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Applying Cognitive Developmental Psychology to Middle School Physics Learning: The Rule Assessment Method

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Abstract. Cognitive developmental psychology often describes children's growing qualitative understanding of the physical world. Physics educators may be able to use the relevant methods to advantage for characterizing changes in students' qualitative reasoning. Siegler[1] developed the "rule assessment" method for characterizing levels of qualitative understanding for two factor situations (e.g., volume and mass for density). The method assigns children to rule levels that correspond to the degree they notice and coordinate the two factors. Here, we provide a brief tutorial plus a demonstration of how we have used this method to evaluate instructional outcomes with middle-school students who learned about torque, projectile motion, and collisions using different instructional methods with simulations.

Keywords: physics education research, developmental psychology, qualitative assessment, student learning
PACS: 01.40.Fk, 01.40.G-, 01.40.Ha

INTRODUCTION

At the heart of many physics phenomena are interactions among multiple variables. These interactions are captured by the many formulas of physics. Proficiency with the formulas does not entail that students have a qualitative understanding of the interactions. Mathematical assessments can make algebraically competent students look more knowledgeable about physics than they really are.[2] Assessments of qualitative understanding often need to take a different form. Developing qualitative assessments can be a delicate matter with each problem requiring an inspiration of cleverness. Moreover, current qualitative assessments often focus on misconceptions, while it is also useful to have qualitative assessments of missing conceptions. Here, we present a relatively simple method for assessing the growth of qualitative knowledge. The "rule assessment method" (RAM) was originally developed by Siegler in the context of cognitive development and has had a large impact on that field. We believe it may also be useful for physics education research, for example in designing and evaluating instruction.

A deep functional understanding of interactions is characterized by the ability to coordinate multiple dimensions or factors. RAM assigns levels of qualitative understanding. For example, to understand density, students need to coordinate mass and volume. One can imagine that some students only attend to the mass. Others know that both mass and volume are relevant, but they cannot coordinate them. Yet others know that the two factors should comprise a ratio. Siegler found a regular progression through various levels of coordination, which enabled him to describe a predictable maturational trajectory. He called each level of coordination a "rule level." While Siegler's goal was to describe cognitive maturation, adopting his rule level approach may be useful for describing learning and the effects of instruction.

THE RULE ASSESSMENT METHOD

In the contexts of balance, probability, and shadow problems, Siegler designed a series of questions to describe children's understanding of the relations that determine the outcomes of various starting conditions. Here, we use the balance problems to explain his method. The balance problems involved a balance scale where masses of different amounts could be placed on either side of a central fulcrum at varying distances. The children answered the question of whether the scale would balance or tip to one side. A key feature of RAM is the identification of *psychologically* dominant and subordinate dimensions. Through interviews with children of different ages, Sielger established that mass is the dominant factor for the balance scale and other psychologists have replicated this claim.[3 4 5]

Students who do not have a good qualitative understanding usually focus on the masses on either side of the fulcrum to make their predictions (Rule Level I). They ignore distance, which is thus the subordinate dimension. Students who have a slightly

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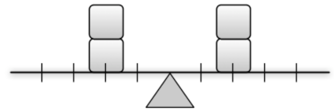
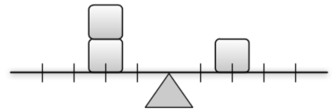
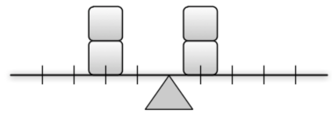
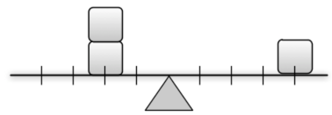
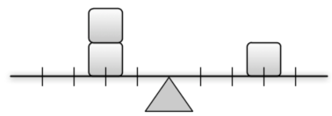
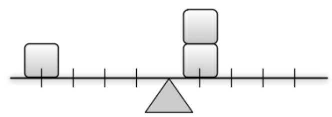
TABLE 1. Description of each of the six problem types administered in the Rule Assessment Method (RAM).

Problem Type	Factors	Example	Result
Equal	Masses Equal Distances Equal		Balanced
Dominant	Masses different Distances equal		Tips toward greater mass
Subordinate	Masses equal Distances different		Tips toward greater distance
Conflict Equal	Masses different Distances different		Balanced
Conflict Dominant	Masses different Distances different		Tips toward greater mass
Conflict Subordinate	Masses different Distances different		Tips toward greater distance

better qualitative understanding will use the subordinate dimension when the masses on either side of the fulcrum are equal (Rule Level II). Students who have a better understanding yet will consider both mass and distance, but may have trouble coordinating them (Rule Level III). Students with the fullest understanding appreciate that it is the product of mass x distance that determines the results (Rule Level IV). At the least developmentally mature level are those children who do not take into account the mass or distances (Rule Level 0).

By systematically varying the dominant dimension (mass) and subordinate dimension (distance) in each problem, six question types can cover the space of possible combinations. By having students complete several questions of each type in a randomly ordered test, it is possible to assign them to a rule level of qualitative understanding. Examples of the six question types are shown above in Table 1. These instances serve as a guide. Many possible variations in number and appearance of the balance scales are possible in creating versions of this test and more than six questions are typically used. The main constraint in designing RAM questions is that each of the six problem types must be assessed at least once.

Individual students can be assigned to rule levels by tabulating their results across each problem type or analyzing their responses to open-ended ‘Explain your

TABLE 2. Characteristic response patterns across each of six problem types according to Rule Level.

Rule Level	Description of Behavior	Equal	Dominant	Subordinate	Conflict Equal	Conflict Dominant	Conflict Subordinate
Level 0	Guess	At chance	At chance	At chance	At chance	At chance	At chance
Level I	Only notice mass	Correct	Correct	At chance	At chance	Correct	Incorrect
Level II	Notice distance only if masses are equal	Correct	Correct	Correct	At chance	Correct	Incorrect
Level III	Notice mass and distance but guess when both factors are different	Correct	Correct	Correct	At chance	Correct	At chance
Level IV	Coordinate different masses and distances using multiplicative relationship	Correct	Correct	Correct	Correct	Correct	Correct

answer' questions. Table 2 outlines the pattern of typical responses that correspond to each Rule Level.

ADAPTING RULE ASSESSMENT FOR PHYSICS LEARNING

We adapted the RAM technique for use with educational interventions around physics concepts based upon simple relationships between two factors.

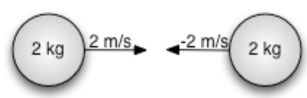
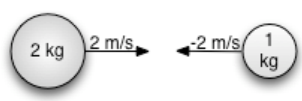
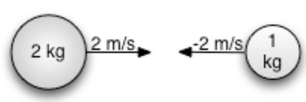
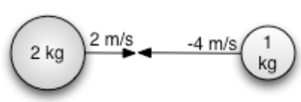
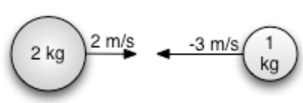
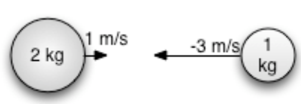
In a series of studies conducted with sixth graders learning early physics concepts, we used RAM as an assessment tool. These studies made use of three simulations created by the PhET group:[6] Balancing Act (balance scale and torque), Projectile Motion, and Collision Lab (inelastic collisions). RAM was well suited to each of these domains because the physical outcomes depend on two variables that pair together in a simple multiplicative relationship (e.g., Torque = Mass * Distance, Distance traveled = Initial speed * Hang time, Momentum = Mass * Velocity). In these three studies, RAM questions were administered after instruction and use of the related simulation. Due to space limitations, we focus on assessment per se, rather than discussing the nature of the instruction.

An Example Case: Collisions

In this example, the RAM materials were used to gain an understanding of students' qualitative knowledge of mechanisms that govern inelastic collisions. To adapt RAM, we created a series of questions that follow Siegler's systematic sampling technique. These questions highlight the influence of both mass and velocity on the momentum of two balls involved in a perfectly inelastic collision. Table 3 shows the adapted series of questions.

Previous studies have not applied RAM to the domain of inelastic collisions and learning about momentum. To find out which factor (mass or velocity) was dominant in students' early conceptions of momentum, we examined the results to the conflict questions. Of the 36 6th grade students in this study, 16 were correct when mass determined the result of the collision, but only eight students correctly answered when velocity determined the result. This led us to conclude that mass tended to be the dominant dimension in children's thinking about momentum. Carrying out RAM analyses in the domain of collisions offered insight into the nature of student

TABLE 3. Adaptation of RAM to evaluate students' knowledge of momentum in inelastic collisions

Problem Type	Factors	Example	Result
Equal	Masses Equal Velocities Equal		Stick and stop
Dominant	Masses different Velocities equal		Move in direction of larger mass
Subordinate	Masses equal Velocities different		Move in direction of larger velocity
Conflict Equal	Masses different Velocities different		Stick and stop
Conflict Dominant	Masses different Velocities different		Move in direction of larger mass
Conflict Subordinate	Masses different Velocities different		Move in direction of larger velocity

learning during our instruction. In our sample, 11 students were at Rule Level 0 and 18 were at Rule Level 1. One student was at Rule Level 2, four students were at Rule Level 3, and two students were at Rule Level 4. Clearly, collisions were a challenging new domain for these 6th graders and RAM showed specific areas of weakness in their thinking. As many students struggled to understand the role of velocity, future instruction could focus on this factor.

FUTURE DIRECTIONS

We have described simple adaptations that lend the Rule Assessment Method to researching student learning of physics concepts. From its bases in cognitive and developmental psychology, this method is easily applied to educational research. By providing a clear indication of students' knowledge of relationships, RAM is more comprehensive than administering a single test item and the creation of the set of items is straightforward. However, the application of the method is currently limited to domains with simple two-factor relationships, although one may imagine a more extensive model to account for more complicated physics relationships among many factors.

In future studies, RAM could be applied to a variety of physics concepts. In conjunction with other assessments or teaching methods, we envision RAM supporting at least three potential categories of investigations. First, RAM can be used to reveal students' understanding of a new domain. As in the collisions study described above, this type of analysis may provide educators with a clear qualitative representation of student knowledge.

Additionally, RAM could be used as a formative assessment to inform instructional decision-making. These assessments could offer insight into instructional methods by evaluating existing student knowledge and highlighting areas for further instruction. For example, based on the RAM collision results, we know that students need help to notice the subordinate dimension of velocity.

Finally, RAM could be used as a tool for educational research. In recent work, rule levels were assessed in the domain of projectile motion as part of a larger experimental study. In this investigation, students who compared and contrasted across a set of cases were compared to others told to invent a math formula to explain the cases. RAM measured students' knowledge about the relationship between hang time, initial speed of a horizontal projectile, and distance traveled. In conjunction with other assessments, the average rule levels between instructional conditions were assessed and indicated that the inventing treatment led to higher rule levels. In this way, RAM can be used to uncover treatment differences in qualitative knowledge.

As demonstrated, RAM's usefulness extends beyond its original descriptive goals in cognitive developmental psychology. Researchers and practitioners can use this technique as a self-contained tool or in conjunction with other assessments and research methods in physics education.

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