# A Developmental Visualization Module that Starts with Inspection and Ends at Solid Modeling Using Real Objects

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**Abstract -** We developed and deployed a learning module that promotes students' comprehension of spatial relationships through inspection of common objects and drawing of rapid-prototype (RP) primitives. The module takes advantage of the natural interplay between object visualization and the use of measurement tools for object inspection. We approach spatial relationship comprehension developmentally through the following steps: 1) inspection of objects to identify them from a catalog, 2) inspection of RP primitives to create a two dimensional orthographic projection drawing with dimensions, 3) inspection of RP primitives to create sketches that are subsequently used to develop a solid model. The module is distributed across a freshman and sophomore course.

This paper provides enough details of this module to facilitate its adaptation to other curricula, and the results of direct and indirect assessments of student learning. Direct measures of the module's effectiveness include the results of quizzes and embedded exam questions. Indirect measures include the reports of in-class observers from the university's Center for Assessment and Research studies.

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## INTRODUCTION

The curriculum of the James Madison University School of Engineering includes an introductory course (Introduction to Engineering) for freshman students and two design courses (Design I and Design II) for sophomore students as part of a four-year, seven course sequence emphasizing engineering design. These introductory courses present students with a range of topics and projects intended to develop understanding of sustainable design and provide experiences in developing and implementing their own designs through the prototype phase. A "sustainable design", as defined here, is a design in which technical, financial, environmental, and societal aspects are considered.

To facilitate more advanced student driven design and prototyping activities, these courses must address and develop students' critical thinking, visualization, and construction skills. This paper describes our instruction associated with visualization skills development in Introduction to Engineering and Design I using two instructional units; a physical inspection unit and computer graphics unit. This approach begins with an inspection unit where students measure familiar objects. The inspection module includes a reading, in-class instruction, in-class group activities, and individual homework. One laboratory session is devoted to the inspection unit. The inspection unit is followed by laboratory sessions that address the creation of 2D drawings and 3D solid models of actual objects distributed to the students while reinforcing inspection skills. Creation of 2D drawings is addressed in the Freshman course while 3D solid model creation is addressed in the Sophomore course. In order to control object complexity, the objects are built "in-house" on a selective laser sintering (SLS) rapid prototyping (RP) machine.

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We chose to use solid models to emphasize the relationship between drawings and "real" objects, thus providing a direct link to engineering practice. Furthermore, the authors suggest that inspection of an object for the purpose of developing a graphic representation develops measurement skills and intuition related to size and shape. As students manipulate the objects for inspection they are adding the modality of touch, increasing the level of activity in their learning experience, which has been shown to improve retention. Finally, the use of real objects and solid models within this module, along with an active learning approach to instruction, promote student engagement with their learning.

**Literature Review**

The introduction of physical objects in traditional engineering graphics curricula is not a new development. Vander Wall describes positive response by students and instructors to Styrofoam models used as learning-reinforcements. Although the significant amount of effort required to produce such models from Styrofoam using an Exacto knife and rubber cement is acknowledged, Vander Wall contends that the benefits outweigh the work [1]. Today, rapid prototyping machines can produce similar models with less human input. Czapka et al. describe a graphics course in which solid models built with a rapid prototyping machine were used as supplemental aids to help students solve orthographic projection problems. In this case use of solid models was shown to be most helpful to students who entered the course with weak visualization skills [2].

Use of models in engineering graphics instruction has been debated in the past; in fact references to the topic go back nearly 100 years. Miller reported the typical arguments [3]: proponents of model use consider them to improve students grasp of orthographic projection [1], [4], [5] while others [6], [7] consider them to be a "crutch". These arguments do not address the "active learning" component introduced by use of models which the authors of this paper consider to be significant.

Finally, those that wish to take this approach to the next level in order to parse visual and touch modalities will be interested in the study by DeJong who studied students' ability to develop orthographic representations of solid models that they were allowed to touch, but not see [8].

## INSTRUCTIONAL UNITS

Our approach to developing students' visualization skills was comprised of two major instructional units; an inspection unit and a computer graphics unit. The details of each unit described below.

**Inspection Unit**

This unit is presented as part of the introductory engineering course. The unit requires one 100 minute lab session and is focused on the development of knowledge and skills required to operate typical distance measuring hand tools and the application of such skills to inspect familiar objects. In this unit, students learn the nomenclature, care, and usage of tape measures, dial calipers, Vernier micrometers (inch), and micrometers (mm). Instruction includes a pre-lab tutorial, in-lab presentation, in-lab demonstrations, an in-lab group activity, and individual homework. During the in-lab activity, teams of two students use worksheet directions to make measurements of artifacts in the laboratory area and objects around the building. The post-lab homework assignment questions assess students' operational knowledge of measurement tools and require students to use measurements they made as part of the in-lab activity to identify an object from a catalog We consider inspection of an existing part to be an appropriate "entry point" to visualization. Part inspection develops sense of shape and size with a heavy emphasis on tactile interaction by the student. In his book that explores the influence that the hands have on human development (*The Hand*), Frank Wilson describes the influence that the hand has on physical knowledge:

> "The reason [brain] messages were going to the hands in the first place was so that the hands would reach for, grasp, touch, turn, weigh, join, separate, bounce, and so on, whatever it was that came into their possession. The hands were moved, among other reasons, to obtain information that could be obtained only by acting upon the object being held. The information returned to the brain was written in the tactile and kinesthetic language of manipulation, and was compared with information coming from the visual system, as part of a process through which the brain creates visuospatial images" [9].

This suggests a strong correlation between the manipulation of objects by hand and physical understanding of objects and materials.

Materials

The materials required for the in-lab activities include the measurement tools, micrometer standards (gauge blocks, feeler gauges, etc.) for demonstration, and a number of standards for measurement practice. We chose 12' tape measures with 1/16" and 1/32" resolution scales, 6" dial calipers with 0.001" resolution, and 0.100" per dial revolution, 1" Vernier micrometers with 0.0001" resolution, and 25 mm micrometers with 0.01mm resolution.

Measurement tools and inspection equipment are available for a wide range of quality and price points. Our approach was to purchase tools that were the least expensive of those expected to give reasonable value. We chose to avoid non-name-brand "economy" tools that were about half the price of our choices. The total cost of tools and calibrated measurement items was around $1700.00.

Instruction and Assignments

The instruction for this unit includes a pre-lab tutorial for the students, in-lab presentation, in-lab demonstrations, an in-lab group activity, and individual homework. A 21 page pre-lab tutorial, including several pictures and diagrams, was developed as a comprehensive student reference for this instructional unit. Further, the information can serve as a "refresher" document in the future in the case that students forget material.

*Pre-lab Tutorial*

The pre-lab tutorial includes information on tape measures, calipers, and micrometers. It is intended to teach students proper usage, names of components, and scale reading for each measurement tool. The emphasis of the tutorial is on scale reading; nine exercises with a total of 65 individual questions are included in the tutorial so that students can practice scale readings. The exercises are not collected; the answers to each of the exercises are included at the end of the tutorial. *In-lab Presentations, Demonstrations, and Activities*

The in-lab presentation is broken into three parts; tape measure, dial caliper, and micrometer. Each presentation and demonstration lasts from 5-10 minutes and is followed by 20-25 minutes of student exercises. The student exercises are performed in groups of two and are directed by a worksheet. During the lab exercise students perform three activities, each related to the primary instruments presented in the laboratory demonstration. Each activity requires the student teams to make twelve or more measurements with the tool just demonstrated. Activities begin with two or three qualitative "guided inquiry" questions designed to make the students more familiar with the measurement tool. The activities then direct the students to measure specific objects around them both in the lab and in other locations in the building. The sequence of measurements in each activity intentionally starts with straightforward measurements to develop familiarity, and then graduates to more difficult measurements. For instance, in the tape measure activity students begin with a measurement of the top surface of their desk, and later are asked to determine the diameter of large columns. Additional time and access is allowed outside of class for teams that do not complete the activity in one lab period. Details of the measurement demonstrations are presented below:

- Tape Measure:
  Although we expect most students to have some familiarity with tape measures, we include a brief, formal instruction for two reasons: (1) to allow those unfamiliar with the tape measure an opportunity to catch up, and (2) to emphasize care and appropriate usage, recognizing that prior familiarity may not equate to appropriate knowledge. The presentation covers proper handling such as not allowing the hook to slam against the case when the tape is rewound, not overextending the tape, and not allowing the tape to develop a kink. Next, three to five measurements are demonstrated to the class using the document camera at the instructor's station. This presentation is followed by a student exercise that includes responses to be used as inputs to homework questions.

- Dial Caliper:
  Unlike tape measures, we do not expect incoming students to be familiar with dial calipers; therefore, the instructional presentation is somewhat longer than that for the tape measure. Prior to the presentation each group of two students obtains a caliper. The presentation starts with a review of nomenclature covered in the tutorial. Next, the document camera is used in the description of the principle of operation, proper storage, measuring techniques, and to review scale reading. More advanced topics are also included such as measuring ODs and IDs, zero adjustment and potentially misleading readings (readings near the needle zero that may require common sense to sort out). The students are also introduced to the idea of "feel", and how to develop their sense of feel using the available gage blocks and feeler gages as reference. The

presentation is followed by a student exercise that includes responses to be used as inputs to homework questions.

- Micrometer:
  Although two types of micrometers were used in the exercises, the presentation is focused on the inch Vernier micrometer. Since the micrometer is more complex than the dial caliper, the presentation is longer than the dial caliper presentation.

  The document camera is again used to aid a discussion of principle of micrometer operation by showing the thread on a disassembled micrometer and making the association between thread pitch, thread "lead", and how the marks on the micrometer make use of this result. Additional demonstration includes proper storage, holding, and measuring techniques. More advanced topics are also included such as zero adjustment, full scale check (with calibrated gage) and potentially misleading readings (readings near the sleeve zero that may require common sense to sort out). The students are encouraged to develop their "feel" using the available gage blocks and feeler gages of known size. The presentation is followed by a student exercise.

<u>Individual Homework</u>

A short individual homework comprised of 6 questions is assigned at the end of the lab session. The purpose of the homework assignment is to get the students to reflect on the material covered in the lab and to show application for some of the measurements made during the lab activity. In particular the homework encourages development of visualization skills to make calculations and assessments of varying difficulty. For instance they are asked to determine the square footage of a doorway they measured; this requires conversion from inches to feet, and multiplication. A more complex extension question requires students to calculate the weight of a sheet of perforated metal using laboratory measurements and density information.

Students are also required to use an online stock list to determine the specification for a structural channel based on measurements made as part of the lab activity. The activity worksheet includes a brief outline of the nomenclature associated with structural channels and instructs students to measure the depth, web thickness, and flange width of an exposed support channel in the hallway. This information is then used in the homework to identify the support channel from the stock list.

**Graphics Unit**

The graphics unit is comprised of three parts, orthographic technical sketching, 2D CAD (A+ CAD), and solid modeling (SolidWorks). Technical sketching and 2D CAD is introduced in the introductory engineering course. Solid modeling is subsequently introduced in the first course of the design sequence. In each of the three parts of this module students are assigned a small solid model to represent graphically.

The 24 solid models used for this exercise were based on sketching problems presented as isometric sketches in a drawing textbook [10]. The objects represented by the sketches were modeled in SolidWorks and built using a rapid prototype (RP) machine. Although any ordinary object could be used for this exercise, even simple objects, such as a pen or coffee cup, have complex shapes and features that may be difficult for a beginner to represent. We chose to use the RP objects to control object complexity. The approximate part size is 2" x 2" x 3", each part cost roughly $40 to produce.

The ability to assign a different model to each student in a section is important to our approach. We want our students to be able to learn from each other, but do not wish to promote rote copying. Use of different models encourages students to collaborate at a process level to share knowledge of orthographic projection and CAD commands rather than sharing their solutions.

<u>Technical Sketching and 2D CAD</u>

Students were given tutorials, in-class demonstrations, and activities to develop their orthographic projection skills as well as operational instruction related to technical sketching and 2D CAD. A total of two 100 minute lab sessions were dedicated to technical sketching instruction and practice and 3 sessions were dedicated to 2D CAD instruction and practice. Of these five sessions, two were dedicated to the culminating activity: making orthographic drawings of RP parts. In the culminating activity each student is given a small solid model and asked to document the model, each student in a class section worked with a unique model. Students worked through this exercise twice. First, students completed a pencil and paper 2D orthographic projection sketch. Later in the semester, during the CAD portion, students drew a 2D orthographic representation of a different RP solid model using a 2D CAD software package. Figure 1 shows a student performing the CAD exercise. Note the measuring scale and solid model in the lower right corner of the picture, and the corresponding CAD drawing on the computer screen.

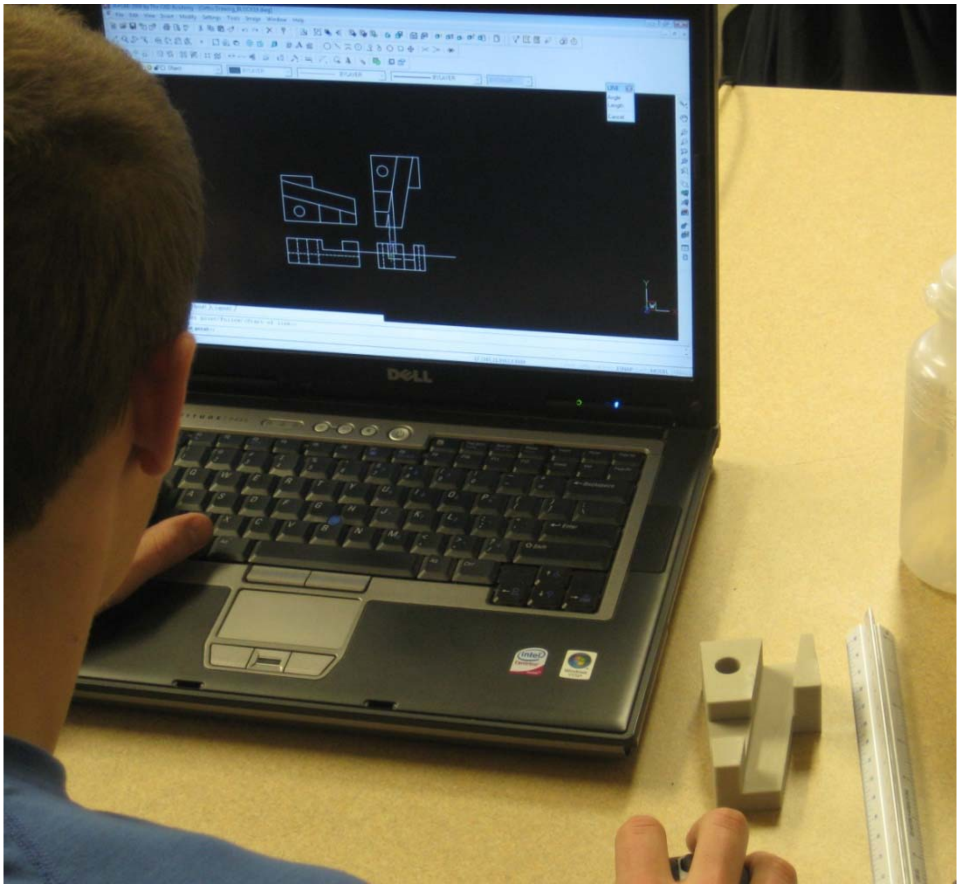

**Figure 1: A student documents their assigned solid model as a three-view drawing in CAD**

Solid Modeling

The third part of the visualization module was designed to reinforce the measurement and visualization skills previously presented while introducing students to the concepts and skills required for 3D solid modeling. This module was taught in a 100 minute laboratory session with homework problems. The instruction phase of this module primarily concentrated on the concepts and basic functions of a parametric solid modeling software package. Students were instructed on the advantages of using a solid modeling software package as a prototyping tool, the importance of properly defined model relationships, and the connection between 2-D drawings and the primitive shapes that comprise a 3-D solid model. Following a brief introduction to the mechanics of the software package, students were given one of the 24 rapid prototype primitives. They were then instructed to measure the RP object and produce a hand-drawn sketch of the RP object with the measured dimensions. For this inspection phase, students were not explicitly provided with measurement tools; rather, they were asked to draw upon prior knowledge and experience from the initial measurement and inspection modules to select the appropriate measurement tools. Following this measurement and sketching exercise, the students were then assigned the task of producing a solid model and an associated 2-D orthographic projection drawing based on their hand drawn sketch. During this exercise phase, students were encouraged to work together to address measurement and software questions. As with the previous 2D sketching and CAD module, this approach provided students with the opportunity to work together to address process and software questions while avoiding “copying” or relying on others to complete more complicated portions of the assignment. As an out-of-class homework assignment, students were randomly assigned a different RP object to measure, sketch, and model.

## ASSESSMENT

Assessment of the units within the module includes direct assessments of student work, instructor observations related to student work and attitudes, and third party observations. The assessments provide insight into student learning as well as the active learning environment we foster.

### Inspection

Assessment of student learning in the inspection unit is ongoing. The course included assessments of inspection tool nomenclature, scale reading, and a practical quiz. Ongoing assessment is conducted by embedding inspection tasks within other projects. Assessment that is focused on student use of inspection tools to determine the size of part features is considered to be highly relevant to the visualization module and is the focus of this section.

A practical quiz is given to the students as an assessment of skills related to the usage of dial calipers, inch Vernier micrometers, and millimeter micrometers. The practical quiz is given three weeks after the lab session in which the inspection tools are introduced. The quiz requires students to measure the width of an object with each tool (a different object for each tool). The objects to be measured are calibrated gauge blocks so that the student responses can be compared to known values. Students were given tools that were properly calibrated and zeroed so that they did not have to make adjustments. Each student was given seven minutes to complete the three measurements. Table 1 shows the results of the practical quiz.

Longitudinal assessment of student ability to use dial calipers was realized in a construction assignment in a sophomore course (Design I). The assignment requires students to build a part to their own specification, and then to inspect two critical dimensions to verify that they are within tolerance. Regardless of proper build, student ability to determine a part size can be assessed from this activity. Table 1 shows the results of this embedded assessment.

**Table 1: Results of Assessment of Student Inspection Skills**

| | Tolerance on Correct Response | **Practical Quiz (Introductory Course)** | **Embedded Assessment (Design I)** | |
|---|---|---|---|---|
| | | Correct Response (%) | At Least One Correct Response (%) | Both Responses Correct (%) |
| **Dial Caliper** | ±0.002" | 73 | 58 | 34 |
| **Vernier Micrometer (inch)** | ±0.0002" | 62 | | |
| **Micrometer (mm)** | ±0.02 mm | 59 | | |

The definition of a "correct" response is taken to be any response that is within ± twice the gauge resolution. This value is shown in the second column. Although benchmarks for these outcomes have not been established, the results suggest that student performance would likely be considered marginal. Possible mitigating factors to note include:

- Some students measured the wrong dimension of the gauge block and therefore gave an incorrect response (although students received a demonstration of which dimension to measure via the document camera, and the quiz instructions also indicated which dimension to measure).
- Some students did not record their responses with correct precision and therefore gave an incorrect response. Precision is not discussed in the tutorial or the demonstration, perhaps it should be addressed.
- Not all students remembered to inspect their parts as part of the embedded assignment in Design I.

These factors aside, it appears that although generally speaking 73% of the students demonstrated adequate skill with dial calipers and about 60% of the students demonstrated adequate skill with micrometers, these skills deteriorate with time.

**Technical Sketching and 2D CAD**

Assessment of student learning in this unit is complete. The course included assessments of student technical sketches and CAD work, embedded questions on exams related to related to CAD commands and visualization, as well as classroom observation. Assessment that is focused on visualization and third party observations of student working with solid models is considered to be highly relevant to the visualization module and is the focus of this section.

Embedded Assessment

Six final exam questions were related to visualization. The questions required students to match orthographic drawings to isometric sketches. Students scored a collective 96% on the visualization questions. Although this score seems quite high, it should be noted that the questions were considered to be less challenging than typical questions in the Purdue Spatial Visualization Test [11].

Classroom Observation

During the introductory course, graduate students from the Center for Assessment Research Studies (CARS) at __________ University were available to observe course sessions and provide qualitative third party feedback. Two sections of students were observed during the CAD exercises in which students were creating orthographic representations of assigned solid models. The following notes are the result of these observations and address the students experience with the solid models as well as the active learning approach of the lab session.

4/14/09 10:00AM

Observations:

- Students were then given their own block that differed from their peers. Again students were able to progress through the [representation] of their new object without much difficulty. With the block, students were able to make decisions about which side would be represented as the front, top and side. I was able to ask about how they made their decisions on how they would represent the different sides of the block. The students with the more complex blocks were more articulate in their decisions about how the blocks would be displayed.
- I was able to ask one student about the skills for engineering he was gaining through this project. He stated that he learned rules for drawing objects. He was able to articulate that there is value in being able to design objects in ways that allows someone to build it.
- Students were increasing their self-efficacy with the A+ CAD software. This activity creates another reference point within their domain knowledge of tools used by engineers.
- The students were engaged in the instruction. There were many questions about using the software.
- The students were very cooperative with one another.
- This activity is very procedural. The problem and the solution are very clear. Students seemed to rely on familiarity with the software to complete the activity. Students with more experience in using A+CAD and similar software were noticeably better at designing their objects. Overall, students seemed to have a good grasp on the software. At one point Rob asked how to do a certain procedure and the students responded with several ways of doing the procedure. None of the ways were what Rob was looking for, but they were all correct. This is evidence that the students seem to be gaining mastery of the software.

These observations support the notion of a laboratory session humming with activity where students do their own work but are also engaged in helping each other gain the required level of mastery of orthographic projection and the CAD software.

**Solid Modeling**

Student learning and progression with respect to visualization and measurement for this portion of the module was assessed quantitatively and qualitatively. The RP hand sketches, measurements, 3-D solid model, and 2-D orthographic projection drawings were evaluated for proper capture of important model geometry, measurement accuracy, and completeness of measurement (i.e., properly obtaining measurements for locating all important RP features). While a formal qualitative assessment was not performed, informal student interviews with students regarding module learning and attitudes towards visualization and solid modeling were conducted.

For the hand sketching portion of the solid modeling assignment, all students provided an accurate sketch representation of the assigned RP model with appropriately measured dimensions. These sketches were sufficient for students to use to create their solid models; however, some deficiencies with the finer points of measurement were notes. For example, several sketches had unnecessarily measured dimensions and measurements make to the edges of holes, as opposed to hole centers; however, it is the authors' assertion that such measurement skills and knowledge of appropriate measurements to make are improved by exposure and experience. Despite these minor errors, all of the appropriate descriptive geometry was captured in the hand sketches, 3D solid model, and associated CAD generated orthographic projection drawing.

Deficiencies in the appropriate dimensioning of the CAD generated orthographic projection drawing were noted. Out of the four assessed drawings assignments assigned to the 55 students, 22% presented an orthographic projection different from the assignment specified 3$^{rd}$ angle projection. Less than 15% of the four solid modeling assignments assessed had dimensioning deficiencies while 17% exhibited over dimensioning or repeated dimensions. Finally, 60% of the assessed drawings provided appropriate dimensioning precision and tolerancing practices. However, these instructional units were focused on inspection, measurement, and introductory drawing and solid modeling; therefore, explicit instruction in dimensioning and tolerancing was not included. In the future, additional instruction, either within or external to these instructional modules, will address these deficiencies.

Qualitatively, students obtained an understanding for and an appreciation of solid modeling and the relationship between physical objects and those represented as solid models. Further, this solid modeling module reinforced the measurement, inspection, and sketching skills previously developed. Informal interviews with students reinforced the authors' assertions that an active, hands-on approach to inspection, drawing, and solid modeling provides a valuable experience, increases appreciation for and understanding of the engineering representation of objects, and improves material retention. Several students commented that the use of the RP models in this module provided some "realism" to the computer generated solid model and, as intended, provided a better sense of scale for virtually generated objects. Further, many students, upon learning that the RP objects were generated "in-house" became more engaged in learning the solid modeling package in order to be able to generate their own RP models.

## FUTURE DIRECTION

While the overall approach of progressing from inspection to 2D representation to 3D modeling of RP primitives is unlikely to change in the near term, we are considering some modifications to the module to incorporate more instruction on measurement precision and drawing and dimension tolerancing. We intend to use the Purdue Spatial Visualization Test as a pre and post assessment of student visualization skills. This will give us some indication of how much the students benefit from the module as well as signal areas of improvement for incoming students. We are also considering how to best share our approach with others who may be interested in trying it; while we are willing to share our course handouts and assignments on an informal basis we may choose to share them formally via a website. Although we do not intend to "go into business" as a provider of RP primitives, arrangements could be made on a case by case basis.

## CONCLUSION

Students in the early engineering courses at James Madison University develop visualization skills through a variety of active exercises that include real objects. Students begin by learning to inspect familiar objects using typical engineering inspection tools: tape measures, calipers, and micrometers. Students then learn to create their own formal drawings of objects using sketching, 2D CAD, and 3D solid modeling techniques. Rather than copy pictures from a book or develop drawings from isometric representations, students are given real objects to represent.

Qualitative assessment suggests that this active approach promoted students engagement and inter-student cooperation. Because each student is given a different object to draw, student cooperation is more likely to be process based and less likely to degenerate to providing specific answers. On the other hand, quantitative longitudinal assessment of inspection skills suggests that these skills did deteriorate with time.

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