# Specifying Inch Fits: Students' Understanding of Size and Scale

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***Abstract***

*A topic that has received some attention in science education has been students' understanding of the concepts of size and scale for objects ranging from extremely small (atomic nucleus) to extremely large (distance from earth to sun). Students have difficulty conceptualizing the size of objects when the objects are at the extremes or when students do not have direct experience with the objects. Over the last three years, this difficulty has also been observed in a geometric dimensioning and tolerancing course at Illinois State University. This digest will describe student activities related to determining specified fits in TEC333, summarize student outcome data since 2016, and present the results and conclusions.*

## Introduction

Understanding the concepts of size and scale is important in many different disciplines. Science educators have investigated students' abilities to make accurate estimates of size from nano- sized objects to extremely large objects or distances (Tretter, Jones, Andre, Negishi, & Minogue, 2006; Light, Swarat, park, Drane, Tevaarwerk, & Mason, 2007; Swarat, Light, Park, & Drane, 2011). Tretter, et al. (2006) found that students are better at making predictions about relative scale than absolute scale, and students conceptualize scale much differently for objects in which they have direct experience (height of an adult person, height of an elephant, or the length of football field) versus objects or distances for which they experience indirectly (diameter of the nucleus of a carbon atom, diameter of a human cell, or distance from the sun to the earth). Light, et al. (2007) recommend that faculty need to find alternative strategies for students to "experience small, non-visible phenomena" (p. 12).

Engineering graphics instructors may experience student misconceptions of size and scale when discussing tolerancing concepts. Since most of the activities related to tolerancing deal with very small distances, students may not have sufficient background to understand the significance between inch tolerances of .1, .01, or .001. Even students who have experience with machining and precision measurement still specify large tolerance values.

These issues have been observed in TEC333: Geometric Dimensioning and Tolerancing at Illinois State University. During the last three fall semesters, this course has been offered as an elective for undergraduate Engineering Technology majors and graduate students who have a background in engineering or technology. Prerequisites to the course include TEC130: Introduction to Manufacturing Processes and TEC216: Constraint-Based Solid Modeling and Production Drawings. Limit dimensioning and other tolerancing concepts are covered in both prerequisite courses. On the first day of class in TEC333, students take a pretest to assess previous knowledge related to a wide range of tolerancing concepts. An area of low performance on the pretest has been specifying limit dimensions from standard inch fit tables (Figures 1 & 2). Values in the body of the table (Figure 2) are in thousandths of an inch. This is highlighted on the pretest. Of the 41 students who have taken TEC333 in the last 3 years, only 2 students have answered this question correctly. Figure 3 shows examples of student answers on the pretest. Figure 4 displays the correct answer to the pretest question.

*Pretest Item:* Conventional Tolerancing – Using the table on the next page, add the limit dimensions for the pin and the machined hole per the following specifications.

RC2 fit with a basic size of 1.5000 inch.

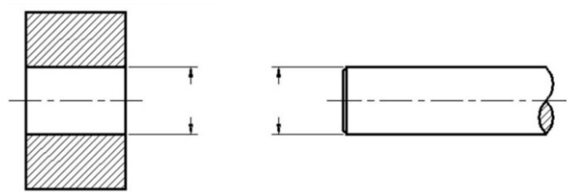

**Figure 1. Question from TEC333 pretest**

| Nominal Size Range, Inches (Over To) | Class RC 1 | | | Class RC 2 | | |
|---|---|---|---|---|---|---|
| | Limits of Clearance | Standard Limits | | Limits of Clearance | Standard Limits | |
| | | Hole H5 | Shaft g4 | | Hole H6 | Shaft g5 |
| 0-0.12 | 0.1<br>0.45 | +0.2<br>–0 | –0.1<br>–0.25 | 0.1<br>0.55 | +0.25<br>–0 | –0.1<br>–0.3 |
| 0.12-0.24 | 0.15<br>0.5 | +0.2<br>–0 | –0.15<br>–0.3 | 0.15<br>0.65 | +0.3<br>–0 | –0.15<br>–0.35 |
| 0.24-0.40 | 0.2<br>0.6 | +0.25<br>–0 | –0.2<br>–0.35 | 0.2<br>0.85 | +0.4<br>–0 | –0.2<br>–0.45 |
| 0.40-0.71 | 0.25<br>0.75 | +0.3<br>–0 | –0.25<br>–0.45 | 0.25<br>0.95 | +0.4<br>–0 | –0.25<br>–0.55 |
| 0.71-1.19 | 0.3<br>0.95 | +0.4<br>–0 | –0.3<br>–0.55 | 0.3<br>1.2 | +0.5<br>–0 | –0.3<br>–0.7 |
| 1.19-1.97 | 0.4<br>1.1 | +0.4<br>–0 | –0.4<br>–0.7 | 0.4<br>1.4 | +0.6<br>–0 | –0.4<br>–0.8 |

**Figure 2. RC fit table for pretest (sections were not highlighted for students)**

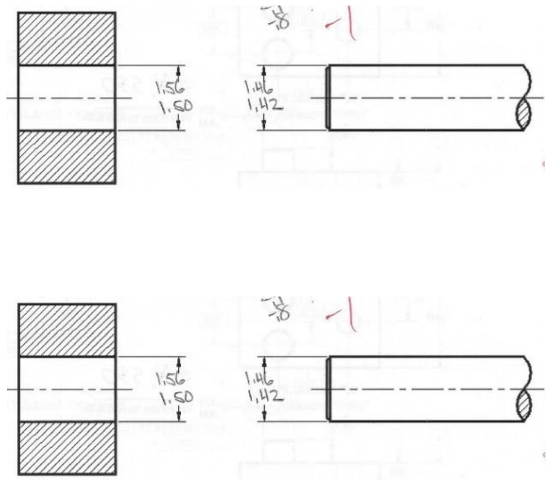


**Figure 3. Student response examples from pretest**

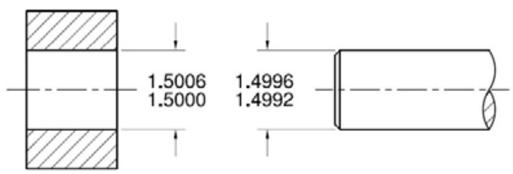


**Figure 4. Correct response to limit question**

To better assess of some of the issues related to students' understanding of size and scale in TEC333, the following research questions are addressed in this digest:

1. Is there a relationship between where the prerequisite introductory manufacturing course was taken and the deviation from the correct tolerance value on the pretest?
2. Is there a relationship between where the prerequisite constraint-based modeling course was taken and the deviation from the correct tolerance value on the pretest?
3. Is there a relationship between when students took TEC233 (CNC course) and the deviation from the correct tolerance value on the pretest?

**Method**

*Participants:* The 41 participants in this study were mainly Engineering Technology students at Illinois State University. There were four graduate students included in the study, three of which were recent graduates of the undergraduate Engineering Technology program. Table 1 displays the number of students across the last three years in TEC333, Table 2 displays their academic year, and Table 3 shows how students entered the university.

**Table 1. Participants by semester**

| Semester | Freq | Percent |
|---|---|---|
| Fall 2016 | 12 | 29.3 |
| Fall 2017 | 19 | 46.3 |
| Fall 2018 | 10 | 24.4 |
| Total | 41 | 100.0 |

**Table 2. Participants by academic year**

| Academic Year | Freq | Percent |
|---|---|---|
| Junior | 9 | 22.0 |
| Senior | 28 | 68.3 |
| Graduate | 4 | 9.8 |
| Total | 41 | 100.0 |

**Table 3. How students entered the university**

| Student Type | Freq | Percent |
|---|---|---|
| Freshmen | 10 | 24.4 |
| Transfer | 30 | 73.2 |
| Grad Admit | 1 | 2.4 |
| Total | 41 | 100.0 |

As stated earlier, most of the students enrolled in TEC333 were undergraduates, and almost 70% of the students were seniors. Less than 25% of the students entered the university as freshmen. The majority, 73%, entered as transfer students. Since a most of the students transferred into the university, it was necessary to see where they completed the prerequisite courses. Another point of interest was to determine if students had already completed TEC 233: CNC and Machining. Tables 4-6 display data for the prerequisite courses and TEC233.

**Table 4. Time of TEC130 - Intro to Manufacturing**

| Time of Course | Freq | Percent |
|---|---|---|
| Taken at Illinois State University | 35 | 85.4 |
| Transferred in | 5 | 12.2 |
| Waived | 1 | 2.4 |
| Total | 41 | 100.0 |

**Table 5. Time of TEC216 - Constraint-Based CAD**

| Time of Course | Freq | Percent |
|---|---|---|
| Taken at Illinois State University | 37 | 90.2 |
| Transferred in | 2 | 4.9 |
| Waived | 2 | 4.9 |
| Total | 41 | 100.0 |

**Table 6. Time of TEC 233 - CNC Course**

| Time of Course | Freq | Percent |
|---|---|---|
| Taken at Illinois State University before TEC333 | 28 | 68.3 |
| Transferred in | 4 | 9.8 |
| Taken concurrently | 6 | 14.6 |
| Taken after TEC333 | 3 | 7.3 |
| Total | 41 | 100.0 |

Most of the students completed the prerequisite courses at Illinois State University. Five students transferred TEC130 from a community college, and one student received a waiver for the prerequisite. Thirty-seven students completed TEC216 at Illinois State University, and 68% of the students completed the CNC course before taking TEC333.

*Pretest: A 25 item pretest was given on the first day of TEC333 in each of the previous 3 semesters.* The purpose of the pretest was to assess students' prior knowledge of a wide range of tolerancing and GD&T concepts. For this study, only the question related to limit dimension calculations will be addressed.

**Results**

To better understand how student responses varied from the correct values for the RC 2 fit calculations, all student responses were recorded and deviations from the correct values were calculated. Figure 5 shows how far student responses deviated from the correct values for the lower tolerance (blue) and the upper tolerance (orange) for the Hole. Figure 6 displays the RC 2 fit deviations for the Shaft.

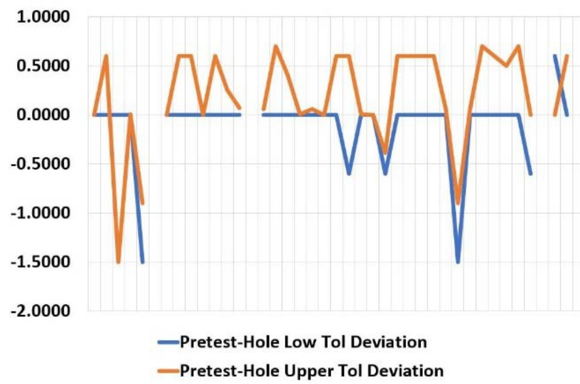


**Figure 5. Deviations for Pretest Hole Tolerance**

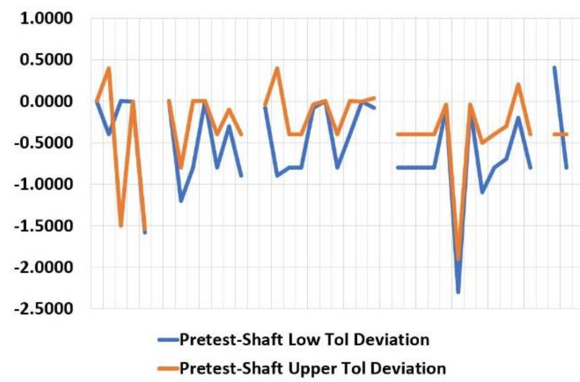


**Figure 6. Deviations for Pretest Shaft Tolerance**

Figure 4 illustrates that 31 of the 41 participants correctly specified the lower tolerance for the hole since there was no deviation (.0000). Two of the participants specified the tolerance as

.0000 (-1.5000 deviation), three specified .9000 (-.6000 deviation), and one participant specified 2.1000 (+.6000 deviation). Four participants did not respond. There was much more variety in the responses for the upper tolerances. Only 4 participants correctly specified the upper tolerance value for the hole.

Participants also had difficulty specifying the upper and lower tolerance values for the shaft. Only 3 participants correctly identified the lower tolerance, and only 2 correctly identified the upper tolerance for the shaft.

To determine if relationships existed between the prerequisite courses (nominal data) and the deviations from the correct tolerance values (continuous data), Kruskal-Wallis H tests were conducted (Sheskin, 2007). Tables 7-9 present the results from these tests.

**Table 7. Correlation between where student took [manufacturing course] and deviation on pretest**

| Tolerance | K-W | Df | Sig |
|---|---|---|---|
| Hole Lower Tol | .495 | 2 | .781 |
| Hole Upper Tol | .978 | 2 | .613 |
| Shaft Lower Tol | 6.003 | 2 | .050 * |
| Shaft Upper Tol | 2.479 | 2 | .289 |

**Table 8. Correlation between where student took [constraint-based CAD course] and deviation on pretest**

| Tolerance | K-W | Df | Sig |
|---|---|---|---|
| Hole Lower Tol | 2.741 | 2 | .254 |
| Hole Upper Tol | .434 | 2 | .805 |
| Shaft Lower Tol | 5.413 | 2 | .067 |
| Shaft Upper Tol | 5.230 | 2 | .073 |

**Table 9. Correlation between when student took [CNC course] and deviation on pretest**

| Tolerance | K-W | Df | Sig |
|---|---|---|---|
| Hole Lower Tol | 2.520 | 3 | .472 |
| Hole Upper Tol | 4.659 | 3 | .199 |
| Shaft Lower Tol | 1.452 | 3 | .693 |
| Shaft Upper Tol | 4.713 | 3 | .194 |

Only one of the values indicated a significant relationship. There was a significant relationship between where participants took the introductory manufacturing course and the deviation from the correct value for the lower tolerance on the shaft. Figure 7 shows a scatterplot of these values.

To determine the effect size of the relationship, a crosstab analysis was conducted, and the Eta squared value was calculated (see Table 10).

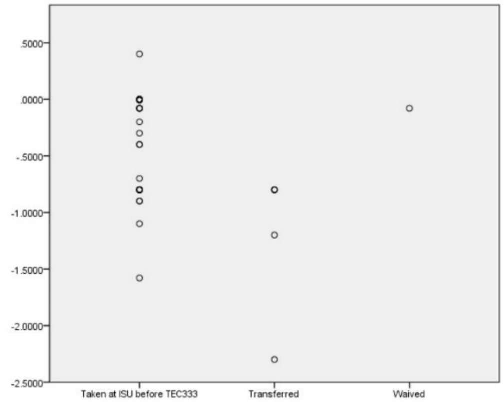


**Figure 7. Where Participant took the Introductory Manufacturing Course by Deviations for Pretest Shaft Lower Tolerance**

**Table 10. Crosstab analysis with Eta2**

| Tolerance | Eta | $Eta^2$ |
|---|---|---|
| Shaft Lower Tol | .493 | .243 |

The Eta2 calculation indicates the effect size of the analysis. In this case, 24% of the variation in the shaft lower tolerance deviation is explained by where participants took the introductory manufacturing course. After examining Figure 7, it appears participants who took the manufacturing course at Illinois State University were more likely to accurately determine the lower tolerance of the shaft dimension. The analysis still indicates a large amount of variation that is unexplained.

## Discussions and Conclusions

There are several initial conclusions that can be made from this study. First, it was clear that many participants did not have a clear understanding of size and scale. A large number of specified tolerance values were 3 orders of magnitude greater than the correct specification. There could be many reasons for these errors. Participants may not have taken the time to check their calculations. It is also possible that they did not realize that .6000" or .8000" is a very large and unreasonable tolerance for a 1.5000" hole.

Overall, it did not appear that taking the prerequisite courses at Illinois State University or transferring them into the university had any effect on participants' ability to correctly specify tolerance values on the pretest. Only 5 students took an introductory manufacturing course at a community college, and only 2 students completed a constraint-based CAD course at a community college. In addition, the semester participants took TEC233 did not have a bearing on their ability to correctly specify the tolerances on the pretest.

The early topics in TEC333 include a review of conventional tolerancing concepts, including the specification of standard fits. This instruction appeared to result in students' better understanding tolerancing concepts. Figures 8 & 9 illustrate only one student still had difficulty understanding the scale of the value.

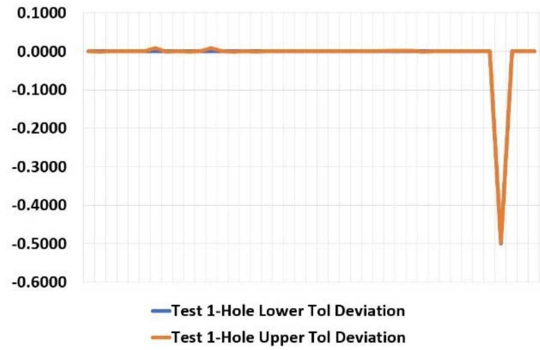


**Figure 8. Deviations for Test 1 Hole Tolerance**

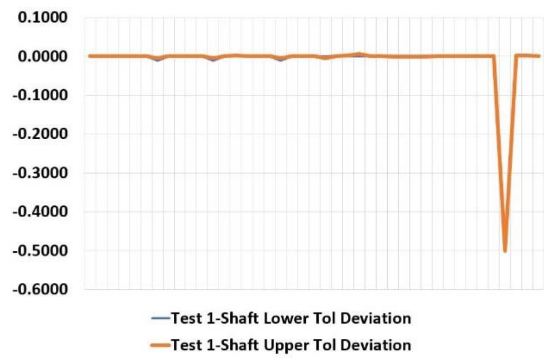


**Figure 8. Deviations for Test 1 Shaft Tolerance**

**Future Research**

There are two areas of recommended future work.

To gain a better understanding of students' thought processes, qualitative data could be collected while students verbalize their strategies during the tolerancing activity. This would help researchers to narrow down the types of errors students are making during the process.

Some of the laboratory assignments in TEC333 include the operation of coordinate measuring machines (CMM). Early lab reports and student reflections also indicate students' lack of understanding of size and scale. Studies can be developed to investigate why students continue to make mistakes later in the course.

**References**

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