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Using 3D Printed Teaching Pass-Arounds for Mechanical Design Courses

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Using 3D Printed Teaching Pass-Arounds for Mechanical Design Courses

Abstract— Inexpensive additive-manufacturing (three-dimensional printers) allows faculty to create tools that address diverse learning styles, especially visual and kinesthetic learners. Inexpensive 3D-printing has unleashed solid mechanics instructor creativity to produce physical representations of the mechanical parts being taught. These 3D-printed "pass-arounds" are touched and manipulated by students as important design features are introduced and discussed. 3D printing capability allows an engineering instructor to develop and implement ideas for new teaching aids quickly. This paper presents five different solid mechanics and mechanical design teaching aids that were rapidly conceived, designed, printed, and implemented within two semesters of acquiring a dedicated instructor 3D printer. The tools generated enhanced student learning and helped them build connections between what's on paper and real objects in a constructivist manner. There is considerable potential for instructor creativity while developing innovative solutions quickly, but these ideas can also be easily shared with other instructors as open-source printable files. This paper demonstrates the example ideas with the purpose of sharing the tools and inspiring fellow faculty to improve and build upon them. These teaching tools and more like them can be printed with inexpensive printers making them accessible everyone.

Keywords—spatial visualization, solid mechanics pedagogy, gear design, 3D printed instructional tools

I. Introduction

This article describes the use of 3D printed teaching aids, dubbed "pass-arounds", in two machine design courses. The objects were passed around the class when introducing topics so students could become familiar with them as real physical objects and to help visualize specific aspects that are more difficult to understand via diagrams, pictures, written descriptions or oral explanations. By touching and manipulating these pass-arounds, kinesthetic learners and visual learners can make their own observations and digest the important attributes and details as they are being described during the lecture; this is essentially constructivist learning.

The machine design courses at the University of Hartford are Elements of Mechanical Design (ME 370) and Mechanical Design (ME 470). These are typically taken by mechanical engineers in the Fall and Spring their junior year, respectively, and are among the most challenging they face based on historic passing rates and end-of-semester testimonials. ME 370 focuses on building upon Mechanics of Materials and Statics from their sophomore year and applying those ideas to relatively simple design and analysis scenarios. Often students struggle applying the prerequisites either because they have forgotten what they learned or never mastered the topics in the previous semesters. Often, their challenges seem to stem from spatial visualization issues, including the inability to draw different views of a three-dimensional object or identify different types and forms of stresses acting on a stress element.

ME 470 builds upon ME 370 and focuses on different machine components and includes a design project that runs throughout the semester where students must apply what they've learned in both courses. Students have often heard of the components in ME 470 and may have seen them before, but typically most have not held them in their hands or observed them closely. Many of the details of selecting or designing each component are tied into concepts from ME 370, but there are many other details specific to the components that students must understand.

3D printed learning aids have become increasingly common in a wide variety of disciplines and courses throughout academia. A comprehensive literature review of the use of 3D printers in education is [1] which includes a section on literature that describes "using 3D printing to produce artefacts that aid learning." Numerous fields such as anatomy, chemistry, dentistry, and physics have substantial literature describing the benefits of using 3D printed models to promote learning. A repeated theme in these papers seems to be how much better a physical object students can hold is than a 3D graphic representation. The use of 3D printed models in anatomy courses in particular have been written about.

Reference [2] documents the use of 3D printed crystallographic unit cells for learning materials science and postulates that kinesthetic learners may benefit most from using these objects in conjunction with the other learning preferences.

Research on VARK (visual, auditory, read/write, and kinesthetic) learning preferences [3] describes kinesthetic leaners as those who "want concrete, multi-sensory experiences in their learning." Approximately 32% of first year engineering students responding to the VARK quiz at one university [4] indicated kinesthetic was at least one of their learning preferences. This would indicate that a significant portion of Passing around objects is inherently an active learning activity. While some students will pass the object to the next person without as much as look at it, most students will turn it around and look for the features being discussed. Using 3D physical models was shown to improve communication of spatial design in [5]. A similar concept to the pass-arounds described in this paper is [6] where the objects are referred to as "Tactile Teaching Tools" (TTT) consisting of 3D printed molecular puzzles designed to improve the inclusion of students with visual disabilities into STEM education.

Reference [7] documents an ongoing effort to incorporate 3D printing into a first-year engineering curriculum. That work showed that students place value on using new technology, specifically 3D printers.

This paper presents the experience in creating and implementing five different pass-arounds. The purpose in sharing this experience is to inform other instructors of how easy this is to implement in these two solid mechanics courses and to inspire other instructors to create their own teaching tools. Because solid modeling is almost universally being taught to engineers in lieu of the traditional drafting and 2D CAD and because 3D printers are common in maker-spaces and design labs, creating these or similar learning tools is easily done by instructors or students as part of a class project. These pass-arounds and others like it can be used instead of expensive instructional aids from commercial vendors.

II. Approach

Beginning just before the Fall semester of 2019, the author worked with a colleague with significant experience working using 3D printers to print out some instructional tools to pass around the class. The first were some “gear teeth finger puppets” (described in more detail later) and an object to represent an example problem in ME 370 that looks like a “door handle”. The university’s Maker Space printers were used for the door handle, and the colleague printed the gear finger puppets on his personal 3D printer at home. Later in the semester, the author purchased a $340 3D printer (Fig. 1) after finding the university’s much more expensive printers were often occupied by students (as they should be). Having the 3D printer available allowed for numerous revisions of ideas without having to wait in the queue. It also enabled the author to monitor the printing progress, and to intervene when a print would go wrong, which was often. This model was selected after numerous discussions with students, many of whom have significant experience with inexpensive 3D printers and plenty of advice.

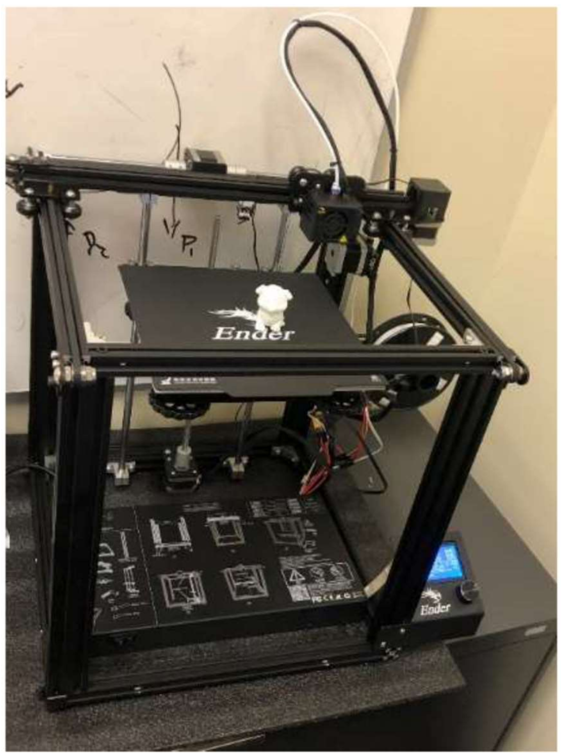

Figure 1: Inexpensive 3D Printer Purchased by Author

Throughout the next two semesters, the author printed many pass-arounds. Five “pass arounds” are discussed here:

- 3D Door Handle
- Two-Stage Gear Train
- Ball and Cylindrical Bearings
- Gear Finger Puppets
- Planetary Gear Set Trainer

A. 3D Door Handle

The two most common problem basic types in the early stages of the machine design course can be described as "door handles" and "3D shafts." A quick perusal through the problems section of a machine design textbook will confirm this trend. The most basic door handle is shown in Fig. 2, but much more complicated ones are possible such as those in Fig. 3, and these are much more challenging.

The "door handle" problem is a cantilevered beam subjected to moments about more than one axis (including torsion) and is well suited for combined stress problems. Students tend to struggle drawing Free Body Diagrams (FBDs) of the 3D door handle in three views, placing the forces at the correct locations, and solving for the reactions. Students also struggle with identifying which loads cause which stresses on a stress element, whether the normal stresses are tension or compression, and which direction to use with the torsional and transverse shear stresses.

Figure 4 shows the solid model used to print the door handle in Fig. 5. This was designed with a number features to address student struggles. These include holes at the tip where loads are typically placed. Toothpicks can be placed on any side, to represent the forces applied. By rotating the handle into the appropriate view the student can visualize the which force appears in which view and the appropriate directions.

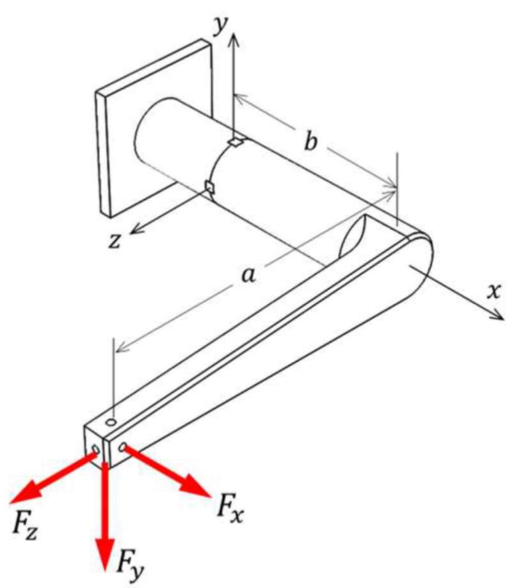

Figure 2: The Classic 3D Door Handle Problem

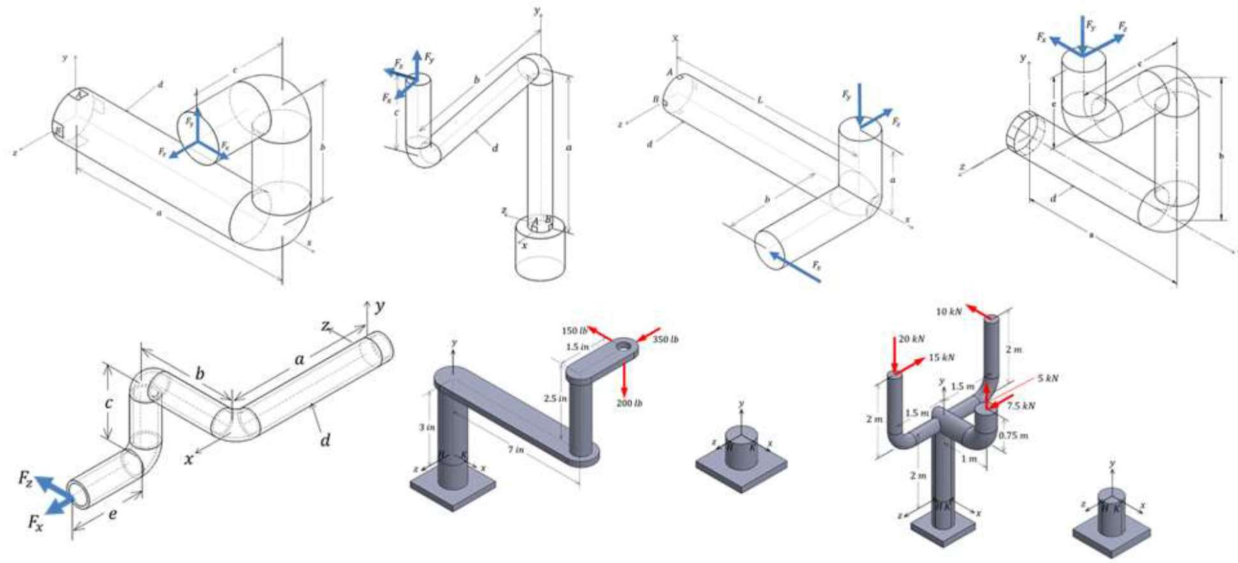

Figure 3: Variations on the 3D Door Handle Problem

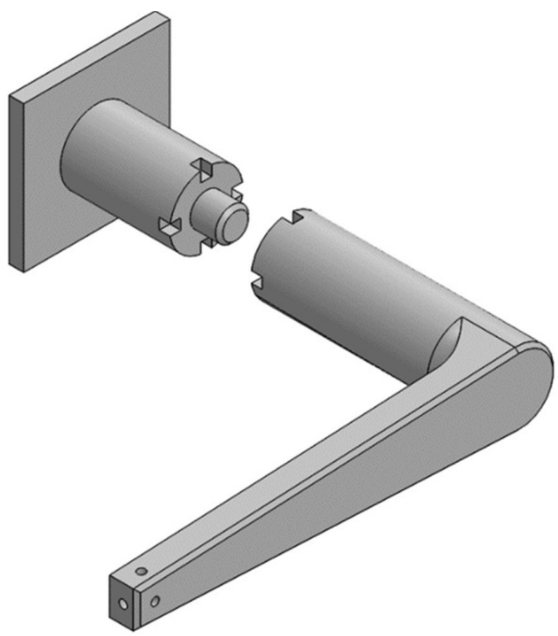

Figure 4: Solid Model of the 3D Door Handle Pass-Around

Figure 5: 3D Printed Door Handle Pass-Around Assembled and Disassembled, including Eraser Fragment Stress Elements

The 3D printed door handle also splits at the stress elements so the "stump" and the FBD can be discussed. The stress elements are represented by missing rectangular prisms. Small rectangles made from cut apart erasers can just barely fit into these slots. There is also substantial clearance between the FBD portion and the stump which, when the eraser pieces are put into place, allows some motion of the parts relative to one another and some noticeable motion in the eraser. That motion can be used to describe the tension, compression and shear due to the loadings and the student can actually feel and see this motion for themselves. The parts for this demonstration unit are available at the following link: https://www.thingiverse.com/thing:4786961 .

B. Two-Stage Gear Train

The other most common problem discussed in ME 370 is a 3D shaft as used as the intermediate shaft in a two-stage gear train. Many of the pictures within the textbook used for ME 370 [8] don't show the other gears, only the forces applied at the pressure angle. This can be quite confusing for students unfamiliar with the actual arrangement of a gear train. The two-stage gear train pass around helps put this basic problem into context of an actual machine. This also provides some motivation since it is not longer an abstract object but and actual application.

While passing around the demonstration the instructor can mention feature they will learn about later in ME 470, such as the idea of a pressure angle or the direction of forces. Towards the end of the semester in ME 370 a stepped shaft design project is assigned as shown in Fig. 6. The students apply the design concepts covered in the semester and design the shaft for static and fatigue strength and analyze it for deflection. Their deliverables are a drawing similar to Fig. 7 and supporting calculations.

Figure 8 shows an exploded view of the solid model used to make the 3D printed pass around shown in Fig 9. The intermediate shaft in Fig. 10 is passed around in ME 370 during the shaft design project discussion to introduce details such as the relative diameters of the steps in the shaft, fillets, and keyway. By showing these details using the pass-around, the expectations for details can be better communicated. Details such as typical proportions of a stepped shaft or what a keyway looks like were often missed in previous semesters before using the pass around.

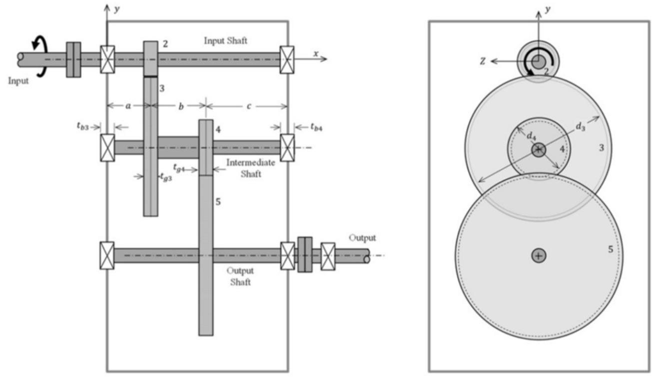

Figure 6: Arrangement Provided to Students of a Two-Stage Gear Train for a Stepped Shaft Design Project

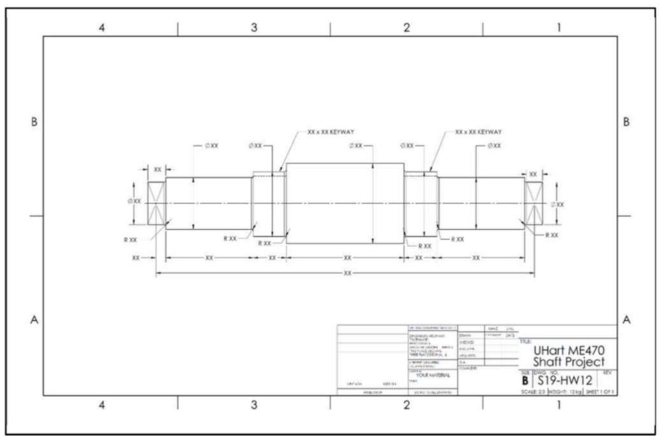

Figure 7: Typical Stepped Shaft Drawing Provided to Students to Communicate Expectations of Shaft Design Project Deliverable

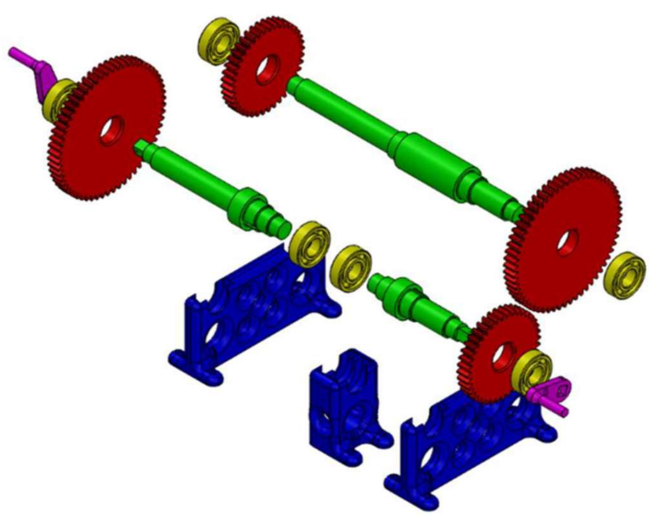

Figure 8: Solid Model Exploded View of Two-Stage Gear Train Pass-Around

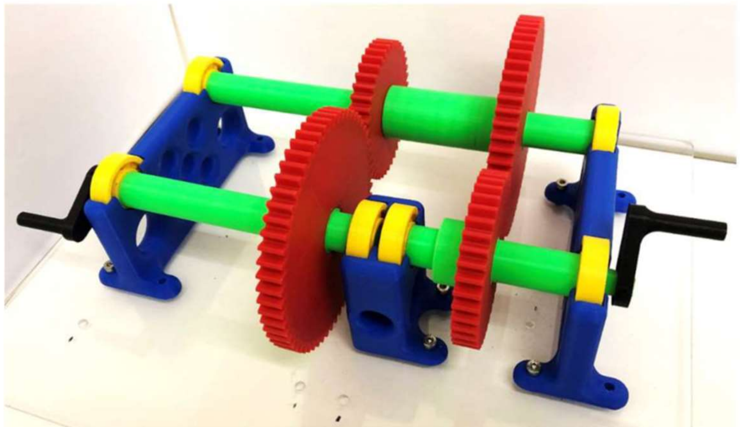

Figure 9: 3D Printed Gear Train Pass-Around

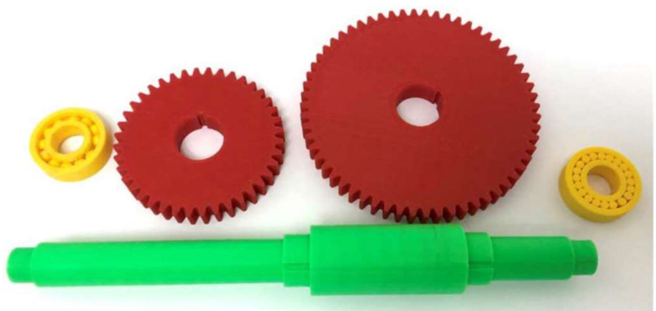

Figure 10: 3D Printed Shaft, Gears and Bearings

In ME 470 students learn to design/specify the bearings and gears, so the gear train pass-around is used again, but now more design features and details can be introduced on a machine they're already familiar with. Concepts such as the reversing of shaft direction with each stage, the inverse relationship between torque and speed, speed reducers versus speed increasers, the need for a keyway and the pressure angle can be discussed while the students play handle the pass-around. Students can feel the resistance of the output versus the input and take the components apart. Discussion of the features is now referring to an actual object rather than a picture on a slide. The parts for this demonstration unit are available at the following link: https://www.thingiverse.com/thing:4786935 .

C. Ball and Cylindrical Bearings

Inspired by other 3D models on www.thingiverse.com, ball and cylindrical bearings were created as assemblies (Fig. 11) and printed (Fig. 12) in-situ. That is, they were printed as assemblies. The clearances had to be carefully set in the solid model and the printer settings adjusted through several iterations before the components would print properly but break apart for somewhat smooth operation. Students unfamiliar with in-situ printing were often quite impressed this is possible. The results are inevitably imperfect, but this is an excellent opportunity to discuss how rolling bearings fail. Also the differences between these types of bearings can be discussed as they are passed around. Students feel the effects of imperfections, appreciate the effects of the amount of clearance, get a sense of the relative smooth operation of cylindrical versus ball, and observe the limitation of angular deflection on a shaft.

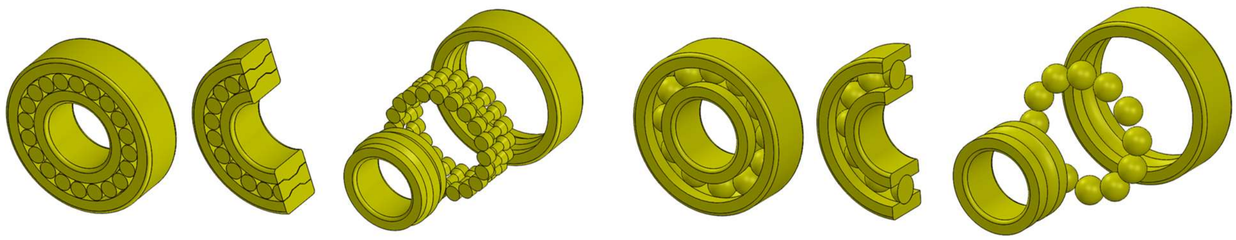

Figure 11: Solid Models of Cylindrical and Ball Bearings Showing Assembled, Cut-away, and Exploded Views

Figure 12: 3D Printed Ball and Cylindrical Bearings for Pass-Around

D. Gear Finger Puppets

The Gear Finger Puppets shown in Fig. 13 were inspired by a wooden set owned by Dr. Don Houser of Ohio State University and shown to the author while taking the OSU gear vibration short course. Dr. Houser said they were a gift from a former student created because when describing conjugate action, everyone inevitably uses their fingers to show the hand-off from one tooth pair to another. These finger puppets allow for explaining more nuanced features, especially aspects such as conjugate action, pressure angle, rolling and sliding action, interference, and contact ratio. By having two different pitches (2 and 6 teeth-per-inch), students can also appreciate the effect of pitch on quantity of teeth since these have nearly the same diameter but significantly different amount of teeth per inch (circular pitch). The gear puppet with 2 teeth-per-inch pitch also clearly demonstrates the involute tooth profile shape.

E. Planetary Gear Demonstrator

ME 470 students often struggle to understand what a planetary gear actually looks like based only on textbook illustrations. Solid models of the planetary gear demonstrators (Fig. 14) were inspired by some offered by NADA Scientific [9]. Multiple sets with various colors were printed (Fig. 15) so several could be passed around at the same time during the lesson.

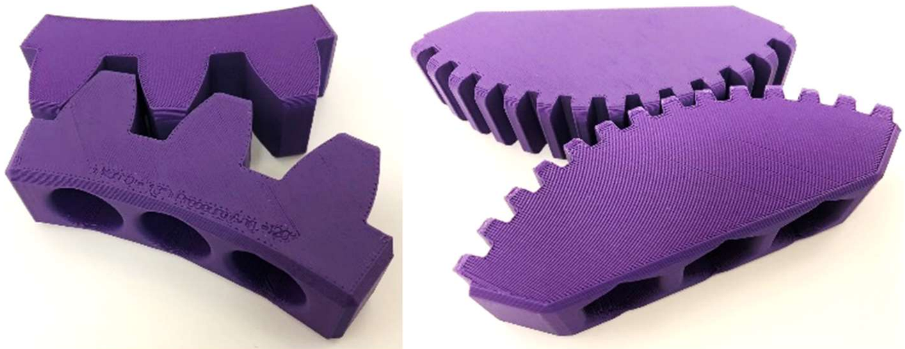

Figure 13: 3D Printed Gear Finger Puppet Pass-Arounds with Diametral Pitches of 2 and 6 Teeth/Inch.

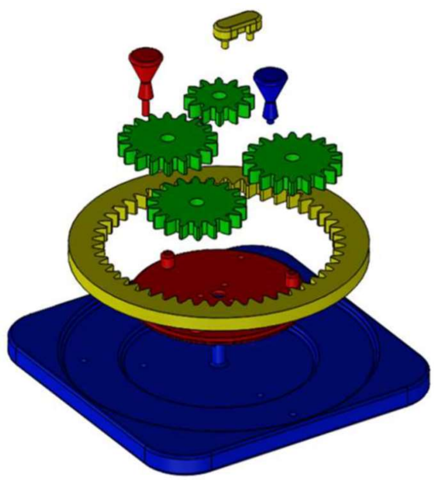

Figure 14: 3D Solid Model Exploded View of Planetary Gear Demonstration Pass-Around

Figure 15: 3D Printed Planetary Gear Demonstration Pass-Around

The relevant lesson for planetary gears deals with the different combinations of input and output possible depending on which part is held stationary. The holes in the sun, ring and carrier can accept the blue pin which is longer than the other two pins and passes through to another hole in the base. The other two shorter pins are placed as input or output on the movable part and act as knobs to hold. The yellow clip can make the sun stationary. Different ratios and reversing are possible. While graphics and video demonstrations can communicate these concepts, having students try each themselves helps cement them into place.

III. Results

To assess the effectiveness of the pass-arounds, indirect and direct assessments were made. In Fall of 2020 a survey of former students was sent out with 50% response rate as an indirect assessment. In Spring 2021, students were given a quiz, handed a teaching aid, and asked to update their responses.

Fall of 2020

A survey of 42 students who had taken ME370 and ME470 while these Pass-Arounds were first implemented was conducted in August, 2020, three months or more since they'd been in class, with 21 students replying.

In the survey the following questions were asked with each pass-around:

• Do you recall passing around the ___________ in class? (please don't answer any more questions about the _______ if you do not recall ever using it in class)

• Rate how the ____________ helped you understand / distinguish (some aspect of the object)

• Do you have any comments about the ________ learning aid, positive or negative, that you'd like to contribute? (note, you may be quoted in the paper)

This was done since not every surveyed student had experienced every pass-around as they were being produced during this same period.

The ratings available were as follows:

• 1 = Not at all

• 2 = A little bit maybe

• 3 = It definitely helped

• 4 = It really made me finally understand

• No opinion

• Seeing in now helped me recall how to distinguish between these.

Note that last choice could be selected in addition to the ratings.

The survey questions which follow were asked and the numbers and letters used here correspond to the results presented in Table 1. The results were overwhelmingly positive with 41% choosing "It definitely helped" and 48% selecting "it really made me finally understand."

1. 3D Door Handle:

a. Rate how well the door handle helped you visualize the 3 views for an FBD

b. Rate how the door handle helped you tell the difference between reaction forces and moments on the FBD vs equivalent forces and moments on the stump

c. Rate how the door handle helped you distinguish between tension vs compression on the stress elements due to bending moments, the combined axial stresses, and the combined torsional and transverse shear stresses.

2. Two-Stage Gear Train

a. Rate how well the gear train helped you understand the trade off between torque and speed.

b. Rate how well the gear train helped you understand the arrangement and roles of the stepped shaft, keyway, bearings and gears.

3. Planetary Gear Trainer

a. Rate how well the Planetary Gear Trainer helped you understand the possible reduction ratio combinations and ability to reverse.

4. Gear Finger Puppets

a. Rate how well the gear finger puppets helped you understand the involute shape and how it relates to conjugate action.

5. Bearings

a. Rate how well the 3D printed bearings helped you understand the differences in cylindrical vs ball bearings.

b. Rate how well the 3D printed bearings helped you understand why some bearings can handle shaft angular deflection better than others.

Table 1: Fall 2020 Survey Results

Question		Responses	1	2	3	4	No Opinion	Oh Yeah!
1	a	16	0	0	6	10	0	2
	b	17	0	3	9	5	0	1
	c	16	0	0	3	11	2	1
2	a	12	0	2	5	5	0	1
	b	12	0	1	3	8	0	1

3	a	11	1	1	2	7	0	0
4	a	17	0	4	7	6	0	1
5	a	11	0	0	8	3	0	1
	b	10	0	2	6	2	1	0

Example Student Survey Comments

Students' comments are often quite insightful. While anecdotal, they do help by way of testimonial. One must acknowledge these responses are somewhat biased towards positive by the nature of the question, and that they responded at all would tend to indicate they had a positive experience in the class. To reduce the length of this paper not all responses are included.

1) Door Handle Comments

• I believe it's a perfect example to start off the course or a refresher.

• It was very useful in visualizing the stresses from different forces and moments, especially for a hands on learner like myself.

• It helped me understand that the forces and moments are opposite on the stump from the handle itself

• I recall seeing this door handle visual aid early in the semester of ME370. It helped me be able to completely envision the different forces acting on the door handle as well as the corresponding stresses and reactions. It also was interesting to know that it was created using a 3D printer.

• Visualizing the direction of shear stress was always difficult for me, but being able to see it in 3d really helped me learn how to visualize it better.

2) Two-Stage Gear Train Comments

• The gear train was a fantastic visual aid that showed exactly how all the pieces came together after the design stage. This visual aid is essential to the design process so that the will be no interference between gear and the shafts which they rest on.

• The gear train learning aid helped me in multiple ways. I was able to see how a shafts rpm correlates to the rpm of the gears on the shaft. Also, seeing what a key way was proved to be very helpful. Without that aid, I don't think i would've been able to fully understand the impact of it.

• Having the hands on element to turn it and mess around with it was definitely useful in understanding how gear trains work

• Very useful gear system that highlighted the individual components of a gear train set up and visually demonstrated the concepts of changing gears for different speed and torque

3) Gear Finger Puppets Comments

• The gear finger puppets, although the simplest, were likely the most helpful to me. I was able to see how interference works and why gear ratios are very important. Lastly, much like the gear train, seeing how the components worked together was helpful because I would be able to visualize these motions whenever going thru problems in class or definitely on tests.

• When this was passed around the class I had a better understanding of the importance of the involuted shape of gear teeth to insure no interference occurred in mating gears. It was a great tool that enhanced my learning experience.

• I especially liked the finger puppet gears because rather than having a 2D image of a gear and being told what happens on the tooth surface, we were able to look at it from various angles and see exactly what's causing the wear and where the damage is occurring

4) Bearings

• Along the same lines as the planetary gears, this representation really helped me understand cylindrical bearings.

• It helped understand the difference in the two types of bearing but it lacked slightly in understanding how they withstood deflection.

• The 3D printed ball bearing where quite helpful for understanding how bearings work.

5) Planetary Gear Trainer Comments

• I'm a visual learner and the planetary gear systems seemed pretty nebulous until I could really get one in front of me and in my hands to experiment with After that, things started to click.

• The planetary gear train was excellent at showing how each gear can manipulate the overall motion of the train. This specific aid was essential to my understanding of how gears transmit forces between each and how the direction each gear is rotating can be determined.

• The planetary gear train gave a perfect visual for understanding planetary gears. I think hands-on examples like this help students, like me, that learn more from seeing real-world examples/ something in front of them.

Spring 2021

An attempt at direct assessment of the impact of the gear finger puppets was made in Spring 2020. A short, two-part, ungraded quiz was administered in Class 10 where the students were asked first to write down their recollection of two key features of gears:

- Describe what conjugate action is and how it's achieved.
- Explain gear contact ratio.

The gear finger puppets (and hand sanitizing wipes) were then passed around class and the students encouraged to manipulate them and then update their answers and comment on whether this helped recall any details. The students were also asked to give their frank opinion on the usefulness of the teaching aid and specifically told to not "tell me what I want to hear but what you think". This, of course, doesn't prevent them from doing just that.

When these topics were originally introduced (Class 3) the gear finger puppets were shown using a document camera but not passed around as it had not occurred to the author to use the available sanitizing wipes.

The results of the ungraded quiz were mixed. Notably only 8 of the 13 students were in-person for the quiz due to COVID, so only the results from those students who could pass around the teaching aids are discussed here. Of the eight students, five described conjugate action acceptably, and four explained contact ratio well enough to demonstrate they understood/recalled the idea. After the gear finger puppets were passed around, only one student significantly improved their description and explanation of conjugate action and contact ratio, with the comment "Having the models did help me see the hand off between teeth which I recognized it as a contact ratio." Other example comments from students who answered correctly include:

- I think the passing around of the 3D printed learning aids is very useful throughout the learning process. Getting to actually handle and observe for myself makes complex concepts come to life.
- after handling the physical model it is easier to understand.
- This might have been useful when we were first learning the topics. I think I'm familiar with this by now.
- Holding the 3-D printed gears would've helped when learning the actual concepts to both contact ratio and conjugate action.
- The model gave me some ideas of what it is but I'm struggling to remember. The gear model helped.

IV. Conclusions

This paper presents five examples of the potential uses of 3D printers for creating mechanical engineering teaching aids. Having tangible parts students can handle, manipulate and pass around, is arguably, inherently better than just pictures on a projection screen or in the textbook and more engaging than words on a page. Quantifying the value of passing around a tangible object to convey details of mechanical components versus presenting image slides is challenging. The limited direct assessment performed here was hampered by COVID restrictions to both in-person attendance and need for precautionary contact transmission measures. Student feedback in both efforts to measure it was overall very positive (88% felt it helped them learn), and there is ample room for further study. Additional ideas for related innovation and future work include having the students use the 3D printers to create the parts themselves and possibly in conjunction with coordinated simulation of the mechanical parts.

In addition to the benefits students can gain from passing around these teaching aids, instructors can benefit from the availability of inexpensive 3D printers and share their innovations. The author has uploaded CAD files of several of these teaching aids to a 3D print file sharing website so other instructors can print them out and use them in their classes. It is hoped that other solid mechanics and machine design instructors will be inspired from this paper and similarly create and share their teaching tools.

Acknowledgement

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