ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #28655

The Way Things Work: Sketching and Building to Improve Visual Communication and Spatial Reasoning Skills

Dr. Vicki V. May P.E., Dartmouth College

Vicki V. May, Ph.D., P.E., is an Instructional Professor of Engineering in the Thayer School of Engineering at Dartmouth. Her research focuses on engineering education and K-12 outreach. She teaches courses in solid mechanics, structural analysis, and design at Dartmouth. Prior to relocating to the east coast, Professor May was an Associate Professor of Architectural Engineering at the California Polytechnic State University in San Luis Obispo.

David Alexander Macaulay Mr

The Way Things Work:
Sketching and Building to Improve Visual Communication and Spatial Reasoning Skills

Introduction

The Ways Things Work, a course offered by the Thayer School of Engineering at Dartmouth based on the book by the same title, focuses on helping students understand engineered systems by sketching and building. The course is co-taught by Vicki May, a professor of engineering, and David Macaulay, illustrator of the *The Way Things Work* [1],[2] and carries art credit (all Dartmouth students must take at least one art course). The goal of the course is to help students become more aware of the engineered world around them while developing some of the skills needed to be successful in engineering. Through this course students will:

- Improve their ability to reason spatially;
- Visually communicate how engineered systems work; and
- Critically evaluate their own work and that of their peers.

Research Questions and Approach

This paper describes a study aimed at answering the following questions:

- How are students' spatial reasoning skills changed by taking *The Way Things Work*?
- How are students' visual communication skills changed by taking *The Way Things Work*?
- Do students' spatial reasoning and visual communication skills vary by gender?

The ability to reason spatially is correlated with success in engineering [3], [4]. By sketching, building, and observing the authors hypothesize that students' spatial reasoning skills will improve, thus helping them to succeed in future engineering courses. The Purdue Spatial Visualization Test: Rotations (PSVT:R) [5], [6] has been widely used in engineering to measure spatial reasoning ability [3]. An updated and modified version of the PSVT:R [6] was chosen to measure spatial reasoning ability among students enrolled in *The Way Things Work* by administering the test at both the beginning and end of the course. An example question from the updated PVST:R is given in Figure 1. The PVST:R consists of 10 questions, similar to the one shown in Figure 1, that require the students to rotate an object with fairly complex geometry.

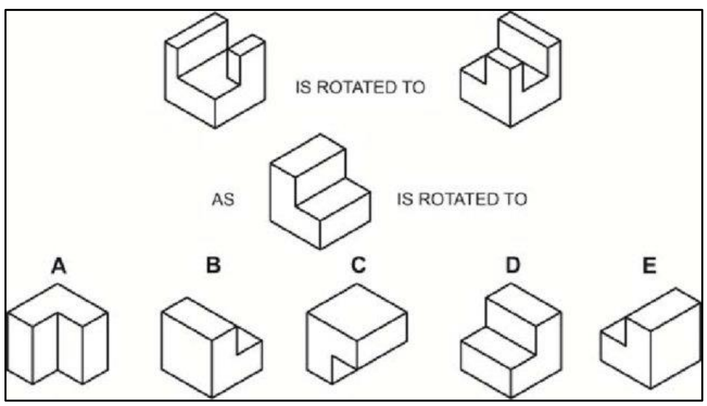

Figure 1. Example Problem from the Purdue Spatial Visualization Test: Rotations

The ability to communicate visually is a critical but often overlooked skill in engineering. Brumberger [7] argues that "the ability to analyze and interpret images and other visual material, although critical, is not by itself sufficient for full visual literacy; it must be accompanied by some ability to create visual material." ABET [8] also emphasizes the importance of engineering students' ability to communicate effectively through criterion 3, though ABET makes no distinction between different modes of communication. While the engineering community recognizes the importance of communication skills, research on measuring visual communication skills of engineering students is limited [9]. For the study presented in this paper, students' visual communication skills were assessed by comparing visual displays submitted early in the term with those submitted at the end of the term.

The study population used for this paper includes 71 students who have enrolled in and completed the course, *The Way Things Work*, in 2017, 2018, and 2019. Class enrollment by year and gender are given in Table 1. Note that in 2017 enrollment was not limited but in 2018 and 2019 enrollment was limited to 16 students and 24 students, respectively. In 2017, the course carried Technical and Applied Science (TAS) credit. All Dartmouth student must take at least one TAS course. Engineering students must take many TAS courses. Students enrolled in the course in 2017 were all non-engineering majors and mainly juniors and seniors who were looking for a TAS course to fulfill that requirement. In 2018 and 2019, the course was changed to carrying Art credit rather than TAS credit with the goal of attracting engineering students to the course. All students must also take one art course before they graduate and offering an art course in engineering enabled us to expose students to engineering while allowing them to fulfill their art course requirement. Students enrolled in the course in 2018 and 2019 have all been either considering engineering as a major or already declared engineering as their major. In addition, in 2018 and 2019, the majority of students were freshmen and sophomores.

Table 1. Class Enrollment by Year and Gender

	2017	**2018**	**2019**	**Total**
Men	13	7	11	31
Women	18	9	13	40
All	31	16	24	71

Course Overview

The course, *The Way Things Work*, is separated into four units, with each unit focused on a different type of engineered system: Unit 1 – Structural and Mechanical Systems, Unit 2 – Electrical and Energy Systems, Unit 3 – Biomedical and Robotic Systems, and Unit 4 – Choice. For each unit, students are expected to create a display (poster, brochure, animations, or video) that visually communicates how an engineered system of their choice works. While the students work individually on the displays for each unit, they collaborate with peers in the class to brainstorm ideas, improve drafts and evaluate the final projects. Engineered systems that students have selected to explain include clocks, LED lights, bicycle gears, stethoscopes, games, thermometers, wind turbines, photovoltaics, and more. The course syllabus is provided in Appendix A.

In addition to the projects, each unit includes introductory lectures related to engineering, sketching lessons and exercises, hands-on building projects, and reverse engineering activities. The following sections presents additional details about the course.

Building Activities

For unit 1, which focuses on structural and mechanical systems, students build tensegrity structures, foam-core beams or columns, and automata. Tensegrity structures, as shown in Figure

2, help students understand tension and compression. Guidelines for building tensegrity structures may be found in [10]. Equipped with some idea of tension versus compression, students are next tasked with designing and building a column or beam out of foam-core that is able to support a person. As the main building project for unit 1, students design and build automata, a whimsical machine that uses cams, gears, or levers to create motion. Examples of automata built by the students are given in Figure 3. Additionally, students in the course take apart mechanical toys to determine how they work, sketching them as they take them apart.

Figure 2. Tensegrity

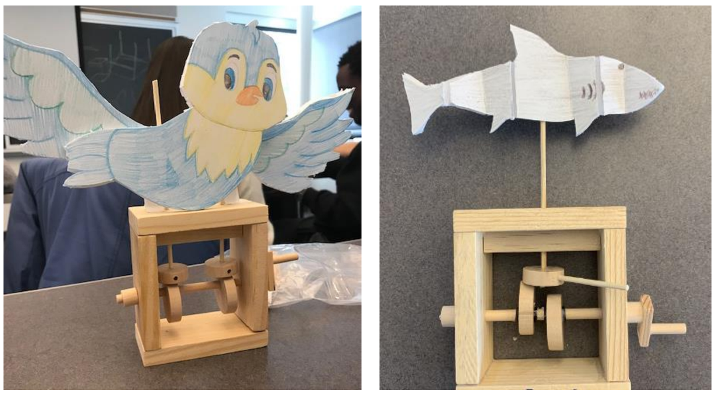

Figure 3. Automata.

Unit 2 focuses on electrical and energy systems. Students create paper circuits using copper tape, LEDs, and batteries, which many then use to illuminate their project for unit 2. In addition they build solar lanterns as shown in Figure 4 by laser-cutting boxes to encase the lantern and soldering solar panels, LEDs, and circuits together to illuminate the lantern boxes. Students are given computer-aided design (CAD) files for a basic box that they modify to incorporate their own designs while gaining a bit of experience using CAD software. They also build wind turbine blades, measuring the voltage and current converted by different blade designs. Further, they reverse engineer or take apart flashlights and broken computers.

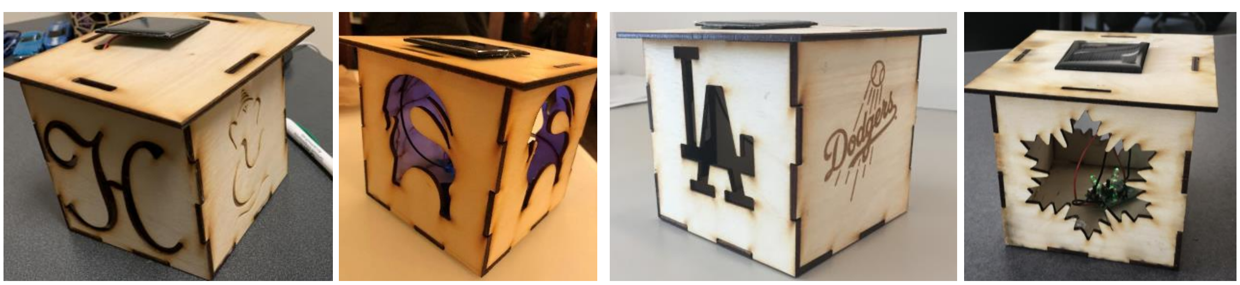

Figure 4. Solar lanterns.

Biomedical and robotic systems are the focus of unit 3. For this unit students cast and sketch their own hands and take apart biomedical devices. Images of their cast hands are given in Figure 5. Through the hand casting project students learn how to create casts, a process used fairly often in our machine shop to create multiple prototypes, and are able to use their casts to study and sketch their own hands. Students also build robotic arms using cardboard or wood, rubber bands, and fasteners; the challenge is to design a robotic arm that can pick up a range of different objects and move them.

Figure 5. Cast hands.

Sketchbooks

Students also are responsible for completing weekly observation and sketching exercises. Each student is given a sketchbook at the beginning of the term in which to sketch, ideally on a daily basis. Students are required to scan and submit samples from their sketchbooks electronically every week. Sketching is used as a way to get students to better observe engineered systems; ‘sketching to understand and communicate’ is the motto of the course. Professor Macaulay leads weekly sketching lessons focused on helping students better see and understand engineered systems rather than on producing art. He helps students break down complicated systems into simple shapes like cubes and cylinders, develop a sense of different perspectives, and observe the scale of objects. A few student sketchbook entries are given in Figure 6; for this assignment students were asked to sketch chairs, with a focus on identifying and drawing simple shapes and planes.

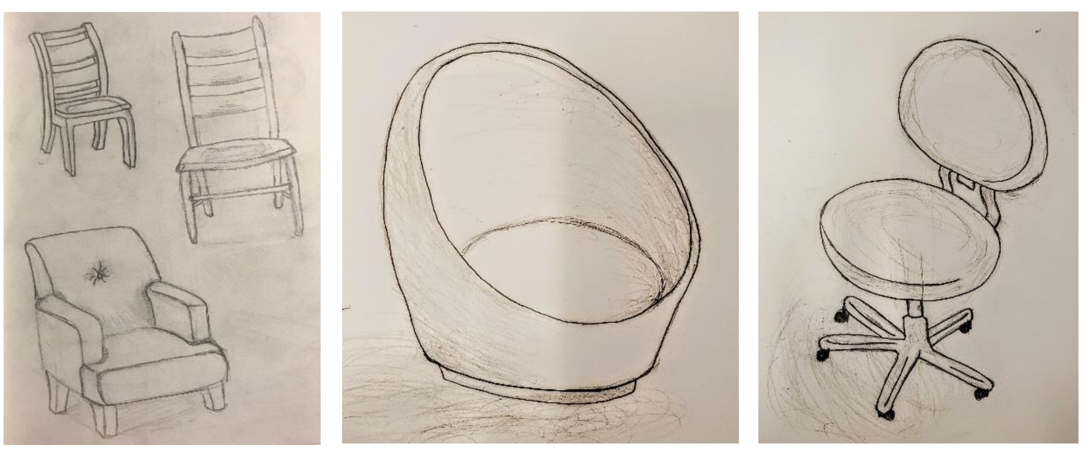

Figure 6. Chair sketches.

Visual Communication Skills

For each of the four units of the course, students are required to create a display to visually communicate how an engineered system of their choice works. The focus is on how the system works rather than how it is put together. For unit 1 students create an 11”x17” poster or display to visually describe how a structural or mechanical system works. For unit 2 students create a brochure to visually describe how an electrical or energy system works. For unit 3 students create an animation that is based on sketches to visually describe how a biomedical or robotic device works. Finally, for unit 4 students may choose both the medium and the type of engineered system for their final project display, which is shared publicly at an end of the term event attended mainly by others in the engineering department.

The rubric used to evaluate the projects is given in Appendix B. Students are evaluated based on 5 separate categories: Focus, Technical Details, Interest, and Illustration. The ‘focus’ category refers to whether or not the project focuses on an appropriate type of engineered system. For unit 1, students are asked to focus on a structural or mechanical system; for unit 2, they focus on an electrical or energy system; unit 3 focuses on a biomedical or robotic system; and for unit 4 students have their choice of engineered system (so there are no points assigned for ‘focus’ for project 4). For the ‘technical details’ portion of the grade, students are evaluated as to the level of accuracy of their technical details: it is clear how the components of the chosen system work together? Are all needed details included? For the ‘interest’ portion of the grade, students are encouraged to get the viewer interested in learning more about the engineered system that they chose, similar to the approach that is used in *The Ways Things Work*, with the goal being to help the viewer understand the significance of the selected system. How does it work and why? Students often fall into the trap of labeling parts and creating an instruction manual of how the components fit together and must be encouraged to make the display interesting. The ‘illustration and integration’ section of the rubric is used to evaluate whether the display is aesthetically pleasing, easy to read/view, and balanced. The focus is on clarity and communication rather than on sketching ability. In addition, students earn points for producing a draft of their display and for providing feedback on their own and peers’ drafts and final displays. Students work in small groups to evaluate their own drafts and projects as well those of the peers in their group using the feedback form that is included in Appendix C.

In order to determine if students’ visual communication skills improved, grades for project 1 are compared with those for project 4 as given in Table 2. Grades listed in Table 2 were assigned using the rubric given in Appendix B. Note: the rubric for project 1 includes 5 points for the focus of the project but this portion of the grade is not included in Table 2 so that direct comparisons may be made between project 1 and project 4. Project 4 does not include points for the focus of the project since students are allowed to choose their topic for project 4. Three different aspects of each project are considered in Table 2 as described previously: technical details, interest, and illustrations, with 25 points assigned to each of these 3 categories. The grades reported in Table 2 are the averages for the seventy-one students who took the course in 2017, 2018, and 2019. The projects are graded by each of the two professors in the course and then the two scores are averaged. The breakdown of students enrolled in the course by year and gender are given in Table 1. In 2018, enrollment was limited to 16 but that enrollment limit was increase to 24 in 2019.

As shown in Table 2, the grades for project 4 in all categories are higher than those for project 1. The average grade for all students went from a 76% on project 1 to an 86% on project 4. Student grades are bound to improve over the duration of a course as student work improves and they better understand what is expected of them but it is still encouraging to see an improvement. Scores are not disaggregated by gender as there was no significant difference in grades between men and women. Samples of project 1 and project 4 submissions are given in Figure 7 and 8, respectively. While students had a choice of medium for project 4, only poster-type displays are included here for a more direct comparison. Project 4 posters tended to be bolder, more interesting, and focused on the key details of the chosen system than project 1 posters. Future work will go beyond grades to use visual communication rubrics [11] or other approaches to assess changes in visual communication skills.

Table 2. Comparison of Project 1 and Project 4 grades (2017, 2018, and 2019; n=71)

	Technical Details (average points/25)	**Interest** (average points/25)	**Illustrations** (average points/25)	**Total** (points/75)	**Percentage**
Project 1	18.2	19.4	19.3	56.9	76%
Project 4	20.4	22.3	21.6	64.3	86%

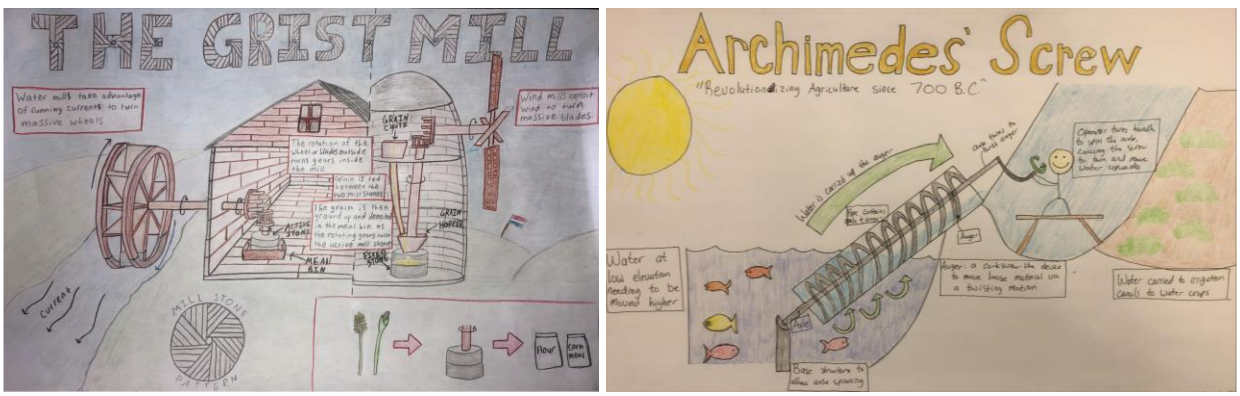

Figure 7. Project 1 Sample Posters.

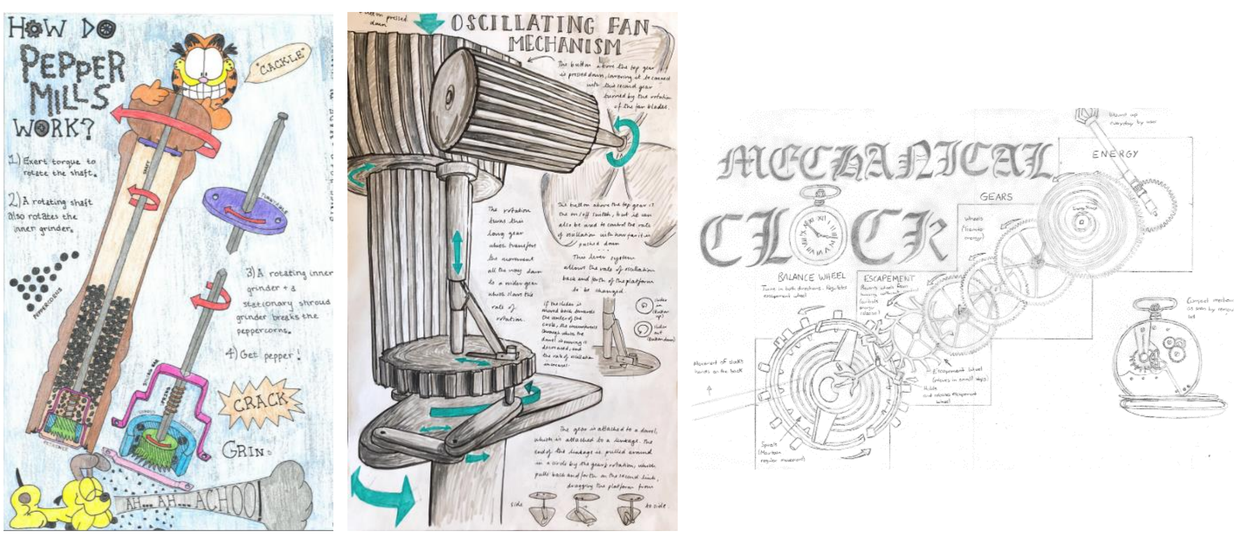

Figure 8. Project 4 Sample Posters.

Spatial Reasoning Skills
Comparison of pre- and post-course achievement on the PVST:R [5] from the past three years shows that students' spatial reasoning skills improved over the ten-week course. Figure 10 compares the percentage of correct answers on the PVST:R on the first day of class (Pre) with those on last day of class (Post). As shown, the percentage of correct answers increased. These increases are statistically significant as indicated by a one-sided paired samples t-test run in Excel (p=0.03) for the 71 students in the course over the past three years. Only 4 of the 71 students in the course got fewer correct answers on the post-test than on the pre-test; all other students scored the same or better on the PVST:R post-test than on the pre-test.

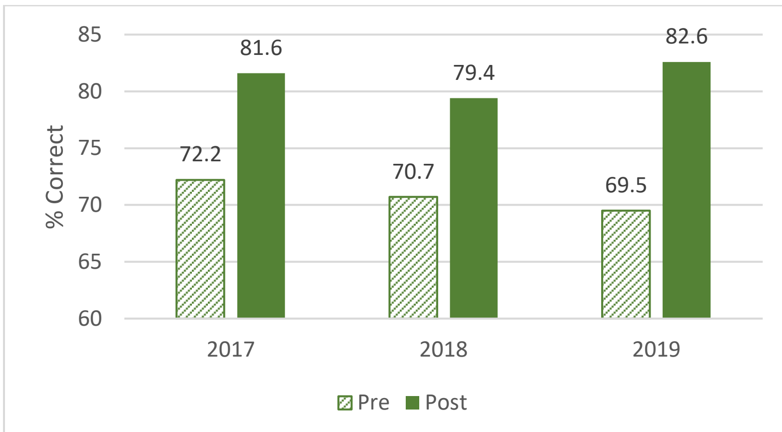

Figure 10. % Correct Answers on the Purdue Spatial Visualization Test (all students)

As shown in Figure 11, the average time to complete the PVST:R decreased, though only slightly and is not statistically significant. The average time to complete the PVST:R on the first day of class (Pre) as compared to the average time to complete the PVST:R on the last day of class (Post) decreased by almost 2 minutes in 2017 but less then one minute in 2018 and 2019. The PVST:R was administered online through Canvas, the learning management system used by the campus. A time limit of 15 minutes was used for the PVST:R but very few students used the full 15 minutes. The largest decrease in average time to complete the PVST:R occurred in the first year the course was offered, 2017. One possible reason for this larger decrease in the time required to complete the test in year 1 is that the course carried *technical* distributive credit rather than *art* distributive credit this first year; thus, a much larger portion of the students in the course in 2017 were non-engineering majors. In 2018, the course changed to art distributive credit and the demographics in the class shifted to include a much higher portion of students considering engineering as a major. We hypothesize that this population of student (those considering majoring in engineering) tended to enter the course with higher confidence in their spatial reasoning ability.

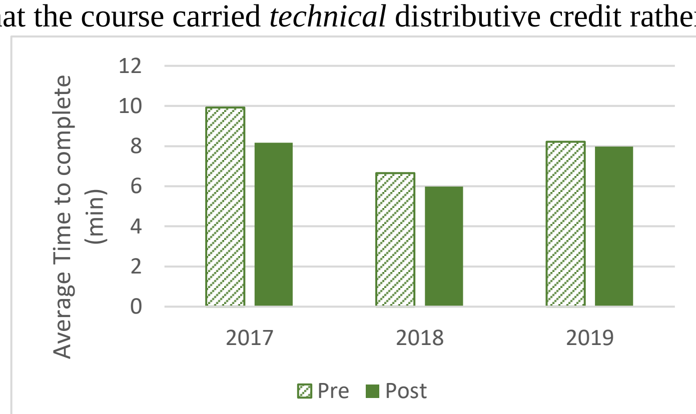

Figure 11. Average Time to Complete the Purdue Spatial Visualization Test (all students)

Several studies [3], [12], [13] have found that spatial reasoning ability varies by gender, with men tending to perform better on spatial reasoning tests than women. Students in *The Way Things Work* followed this trend, with men tending to get a higher percentage of rotations correct on the PVST:R, both on the pre- and post-test. The pre- and post-test results for students in *The Way Things Work* are disaggregated by gender in Figure 12. It is somewhat disheartening to find that women continue to lag in spatial reasoning skills but encouraging to see that it is possible to improve spatial reasoning abilities. Note that in all years except 2019, men got a higher percentage of answers correct on the pre-test than women. In 2019, men got 63.3% of the answers correct on the pre-test, while women got 74.2% correct on the pre-test. Further investigation finds that one of the men in the 2019 class got a zero on the pre-test and a 10 on the post-test; while this scenario is possible, it is more likely that there was a problem with the online administration of the pre-test in this individual case. Thus, the results, at least for the men, in 2019 are slightly suspect.

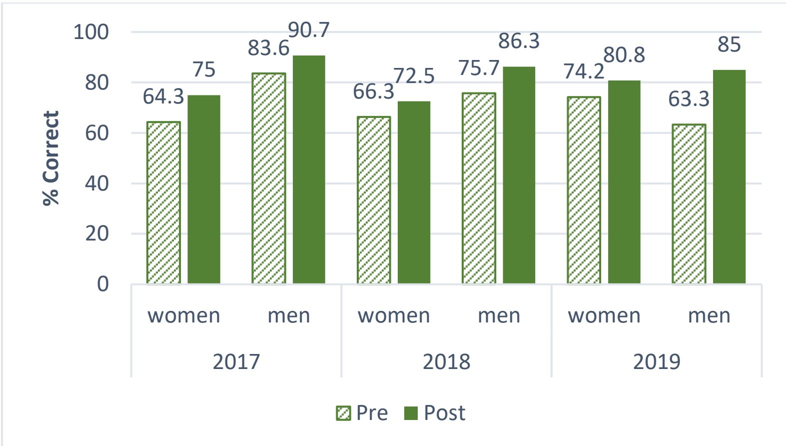

Figure 12. % Correct Answers on the Purdue Spatial Visualization Test by Year and Gender

Conclusions and Future Work

Students who took *The Way Things Works* over the past three years increased their ability to visually communicate and to reason spatially as evidenced by their scores on initial and final projects as well as on pre and post versions of the Purdue Spatial Visualization Test: Rotations. Future work will assess whether the building activities, sketching exercises, or projects have the largest impact on student performance in the course. Future work will also assess whether these improvements in spatial reasoning and visual communication have an impact on student choices (are these students more likely to major in engineering?) and student outcomes (do these students perform better in later engineering courses?). Future work will also use rubrics [11] or instruments to assess changes in visual communication skills.

References

[1] Macaulay, David (1988). *The Way Things Work*. Houghton Mifflin.

[2] Macaulay, David (2016). *The Way Things Work Now*. Houghton Mifflin Harcourt and Dorling Kindersley.

[3] Maedo and Yoon, (2013). "A Meta-Analysis on Gender Differences in Mental Rotation Ability Measured by the Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R)." *Educational Psychological Review,* 25(1), 69–94.

[4] Walton et al., (2015). "Spatial Visualization Skills Intervention for First Year Engineering Students: Everyone's a Winner!" *Proceedings of the 2015 Annual American Society of Engineering Education Conference*. Seattle, WA.

[5] Guay, R. (1976). *Purdue Spatial Visualization Test - Visualization of Rotations*. W. Lafayette, IN. Purdue Research Foundation.

[6] Branoff, T. J. (2000). "Spatial Visualization Measurement: A Modification of the Purdue Spatial Visualization Test-Visualization of Rotations." *Engineering Design Graphics Journal*, 64(2), 14-22.

[7] E. Brumberger, "Visual literacy and the digital native: An examination of the millennial learner," Journal of Visual Literacy, vol. 30, no. 1, pp. 19-46, 2011.

[8] ABET, "Criteria for accrediting engineering programs, 2016-2017," ABET, Inc., Oct. 16, 2015.

[9] Keller, C.A., Robinson, L.A., and Ault, H.K., (2018). "Visual Literacy in Mechanical Engineering Design: A Practical Approach to Assessment and Methods to Enhance Instruction." *Proceedings of the 2018 ASEE Annual Conference*. Salt Lake City, UT.

[10] May, Vicki V. (2016). "Building Tensegrity Structures to Explore Interactions between Tension and Compression (P12 Resource Exchange)." *Proceedings of the 2016 Annual American Society of Engineering Education Conference*, New Orleans. https://www.asee.org/public/conferences/64/papers/15164/view

[11] T. Bowen, "Assessing visual literacy: A case study of developing a rubric for identifying and applying criteria to undergraduate student learning," Teaching in Higher Education, vol. 22, no. 6, pp. 705-719, February 2017.

[12] Ginn, S.R., and Pickens, S.J. (2005). "Relationships between spatial activities and scores on the mental rotation test as a function of sex." *Perceptual and Motor Skills*. Vol. 100, p. 877-881.

[13] Guay, R. (1978). "Factors affecting spatial test performance: Sex, handedness, birth order, and experience." Paper presented at the *Annual Meeting of the American Educational Research Association*, Toronto, CA.

Appendix A. Course Syllabus

ENGS11. The Way Things Work:
A Visual Introduction to Engineering

THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Instructors:	David Macaulay / david.a.macualay@dartmouth.edu Vicki V. May / MacLean 306 / vicki.v.may@dartmouth.edu
Office Hours:	Wednesday noon-1:30pm in MacLean 306 (Vicki's office). Additional help available as needed – send a note to Vicki or one of the TAs.
Course Time:	[10A] Tuesday and Thursday 10:10am-12noon
X-hour:	Wednesday 3:30-4:20pm
Course Location:	MacLean 201 (Rett's Room)
Teaching Assistants:	Julia Marcotte and Carolina Almonte

Learning Objectives: Through this course students will:

- Improve their ability to observe, sketch, and visually communicate;
- Develop their creativity skills;
- Explain both verbally and visually how engineered systems work;
- Critically evaluate their own work and that of their peers.

Prerequisites: None

Enrollment: Limited to 24 students

Course Description: Students will explore and compare engineered systems and processes in the world around them. They will sketch and build models to help them understand and communicate. Each week, students will learn new sketching and visual communication techniques that they will use to visually explain how engineered systems or processes work. Students will also maintain a sketchbook to practice new sketching techniques. After being exposed to some basic engineering principles students will further investigate specific engineered systems through sketching, research, disassembly, and building. They will communicate their findings visually to the class, to the Thayer community, and beyond.

Distributive: **ART**

Resources:
The Way Things Work Now by David Macaulay
Experiences in Visual Thinking by Robert H. McKim
Building Big by David Macaulay

Units: The course will be separated into three units or topics, with the following focuses: 1) structural and mechanical systems, 2) electrical and energy systems, and 3) biomedical and robotic devices. Each unit will begin with a brief introduction of the basic principles associated with that topic. Students will be encouraged to sketch, build, and take objects apart. For each unit students will investigate an engineered system of their choice related to that unit. Students will present their findings visually at the end of each unit.

Teaching Approach: Lectures will be kept short with much of each class period spent sketching, building, taking things apart, and working on the projects for the course.

Projects: Each unit will culminate in a project through which students communicate visually and verbally how an engineered system or process of their choice works. Projects will be completed individually but developed collaboratively in small groups.

Sketchbook: Each student must keep a sketchbook that is dedicated to the class. Sketchbook pages will be submitted weekly, with each week focusing on a different sketching technique.

Exercises: Weekly exercises are designed to help students develop creativity skills and better understand engineered systems and process. Exercises will include online exercises, hands-on activities, and written exercises.

Final Exam: No final exam will be given but there will be a final project and exhibition.

Grading:

Sketchbook – 15%
Building Exercises – 10%
Projects – 75%
- *Project 1 (Structural and Mechanical Systems) – 20%*
- *Project 2 (Electrical and Energy Systems) – 20%*
- *Project 3 (Biomedical and Robotic Devices) – 20%*
- *Final Project (Choice) – 15%*

Tentative Course Calendar

Unit	Date	Topics/Activities	Deadlines/Notes
1: Structural and Mechanical Systems	Tues., Jan. 7	• Intro to the course • Trusses and Tensegrity • Build tensegrity structures • **Sketching Thoughts 1**	
	Wed., Jan. 8	• Sketching Hour (optional)	
	Thurs., Jan. 9	• Beams and columns • Build beams • Identify and sketch beams and columns	*Tensegrity Due* Sketchbook 1 Due
	Tues., Jan. 14	• **Sketching Thoughts 2** • Introduction to Mechanical Systems • Design automata • Brainstorm ideas for project 1 • Evaluate layouts from *The Way Things Work*	
	Wed., Jan. 15	• Sketching Hour (optional)	
	Thurs., Jan. 16	• Build (and sketch) automata • Share and discuss project 1 ideas	Sketchbook 2 Due
	Tues., Jan. 21	• **Sketching Thoughts 3** • Take apart (and sketch) a mechanical system • Review project drafts	Project 1 Draft Due *Automata Due*
	Wed., Jan. 22	• Sketching Hour (optional)	
	Thurs., Jan. 23	• Share and evaluate unit 1 projects	**Unit 1 Project Due**
2: Electrical and Energy Systems	Tues., Jan. 28	• **Sketching Thoughts 4** • Intro to circuits and electrical systems • Experiment with circuits	
	Wed., Jan. 29	• Sketching Hour (optional)	
	Thurs., Jan. 30	• Intro to energy systems • Solder solar lanterns (*Couch reserved*) • Brainstorm ideas for project 2	Sketchbook 3 Due
	Tues., Feb. 4	• **Sketching Thoughts 5** • Build solar lanterns and wind turbine blades	
	Wed., Feb. 5	• Sketching Hour (optional)	
	Thurs., Feb. 6	• Take apart (and sketch) electronic devices • Review project 2 drafts • *Vicki away*	Project 2 Draft Due *Solar Lanterns Due* Sketchbook 4 Due
	Tues., Feb. 11	• **Sketching Thoughts 6** • Share and evaluate unit 2 projects	**Unit 2 Project Due**
	Wed., Feb. 12	• Sketching Hour (optional)	

3: Biomedical and Robotic Devices	Thurs., Feb. 13	• Intro to biomedical and robotic devices • Take apart a biomedical device • Brainstorming for project 3	Sketchbook 5 Due
	Tues., Feb., 18	• **Sketching Thoughts 7** • Cast hands in shop	
	Wed., Feb. 19	• Sketching Hour (optional)	
	Thurs., Feb. 20	• Build/sketch grabber • Review project 3 drafts	Project 3 Draft Due
	Tues., Feb. 25	• **Sketching Thoughts 8** • Share and evaluate unit 3 projects	**Unit 3 Project Due**
	Wed., Feb. 26	• Sketching Hour (optional)	
4: Choice	Thurs., Feb. 27	• Project work time and sharing	*Grabber Due* Sketchbook 7 Due
	Tues., March 3	• Review final project drafts	Final Project Draft Due
	Wed., March 4	• Sketching Hour (optional)	
	Thurs., March 5	• Share and evaluate final projects	**Final Project Exhibition**

Appendix B. Project 1 Rubric

ENGS11. **Project 1 Rubric**

Winter 2020

Name: ____

	Requirements: simply completing each of these aspects does not mean you will get full points. High-quality, accurate, and easy to understand work will receive full points.	**Points**
Focus	A structural or mechanical element or system is the primary focus of the display.	/5 points
Technical Details	Technical details are explained well. Is it clear how the selected element or system works to support loads or to complete a task.	/25 points
Interest	The display draws the viewer in and piques their interest. The significance of the selected system or element is clear.	/25 points
Illustrations and Integration	The display is aesthetically pleasing, easy to read/view, and balanced. Sketches and images are clear, used effectively and well integrated.	/25 points

Comments:

Appendix C. Peer Feedback form

Project 1 – Peer Feedback

ENGS11. Winter 2020

	Are the visual explanations clear?	
	What do you find most interesting?	
	What questions do you have?	
	What could be improved?	
	Are the visual explanations clear?	
	What do you find most interesting?	
	What questions do you have?	
	What could be improved?	
	Are the visual explanations clear?	
	What do you find most interesting?	
	What questions do you have?	
	What could be improved?	
	Are the visual explanations clear?	
	What do you find most interesting?	
	What questions do you have?	
	What could be improved?	