How to Incorporate Tolerances in Freshman-level Classes

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Perry Wood is an Instructor\Lab Manager of Mechanical Engineering at Northern Arizona University (NAU), where he has been here since 2004. He is currently teaching multiple sections of ME180 Introduction to Engineering Graphics. Perry has lectured at Xi'an University of Science and Technology, Xi'an China and Ningbo University, Ningbo China on various topic including engineering graphics and Solid Modeling. In 2014 Perry mentored Hooper Grant funded mechanical engineering students in Geometric Dimensioning and Tolerancing and traveled with them to present their research at Xi'an University of Science and Technology, Xi'an China. Perry is also pursuing a doctoral degree in Earth Sciences and Environmental Sustainability with an emphasis in fatigue characterization of magnetic shape memory alloys at Northern Arizona University.

Prior to his current work, Perry worked in the Aerospace and Renewable Energy industries for 16 years on various projects including Boeing\Air force GPS IIF satellite, NASA Space Shuttle, Sandia Laboratory Sunshade, Orbital ATK Taurus\Pegasus rockets, Raytheon patriot missile program, Naval Precision Optical Interferometer and NREL\SouthWest WindPower Skystream Wind Turbine.

Perry is the NAU American Society of Mechanical Engineers faculty adviser which is the most active student section in Arizona. At the 2014 ASME HPVC WEST competition NAU ASME students placed 1st in the women's sprint competition, 2nd in design, 2nd in innovation, 3rd in endurance, and 2nd overall, out of 29 universities, from around the world.

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INCORPORATING TOLERANCES INTO FRESHMAN LEVEL CLASSES

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Abstract

The purpose of this research is to evaluate Mechanical Engineering first-year students' ability to understand tolerancing theory and implement tolerances into engineering drawings. Students are introduced to parametric modeling and the ASME Y14.5-1994 dimension and tolerance standard in upper division classes of the college curriculum. Tolerancing concepts are applied in lower division classes of the engineering curriculum without the students having a basic understanding of the fundamentals. It is important for students to have a fundamental understanding of tolerances before proceeding to advance courses. The goal of this project is to evaluate a student's ability to properly tolerance using Clearance, Transition, and Interference Fits through designing an assembly to be rapid prototyped, where they then can physically perceive the effect of their tolerance values when they put the assembly together. The students write a report after they assemble their rapid prototype, addressing if their assembly meets the required form, fit, and function of the assignment. A lecture is constructed and given to students before their assembly design project. The lecture presents the basics of tolerancing, including the types of fits and when to implement them. The lecture content is reconstructed each semester for 3 semesters based upon the students' feedback. Data is gathered through students' self-evaluation of their learning utilizing a questionnaire, as well as grading of their reports. After the first semester, students show signs of understanding tolerance theory concerning the types of fit and importance, but 6 out of 9 submitted questionnaires expressed confusion for how to implement it in engineering design. The lecture is edited to clarify the implementation of tolerances and is presented to new students, for another set of data and results to be gathered. The second semester shows signs of improvement in understanding how to implement tolerances, but the topic could still be clarified further as 5 out of 17 submitted questionnaires still reported confusion. The lecture will be altered and presented for a third semester. The results of this study show that students have a better understanding of tolerances after each lecture iteration. The results also show that students better understand tolerances when they have a more hands-on application with them. Based upon these results, tolerances will be included in the ME180 curriculum using a hands-on assignment and lecture format.

Introduction

Current students within the Mechanical Engineering program at Northern Arizona University (NAU) do not learn how to implement tolerances until their upper division courses. However, students are required to rapid prototype a component which involves an accurate tolerancing in their second-year class ME286. Because students do not learn how to design for tolerances before this project, many components fail on the first attempt, and the student is forced to redesign and reprint their piece without proper understanding of tolerancing. The purpose of this project is to determine the best way to teach students tolerancing as they learn how to design in ME180 so that they can implement it in all future design projects both inside and outside of school. Tolerance is an essential part of engineering design as it allows for variances in parts due to a manufacturing process. Applying proper tolerancing to engineering drawings communicates the design intent in terms of the form, fit, and function of the design. Mechanical Engineers design parts that are interchangeable and allow for variance due to varying manufacturing processes. Students do not learn tolerancing at NAU until their later years of engineering education. However, students begin designing during their second or third semester of a standard 8-semester enrollment. Although not graded on their use of tolerances, students learn that their designs do not work according to the design's form, fit, and function if they do not account for the types of fit they need. Students are using the concept of tolerancing without knowing what the correct terminology and application are. Some students may design incorrectly without understanding how to calculate for the clearance or interference fit needed. The engineering curriculums of other universities were researched and compared to the curriculum at NAU to determine if tolerancing is a subject commonly taught. From these observations, it is concluded that students should learn the basics of tolerancing when they learn how to design in ME180. The depths of the math behind tolerances are unnecessary for a first-year student to learn, but the theory, terminology, and general understanding of application would benefit the students' college experience in the engineering curriculum.

Methods

To design a lecture that contains the importance of tolerance as well as the basic fundamentals of the subject, the curriculums of other schools are researched and compared to the current curriculum at NAU. Portland State University, a university similar to NAU, has 3 separate Intro to Engineering classes that are required over the Fall, Winter, and Spring semesters of a student's first year [1]. These classes are titled Introduction to Engineering, Introduction to Systems and Control, and Introduction to Design. These classes focus on teaching the students the importance of engineering design [2]. Stanford University also requires that first-year students take Introduction to Solid Mechanics, a course dedicated to teaching first year students the mathematics behind design [3-4]. Stanford does not teach their students Engineering Drawing until their second year, but they still made this class a requirement before advanced engineering design classes [3]. These colleges are similar to NAU's Mechanical Engineering 4-year progression plan because they require introductory mathematical and engineering design courses in the students' first years. However, these colleges differ from NAU's 4 year progression plan because students are taught geometric dimensioning for engineering drawings and design throughout multiple classes and implement their learnings with assignments, whereas NAU's students are taught geometric dimensioning for engineering drawings in a single class. Therefore, it is essential that first-year Mechanical Engineering students are taught tolerances during this class at NAU, and also implement their learnings with an assignment. According to these findings, it is determined that students should understand the types of tolerances and have experience identifying and applying them through the use of in-class exercises and a homework assignment.

The types of tolerances need to be understood before a lecture is constructed for first-year students. Shigley's Mechanical Engineering Design textbook says tolerances are "the total amount a specific dimension is permitted to vary" [5]. Shigley is used for the definitions of Clearance, Interference, and Transition fit. The "3 F's" need to be understood further as part of the research. The 3 F's are Form, Fit, and Function. These are defined as the physical shape of a part, the way a part is put together in an assembly, and how the part is supposed to behave while in the assembly [5]. To help solidify their meanings in the presentation, PVC piping is used as an example as shown in Figure 1. Tolerance zone is also introduced to the students, as the concept is used when classifying each type of fit. After explaining the definitions and the types of fit, A visual example, shown in Figure 2, is given to ensure the students understand the spacing (tolerance zone) of each type of fit.

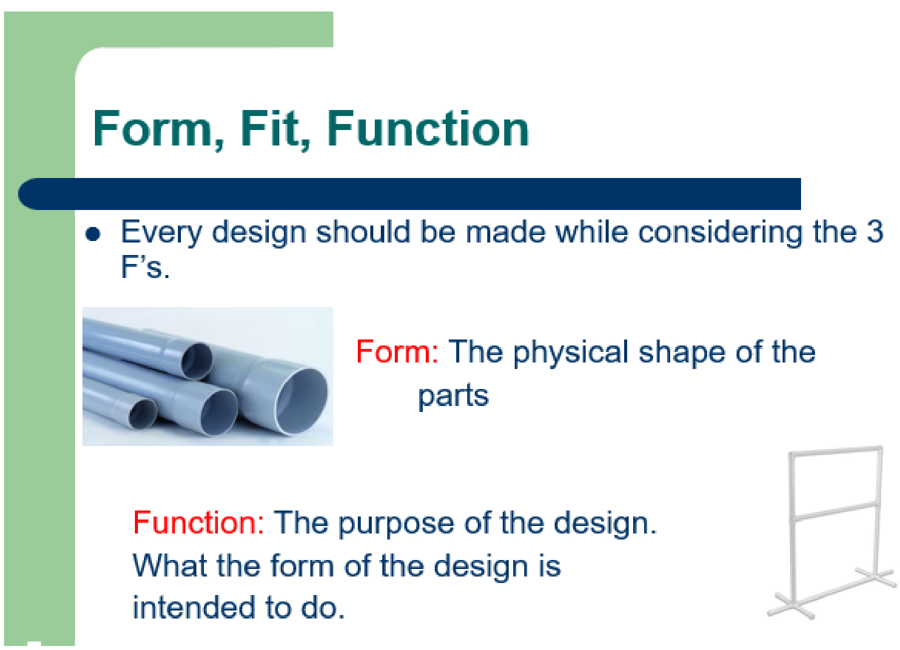


Figure 1: *PVC Example*

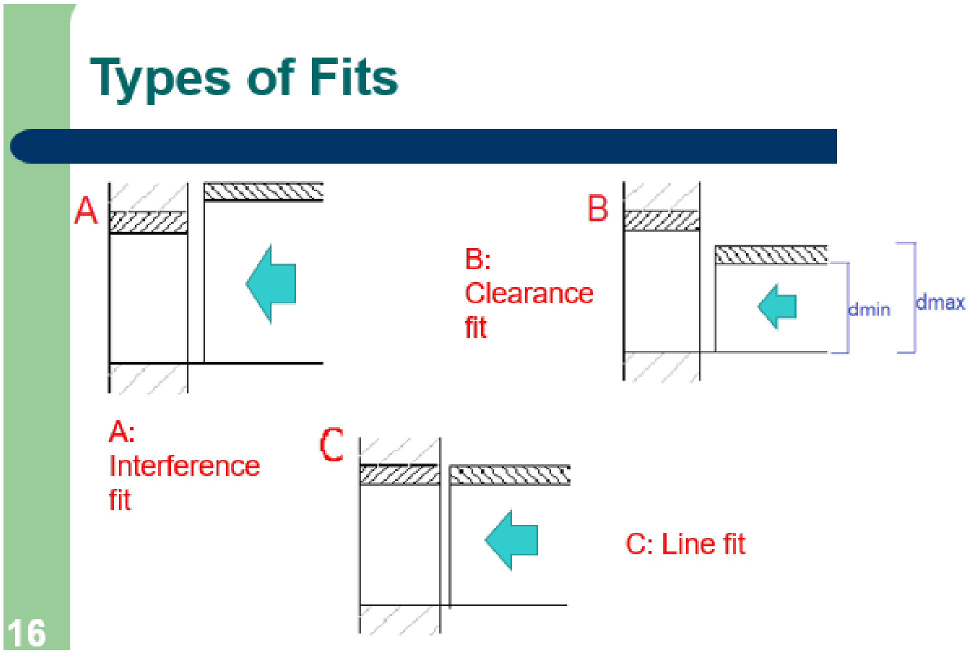


Figure 2: *Types of Fit Exercise*

The importance of tolerancing is emphasized in the lecture as necessary because assemblies need to meet their 3 F's, machines have their own tolerance, and a zone of variance is necessary when designing because components are not manufactured to their exact dimensions. In order to help introduce the students to tolerances, an activity is given where the students use calipers to measure the dimensions of a block, shown in Figure 3. The students are given a drawing of the block with blank dimensions to fill in. The students are then shown the original drawing with the actual dimensions. The variance between the student measured dimensions and the SolidWorks dimensions is an example of how machines, such as rapid prototype machines, have a machine tolerance. This activity solidifies what the lecture previously mentioned.

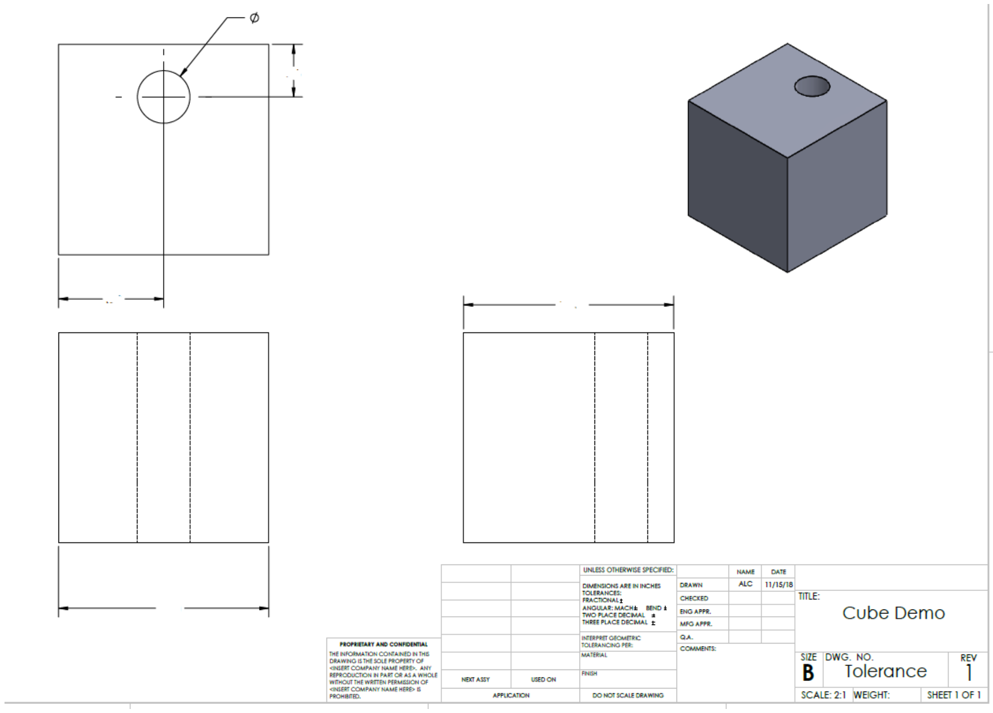


Figure 3*: Block Activity Blank Drawing*

Regarding their homework assignment, the students need to only understand these definitions and identifications. However, it is important for them to have more knowledge before they proceeded to future engineering classes. To further their education, the mathematics behind tolerance for fits is demonstrated through some walked-through examples. It is here that material conditions and how to solve for them and apply them to the types of fit was mentioned, shown in Figure 4.

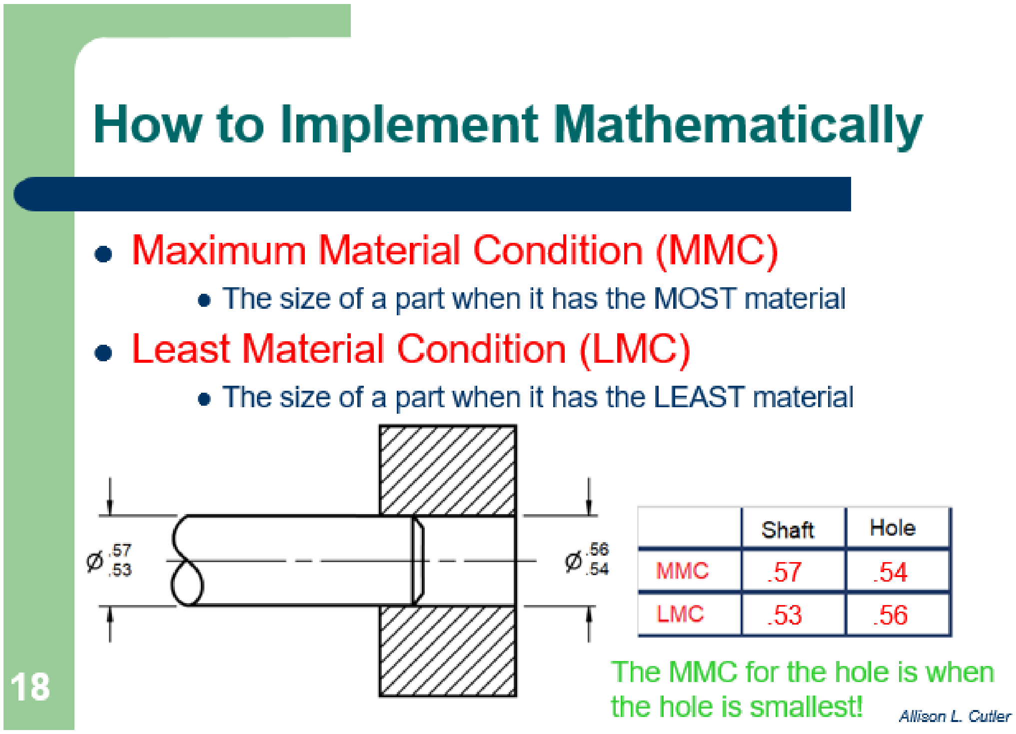


Figure 4: *Mathematical Implementation Slide Example*

With this topic, examples are given on how to identify which dimension falls under which material condition using a shaft and a hole. Examples on how to use these material calculations in clearance calculations to determine the type of fit are given. A full copy of the final lecture is in Appendix A for reference.

The homework assignment given is for the students, in groups, to design an assembly that must match a type of fit in order for the assembly to work. There are 5 assemblies randomly assigned to each group. Each assembly has many parts, an example drawing, and a list of hints relating to the assemblies form and function that help the students determine the type of fit. The full list of assemblies is shown in Appendix B. The students are required to design their assembly in SolidWorks, including into the dimensions the tolerance they need to make their type of fit. The students then 3D print their parts using the Maker's Lab at Cline Library NAU. With the physical components, the students reconstruct their assembly and reflect upon the final products' form, fit, and function. For example, if the assembly is the sliding shelf, the students' should have designed for a clearance fit and the shelves should successfully slide within the cabinet. Students are also expected to comment on the effectiveness of their tolerances given. With the sliding shelf, if the shelves are too wobbly within the cabinet, the students are expected to comment on their tolerances being too large. The full homework assignment is in Appendix C.

The grading rubric, shown in Figure 5, is used when grading the homework assignment. Keywords from the students' papers are picked out and verified that they are used correctly. The list of keywords presented to the students is in Figure 6. As the homework is a group assignment, a peer evaluation that included multipliers is included in the grading, because the grading needed to be fair and as deserved. In other words, if a student does not contribute and the evaluation reflected that, then their grade is lower if not nil. On the contrary, if a student contributes more and the evaluations reflect that, their grade is higher than their team members. Both the group's report grade before evaluation and the individual students' grades after evaluation are analyzed. Based upon the grades received, changes are made to the homework assignment requirements and lecture based upon noticed areas of confused terminology.

Grading Rubric (25 pts)

	Excellent (5 pts each)	**Moderate (3 points each)**	**Poor (1 point each)**
Correct use of form, fit, and function.	The students demonstrate complete understanding and proper use of these terms.	The students demonstrate a decent understanding of the terms, with little error in their application.	The students do not understand the terms and used them incorrectly.
Correct use of the term "tolerance".	The students show a complete understanding and proper use of the term.	The students demonstrate a decent understanding, with little error in their application.	The students do not understand the term and used it incorrectly.
Logical rationale used in conclusion.	The students used a good analysis of the design when reporting why their parts did or did not fulfill the design intent.	The students used a decent analysis of the design when reporting why their parts did or did not fulfill the design intent, but could have elaborated more.	The students did not provide an analysis of the design, did not explain why or why not the design intent was fulfilled, or did not provide reasoning behind their conclusion.
Grammar and Format	Few or no grammatical errors.	A decent amount of grammatical errors.	A lot of grammatical errors.
Correct application of tolerance.	The students properly dimensioned their parts to fulfill the design intent, or properly explained how they would change their dimensions to fulfill the design intent.	The students decently dimensioned their parts to fulfill the design intent, and gave an acceptable explanation on how they would change the dimensions to do so.	The students did not properly dimension their parts to fulfill the design intent, and did not explain how they would change the dimensions to do so.

Figure 5: *Grading Rubric*

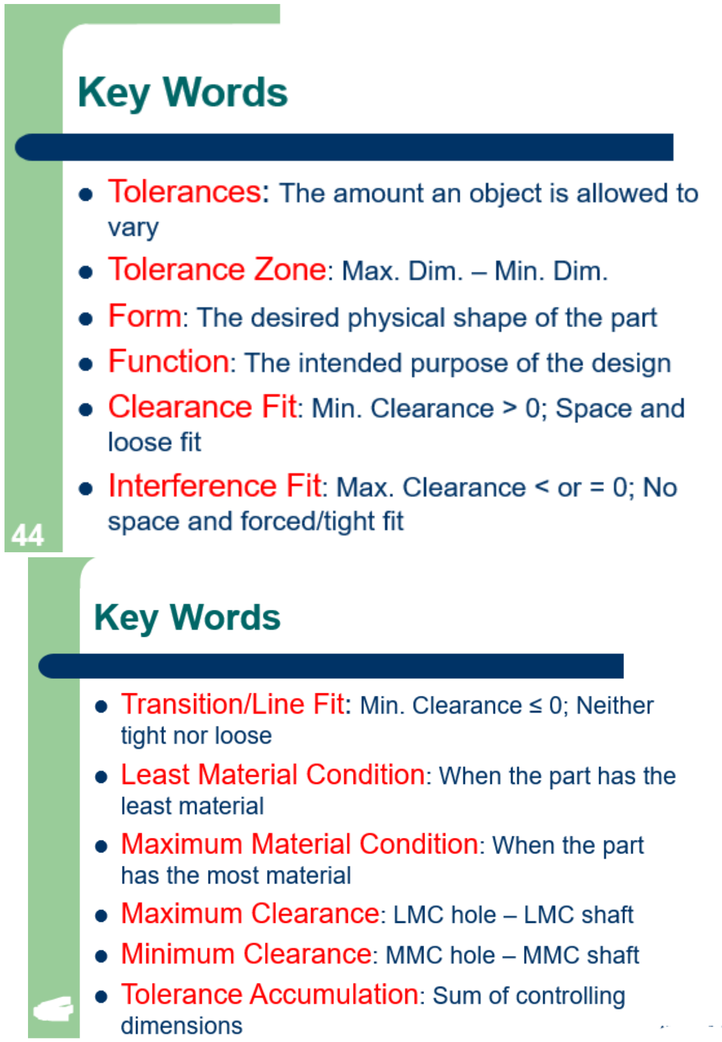


Figure 6: *Key Words*

An ungraded and anonymous questionnaire is used to better judge how the students understood the lecture and homework assignment as well as the subject of tolerancing. It is from these questionnaires that it is determined what material is necessary to change in the lecture before the next semester presentation. The questionnaire given to the students is in Appendix D. The responses are grouped into common categories based upon points of feedback shared among multiple students of questions 3, 4, and 5 of the questionnaire. Questions 1 and 2 are plotted to visualize a trend and determine the effectiveness of the homework assignment. From the feedback given in the questionnaire, topics where students express confusion are further researched and discussed with the faculty advisor in order to clarify and improve the lectures quality.

This system is repeated for a total of 3 semesters: Spring 2018, Fall 2018, and Spring 2019. Between the 3 semesters, a total of 121 students were given the lecture and homework assignment, meaning 121 students were used to gather data.

Results

Each paper is graded according to the rubric, and different factors need to be evaluated for causal or coincidental relationships. These factors include the placement of the tolerance lecture in the curriculum, format and grammatical errors considered accounted for in the final grade, and the number of questionnaires received each semester.

Two lines, shown in Figure 7, are used to evaluate the grade distribution for Spring 2018; the first distribution (blue) is the group grade before peer evaluation multipliers and the second distribution (orange) is the individual grades after multipliers. The first distribution is most important in determining if the lecture was effective because it is the grade given based upon the use of terminology and understanding of the application. The second distribution is important in observing the effect of making the homework a group assignment. The grades are compared to the number of students in order to visualize the quantity and to keep students' identities anonymous.

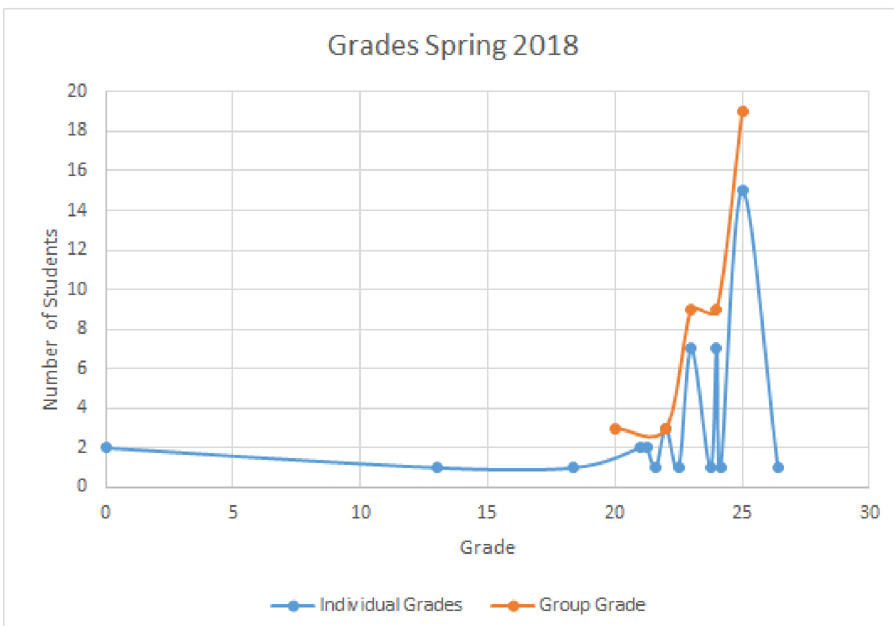


Figure 7: *Grades Spring 2018*

From this distribution, it is observed that there are a total of 36 A's from the group grade but only 30 A's for the individual grades. There are no grades lower than a C for the group grade, but 5 grades lower than a C individually. The change in the number of A's between group grade and individual grade suggests that the work among groups was uneven as several students lost points due to their lower level of contribution.

The distribution for Fall 2018 is in Figure 8.

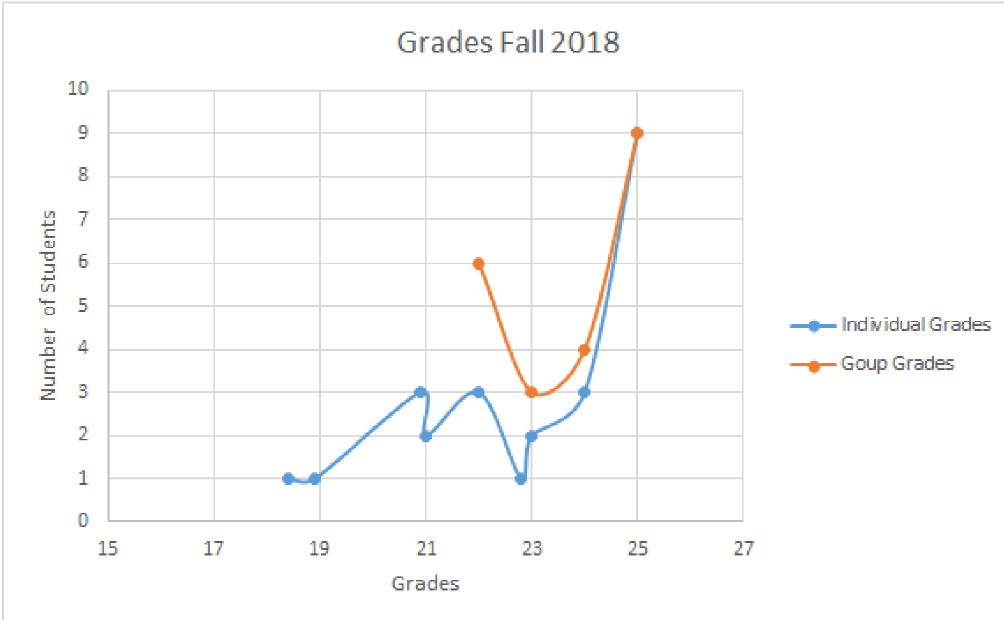


Figure 8: *Grades Fall 2018*

This semester has a total of 16 A's for the group grade and 15 A's for the individual grade, meaning that more students contributed equally in their groups. There are no grades lower than a C this semester, both with the group and individual grades. The reason for this improvement in grade distribution from the Spring 2018 semester most likely relates to the lecture timing in the curriculum as well as emphasizing the importance of the peer evaluation during the assignment date. These factors will be taken into consideration during the Spring 2019 analysis. Overall, more students received A's and B's in the Fall 2018 semester than the Spring 2018 semester because of the improvement to the lecture content.

The questionnaire is an ungraded assignment. Each question is broken down into groupings of answers. Questions 1 and 2 were plotted against each other to show the effectiveness of having a homework assignment. Figure 9 shows the results of the Spring 2018 semester.

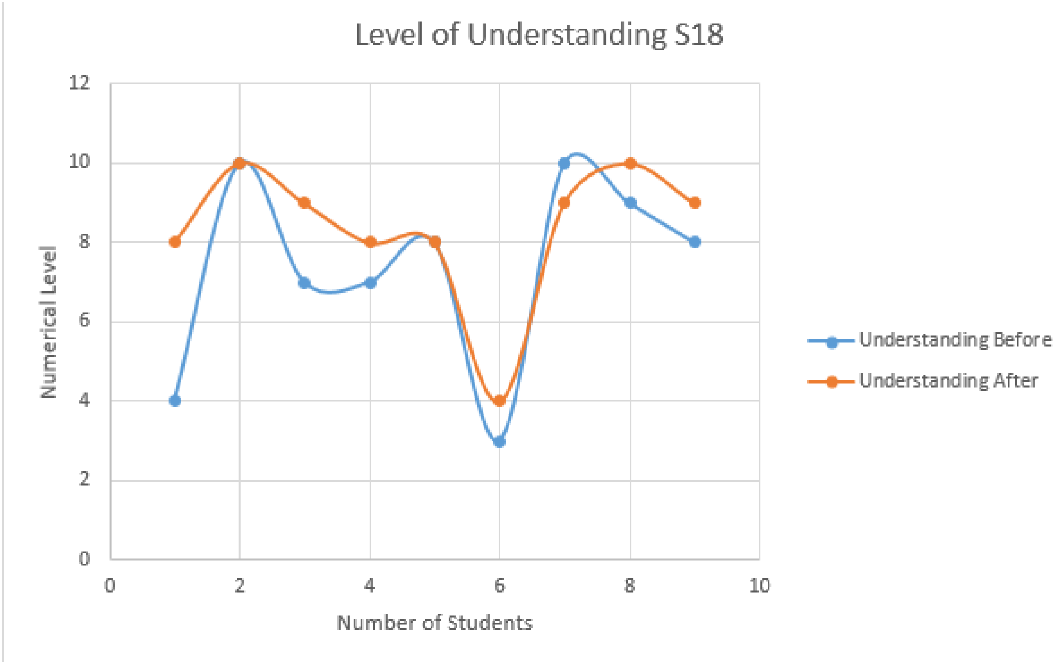


Figure 9: *Numerical Level of Understanding S18*

From the Spring 2018 semester, a total of 9 students submitted the anonymous questionnaire. From these results, 6 students understand the subject better after the homework assignment, 2 students understand the subject to the same amount, and 1 student understands the subject worse. Questions 3, 4, and 5 of the questionnaire are grouped into common comments and charted in Figure 10.

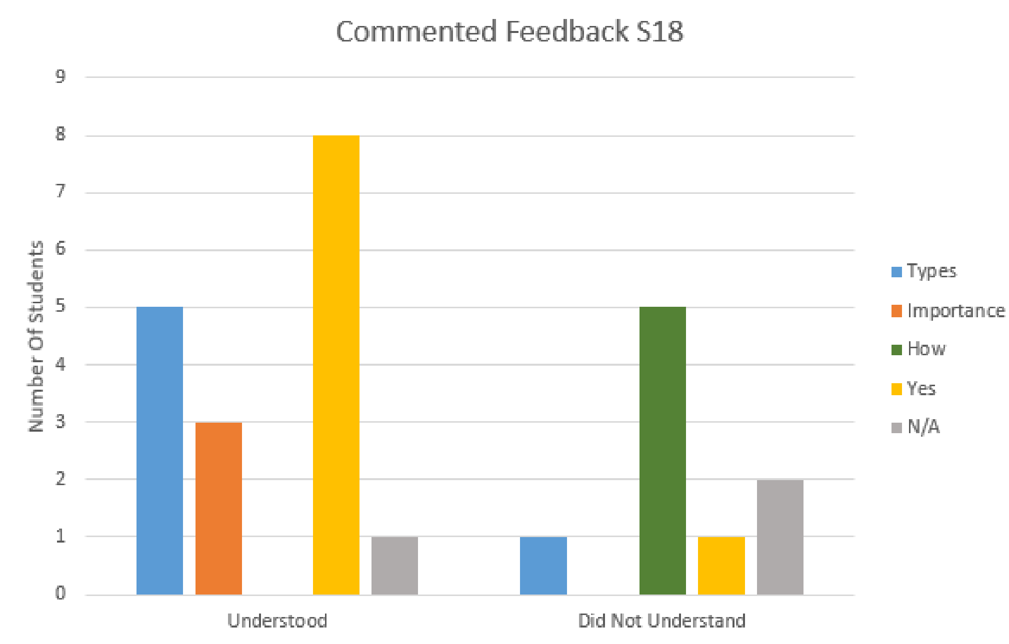


Figure 10: *Feedback S18*

For simplicity, each comment group is given a keyword to summarize the comments. “Types” refers to the types of fits there are in tolerancing, “importance” is the importance of tolerancing, “how” is how to properly implement, calculate, and find the tolerance zone, “yes” refers to question 5 and whether the student understands the homework assignment in its entirety, and “N/A” means the student did not answer the question. The answers are separated based upon if they are in response to question 3 of “Did Not Understand” and question 4 of “Understood”. From these findings, the types of tolerances are the most understood, with only 1 student finding confusion. This feedback says that the way the lecture talks about the 3 types of fit is mostly clear to the students, with the interference fit as the only type of fit mentioned out of confusion. Next, students report that the importance is understood with no complaints of confusion, which suggests that the lecture sufficiently presents the importance of tolerancing. For the subject of how, 5 out of 9 students report confusion, meaning that the lecture needs to improve in covering how tolerances are calculated and applied. 8 out of the 9 students answer yes to the homework being clear, with 1 student commenting that it would be better if the approximate size of the parts were given. Other comments not included in a common keyword are that the project is not the best at teaching the students how to apply tolerances. This feedback was taken into account when making the lecture for Fall 2018.

Figure 11 shows the questionnaire results of Fall 2018.

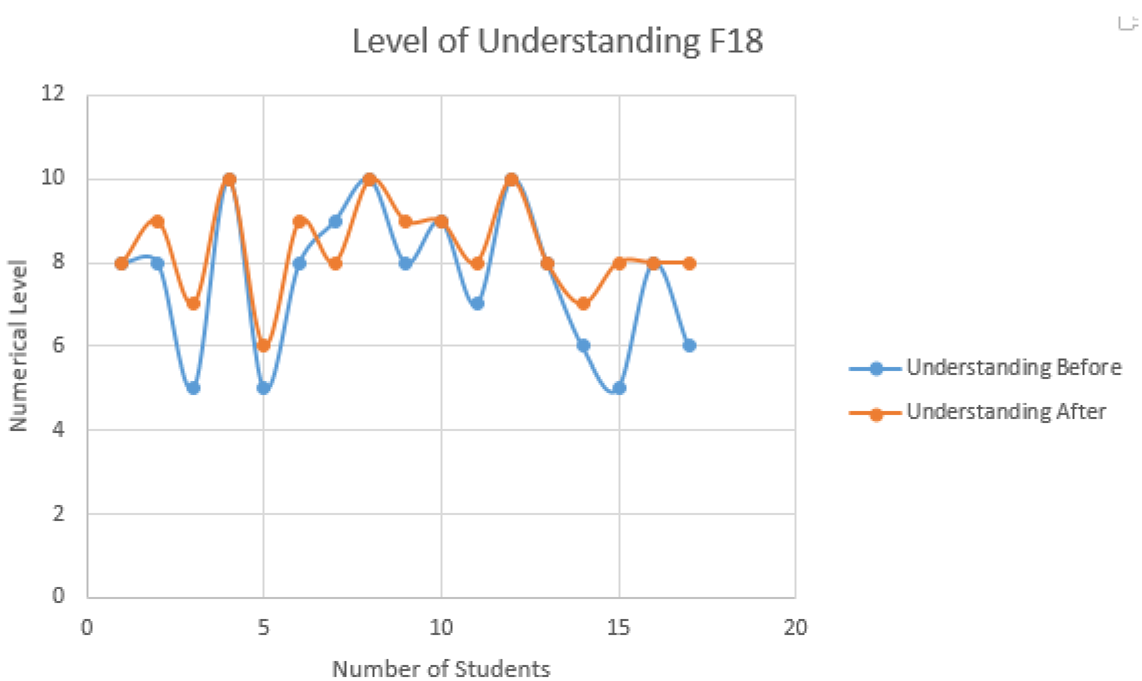


Figure 11: *Numerical Level of Understanding F18*

From the Fall 2018 semester, a total of 17 students submitted the anonymous questionnaire, almost double the feedback from the previous semester. 9 of the students say they understand the subject better after the homework assignment, 5 students say they understand it to the same amount, and 1 student says they understand it worse after the homework. Figure 12 shows the student responses to questions 3, 4, and 5.

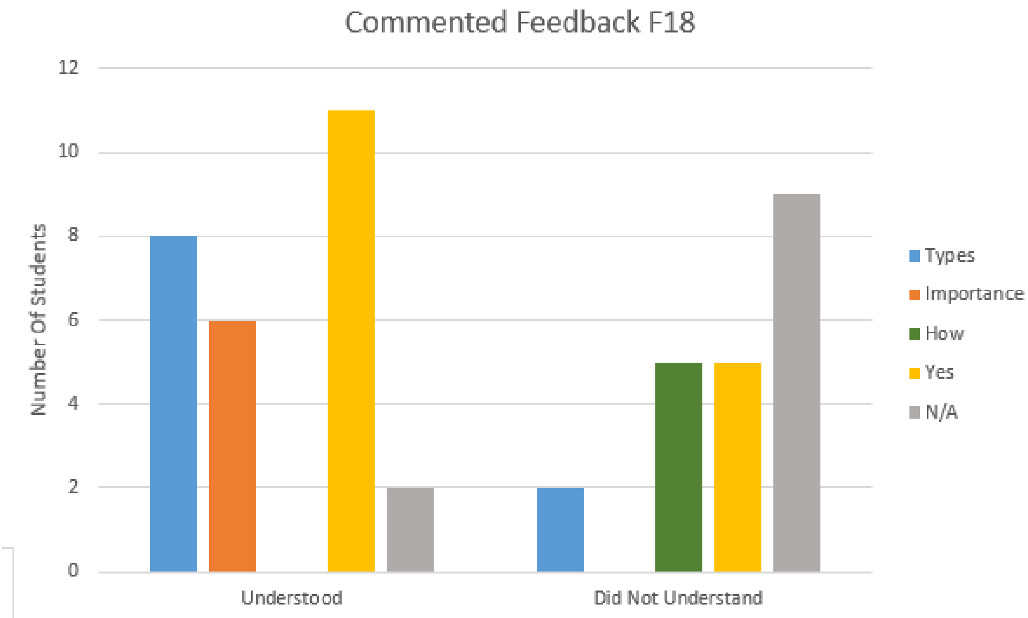


Figure 12: *Feedback F18*

Similar to the previous semester, the majority of students report that they understand the types of fit, with only 2 students mentioning confusion about the interference fit and the transition fit. These fits will need more examples and attention when explaining them to the class in the next lecture. The importance is well understood by 6 students that mentioned it, with no areas of confusion. The importance does not need to be improved upon by the next lecture. The previous semester, more than half of the questionnaire responses contain confusion on how to implement the tolerances, whereas this semester 5 out of 17 students mentioned confusion. This change in reports of confusion suggest improvement from the last lecture, but the topic of how still needs improvement before the next lecture. There are more comments about the clarity of the homework this semester, with 5 of the 17 students saying they are confused and 11 of 17 saying they understand, with 1 student leaving the question blank. Two of the comments about the homework clarity request clearer instructions on how to submit the group and individual components, as they are not documented anywhere. One comment is a complaint about the project being due during Finals week, saying that it is “annoying and should be done earlier or not at all”. This feedback is taken into consideration for improving the lecture before the Spring 2019 semester.

Discussion

During the Spring 2018 semester, the lecture is given before the students learned how to create assembly drawings. This time change does not appear to impact their abilities to design their parts. Some students use math to determine the size of each component, while some students decide to get ahead and teach themselves how to make assemblies. Benefits of giving the lecture during this time in the curriculum include the opportunity for students to challenge themselves, as well as having to think more about the dimensions due to not testing if components will fit together inside SolidWorks. During the Fall 2018 semester, the lecture is given after the students learn about assemblies, and before they learn about drawing views. The students are then able to use SolidWorks' assembly function to test their design before submitting the parts for 3D printing. It is observed that some students are surprised to see their parts fit well together in SolidWorks, but have problems when assembling after 3D printing. Giving the lecture after the students learn assembly modeling helps teach the students about machine tolerances and is beneficial to their overall understanding of tolerances. Both placements of the lecture have benefits and downsides. To summarize, teaching tolerances before assemblies force the students to think about their dimensions and tolerances in greater depth, but students struggle more in understanding how tolerances work and are calculated without seeing their assembly together. Teaching tolerances after assemblies allow students to better estimate their tolerances and teaches them about machine tolerances in the cases where the assembly failed, but the assignment is stressful for students so close to the end of the semester. From Spring 2018 to Fall 2018 there is an increase in A grades received, suggesting that the improvements made to the lecture between these semesters are beneficial.

Other observations made about the homework assignment are that most students appear to enjoy having a different format of assignment in the ME180 class. While most assignments require a design in SolidWorks, this assignment requires a report and analysis. Most students also have no experience with rapid prototyping before this homework, and they thoroughly enjoy the opportunity to do so. There are mixed feelings about the homework being a group project, and the data gathered from the group grade and individual grade comparison proved inconclusive, meaning that some semesters have a large fluctuation and some do not. In order to complete the analysis of whether the project should be a group or individual assignment, further data needs to be gathered by a semester where the homework is assigned individually in order to see if there is a change on grade impact as well as learning experience.

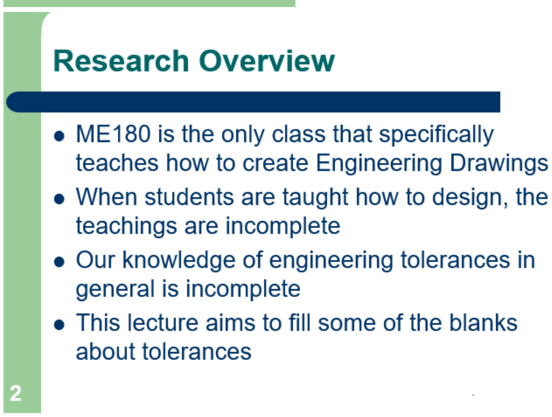
This study demonstrates that students learn and retain the information better when they have to apply the concepts given to them in an assignment. This is evident in how the grades improve from the Spring 2018 semester to the Fall 2018 semester after the lecture and homework assignment was altered to contain more clarity and explanation of tolerancing theory. The lecture in Fall 2018 focused more on how to implement tolerances based upon feedback given in Spring 2018. As a result, the students better understood what was taught, and the grades reflected that.

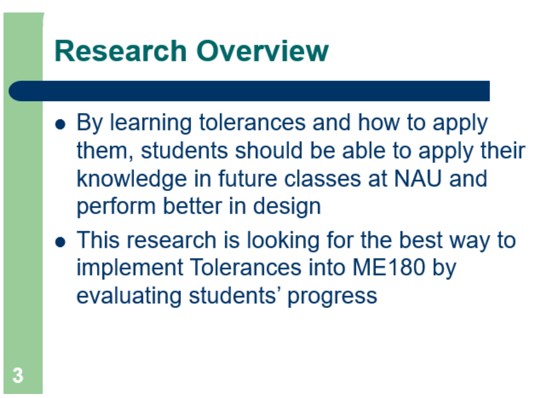
Conclusion

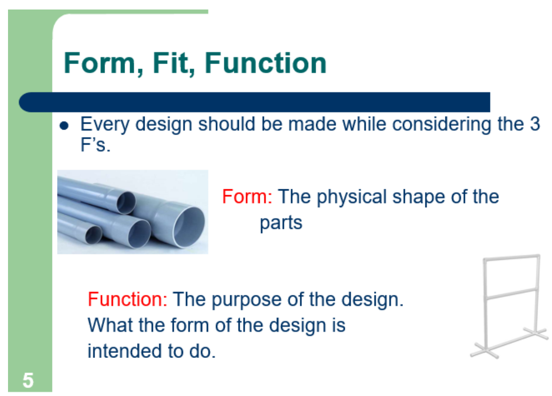
Students at NAU do not learn tolerancing until their later years of engineering education. However, students begin designing during their second or third semester of a standard 8-semester enrollment. Although not graded on their use of tolerances, students learn that their designs do not work correctly if they do not account for the types of fit they need. Students are logically using the concept of tolerancing without knowing what it is. Some students may design incorrectly without understanding how to calculate for the clearance or interference fit needed. From these observations, it was concluded that students should learn the basics of tolerancing when they learn how to design in ME180. The depths of the math behind tolerances are unnecessary for first-year students to learn, but the theory, terminology, and general understanding of application would benefit the students' college experience in the engineering curriculum. To determine the best way to incorporate tolerances into ME180, a lecture and homework assignment are constructed and altered based upon student feedback for a total of 3 semesters to analyze the students' understanding of tolerances. The first semester, there are 30 A's, 8 B's, 1 C, 0 D's, and 3 F's individually for the homework assignment, high understanding of the types of fits and the importance of tolerancing, and high confusion about how to calculate and implement tolerances. After making alterations to the lecture for the second semester, there are 15 A's, 8 B's, 2 C's, 0 D's, and 0 F's for the homework assignment, an equal understanding of the types of fits and the importance of tolerancing as the previous semester, and lower confusion about how to calculate and implement tolerances but still questions regarding the subject. Furthering the improvement of the homework and lecture, the third semester's data is yet to be gathered as the Spring 2019 semester is currently ongoing. Once the lecture is given in the Spring 2019 semester, the data will be analyzed following the same methods as Spring 2018 and Fall 2018. Ways the experiment could have been done differently to include more data are following up with students in later semesters to see if learning tolerances their first year improved their work and understanding in future classes. The factor of the homework being a group or individual assignment should also be included in the experiment in order to further evaluate the grade distribution and learning outcome between completing the homework as a group or individually. From the data gathered these 3 semesters, a suitable tolerance lecture was finalized and given to the faculty to continue to use. This research found that students better understand the concept of tolerances if they apply what they learn in an assignment. This research also discovered that students could understand the definitions of the types of fits easily, but needed more expansion on how to implement the tolerances. The data gathered from this research is used to determine how to teach first-year students tolerances through a lecture and homework assignment in a way that the students understand the terminology and the application.

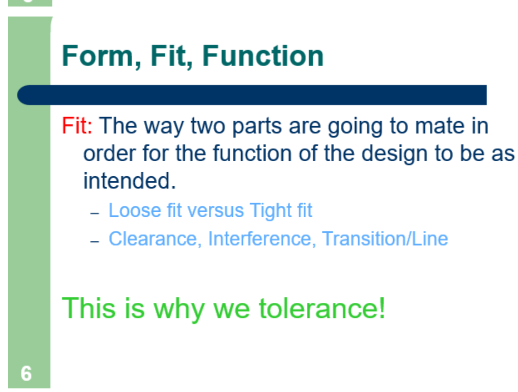
As a result, this lecture format and homework assignment will be given in future semesters at NAU as part of the curriculum.

Appendix A: Complete Lecture



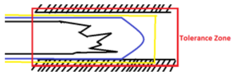






What is Tolerance?

- "The total amount a specific dimension is permitted to vary" [1]
  - The amount of clearance necessary for an assembly (multiple parts) to meet its desired function.
  - As long as a part falls within the tolerance zone, it will meet its required fit.

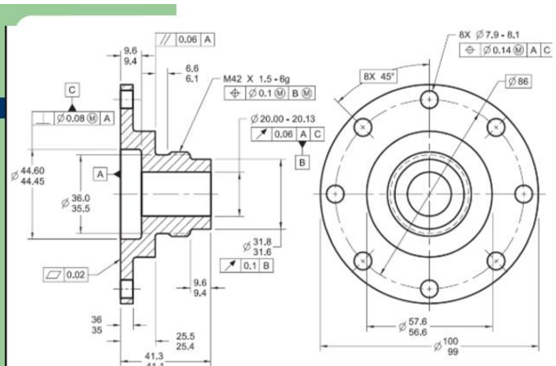


7

Tolerance

- Important in manufacturing
  - the manufacturer should look at a drawing and understand what the engineer needs
- When drawings are created, the engineer thinks about the theoretical requirements (form, fit, function)
  - This is where the tolerance zone is applied

8



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Tolerance Zone

- The assembly still meets its form, fit, and function as long as the mating pieces are within this zone
- Determined through statistics and testing

9

Tolerance

- Tolerance is the maximum dimension a part can be minus the minimum dimension that part can be.

Maximum size is 1.753 mm, Minimum size is 1.720 mm

Tolerance = Max – Min

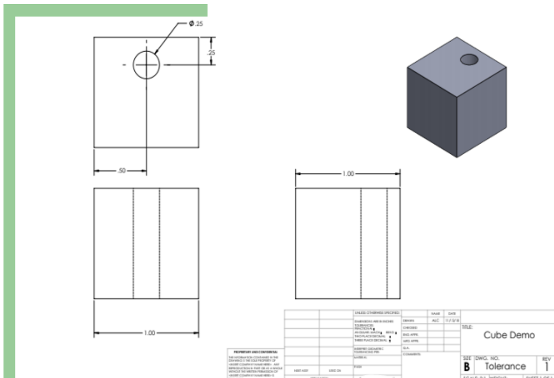
Tolerance = 1.753 – 1.720 = 0.033 mm

10

Activity

1. Grab a Cube, Caliper, Drawing, and Partner
2. Measure the missing dimensions and record them on the drawing
3. Once complete, return the drawings to me
4. I will take the maximum and minimum to determine the tolerance on this cube

11



11

Purpose of the Block

- Understand how the tolerance spec of the manufacturer's machine works
- With this activity, the tolerance of the specific 3D printing machine from the Maker's Lab is observed

12

How to Denote Tolerance

- Limit Dimensions
  - Maximum limit is written above the minimum limit
  - Minimum limit is written before the maximum limit

$\varnothing\,{}^{1.753}_{1.720}$ or $\varnothing 1.720\text{-}1.753$

- +/- Tolerances
  - The basic dimension has the positive variance and the negative variance written next to it

$1.0^{+0.3}_{-0.1}$ The variances need to be t same number of decimal pl

13

Types of Fits

- Clearance Fit
  - Always a space
  - The parts are meant to be inserted and removed with ease
  - Allows for rotation
- Interference Fit
  - No space
  - Force needed in order to mate parts
  - Parts are meant to be connected and remain connected, b extremely difficult or impossible to separate

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Types of Fits

- Transition/Line Fit
  - When the dimension and tolerance of the hole equals t dimension and tolerance of the shaft
  - Ideally, the surface of the hole should touch the surface shaft.
    - Due to tolerances, the diameter of the hole and the diam the shaft are never perfectly equal
      - Line: When there is a space or contact between sur
      - Transition: When there is a space or no space

Sound like the same

Shaft: 1.0 ± 0.02

Hole: 1.0 ± 0.02

That is bec

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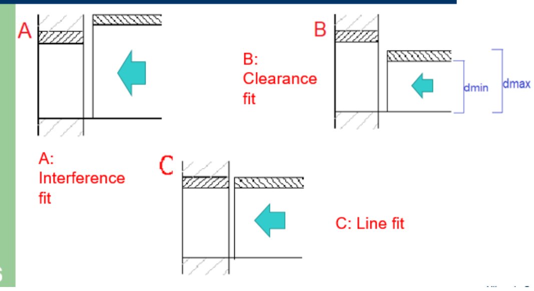
Types of Fits



16

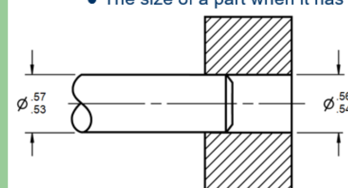
Where does the Tolerance come from?

- Statistical analysis
  - Measure a batch and calculate the average and standard deviation
- Understanding the manufacturing process and capabilities
- Understanding the engineering requirements

17

How to Implement Mathematically

- Maximum Material Condition (MMC)
  - The size of a part when it has the MOST material
- Least Material Condition (LMC)
  - The size of a part when it has the LEAST material



	Shaft	Hole
MMC	.57	.54
LMC	.53	.56

The MMC for the hole is when the hole is smallest!

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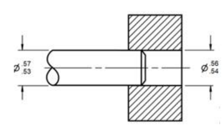
How to Implement



- Maximum Clearance: Most Space

LMC hole - LMC shaft

.56 - .53 = 0.03

What does positive mean?
- Clearance!

- Minimum Clearance: Least Space

MMC hole - MMC shaft

.54 - .57 = -0.03

What does negative mean?
- Interference!

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How to Implement Mathimatically

- Clearance Fit
  - Minimum clearance > 0
- Interference Fit
  - Maximum clearance ≤ 0
- Transition/Line Fit
  - Maximum clearance > 0
  - Minimum clearance ≤ 0

Remember:
Max. Clearance = LMC hole – LMC shaft
Min. Clearance = MMC hole – MMC shaft

Shaft	Hole
1.498 - 1.500	1.503 - 1.505

MMC hole - MMC shaft

1.503 - 1.500 = 0.003

0.003 > 0 Clearance!

Shaft	Hole
.247 - .250	.250 - .255

MMC hole - MMC shaft

.250 - .250 = 0

LMC hole - LMC shaft

.255 - .247 = 0.08

Line!

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How to Implement

- These factors also determine the tolerance used:
  - Bearing load
  - Speed
  - Lubrication
  - Temperature
  - Humidity
  - Material
  - Length of engagement
  - Experience of the Engineer
  - Cost

The smaller the tolerances, the higher the manufacturing cos

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Practice!

- You want to design a key and lock system. To do this, the key must easily slide into the lock, and easily be removed. What kind of fit should you design for?

  Clearance

- You are assembling a table from IKEA. The instructions say to line up a hole on a leg and a hole on the table top, and then hammer a given peg through these holes. What type of fit was used in this design?

  Interference

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Practice!

- You are designing a storage box. You want the lid of the box to easily slide onto the box and be removed. However, you do not want the lid to be wobbly while on the box. What type of fit should you use?

  Transition/Line

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Practice!

Remember:
Max. Clearance = LMC hole – LMC shaft
Min. Clearance = MMC hole – MMC shaft

- Given the following example, solve for Max. Clearance and Min. Clearance, then determine the type of fit.

Shaft	Hole
.751 - .755	.747 - .750

Minimum Clearance?

.747 - .755 = -0.008

Maximum Clearance?

.750 - .751 = -0.001

Interference

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Stacking Tolerances

- Tolerance Accumulation is how the dimensions of a part are combined in order to describe the part
  - These controlling dimensions could be a single dimension or multiple dimensions
  - As the number of controlling dimensions increases, the tolerance accumulation increases

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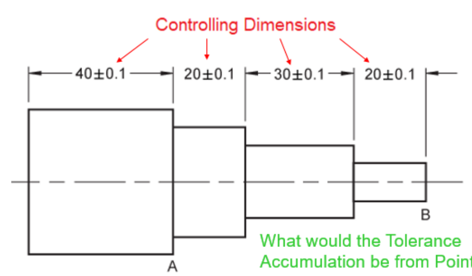
Stacking Tolerances



What would the Tolerance Accumulation be from Point A to Point B?

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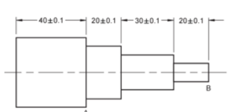
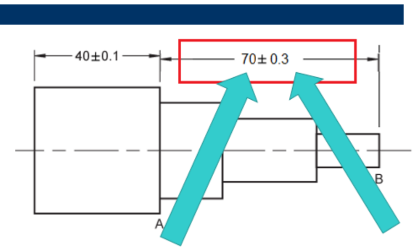
Stacking Tolerances





20 + 30+ 20 = 70

Sum the Base Dimensions

0.1 + 0.1 + 0.1 = 0.3

Sum the Tolerances

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ANSI Standard

- The following fits are in accordance with the **ANSI B4.1-1967(R1994)** standard [3]
- The charts are to give an idea of how tolerances are calculated for shaft and hole assemblies given the desired fit

Use of Tables

- Help determine type of fit
- Created to help future engineers more easily determine tolerance in certain situations
- These ones are specific to pin and hole assemblies
- This tables are to show real world examples and are NOT TO BE USED on the homework

ANSI Standard

- RC: Running (or Sliding) Clearance Fit
- RC9 (loosest) – RC1 (tightest)
- Guarantee Clearance

RC 1 Close sliding fits are intended for the accurate location of parts which must assemble without perceptible pl
RC 2 Sliding fits are intended for accurate location, but with greater maximum clearance than class RC 1. Parts r this fit move and turn easily but are not intended to run freely, and in the larger sizes may seize with small temperature changes.
RC 3 Precision running fits are about the closest fits which can be expected to run freely, and are intended for pre work at slow speeds and light journal pressures, but are not suitable where appreciable temperature differe are likely to be encountered.
RC 4 Close running fits are intended chiefly for running fits on accurate machinery with moderate surface speeds journal pressures, where accurate location and minimum play are desired.
RC 5 / RC 6 Medium running fits are intended for higher running speeds, or heavy journal pressures, or both.

ANSI Standard

Diameter Size Ranges:

Class	0 - 0.12		0.12 - 0.24		0.24 - 0.40		0.40 - 0.71		0.71 - 1.19	
RC1 Hole	+0.2	-0.0	+0.2	-0.0	+0.25	-0.0	+0.3	-0.0	+0.4	-0.0
RC1 Shaft	+0.1	-0.25	-0.15	-0.3	-0.2	-0.35	-0.25	-0.45	-0.3	-0.55
RC2 Hole	+0.25	-0.0	+0.3	-0.0	+0.4	-0.0	+0.4	-0.0	+0.5	-0.0
RC2 Shaft	-0.1	-0.3	-0.15	-0.35	-0.2	-0.45	-0.25	-0.55	-0.3	-0.7
RC3 Hole	+0.4	-0.0	+0.5	-0.0	+0.6	-0.0	+0.7	-0.0	+0.8	-0.0
RC3 Shaft	-0.3	-0.55	-0.4	-0.7	-0.5	-0.9	-0.6	-1.0	-0.8	-1.3
RC4 Hole	+0.6	-0.0	+0.7	-0.0	+0.9	-0.0	+1.0	-0.0	+1.2	-0.0
RC4 Shaft	-0.3	-0.7	-0.4	-0.9	-0.5	-1.1	-0.6	-1.3	-0.8	-1.6
RC5 Hole	+0.6	-0.0	+0.7	-0.0	+0.9	-0.0	+1.0	-0.0	+1.2	-0.0
RC5 Shaft	-0.6	-1.0	-0.8	-1.3	-1.0	-1.6	-1.2	-1.9	-1.6	-2.4
RC6 Hole	+1.0	-0.0	+1.2	-0.0	+1.4	-0.0	+1.6	-0.0	+2.0	-0.0
RC6 Shaft	-0.6	-1.2	-0.8	-1.5	-1.0	-1.9	-1.2	-2.2	-1.6	-2.8
RC7 Hole	+1.0	-0.0	+1.2	-0.0	+1.4	-0.0	+1.6	-0.0	+2.0	-0.0
RC7 Shaft	-1.0	-1.6	-1.2	-1.9	-1.6	-2.5	-2.0	-3.0	-2.5	-3.7
RC8 Hole	+1.6	-0.0	+1.8	-0.0	+2.2	-0.0	+2.8	-0.0	+3.5	-0.0
RC8 Shaft	-2.5	-3.5	-2.8	-4.0	-3.0	-4.4	-3.5	-5.1	-4.5	-6.5
RC9 Hole	+2.5	-0.0	+3.0	-0.0	+3.5	-0.0	+4.0	-0.0	+5.0	-0.0
RC9 Shaft	-4.0	-5.6	-4.5	-6.0	-5.0	-7.2	-6.0	-8.8	-7.0	-10.5

ANSI Standard

- LN, LC, LT: Location Fits
  - N: Interference
  - C: Clearance
  - T: Transition
- LC/LT/LN 1 (loosest) – LC11/LT6/LN3 (tightest)
- Locational Fits help determine the location of the mating parts

ANSI Standard

- FN: Force Fits
- F5 (tightest) – F1 (loosest)
- Guarantee Interference

Table A-1-2 FORCE AND SHRINK FITS

Class		Diameter Size Range (in.) 0.00 - 0.12		0.12 - 0.24		0.24 - 0.40		0.40 - 0.56	
FN1	Hole	+0.25	-0.00	+0.30	-0.00	+0.40	-0.00	+0.40	-0.00
	Shaft	+0.50	+0.30	+0.60	+0.40	+0.75	+0.50	+0.80	+0.50
FN2	Hole	+0.40	-0.00	+0.50	-0.00	+0.60	-0.00	+0.70	-0.00
	Shaft	+0.85	+0.60	+1.00	+0.70	+1.40	+1.00	+1.60	+1.20
FN3	Hole								
	Shaft								
FN4	Hole	+0.40	-0.00	+0.50	-0.00	+0.60	-0.00	+0.70	-0.00
	Shaft	+0.95	+0.70	+1.20	+0.90	+1.60	+1.20	+1.80	+1.40
FN5	Hole	+0.60	-0.00	+0.70	-0.00	+0.90	-0.00	+1.00	-0.00
	Shaft	+1.30	+0.90	+1.70	+1.20	+2.00	+1.40	+2.30	+1.60

Class		Diameter Size Range (in.) 0.56 - 0.71		0.71 - 0.95		0.95 - 1.19		1.19 - 1.58	
FN1	Hole	+0.40	-0.00	+0.50	-0.00	+0.50	-0.00	+0.60	-0.00
	Shaft	+0.90	+0.60	+1.10	+0.70	+1.20	+0.80	+1.30	+0.90
FN2	Hole	+0.70	-0.00	+0.80	-0.00	+0.80	-0.00	+1.00	-0.00
	Shaft	+1.60	+1.20	+1.90	+1.40	+1.90	+1.40	+2.40	+1.80
FN3	Hole					+0.80	-0.00	+1.00	-0.00
	Shaft					+2.10	+1.60	+2.60	+2.00
FN4	Hole	+0.70	-0.00	+0.80	-0.00	+0.80	-0.00	+1.00	-0.00
	Shaft	+1.80	+1.40	+2.10	+1.60	+2.30	+1.80	+3.10	+2.50
FN5	Hole	+1.00	-0.00	+1.20	-0.00	+1.20	-0.00	+1.60	-0.00
	Shaft	+2.50	+1.80	+3.00	+2.20	+3.30	+2.50	+4.00	+3.00

Class		Diameter Size Range (in.) 1.58 - 1.97		1.97 - 2.56		2.56 - 3.15		3.15 - 3.94	
FN1	Hole	+0.60	-0.00	+0.70	-0.00	+0.70	-0.00	+0.90	-0.00
	Shaft	+1.40	+1.00	+1.80	+1.30	+1.90	+1.40	+2.40	+1.80
FN2	Hole	+1.00	-0.00	+1.20	-0.00	+1.20	-0.00	+1.40	-0.00
	Shaft	+2.40	+1.80	+2.70	+2.00	+2.90	+2.20	+3.70	+2.80
FN3	Hole	+1.00	-0.00	+1.20	-0.00	+1.20	-0.00	+1.40	-0.00
	Shaft	+2.80	+2.20	+3.20	+2.50	+3.70	+3.00	+4.40	+3.50
FN4	Hole	+1.00	-0.00	+1.20	-0.00	+1.20	-0.00	+1.40	-0.00
	Shaft	+3.40	+2.80	+4.20	+3.50	+4.70	+4.00	+5.90	+5.00
FN5	Hole	+1.60	-0.00	+1.80	-0.00	+1.80	-0.00	+2.20	-0.00
	Shaft	+5.00	+4.00	+6.20	+5.00	+7.20	+6.00	+8.40	+7.00

Why do Tolerances Matter?

- Allow for variation in manufacturing processes
- Design for Thermal Expansion
- Allow for interchangeability of parts

Key Words

- Tolerances: The amount an object is allowed to vary
- Tolerance Zone: Max. Dim. – Min. Dim.
- Form: The desired physical shape of the part
- Function: The intended purpose of the design
- Clearance Fit: Min. Clearance > 0; Space and loose fit
- Interference Fit: Max. Clearance < or = 0; No space and forced/tight fit

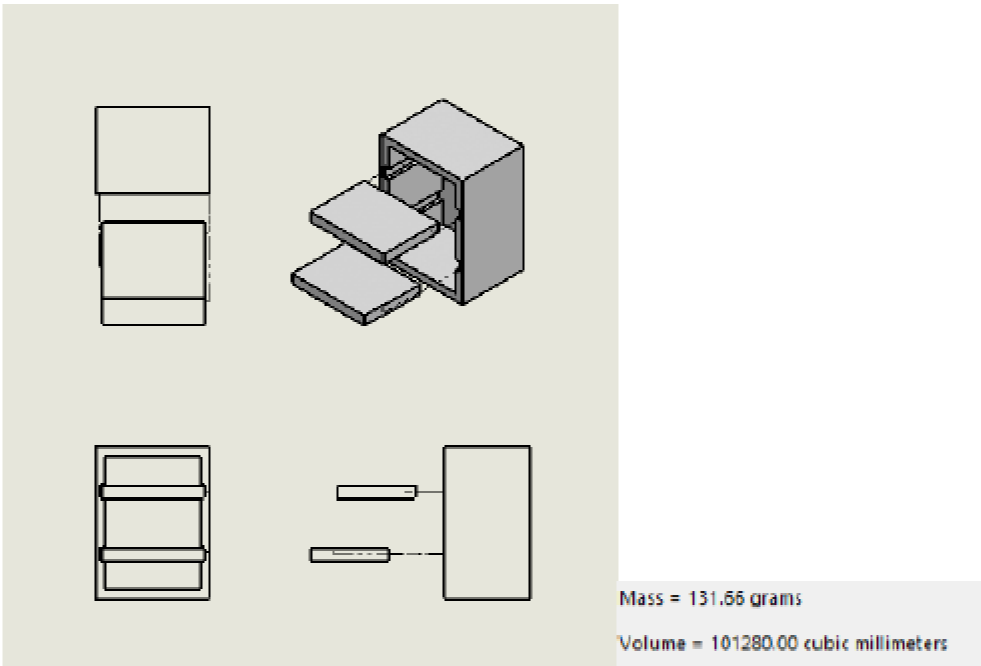
Key Words

- Transition/Line Fit: Min. Clearance ≤ 0; Neither tight nor loose
- Least Material Condition: When the part has the least material
- Maximum Material Condition: When the part has the most material
- Maximum Clearance: LMC hole – LMC shaft
- Minimum Clearance: MMC hole – MMC shaft
- Tolerance Accumulation: Sum of controlling dimensions

Appendix B: Assembly Hints

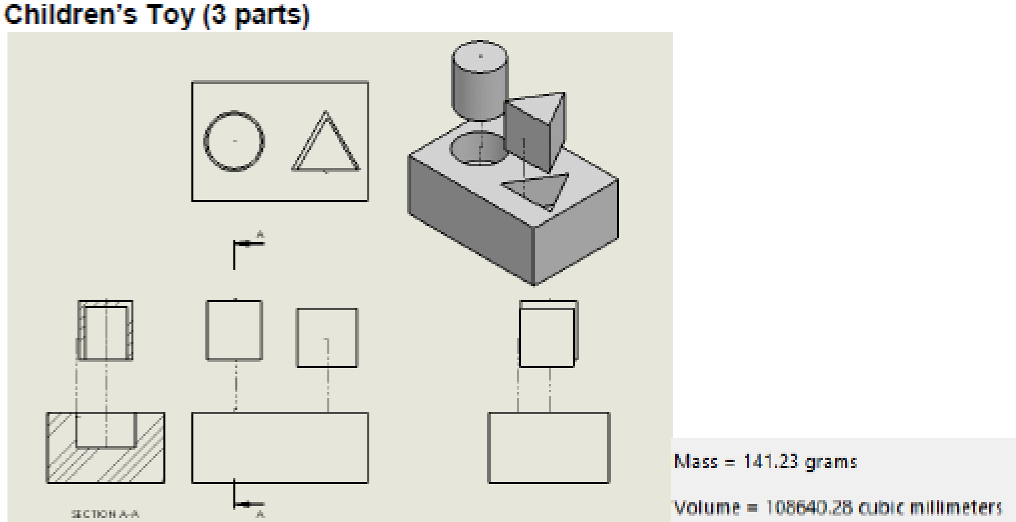
Assembly Form and Size References

1) Sliding Shelf (3 parts)



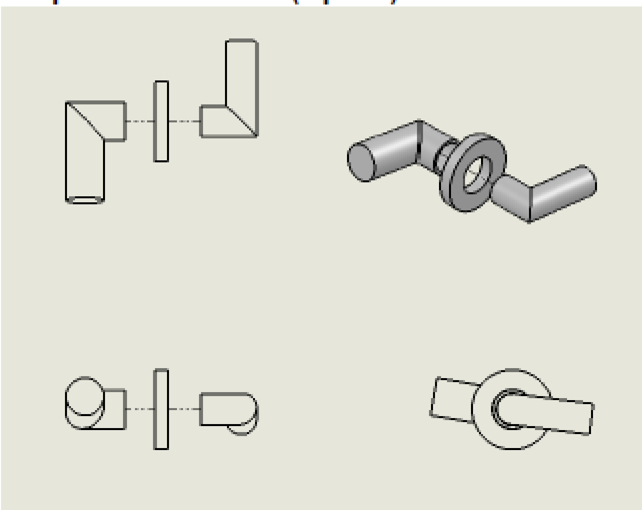
- The shelves must slide smoothly in and out
- The shelves must not be wobbly when inserted. This includes up and down, as well as side to side (you must determine how to achieve this)

2) Children's Toy (3 parts)



- Use Shell Feature to reduce mass and volume if necessary
- The triangular block must not fit into the circular hole
- The cylindrical block must not fit into the triangular hole

3) Simple Bike Crankset (3 parts)

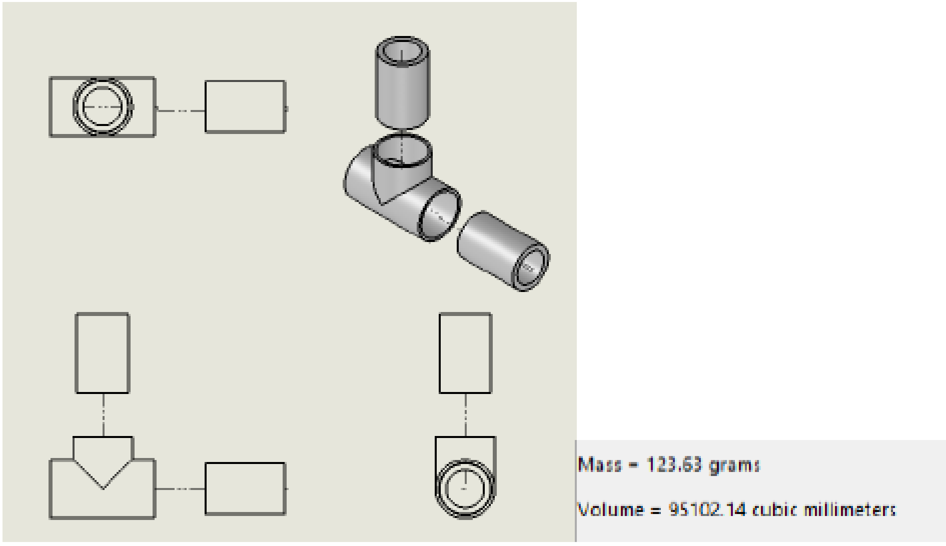


Mass = 135.82 grams

Volume = 104474.31 cubic millimeters

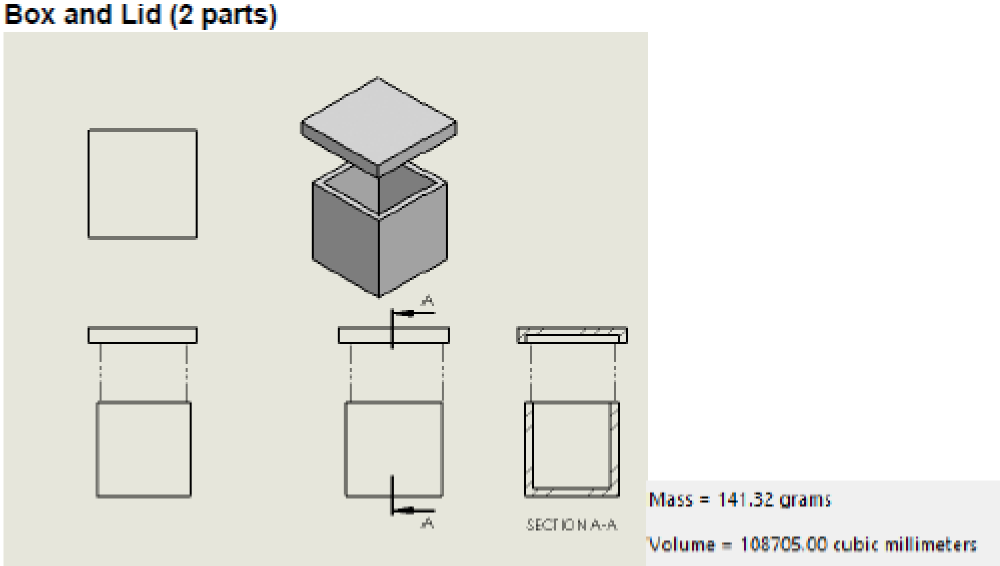
- One handle will have a larger inner diameter than the other handle, in order for the two to be connected (you must determine by how much)
- The hole diameter of the middle part will be the largest diameter (you must determine by how much)
- The idea is that rotating one handle with force the circular piece and the second handle to move. ***This should behave like peddles on a bike, except much simpler.***


4) **PVC Pipe (3 parts)**



- This is really two parts, with one part duplicated
- The pipes must not fall out of the connecter if rotated or moved

5) **Box and Lid (2 parts)**



- The lid must not be forced onto the box, nor forced off the box
- The lid must not wobble while on the box
- Although this assembly appears simple, I will be harsher when grading your critical thinking in the report

Appendix C: Homework Assignment

In your groups, design the assigned assembly in SolidWorks. Follow the guidelines below:

Assembly	Recommended # Parts	Maximum Volume
Box and Lid	2 parts	108705.00 mm^3
PVC Pipe	3 parts	95102.14 mm^3
Shelf	3 parts	101280.00 mm^3
Child Toy	3 parts	108640.28 mm^3
Simple Crankset	3 parts	104474.31 mm^3

Each team has a budget of $15. Anything exceeding this budget is the responsibility of the student. Cline Library Maker's Lab charges $0.10/gram of material used. Make sure to check the mass properties. Use maximum volume dimensions provided as a reference.

1) It is up to your team to determine the basic dimensions and the tolerances on your part, based upon your desired goal. Use your notes from today and the lecture slides posted in BBLearn to <u>determine if your assembly requires a clearance, interference, or line fit.</u> Design each part of your assembly separately in SolidWorks.

2) Submit your parts to the Maker's Lab (https://nau.edu/library/makerlab/) to be 3D printed. Once printed, your group will need to assemble the parts. *Note: You may need to trim or sand some of the parts after they are printed. The Maker's Lab has all the tools necessary to do this, so speak with someone at the front desk if you need to use these tools.*

3) Write a one-page report based upon your results. The report should include:

- Did your assembly fit together? Why or why not? Give examples of the dimensions you assigned to the parts, and how these did or did not help the assembly mate.
- Did the mating parts have the desired form, fit, and function intended?
  - if YES: explain what fit type (clearance, interference, line) you used and if the tolerances you applied were the *best possible*.
  - if NO: explain the fit type used (clearance, interference, line) and how and why it failed in terms of tolerances. *(Was the fit type the wrong fit? Were your dimensions off, meaning you had too large or small a clearance? Did the parts stick too much together, or wiggle too loosely? etc)*
- If you had a second chance to print the assembly, would you change the dimensions to get a better fit and function? Why or why not?

- Include screenshots of your parts in SolidWorks

Appendix D: Questionnaire

DO *<u>NOT</u>* *WRITE YOUR NAME. Please answer the questions below honestly and to the best of your ability. If you requested not to be a part of my research, you do not need to fill out the questionnaire. Thank you for your participation! ~Allison Cutler*

1) On the following scale (1 = terrible, I am very confused; 10 = awesome, I could teach this), <u>how well did you understand tolerances after *only* the lecture</u>?

1 2 3 4 5 6 7 8 9 10

2) On the following scale (1= I'm still very confused and have NO idea what is happening, 10 = I am a master), <u>how well did you understand tolerances *after* completing the homework assignment?</u>

1 2 3 4 5 6 7 8 9 10

3) <u>List what concepts you are still confused on (if any</u>).

4) <u>List what concepts you understood very well</u> (try to be specific. You can put 'everything' but provide examples).

5) <u>Were the requirements of the homework assignment clear and comprehendible? If not, please explain.</u>

References

[1] Department of Mechanical and Material Engineering, “ME 320 First Plan,” Portland State University, 2017. Available: https://www.pdx.edu/mme/sites/www.pdx.edu.mme/files/ME%20320%20Course%20Plan%20AY%2017-18.pdf

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[4] Stanford University, “EGNR 14: Intro to Solid Mechanics,” *Bulletin: Explore Courses.* 2017. Available: http://explorecourses.stanford.edu/search;jsessionid=1sf5g0ccwikbg1bp2pk9ehltcs?q=ENGR+14%3a+Intro+to+Solid+Mechanics&view=catalog&filter-coursestatus-Active=on&academicYear=20172018

[5] R. Budynas and K. Nisbett, *Shigley's Mechanical Engineering Design 9th Edition.* NY: McGraw-Hill Higher Education, 2010