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Fostering Adaptive Expertise: Design Based Instruction in High School Engineering

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Fostering Adaptive Expertise:
Design-Based Instruction in High School Engineering

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Introduction

Texas's goal of having at least one engineering teacher in each high school is indicative of the tremendous growth in demand for high school engineering classes. However, given the open-ended nature of design, the breadth of content across the various engineering disciplines, and that some teachers have limited engineering backgrounds; training a large number of teachers is a daunting task. We believe that part of the answer is to train teachers and students for adaptive expertise (AE). Experts are adaptive if they are able to solve typical problems in their field appropriately and expeditiously (*efficient*), but also create solutions to novel problems in fluid situations (*innovative*).

Previous research (Martin, Rivale, & Diller, 2007) established that AE could be developed through challenge-based instruction (CBI) for engineering problem solving. Our research question is: Can the innovation component of AE be increased thorough design-based instruction (DBI) in a one-year high school engineering course? Secondarily, we consider the curriculum's impact on the efficiency component.

Background

Expertise

According to Hatano and his colleagues (Hatano & Inagaki, 1986; Hatano & Oura, 2003; Inagaki & Miyake, 2007), there are two types of experts. Routine experts are skilled at solving the typical problems in their field effectively, but may not perform well when confronted with atypical problems. They may make conceptual errors, misapply principles, or make procedural mistakes (Bransford, Brown, & Cocking, 2000). Adaptive experts (Hatano & Inagaki, 1986), on the other hand, are able to think more fluidly and solve problems that they are unfamiliar with (often called "novel problems" in the AE literature), as well as the typical problems in their field. Frequently, adaptive experts actively seek new contexts, reflect on their own understanding, and consider multiple viewpoints (Bransford et al., 2000; Wineburg, 1998).

Engineering can be thought of as the creative application of fundamental principles to solve a problem given limited resources. Because engineers may be required to solve a different problem under different limitations each on project, engineering students need to strive to be adaptive experts, and engineering education needs to teach for this.

Teaching for Adaptive Expertise

Hatano (1988) lists three conditions that he believes help motivate the development of adaptive expertise, instead of just routine, expertise:

1. Students are frequently exposed to "novel" problems, i.e. problems that they are not familiar with and require them to ponder instead of simply following a procedure already known by the student.
2. Seeking comprehension is encouraged instead of just execution.
3. Students are not under intense pressure for external reinforcement, such as producing correct answers under tight deadlines.

Furthermore, he notes that dialogical interaction between students, such as discussion and reciprocal teaching often promotes comprehension better than students working alone.

Several techniques for teaching for adaptive expertise have been proposed. Itakura (Hatano, 1988) developed a method where, students choose an answer from a list of plausible solutions after being presented with a novel problem. Then, the students generate and present arguments for their answers. After they are given a chance to switch to another solution, the students are given the correct answer. The goals of the Foster Communities of Learners program (Brown, 1997) seem to be similar to developing AE. They advocate using techniques (e.g., jigsaws) where students do individual work, share their knowledge with the class, and then the class uses the collected knowledge to accomplish a task.

Challenge-based instruction is centered on giving students open-ended problems. Figure 1 shows the STAR.Legacy Cycle (SL Cycle) (Schwartz, Brophy, Lin, & Bransford, 1999) which illustrates the series of steps that students should progress through in order to solve the challenges. After being presented with the problem in The Challenge, students examine their prior knowledge and what they need to learn in Generate Ideas. Under Multiple Perspectives, they try to approach the problem from different perspectives and then improve their ideas in Research and Revise. Students assess their solution with the teachers in Test Your Mettle and present their project to the class in Go Public.

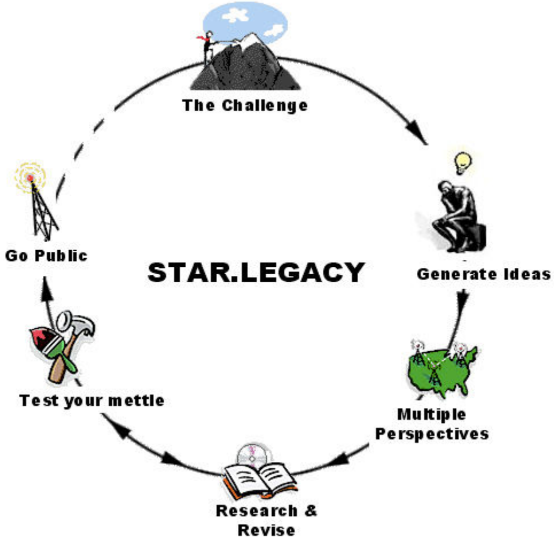

Figure 1. STAR.Legacy Cycle

Since experts agree that a high school level engineering class should be centered on design (Katehi, Pearson, & Feder, 2009), we adapted features of CBI to create design-based instruction (DBI). DBI contains various open-ended and extended time design projects that combine STEM content knowledge with engineering design methodology. Figure 2 shows the design cycle we used, which was based on an abstracted version of the engineering design process. As in professional design projects it is possible to fall back to an earlier step at any point along the DBI design cycle.

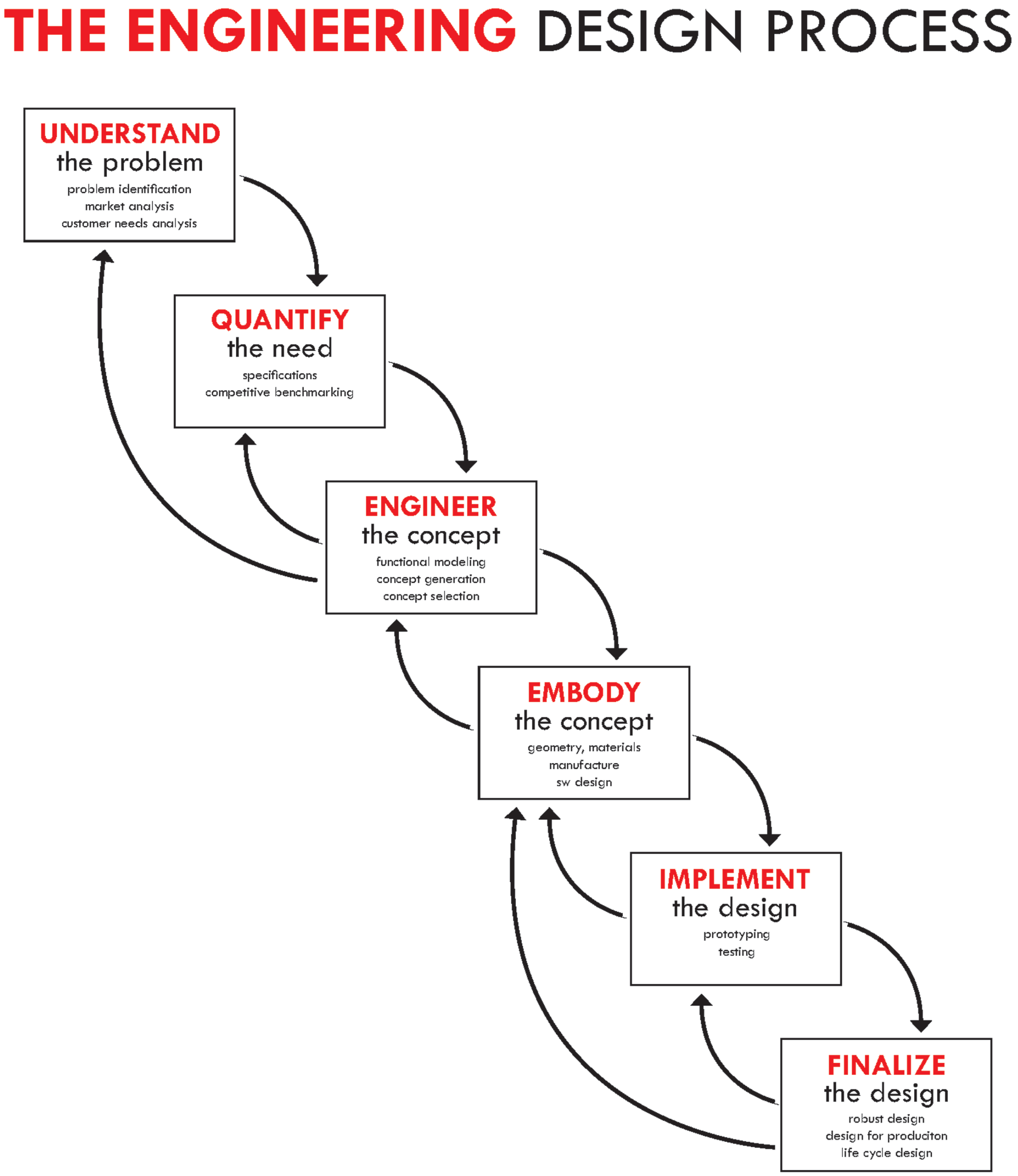

Figure 2. UTeachEngineering DBI Design Cycle

Methods

Participants

The subjects of the study are high school teachers and students in the seven schools that used the UTeachEngineering DBI pilot curriculum during the 2010-2011 school year. The schools surround a major city in the southern United States, including populations with both high and low socioeconomic status and span several districts in urban and suburban settings. Table 1 contains a summary of the demographic information of each participating school. Data was collected from over 100 consented students in the pilot course. Because of absences on days tests were administered, not all students participated in each pretest/posttest.

Table 1. Demographics of schools participating in study.

School	School student population	School setting	School population economically disadvantaged	Minority population of school	# of students participating in study
A	~2900	urban	~15%	~46%	24
B	~1600		~65%	~83%	18
C	~1800		~43%	~58%	16
D	~800		~91%	~98%	10
E	~400		~90%	~99%	5
F	~2500	suburban	~37%	~65%	43
G	~1200	suburban	~7%	~17%	43

Instructional Intervention

The Texas state legislature passed a law in 2006 raising the number of science courses required of all public high school students from three to four. An appropriate engineering class may be used to fulfill the requirement in place of a traditional science class. The UTeachEngineering group has created a course aimed at high school seniors based on the emerging Texas engineering curriculum. The course prerequisites are Geometry and Chemistry, while Algebra II and Physics are corequisites. A pilot version of the class was offered in seven schools during the 2010-2011 school year. The class consisted of four major units, each with design challenges.

A. Energy
Students learned about various methods of energy generation and completed a project where they designed, built, tested, and optimized blades for a wind turbine.

B. Reverse Engineering
Using a common household product, such as a hair dryer, students performed a needs analysis and wrote performance metrics. The students were asked to predict the inner workings of the product and then compare their predication against a disassembled device. Requirements specification and product design are the focuses of this unit.

C. Robotics
Students learned how to use LEGO MINDSTORMS© to perform various tasks. Students started from basic physics and mechanical engineering concepts (e.g. torque, gear ratios) and progressed to using LABVIEW© to program the microcontroller to activate sensors and motors.

D. Final design project
Students were provided with the opportunity to work on a group project over several months to experience all phases of the design cycle shown in Figure 2, and to conclude the course with a presentation to the class. Depending on the school, students either optimized a construction helmet to maximize impact protection or designed an emergency shelter.

Measures and Results

Engineering Design Knowledge

Students in the pilot classes were given brief tests corresponding to the three instructional units (Energy, Reverse Engineering, Robotics). The tests are meant to measure whether the student could apply the concepts taught in the unit, and also to provide a measure of innovation. Our innovation questions were designed to measure the students' ability to think on a more abstract and broader level (imagining situations, explaining how or why something happens, describing the design process, and using judgment). Pretests and posttests were given on the first and last days of each unit, respectively. The tests ranged from 3 to 6 questions each, and the questions were scored from 0-3 points. While longer tests may have provided more detail, they would have taken an unacceptable amount of instruction time away from the class. Furthermore, since our tests are not appropriate for use as a classroom grade, students had little incentive to persist in providing high quality answers over a longer instrument. For these reasons, the engineering design knowledge tests were purposefully kept short with care to gather as much information as possible to answer our research question. For the energy and reverse engineering tests, two researchers came to a consensus grade on each question. A single researcher scored all the robotics tests. The three unit tests are included in Appendix A.

Each content test was analyzed using a repeated measures ANOVA with one within-subjects factor: time (pretest, posttest). Our criterion for significance was $p < .05$ and the sample sizes were n=79, 76, and 98 for the energy, reverse engineering, and robotics tests, respectively. Students showed significant improvement in their innovation levels from the pre- to posttest on both the Energy, $F\,(1, 78) = 23.49$, $MSE = .15$, and Robotics, $F\,(1, 97) = 37.27$, $MSE = .18$, tests. Reverse Engineering test scores did not indicate a pre-/posttest gain, $F\,(1, 75) = 2.22$, $MSE = .07$. Figures 3-5 show engineering design knowledge changes in pre-/posttest scores.

Engineering Design Beliefs

Mosborg et al. (2005) contained a series of instruments that were developed to assess engineering design expertise and attitudes associated with expertise. The *Design Survey* we used is one of the instruments from that study, and it consists of 27 Likert scale statements and beliefs about engineering design. We divided the statements into those that indicated innovative attitudes and those indicating efficiency attitudes. An example of something we classified as innovative is "Creativity is integral to design, and in every design project creativity can be found." An example of a statement that we classified as efficiency is "Good designers get it right the first time." Questions without a clear distinction between innovation and efficiency were not analyzed. The Design Survey was administered to students at the beginning of the school year and during the final month of class. The Design Survey is included in Appendix B.

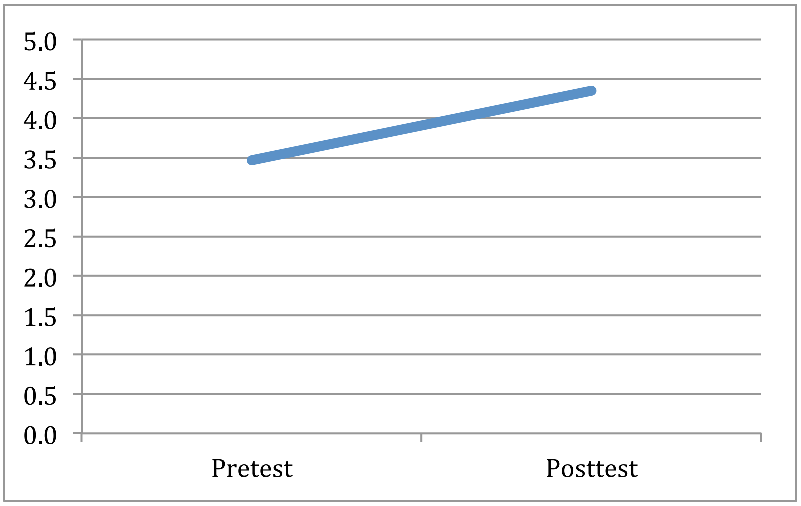

Figure 3. Energy Unit innovation pretest to posttest scores, n=79

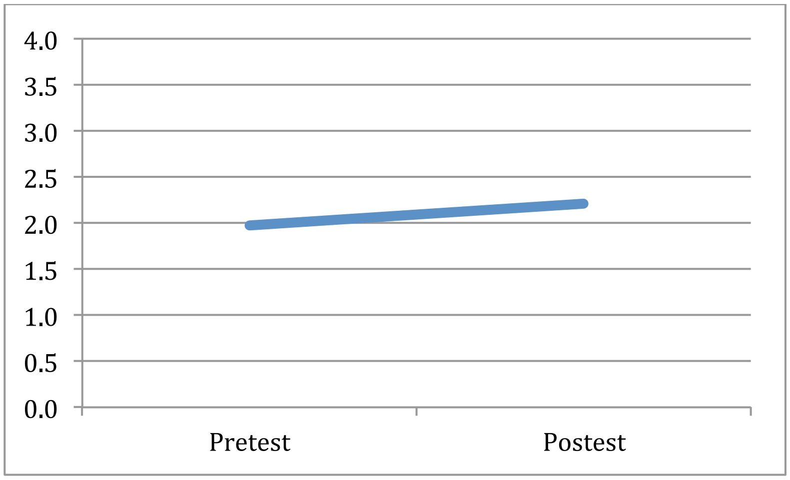

Figure 4. Reverse Engineering Unit innovation pretest to posttest scores, n=76

We analyzed results of the Design Survey using a 2 x 2 repeated measures ANOVA with two within subjects factors: time (pretest, posttest) and measure (innovation, efficiency). The sample size was n=97 and the significance criterion was $p < .05$ for all measures. On the pre and post measures of design understanding, there was not a significant main effect of time, $F\ (1, 96) = .30$, $MSE = .24$. However, students' overall innovation averages were significantly higher than their overall efficiency averages, $F\ (1, 96) = 193.83$, $MSE = .27$, and this was a large effect ($\eta_p^2 = .67$). Post hoc tests using the Bonferroni adjustment indicate that innovation was significantly higher than efficiency on both the pre and posttests. Both main effects are dependent upon the other, as indicated by the significant interaction between time and measure, $F\ (1, 96) = 6.20$, $MSE = .12$, which was a moderate effect ($\eta_p^2 = .06$). Post hoc comparisons using the Bonferroni adjustment showed that the students relate engineering design to innovation significantly more than they relate it to efficiency. There was a crossover between innovation and efficiency from pre to posttest with innovation decreasing and efficiency increasing, but neither of these effects is significant in post hoc analysis.

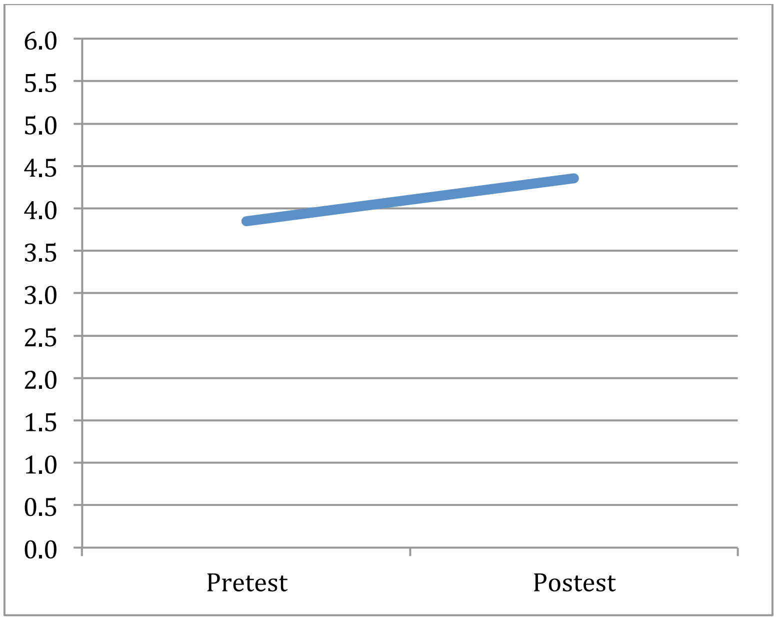

Figure 5. Robotics Unit innovation pretest to posttest scores, n=98

Conclusions

After participating in the pilot DBI UTeachEngineering course, high school students demonstrated an increase in their innovation on each of the unit tests, with the increase being significant on two of the three tests. From the Design Survey, we examined the responses to questions that relate to beliefs about efficiency and innovation. Students demonstrated significantly higher attitude levels of innovation than efficiency on both the pre and post survey, but their beliefs about innovation and efficiency did not change significantly over time. To be clear, we note that a higher attitude in innovation or efficiency on this survey does not equate to higher skill in either area nor does it equate to a student's like or dislike of the components of AE.

Unfortunately, we do not have a control group with which to compare our results. Thus, we must temper our conclusions with this in mind. There is evidence that the DBI pilot curriculum increased students' innovation when dealing with engineering content. Their attitudes about the relationship between engineering design and innovation were higher than their beliefs about the relationship between engineering design and efficiency. Perhaps a refinement in the curriculum and greater teacher experience with using a DBI curriculum could enhance students' development of AE. The UTeachEngineering group is currently revising the curriculum based on teacher feedback and results from this and other related studies.

This study is specifically tailored to the UTeachEngineering curriculum, but there are some general lessons we learned that can be used to inform other programs. We believe this work provides further evidence that K-12 engineering programs can raise student innovation such that they can take their knowledge and apply it more broadly and abstractly, like adaptive experts. However, student beliefs are “sticky” and are challenging to change significantly.

Acknowledgments

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Appendix A

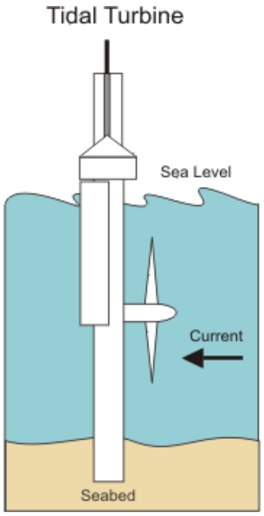
The three unit pre/post-tests are included below. The questions in italics are the innovation questions that we used in our analysis. The questions that we did not use in the analysis are included below to help the reader establish context.

Instrument A1. Energy Unit pre/posttest

Wind turbines harvesting energy from the wind are becoming increasingly common sights. A typical commercial scale wind turbine may have blades hundreds of feet long and the blades would be made to withstand highly variable wind speeds, ranging from a few miles per hour to hurricane force winds (in excess of 75 mph).

Source: Department of Energy (http://www1.eere.energy.gov/windandhydro/wind_how.html)

Another possibility for harvesting energy from moving fluids is to place turbines under water and to harvest the energy of tides or ocean currents. A drawing of one of these devices is shown below.



Source: US Department of Energy (http://www.eia.doe.gov/cneaf/solar.renewables/page/trends/highlight13.html) *a.) Sketch your ideas for the design of the blades of an underwater tidal turbine. Would you expect tidal turbine blades to be longer or shorter than wind turbine blades? Why? Would you expect the shape to be the same or different? Why?*

b.) What factors would cause the wind turbine blades to be designed differently than the tidal turbine blades?

Instrument A2. Reverse Engineering pre/posttest

1. Please sketch how you believe the mechanism inside a soda vending machine works.
2. *What improvements do you think have been made to soda vending machines since they were invented?*
3. What steps would you take to determine what improvements should be made to the next generation of soda vending machines.
4. *Suggest some ideas for improving soda vending machines.*

Instrument A3. Robotics Unit pre/posttest

1. Think of an item you use every day that includes sensors.
   a. What sensors does the device use and types of inputs are monitored?
   b. What actions, if any, occur as the result of the sensor input?

2. *Describe a real world industrial application where control and automation (robotics) is utilized to solve problems. Explain how the implementation of control and automation in your example has benefitted workers, consumers and/or society.*

3. Turning a stove-top burner knob to “Hi” and turning an oven pre-heat cycle knob to 350˚ F are both actions intended to specify a specific heat setting.

   a. Which system is the closed loop system? Explain what makes the system a closed loop.
   b. Draw a system diagram for each system showing the inputs, outputs and feedback, if any.

4. *Consider a common automatic store door (think of HEB, Randall’s, WalMart, etc.). The door remains closed until a person approaches from either the inside or the outside. The door then opens. After the person passes through the door closes. As the door is closing, if another person approaches the door (again from either side), the door will reverse directions and open again.*

   Design a flow chart for the control algorithm of this door.

Appendix B

The questions in this section are taken from the 27 question *Design Survey* from Mosborg et al. (2005). We labeled questions *Efficiency* or *Innovation* if we believed that the attitude expressed by the question is related distinctly to efficiency or to innovation. We labeled questions *N/A* if this distinction was unclear. These labels were not on the survey students completed.

Please answer questions 1-27 in this part on the scantron bubble sheet using the following rating scale:
A = strongly disagree
B = disagree
C = neutral
D = agree
E = strongly agree

1. Good designers get it right the first time. *(Efficiency)*
2. Good designers are born with a talent for design. *(Efficiency)*
3. In design, one of the main questions that needs to be answered is "Who will be using the product?" *(N/A)*
4. Drawing, diagrams, and models are usually used to describe the final design to a teammate or the client. *(Efficiency)*
5. Engineering design is the process of creating a system, component or process to fulfill a need. *(Innovation)*
6. Design is the essence of engineering; Design, above all else, is what makes engineering different from science. *(Innovation)*
7. Design begins with the figuring out what is needed and ends with a product or system in the hands of a user. *(N/A)*
8. Design is mainly putting ideas together rather than breaking down big ideas into small pieces, which is central to engineering science. *(N/A)*
9. … design is a form of communication that tries to plan and shape human experience. Designers take ideas and information from the arts and sciences to conceive, plan, and build things that are useful to people. *(Innovation)*
10. Design is as much a matter of finding problems as it is of solving them. *(Innovation)*
11. In design it is often not possible to say which bit of the problem is solved by which bit of the solution. One element of a design might solve more than one part of the problem. *(Innovation)*
12. Design is a highly complex and sophisticated skill. It is not a magical ability that can only be done by people who are born with a natural talent for it. *(Innovation)*
13. Design is a conversation with the available materials. *(N/A)*
14. Design defines engineering. It's an engineer's job to create new things to improve society. *(Innovation)*
15. Design is not about describing what you see, it is about exploring different possibilities. *(Innovation)*

16. Often, the designer will suggest different solutions in order to better understand the problem. *(Innovation)*
17. When designing, often an advance in the solution leads to a new understanding of the problem, and a new understanding of the problem leads to a 'surprise' that drives the originality streak in a design project. *(Innovation)*
18. Design is a goal-oriented, decision-making activity, with many requirements to meet. *(Efficiency)*
19. Designers operate based on how they think their work fits in to the world. *(Innovation)*
20. Creativity is integral to design, and in every design project creativity can be found. *(Innovation)*
21. Engineering design impacts every aspect of society. *(Innovation)*
22. Environmentalism is important to design. It is critical to use eco-friendly principles such as using green materials, design for dismantling, and increased energy efficiency, when developing products, services, and systems. *(N/A)*
23. Design is "world" creation; everyone designs all the time. It is the oldest form of human inquiry giving rise to everything from ideas about the universe to making tools. *(Innovation)*
24. Design, in itself, is a learning activity where a designer continuously refines and expands their knowledge of design. *(Innovation)*
25. Designers use drawings, diagrams and models to help generate ideas and create form. *(Innovation)*
26. Information is central to designing. *(N/A)*
27. A key part of design is iteration. *(Innovation)*