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Industry Feedback Leads to an Instructional Scaffold Approach to Teaching Geometric Dimensioning

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Geometric Dimensioning and Tolerancing (GD&T) is a powerful tool for designing and manufacturing products. If used correctly, GD&T can streamline and optimize the manufacturing of products, saving companies a tremendous amount of time and money. In trade schools, GD&T is traditionally taught in the machine shop in parallel to learning equipment in the machine shop. At the university level, traditional engineering curriculum conventionally teaches GD&T in design courses, many times without the use of the machine shop or understanding of the machine shop equipment capabilities. Students at universities tend to struggle with grasping GD&T concepts if 'hands-on' assignments or projects are not designed to reinforce concepts learned in the classroom. (Waldorf, 2016)

At UNIVERSITY, the incorporation of GD&T into the classroom began with a recommendation from the UNIVERSITY's industrial advisory board in addition to interviews with several companies both locally and nationally. The recommendations stemmed from students not having adequate GD&T and machine shop skills for both designing and manufacturing products upon graduation. Based on these recommendations, UNIVERSITY redesigned a traditional field session course into a successful 1) online and 2) 'hands-on' scaffolded approach to teaching GD&T and machine shop skills to engineering students with the goal of translating these teaching modules into modules for the current workforce development.

Throughout the past year, over 23 interviews have been conducted at companies across the country (support NSF-PEER, Award Number 1935674). These interviews have focused on manufacturing-centric companies, specifically asking about current work force development. From initial qualitative interview results, an aspect of GD&T or engineering design had 84 occurrences throughout these interviews. Many interviewees, were engineers within companies, stating that GD&T is currently lacking from the skillsets of engineers. There is a need to improve GD&T curriculum at the undergraduate and graduate levels as well as within the current work force.

This paper discusses the development of a three-tiered instructional framework to teach core GD&T concepts to undergraduates, graduates and the current work force. The goal of using instructional scaffolding is to bring abstract concepts to life through 'hands-on' experiences and repetition. Additionally, the UNIVSERITY'S Teaching and Learning center created an asynchronous online platform for online course development based on best practice guidelines through Engineering and Facilitating Online Learning (EFOL). Finally, this paper will report on the assessment practices that took place over a two-year time period, to evaluate students understanding of GD&T concepts throughout their academic careers.

Background on past curriculum

At UNIVERSITY, the undergraduate degree program requires all Mechanical Engineering students to complete a sophomore-level core course called *Introduction to Design and Fabrication*. This course reinforces CAD skills using SolidWorks, teaches students GD&T and also trains students on the manual mill, manual lathe and CNC mill. Over 150 students take the course every semester (fall and spring).

Historically, this course was taught as units, teaching students CAD skills, then GD&T and then machining, with an end of semester project that was tied all units together. Students were missing the connection between these units as seen through their final drawing packages. Average grades on final drawing packages was around a 75% based on several best practices identified by a core team of faculty. Additionally, during Senior Capstone, students were struggling to create drawing packages that clients were happy with. It was clear that this model of teaching CAD, GD&T and machining was not clicking with students. Additionally, their excitement around the topic was far from excitable.

The learning outcomes for the course did not change. Below lists the learning outcomes for the course, with number 4 and 5 directly being related to GD&T curriculum. These outcomes will be discussed later on in the assessment portion of the paper.

By the end of the course, students will be able to:

1. Generate pencil-and-paper and computer prints for basic parts and assemblies.
2. Identify and apply fundamental dimensioning rules from ANSI standards.
3. Correctly implement ANSI symbols, terms, datums, material conditions and tolerances in characterizing parts and assemblies.
4. **Utilize modern tools to measure part features and identify if parts meet defined specifications based on dimensions, tolerances and GD&T.**
5. **Design simple assessment gauges to evaluate form tolerances called out using GD&T.**
6. Apply statistical analysis to create charts and tables from known uncertainty for both measurements and manufacturing errors.
7. Utilize SolidWorks to design an object and/or product for manufacturing.
8. Pass safety training for the ME machine shop.
9. Identify proper tooling for various materials and applications for the manual lathe, manual mill and drill press.
10. Manually use horizontal bandsaw, vertical bandsaw, sheer/break or hand saw to cut various materials to stock sizes.
11. Use hand tools for final assembly of parts.
12. Distinguish the capabilities and best applications for a CNC mill.
13. Distinguish the capabilities and best applications for FDM printing.

Details of scaffold curriculum development

Moving forward, in the Fall of 2018, the course received a major revamp to address the need for students to create better drawing packages and also an industry need from the department's Industrial Advisory board to incorporate more GD&T and quality control. The development of the course transitioned into a scaffold approach, where students would learn about all core concepts at once, learning how they are related to one another. As the semester progressed, concepts would get more complex, however all concepts were continuously reinforced throughout the semester. Additionally, two hands-on projects were incorporated, starting with very basic with specific guidelines and becoming more open-ended by the end of the semester. The broader learning objectives that were reinforced throughout the semester included:

- Good drawing practices based on ANSI standards
- Proper incorporation of GD&T into prints based on ANSI standards and understanding how parts should be inspected based on dimensional and tolerance callouts.
- Understanding how to check a part to see if it is within specification.
- Incorporating the manual mill, lathe and CNC mill when appropriate based on specified tolerances and functionality of the design part.

Instructional scaffolding is a proven technique for teaching engineering problem solving, especially to address hard to teach topics such as open-ended design. (Girgis 2015, Allam 2012, Rosenshine 1992, Pea 2004) A summary of the instruction scaffolding approach is listed below:

- An instructor adds supports for students in order to enhance learning and aid in the mastery of tasks.
- This is done by systematically building on student’s experiences and knowledge as they learning.
- Just like the scaffolding for construction, these supports are temporary and adjustable. As students master the assigned tasks, the supports are gradually removed.

Examples of assignments and projects

At the beginning of the semester, students are introduced to the course and the learning outcomes are discussed. The instructional scaffold approach is explained to students with regards to the two semester projects.

For the first project, students are required to design a simple Roller Caster with various features machined on the lathe and mill based on engineering prints and basic GD&T callouts. The part requires assembly as well as QA/QC (quality assurance and quality control) checking. This aspect forces students to truly consider GD&T callouts, thinking about which callouts are required for the part to be functional. Additionally, there is an assembly aspect to the part that requires standard bolts and fasteners that students are required to look-up and fully understand using an educational version of a machinists handbook (The Engineers Blackbook).

Before the start of this project, students review basic CAD skills through Solid Professor, which students are required to do on their own time. In-class discussions start around GD&T basics and how to use quality control equipment and instrumentation are discussed. These units are intertwined for several weeks, before the first project kicks-off. An example schedule is seen in Figure 1.

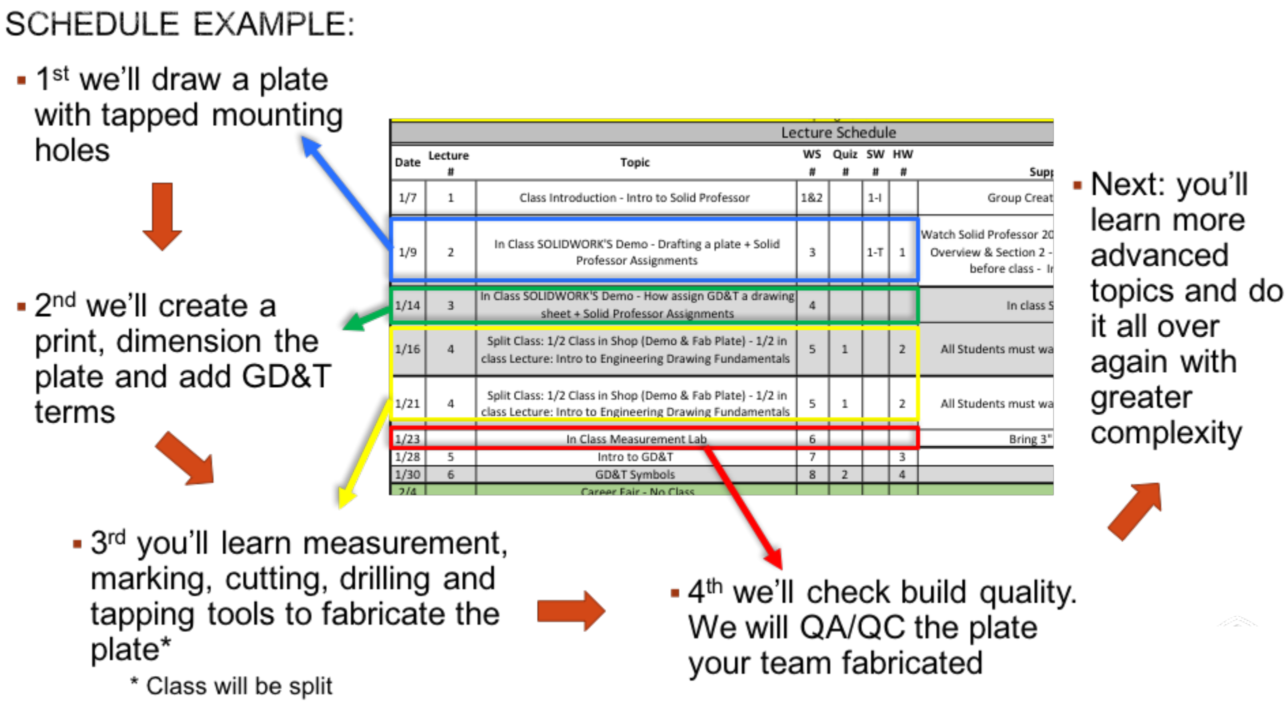

Figure 1: Instructional Scaffolding Schedule

Instructional scaffolding framework for teaching skillsets, requires clear understanding of the pathway for learning (Rosenshine 1992). Students are presented with slides at the beginning and throughout the semester to show the pathway from which they are learning.

A review of the first project is seen in Figure 2 below. This image shows how the various skillsets taught in class are linked together, especially with regards to the project. This project incorporates and general design with standardization of parts. However, with all engineering design, these projects consist of iterative approaches to learning as students constantly make up-dates on their CAD drawings based on changes in customer demand (ie: the instructor), effecting and altering the GD&T callouts and therefore quality control instrumentation. Throughout the design process, the instructor requests that students make changes to the design based on supply and certain materials for the Roller Caster being 'out of stock'. Students learn about design iterations and by showing students what instructional scaffolding looks like early on, we are better setting students up for success in understanding the material.

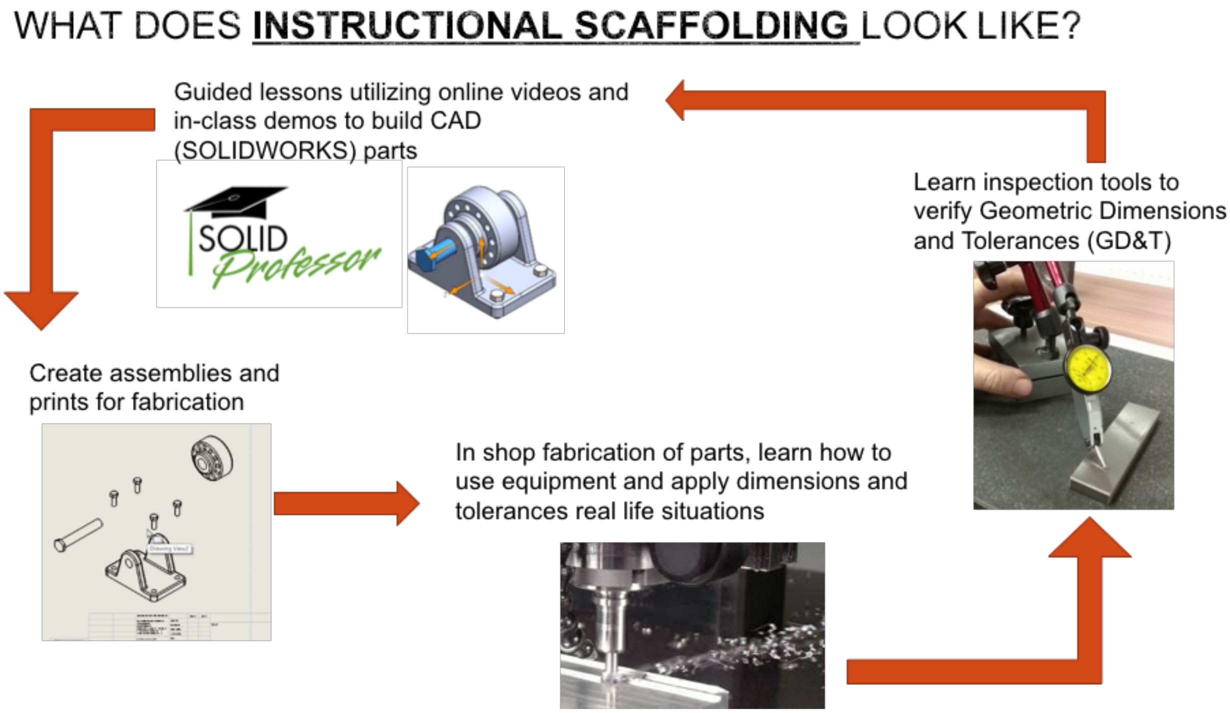

Figure 2. Overview of the first project.

After the completion of Project 1, students quickly go into Project 2, which runs for 6 weeks throughout the semester. Project 2 challenges students to take the training wheels off and really start applying the learned skillsets taught throughout the course. Students are asked to design and fabricate a derby car that will be raced at the end of the semester. Students are given minimal constraints except for material and overall size, however by providing students with an open-ended design platform, students are forced to start thinking about what they learned in class thus far. Students begin to apply these learned skillsets to their designs, and better understand the idea of iteration in the design process.

Project 2 is especially exciting for students because they get to race their cars at the end of the semester. Students get excited about designing and machining their cars, therefore they get excited about the skillsets learned in class. A general survey went out to students at the end of the semester and over 80% of the students in class stated that the Derby Car project was exciting and motived them to create a winning car. This is a critical aspect of the project, since it is one of the motivating factors behind encouraging learning. (Grunert 1997)

Figure 3 is an overview of Project 2, the open-ended designed Derby Car. One of the steps that is most important in Figure 3, is the aspect of iteration with regards to the design. Students many times want to design then build without checking their designs. It is critical that students consider the quality check during the design process and also GD&T as this can greatly change the design of their cars. As a client, the instructor makes various announcements through the design stage of the project. For instance, the standard fastener used is out of stock for a month, so a new one needs to be considered. Students quickly learn that design and fabrication is an iterative process, just like the engineering design process and every other problem solving process that they learn about and experience.

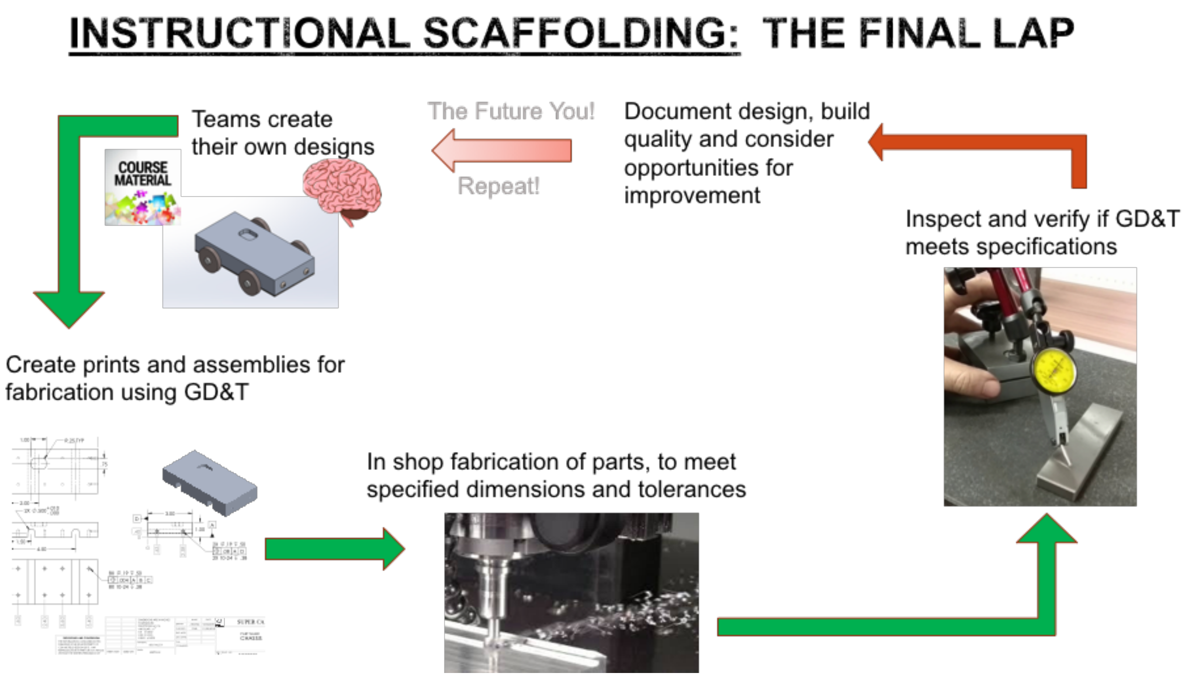

Figure 3. Project 2 overview.

Assessment methods and models

Assessment for the course has been a triangulated approach, taking the multisource assessment and feedback processes in the classroom and the potential impact on student learning in engineering (McGourty 2000, Ghrayeb 2011, Lui 2018, Cruz 2019). Assessment was based on 1) student focus groups, 2) student performance on the final competency (interview) exam and 3) final project review. Assessment measures 1 and 2 were individually focused, while assessment measure 3 is based on a group assignment, linked to a peer evaluation.

Student focus groups are conducted at the end of the semester by faculty. Recent feedback from students stated that they are excited about the learning the material. However, many students still find the content to be dry, especially if they are not originally interested in the subject matter. In some way, student feedback provides some insight that the course should be taught later on in the curriculum, after students go through several design projects in other courses and start to see the importance of the material.

Student focus groups were also conducted with several senior. capstone students. Much of the feedback confirmed this finding as students stated that they wished they had realized the importance of the course earlier on, as it was clear during senior capstone that the tools and skillsets learned in the course better prepared students for capstone.

The final competency exam at the end of the semester is a 10 min interview where students are required to understand drawings and dimensions, GD&T callouts and show they understand how to perform quality control measurements, one-on-one with an instructor. All 150 students, every semester go through the interview final. Results have shown that students are perform well in dimensioning, tolerancing and GD&T with over 80% of the class scoring an 80% or higher on the final exam. Final competency exams were not conducted in earlier semesters before the course revision was made. In past semesters, final exams were short answer and also based on pre-drawn CAD drawings.

In order to assess a comparative study with how students did before and after the course changes, final CAD drawing packages were assessed based on the same grading rubric (Table 1) and the same learning outcomes for the course (LO 4 and 5) before and after course redesign. These best practices are based on ANSI dimensioning and tolerancing standards.

CAD packages were graded and evaluated at the end of the semester from final projects in the class. Similar to the course redesign, several past semesters also had a final design and fabrication focused Derby Car project. Historically, students have struggled with appropriate incorporation of GD&T into their engineering prints, not focusing on the functionality of the part.

Best Drawing Practices/GD&T	
100.0 pts	The drawing has used correct GD&T (or is not needed) and adheres to the best drawing practices fully
90.0 pts	The drawing has used mostly correct GD&T (or is not needed) and/or mostly adheres to the best drawing practices
80.0 pts	The drawing has used mostly correct GD&T (or is not needed) with some errors and/or mostly adheres to the best drawing practices with some errors
70.0 pts	The drawing has used mostly correct GD&T (or is not needed) but with greater error and/or adheres to the best drawing practices with greater error
60.0 pts	The drawing has used somewhat correct GD&T (or is not needed) and/or moderately adheres to the best drawing practices
50.0 pts	The drawing has used lacking GD&T (or is not needed) and/or misses several of the best drawing practices
40.0 pts	The drawing has used poor GD&T (or is not needed) and/or poorly adheres to the best drawing practices
30.0 pts	The drawing has used incorrect GD&T (or is missing and needed) and/or does not adhere to the best drawing practices
20.0 pts	The drawing has used very little correct or no GD&T and/or does not adhere to the best drawing practices
10.0 pts	The drawing has used very little correct or no GD&T and does not adhere to the best drawing practices
0.0 pts	No Marks
100.0 pts	
This criterion is linked to a Learning OutcomeDesign for Manufacturing	
100.0 pts	The design is created/drawn with a focus on realism and being designed for manufacturing
90.0 pts	The design is mostly created/drawn with a focus on realism and being designed for manufacturing
80.0 pts	The design is overall created/drawn with a focus on realism and being designed for manufacturing
70.0 pts	The design is somewhat created/drawn with a focus on realism and being designed for manufacturing
60.0 pts	The design is created/drawn with a focus on realism and being designed for manufacturing but has errors
50.0 pts	The design is created/drawn with a focus on realism and being designed for manufacturing but has major errors
40.0 pts	The design is lacking to be created/drawn with a focus on realism and being designed for manufacturing
30.0 pts	The design is heavily lacking to be created/drawn with a focus on realism and being designed for manufacturing
20.0 pts	The design would likely be very difficult or unrealisitic to manufacture
10.0 pts	The design would be nearly impossible or prohibitly expensive to manufacture
0.0 pts	The design could not be manufactured
100.0 pts	

Table 1. Drawing

Over the past four semesters, the same grading rubric above has been used to assess students final CAD packages. The following table provides an overview of the results from the past four semesters, before and after the course redesign (Table 2).

	Ave Grade Best Drawing practices with GD&T	Ave Grade for DFM
Summer Semester 2017 - Before course redesign	75%	85%
Fall Semester 2018 - After course redesign	70%	80%
Spring Semester 2019	85%	85%
Fall Semester 2019	87%	86%

Table 2. Results from the past 4 semesters – before and after course redesign.

Results show that students originally did worse on the Best Drawing practices with GD&T after the initial course redesign. This is due to several factors as in redesigning any new course. Several modules were not fully in-place and it was found that many changes needed to be made to the redesigned curriculum, mostly for clarity purposes, but also for better documented support. Between Fall 2018 and Spring 2019, appropriate revisions were made to the curriculum. These included, more in-class workshops that paralleled lecture, incorporation of several quizzes and tweaking the project scope. It was found that after the updates to the course, the student average went up 15% and continued to stay high the following semester as well. The course has continue to have minor changes every semester.

Conclusions

Overall, the instructional scaffolding approach for teaching GD&T with regards to machining and QA/QC has shown to be an effective way of teaching these hard to teach subjects. Additionally, we have reviewed the syllabus with various industry partners and the feedback has always been, 'that is exactly what we are looking for'.

Results from ongoing assessment of drawing packages show that there was improvement in student performance with understanding of GD&T after the course redesign. However, focus groups presented feedback that the course is most likely offered too early in the curriculum for students to really grasp the concepts with regards to open-ended design.

In the future, we would like to survey several students who have graduated and who are in industry to discuss the course and possible course improvements. We will also continue to think about either pushing the class later in the curriculum or how to better engage students early on with these skillsets.

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