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Tutoring 3-Dimensional Visual Skills: Dynamic Adaptation to Cognitive Level

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Abstract. Teaching is maximally effective when targeted to a student's cognitive or developmental level. This paper describes the construction and evaluation of the Rotation Tutor, which uses intelligent methods to dynamically adapt problems to a user's fluctuating skill level in the domain of 3-dimension rotation of objects. We first measured the complexity of rotation tasks and then associated these tasks with user skills. The Tutor used this complexity metric to assesses a student's ability in real time and generate appropriate tasks to facilitate a close match between skill level and learning. The intelligent multimedia tutors maximize their effectiveness for a broad mix of students while minimizing the development time and cost for the faculty involved.

1 Adapting Teaching to Cognitive Level

Learning and cognitive development are tightly coupled; cognitive theory has informed the design of educational curricula since the beginning of the twentieth century including decisions about when to teach a particular topic or which pedagogical method to use (e.g., constructivist or drill/practice) [1]. However, people vary widely in developmental levels and an individual's competence might vary from moment to moment based on social context, motivation and physiological state [2-3]. A child can exhibit improved developmental levels if she has the support of an experienced peer [3]. Since it is not feasible to construct separate tutors for ever population of students, more adaptable tutors are needed.

This project sought to advance the understanding of human visualization and spatial reasoning and to use this knowledge to develop computer-based visualization tutors. Visualization and spatial skills are integral to human reasoning and critical to a wide variety of topics across science, mathematics and engineering. Yet, research indicates that adults and college students have difficulty learning to visualize and reason spatially about the transformation of physical objects around rotational axes [4-5]. Faculty and

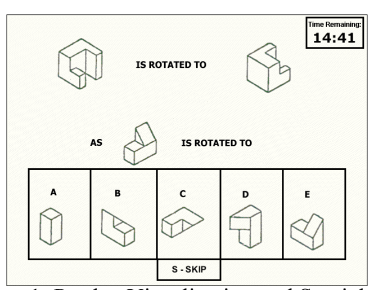

Figure 1: Purdue Visualization and Spatial Test (PVST). The student infers the rotation of the object in the top row and applies that rotation to the object in the middle row.

researchers have little understanding of how to teach spatial reasoning skills.

2 Overview of the Rotation Tutor

The problem domain of the Rotation Tutor originates from the Purdue Visualization and Spatial Test (PVST), Figure 1, which as a pencil and paper test, has been used for years to identify student visualization skills. The problem is easy to describe. In the top row, two views of Object 1 are presented and the student infers the rotation required to rotate the object from the left view to the right. The student is then asked to apply that same rotation to Object 2 (middle row, Figure 1).

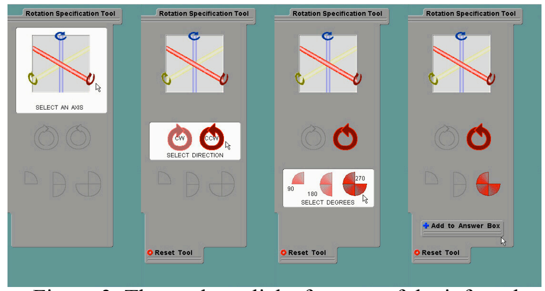

Figure 3. The student clicks features of the inferred rotations, including orthogonal axes, direction clockwise (C) or counterclockwise (CW) and number of degrees (90, 180, or 270).

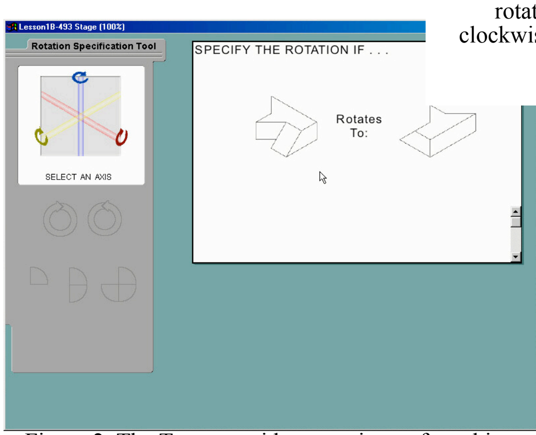

Figure 2. The Tutor provides two views of an object (right) and the student identifies features of the rotation by clicking (left), see Figure 3.

The Rotation Tutor tracks a student while she infers the rotation of Object 1. The Tutor models all required skills and is sensitive to differences among an individual's spatial abilities. It initially assigns .5 probability that the student knows each skill (Section 4) and provides two views of a a fairly simple object at the beginning, right Figure 2. The student is asked to infer the rotation and to click on the features of the needed rotation, Figure 3, (e.g., orthogonal axes, direction clockwise (C) or counter-clockwise (CW), and number of degrees (90,180, or 270)). The student's solution is automatically submitted, Figure 4. If correct, the tutor assigns a higher probability for the associated skills and selects a more difficult problem. When the average of the major skills rise above threshold, the student is promoted to the next tutor program (Phase 2).

If the student's solution is not correct, the tutor provides four levels of graduated hints, including an animated version of the student's rotation steps ("play" a 3D animation of the rotation, left Figure 5), and several alternative correct solutions. If one (or many) sub-skill(s) drop below the current remediation level, a flag is sent to the *Student Model* (Section 4) which then requests a textual remediation for that skill. Graduation or remediation levels are adjusted dynamically based on the student's performance. Students who have been struggling are allowed to "graduate" at a lower value or are remediated sooner, while stronger students are pushed to graduate at a higher score and remediation is delayed. This behavior is designed to mimic traditional teaching. Feedback continues as long as the student continues to give wrong answers and remediation is provided for a specific skill, if the *Student Model* indicates that the student's skill is below threshold.

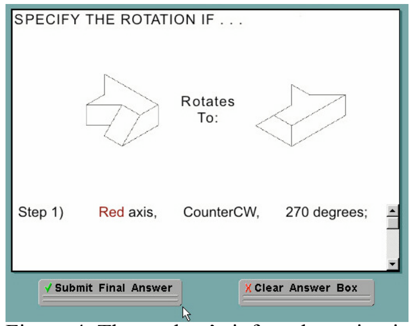

Figure 4. The student's inferred rotation is automatically submitted to the Rotation Tutor.

3 Learning Complexity in Rotation Skills

This section describes the cognitive studies that identified the assumed rotational skills. Engineers have real difficulties performing mental rotations. We combined research paradigms from psychology, education, engineering and computer science to advance the basic understanding of cognitive models of visualization and to understand cognitive and mental processes that students use to visualize objects and reason about their spatial transformations. Such problems may well overload visual short-term memory (e.g., keeping track of the 3-D orientation of a complex figure rotated possibly around 3 axes) and training should break the problems down to several stages. We wanted students to be trained generally to develop good solutions to various visualization problems, including box folding, quadrilateral folding and engineering drawing. Eye trackers were used to infer strategies that individuals use and to test alternative theories of how individuals represent mentally and reason spatially about 3-D objects and their transformations. We identified which parts of the task are most difficult and evaluated strategies that students might be taught that could reduce the difficulty of the most problematic portions of these tasks.

Skills Analysis. There are six logically different rotations around a single axis, or a total of 18 logically different rotations around either the x, y or z axes. Continuing, there are a total of 36 logically different rotations around any one pair of axes, so there are a total of 3 X 36 = 108 different pairwise rotations of axes. And, finally, there are a total of 216 different logically different combinations of rotations around all three axes. Interestingly, these 342 logically different rotations can be parsed into 24 different final sets, each set corresponding to a different view of the initial object after rotation. Thus, there is a many to one mapping: many logically different rotations can map an initial view onto a final view of a object.

Problems in the PVST are made more difficult by making the rotated object more complex. We identified rotation characteristics that differentiated objects that were easy to rotate from those that were hard to rotate and identified various subskills that governed student performance. Performance is broken into into two phases, Table 1. In Phase 1, students need to correctly infer the rotation of Object 1 (top row, Figure 1). Second, students need to apply this rotation to Object 2. Experiments showed that students had difficulty inferring the rotation of Object 1 and difficulty applying that rotation to Object

2. One experiment tested students' ability to infer rotations of Object 1 and one tested students' ability to apply rotations to Object 2. Students have a surprisingly hard time identifying the rotation that maps view 1 of Object 1 into view 2 of this same object. 25% of the subjects could not correctly infer single axis 90 degree rotations and fully 60% of the subjects could not correctly infer two axis rotations, where the rotation around one axis was 90 degrees and the rotation around the other was 180 degrees.

Students have equal if not greater difficulty applying a rotation to view 1 of Object 2 in order to generate the correct answer to a problem. In fact, it is the generation skill that is the fundamental missing ingredient in the problems. If students could easily generate a rotation, they would not have difficulty with any of the 90 degree rotations.

Subskills. Experimental data shows that students have increasing difficulty as the number of axes around which a object is rotated increases. Thus, we broke down the rotation problems into one, two and three axis problems and, within each made further delineations. We ensured that students can equally well generate 90, 180 and 270 degree rotations of a object clockwise or counterclockwise around the *x*, *y* or *z* axes. For two axis problems, we ensured that students can equally well generate all combinations of rotations around two axes, combinations which are determined by the axis of rotation, the degrees of rotation around each of the axes, and the direction of rotation. And finally, for three axis problems we ensured a similar capability across all possible combinations.

	Knowledge Type	**Parameters**	**Features of Parameter**
Phase 1: Recognize Rotation	Scan Object 1 (first row) and infer its rotation	Shape complexity. C or CW, axis and degree rotation	Identify Object 1 (hidden lines, cuts, inclined surfaces, intersections, oblique lines). Infer C or CW rotation along X, Y, or Z axis, and 90, 180, or 270 degree rotation.
Phase 2: Apply Rotation	Transform Object 2 (second row) based on the inferred rotation.	Rotation along axis, degree, and C/CW.	Apply rotation from Object 1 to Object 2. Rotate Object 2 C/CW, along X, Y, or Z axes; and 90, 180, 270 degree

Table 1. Cognitive Tasks in the Purdue Visualization and Spatial Test.

4 Probabilistic Measure of Presumed Knowledge

The Rotation Tutor contains significant intelligence in the form of an expert system designed to generate problems dynamically. Based on the student's current skill values, e.g., complexity of the object and rotation, the tutor isolates the "weakest-link" and targets new problems for that area. In this way, either the student learns to recognize this feature by shear practice, or a remedial need is identified. If no clear weak area can be identified, or if each skill has been brought up to the same level as the other skills, the expert system defaults to a simple increasing difficulty approach. The expert system queues multiple related problems and keeps track of recent problems to avoid redundancy

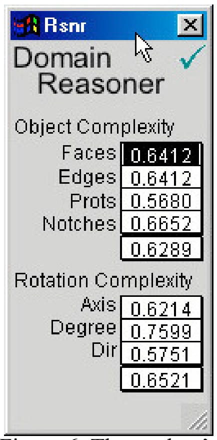

Figure 6. The student's "skill" values are stored as "probably known" coefficients, first as Object Ability Skills, (containing edges, faces, protrusions, notches) and then as Rotation Ability Skills (including axes, degrees and direction).

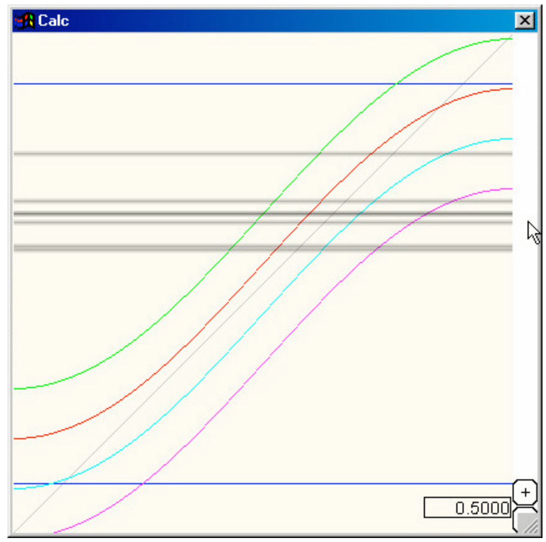

Figure 7: The linear approximator returns the resulting probability that a student knows a skill, ased on the skill's current probability, and the "hint level"

and boredom.

Domain Knowledge. We enumerated and categorized the total number of logically different rotations (assuming that the number of different levels of degrees of rotation is itself finite). Problems about the same topic can be of varying levels of complexity. Rotation adjusted the level of complexity of the presented problem based on the number of subskills required and the complexity of their application. The Domain KB coordinates the storage and retrieval of all objects available to the Tutor. It stores files for 3D model manipulation, as well as pre-configured 2D drawing of each object's key orientations. The Domain KB also contains vital property values for each object, as well as all the views. The API provides for retrieval of a closest match object and pair of views, given desired object and rotation parameters. [???Dan will write up how each object was categorized. ie- what "edges=2" means.]

Student Model. The *Student Model* aids in pedagogical decision making. It governs the maintenance of the student's "skill" values stored as a "probably known" coefficient for each of seven sub-skills: edges, faces, protrusions, notches, axes, degrees and direction, Figure 6. The first four skills are categorized under Object Ability Skills, which

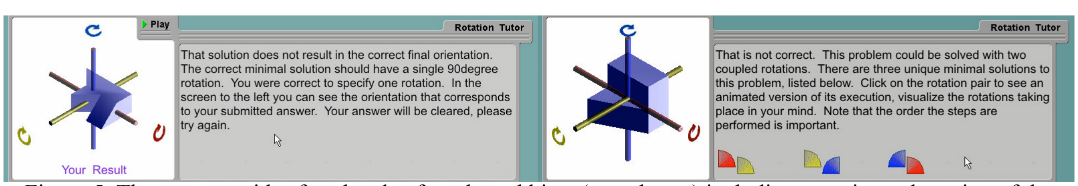

Figure 5. The tutor provides four levels of graduated hints (two shown) including an animated version of the student's proposed rotation steps ("play" button, left) as well as alternative correct solutions.

provides an average probability value for this master skill. The latter three sub-skills are grouped as Rotation Ability Skills and an average provided. Based on information from the (??? Linear Approximation) the *Student Model* is responsible for triggering when a student has met the criteria for "graduation" to the next level, or when a sub-skill requires remediation.

Linear Approximation—??Check Shute [7] Based on the skill's current probability, and the "hint level" for the given question, the??? returns the resulting probability for that skill, Figure 7. The curves that dominate this calculation are based on expert opinion and data from previous experiments and are represented as purely sinusoidal curves that allow for similar handling of remediation (bottom horizontal line) and graduation (top horizontal line), Figure 7. Each of the four sinusoidal curves in the middle of the graph represent action taken for each of the four hint levels, see Figure 5. The highest curve represents Hint Level 0 (the user responded correctly without assistance). The next lines moving to the bottom of the page represent the next levels, e.g., Hint Level 1(the user responded correctly on the second try based only on the information that their first attempt was incorrect) and Hint Level 3 (lowest curve) the user has not responded correctly and is shown the correct answer. The straight diagonal line shows the effective "win-loss" of each curve. The straight horizontal lines show the current value for each of the 7 sub-skills (some overlap). The top most horizontal line represents the current graduation level and the bottom horizontal line below most of the curves represents the need for remediation. When the average of the two main skills (not shown as such) rise above the graduation line (top horizontal line), the student is promoted to the next tutor program (Phase 2). If one (or many) sub-skill(s) drops below the current remediation line, a flag is sent to the *Student Model*, which requests remediation for that skill. These levels are adjusted dynamically based on the student's performance. Struggling students are allowed to "graduate" at a lower value or are remediated sooner, while stronger students are pushed to graduate at a higher score and remediation is delayed. This behavior is designed to mimic traditional teaching. The *Student Model* contains a small handful of API functions specific to maintaining any given subskill.

5 Evaluation and Discussion

Twenty-eight participants (twenty-one males and seven females) were recruited from the schools of engineering and computer science to evaluate the rotation tutor. All participants were given two pretests. The first pretest was the Shepard and Metzler's M.R.T. Test of Spatial Ability (MRT). As a second pretest, participants were randomly assigned to receive either odd or even numbered problems from the Purdue Spatial Visualization Test (PSVT). The ten highest scoring participants on the MRT were classified as "high spatial". The ten lowest scoring participants were classified as "low spatial." The remaining eight participants were considered "neutral".

After interacting with the tutor, as a posttest the participants retook the MRT. The two sections of the test were reversed and the answers shuffled, otherwise they received similar questions as in the pretest. The students also took the PSVT again as a posttest, this time taking the PSVT problems they did not receive on the pretest.

The most interesting results were realized when comparing the ten high spatial to the ten low spatial participants. On the MRT, high spatial students had an average increase in score from pre to posttest of 1.10 points with the mean increasing from 35.0 to 36.1.

The low spatial students had an average increase of 8.4 points with the mean increasing from 13.0 to 21.4. Using a one-way ANOVA, this result was statistically significant, $F_{(1,18)}=10.763, p < .01$.

The expert system was designed such that students with advanced spatial abilities would graduate from the tutor faster than students with lower spatial abilities. This allowed lower spatials to receive more practice and feedback during their session while, at the same time, preventing high spatials – who already have an intuitive grasp on the subject matter – from becoming bored or frustrated. The high spatials required an average of 9.7 problems to reach mastery criterion while the low spatials required an average of 17.9 problems to reach mastery criterion. This result was statistically significant, $F_{(1,18)}=6.717, p < .01$.

Finally, the results from the PSVT also showed interesting results. There was an across the board increase in PSVT scores as well. While the high spatials had higher overall scores (41.5 pretest; 51.5 posttest; 10.0 point change) than low spatials (37.8 pretest; 37.8 posttest; 7.2 point change), there was no significant difference between high and low spatial participants on PSVT score increase. This demonstrates that the additional practice the low spatials received with the tutor helped their overall scores the same amount as practice helped the high spatials.

6 Related Literature

A student's performance with a computer tutor can be highly correlated to that student's cognitive development [9] Educational tasks need to be matched to a user's cognitive level in an appropriate manner to maximize educational efficiency. . The most frequent modeling approach is to measure the degree of the student's ability in a "topic" or the probability that he has mastered a topic. This decision is used to reason whether to promote the student to a more complex topic or to control the difficulty level of the activity [6]. However, more complicated types of reasoning are often required. For example, should the system review a previously learned topic, should it give the student a new problem to solve or resent another example of the processes involved? Is the student confused or has he forgotten this topic?

[bev to complete this] [10] defined a range of next possible topics for each student. {Cite [11]} cite Ben doubly} Dynamic Cognitive Range

Intelligent computer tutors have been used to identify student's cognitive range, track their changing states dynamically and adapt the curriculum optimally to the individual's learning needs in real time [Arroyo, Codeine, Anderson, Beck]. Such tutors have mapped each student's developmental or cognitive level, tracked her position within the range [DuBouley] and dynamically varied the problem or level of complexity of the task to match skill level in real time. Evidence of improved learning efficiency using intelligent tutors shows that they can achive 2 sigma improvement over classroom leaning of the same topics [Shute, Fletcher].

[Describe engineering tutors???]

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[12][13] Arroyo, Codeine, Anderson, Beck Intelligent computer tutors have been used to identify student's cognitive range, track their changing states dynamically and adapt the curriculum optimally to the individual's learning needs in real time
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