# Sketching as the First Step to Making

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**Abstract**

Making has the potential for increased student engagement and propelling students into pathways in STEM and the Arts. However, students come into school with a wide range of Making skills, and many are intimidated by the prospect which can limit their engagement. This paper reviews a number of Maker projects in introductory high school and college engineering courses and identifies a common theme that has increased students' initial success. This theme is the role that freehand sketching plays. Sketching is among the most accessible skills and is key for personalization of projects. The personalization is often seen as an essential component of Arts and Crafts projects but is often an afterthought in an engineering curriculum. This paper describes an introductory individual project where a personalization component has taken on an increased role. Also described are team projects. In all these projects, sketching are a key first step. Survey results illustrate the step-by-step increase in how students rate their confidence with hands-on design and fabrication. This paper shares the authors' experiences in implementing projects with high student engagement, and how sketching can become the first step in the pathway to Making. As we attempt to engage a wider and more diverse group into the world of Making, the first step has can be critical.

**Introduction**

There is an estimated need for 1 million more Science Technology Engineering and Math (STEM) professionals in the U.S., yet many young children are intimidated by or have a negative impression of STEM [1, 2]. Many American students "conclude early in their education that STEM subjects are boring, too difficult, or unwelcoming" [3]. A widely cited book on STEM in college concluded that most of the major change and dropouts from STEM majors occur in the first or second year of college [4]. A promising approach to reduce STEM dropout is Project-Based Learning (PBL), and indeed participating in a PBL course in the first 2 years of college is correlated with an increase in students' perception of STEM and of careers in STEM [5, 6]. However, PBL courses are often elective [5], so there remains a need to for such courses to welcome all students.

In order to increase the number and diversity of students pursing STEM, Making activities have been introduced into the K-12 and First Year Engineering curriculums. A key purpose of these Making activities is to increase engagement and interest in courses to come. Indeed, FIRST Robotics [7] is an example of a highly successful program that engages high school students in Making. One consequence of such K-12 elective Making opportunities is there is an increase in the range of Making experience that incoming college students have. Students who did not participate in K-12 Making activities may have a lack of confidence in participating in such classes and feel that STEM is not for them. Accordingly, there is a need for appropriate scaffolding to bring all students up to speed in Making and to welcome students of all backgrounds.

Educational scaffolding is an approach that supports students as they learn new concepts. In subjects such as math scaffolding is important since it helps students learn material that becomes the foundation for following material. In PBL early scaffolding can be even more essential, since without early success and confidence in one's ability, students may have limited success with self-guided exploration and may be left behind by their peers. It is the authors' opinion that some PBL initiatives with Making are started without sufficient scaffolding to broaden the tent of the Making. One example is bringing 3D Printing into the classroom motivated by the popularity of the topic with the general public. However, an article that reviewed close to 300 cases of incorporating 3D printing into education and found that implementation "remains immature" [8]. A related example is that even introductory tools such as Tinkercad can be difficult for younger students to master [9]. The authors have also seen a wide range of ability in Computer Aided Design (CAD) within First Year Engineering courses in college. Indeed, getting started with 3D printing and other Maker projects can be intimidating for some students, and to increase inclusivity there is a need for attention to the first steps of becoming engaged with Making.

The focus of this article is to explore the role that freehand sketching can play in scaffolding Making and PBL activities. Freehand sketching is natural from a young age and have a very low barrier to entry. Sketching is also seen as an important component of creativity and professional practice ([10, 11]). There has been an increased interest in freehand technical sketching in the past decades since it has been shown to improve spatial visualization skills and subsequently graduation rates in STEM [12, 13, 14], especially among women and other underrepresented minorities in STEM [15].

This paper aims to explore other advantages of sketching, which include personalization of Making projects and as a starting place for design projects. The authors describe a number of Making projects in their courses, and how sketching plays an important first step in the Making process.

### A. *Individual Pendulum Clock Project*

This Pendulum Clock Project is part of an Introduction to Design and Engineering Graphics class, MAE 3, at the University of California, San Diego (UCSD). This class is taught to freshmen and sophomore Mechanical and Bioengineering students, and includes both a lecture and lab component. This is 1 quarter (10 week) class, with up to 196 students each time this class is taught which is typically twice a year. The class culminates in a head-to-head robotics competition with teams of 4 students building small joystick controlled robots.

Because of the short quarter, there was a temptation to start the team project at the beginning of the quarter. However, there was concern that those students who had prior design experience in high school, would dominate the decision-making process of their team. To address this issues of wide variation in Making skills, the first 3.5 weeks are dedicated to an individual project that is meant to build up technical skills of shop use, introduction to Computer Aided Design (CAD), and develop confidence in ability for all students. The topic of the project is to build a pendulum clock as shown in Fig. 1.

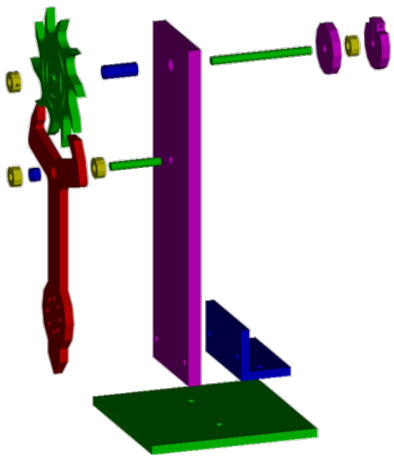


***Fig.1 Pendulum Clock Components [16]***

Mechanical clocks were among the most advanced technology in the 1700s, and a full-size pendulum clock on campus inspired this project. In the MAE 3 class project, students CAD and Laser cut an escapement wheel and a pendulum with pallets that engage with the wheel. They also learn to drill, tap, ream, and press fit bearings. The escapement wheel is attached to a shaft to transfer torque to a hanging weight. The clock ticks for about a minute and students perform the analysis to predict the timing of their clock before it is finally assembled (both the point mass and rigid body natural frequencies are calculated). Complete details for fabricating this clock are online [16].

When the project was first created, as an afterthought of the instructor, students were told they could design the bottom portion of the pendulum to be any shape they wished. It turned out that students spent significant effort on personalizing their shape of their pendulum despite the fact that no extra credit was provided for this personalization. Student designs included dancers, musical instruments, surfers, and Pokémon. See sample clock designs in Fig. 2. One student designed his clock for his significant other; they are married now and the student became a professor of mechanical engineering (they kept the clock).

***Fig.2 Personalization of Clocks [16]***

The individual pendulum clock project is a getting started to Making project, and sketching is the first step of this project. The first assignment in the MAE 3 course is for students to draw a hand sketch of the pendulum shape they wish to fabricate. Rough guidelines are given, students' freehand sketching of their desired pendulum initiates the pathway to personalization of their Maker project. In the first CAD lab students learn to convert their hand sketch to a 2D CAD drawing which they ultimately laser cut to create the part. Students also learn to press fit bearings, and they receive extra credit if they reduce the friction on their clock such that the hanging weight needed is just a single nut. In the clock project the aesthetics were open ended, but not the functional components such as the escapement wheel, pallet location, and bearings and shafts. The goal is for all students to succeed without the need for iteration in this first project. Since it is an individual project, students get to keep their clock.

While it may have been obvious in an Arts and Craft class for young children that personalization was key, it was a revelation to the instructor how significant a role it played in an engineering course. In retrospect, the role of sketching as the first step in design has become clearer. Completing the clock project is where students learn to walk, and the team project described below is where they start to run.

### B. *Team Robot Project*

Team projects are a staple of engineering design, and for the last 6.5 weeks of MAE 3 students work on a robot project in teams of 4. Each quarter the class is taught, a new contest is developed, so that the challenge is truly open ended. Emphasis is placed on creativity, risk reduction, and managing the iterative nature of the design process. As with the clock project, the first assignment involves sketching. Each student is tasked with individually developing 3 design concepts for their robot. An example of an initial student sketch is shown in Fig. 3. By this point students have learned the fundamentals of isometric and orthographic sketching. The instruction approach for sketching will be described in a later section of this paper.

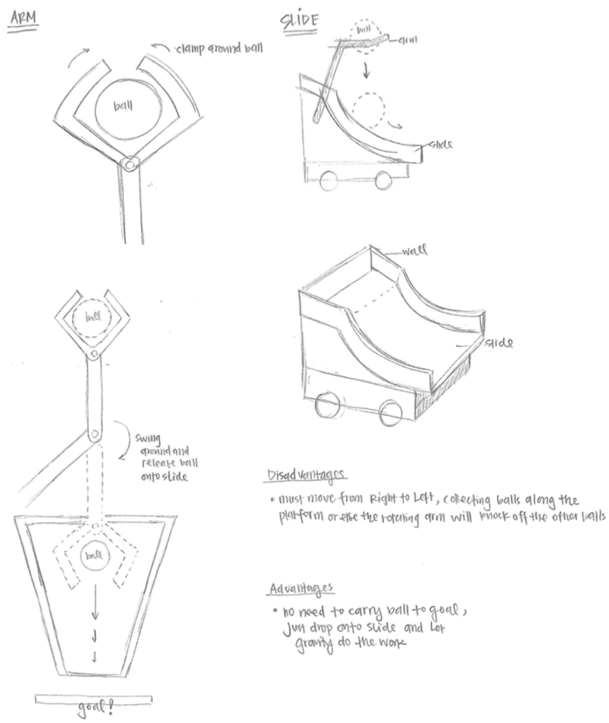



***Fig.3 Sketches of Robot Design Concepts in MAE3***

The student teams use the Pugh Chart method to communicate their design and pursue risk reduction and fabrication together. Instructions are provided regarding effective teamwork, and a peer review tool [17] is used for students to give feedback to their teammates midpoint and at the end of the project. Students also create a short webpage describing their robot, which are often featured on their resumes [18]. An example CAD of a robot built in MAE 3 is shown in Fig 4.

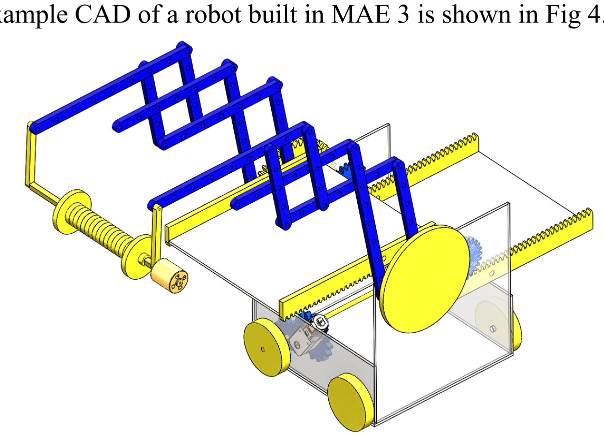


***Fig.4 CAD of Completed Robot in MAE 3***

### C. *Gain in Confidence*

A survey was conducted in an MAE 3 class of 128 students, where 64 completed the survey and allowed for the results to be used for research. To assess growth in the course the students were asked to "Rate your confidence with hands-on design and fabrication (5 Very high, 4 High, 3 Medium, 2 Low, 1 Very low)" at different times in the course. The percentages of those answering Very High or High broken down by gender were:

Table 1: Rating of Confidence With Hands-On: as High or Very High

| | Male | Female |
|---|---|---|
| Beginning of course | 38% | 16% |
| After individual project | 58% | 32% |
| After team project | 91% | 84% |

As seen, there was a significant increase in confidence with hands-on design, with the female students starting off at a lower level but the two groups reaching much closer levels by the completion of the course. Moreover, fewer than half the students in each gender rated their confidence as high at the beginning of the class, but a significant majority in each gender felt high confidence in design and fabrication by the end of the course. This incremental increase in the number of students with high confidence illustrates how confidence can be increased gradually, ultimately resulting in a large majority of students demonstrating self-efficacy.

In a different quarter when MAE 3 was offered with 114 students in the class, a weekly reflection assignment was part of the course assignments. The reflection was aimed to improved student awareness of how they were learning and what they could do to improve. The reflections were also used under IRB for pedagogical research. One question in the reflection was "How comfortable do you feel in using the Design Studio shop tools for the past week's assignments?" The answered ranged from 1-5 (1=very uncomfortable, 5=

very comfortable). The average responses over the weeks with standard deviation bars is shown in Fig. 5 below:

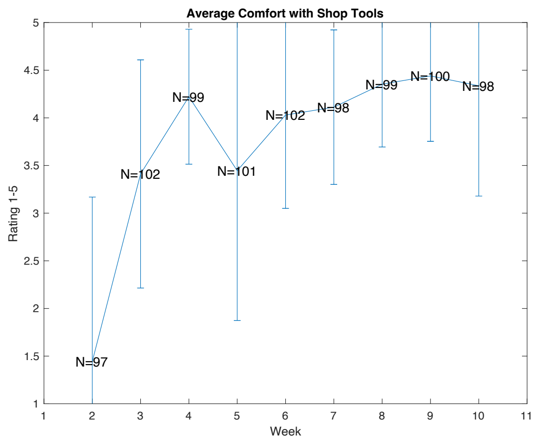



***Fig.5 Survey Responses Per Week***
1=very uncomfortable, 5= very comfortable

As seen the self-reported comfort with shops tools increases significantly and the standard deviation decreases in the first 4 weeks, which are primarily the individual project. There is a slight drop in week 5 when students start the more difficult team project, and then a gradual increase with comfort as the team project progresses. Overall, we see that student comfort with their hands-on ability increases over time, and that the individual project seemed to have served its purpose of providing a more uniform comfort with hands-on before the team project is initiated.

*Rube Goldberg Team Project*

Similar team projects are implemented in the Department of Structural Engineering. In an introductory Engineering Graphics course, students were taught the fundamental operations of CAD software packages and then guided to explore more advanced modeling techniques to support the design and manufacturing of the team term project: a miniature Rube Goldberg machine. The purpose of a Rube Goldberg machine is to intentionally over-engineer a complicated machine or contraption to perform a simple task.

The SE 3 Term Project required several milestones throughout the quarter to ensure successful completion of the Rube Goldberg machine. The initial milestone consisted of conceptual hand sketches, where teams of students assessed the project limitations, guidelines, and goals of the project to design a portion of their Rube Goldberg machine to accomplish a given task. The *Conceptual Sketches* were a series of freehand sketches that represented the conceptual ideas for their Rube Cube and provided a clear idea to what each team intended to pursue for their project (Fig. 6A and 6B). The preliminary sketches had to be neat, clearly labeled, and dimensioned where applicable, and follow freehand sketching guidelines presented in lecture. The sketches were then migrated into tangible 3D models using computer aided design software. Once the 3D models were assembled, teams manufactured their Rube Goldberg machines in the Envision Maker Studio, which required an iterative design and build process as students discovered the importance of tolerances, workability, manufacturability, time management, good graphical representations, and the balance between design and construction labor.

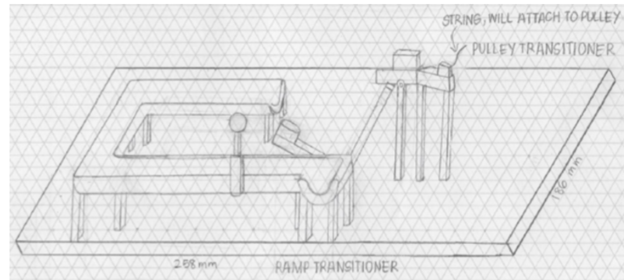



***Fig.6A Conceptual Isometric Sketches of Mechanisms in a Team's Rube Goldberg Project***

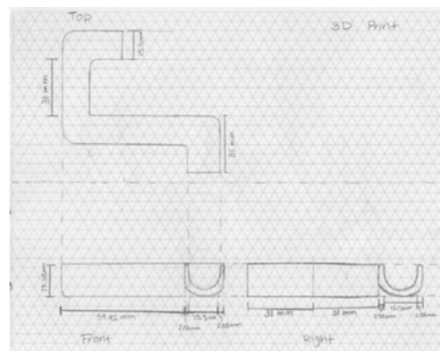
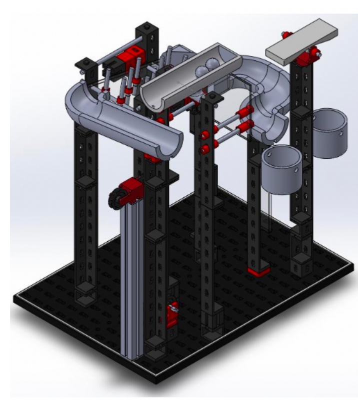



***Fig.6B Conceptual Orthographic Sketches of Mechanism in a Team's Rube Goldberg Project***

One of the most important deliverables for the project was the submission of the final *Construction Drawings* to demonstrate that students could apply the concepts learned in their Engineering Graphics course to a real project (Fig. 7). All drawings were required to be compiled on sheet size A and use ANSI standards. Students produced drawings using both AutoCAD and SolidWorks with the goal of demonstrating little visible difference between the drawings from the two different software programs.



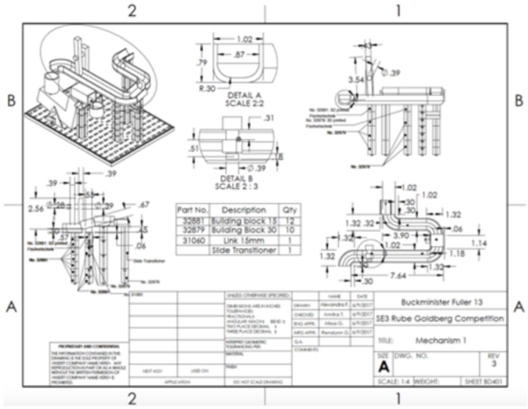



*Fig.7 CAD and Construction Drawings of Rube Cube Assembly [19]*

In an end-of-course survey students responded to several questions such as, "Give one specific example of something you learned from the team that you probably would not have learned working alone". One student's response was, "I learned how to communicate my ideas clearly! Specifically, I learned how to make free hand sketches that were clear and detailed enough that my partner could pick it up and replicate it in SolidWorks".

## D. *Wind Turbine Tower Team Project*

In another introductory first year Structural Engineering design course, students participated in a team-based design-build-test project to learn the importance of mechanics, materials, design, and analysis as fundamental structural engineering concepts required to design any type of structure. Teams designed a wind turbine to meet the energy and structural requirements of a specific site, be cost effective, and be aesthetically pleasing. Deliverables included conceptual hand sketches of the proposed designs (Fig. 8), physical working prototypes, and a written proposal report and presentation. The students designed a combined civil and aerospace structure. The three primary goals were to:

- Design the blades of a wind turbine that are aerodynamic and capable of producing as much energy as possible.
- Design the frame of the wind turbine structure to withstand a lateral load (seismic or wind) and maintain adequate stiffness.
- Create an "efficient" structure that utilizes the least material, but still performs well.

The blades were tested with a real wind load and voltage was measured to see which produced the most energy while the towers were tested separately with a lateral load applied and Force. Vs. Defection measured (Fig. 9).

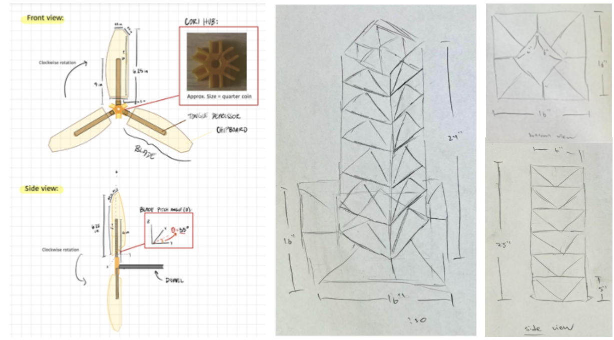



*Fig.8 Sample Conceptual Sketches of Wind Turbine Tower Project*

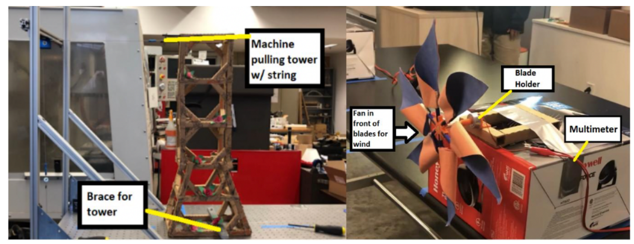



*Fig.9 Testing of the Blades and Tower*

During the end of course survey, many students indicated that their favorite part of the class was the design-build project , "I enjoyed the building and testing part since it allowed us to actually use the design process and felt the most engineer-like throughout the class," and "What I enjoyed most were having to come up with a solution for a project that involved being hands on and designing the solution from scratch."

## E. *Team Recursive Water Balloon Drop Project*

Another team project that starts with sketching is the Recursive Water Balloon Drop [20]. The project was implemented as part of a summer California State Summer School for Mathematics and Science [COSMOS] for high school students. The project was motivated by the egg drop contest which is a common science K-12 project where students build a structure to protect an egg from breaking and then drop their device to test it. However, with the traditional egg drop contest students never learn why their egg broke or survived, and they often do not get a chance to redesign their protective structure.

In the Recursive Water Balloon Drop project, instead of a single egg, we give teams of high schoolers a bucket of water balloons. An iPhone or Android phone with slow motion mode (high frame rate) is set near the ground to capture the impact. The structures are dropped at increasing height until the water balloon bursts. The students analyze the videos, develop hypotheses as to why the balloon bust, and develop new design concepts to test.

The first task of the project is for each student to individually sketch 3 design concepts, an example of which is shown in Fig. 10. As seem by this point in the class, the students have learned to sketch isometric and orthographic views. A structure that was built is shown in Fig. 11, and of one of the high frame rate videos of the impact is as [21].

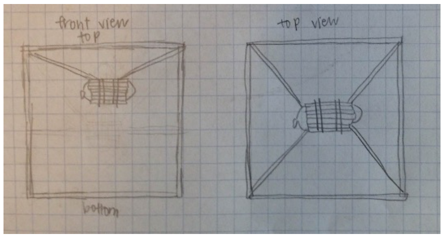



***Fig.10 Initial Sketches for Recursive Balloon Drop***
***Note use of orthographic views***

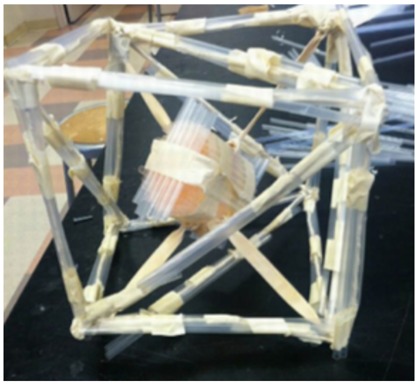


***Fig.11 Prototype Built for Recursive Balloon Drop***

## F. *Instruction of Freehand Sketching Skills*

Each of the projects described in this paper starts with a sketching assignment. For the Pendulum Clock project, no specific instruction is provided for how to sketch. This is a 2D rough drawing of the aesthetics of their desired pendulum and students can generally manage this without training. However, for the open-ended design projects students need to be able to describe their concepts in 3D as wells as various 2D views (top, front, side). To teach students how to sketch 2D and 3D views, and increase their spatial visualization ability, the students in all projects described in the paper used the Spatial Vis software [22]. This software has a set of orthographic and isometric drawing assignments, as well as folding and rigid body rotation assignments. The software automatically grades the students' sketches and provides personalized feedback. A benefit of using the software was that it could be assigned early in the class and training could proceed in parallel with the design content. By the time students began their team assignments, they already acquired key sketching skills.

## G. *Discussion*

Educational scaffolding is a widely used pedagogical technique in many traditional subject areas. The authors propose sketching as a scaffolding tool for engaging a wider group of students in Making. In PBL with Making there can be a barrier to entry for students who do not feel confident with hands-on design and fabrication. The authors present examples where early sketching has been used as the first step in Making projects. Student surveys illustrate how confidence in Making increases and how sketching is used as part of the design process. In the examples described, freehand sketching is purposefully introduced before CAD modeling is performed to increase creativity and lower the barrier to design. Sketching can also be a key component in personalization of a Making project to further increase engagement. These approaches can be an important part of Making in academic environments for increasing engagement in STEM.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## Disclosure

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