS/MS degree done in four years, or pursue undergraduate research.

As an intermediate step toward approval of the postdisciplinary engineer curriculum, we have implemented all but two of the courses and have implemented a wide variety of both maker education activities and entrepreneurial mindset building activities into our Honors College programming. Some of these are bundled into the aforementioned Basics of Making course, but most of the honors students want to learn them before waiting until junior or senior year. Teaching such students on a one-on-one basis isn’t a productive use of faculty time, but if there were a framework in place to consolidate such training, then it could be a major boon for a university. What follows is a summary of the Honors College activities.

[The Basics of Making](https://engineeringunleashed.com/card/1823)

The Basics of Making bundles all skills necessary for students to be able to design and build capstone design projects and/or become productive researchers, with the KEEN mindset development interspersed at almost every stage, as highlighted in the hyperlinked KEEN cards.

[Questions and Issues Sheets:  A Quick Way to Define Projects](https://engineeringunleashed.com/card/2000)

[Computer Programming for Makers:  LabView, Python, C++, and Arduino](https://engineeringunleashed.com/card/1790)

[Wiring, Soldering, and Wiring Diagrams - How to Teach Them to non-ECE's](https://engineeringunleashed.com/card/1983)

Electrical Circuits and Arduino

[Using a Journal and Patent Literature Search to Demonstrate Curiosity and Connections via Information Integration](https://engineeringunleashed.com/card/2769)

CAD Drawing

Stepper, Servo, and DC Motor Control

Editing of CAD Drawings Prior to 3D Printing

3D Printing

Laser Cutting

Combining All Prior Maker Skills into the Bucknell Speaker Box

[Process Flowsheeting, Piping & Instrumentation Diagrams (P&ID's), and Plumbing](https://engineeringunleashed.com/card/651)

Printed Circuit Boards (PCB's)

Virtual Reality, Augmented Reality, & Advanced Visualization

[Electrochemical Concentration Measurement Using a Multiplexed Potentiostat](https://engineeringunleashed.com/card/2075)

[Celebration of the 3C’s: A Showcase for Makers](https://engineeringunleashed.com/card/821)

Student Development Activities through the Honors College and Courses

The first four activities are from the six co-developed as part of the Kern Family Foundation grant that funded this work. While some of these activities are integrated into courses, by having them integrated into an honors program, the most curious students have a formalized pathway for learning everything they need to become independent innovators, especially those that aren't necessarily easy to build an entire course around. The faculty are more productive by not having to dedicate time to teaching what they consider to be prerequisite skills for research.

- [Scavenger Hunt](https://engineeringunleashed.com/card/653)

- [Celebrate Good Times! Come On! - Making in Fluid Mechanics](https://engineeringunleashed.com/card/233)

- [3D Scanning](https://engineeringunleashed.com/card/2325)

- [ArtDuino Make-A-Thon](https://engineeringunleashed.com/card/1152)

The Scavenger Hunt is meant to be an activity to not only introduce students to makerspaces in a non-threatening way, but to start to establish both a maker culture and a community. While there is an expectation that students know all of the maker skills and some of the mindset already by the start of senior year, even after graduation, most students are missing multiple skills, delegating them to teammates who do already know them. Most mechanical and aerospace engineers (MEE/AEE) have a design and build experience during freshman year, but the methods used for prototyping are usually limited to those that they are taught up to that time. By senior year, it is expected that MEE and AEE students have learned all the manufacturing methods they need to learn, but usually at most universities they have not. Moreover, most universities do not have sophomore and junior design/build experiences. This is part of the reason why the [Celebrate Good Times! Come On! - Making in Fluid Mechanics](https://engineeringunleashed.com/card/233) project was chosen. We are considering breaking The Basics of Making into a required second semester first year experience and a junior/senior second semester class to prepare non-chemical engineers for senior design and to give second semester senior chemical engineers a much more in-depth Design of Experiments experience. The

[3D Scanning](https://engineeringunleashed.com/card/2325) experience, when combined with virtual/augmented reality activities, provide more advanced students an opportunity to grow their toolkit. This is especially important for biomechanics projects because it is impossible to outfit humans with a sufficient number of sensors and servo controls to get the fine control humans expect. The [ArtDuino Make-A-Thon](https://engineeringunleashed.com/card/1152) activity not only gives students at all levels an opportunity to compete in a non-threatening way, but can help build community.

- [Movie Series to Enhance Entrepreneurial Mindset](https://engineeringunleashed.com/card/436): Inspirational content drawn from movie, TV, historical, sports, literary, comedic, and personal sources listed at the

[Hooray for Hollywood KEEN card](https://engineeringunleashed.com/card/436) is an EML and community builder as part of dorm programming for a new Honors Maker Minor Program. Each activity is preceded by a two minute faculty briefing explaining what EML and/or making objectives that the dorm programming is designed to target.

- [Leonardo daVinci Workshop](https://engineeringunleashed.com/card/2402): Evolved out of the [ArtDuino Make-A-Thon Tool](https://engineeringunleashed.com/card/1152), this

evolved into a [2021 KNC workshop](https://engineeringunleashed.com/card/2402) by Chris Sharp of George Fox University.

- [Taking Your Education Into Your Own Hands](https://fit.instructure.com/courses/565700/assignments/4985065): Having evolved out of a summary of

the surveys posted by KEEN members nationwide, advisors now tell students to evaluate themselves before each school year regarding how they have developed both mindset and skill set.

- [How to Plan Your Career](https://fit.instructure.com/courses/565700/assignments/4933057): Students exhibit curiosity by going to the National Science

Foundation's REU site and searching for which faculty are the leaders in their respective fields, before reporting on it as part of an entrepreneurship exercise integrated into the Nanotechnology Lab course.

- [Literature Review](https://fit.instructure.com/courses/565700/assignments/4933091): Students work with faculty to conduct Web of Science and patent

searches in the Nanotechnology lecture and in the Basics of Making course, with points awarded based both on number of pertinent references examined and on the depth of insight shown in integrating information from various sources.

- [Mining, Refining, and 3D Printing a Lunar Colony](https://fit.instructure.com/courses/565700/assignments/4933039): This is a literature review analysis,

not integrated into any course, of what has been published toward the development

of a lunar colony on behalf of a local business offering internships to those who

best exhibit KEEN's 3C's.

- [3D Printing and Laser Cutting](https://fit.instructure.com/courses/565700/assignments/4933041) and [CAD Drawing](https://fit.instructure.com/courses/565700/assignments/4933113): The proof that students have mastered

these skills is demonstrated through the [Celebrate Good Times! Come On!](https://engineeringunleashed.com/card/233) tool.

- [LabView/Python Programming](https://fit.instructure.com/courses/565700/assignments/4933057): Before implementing this into the [Basics of Making](https://fit.instructure.com/courses/604044) class, a lack of computer programming experience was a common complaint, but neither students nor faculty wanted a three credit courses solely dedicated to it. This condenses what the students need to learn into two in person hours and eight self-paced hours of homework.

All of what is in this review paper formed the basis for a proposal entitled "[Creating Research Ready Students through the Vertical Integration of a KEEN-Focused Nanotechnology/Maker Curriculum](https://engineeringunleashed.com/forum/102/topic/15495)". At that link and its parent is a thorough discussion of how faculty can better prepare students for undergraduate research.

6. What Connections Do We Expect to Make?

KEEN Cards Relevant to Maker Initiative & Nanotechnology Subnet

Summary of KEEN Cards Relevant to Education in Making Environments

This section is geared toward

a) determining whom Florida Tech faculty should make connections with as part of the process to determine which universities to select for Phase 2 of the 2019-2021 KFF grant;

b) organizing visitation schedules associated with a);

c) completing the literature review process associated with Phase 1 of the grant; and

d) determining which best practices to incorporate into Florida Tech's maker initiative.

The following list contains links to the following tables:

[Table 6.1 - Summary of KEEN Cards Relevant to Education in Making Environments](#TableX1)

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Table 6.1 - Summary of KEEN Cards Relevant to Education in Making Environments

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
|  |  |
| 3D Printing Facilities/Courses | Stewart, Roszelle, & Caston (Denver; [101](#Ref101)); Eberle (Bucknell; [102](#Ref102)); Zhen (ASU; [103](#Ref103)); Harlow (Lehigh; [104](#Ref104)); Hoover and Breitbart (Olin; [105](#Ref106)); Naito (Lehigh; [106](#Ref106)-[107](#Ref107)); Aukes (ASU; [209](#Ref209)); |
| Laser Cutter | Aukes (ASU; [209](#Ref209)) |
| VR/AR & Other Visualization | Alagic, Bagwill, Sakic-Lazic, and Crandell (Saint Louis; [146](#Ref146)); Ji (WPI; [150](#Ref150)); Beal, Cole, & Siegel (Bucknell; [158](#Ref158)); Zimmers (Lehigh; [205](#Ref205)); |
|  |  |
| Brenner Engineering Instrumentation Course (most similar to BME instrumentation or ECE microcontroller courses, but with more motor controls, mass balances, MEMS, and process control) | Meyer & Nasir (Lawrence Tech; [110](#Ref110), [111](#Ref111), [112](#Ref112), [113](#Ref113), [114](#Ref114), [115](#Ref115), [116](#Ref116)); Dougherty (Villanova; [119](#Ref119)-[120](#Ref120)); Nepal (ASU; [121](#Ref121)-[122](#Ref122)); Holland (James Madison; [123](#Ref123)); Lee (Santa Clara; [132](#Ref132)); Chiu (Rose-Hulman; [139](#Ref139)); Pai (Ga. Tech; [140](#Ref140)); Gettens (Western New England; [141](#Ref141)); Rust (Western New England; [142](#Ref142)); Weaver (Detroit Mercy; [143](#Ref143)); Benner (Western New England; [124](#Ref124)); Page (New Haven; [152](#Ref152)-[153](#Ref153)); Elmer (Villanova; [165](#Ref165)); Ersay (Lehigh; [182](#Ref182)); Kleim, Peña, and Reitmeier (ASU; 3rd card); Holland (James Madison; [123](#Ref123)); Kleim and Muthuswamy (ASU; [217](#Ref217)) |
| Summer 3D Printing or Arduino Short Course | Meyer & Nasir (Lawrence Tech; [114](#Ref114)); Dougherty (Villanova; [119](#Ref119)-[120](#Ref120)); Samani ([169](#Ref169)); |
| Robots & Mechatronics | Stafford (WPI; [154](#Ref154)); Mynderse (Lawrence Tech; [194](#Ref194)); Marvi (ASU; [206](#Ref206)); Brown, Sabatino, Hummel, and Boerchers (Lafayette; [213](#Ref213)) |

Table 6.2 - Summary of KEEN Cards Relevant to EML Relevant to the Maker Initiative

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
|  |  |
|  |  |
| Inventions | Sabancu (WPI; [170](#Ref170)) & Olson, Melton, and Schumacher (KFF; [170](#Ref170)) |
| KEEN Outcomes & Activities | Trollinger, Dillon, Welch, and Ralston (Portland; [172](#Ref172)); Young, Johnson, and Misko (KFF; [173](#Ref173)); Hylton, Mikesell, LeBlanc, and Yoder (Ohio Northern; [174](#Ref174)); Estell (Ohio Northern; [186](#Ref186a)), Ochs (Lehigh; [186](#Ref186a)), Young (KFF; [186](#Ref186a)), and Brackin (Rose-Hulman; [186](#Ref186a)) |
| Persistence | Li, Gobel, Carnasciali, Baggili, Erdil, and Harichandran (New Haven; [176](#Ref176)) |
| Prototype Assessment | Peña and Lande (ASU, [200](#Ref200)) |
| Incentives | Henthorn (Rose-Hulman; [108](#Ref108)), Gipson (James Madison; [108](#Ref108)), Devasher (Rose-Hulman; [108](#Ref108)); Henthorn, Devasher, and Weatherman (Rose-Hulman; [210](#Ref210)) |
| Credentials | Hentham (Rose-Hulman; [108](#Ref108)), Gipson (James Madison; [108](#Ref108)), Devasher (Rose-Hulman; [108](#Ref108)) |
| Tool Simulation | Sebold, Mayled, and Zeinolabedinzadeh (ASU; [109](#Ref109)); Bilsky (Lehigh; [201](#Ref201)) |

Table 6.3 - Summary of KEEN Cards Relevant to Prerequisites & Related Topics for Making

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
|  |  |
|  |  |
| ECE Microcontrollers, &/or Embedded Systems | Nepal (ASU; [121](#Ref121)-[122](#Ref122)); Holland (James Madison; [123](#Ref123)); Khan, LeBlanc, and Al-Olimat (Ohio Northern; [125](#Ref125)); Rahnamai (Western New England; [151](#Ref151)); Clavijo (Stevens Tech; [159](#Ref159), [160](#Ref160), [161](#Ref161), [162](#Ref162)); Jupina (Villanova; [166](#Ref166)); Butler (Lehigh; [208](#Ref208)); Pearce (Michigan Tech: [219](#Ref219)) |
| ECE Circuits | Khan, LeBlanc, and Al-Olimat (Ohio Northern, [125](#Ref125)); Zewde (Wichita State. [155](#Ref155)); Frey (Lehigh, [179](#Ref179)); Ersay (Lehigh, [182](#Ref182)); Holland (James Madison, [123](#Ref123)); Dillon (Portland, [207](#Ref207)); |
| ECE Printed Circuit Boards (PCB's) | Nepal (ASU; [121](#Ref121)-[122](#Ref122)); Holland (James Madison; [123](#Ref123)); Ludwig (WPI; [163](#Ref163)); Taha (Dayton; [216](#Ref216)) |
| Other Sensors | Poor and Welch (Portland; [148](#Ref148)); Zhao (Western New England; [149](#Ref149)); Read-Daly and Baptista Abreu (Elizabethtown; [183](#Ref183)); |
|  |  |
| Controls | Clancy (WPI BME; [171](#Ref171)); Brown, Sabatino, Hummel, and Boerchers (Lafayette ME; [213](#Ref213)); Pearce (Michigan Tech: [219](#Ref219)) |
| CAD | Beal, Cole, & Siegel (Bucknell; [158](#Ref158)); Brooking (Wichita State; [178](#Ref178)); Zimmers (Lehigh; [205](#Ref205)) |
|  |  |
| Nano, MEMS, Electrochem, & Drug Delivery (not Biomaterials & Tissue Engg.) | Letfullin (Rose-Hulman; [130](#Ref130)); Abel, Coburn, and Dodson (WPI; [131](#Ref131)); Lee (Santa Clara; [133](#Ref133)-[134](#Ref134)); Alagic, Bagwill, Sakic-Lazic, and Crandell (Saint Louis; [147](#Ref147)); Zhao (Western New England; [149](#Ref149)); Staehle (Rowan; [167](#Ref167)); Wile (Ohio Northern; [177](#Ref177)); McIntosh (Lehigh; [203](#Ref203)); Tatic-Lucic (Lehigh; [214](#Ref214)); Zhang (Milwaukee SOE; [218](#Ref218)) |
|  |  |
| LabView | Benner (Western New England; [124](#Ref124)) |
| Python | Page (New Haven; [152](#Ref152)); Dunston & Koerner (St. Thomas; [180](#Ref180)) |
| C++ | Page (New Haven; [153](#Ref153)) |

Table 6.4 - KEEN Cards of Mechanical/Aerospace Engineers Interested in Maker Topics

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities and Disciplines; ref. #'s) with KEEN Cards |
|  |  |
| Capstone Design | Demoret (FIT AEE; [156](#Ref156)); Wakabayashi & Cohen (Bucknell Interdisciplinary; 157); Estell (Ohio Northern; [186](#Ref186b)), Ochs (Lehigh; [186](#Ref186b)), Young (KFF; [186](#Ref186b)), and Brackin (Rose-Hulman interdisciplinary; [186](#Ref186b)); Breitbart (Olin many disciplines; [193](#Ref193)); Perkins and Fehrman-Cory (Dayton; [198](#Ref198)); Peña and Lande (ASU; [200](#Ref200)) |
| Robots & Mechatronics | Stafford (WPI; [154](#Ref154)); Mynderse (Lawrence Tech; [194](#Ref194)); Marvi (ASU; [206](#Ref206)); Brown, Sabatino, Hummel, and Boerchers (Lafayette; [213](#Ref213)) |
| Controls | Clancy (WPI BME; [171](#Ref171)); Brown, Sabatino, Hummel, and Boerchers (Lafayette ME; [213](#Ref213)) |
| Manufacturing | Song (ASU; [199](#Ref199)) |
| Fluid Mechanics | Weaver (Detroit Mercy; [143](#Ref143)) |
| CAD | Beal, Cole, & Siegel (Bucknell; [158](#Ref158)); Brooking (Wichita State); Zimmers (Lehigh; [205](#Ref205)) |
| MEE/AEE 1st Yr. Course | Sen (FIT; [302](#Ref302)); Brooking (Wichita State; [178](#Ref178)); Read-Daly and Baptista Abreu (Elizabethtown; [183](#Ref183)); |

Table 6.5 - KEEN Cards of Electrical Engineers, Computer Engineers, and Computer Scientists Relevant to Education in Making Environments

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
|  |  |
| ECE Microcontrollers, &/or Embedded Systems | Nepal (ASU; [121](#Ref121)-[122](#Ref122)); Holland (James Madison; [123](#Ref123)); Khan, LeBlanc, and Al-Olimat (Ohio Northern; [125](#Ref125)); Rahnamai (Western New England; [151](#Ref151)); Clavijo (Stevens Tech; [159](#Ref159), [160](#Ref160), [161](#Ref161), [162](#Ref162)); Jupina (Villanova; [166](#Ref166)); Butler (Lehigh; [208](#Ref208)); Pearce (Michigan Tech: [219](#Ref219)) |
| ECE Circuits | Khan, LeBlanc, and Al-Olimat (Ohio Northern; [125](#Ref125)); Zewde (Wichita State; [155](#Ref155)); Frey (Lehigh; [179](#Ref179)); Ersay (Lehigh; [182](#Ref182)); Holland (James Madison; [123](#Ref123)); Dillon (Portland; [207](#Ref207)); |
| ECE Printed Circuit Boards (PCB's) | Nepal (ASU; [121](#Ref121)-[122](#Ref122)); Holland (James Madison; [123](#Ref123)); Ludwig (WPI; [163](#Ref163)); Taha (Dayton; [216](#Ref216)) |
| ECE Sensor Networks | Clavijo (Stevens Tech; [159](#Ref159)) |
| Other Sensors | Poor and Welch (Portland; [148](#Ref148)); Zhao (Western New England; [149](#Ref149)); Read-Daly and Baptista Abreu (Elizabethtown; [183](#Ref183)) |
| LabView | Benner (Western New England; [124](#Ref124)) |
| Matlab | Ji (WPI; [150](#Ref150)) |
| Python | Page (New Haven; [152](#Ref152)); Dunston & Koerner (St. Thomas; [180](#Ref180)) |
| C++ | Page (New Haven; [153](#Ref153)) |
| Other Computer Programming | Rangarajan (Lehigh ChE; [181](#Ref181)) |

Table 6.6 - KEEN Cards of Biomedical Engineers Relevant to Education in Making Environments

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
|  |  |
| BME Design Integration | Kleim and Peña (ASU; [190](#Ref190)); |
| BME Sr. Design | Meyer & Nasir (Lawrence Tech; [112](#Ref112)); Staehle (Rowan; 168) |
| BME Instrumentation | Meyer & Nasir (Lawrence Tech; [110](#Ref110), [111](#Ref111), [113](#Ref113)); Lee (Santa Clara; [132](#Ref132)); Chiu (Rose-Hulman; [139](#Ref139)); Pai (Ga. Tech; [140](#Ref140)); Gettens (Western New England; [141](#Ref141)); Rust (Western New England; [142](#Ref142)); Kleim, Peña, and Reitmeier (ASU; [191](#Ref191)); Kleim and Muthuswamy (ASU; [217](#Ref217)) |
| Biomaterials & Tissue Engg. | Perry (Lehigh; [136](#Ref136), [137](#Ref137), [138](#Ref138)); Jedlicka & Cheng ([185](#Ref185)); Zhang (Lehigh; [202](#Ref202)); |
| BME Biomechanics w/Arduino | Meyer & Nasir (Lawrence Tech; [117](#Ref117)-[118](#Ref118)); Zustiak (Saint Louis; [164](#Ref164)) |
| BME 1st Yr. Design | Meyer & Nasir (Lawrence Tech; [115](#Ref115)); Perry (Lehigh; [138](#Ref138)); Elmer (Villanova; [165](#Ref165)); Kleim, Peña, and Reitmeier (ASU; [188](#Ref188)) |

Table 6.7 - KEEN Cards of Interest to a Future Nanotechnology Subnet

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
| Materials Science & Engg. (not BME or Nano) | Freeman (Clarkson; [126](#Ref126)), Huang (Villanova; [127](#Ref127)); Dupont (Lehigh; [128](#Ref128)-[129](#Ref129)); Moyer (Lehigh; [184](#Ref184)); Chow (Lehigh; [211](#Ref211)) |
| Nano, MEMS, Electrochem, & Drug Delivery (not Biomaterials & Tissue Engg.) | Letfullin (Rose-Hulman; [130](#Ref130)); Abel, Coburn, and Dodson (WPI; [131](#Ref131)); Lee (Santa Clara; [133](#Ref133)-[134](#Ref134)); Alagic, Bagwill, Sakic-Lazic, and Crandell (Saint Louis; [147](#Ref147)); Zhao (Western New England; [149](#Ref149)); Staehle (Rowan; [167](#Ref167), [168](#Ref168)); Wile (Ohio Northern; [177](#Ref177)); McIntosh (Lehigh; [203](#Ref203)); Tatic-Lucic (Lehigh; [214](#Ref214)); Zhang (Milwaukee SOE; [218](#Ref218)) |
| Biomaterials & Tissue Engg. | Perry (Lehigh; [136](#Ref136), [137](#Ref137), [138](#Ref138)); Jedlicka & Cheng ([185](#Ref185)); Zhang (Lehigh; [202](#Ref202)); |
| Fluid Mechanics | Weaver (Detroit Mercy; [143](#Ref143)) |
| Mass & Energy Balances | Henthorn & Henthorn (Rose-Hulman; [144](#Ref144)) |
| Unit Operations Lab | Tuzla (Lehigh; [187](#Ref187)) |
| Transport Phenomena | Caplan (ASU; [197](#Ref197)) |
| Thermodynamics | McIntosh (Lehigh; [204](#Ref204)) |
| Reactor Design | Brown (Lehigh; [215](#Ref215)) |

7. The Basics of Making Course

This is going to be the first of the co-developed tools specified in the Florida Tech proposal to KFF that was funded for 2019-2021. About 50% of it is based on the "Quantified Self" course developed by Eric Meyer and Mansoor Nasir at Lawrence Tech ([23](#Ref23)), with quite a few additions and links to what ought to be prerequisite content. One of the major challenges in teaching such a postdisciplinary course is that everyone has some strengths and some glaring prerequisite omissions coming in. A large portion of this prerequisite content will be posted on a web site this summer for students to start learning at least one month prior to the start of the course. Note that in the table that correlates course outcomes with programmatic outcomes (that follows in several pages) that the full matrix of KEEN student outcomes outlined by Estell *et al*. ([186](#Ref186)) is included. As most maker classes will have a range of CAD, Arduino, 3D printing, and computer programming experience ranging from zero to skilled, we recommend the following:

1) online tutorials that are encouraged PRIOR to the course;

2) an initial exercise similar to that used in which the more experienced students assist the workshop coordinators in getting those without relevant experience up to speed (A CAD exercise of this type should involve a 3D printer part or a part associated with a common prototyping mini-project. A computer programming project of this type should be related to the robotics and Python curricula developed by Balch at Georgia Tech ([701](#Ref701)) extended to C++ by a group from The University of Tennessee ([702](#Ref702)), and simplified for use by the Florida Virtual School ([703](#Ref703));

3) supplement the initial exercise with both individual (a 2nd part related to item 2)) and group (such assembly of multiple parts into a subsystem of a mini-project) homework;

4) online tutorials with higher level skills recommended. but not required;

5) a common mini-project involving CAD, 3D printing, Arduino, and assembly; and

6) a group end-of-semester project involving all of the above and some computer programming to be presented as part of a design showcase (gallery walk) where all of the KEEN outcomes can be emphasized.

7.1 – The Syllabus, Learning Outcomes, and Assessment

**CHE/BME 4568: The Basics of Making**

**2019-2020 Catalog Data: The Basics of Making.** After a brief review of the basics of computer programming, CAD drawing, and circuit breadboard prototyping, this class will emphasize the use of Arduino microcontrollers and LabView for sensors, data acquisition and controls, followed by 3D printing with a final project competition with 3D printed wearable sensors.

**Credits & Contact Hours:** 3 Credits, 13 lectures (50 mins.), 30 labs (110 mins.)

**Required or Elective or Selected Elective:** Technical Elective.

**Prerequisite and Co-Requisite Courses:** Calculus 2 prerequisite AND junior standing in one’s major

(not to be confused with junior standing purely based on the number of credits). Typically, this is cross-listed with graduate offerings (CHE 5568/BME 5568), with the major differences for

honors students or graduate students being implementation of more controls and of a project

management requirement

**Prerequisite and Co-Requisite Topics:**

1. Mathematics - Numerical derivatives and integrals, and curve fitting
2. Chemistry (preferred) – spectroscopy (Gen Chem 1), chemical reaction kinetics (Gen Chem 2), equilibrium constant (Gen Chem 2)
3. Materials Science (preferred) – electrical properties
4. Computer Programming (preferred) - proficiency in any language
5. General Engineering – PowerPoint, basic circuits (preferred), CAD drawing (preferred, in any software package)
6. Chemical Engineering (preferred) - mass and energy balances (CHE 2101), process flowsheeting and piping & instrumentation diagrams (CHE 1101)

**Textbook (T) and References (R):** (R) J. R. Brenner, Compilation of relevant topics at [http://my.fit.edu/~jbrenner/thebasicsofmaking.zip](http://my.fit.edu/~jbrenner/thebasicsofmaking), July, 2019.

**Instructor**

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**Course Outcomes:** Upon completion of this course the students will achieve the outcomes as

1. Computer Programming - 90% of students will demonstrate the ability to write and/or modify computer code in both LabView and in Arduino.

2. Wiring/Soldering - 100% of students will be able to safely construct a circuit containing soldering, butt splicing, and heat shrinking.

3. Arduino- and LabView-Based Based Circuits - 100% of students will successfully connect an Arduino to their computers and to a breadboard, and communicate with their circuit with both Arduino and LabView software.

4. Arduino- and LabView-Based Data Acquisition, Sensors, Motors, and Controls - 90% of students will properly calibrate a pH meter. 80% of students will successfully control a stepper motor-based syringe pump to titrate an acid with a base. 70% of students will read a thermocouple's temperature in an ice water bath and control both stepper and servo motors outside of class.

5. Concentration Monitoring and Potentiostats - 80% of students will calibrate electrical conductivity (EC)/salinity probes BEFORE an in class lab. In lab, they will compare their "home results" with those of a commercial potentiostat

6. Microfluidic flow - All students will construct a LabSmith microfluidic flow kit and demonstrate the lack of mixing in laminar flow.

7. CAD Drawing - 90% of student groups and 70% of students will successfully prepare CAD drawings for a wearable sensor and a cylindrical or rectangular prismatic object with machined holes during homework and quizzes, respectively.

8. 3D Printing - All students will successfully print an object, vary at least two aspects of the G code printing parameters, and assess both the effects of those parameters and the fit of machine screws into the holes associated with their prints.

9. Fabrication of Wearable Sensors - All student groups will 3D print at least one component of a customized wearable sensor as part of an end-of-semester project.

10. Poster Presentation and Demonstration of Wearable Sensors - All student groups will present a poster as part of the end-of-semester project on the design and fabrication of a customized wearable sensor, with 80% of the sensors will communicating data via USB and 40% communicating wirelessly.

11. Multidisciplinary Teamwork - 90% of students will be able to function properly in multidisciplinary teams as assessed by self, team, and faculty evaluations of their performance as being "acceptable" on the end of semester project.

**Topics Covered and Associated Time:**

1. National Instruments LabView Programming Basics: Common variable types, If/Then/Else, Do and While Loops, Data Acquisition and Control (DAQ) hardware (1 week)
2. Same programming concepts in C++ for Arduino and G Code for 3D printing (1 week)
3. Wiring a light bulb circuit and soldering (1 lab hour)
4. Intro to breadboard circuit concepts in TinkerCAD Circuits (1 lab hour)
5. Wiring breadboard circuits using Arduinos: Blinking LED, resistor circuit, resistor/capacitor & introduction to Arduino programming (2 lab hours)
6. Arduino/LabView DAQ for temperature, liquid level, pH, electrical conductivity (EC), dissolved O2 (DO), oxidation reduction potential (ORP), mass, and flow rate (1 week)
7. Arduino/LabView servo and stepper motor control (1 week)
8. Concentration monitoring using a CheapStat potentiostat (1 week)
9. LabSmith microfluidic flow kit - assemble & test (1 week)
10. CAD drawing (2 weeks incl. fall break)
11. CAD to .stl and 3D printing, including G code modification (2 weeks)
12. Assembly of a fully instrumented bioreactor with automated feeds, aforementioned sensors & controls, stepper-based syringe pumps, etc., with instruction in and integration of prewritten computer code for mass and energy balance closure, process control, and hazardous operability (HAZOP) analysis (2 weeks of lab + 3 lectures)
13. Student design, parts fabrication, and assembly of prototype (remainder of labs in course)
14. Final project explanation, with emphasis on Kern Entrepreneurial Education Network (KEEN) goals of curiosity, connections, and creating value (2 lectures), as well as multidisciplinary teamwork survey and expectations
15. Poster/demo contest for function & creativity to engender entrepreneurial mindset (in lieu of final exam)

**Class Schedule:** Common Lecture: Monday 8-8:50 AM;

Labs (WF 8-10 AM; TR 11-1; M 9-11 and WF 10-11)

**Grading**: Grades: 90, 80, 70, etc. Quizzes: 20%; Homework: 24%; In-class assignments:

12%; Lab Report: 4%; Performance of, meeting of minimal requirements for, and

complexity of customized wearable sensor: 12%; Poster presentation of customized

wearable sensor: 12%; Final report on customized wearable sensor: 16%.

**Relationship of Course Outcomes to Student Outcomes:** See following assessment matrix. KEEN outcomes as delineated by Estell *et al*. ([186](#Ref186)) have been included.



Graded Work

HW 1 - LabView programming basics

HW 2 - Arduino & G code programming basics

HW 3 - Arduino basic circuits

HW 4 - Arduino thermocouple data acquisition

HW 5 - Arduino stepper motor control

HW 6 - Arduino servo motor control

HW 7 - Arduino electrical conductivity (EC) data acquisition and calibration

HW 8 - CAD drawing

In Class Grade 1 - LabView programming basics

In Class Grade 2 - Arduino programming basics

In Class Grade 3 - G code programming basics

In Class Grade 4 - Light bulb circuit

In Class Grade 5 - TinkerCAD circuits

In Class Grade 6 - Arduino pH data acquisition and calibration

In Class Grade 7 - Arduino control of a stepper motor-based syringe pump

In Class Grade 8 - Arduino titration of acid with base

In Class Grade 9 - Comparison of EC calibration with commercial potentiostat

In Class Grade 10 - Assembly of LabSmith microfluidic flow kit and validation of the lack of

mixing associated with laminar flow

In Class Grade 11 - In Class CAD drawing

In Class Grade 12 - 3D printing of an object

Quiz 1 - Computer programming

Quiz 2 - Circuits

Quiz 3 - pH data acquisition and acid/base titration

Quiz 4 - Mass & energy balance closure, process control, & hazardous operability (HAZOP) analysis

Quiz 5 - CAD drawing

Lab Report 1 - Includes CAD drawing, 3D printed object, printing parameters, assessment of fit of machine screws into printed holes, any necessary revisions, and assessment of any necessary revisions.

Project Outcome 1 - Questions and issues sheet for customized wearable sensor

Project Outcome 2 - Motivation and value proposition for customized wearable sensor

Project Outcome 2 - 3D-printed part of standardized wearable sensor

Project Outcome 3 - Assembly of standardized wearable sensor

Project Outcome 4 - Hand-drawn sketches of customized wearable sensor

Project Outcome 5 - CAD drawing(s) of customized wearable sensor

Project Outcome 6 - 3D-printed parts of customized wearable sensor

Project Outcome 7 - Assembly of customized wearable sensor

Project Outcome 8 - Evaluation of multidisciplinary teamwork effectiveness

Project Outcome 9 - Curiosity as number of hours spent on project in making environments

Project Outcome 10 - Connection of content from multiple courses and integration/synthesis of

different kinds of knowledge, as assessed in the end of semester final

project report

Project Outcome 11 - Value created as assessed by combination of student, faculty, and general

public feedback during the poster presentation and performance evaluation

Performance of Final Project Prototype

Poster Presentation of Final Project Prototype

Final Report on Final Project Prototype

7.2 – Online Learning, Homework, and Quizzes

Students will have a highly varied set of prerequisite experience prior to starting this course, regardless of major or class standing. Students should be encouraged to do as much of the assignments 7.2.1 – 7.2.4 prior to starting the course as possible.

7.2.1 – Downloading and Installation of Software, Videos, etc.

7.2.2 – CAD Drawing Online Learning

7.2.3 – 3D Printing Online Portion of Certification

7.2.4 – Laser Engraving Online Portion of Certification

7.2.5 – HW 1 – Identification of Kit Items

7.2.6 – HW 2 – Questions & Issues Sheets for Group Project

7.2.7 – HW 3 – National Instruments LabView Computer Programming

7.2.8 – Quiz 1 – National Instruments LabView Computer Programming

7.2.9 – HW 4 – Python Computer Programming

7.2.10 – Project Report – Literature Review & Business Case

7.2.11 – HW 5 – Introduction to KiCAD for Wiring Diagrams

7.2.12 – HW 6 – CAD Drawing

7.2.13 – HW 7 – Meshmixer or Inkscape for Editing .STL Files

7.2.14 – HW 8 – Data Acquisition, Mass & Energy Balance Closure, Process Control, &

Hazardous Operability (HAZOP) Analysis

7.2.15 – Quiz 2 – CAD Drawing

7.2.16 – Project Report – CAD Drawing, 3D Printing, Fit & Finish

7.2.17 – Quiz 3 – Computer Programming & Control Quiz (Honors Program/Grad Version)

7.3 – Lecture Content

7.4 – Lab Content

7.4.1 – National Instruments LabView In Class Assignment

See Canvas/Files/labview and its subdirectories, particularly [Download labviewinclassinstructions.docx](https://fit.instructure.com/courses/604044/files/45147003/download?download_frd=1).

Copy and paste chebme4568chebme5568 folder from computer's desktop to your flash drive, if you are taking the in-class Basics of Making version of this.  It is way too big to put on Canvas.  If you are doing this for any other class or for an Honors Program project, skip this paragraph.

[Download labviewbeginnerscontent.zip](https://fit.instructure.com/courses/604044/files/45146995/download?download_frd=1) and unzip it.  Within that, unzip labview6.zip.  Install LabView 6 on your home computers from labview6.zip.  Do not register it.  I do have privileges to distribute this, but only to FIT students.  A newer version of LabView may also exist on your computers.  The newer versions of LabView is much more complicated and doesn't add all that much and is in a sufficiently different version from the instructions that there is a decent chance that you may get confused.

Also within the  [Download labviewbeginnerscontent.zip](https://fit.instructure.com/courses/604044/files/45146995/download?download_frd=1), unzip the following two paragraph's contents:

[Download labviewtrainingFIT.zip](https://fit.instructure.com/courses/604044/files/45147085/download?download_frd=1) = contains what we will do in the lab, including instructions for those who miss the first lab.

[Download labview2017.zip](https://fit.instructure.com/courses/604044/files/45147083/download?download_frd=1) - contains all of Dr. Brenner's LabView files plus LabView Basics exercises and instructions. If you can't find a particular file referred to in the instructions, look in the above two .zip files or .zip files therein.

A step-by-step introduction to LabView for those who really like it that way is in [Download LabviewBasics1manual.pdf](https://fit.instructure.com/courses/604044/files/45146833/download?download_frd=1).  In the really old days, this used to be an in-person training course, but it became easier for National Instruments (NI) to make shorter forms of this available as

[Download Introduction\_to\_LabView\_8\_in\_6\_Hours.zip](https://fit.instructure.com/courses/604044/files/45146863/download?download_frd=1) and even

[Download lv\_86\_in\_3\_hours\_updated.zip](https://fit.instructure.com/courses/604044/files/45146639/download?download_frd=1).

My experience is that those are only for people who have already programmed in another language.

Canvas/Files/lecturenotesf19/ [Download week1thebasicsofmaking.pdf](https://fit.instructure.com/courses/604044/files/45146937/download?download_frd=1)- pp. 3 to 5

Also Canvas/Files/labview/ [Download labviewinclassinstructions.docx](https://fit.instructure.com/courses/604044/files/45147003/download?download_frd=1) and

Canvas/Files/labview/ [Download labviewnotes.pdf](https://fit.instructure.com/courses/604044/files/45146793/download?download_frd=1)

Prerecorded version:  Canvas/Files/LiveLectures/[labviewforbeginners-prerecorded.mp4](https://fit.instructure.com/media_objects_iframe/m-4iKdDzKnsgXbQt7EkUbmM8pjdrMYgJs8?type=video?type=video)

Live lecture version:   Canvas/Files/LiveLectures/[labviewforbeginners-live.mp4](https://fit.instructure.com/media_objects_iframe/m-4ih61z9vg5YSwKj3Wfks3jJR5c65k9wh?type=video?type=video)

The file you will generate as the assignment:  [Download CtoF.vi](https://fit.instructure.com/courses/604044/files/45146469/download?download_frd=1)

Note that .vi files are very version dependent.  .vi files created in "older" versions of LabView like LabView 6 will NOT run on newer versions.

An example of a .vi I created for my H2 research many years ago:  [Download h2frontpanel.ppt](https://fit.instructure.com/courses/604044/files/45147999/download?download_frd=1)

Homework:  Canvas/Files/labview/ [Download labviewHWinstructions.rtf](https://fit.instructure.com/courses/604044/files/45146617/download?download_frd=1)

and what it refers to from the other files you have already downloaded.

[labviewbeginnerscontent.zip](https://fit.instructure.com/courses/604044/files/45146867?wrap=1)

7.4.2 – Wiring a Light Bulb Circuit

7.4.3 – Arduino Blink

7.4.4 – Soldering of Load Cell to Load Cell Shield

7.4.5 – Bucknell Speaker Box Soldering of LED’s

7.4.6 – Temperature Sensor – Arduino

7.4.7 – Load Cell Sensor – Arduino

7.4.8 – pH Sensor – Arduino

7.4.9 – Electrical Conductivity / Salinity Sensor - Arduino - Total Dissolved Solids (TDS)

7.4.10 – Martin Gallagher lecture on a full body virtual reality (VR) suit; discussion of finer aspects of 3D

printing; 3D scanning, including turntable photography; VR glasses, particularly for biomechanics

projects; 3D Vista software vs. Matterport for 3D virtual modeling tours; LiveFace; Vinyl cutter

7.4.11 – 3D Printing and Laser Cutting Group Training

7.4.12 – Python Computer Programming

7.4.13 – Stepper, Servo, and DC Motors

7.4.14 – Arduino & Bluetooth Motor Control of Robots

7.4.15 – Microfluidic Flow & Lab-on-a-Chip Devices

7.4.16 – 3D Printer Configuration and Subsystems, G-Code, and Conversion of CAD to .STL

7.4.17 – 3D Printing of Bucknell Speaker Box Feet

7.4.18 – Laser Engraving of Bucknell Speaker Box Top

7.4.19 – Electrochemical Concentration Monitoring

7.4.20 – Editing of .STL Files with Meshmixer/Inkscape

7.4.21 – Bucknell Speaker Box Construction & Wiring

7.4.22 – Bluetooth/Arduino Speaker Box Configuration

7.5 – End-of-Semester Project

[7.2.6 – HW 2 – Questions & Issues Sheets for Group Project](#Section_7_2_6)

[7.2.9 – Project Report – Literature Review & Business Case](#Section_7_2_9)

[7.2.15 – Project Report – CAD Drawing, 3D Printing, Fit & Finish](#Section_7_2_15)

8. MakerSpace Education Grant Summary

The current generation of students expects to find everything they want on the Internet, including software downloads, .stl files, and step-by-step instructions (often in YouTube video format) on how to make what they want to make. Fortunately, many making environment tools and supplies are reasonably more affordable and becoming moreso; however, many are not (lathes, CNC's, virtual reality/augmented reality (VR/AR) visualization tools, etc.). Making environments include not only on-campus makerspaces and off-campus FabLabs, but also VR/AR labs on the visualization end of the making spectrum to student design centers to machine shops on the fabrication end of the making spectrum.

The first part of the first phase of this grant was to conduct a very preliminary survey to find who is in charge of each of the types of making environments on each campus.

Our goals are as follows:

1) To identify 7-10 universities to visit in the next few months, from which 3 universities will be selected and granted ~$40 K each spread out over the remainder of the KEEN grant to co-create modules with, exchange modules with as part of beta testing, and finally distribute the beta-tested modules to all KEEN network partners;

2) In the 2nd survey, to identify best practices for starting and sustaining making environments and for student training. The survey is broken down into subcategories of the three C's. As a function of experience in each type of making environment, each person surveyed will rate at least each of the following:

a) user curiosity in each type of making environment;

b) the impact that the user expects that experience in that type of making space would have on their careers;

c) ease of making connections with staff in each type of making environment;

d) ease of making connections with other users in each type of making environment;

e) training availability;

f) types and level of training required;

g) ease of learning of equipment;

h) the most valuable capability in each type of learning environment for the person being surveyed;

i) the most valuable capability in each type of learning environment for most users;

j) the capability in each type of environment that the person being surveyed wished they had;

k) equipment reliability;

l) adequacy of available equipment; and

m) ease of use of available equipment.

3) Following compilation of the 2nd survey, a summary will be shared with KFF staff, then with deans, and then with the entire network.

4) The KEEN Report Summary Statement that follows is meant to focus the questions to be addressed as part of this grant, as well as the hypotheses that we have made.

**KEEN Report Summary Statement**

***The purpose of this Summary Statement document is to guide the Report and the Development of the Survey that will be used to collect data for the report.***

Provided below are a series of Questions and associated Hypotheses (revise as necessary) that will be used to target the report.

* **Question**: Can Making Spaces be used to enhance EML and promote the 3 C’s?
* **Hypothesis**: Making Spaces are an integral part of EML and inherently promote the 3 C’s.
* **Question**: How can Making Spaces be more effectively used to enhance EML and promote the 3 C’s?
* **Hypothesis**: By integrating Making Spaces into classroom lectures and assignments, faculty can better promote EML and the 3 C’s.

* **Question**: How are the “in network” universities using Making Spaces?
* **Hypothesis**: Making Spaces are widely used in conjunction with capstone projects and as supplemental learning to classroom teaching.

What information do we need to collect from the selected universities in order to address the questions/hypotheses listed above?

We should breakout the questions into those that are relevant for each of the following groups:

* **Director of the Making Space**
* **Staff/Student Assistants that work in the Making Space**
* **Faculty**
* **Students**

The makerspace education grant can be broken down as follows:

A) Initial proposal (http://my.fit.edu/~jbrenner/keen/KEEN.FloridaTech.Release.pdf; name = fltech password = brenner) to document quantitatively (not anecdotally) relationships between making environments and EML in 2019, and if successful, partner with three other KEEN universities in 2020 for co-development of making tools and in 2021 for beta testing of the co-developed tools. In this document, making environments are being defined in a larger context as shown in Figure 8.A.1 below to include everything from ideation to conversion into a computer-aided drawing (CAD) and finally into a working prototype. Thus environments include visualization labs (not only for CAD but also for virtual and/or augmented reality (VR/AR)), makerspaces (3D printing, laser cutting, water jets, Arduino microcontrollers, soldering, etc.), student (not just for senior) design centers, and machine shops.

Figure 8.A.1 – Types of making environments

A summary of the goals of the grant is as follows:

2019 - Providing evidence for EML integration into making - Connecting to the Making World

2020 - How should EML be integrated into making? - Contributing to the Making World

2021 - How may we enable faculty/staff to integrate EML into making?

- Disseminating to the Making World

We do not claim that we have figured out how best to leverage making spaces for EML, although we do have all of the different types of making environments and almost all of the relevant equipment. Part of the motivation for us writing this proposal was that we were sick and tired of training students on individual skills only to find out soon thereafter that a different skill was limiting their success in our research labs. This led to enough student and faculty frustration that this defined the need for this effort. *Formalization of the maker skill set training process would address the primary* ***pain point*** *of dampened enthusiasm associated with* ***deficiencies in the skill set*** *heretofore resulting in a* ***lack of persistence*** *toward students' and faculty members' professional goals.*

Together, we will make connections and establish best (and worst) practices to create value for the entire KEEN network so that no one has to re-invent the wheel and so that aspiring engineers can satisfy their curiosity and create value through persistence toward their goals through prototype construction.

The key questions and issues to be addressed in this grant are as follows:

1. What do students gain through making experiences?

2. What do students accomplish in making spaces? Are there specific themes/use cases?

3. What direct vs. indirect learning occurs in making spaces?

4. Is there latent value gained from using maker spaces (compared to not using it)?

5. Are there opportunities for making to enhance students 3C’s? Are those opportunities realized?

6. Could those 3C's opportunities in making experiences be reframed to promote EML? If so, could

this be formalized and packaged in a manner as to ensure every student who uses making environments at this institution and peer institutions can gain exposure to EML?

B) Preliminary survey ([Appendix 8.B.1](#Appendix8B1)) designed to identify all of the learning environments throughout the KEEN network, who supervises them to send the more detailed survey in 3) below to, and identify which universities merit site visits as candidates as part of 3). Because of size, this file is not included in this document as an appendix.;

C) More detailed survey ([Appendix 8.C.1](#Appendix8C1)) geared toward primarily toward faculty and staff to gather data to support the idea that EML enhances education in making environments that will be administered at the university being visited and/or sent via e-mail to the learning environment site supervisors identified as part of 2);

D) Additional surveys for staff ([Appendix 8.D.1](#Section8D1staffquestionnaire)), faculty ([Appendix 8.D.2](#Appendix8D2facultyquestionnaire)), and students ([Appendix 8.D.3](#Appendix8D3studentquestionnaire)) to be administered less formally either during visits or via a web site after visits (for students only as most of them will not be there during the summer);

E) Analysis of the surveys from C) and D) according to the coding tool in [Appendix 8.E.1](#Appendix8E1CodingTool); and

F) Narrowing down of the universities being visited in 3) to three universities to partner with in 2020 for co-development of making tools and in 2021 for beta testing of the co- developed tools/modules and simultaneous identification of what making tools/modules to co-develop.

Criteria for selection for partnering include the following:

1) Participation in the 2019 KEEN National Conference "maker education" workshop put on by

Caston *et al*. from The University of Denver ([101](#Ref101)) and personal discussions there

and since;

2) Interest expressed via the preliminary survey in Appendix 8.C.1;

3) Maturity of making environments as assessed by the same preliminary survey (A weakness in

one or more areas might actually be beneficial, as the partnering university has to see that it will benefit from being a beta tester in 2021.);

4) Size of College of Engineering (For example, The University of Denver has more students overall than Florida Tech (4800), but far fewer engineers (300 for Denver vs. 2100 for Florida Tech)).

5) Diversity of types of making environments;

6) Penetration of maker education into the curriculum;

7) Percentage of faculty who participate in KEEN, with particular emphasis on making, etc.

G) Co-development of the tools/modules identified in part F) during 2020 according to the process outlined in Figure 8.G.1 and described below.

 Figure 8.G.1 - Tool/module co-creation and exchange method

The co-create and exchange method ensures that the tools developed are both robust and transferable. Each school (A & B in Figure 8.G.1 above) will co-create at least one tool with each of the other schools collaboratively. Schools will be chosen to be as different as possible in a critical variable: volume of students, makerspace maturity, diversity of making environments, inclusion of making into curricula, etc. Each school will co-create at least three tools (Ex. A with B, C, and D) and receive tools co-developed by others (A receives tools co-developed by B/C, B/D, and C/D teams) and then validates those tools prior to dissemination to the entire KEEN network.

H) Exchange and beta testing during 2021 of the tools/modules co-developed in part G) during 2020 according to the process outlined in Figure 8.G.1;

I) An end-of-July 2021 workshop put on by the four partner schools from G) and H) at Florida Tech.

9. Early Survey Results and Plans for Remainder of Summer 2019 Visits

1) Using the criteria described in Section 8.F but mostly based on participation in the 2019 KEEN National Conference and on the enthusiasm and thoroughness of the response to the preliminary survey in Section 8.B, the list of potential partner universities was narrowed as follows:

Clear choices for visits: Bucknell, Lawrence Tech, Denver, Georgia Tech, Vanderbilt

Strong maybes for visits: Rochester Institute of Technology, Olin College (both being visited)

Maybes for visits: Arizona State, Dayton, Milwaukee School of Engineering, Marquette, Lafayette, Lehigh, Ohio Northern, Rose-Hulman, Rowan, James Madison, George Washington, Worcester Polytechnic Institute, New Haven, Wichita State

We are maximizing our impact by making numerous side trips to visit universities. For example, Profs. Morkos and Demoret plan on attending a 3D printing workshop in Youngstown, Ohio in August and are adding a side trip to Dayton. Milwaukee School of Engineering and Marquette will get visits as part of a trip to a KEEN workshop in Milwaukee by Profs. Mesa-Arango and/or Weaver. Prof. Mesa-Arango and/or Prof. Sen are attending a KEEN workshop in northern Virginia in November and will add a day to visit George Washington University as well as NSF. The next proposal that Florida Tech will write related to the maker education initiative will be to NSF related to the 2021 workshop at Florida Tech mentioned earlier and its continuation and/or expansion.

Dr. Brenner visited Bucknell's "maker" summer school ([26](#Ref26a)) in late July of 2019. He will fly through Philadelphia as part of the trip and may visit Drexel University and/or Rowan University then.

Dr. Brenner visited Lawrence Tech in August of 2019. Prof. Brenner thinks that Arizona State should have gotten a visit. Given the selection criteria, one and only one of the three selected partners can be a large university. That meant that we had to choose either Georgia Tech, Arizons State, or Ohio State. Given Georgia Tech's proximity to Florida Tech and David Beavers' relationship with Georgia Tech's makerspace coordinator, Marty Jacobsen, who is one of the pioneers we consulted to start our own makerspace, Georgia Tech will be one of the three partners.

2) Several Florida Tech faculty and staff were discussing how best to teach the maker skills. We have boiled the question of delivery methods of such skills into the following categories: a) for credit course work such as "The Basics of Making" course described in Chapter 7 at the junior/senior level, such as the "Quantified Self" course at Lawrence Tech ([23](#Ref23)) or even at the freshman level as at George Fox University ([25](#Ref25)); b) summer short courses like that at Bucknell ([26](#Ref26a)), George Fox ([27](#Ref27)), or Florida Tech ([28](#Ref28)); or c) *a la carte* skills workshops like those at Florida Tech's Harris Student Design Center (HSDC; [29](#Ref29)) at the small business Project Based Learning run by former Florida Tech students. One of the problems with *a la carte* workshops is the dichotomy between the entering experience levels of the students. Moreso than in traditional courses, students in *a la carte* workshops range from no experience with expected prerequisite skills to so much experience that they might be able to teach the class.

3) There is a strong gravitation for students to use tools that they know already, even if they are the wrong tools for the job, over using tools that they have never used. Machine shop supervisors at both Florida Tech and George Fox University both remarked that students who have used 3D printers prior to college often will use them rather than a machine shop tool. George Fox University has a much bigger woodworking area than Florida Tech and finds that it gets more use by freshmen because many of them have used some of the same tools before.

4) The equipment bases at Florida Tech and George Fox University in each of the different making environments are pretty similar. The highest item on George Fox’s wish list is a Haas 4-axis CNC mill of the same model that Florida Tech just received in May of 2019. Use of making environments was similar, with the following exceptions. All freshmen at George Fox take a general engineering two-semester sequence that involves a first semester course with more mechanical engineering and machine shop experience in the design, fabrication, and testing of a simple, yet novel engine. Prof. Neal Ninteman’s first semester course could easily serve as a model for others. Prof. Ninteman and more recently Prof. Ben Guidice of George Fox teach a second semester course that contains much of the basic circuits, electrical breadboarding, and Arduino microcontroller prerequisites prior to the basics of 3D printing, laser cutting, and water jet work as part of a general/electrical engineering design/build experience.

5) A strength of George Fox’s MakerHUB is the amount of online prep for training, although I am sure that there are other universities that have much more online prep for training. This is definitely an area for improvement at Florida Tech. There was general agreement between Florida Tech and George Fox faculty and staff that this should be a topic for tool/module development.

6) An area for improvement at both Florida Tech and George Fox is the amount of course integration of visualization skills beyond freshman CAD classes. There is almost no virtual or augmented reality (VR/AR) course integration even though Florida Tech has facilities and staff (Martin Gallagher; also the inventor of the GBotz 3D printer) that could easily make that happen at its library. George Fox University had a fascinating augmented reality (AR)-assisted welder that allows one to “see” what the weld will look like before making the weld. Bucknell ([158](#Ref158)) is better with regard to visualization tools than most universities.

7) The preparation for conducting a survey at another institution requires preparation. Lessons learned during the first couple of visits are summarized in [Appendix 9.1](#Appendix9aLessonLearnedDuringsurveyadmin). A typical visit summary is in [Appendix 9.2](#Appendix8EDenversummary).

10. Possible Topics for Module Co-Development

Table 10.1 - Possible Topics for Module Co-Development

A) Benefits, Implications, & Challenges of Education in Making Environments

1) Benefits, Implications, & Challenges of 3D Printers

2) Effect on Creative Thinking

3) Maker Environment Startup Requirements & Options

4) Open Source vs. Distinction in Sharing Economies

5) Importance of Community & Psychological Benefits

B) How Makers Think

1) Importance of Community & Psychological Benefits

2) Unique Aspects of a Maker's Mindset

3) STEM Literacy Practices of Experienced Makers

4) Open Source vs. Distinction in Sharing Economies

5) Effect on Creative Thinking

C) Conversion of Thought to Design

1) Effect on Creative Thinking

2) Design for Additive Manufacturing

3) AR/VR Library Spaces

D) What Should Be in Each Making Environment

1) Making Environment Startup Requirements & Options

2) AR/VR Library Spaces and Courses

3) Pre-College

4) Business Models for Making Environments

5) Small Business's Opinions Regarding Making Environments

E) Business Aspects

1) Open Source vs. Distinction in Sharing Economies

2) Business Models for Making Environments

3) Small Business's Opinions Regarding Makerspaces

F) How to Deliver the Content

1) One Week Summer Short Courses (often to high schoolers)

2) 2-3 Hour Workshops (*a la carte* or as part of a series)

3) Zero Credit Machine Shop Certification Courses

4) Three-Credit Semester-Long Courses

5) Web Sites and YouTube Videos

G) General Engineering Customers vs. Discipline-Specific Customers

H) Consolidated Spaces vs. Distributed Spaces

Prior to the first site visit in May of 2019, most of the following possible topics for module co-development were identified through the preliminary analysis of the literature described in Section 5 of this document. Many subtopics in Sections A-E in Table 10.1 below fall under multiple larger topics. One of the changes from Section 5 is that "MakerSpace" was replaced by the more general "Making Environment" to reflect the multiple environments where "maker" learning occurs. Sections F-H in Table 10.1 evolved out of the development of selection criteria for 2020/2021 partner selection for module co-development. Item G regarding "general" engineering vs. discipline-specific customers is a variant of the big vs. small school dichotomy. Large universities will likely have making environments all over campus; small schools may (ex. George Fox) or may not consolidate their spaces into hubs (Item H).

What follows is a summary of site visit results to all making environments at Florida Tech, George Fox University, and The University of Denver. Some of the preliminary conclusions fall within the categories defined in Table 10.1, and some generate entirely new topics for collaboration.

1) There should be a collaboration between two partners regarding a freshman design and prototype construction/valdiation course in general/mechanical/aerospace engineering that includes CAD drawing and machine shop skill set experiences. This was not on the list in Table 10.1 Prof. Neal Ninteman’s first semester course at George Fox described in Section 9 is a prime candidate for this partnership. Undoubtedly more will emerge during the narrowing/selection process.

2) A hybrid of Lawrence Tech’s “Quantified Self” (ref. 14), George Fox’s 2nd semester freshman general/electrical engineering course, and/or Florida Tech’s “The Basics of Making” course is almost certain to be one of the co-developed tools for 2020. There may be other partners on this topic, including Bucknell given its 3D printing workshops for both students and faculty (ref. 26) that Prof. Brenner will attend in late July of 2019. At this point, but given the research similarities between Profs. Wikswo and Cliffel at Vanderbilt (ref. 9) and Prof. Brenner at Florida Tech, Vanderbilt would be an intriguing partner as a beta tester if Vanderbilt has no course in this category. This topic for module development falls under F.4 in Table 10.1.

3) There definitely should be module development in the "Visualization and Virtual/Augmented Reality (VR/AR)" category (Section C.3 in Table 10.1. While most universities have some visualization studio, most are geared toward CAD drawing only and do not take advantage of VR/AR as much as they should, primarily because the professors do not know enough about such technology. Of the making environments, this type is the least implemented thus far, and definitely the type of making environment that many universities would like guidelines for before making large equipment investments in items that will not get used frequently. At Florida Tech, this visualization studio, including 3D scanning, is adjacent to a 3D printing service inside our library and is called a digital scholarship laboratory (DSL). Supervised by Martin Gallagher, a 3D printer inventor/entrepreneur, this facility receives considerable use but easily could have enough additional use to justify a staff several times larger if faculty knew better how to coordinate with all of the DSL's services. Bucknell (ref. [158](#Ref158)) is a likely partner with regard to visualization tools.

Many of Florida Tech's best students work at The Center for Advanced Manufacturing and Innovative Design (CAMID), but a lot more students could benefit from CAMID's presence. The concept for CAMID is based on a virtual, digital equivalent to a physical product, which Grieves termed a Digital Twin ([251](#Ref251)). Many of the senior design project winners take the initiative to learn the skills they need to win those awards at the Florida Tech MakerSpace and work at CAMID, and, until Fall of 2019 when [The Basics of Making](#Section8TheBasicsofMakingCourse) was offered for the first time, without having a specific course to learn those skills. Consequently, Prof. Brenner has proposed a Center for Advanced Manufacturing, Nano, & Embedded Sensor Technologies (CAMNEST) to serve as a nest from which students will move on to CAMID.

4) A consolidated MakerHUB (consolidation of Items G & H in Table 10.1) like that at George Fox University has the advantage of "one-stop shopping" like that of a WalMart. The time savings benefit for hub consolidation needs to be measured. By contrast, large universities can offer discipline-specific premium services (ex. bioprinting at Georgia Tech's Biomedical Engineering Department) that smaller universities do not have the resources to offer.

5) As KEEN's focus is on developing the mindset to accompany the skill set, one module that should be developed should revolve around the unique aspects of makers' mindsets (Section B.2 in Table 10.1), particularly those of the very [wealthy entrepreneurial donors described in Section 4](#Section4point6wealthyentrepreneurs) who finance the making environments and summarized in the 1989 Kevin Costner baseball movie "Field of Dreams": "If you build it, they will come. They will most definitely come" (ref. 24). This is critical because such donors are a huge part of the business model for making environments (Section E.2 of Table 10.1). These subjects (the entrepreneurial maker/donors' mindset and the business model for making environments) should probably be merged into one module to be co developed.

One such entrepreneurial maker/donor, David Beavers of Florida Tech, insists that this project must address the community and psychological benefits associated with working in making environments (Beavers, [252](#Ref252)). Makerspaces are unique amongst the types of making environments in the percentage of projects that are initiated due to student self-interest with no association with a class project (This is clearly borne out in the few surveys and particularly the makerspace staff/student assistant interviews we have conducted so far, but will need to be statistically quantified in the remainder of 2019.). Beavers estimates that while only 10% of the projects are generated by students in the process of satisfying their intellectual curiosity, but 70% of the students who spend time in his makerspace collaborate on such projects ([252](#Ref252)). Thus, personal connections are made, and intellectual curiosity is multiplied.

6) An interesting topic to explore was described in the [literature review (Section 5) regarding openness vs. distinction in sharing economies](#opennessvsdistinctioninsharingeconomies). This may not be something that is best addressed via a co- developed module. We are recommending that it be the subject of student-driven survey at least at Florida Tech and hopefully at other universities. At Florida Tech, students are required as part of their Scientific and Technical Communication course to develop a survey to be administered anonymously via SurveyMonkey and advertised through the university's student e-mail list server forum. Results from this can be distributed at the 2020 KEEN National Conference in the proposed Maker Education Workshop described [in Section 14](#Section142020KNCplans). The same survey will be posted on the KEEN Maker Subnet prior to the conference for both optional completion by faculty and moreso for stimulating chat discussions on the subnet.

7) An obvious module for collaboration will revolve around modes for content delivery (Item F in Table 10.1). Short courses at Bucknell (ref. [26](#Ref26b)), Lawrence Tech (ref. [114](#Ref114)), and Florida Tech (ref. [28](#Ref28a)) have been used for skill set development for students and even faculty (at Bucknell). Florida Tech is among those who conduct 2-3 hour workshops in *a la carte* mode or as part of a series. Many universities have machine shop certification courses as well. Three-credit semester long courses are an option for content delivery described in item 2) above. Finally, there is a wealth of information on web sites and YouTube videos. Ultimately there will have to be some hybrid of most or all of these content delivery methods, but the web site and YouTube video approach will make the modules developed as part of this grant more easily disseminated to other KEEN network partners.

8) After KEEN partner universities complete the more comprehensive survey (Section 8.C and Appendix 8.C.1) and these results are summarized in a form that protects personal and institutional privacy, equipment and/or software common to making environments where learning occurs will be evaluated through the KEEN Making Subnet discussion forum in an Angie's List or Consumer Reports format. Ultimately all these recommendations will be distributed to KFF staff, then to deans, and then to the faculty and staff at each of the KEEN partner institutions.

11. KEEN Cards

11 A) The following [KEEN card (fully displayed in Appendix 11.A.1)](#Appendix11A1) includes information for an entire KEEN-focused nanotechnology minor program, not just a single course.

32. James Brenner, Florida Tech, "Nanotechnology",

<https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=2659c514-e143-417a-a280-0f9721c3707b>

Plans for 2019-2020 for Dr. Brenner include the following to break the KEEN card content above into multiple cards and thus increase the impact for the KEEN network.

a) Describe ethics debates in first year nanotech lab course;

b) Alternate activity to a) in which student groups pitch a nanotech product that they want to invent or improve upon, demonstrate what value they will create with their invention or innovation, and both exhibit curiosity and make connections by doing a preliminary literature, patent, and web search for faculty researchers and companies worldwide with whom they could intern as part of the process to reach their ultimate invention/innovation goals;

c) Questions & issues sheet for defining technical & nontechnical aspects of a problem (ref. 32);

d) Root cause analysis;

e) Driver's test approach to materials characterization training;

f) How to add equipment to a lab without a government grant;

g) Self-assembly of nanomaterials: A study in connections of concepts;

h) Preparing a common basis for student success in postdisciplinary courses; and

i) Adding EML to a literature review.

11 B) The following [KEEN card (fully displayed in Appendix 11.B.1)](#Appendix11B1) includes information for Prof Beshoy Morkos.

301. Beshoy Morkos, Florida Tech, "Beshoy Morkos",

<https://engineeringunleashed.com/user-profile.aspx?userguid=0a66fde5-e564-484f-8082-e5ed6f6db142>

11C) The following [KEEN card (fully displayed in Appendix 11.C.1)](#Appendix11C1) includes information for "Incorporating EM in a Freshman Engineering Course", by Chiradeep Sen.

**Incorporating EM in a Freshman Engineering Course**

Created: 5/23/2019 9:08PM ET by [Chiradeep Sen](https://engineeringunleashed.com/user-profile.aspx?userguid=6c2cfd95-89cf-46ed-a87c-4dfbb534e081) Updated: 5/23/2019 10:13PM ET by [Chiradeep Sen](https://engineeringunleashed.com/user-profile.aspx?userguid=6c2cfd95-89cf-46ed-a87c-4dfbb534e081)

302. Chiradeep Sen, Florida Tech, "Incorporating EM in a Freshman Engineering Course",

<https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=04cac34f-4429-42ca-a403-1e19ff44e0f2>

11D) The following [KEEN card (fully displayed in Appendix 11.D.1)](#Appendix11D1) is an exercise for a statics course offered by Kimberly Demoret.

**Teams Teaching Statics; Statics Photo Safari: Small Steps Towards EML**

Created: 2/19/2019 4:14PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568) Updated: 5/14/2019 4:37PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)

303. Kimberly Demoret, Florida Tech, "Teams Teaching Statics; Statics Photo Safari: Small Steps Toward EML", <https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=31ae7ce0-62d7-43d3-a83b-b97d4f3670fe>

11E) The following [KEEN card (fully displayed in Appendix 11.E.1)](#Appendix11E1) is an exercise regarding Design Thinking in Team Projects by Kimberly Demoret.

**Design Thinking in Team Projects**

Created: 1/2/2019 4:32PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568) Updated: 5/22/2019 6:04PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)

304. Kimberly Demoret, Florida Tech, "Design Thinking in Team Projects",

<https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=e431c9c7-c57b-4392-bac8-8fd8e445aeab>

11F) The following [KEEN card (fully displayed in Appendix 11.F.1)](#Appendix11F1) is an exercise for defining need and creating value in capstone design courses, by Kimberly Demoret.

**Capstone Topics: Defining the Need and Creating Value**

Created: 5/24/2019 4:39PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568) Updated: 5/24/2019 4:41PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)

305. Kimberly Demoret, Florida Tech, "Capstone Topics: Defining the Need and Creating Value",

<https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=d48a1471-7b05-4a89-b22f-ed3805eeb45b>

12. Plans for the Maker Subnet

1) Publish [postdisciplinary engineer curriculum](#Appendix2point1) and accompanying explanation from this report on KEEN maker subnet for comment;

2) Publish [maker minor curriculum](#Appendix3point1) and accompanying explanation from this report on KEEN maker subnet for comment;

3) Do a search on KEEN's site for faculty who have interest in topics related to making in addition to what some faculty have published KEEN cards on topics relevant to making described in [Section 6](#Section6ConnectionsandKEENCards);

4) Request KEEN for space in their monthly newsletter to advertise the subnet and 1-3) above.

5) E-mail all possible connections from 1-4) as follow-up; and

6) [Session (perhaps 2 or even 3 for people who can't make the 1st one) at 2020 KEEN Conference](#Section142020KNCplans)

(Details in Section 14 can be found via the above link.)

13. Plans for a Nanotechnology Subnet

1) Plans for 2019-2020 include the following to break the KEEN card content described in

https://engineeringunleashed.com/card/1922 ([32](#Ref32b)) into multiple cards and thus increase the impact for the KEEN network.

a) Describe ethics debates in first year nanotech lab course;

b) Alternate activity to a) in which student groups pitch a nanotech product that they want to invent or improve upon, demonstrate what value they will create with their invention or innovation, and both exhibit curiosity and make connections by doing a preliminary literature, patent, and web search for faculty researchers and companies worldwide with whom they could intern as part of the process to reach their ultimate invention/innovation goals;

c) Questions & issues sheet for defining technical & nontechnical aspects of a problem ([32](#Ref32b));

d) Root cause analysis;

e) Driver's test approach to materials characterization training;

f) How to add equipment to a lab without a government grant;

g) Self-assembly of nanomaterials: A study in connections of concepts;

h) Preparing a common basis for student success in postdisciplinary courses; and

i) Adding EML to a literature review;

2) Contact the faculty in Table 13.1 below:

Table 13.1 - KEEN Cards of Interest to a Future Nanotechnology Subnet

|  |  |
| --- | --- |
| Field of Endeavor or Major/Course/Year | Professor (Universities; ref. #'s) with KEEN Cards |
| Materials Science & Engg. (not BME or Nano) | Freeman (Clarkson; [126](#Ref126)), Huang (Villanova; [127](#Ref127)); Dupont (Lehigh; [128](#Ref128)-[129](#Ref129)); Moyer (Lehigh; [184](#Ref184)); Chow (Lehigh; [211](#Ref211)) |
| Nano, MEMS, Electrochem, & Drug Delivery (not Biomaterials & Tissue Engg.) | Letfullin (Rose-Hulman; [130](#Ref130)); Abel, Coburn, and Dodson (WPI; [131](#Ref131)); Lee (Santa Clara; [133](#Ref133)-[134](#Ref134)); Alagic, Bagwill, Sakic-Lazic, and Crandell (Saint Louis; [147](#Ref147)); Zhao (Western New England; [149](#Ref149)); Staehle (Rowan; [167](#Ref167), [168](#Ref168)); Wile (Ohio Northern; [177](#Ref177)); McIntosh (Lehigh; [203](#Ref203)); Tatic-Lucic (Lehigh; [214](#Ref214)); Zhang (Milwaukee SOE; [218](#Ref218)) |
| Biomaterials & Tissue Engg. | Perry (Lehigh; [136](#Ref136), 137, [138](#Ref138)); Jedlicka & Cheng ([185](#Ref185)); Zhang (Lehigh; [202](#Ref202)); |

3) Do a search on KEEN's site for faculty who have interest in topics related to nanotechnology, materials science & engineering, biomaterials, and tissue engineering in addition to what some faculty have published KEEN cards on topics relevant to making described in [Table 6.7](#TableX7) to suggest a discussion table in the PM session for discipline-specific connections.

4) Request KEEN for space in their monthly newsletter to advertise the subnet and 1-3) above.

5) E-mail all possible connections from 1-4) as follow-up.

14. Plans for 2020 KEEN National Conference

1) Session (perhaps 2 for people who can't make the 1st one) at 2020 KEEN Conference with following general layout:

a) 7 minute summary of FIT, makerspace education grant phases, including partnerships for 2020 and 2021 by Kimberly Demoret;

b) highlights (and distribution) of 2nd survey (that many will have already taken), along

with a link to the full 2019 Phase 1 report (5 min.; Kastro Hamed);

c) 3 minute summary by Jim Brenner of a “postdisciplinary” engineer;

d) 20 minute table discussion of what a “postdisciplinary” engineer should be able to do,

followed by what a “maker” needs to be able to do;

e) 10 minute room-wide discussion of d), along with Jim Brenner distributing proposed curricula for the maker minor and the postdisciplinary engineer;

f) What is different about the mindsets of makers? How do we reach/teach them?

(10 min. table discussion);

g) Shared vs. distinction economy – Brenner talks for 5 minutes about how the recent

KEEN grant has changed his perception of what entrepreneurship means;

h) 10 minute table discussion of g) + 5 minute room-wide discussion of g); and

i) Individual gallery walk to show interest in proposed co-developed tools, described on mini-posters (10 minutes) to aid in final selection process for 2020.

2) Posters at the Expo at the 2020 KEEN National Conference:

a) Poster related to making environment grant, including updates related to the survey findings and a list of which partners will collaborate with whom on what topics;

b) Same nanotechnology minor poster as at the 2019 KEEN National Conference,

along with a table at the “networking hour” designed for networking with other

faculty within one’s discipline or related topics.

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34375

105c

106c

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[One CardDeck to Rule Them All](https://engineeringunleashed.com/card/2167)

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Section 13 References

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Section 14 References

Appendix 2.1 - Postdisciplinary Engineer Curriculum

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| KERN FAMILY FOUNDATION HONORS BACHELOR OF SCIENCE  DOUBLE MAJOR IN MAKER ENGINEERING (7077)  & either BIOMEDICAL ENGINEERING (7048) OR CHEMICAL ENGINEERING (7033)  with MINOR in NANOSCIENCE/NANOTECHNOLOGY (6050)  2020-2021 CATALOG | | | | | | | | | | |
| Name | |  | | Student # | | | |  | | |
| Advisor | |  | | Phone # | | | |  | | |
|  | | E-mail | | | |  | | |
| Comments | | | | | | | | | | |
| COURSE # | | COURSE | | | | CR. | | | SEM. | GRADE |
| YEAR 1 - FALL SEMESTER | | | | | | | | | | |
| HON 1000 | | Honors Entrepreneurially-Minded Learning (EML) | | | | 1 | | |  |  |
| BIO 1010 | | Biological Discovery 1 OR Honors equivalent | | | | 3 | | |  |  |
| BIO 1030 | | Introduction to Biotechnology for BME's only (can be postponed\*) | | | | 1 | | |  |  |
| BIO 1045 | | Introduction to Biomedical Engineering for BME's only (can be postponed to Year 2 Fall) | | | | 1 | | |  |  |
| CHE 1101 | | Intro to Chemical Engineering 1 (Process Flowsheeting + PowerPoint) | | | | 2 | | |  |  |
| CHM 1101 | | General Chemistry 1 OR Honors equivalent | | | | 4 | | |  |  |
| COM 1101 | | Composition and Rhetoric - Honors Version emphasizing entrepreneurship | | | | 3 | | |  |  |
| MTH 1010 | | Honors Calculus 1 (Prerequisite: MTH 1000 [OR high school algebra and trig and a passing score on the placement test]) | | | | 4 | | |  |  |
|  | | TOTAL | | | | 17/19 | | |  |  |
| YEAR - 1 SPRING SEMESTER | | | | | | | | | | |
| AEE 1202 | | Aerospace Practicum (CAD + design exp. w/machine shop + electronics) | | | | 2 | | |  |  |
| CHE 1102 | | Intro to Chemical Engineering 2 (Excel plotting, curve fitting, iterative solutions, & statistics) | | | | 1 | | |  |  |
| CHM 1102 | | General Chemistry 2 (Prerequisite: CHM 1101) OR Honors equivalent | | | | 4 | | |  |  |
| MTH 1020 | | Honors Calculus 2 (Prerequisite: MTH 1010) | | | | 4 | | |  |  |
| PHY 1001 | | Physics 1 (Prerequisite: MTH 1010; Co-requisite: MTH 1020) OR Honors equivalent | | | | 4 | | |  |  |
| CSE 1509 | | New Honors Computer Science (LabView, C++, Python, & G Code) | | | | 3 | | |  |  |
|  | | TOTAL | | | | 18 | | |  |  |
| YEAR 2 - FALL SEMESTER | | | | | | | | | | |
| CHE 2101 | | Chemical Process Principles 1 (Prerequisites: CHM 1101, MTH 1001) | | | | 3 | | |  |  |
| CHM 2001 | | Organic Chemistry 1 (Prerequisite: CHM 1102) for BME/ChE's | | | | 3 | | |  |  |
| MAE 2081 OR BME 2081 | | Applied Mechanics: Statics for MEE/AEE's OR Rigid Body Biomechanics for BME/ChE's | | | | 3 | | |  |  |
| MTH 2001 | | Calculus 3 (Prerequisite: MTH 1002/1020) | | | | 4 | | |  |  |
| PHY 2002 | | Physics 2 (Prerequisite: PHY 1001) | | | | 4 | | |  |  |
| PHY 2091 | | Physics Laboratory 1 (Co requisite: PHY 1001) OR Honors equivalent | | | | 1 | | |  |  |
|  | | TOTAL | | | | 18/18 | | |  |  |
| YEAR 2 - SPRING SEMESTER | | | | | | | | | | |
| CHE 2102 OR BIO 3201 | Chemical Process Principles 2 (Prerequisites: CHE 2101, MTH 1002/1020;  Co-requisite: CHM 1102) OR Anatomy & Physiology I (Prerequisites: BIO 1010) | | | | | | 3 or 4 | |  |  |
| CHE/CHM 1091 | Nanotechnology Lab 1 (Prerequisite: CHM 1001) | | | | | | 1 | |  |  |
| CHE 3260 OR BME 3260 | Materials Science and Engineering (Prerequisites: CHM 1101, PHY 1001; Co-requisite: MTH 1002) for non-BME's OR Biomaterials (Prerequisites: BIO 1010 AND ... OR (Nanotechnology AND CHE 3260 AND MTH 2201) OR Graduate standing) for BME's | | | | | | 3 | |  |  |
| CHE 3265 | Materials Laboratory (Prerequisites: MTH 1002, PHY 2091;  Co-requisite: CHE 3260) includes statistics and data analysis to satisfy ABET | | | | | | 1 | |  |  |
| ECE 4991 | Electric and Electronic Circuits (Prerequisites: PHY 2002, MTH 2001) | | | | | | 3 | |  |  |
| COM 1102 | Honors Writing About Literature (Prerequisite: COM 1101) emphasizing entrepreneurship | | | | | | 3 | |  |  |
| MTH 3200 | Honors Differential Equations/Linear Algebra (Prerequisite: MTH 1002) | | | | | | 4 | |  |  |
|  | TOTAL | | | | | | 18/19 | |  |  |
| YEAR 3 - FALL SEMESTER | | | | | | | | | | |
| CHE 3101 OR BME 3030 | Transport Processes (Prerequisite: CHE 2102; Co-requisite: MTH 2201/3200) OR Biofluid Mechanics (Prerequisite: PHY 2002; Co/Prerequisite: MTH 2201/3200) | | | | | | 3 | |  |  |
| CHE 4563/5563 | Materials Characterization Lab (Prerequisites: (CHE 3260 OR BME 3260) AND (CHM/CHE 1091)) | | | | | | 3 | |  |  |
| CHE 4240 OR BME 3240 | Advanced Computational Methods (Prerequisites: CHE 2102, MTH 2201/3200) OR Computational Methods for Biological Systems (MTH 2201/3200, MTH 2001/2010, AND BIO 1010) | | | | | | 3 | |  |  |
| CHM 3001 OR BME 3081 | Physical Chemistry 1 (Prerequisites: CHM 2001, MTH 2001/2010;  Co-requisite: PHY 2002) OR Biomechanics (Prerequisite: BME 2081) | | | | | | 3 | |  |  |
| CHE 4568/5568 OR BME 4568/5568 | The Basics of Making (Prerequisites: (MTH 1002/1020 prerequisite AND (CHE 3260 prerequisite OR BME 3260 prerequisite OR CSE 2410 prerequisite OR ECE 3551 co/ prerequisite) AND junior standing) OR Graduate standing) | | | | | | 3 | |  |  |
| CHM 2002 OR BIO 3202 | Organic Chemistry 2 (Prerequisite: CHM 2001) for ChE's OR Anatomy & Physiology 2 (Prerequisites: BIO 3201) for BME's | | | | | | 3 | |  |  |
|  | TOTAL | | | | | | 18 | |  |  |
| YEAR 3 - SPRING SEMESTER | | | | | | | | | | |
| CHE 3103 OR BME 4252 | Heat Transfer Processes (Prerequisites: CHE 2102, MTH 2201/3200 OR Biomedical Measurement and Instrumentation (Prerequisites: BIO 3201, ECE 4991) | | | | | | 3 | |  |  |
| CHE 3104 OR BME 4241 | Mass Transfer Processes (Prerequisites: CHE 2102, MTH 2201/3200)) for ChE's OR Transport in Biological Systems (Prerequisites: MTH 2201/3200, 2001, and BIO 1010) for BME's | | | | | | 3 | |  |  |
| BME 3222 | Biological Signals & Applications (Prerequisites: ECE 4991, MTH 2201/3200) | | | | | | 3 | |  |  |
| CHE 3110 OR MEE 3191 | Chemical (Prerequisite: CHE 2102) OR Mechanical (Prerequisites: CHM 1101, MTH 2001/2010, PHY 1001) Engineering Thermodynamics | | | | | | 3 | |  |  |
| BME 4253 | Biomedical Measurement and Instrumentation Lab (Co/Prerequisite: BME 4252) for BME's only | | | | | | 1 | |  |  |
| COM 2223 | Scientific and Technical Communication (Prerequisite: COM 1102) OR  (Allowed Substitution: COM 2370 Speech for transfer students) | | | | | | 3 | |  |  |
| CHE 4567/5567 OR BME 4050/5790 | Nanotechnology (Prerequisites: CHE 3260 OR CHM 2002 OR BME 3260 OR Graduate standing) | | | | | | 3 | |  |  |
|  | TOTAL | | | | | | 18/19 | |  |  |
| YEAR 4 - FALL SEMESTER | | | | | | | | | | |
| CHE 4122 OR MEE 4014 OR AEE 4014 OR ECE 4231 | Chemical (Prerequisites: CHE 2102, MTH 2201/3200) OR Mechanical (Prerequisites: MTH 2201/3200) OR Aerospace (Prerequisites: MTH 2201/3200) OR Electrical (Prerequisites: ECE 3222 or BME 3222) Engg. Process Control | | | | | | 4 or 3 | |  |  |
| BME 4292 | Biomedical (Prerequisites: BME 4191 OR (CHE 4181 AND The Basics of Making) Co/Prerequisite AND + Maker Program Admission) Engineering Senior Design I. | | | | | | 3 | |  |  |
| CHE 3115 OR BME 3261 | CHE Processes Laboratory 1 (Prerequisites: CHE 3101, CHE 3103) OR Biomechanics and Biomaterials Lab (Prerequisites: PHY 2091, BME 3260, & BME 3081) | | | | | | 2 or 1 | |  |  |
| PHY 2092 | Physics Laboratory 2 (Prerequisite: PHY 2091; Co-requisite: PHY 2002) | | | | | | 1 | |  |  |
| CHE 4151 | Chemical Engineering Reactor Design (Prerequisites: CHE 3101, CHE 3103 OR New Alternate of CHE 2101, MEE 3191 Thermodynamics, BME Transport (BME 4241) | | | | | | 3 | |  |  |
| BME 4410/5500  OR CHE 4131 | Double-Counted BME Restricted/Nanotech Elective: (Tissue Engineering BME 4410/5500 (Prerequisites: BME 3260 OR BME 5300 OR CHE 5300 OR (Nanotechnology AND CHE 3260 AND MTH 2201/3200) OR Graduate standing)  OR Separations CHE 4131 (Prerequisites: CHE 3103, 3104, 3110) for ChE's | | | | | | 3 | |  |  |
|  | Humanities Core 1 Course\* (Prerequisite: COM 1102) for BME's OR Chemical Engineering Plant Design (CHE 4181; prerequisites: CHE 3101 and co/prerequisite of CHE 4131) | | | | | | 3 | |  |  |
|  | TOTAL | | | | | | 19/17 | |  |  |
| Year 4 - SPRING SEMESTER | | | | | | | | | | |
|  | | HON 2000 Honors Seminar (Instructor Permission) OR Humanities Restricted Elective: any Bioethics (HUM 2570; req.'d for BME's), Logic (HUM 2510), Philosophy (HUM 2551, 2552, or 3531), non-ancient History of Science, Sci-Fi Film OR Books course (HUM 3274, 3276, 3352; Prerequisite: COM 1102. Some also have HUM Core Course 1 or 2. | | | 3 | | | |  |  |
| BME 4193 | | Biomedical (Prerequisites: BME 4192) Engineering Senior Design II | | | 3 | | | |  |  |
| CHE 3260 or CHE 4182 | | Materials Science and Engineering (Prerequisites: CHM 1101, PHY 1001; Co-requisite: MTH 1002) for BME's OR Chemical Engineering Plant Design 2 (Prerequisite: CHE 4181) for ChE's | | | 3 | | | |  |  |
|  | | Humanities Core Course 2\* (Prerequisite: COM 1102) | | | 3 | | | |  |  |
|  | | Humanities Core Course 1\* (Prerequisite: COM 1102) for ChE's | | | 3 | | | |  |  |
|  | | Social Science Elective OR Economics Elective OR Marketing Principles (BUS 3610 (Prerequisite: Soph standing)) OR Management Principles (BUS 3501; Prerequisite: Soph standing)) OR Project Management (ENM 4201/5201 (Prerequisite: MTH 2201) OR Systems Engineering Principles (SYS 4310/5310 (Prerequisite: MTH 2201)) | | | 3 | | | |  |  |
|  | | TOTAL | | | 18/18 | | | |  |  |
| Year 4 - SUMMER SEMESTER | | | | | | | | | | |
| MEE 2024 OR BIO 5515 OR BIO 5522 or CSE 4285 OR CHM 5111 OR BME 4410/5259 OR MEE 3024 | | Visualization Requirement: Solids Modeling & 3D Mechanical Design Principles (Prerequisite: AEE 1202 OR MEE 1024) OR Pharmacology and Drug Design (Prerequisite: Grad Standing) OR Bioinformatics, Genomics and Proteomics OR Game Design (Prerequisite: CSE 2010) OR Advanced Topics in Physical Chemistry (Prerequisite: Grad Standing) OR Biomedical Imaging (Prerequisites: BIO 3201, MTH 2201/3200, PHY 2002) OR Computer-Aided Engineering (Prerequisites: MEE 2024, AEE 3083) | | | 3 | | | |  |  |
|  | | TOTAL CREDIT HOURS REQUIRED | | | 147/ 149 | | | |  |  |
| Advisor | | | Program Chair | | | | | | | |
| Date | | | Date | | | | | | | |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Appendix 3.1 - KERN FAMILY FOUNDATION (KFF) MAKER MINOR (6060) | | | | | |
| Name: Student #: | | Major: Major Code: | | | |
| Minor Advisor: Dr. Jim Brenner | | Major Advisor: | | | |
| COURSE # | COURSE | | CR. | SEM. | GRADE |
| *12 CREDITS OF REQUIRED COURSES (Group A):* | | | | | |
| HON 1000 | Entrepreneurially Minded Learning | | 1 |  |  |
| CHE 3260 OR BME 3260 OR ECE 2111 OR ECE 4991 | Materials Science and Engineering (required for CHE's, MEE's, and AEE's) OR Biomaterials (required for BME's) OR Circuit Theory 1 (required for ECE's) OR Electrical and Electronic Circuits (required for all other engineers) | | 3 |  |  |
| CHE 4568/5568 OR BME 4568/5568 | The Basics of Making | | 3 |  |  |
| CHE 1101 | Introduction to Chemical Engineering 1 (required for ChE's) | | 2 |  |  |
| CSE 150x | Computer Science (req'd for MEE's, AEE's, ECE's, & CS; preferably new CSE 1509) | | 3 |  |  |
| *2+ CREDITS OF* | *CAD + Machine Shop Experience from Group B* | |  |  |  |
| AEE 1202 | Aerospace Practicum (required for AEE's) | | 2 |  |  |
| MEE 1024 | Introduction to Mechanical Engineering (required for MEE's) | | 3 |  |  |
| OCE 2002 | Computer Applications in Ocean Engineering (required for OCE's) | | 3 |  |  |
| CVE 1001 | Computer Applications Lab (required for CVE's) | | 1 |  |  |
| CVE 2083 | Construction Measurements Lab (required for CVE's) | | 1 |  |  |
| *+3 CREDITS OF* | *Signal Processing from Group C* | |  |  |  |
| BME 3222 | Biosignals and Applications (required for BME's) | | 3 |  |  |
| ECE 3222 | Signals and Systems (required for ECE's) | | 3 |  |  |
| MEE 5316 | Mechatronics | | 3 |  |  |
| *+3 CREDITS OF* | *Visualization Requirement from Group D* | |  |  |  |
| BME 4410/5259 OR ECE 5259 | Introduction to Biomedical Imaging OR Medical Imaging | | 3 |  |  |
| MEE 5553 | Advanced CAD and Design Automation | | 3 |  |  |
| MEE 3024 | Computer-Aided Engineering (CAE; required for MEE's) | | 3 |  |  |
| MEE 2024 | Solids Modeling & 3D Mechanical Design Principles (required for MEE's) | | 3 |  |  |
| BIO 5515 | Pharmacology and Drug Design | | 3 |  |  |
| BIO 5522 | Bioinformatics, Genomics and Proteomics | | 3 |  |  |
| CHM 5111 | Advanced Topics in Physical Chemistry | | 3 |  |  |
| CVE 3042 OR CVE 3052 | Water and Wastewater Systems for Land Development OR  Municipal Water and Wastewater Systems (One or other req'd for CVE's) | | 3 |  |  |
| CSE 4285 | Game Design | | 3 |  |  |

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *+3 CREDITS OF* | *Group E Electives* | | |  |  | |  |
| ECE 4991 | Electrical and Electronic Circuits (for ChE's only; other majors require it) | | | 3 |  | |  |
| ECE 4342 | Virtual Instrumentation Lab | | | 3 |  | |  |
| CHE 4567/5567 OR BME 4050/5790 | Nanotechnology | | | 3 |  | |  |
| BME 4252 | Biomedical Measurements & Imstrumentation | | | 3 |  | |  |
| BME 4410/5500 | Tissue Engineering | | | 3 |  | |  |
| BME/CHE 5300 | Biomaterials | | | 3 |  | |  |
| ECE 3551 | Microcomputer Systems 1 | | | 4 |  | |  |
| MEE 5318 | Instrumentation and Measurement Systems | | | 3 |  | |  |
| MEE 5650 | Robotics | | | 3 |  | |  |
| MEE 5660 | Robotic Control | | | 3 |  | |  |
| MEE 5552 | Design for Manufacturing Assembly | | | 3 |  | |  |
| OCE 4531 | Instrumentation Design and Measurement Analysis | | | 3 |  | |  |
|  |  | | |  |  | |  |
|  | A second course from Group D | | | 3 |  | |  |
|  | | TOTAL CREDIT HOURS | |  |  |  | |
|  | | TOTAL CREDIT HOURS REQUIRED | | 24-25 |  |  | |
| *(\*) Course must be listed on a Course Substitution Form attached with the student’s Petition to Graduate*  *APPROVALS* | | | | | | | |
|  | | |  | | | | |
| Minor Advisor Date | | | CHE Program Chair Date | | | | |

Major Advisor Date Major Program Chair Date

**Appendix 8: KEEN Report Summary Statement**

***The purpose of this Summary Statement document is to guide the Report and the Development of the Survey that will be used to collect data for the report.***

Provided below are a series of Questions and associated Hypotheses (revise as necessary) that will be used to target the report.

* **Question**: Can Making Spaces be used to enhance EML and promote the 3 C’s?
* **Hypothesis**: Making Spaces are an integral part of EML and inherently promote the 3 C’s.
* **Question**: How can Making Spaces be more effectively used to enhance EML and promote the 3 C’s?
* **Hypothesis**: By integrating Making Spaces into classroom lectures and assignments, faculty can better promote EML and the 3 C’s.

* **Question**: How are the “in network” universities using Making Spaces?
* **Hypothesis**: Making Spaces are widely used in conjunction with capstone projects and as supplemental learning to classroom teaching.

What information do we need to collect from the selected universities in order to address the questions/hypotheses listed above?

We should breakout the questions into those that are relevant for each of the following groups:

* **Director of the Making Space**
* **Staff/Student Assistants that work in the Making Space**
* **Faculty**
* **Students**



**Appendix 8.B.1: Making Spaces: Preliminary Survey**

The purpose of this survey is to collect information on Maker Space utilization inside KEEN network schools. In this context, “spaces” can include everything from traditional machine shops to visualization facilities (for example, the Marquette Visualization Lab). This includes traditional spaces such as, but not limited to 3D printing and augmented/virtual reality spaces.

Through a recently awarded grant from The Kern Family Foundation, Florida Tech is tasked with reporting on the current state of maker space utilization within KEEN schools. The information below will support a more detailed survey at a later date and those results will be detailed, reported, and disseminated to the rest of the KEEN network during the 2020 National Conference. Participation from each KEEN school is necessary for accurate exploration. We appreciate your completion of this survey and support of our effort. Any questions on the survey should be directed to [keenleader@lists.fit.edu](mailto:keenleader@lists.fit.edu)

**Name & School**:**\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_Email**:**\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_**

1. How many major maker/visualization spaces are on your campus?

(First line provided as an example)

|  |  |  |  |
| --- | --- | --- | --- |
| **Space Name** | **Type of Space** | **Space Leader Name** | **Contact Email/Phone** |
| *Florida Tech Maker Space* | *3D printing and collaborative environment* | *David Beavers* | *bdavid@fit.edu* |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |

1. In the spectrum below, list where some of your spaces lie. We have provided an example of our spaces on the top portion of the graphic. We ask you to populate the bottom portion:

Visualization

Fabrication

Fab Lab

Student Design Center

Maker

Space

Machine

Shop

Digital Scholarship Lab

**Appendix 8.C.1: Making Space Questionnaire**

**MAKING SPACE QUESTIONNAIRE**

MM/DD/YYYY

**Our Definition of Making Spaces:** Facilities on campus beyond instructional/academic settings (i.e. class / space) that are designed to support visualization and realization of ideas and/or products.

**School Name:**

**Making Space Name:**

**Curiosity**

**1.** What percentage of work-hours at the Making Space are devoted to developing student-driven concepts or unique designs?

|  |
| --- |
| *(%)* |

**2.** What is the percentage of work-hours devoted by the Making Space staff to guide students toward success in their project design?

|  |
| --- |
| *(%)* |

**Connections**

**3.** Does the Making Space encourage students to connect with those from other majors or disciplines?

*O Yes O No*

**4.** What percentage of projects are related to

- *Individual efforts?*

|  |
| --- |
| *(%)* |

*- Teams assigned by instructors?*

|  |
| --- |
| *(%)* |

*- Self-organized teams?*

|  |
| --- |
| *(%)* |

**Creating Value**

**5.** Are creations from this Making Space featured outside the university (like media reports, conferences, etc.)?

*O Yes, provide examples O No*

|  |
| --- |
| *(Text)* |

**6.** How many intellectual properties have been secured based on products designed in the Making Space?

|  |
| --- |
| *(Number)* |

**Accessibility and Availability**

**7.** By the best estimate, how many unique students use the Making Space:

*- In an average busy week of the semester?*

|  |
| --- |
| *(Number)* |

*- In an average quiet / non-busy week of the semester?*

|  |
| --- |
| *(Number)* |

**8.** Can students use the Making Space without supervision?

*O Yes O No*

**9.** Can students use the Making Space outside regular hours?

*O Yes O No*

**Penetration in Formal Courses**

**10.** What engineering majors collectively account for the top 75% of the overall Making Space usage?

*O Aerospace Eng. O Materials Science & Eng. O Biomedical Eng.*

*O Chemical Eng. O Civil Eng. O Computer Eng.*

*O Electrical Eng. O Mechanical Eng. O Ocean Eng.*

*O Software Eng. O Industrial Eng. O Other. Please specify:*

|  |
| --- |
| *(Text)* |

**11.** What courses account for 75% of the Making Space usage?

|  |
| --- |
| *(Text)* |

**Investment, Assets, and Utilization**

**12.** What has been the average annual budget of the Making Space for operations over the past five years / since inception?

|  |
| --- |
| *(Number)* |

**13.** What is the maximum number of students that can use the Making Space at a time?

|  |
| --- |
| *(Number)* |
|  |

**14.** What are the 5 most used equipment types in the Making Space (rank in order of most usage)?

- 1st

|  |
| --- |
| *(Text)* |

- 2nd

|  |
| --- |
| *(Text)* |

- 3rd

|  |
| --- |
| *(Text)* |

- 4th

|  |
| --- |
| *(Text)* |

- 5th

|  |
| --- |
| *(Text)* |

**15.** What is the next item/equipment in your wish list for the Making Space?

|  |
| --- |
| *(Text)* |

**16.** Indicate the percentage of users working in the Making Space on:

*- Class projects*

|  |
| --- |
| *(%)* |

*- Personal projects*

|  |
| --- |
| *(%)* |

*- Research projects*

|  |
| --- |
| *(%)* |

Thank you for your participation.

**Appendix 8.D.1: Staff/Student Assistant Questionnaire**

**School Name:**

**Maker Space Name:**

**Respondent Name:**

**Respondent email/phone:**

**Main Department/College:**

**Sociodemographic.**

**Gender: Age: Highest education level:**

**Major (latest degree): Race:**

**Nationality:**

**a. Questions for the Staff/Student Assistants on CONNECTIONS:**

|  |  |
| --- | --- |
| 1. Have you ***spread the word*** about the facility? | ❑ Yes ❑ No |
| 1. How many ***people got interested in the facility*** because of you spreading the word? | Estimated number of people. |
| 1. Do you think the facility***promotes team-based work***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of* *team-based work***observed in the facility? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |
| 1. What is the *level of* ***team involvement per user type*** observed in the facility? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ College students.  ☆ ☆ ☆ ☆ ☆ K12 students.  ☆ ☆ ☆ ☆ ☆ Faculty.  ☆ ☆ ☆ ☆ ☆ Staff.  ☆ ☆ ☆ ☆ ☆ Industry representatives.  ☆ ☆ ☆ ☆ ☆ Public officials.  ☆ ☆ ☆ ☆ ☆ Residents of the area.  (without specific affiliation).  ☆ ☆ ☆ ☆ ☆ Non-residents of the area.  (without specific affiliation).  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. Does the facility***promote connection between makers and potential beneficiaries of their creations***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of connection between makers and types of potential beneficiaries of their creations***? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Engineering firms.  ☆ ☆ ☆ ☆ ☆ Consumers (regular people).  ☆ ☆ ☆ ☆ ☆ Education establishments.  ☆ ☆ ☆ ☆ ☆ Public sector / goernment.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. Does the facility***promote connection between makers and suppliers***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of connection between makers and suppliers***? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Raw materials.  ☆ ☆ ☆ ☆ ☆ Machinery.  ☆ ☆ ☆ ☆ ☆ Electronic hardware.  ☆ ☆ ☆ ☆ ☆ Computers.  ☆ ☆ ☆ ☆ ☆ Software.  ☆ ☆ ☆ ☆ ☆ Consulting services.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. What is the ***level of connection between engineering disciplines and creations*** made in the facility? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Aerospace Engineering.  ☆ ☆ ☆ ☆ ☆ Aerospace Engineering.  ☆ ☆ ☆ ☆ ☆ Biomedical Engineering.  ☆ ☆ ☆ ☆ ☆ Chemical Engineering.  ☆ ☆ ☆ ☆ ☆ Civil Engineering.  ☆ ☆ ☆ ☆ ☆ Computer Engineering.  ☆ ☆ ☆ ☆ ☆ Electrical Engineering.  ☆ ☆ ☆ ☆ ☆ Mechanical Engineering.  ☆ ☆ ☆ ☆ ☆ Ocean Engineering.  ☆ ☆ ☆ ☆ ☆ Software Engineering.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. What ***courses*** use this facility? (describe ***how***)     ❑ Do not know | |
| 1. What ***type of training is available***?     ❑ Do not know | |
| 1. Can this facility be used to do ***non-academic projects***? | ❑ Yes ❑ No  Describe:  ❑ Do not know |

**Appendix 8.D.2: Questions for the Faculty**

**School Name:**

**Maker Space Name:**

**Respondent Name:**

**Respondent E-mail/Phone:**

**Main Department/College:**

**Sociodemographic.**

**Gender: Age: Highest education level:**

**Major (latest degree): Race:**

**Nationality:**

**a. Questions for the faculty on CURIOSITY**

|  |  |
| --- | --- |
| 1. When was the ***first time you visited*** the facility? | Term/Year |
| 1. When did you ***start using*** the facility? | Term/Year |
| 1. What are the ***machines that you mostly use***? (rank them) | |
| 1st: | |
| 2nd: | |
| 3rd: | |
| 4th: | |
| 5th: | |
| 6th: | |
| 7th: | |
| 8th: | |
| 9th: | |
| 10th: | |
| 1. Indicate your level of agreement with the sentence: ***Makers use the facility to develop new creations rather than replicating existing products****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***The*** ***facility facilitates the conceptualization of new ideas that can be materialized into creations****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers prefer to find solutions by themselves rather than following instructions****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers tend to develop the same type of creation in this facility****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers employ the most advanced/recent concepts in their creations****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers avoid trying new concepts in creations****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |

**b. Questions for the faculty on CONNECTIONS**

|  |  |
| --- | --- |
| 1. Have you ***spread the word*** about the facility? | ❑ Yes ❑ No |
| 1. How many ***people got interested in the facility*** because of you spreading the word? | Estimated number of people. |
| 1. Do you think the facility***promotes team-based work***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of* *team-based work***observed in the facility? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |
| 1. What is the *level of* ***team involvement per user type*** observed in the facility? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ College students.  ☆ ☆ ☆ ☆ ☆ K12 students.  ☆ ☆ ☆ ☆ ☆ Faculty.  ☆ ☆ ☆ ☆ ☆ Staff.  ☆ ☆ ☆ ☆ ☆ Industry representatives.  ☆ ☆ ☆ ☆ ☆ Public officials.  ☆ ☆ ☆ ☆ ☆ Residents of the area.  (without specific affiliation).  ☆ ☆ ☆ ☆ ☆ Non-residents of the area.  (without specific affiliation).  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. Does the facility***promote connection between makers and potential beneficiaries of their creations***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of connection between makers and types of potential beneficiaries of their creations***? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Engineering firms.  ☆ ☆ ☆ ☆ ☆ Consumers (regular people).  ☆ ☆ ☆ ☆ ☆ Education establishments.  ☆ ☆ ☆ ☆ ☆ Public sector / government.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. Does the facility***promote connection between makers and suppliers***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of connection between makers and suppliers***? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Raw materials.  ☆ ☆ ☆ ☆ ☆ Machinery.  ☆ ☆ ☆ ☆ ☆ Electronic hardware.  ☆ ☆ ☆ ☆ ☆ Computers.  ☆ ☆ ☆ ☆ ☆ Software.  ☆ ☆ ☆ ☆ ☆ Consulting services.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. What is the ***level of connection between engineering disciplines and the creations*** made in the facility? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Aerospace Engineering.  ☆ ☆ ☆ ☆ ☆ Aerospace Engineering.  ☆ ☆ ☆ ☆ ☆ Biomedical Engineering.  ☆ ☆ ☆ ☆ ☆ Chemical Engineering.  ☆ ☆ ☆ ☆ ☆ Civil Engineering.  ☆ ☆ ☆ ☆ ☆ Computer Engineering.  ☆ ☆ ☆ ☆ ☆ Electrical Engineering.  ☆ ☆ ☆ ☆ ☆ Mechanical Engineering.  ☆ ☆ ☆ ☆ ☆ Ocean Engineering.  ☆ ☆ ☆ ☆ ☆ Software Engineering.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. What ***courses*** use this facility? (describe ***how***)     ❑ Do not know | |
| 1. Can this facility be used to do ***non-academic projects***? | ❑ Yes ❑ No  Describe:  ❑ Do not know |

**c. Questions for the faculty on CREATING VALUE:**

|  |  |
| --- | --- |
| 1. Indicate your level of agreement with the sentence: ***Makers’ creations are developed with the objective of adding value to someone/something****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  Explain:  ❑ Do not know |
| 1. What ***communication products*** are encouraged to accompany the creations of the makers? | * + Written reports.   + Oral presentations.   + Videos.   + Websites.   + Instructions/Manuals.   + Talking points.   + Poster.   + Elevator pitch.   + Other. |
| 1. Does the facility ***promote the communication of the creations*** to third parties? | ❑ Yes ❑ No  Types of activities:  ❑ Do not know |
| 1. What are the types of ***third-parties invited to learn about the creations***? | * + College students.   + K12 students.   + Faculty.   + University President, provost, and/or deans.   + Staff.   + Industry representatives.   + Public officials.   + Residents of the area. (without specific affiliation).   + Non-residents of the area. (without specific affiliation).   + News stations.   + Social media users.   + Other. |
| 1. What is the ***level of value that this facility adds to the school and academics***? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |

**Appendix 8.D.3: Questions for the Students**

**School Name:**

**Maker Space Name:**

**Respondent Name:**

**Respondent email/phone:**

**Main Department/College:**

**Sociodemographic.**

**Gender: Age: Highest education level:**

**Major (latest degree): Race:**

**Nationality:**

1. What is your grade level: Fr / So / Ju / Se

1. How many times did you use this facility in the last school year?

1. How many times have you used this facility this year, thus far?

1. Hypothetical scenario: At the end of your senior design project, you have $100 left in the budget. You can do only two things with that money, or lose it: (1) you can have a party among team mates, or (2) you can donate some/all of it to the making facility so that it could continue to deliver its services to future students. How much of that money would you donate to the facility?

$ \_\_\_\_\_\_\_

1. What would be three-five questions, the answers to which you learned or discovered by using this making facility?

* 1. \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_
  2. \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_
  3. \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_
  4. \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_
  5. \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Approximately what percentage of your total operating budget comes from the following sources?

1. University budget \_\_\_\_\_\_\_\_\_
2. College budget \_\_\_\_\_\_\_\_\_
3. Faculty grants \_\_\_\_\_\_\_\_\_
4. In-campus donations \_\_\_\_\_\_\_\_\_
5. Fees paid by students \_\_\_\_\_\_\_\_\_
6. External donations / Fundraisers \_\_\_\_\_\_\_\_\_
7. External pay-per-use \_\_\_\_\_\_\_\_\_
8. Others (specify) \_\_\_\_\_\_\_\_\_

**a. Questions for the student on CURIOSITY**

|  |  |
| --- | --- |
| 1. When was the ***first time you visited*** the facility? | Term/Year |
| 1. When did you ***start using*** the facility? | Term/Year |
| 1. What are the ***machines that you mostly use***? (rank them) | |
| 1st: | |
| 2nd: | |
| 3rd: | |
| 4th: | |
| 5th: | |
| 6th: | |
| 7th: | |
| 8th: | |
| 9th: | |
| 10th: | |
| 1. What is the number of ***new technologies that you gained exposure* *in*** through the facility? | Number |
| 1. What is the number of ***new technologies you have used***? | Number |
| 1. What is the number of ***new technologies you foresee/plan/wish to use in the near future***? | Number |
| 1. What is your ***level of interest about this type of space***? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***My*** ***experience in this space will benefit my future career.*** | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers use the facility to develop new creations rather than replicating existing products****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***The*** ***facility facilitates the conceptualization of new ideas that can be materialized into creations****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers prefer to find solutions by themselves rather than following instructions****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers tend to develop the same type of creation in this facility****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers employ the most advanced/recent concepts in their creations****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***Makers avoid to try new concepts in their creations****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |

**b. Questions for the student on CONNECTIONS**

|  |  |
| --- | --- |
| 1. Have you ***spread the word*** about the facility? | ❑ Yes ❑ No |
| 1. How many ***people got interested in the facility*** because of you spreading the word? | Estimated number of people. |
| 1. Do you ***enjoy working in this facility with others***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. Indicate your level of agreement with the sentence: ***It is more effective for me to work in the facility with other rather than alone.****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  ❑ Do not know |
| 1. Do you think the facility***promotes team-based work***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of* *team-based work***observed in the facility? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |
| 1. What is the ***level of team******connection with each user type*** that I have experienced in the facility? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ College students.  ☆ ☆ ☆ ☆ ☆ K12 students.  ☆ ☆ ☆ ☆ ☆ Faculty.  ☆ ☆ ☆ ☆ ☆ Staff.  ☆ ☆ ☆ ☆ ☆ Industry representatives.  ☆ ☆ ☆ ☆ ☆ Public officials.  ☆ ☆ ☆ ☆ ☆ Residents of the area.  (without specific affiliation).  ☆ ☆ ☆ ☆ ☆ Non-residents of the area.  (without specific affiliation).  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. Does the facility***promote connection between makers and potential beneficiaries of their creations***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of connection between makers and types of potential beneficiaries of their creations***? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Engineering firms.  ☆ ☆ ☆ ☆ ☆ Consumers (regular people).  ☆ ☆ ☆ ☆ ☆ Education establishments.  ☆ ☆ ☆ ☆ ☆ Public sector / government.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. Does the facility***promote connection between makers and suppliers***? | ❑ Yes ❑ No  ❑ Do not know. |
| 1. What is the ***level of connection between makers and suppliers***? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Raw materials.  ☆ ☆ ☆ ☆ ☆ Machinery.  ☆ ☆ ☆ ☆ ☆ Electronic hardware.  ☆ ☆ ☆ ☆ ☆ Computers.  ☆ ☆ ☆ ☆ ☆ Software.  ☆ ☆ ☆ ☆ ☆ Consulting services.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. What is the ***level of connection between engineering disciplines and the creations*** made in the facility? | *Very low* ☆ ☆ ☆ ☆ ☆ *Very high*  *(Empty indicates none).*  ☆ ☆ ☆ ☆ ☆ Aerospace Engineering.  ☆ ☆ ☆ ☆ ☆ Aerospace Engineering.  ☆ ☆ ☆ ☆ ☆ Biomedical Engineering.  ☆ ☆ ☆ ☆ ☆ Chemical Engineering.  ☆ ☆ ☆ ☆ ☆ Civil Engineering.  ☆ ☆ ☆ ☆ ☆ Computer Engineering.  ☆ ☆ ☆ ☆ ☆ Electrical Engineering.  ☆ ☆ ☆ ☆ ☆ Mechanical Engineering.  ☆ ☆ ☆ ☆ ☆ Ocean Engineering.  ☆ ☆ ☆ ☆ ☆ Software Engineering.  ☆ ☆ ☆ ☆ ☆ Other  ❑ Do not know |
| 1. What ***courses*** use this facility? (describe ***how***)     ❑ Do not know | |
| 1. Can this facility be **used in other courses**? | ❑ Yes ❑ No  Describe:  ❑ Do not know |
| 1. Can this facility be used to do ***non-academic projects***? | ❑ Yes ❑ No  Describe:  ❑ Do not know |
| 1. Is ***training available*** in the facility? | ❑ Yes ❑ No  ❑ Do not know |
| 1. What ***type of training is available***?     ❑ Do not know | |

**c. Questions for the student on CREATING VALUE:**

|  |  |
| --- | --- |
| 1. Indicate your level of agreement with the sentence: ***Makers’ creations are developed with the objective of adding value to someone/something****.* | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  Explain:  ❑ Do not know |
| 1. What ***communication products*** are encouraged to accompany the creations of the makers? | * + Written reports.   + Oral presentations.   + Videos.   + Websites.   + Instructions/Manuals.   + Talking points.   + Poster.   + Elevator pitch.   + Other. |
| 1. Does the facility ***promote the communication of the creations*** to third parties? | ❑ Yes ❑ No  Types of activities:  ❑ Do not know |
| 1. What are the types of ***third-parties invited to learn about the creations***? | * + College students.   + K12 students.   + Faculty.   + University President, provost, and/or deans.   + Staff.   + Industry representatives.   + Public officials.   + Residents of the area. (without specific affiliation).   + Non-residents of the area. (without specific affiliation).   + News stations.   + Social media users.   + Other. |
| 1. What is the ***level of value that this facility adds to the school and academics***? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***My experience in this facility has helped me to become a better engineer.*** | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  Explain:  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***My experience in this facility has positively impacted my life, career, and/or resume.*** | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  Explain:  ❑ Do not know |
| 1. Indicate your level of agreement with the sentence: ***My experience in this facility has improved my grades in at least one course.*** | Strongly ☆ ☆ ☆ ☆ ☆ Strongly  Disagree Agree  Explain:  ❑ Do not know |
| 1. Which ***aspects of technology and business do you think you better understand because of the facility***?     ❑ Do not know | |
| 1. Do you think ***customers of technical products care to know about how the item was made***? | ❑ Yes ❑ No  Expand:  ❑ Do not know |
| 1. What is the ***level of difficulty to learn equipment***in the facility? | Very low ☆ ☆ ☆ ☆ ☆ Very high  (Empty indicates none).  ❑ Do not know |
| 1. What ***capabilities do you wish this facility had***?     ❑ Do not know | |

Appendix 8.D.4 - Observation Protocol for Visits

KEEN Site Visit

Observation Protocol

Draft #1

Kastro, Beshoy, Robert, Martin *et al*.

Campus being visited: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Florida Tech Visitors: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Date of Visit:\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Point of Contact on visited campus; \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

Colleagues we interacted with during visit: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

1. How many maker spaces do they have? \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_
2. What types of equipment do they have? 3-D printers? Augmented reality? Virtual Reality?
3. What relevant (Fabrication labs, etc.) do they have?\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_
4. Who uses the facilities (in Q2, 3) above?
5. What has been the average annual spending on new equipment over the past five years (or) since inception?
6. Are there formal training opportunities for potential facility users? If so who provides it? Is there a budget for that?
7. Are there plans to increase the number and or contents of maker spaces on your campus?
8. How are your maker spaces managed?
9. How is student usage tracked, measured, and reported and to whom?
10. What engineering majors make the most use of the facility?
11. Do any of your courses require students to use the maker spaces to complete assignments and projects? If so, which ones?
12. Can students use the making space for non-course related interests?
13. What is the maximum number of students that can use the facility at a time?
14. What are the 5 most used equipment in the facility? From most used to least used…
15. What kinds of student/student and student/mentor interactions do the Maker spaces on your campus support? –(The following 5 questions were taken from the KEEN proposal) elaborate on this one.)

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

1. What do students gain through making experiences?
2. What do students accomplish in making spaces that would not be feasible without maker spaces?
3. Are there specific themes/ use cases?
4. What direct vs. indirect learning occurs in making spaces?
5. What value added does utilizing maker spaces provide that may not be gained without maker spaces?
6. How does the utilization of your maker spaces enhance students’ 3Cs?
7. How is EML integrated in your maker spaces?
8. How is EML integrated in any of your courses?

Appendix 8.E.1 - Coding Tool for Converting Survey Data into EML Enhancements

|  |  |  |  |
| --- | --- | --- | --- |
| **Integration of Making Spaces** | | **Delta EML** | **3C** |
| **Investment, Assets, and Capability** | **Investment**   * In which term was the beginning of operations? * What was the initial implementation cost? * In which term did major renovations take place (if any)? * What was the cost for each major renovation? * What is the average annual budget? * Approximately what percentage of your total operating budget comes from which source   **Assets**   * What is the area of the Making Space? (square feet) * What is the capacity of the Making Space? (maximum number of students) * What type of equipment is available? (top 10 in terms of utilization) * What is the next item (equipment) in your wish list for the Making Space? * What are the functions served by the Making Space? * In your own words, how is the Making Space used? | **Curiosity**   * This Making Space encourages students to connect with those from other majors or disciplines. * Are students allowed to use the Making Space for their own projects/ideas? * Level of use by students who come on their own? * Level of use by students who come NOT as a part of a curriculum driven project? * Students working on a new project: Create a successful design the ﬁrst time; Go through at least one iteration of a design before success is achieved; Test multiple unique designs before selecting the best design to achieve success. * Level to which students come to watch other students creating? * Approximately how many unique creations are created in an average week? * What level of guidance is provided to the students to let them succeed in their project design? * What are 5 questions that students can address by working in the Making Space? * How many intellectual properties have been secured based on products designed in the Making Space? | **Curiosity** |
| **Accessibility and Availability** | * Policy * Freedome to Use   **Accessibility and Availability**   * How do you track access to the Making Space? * Who can access the Making Space? * Please specify what "other" students can access the Making Space. * Do students need permission/clearance to enter the Making Space? * Can students use the Making Space without supervision? * Can students use the Making Space outside regular hours? * Are students able to use the Making Space for non-curricular activities/projects (not course related)? | **Connection**   * This Making Space encourages students to connect with those from other majors or disciplines. * How do students learn about the Making Space? * What percentage of projects are: Individual eﬀorts, Team eﬀorts, Self-organized teams (not assigned by an instructor) * Of the teams that use the Making Space, to what extent members of the following populations are included? * Does the facility promote connection between makers and potential beneﬁciaries of their creations? * What is the level of connection between makers and types of potential beneﬁciaries of their creations? * What is the level of connection between makers and suppliers? | **Connections** |
| **Course Penetration** | **Penetration in formal courses**   * How likely is each engineering discipline to use the Making Space? * Of the teams that work in this Making Space, how many of them include individuals from diﬀerent majors and disciplines? * To what extent can the creations be adapted to diﬀerent disciplines? * Is the Making Space used more for academic or nonacademic projects? * What courses use this facility? | **Creative Value**   * What percentage of current users were also users last year? * Out of the current users what percent are ﬁrst time users? * How many senior students use the Making Space? * How many seniors using the Making Space are ﬁrst time users? * How many juniors use the Making Space? * How many juniors using the Making Space are ﬁrst time users? * What percentage of students use the Making Space 3 times or more? * Please specify. Indicate your level of agreement with this sentence Creations in this Making Space are developed with the objective of creating value for someone or something. * Are makers encouraged to develop communication products to advertise what they have created? * What communication products are encouraged to showcase creations of the makers? * If creations from this Making Space have been featured outside the university (like media reports, conferences, etc.), please provide examples: * What kind of third-parties are invited to learn about the creations * Please specify what "other" kind of third-parties are invited to learn about the creations of the Making Space? * What is the level of value that this facility adds to the school and academics? * How many faculty members used the Making Space in its ﬁrst year? * How many faculty members used the Making Space in the last year? | **Creating Value** |
| **Training & Development** |  |  |

Appendix 9.1 - Lessons Learned Regarding Survey Administration

AGENDA PLANNING

1. If it makes sense logistically, consider a split trip: fly in and do an initial meeting, then follow up the next day. The time to process things overnight may be more productive than one day-long marathon trip.

U. Denver visit: 5/29/2019 (on campus 4:00-6:00 PM) and 5/30/2019 (on campus 0830-3:30 pm)

2. Put the burden of planning your visit on them. Just let them know what you are interested in and your available time window.

3. We got a great deal of info from talking to one of the senior FWS employees who had been there from the beginning (Jacob Goldman); my advice is to ask to meet with one of those for an hour. It took that long to have a good conversation AND get through the student survey, but he was very talkative.

4. Build in a lunch or dinner where you pick up the tab as an informal opportunity to talk. One area of angst- who to invite. We invited our main makerspace point of contact and the main KEEN point of contact. Make sure student workers aren’t included in the meal. Realize people have lives and child care issues, and may not want to kill an evening eating dinner with you, so give them the chance to pick lunch.

TRIP PREP and EXECUTION

5. Prior to the visit, do a comparison between FIT and the visited school:

https://www.usnews.com/best-colleges/compare?xwalk\_id=133881&xwalk\_id=127060

Note this doesn’t tell you the size of the engineering school- U Denver is bigger than us as a school, but much smaller as an engineering school.

6. If there’s a name on the agenda, look to see if they are on KEEN and have a card.

7. Have in mind possible tools before you show up…. Then use your visit to identify what tools might be created, and if you think this might be a possible cohort, think about possible options with this school (either as creator or user)

8. Don’t forget your business cards.

9. Use the informal surveys designed for faculty and students as a crutch or reminder, but don’t try to force asking these questions. In the one-on one with the senior student we really tried to follow the informal survey and got data, but in meetings with the faculty, trying to follow it felt very awkward, so we abandoned the attempt to follow it very early… though we had it with us during the discussion.

10. If travelling with someone, do regular conversations, take notes, and at least start the draft trip report by the end of visit or on the airplane while it’s fresh.

11. Take photos.

Appendix 9.2 - University of Denver Visit Summary

1. University of Denver (UD) is a strong candidate for a heterogeneous cohort school for the following reasons:

- Size Diversity: Much smaller engineering school than FIT (300 engineering students total)

- Maturity Diversity: Most of the makerspace infrastructure is ~2.5 years old; they just completed a growth spurt, and they now need to figure out how to sustain what they have (a very common KEEN network problem)

- Diversity of Maker Penetration in Curriculum: Unusually heavy integration of maker elements and interdisciplinary collaboration in their curriculum (much greater than FIT)

- Complementary skill sets/attributes/technical capabilities: unusually strong entrepreneurial orientation; heavy business and law involvement; new to the KEEN network (only 2 years; no startup grant); strong co-curricular student activities.

2. Recommended Tool Development: If selected as a cohort school, UD could work with FIT to co-create a tool that focuses on applying entrepreneurial thinking to develop a sustainment strategy for KEEN makerspaces. This tool would be of great value to the network because the pains of scarce resources (money, space, staff, knowledge) are all universal problems that the network can relate to. UD would be an enthusiastic partner in this effort since sustainment is a major concern based on their newness, and their strong entrepreneurial ties and business-law partnerships would mean they have enormous talent to apply to the development of the tool.

Formal visits/interviews:

- JB Holston, Dean of Engineering and Computer Science

- Haluk Ogmen, Senior Associate Dean of Engineering and Computer Science

- Breigh Roszelle, Teaching Associate Professor, Dept. of Mechanical and Materials (also Associate Dean and KEEN POC)

- Jason Roney, Teaching Associate Professor, Dept. of Mechanical and Materials Engineering

- Goncalo Martins, Teaching Assistant Professor, Dept. of Electrical and Computer Engineering

- Ann Deml, Visiting Teaching Assistant Professor, Dept. of Mechanical and Materials Engineering

- Laura Dean, Executive Director of Alumni Engagement

Other extended interactions: Isaiah Silva (Innovation labs ops manager (part time); Jacob Goldman, Tom (senior work study students), startup staff, other students

Appendix 11.A.1 - Nanotechnology KEEN Card

32. James Brenner, Florida Tech, "Nanotechnology",

<https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=2659c514-e143-417a-a280-0f9721c3707b>

**Mindset**

Curiosity

* Demonstrate constant curiosity about our changing world

Connections

* Integrate information from many sources to gain insight

Creating Value

* Identify unexpected opportunities to create extraordinary value
* Persist through and learn from failure

**Skillsets**

Design

* Determine Design Requirements
* Develop New Technologies

Opportunity

* Identify Opportunity
* Evaluate Tech Feasibility, Customer Value, Societal Benefits & Economic Viability
* Assess Policy & Regulatory Issues

Impact

* Communicate Solution in Economic Terms
* Communicate Societal Benefits
* Develop Partnerships & Build Team
* Protect Intellectual Property

**Description**

People use their **curiosity** in nanotechnology to discover scientific principles (via **connections**) that form the basis for engineers to maximize surface area to volume ratio to **create value** for customers.    
  
If content below appears as a hyperlink, then your browser will go to hyperlinked content not hosted at engineeringunleashed.org.  If there is no hyperlink, then that content on the nanotechnology subnet may be ready for Prof. Jim Brenner's students, but not yet ready for KEEN faculty distribution.  For each of the hyperlinks below, use name = fltech and password = brenner  
  
------------------------------------------------------------------  
  
[Entire Minor Overview](http://my.fit.edu/~jbrenner/fundraising/FITNanotechMinorPart1.pptx)  
[Nanotechnology Education & Research at Florida Tech](http://my.fit.edu/~jbrenner/fundraising/nanotechminorprogramhistorywithaudio4.pptx)  
See slides 37-148  
  
Where KEEN's Entrepreneurial Mindset Gets Incorporated - Look under Required Courses below.  When you click on the links, KEEN EML content is given in burgundy within the links.  
  
KEEN Student Outcomes & ABET Course Program Outcomes - to be added later, but a start is in the Learning Objectives section much further below.  
  
Questions and comments on the following should be directed to Jim Brenner atjbrenner@fit.edu.  If a course appears as a hyperlink, then your browser will go to a syllabus that has its content hyperlinked.  
  
Required Courses  
Freshman/Sophomore Spring - [Nanotech Lab 1](http://my.fit.edu/~jbrenner/nanotechmanual)  
Sophomore - [Intro to Materials Science & Engineering](http://my.fit.edu/~jbrenner/www3260/che326042.doc) class taken everywhere  
Junior/Senior/Grad Student Fall - Materials Characterization Lab (3-credit) - in prep  
Junior/Senior/Grad Student Spring - [Nanotechnology](http://my.fit.edu/~jbrenner/nanotechnology/NanotechSyllabus/CHE55672019.doc) lecture   
Physics 2 Lab, Materials Lab, &/or Biomedical Instrumentation Lab   
Two [Elective Courses](http://my.fit.edu/~jbrenner/nanotechminor/NanotechMinorGroup3Electives.doc)  
  
----------------------------------------------------  
  
[NanoFlorida](http://my.fit.edu/~jbrenner/nanoflorida2018/NFfinalprogram100218.pdf)  
NanoFlorida 2019 is October 5-6, 2019 at The University of South Florida. [NanoFlorida 2018](http://411.fit.edu/nanoflorida) was at Florida Tech.  The conference has rotated between universities since 2008.  
  
[Relating Nanotech to Prospective Students (3rd - 12th grades)](http://my.fit.edu/~nanotechmanual/Ferrofluids/brennerferrofluidshowto.ppt)  
  
Items to Be Built Upon For the Nanotech Subnet in the Future  
What Are We Curious About?  
How Do We Make the Discoveries About What We Are Curious About?  
Benefits of Being Connected  
KEEN Members in the Subnet  
Useful Non-FIT Resources  
Funding Sources  
  
Conferences  
[NanoFlorida](http://411.fit.edu/nanoflorida) - see above  
  
How Do We Create Value?  
People use their **curiosity** in nanotechnology to discover scientific principles (via **connections**) that form the basis for engineers to maximize surface area to volume ratio to **create value** for customers.    
  
Sharing of Resources with Other KEEN Universities - this page  
[Purchasing & Refurbishing Ancient Equipment to Fill Holes in Capabilities Matrix](http://my.fit.edu/~jbrenner/fundraising/nanotechminorprogramhistorywithaudio4.pptx)  
(see slides 45 & 81-83)  
[Nanotech-Specific Career Fair at NanoFlorida](http://411.fit.edu/nanoflorida/expo.php)  
[Nanotech Companies That Sponsored NanoFlorida](http://411.fit.edu/nanoflorida/sponsors.php)

**Learning Objectives**

Nanotechnology Minor Outcomes (KEEN content in bold)     
  
1.         100% of students will be able to be able to conduct basic and intermediate microscopic (TEM, SEM, AFM, and STM) skills after having to pass written exams on both the theory and practice of such instruments.     
  
2.         80% of students will successfully conduct a range of syntheses including a) pore volume filling via incipient wetness impregnation, b) catalyst preparation, c) ferrofluids synthesis, c) hydrophobic coatings on Ag, d) a polymer/ceramic nanocomposite, e) sputter coating of Au, and f) nanoparticle syntheses of Au and Ag.     
  
3.         All students will be able to conduct a literature search of several articles from a shared RefWorks database of articles collected via the professor's searches of a wide range of nanotechnology topics using Web of Science.    
  
4.         All students will work in groups of two or three to develop a three slide 2-3 minute **PowerPoint elevator pitch of a nanotechnology-based product or service**. The first slide will briefly describe the product or service, as well as a business case. The second slide will illustrate how nanotechnology creates or adds value to the product or service. The final slide will list companies or research groups that might purchase or compete with that product or service. If a research group, then the student entrepreneurs will explain why working for that group as undergrads, or more likely, graduate students will help the student entrepreneurs achieve the goal of producing that product or service.       
  
5.         100% of student groups will be able to define a problem using a **"questions and issues sheet" listing a miminum of 25 technical/engineering, health, safety, environmental, legal, regulatory, social impact, quality, and economic issues.**    
  
6.         90% of students will be able to function properly in multidisciplinary teams as assessed by self, team, and faculty evaluations of their performance as being "acceptable".     
  
7.         80% of students will either successfully conduct a synthesis and characterization of a family of materials either for research or teaching lab purposes OR resurrect a piece of equipment to be used for research or teaching lab purposes OR develop a teaching lab experiment on a recently purchased or resurrected piece of equipment.  Each of these exercises **creates value** by making the next year's version of the course better than it was.     
  
8.         80% of students will be able to effectively write both a task plan within the first week of each semester of an independent study course and a final or intermediate project report at the end of an independent study research course.      
  
9.         All students will show appropriate respect for the equipment and for each other's ability to conduct experiments on the same equipment on a long term basis.  This will be exemplified by less than 20% of the students making dumb mistakes that result in equipment malfunction even once and none of them making such dumb mistakes twice.  80% of students will have no more than one safety incident.      
  
10.       Eighty percent of the students will be expected to get a score of at least an 80 with regard to a) materials analytical tool selection, b) justification regarding why the particular tool was selected, and c) a description of the advantages and limitations of the tool selection.     
  
11.       90% of students will demonstrate an understanding of the relationship between the size of particles and rods in which electrons can be confined with the resulting material's electronic and optical properties as assessed by a grade of 80% on relevant sections of the 1st hourly exam, including interpretation of literature data and calculation of band gap energies or particle dimensions from spectral data.     
  
12.       90% of students will be able to graphically demonstrate the relationships between pH, particle size, and zeta potential (surface charge) and be able to compare and contrast the advantages and limitations of different types of microscopy (TEM, SEM, AFM, STM, confocal laser scanning microscopy), particle size analysis, and spectroscopic equipment as assessed by a grade of 80% on relevant sections of the 1st hourly exam to demonstrate how their materials have superior technical characteristics.      
  
13.       90% of students will be able to make a list of nanoparticle capping agents, be able to list the steps in a nanoparticle or porous material or coating preparation, including selection of templating agents, and be able to explain the reasons why certain reagents are chosen (biocompatibility, corrosion resistance, hydrophobicity, hydrophilicity, receptors for chemical and biological sensors as well as cell targeting, penetration of the blood-brain barrier, catalysis, etc.).  This provides an explanation for the **value that they are creating**.      
  
14.       90% of students will be able to list the steps necessary in making customized sensors such as lab-on-a-chip devices, and be able to compare/contrast the advantages and limitations of various sensing modalities to further explain the value they are creating.     
  
15.       90% of students will be able to demonstrate an understanding of the materials science, chemistry, biology, and physics of the nanotechnology literature.  This will be assessed by a grade of 90% on each of the completed homeworks, 80% on relevant sections of the 1st hourly exam, and 80% on the final presentation.      
  
16.       All students will be able to conduct a thorough literature search using Web of Knowledge and RefWorks.     
  
17.       All students will be able to conduct a thorough examination and summary of the literature as assessed in an end-of-semester multidisciplinary group project.  All students will prepare PowerPoint slides of that literature for their end-of-semester presentation and then make the presentation in a logical order and free of technical errors, as assessed by an 80 on the students' presentations.      
  
18.       Students will convert the oral literature review described in the prior two outcomes into a written literature review that can be revised, time permitting, until the students in the group and professor are satisfied with a publishable article.

**Instructor Tips**

1.  Start with the nanotech lecture first.  
2.  Then add the synthesis component of the nanotech lab.  
3.  Negotiate with your administration to explain how training students on the materials characterization equipment will actually lower maintenance cost because you know the students will have been properly trained.  
4.  The questions and issues sheet is something that can be adapted to any course.

**Engineering Disciplines**

* Aerospace Engineering
* Biomedical Engineering
* Chemical Engineering
* Chemistry
* Electrical & Computer Engineering
* Engineering Education
* Environmental Engineering
* General Engineering
* Health Sciences & Medical
* Mechanical Engineering
* Metallurgical & Materials Engineering

**Author:** [**Jim Brenner**](https://engineeringunleashed.com/user-profile.aspx?userguid=4ebe75c9-0c81-434e-ba10-15e0ed149134), [Florida Institute of Technology](https://engineeringunleashed.com/partners/partner.aspx?institutionguid=083bf5f1-abea-418d-84aa-17c47d5e9069)

**References & Acknowledgements**

|  |
| --- |
| Kern Family Foundation |

National Science Foundation Nanotechnology Undergraduate Education (NUE) grant #’s

0939355 & 0303986

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Appendix 11.B.1 - Beshoy Morkos  301. Beshoy Morkos, Florida Tech, "Beshoy Morkos",  <https://engineeringunleashed.com/user-profile.aspx?userguid=0a66fde5-e564-484f-8082-e5ed6f6db142>  Appendix 11.C.1 - Incorporating EM in a Freshman Engineering Course  **Incorporating EM in a Freshman Engineering Course**    Created: 5/23/2019 9:08PM ET by [Chiradeep Sen](https://engineeringunleashed.com/user-profile.aspx?userguid=6c2cfd95-89cf-46ed-a87c-4dfbb534e081) Updated: 5/23/2019 10:13PM ET by[Chiradeep Sen](https://engineeringunleashed.com/user-profile.aspx?userguid=6c2cfd95-89cf-46ed-a87c-4dfbb534e081)  302. Chiradeep Sen, Florida Tech, "Incorporating EM in a Freshman Engineering Course",  <https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=04cac34f-4429-42ca-a403-1e19ff44e0f2>  **Mindset**  Curiosity   * Demonstrate constant curiosity about our changing world * Explore a contrarian view of accepted solution     Connections   * Integrate information from many sources to gain insight * Assess and manage risk     Creating Value   * Identify unexpected opportunities to create extraordinary value * Persist through and learn from failure   **Skillsets**  Design   * Determine Design Requirements * Perform Technical Design * Analyze Solutions * Develop New Technologies * Create Model or Prototype * Validate Functions     Opportunity   * Identify Opportunity * Investigate Market * Create Preliminary Business Model * Evaluate Tech Feasibility, Customer Value, Societal Benefits & Economic Viability * Test Concepts via Customer Engagement * Assess Policy & Regulatory Issues     Impact   * Communicate Solution in Economic Terms * Communicate Societal Benefits * Validate Market Interest * Identify Supply Chains & Distribution Methods   **Description**  **Background** MEE 1024 Introduction to Mechanical Engineering is a freshman-level course that provides an overall exposure to the ME profession and curriculum.  In addition to teaching basic technical and communication skills such as engineering drawing, freehand sketching, CAD/CAM, technical computing, presenting, and report writing, a majority of the course load comes from a term-long engineering project.  **Setting** The course is taught to incoming freshmen in Mechanical Engineering in the fall semesters.  The class size varies between 120 and 140.  Students are divided into 6-8 sections.  All sections attend lectures together, twice a week for 50 minutes each.  The lectures are taught by the faculty instructor.  The sections attend lab meetings twice for 75 minutes each, at different times.  The lab meetings are supervised by the faculty instructor but mainly executed by graduate students assistants (GSAs).  The class is the largest class in the College of Engineering and Science by student count.    **The BEFORE Picture** Traditionally, the term project asked the students to design and build a technical product that included some elements of entertainment, which was believed to be necessary in order to hold students’ interest and attention.   **1.**The challenge was assigned by the instructor in form of a problem statement. **2.**The task was the same for all student teams in the class.   **3.**The product to be designed and built was picked by the instructor.   **4.**Since the assignment was not presented as a problem faced by stakeholders, it did not force the student to understand the stakeholders' viewpoints or to see engineering as a means to serve humanity by creating value for them.   Example projects are pinball machines and a robot-played soccer game.  **Introduction to KEEN and EML** The faculty instructor was introduced to KEEN and Entrepreneurially Minded Learning (EML) and later served as the Co-PI to a grant from KEEN to the institute.    **The AFTER Picture** In the light of EML, the project was modified in the following ways. **1.**Instead of a "product to be designed", students were given a socio-technical scenario of common interest and global importance, to which everyone could connect easily.  In Fall 2015, the topic was energy – an issue of great importance to engineering that also has social, economic, and political significance.  The scenario was explained in the context of the increased global energy demand, depleting fossil fuel reserves, increased emphasis on low-emission and alternate sources, and the increased public awareness of global climate change.    **2.**Student teams were not given a specific design problem to solve.  Rather, they were asked to choose the area of energy-related issues that they wanted to address and define their own design problem area and problem statement.  **3.**Student teams were asked to do their own self-guided research to study the technical and social challenges involved in the area, and compare the various areas and project ideas before choosing one.  Their challenge must be solvable in a term’s timeline!  **4.** The first deliverable was not a traditional design concept, but a proposal to be submitted to a hypothetical funding agency, where students had to demonstrate their understanding of the social and technical issues of the technology area, along with their approach toward addressing it.  The teams must demonstrate that they visited multiple ideas before choosing one, even at the proposal level, and they must build a case for how their work would create value for the customer. **5.** The student teams were required to present the progress on their work each week to the GSAs during the respective lab meetings.   **6.** The remaining deliverables of the project were left largely unaltered.  They included a concept presentation, a midterm report, a final report, and a showcase where the physical prototypes were to be demonstrated.  **What Changed?** With these changes implemented, each student team picked a different problem.  Each team had different questions and different hurdles, although they were ultimately connected to the same theme of energy and solving an energy-related problem that creates value for stakeholders.  The usual variation between the quality of student work still existed across and within the teams, but the students’ experience through this project assignment was completely changed.  They were forced to think about and ask question about issues that reach beyond technical knowledge into the realm of utility and value of their work, human conditions around different parts of the world, identifying opportunities and risks related to pursuing new technical ideas, the state of the art of technologies and their limitations from social, environmental, economic, and political points of view, and the role of engineers as a social problem-solver and value-creator.  They experienced the difference between force-fittings a technical novelty into an artificially defined market and choosing the right technology for developing a solution for a true need felt in a market.  They had to find ways to answer these questions independently, relying on the team, rather than on the professor.  The resulting projects ranged from wave energy generators to regenerative braking of skateboards, to road surfaces that produce electricity, to children’s shoes that power a light bulb at night in developing economies, to cell phones that recover its heat to extend its own battery life.   Some examples of projects are included in the folders and links.  **Learning Objectives**  **Students**: Upon completing this card content, the students will be able to:   1. Appreciate the engineering profession as an enterprise for creating value for humanity. 2. Explore and discover customers, stakeholders, their needs, and opportunities. 3. Work in a team and consider multiple product ideas and systematically select the ones to pursue in order to maximize the value created for the stakeholders. 4. Create (conceptualize, design, build, and evaluate) novel technical solutions to novel problems using a systematic process that is repeatable and tractable. 5. Communicate their ideas to technical and non-technical audiences. 6. Write professional reports to register their design work.   **Teachers**: Upon assigning this card content, the instructors will be able to:   1. Teach the value-creation aspect of engineering to incoming freshmen. 2. Teach the importance of working and communicating in teams. 3. Teach the importance of connecting to stakeholders.   **Instructor Tips**   1. Give an overview of the systematic product development process. 2. Provide individual guidance to the teams at dedicated weekly office hours. 3. Try not to solve the design problems unless the teams are unable to progress. 4. Allow sufficient time for the discovery phase, where the teams are understanding the market and exploring product ideas.  Allow time for failures at late stages of the projects. 5. Reserve a portion of the grade for each element that you want the students to spend effort on.  For example, there should be grades assigned to the market research and product exploration activities.     **Engineering Disciplines**   * General Engineering      * Mechanical Engineering     **Authors**  [**Chiradeep Sen**](https://engineeringunleashed.com/user-profile.aspx?userguid=6c2cfd95-89cf-46ed-a87c-4dfbb534e081)  [Florida Institute of Technology](https://engineeringunleashed.com/partners/partner.aspx?institutionguid=083bf5f1-abea-418d-84aa-17c47d5e9069)    **References & Acknowledgements**   |  | | --- | | Sen, C., and Larochelle, P., (2016), “Incorporating an Entrepreneurial Mindset in a Freshman  Mechanical Engineering Course”, First Year Engineering Experience Conference, FYEE,  Jul. 31 – Aug. 2, 2016, Columbus, OH. | | **Course Material**  **Description**   |  | | --- | |  | | Assessment / Rubric, .docx, 05/23/2019, 13.90 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/6a25d91a-5238-44eb-b600-a95749356120?sv=2015-12-11&sr=b&sig=asq4wYYFBgki8QTa8eyC07o8Kxp9J3nZCSLG5o%2FpBHU%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%22MEE%201024%20Innovative%20Design%20Project%20Assignment.docx%22) | |  | | Assessment / Rubric, .docx, 05/23/2019, 16.37 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/6586b3b5-1331-4a87-a0d8-c8af75591ba3?sv=2015-12-11&sr=b&sig=A654AS%2BOsLd6zDhmkFXHByhtEdDoSwDcUwPTTxiE0Yc%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%22CDROutline.docx%22) | |  | | Assessment / Rubric, .docx, 05/23/2019, 13.94 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/aafb5e3e-2d2b-43cc-a55e-2470b62f29d2?sv=2015-12-11&sr=b&sig=wHJFOQLey1xWW36Ox4AMa2autiqsIvrrmwZcD7BSyik%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%22FinalPresentationOutline.docx%22) | | |  | | **Publications**  **Description**   |  | | --- | |  | | Journal / Article, .pdf, 05/23/2019, 560.88 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/f53b13b8-2730-4e44-a82b-93fa2d39720a?sv=2015-12-11&sr=b&sig=LPiA8jGOj1hECyEyPy4ketsacEk5YI832iIh4YoWUNc%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%22128.pdf%22) | | |  | | **Sample Outcome**  **Description**  Click the link to see examples of projects with images and Youtube videos.   |  | | --- | |  | | Photo / Graphic, Link, 05/23/2019, --, [View](https://research.fit.edu/rise-lab/teaching/a-case-study-in--entrepreneurially-minded-learning/) | |  | | Photo / Graphic, .jpg, 05/23/2019, 21.35 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/78a10d90-1a98-41f1-b6c5-41e313755493?sv=2015-12-11&sr=b&sig=XBybxchiR%2FhK%2BrvUbrEbz3OjGwOVGHvrgHydGSGg0kU%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%221.jpg%22) | |  | | Photo / Graphic, .jpg, 05/23/2019, 22.40 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/3a81ae7e-253b-40d0-8489-b5ce3f5fa090?sv=2015-12-11&sr=b&sig=l5BmIvdeOCGXMk1vHr2ehDJq0mMeY%2FUzgIGtFRksQjI%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%224.jpg%22) | |  | | Photo / Graphic, .jpg, 05/23/2019, 18.08 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/d6b54e10-7568-4c94-a29e-c90deb43d1bd?sv=2015-12-11&sr=b&sig=WyKIzY%2F7H7UG9wqIZemYhGMgytV%2Btdyx1FLoknJJjE8%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%225.jpg%22) | |  | | Photo / Graphic, .jpg, 05/23/2019, 25.04 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/75783aeb-0873-4e94-94e1-3949377e0c35?sv=2015-12-11&sr=b&sig=AcicFCXjnBFKuRSJZKw1lw2EmXEvJlmpBw%2FnMkuLjOw%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%222.jpg%22) | |  | | Photo / Graphic, .jpg, 05/23/2019, 24.67 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/17408a79-0c9e-4a82-bb35-9604c6be21ad?sv=2015-12-11&sr=b&sig=lwpX1GsdSkXBu9DHyklGwlvTaliDzpKgtrp3GXRo8Q0%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%226.jpg%22) | |  | | Photo / Graphic, .jpg, 05/23/2019, 22.82 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/28d4ffc7-fbb4-4047-a674-be3d8fd2a246?sv=2015-12-11&sr=b&sig=eYNmVafK8OWJ9kH2TmaTRqBunDPXPeO%2B4ZvXPtPWwAE%3D&st=2019-05-31T01%3A49%3A19Z&se=2019-05-31T03%3A54%3A19Z&sp=r&rscd=attachment%3B%20filename%3D%223.jpg%22) | |   Appendix 11.D.1 - Teams Teaching Statics; Statics Photo Safari: Small Steps Toward EML  **Teams Teaching Statics; Statics Photo Safari: Small Steps Towards EML**    Created: 2/19/2019 4:14PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568) Updated: 5/14/2019 4:37PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)  303. Kimberly Demoret, Florida Tech, "Teams Teaching Statics; Statics Photo Safari: Small Steps Toward EML", <https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=31ae7ce0-62d7-43d3-a83b-b97d4f3670fe>  **Mindset**  Curiosity   * Demonstrate constant curiosity about our changing world     Creating Value   * Identify unexpected opportunities to create extraordinary value   **Skillsets**  Design   * Create Model or Prototype     Opportunity   * Identify Opportunity * Test Concepts via Customer Engagement   **Description**  This card contains a simple, low threat project that is ideal for new faculty interested in small steps towards EML. The main assignment requires students to form teams and create and use a product to teach a class concept to someone not on the team.  Some versions of the assignment include a "Statics Photo Safari" where students photograph objects on campus and draw free body diagrams.  The graded deliverable is a short report with photos. This is treated like a big homework project- no class time is required, and students do not need to turn in their product.  This basic idea is applicable to many different types of classes- not just statics.  A variation of the "Teams Teaching Statics" part has also recently been used in a one-credit aerospace freshman lecture class of ~140 students. (Renamed as "Teams Teaching Aerospace")  **Learning Objectives**  In "Teams Teaching Statics" students practice solving an open-ended problem as part of a group and develop a physical product to teach others a topic that they themselves are learning. They develop an appreciation of the difficulty of teaching, and the value of tangible objects ("visual aids") that can help the process.  In the "Statics Photo Safari" students develop experience in applying a critical engineering skill- developing a free body diagram for a physically present object and identifying what support reactions are present.   **Instructor Tips**  Teams can be self-selected, or randomly assigned by CANVAS or other system.  In the statics classes of 50-70, students were allowed to self-organize in groups of 2-4, and the instructor only got involved if a student couldn't find a team. In the freshman aerospace class students were randomly assigned in groups of four using CANVAS. If you choose to assign teams of four, consider making four paragraphs mandatory in the assignment, then require each member to write one of the paragraphs. Instructors are encouraged to adapt the photo safari to stress whatever points they think are most pressing- this version has many parts which may be too much for a "low threat" assignment.    **Engineering Disciplines**   * Aerospace Engineering      * Civil Engineering      * General Engineering      * Mechanical Engineering      * Technical Communications     **Authors**  [**Kimberly Demoret**](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)  [Florida Institute of Technology](https://engineeringunleashed.com/partners/partner.aspx?institutionguid=083bf5f1-abea-418d-84aa-17c47d5e9069)    **References & Acknowledgements**   |  | | --- | | This was created through work with the Kern Entrepreneurial Engineering Network.  More content can be found at EngineeringUnleashed.com. |   Appendix 11.E.1 - Design Thinking in Team Projects  **Design Thinking in Team Projects**    Created: 1/2/2019 4:32PM ET by[Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568) Updated: 5/22/2019 6:04PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)  Share [**Favorite**](javascript:__doPostBack('p$lt$ctl03$pageplaceholder$p$lt$ctl00$CardView$btnFavorite',''))  **Mindset**  Curiosity   * Demonstrate constant curiosity about our changing world     Connections   * Integrate information from many sources to gain insight   **Skillsets**  Design   * Determine Design Requirements * Create Model or Prototype     Opportunity   * Investigate Market * Test Concepts via Customer Engagement   **Description**  This easy-to-use assignment introduces the idea of design thinking to students working on team projects. Design Thinking is a methodology for creative problem solving that emphasizes early contact with people in order to understand and define the real problem.  This project was used in capstone design, but can be adapted for other large team projects.  As described here, immediately after teams and topics were defined, students worked together to make a cardboard prop to represent their project, and plan interviews to gather data. Once the prop and their plan was completed, they split into groups to interview others about their problem and possible design solutions.  The graded assignment was a PowerPoint presentation with lessons learned that included photos of the interview teams and interviewees along with the prop.  This assignment was described as part of a  PechaKucha presentation at the 2019 KEEN national conference.  **Learning Objectives**  This project introduces the concept of design thinking and allows students work through the initial stages of the process. It also serves as a team icebreaker- allowing students on the team to become more comfortable with each other, and with the various faculty members, customers, or subject matter experts that they interview.  **Instructor Tips**  In this version of the project one class session was used to make the prop used in the interviews, and another class session was used for the PowerPoint outbriefs.  By requiring the use of photos and student names in the powerpoint presentation, the instructor can visually verify all students participated in the interviews.    **Engineering Disciplines**   * Aerospace Engineering      * General Engineering      * Mechanical Engineering      * Technical Communications     **Authors**  [**Kimberly Demoret**](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)  [Florida Institute of Technology](https://engineeringunleashed.com/partners/partner.aspx?institutionguid=083bf5f1-abea-418d-84aa-17c47d5e9069)    **References & Acknowledgements**   |  | | --- | | This was created through work with the Kern Entrepreneurial Engineering Network. | | **Design Thinking in Capstone Design**  **Description**  The word document contains the assignment as presented to the students. The pdf contains slides that describe the implementation of the activity and include instructor notes   |  | | --- | |  | | Presentation, .pptx, 05/22/2019, 6.09 MB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/2e9c8bbd-2414-4f34-9311-c964917a57c8?sv=2015-12-11&sr=b&sig=5rvFkmC5fgwzGwJPpn%2FCSce03Stf9bJgdHnnbAg4p2Y%3D&st=2019-05-31T01%3A37%3A12Z&se=2019-05-31T03%3A42%3A12Z&sp=r&rscd=attachment%3B%20filename%3D%22Selected%20class%20slides-CapstoneTeams%20and%20DesignThinking%282019%29.pptx%22) | |  | | Activity / Handout, .docx, 05/22/2019, 318.20 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/f8be696c-09b1-4fe4-b500-236f43a8e01d?sv=2015-12-11&sr=b&sig=pR1YoD0uWA32Rs1PuCXx7gBGLWPX9y5DGcjid1ydya8%3D&st=2019-05-31T01%3A37%3A12Z&se=2019-05-31T03%3A42%3A12Z&sp=r&rscd=attachment%3B%20filename%3D%223.%20Design%20Thinking%20Exercise%282019%29.docx%22) | |  | | Other, Link, 05/22/2019, --, [View](https://dschool.stanford.edu/resources/getting-started-with-design-thinking) | |  | | Student Artifact / Example, .pptx, 05/22/2019, 2.38 MB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/f38f2a10-0a0e-4b53-a40e-e8a5cf59bed3?sv=2015-12-11&sr=b&sig=FTShSisCsCxapNBk%2FHZXXDg9GQYJRuhHC%2FErqxpjaNQ%3D&st=2019-05-31T01%3A37%3A12Z&se=2019-05-31T03%3A42%3A12Z&sp=r&rscd=attachment%3B%20filename%3D%22Student%20example_Mars%20Aerial%20Survey%20System.pptx%22) | |  | | Student Artifact / Example, .pptx, 05/22/2019, 973.21 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/90a260e0-48c3-4bde-b18e-6d8c71ae62b9?sv=2015-12-11&sr=b&sig=Mcrt%2BFY132vmTbM4dIkzkZAZmhsZzuaKRHcnI2f4z1I%3D&st=2019-05-31T01%3A37%3A12Z&se=2019-05-31T03%3A42%3A12Z&sp=r&rscd=attachment%3B%20filename%3D%22Formula%20example.pptx%22) | |   Appendix 11.F.1 - Capstone Topics: Defining the Need and Creating Value  **Capstone Topics: Defining the Need and Creating Value**    Created: 5/24/2019 4:39PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568) Updated: 5/24/2019 4:41PM ET by [Kimberly Demoret](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)  305. Kimberly Demoret, Florida Tech, "Capstone Topics: Defining the Need and Creating Value",  <https://engineeringunleashed.com/cards/cardview.aspx?CardGuid=d48a1471-7b05-4a89-b22f-ed3805eeb45b>  **Mindset**  Curiosity   * Explore a contrarian view of accepted solution     Connections   * Integrate information from many sources to gain insight     Creating Value   * Identify unexpected opportunities to create extraordinary value   **Skillsets**  Opportunity   * Identify Opportunity * Investigate Market   **Description**  A lecture and assignment describes the entrepreneurial mindset and other issues to consider when defining capstone topics. "Connections" are discussed in the context of Steven Johnson's book, "Where Good Ideas Come From: The Natural History of Innovation".  Students must write an assignment that references the Strategyzer value proposition canvas.  Several relevant videos are in the slides and folder below. These materials were used in the Aerospace Capstone Design program, where some projects are defined by students.  **Learning Objectives**  **Instructor Tips**    **Engineering Disciplines**   * Aerospace Engineering      * General Engineering      * Mechanical Engineering     **Authors**  [**Kimberly Demoret**](https://engineeringunleashed.com/user-profile.aspx?userguid=aa84ad7f-8821-44f7-86cf-41fc93e47568)  [Florida Institute of Technology](https://engineeringunleashed.com/partners/partner.aspx?institutionguid=083bf5f1-abea-418d-84aa-17c47d5e9069)     |  |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | --- | | **Lecture Slides and Student Assignment**  **Description**  Lecture slides, the related student assignment, and two student examples are included below.   |  | | --- | |  | | Presentation pptx. 05/24/2019, 4.66 MB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/7bd866fd-c002-4d42-a87b-1874d4c8207a?sv=2015-12-11&sr=b&sig=cjAm6ENOBvZcic02ZZhof9OwewACUp3afnMr3GU9EAE%3D&st=2019-05-31T01%3A08%3A08Z&se=2019-05-31T03%3A13%3A08Z&sp=r&rscd=attachment%3B%20filename%3D%22Slides-%20Defining%20the%20Need%20and%20Creating%20Value.pptx%22) | |  | | Assessment / Rubric .docx, 05/24/2019, 80.94 KB [Download](https://keenwarehouseprod.blob.core.windows.net/cards/c1894511-38b4-4944-994f-90984cb36d8a?sv=2015-12-11&sr=b&sig=%2FYfAdgNVEJnZoMKCGQmwnvmJvea%2BHRi5gAQa7Hnyl6w%3D&st=2019-05-31T01%3A08%3A08Z&se=2019-05-31T03%3A13%3A08Z&sp=r&rscd=attachment%3B%20filename%3D%22Assignment-Capstone%20Project%20Ideas.docx%22) | |  | | Student Artifact / Example .docx, 05/24/2019, 60.34 KB [Download](https://keenwarehouseprod.blob.core.windows.net/cards/cfe09ab5-9f58-4443-a30f-1539f592f3ac?sv=2015-12-11&sr=b&sig=9hHOYTcOGw7mIAxbmDzt0BBFoFDQrTA8C9e1B9glKGw%3D&st=2019-05-31T01%3A08%3A08Z&se=2019-05-31T03%3A13%3A08Z&sp=r&rscd=attachment%3B%20filename%3D%22Student%20Example-%20Capstone%20ideas.docx%22) | |  | | Student Artifact / Example .docx, 05/24/2019, 41.89 KB, [Download](https://keenwarehouseprod.blob.core.windows.net/cards/821511a4-8845-429e-9040-fb9f5c8f3c65?sv=2015-12-11&sr=b&sig=xr1swkUVap8WoCSm8gE1%2FD171mfJfra2vNV3XyEFp78%3D&st=2019-05-31T01%3A08%3A08Z&se=2019-05-31T03%3A13%3A08Z&sp=r&rscd=attachment%3B%20filename%3D%22Student%20Example2-%20Capstone%20ideas%28MASS%29.docx%22) | | |  | | **Reference Links**  **Description**  Video Links below in order: KEEN: Entrepreneurial vs. Traditional Engineering (KEEN) WHERE GOOD IDEAS COME FROM by Steven Johnson Painstorming for Opportunity Recognition & Ideation Stimulus by Dr. Ken Bloemer (KEEN)  Biomimicry Database: AskNature   |  | | --- | |  | | Video, Link, 05/24/2019, [View](https://www.youtube.com/watch?v=ufdgKZ_3Zco&list=PLvITFYQeu1sFKecbGpVFBH44TCFnbanly) | |  | | Video, Link, 05/24/2019, [View](https://www.youtube.com/watch?v=NugRZGDbPFU) | |  | | Video, Link, 05/24/2019, [View](https://www.youtube.com/watch?v=SCgoI2cPK-E) | |  | | Video, Link, 05/24/2019, [View](https://asknature.org/) | | |