

Rounding Up Students' Conceptions on Circular Motion



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ABSTRACT: The purpose of this paper is to provide insight on how introducing circular motion with a carefully designed sequence of demonstrations and activities consistent with the national standards, pedagogical knowledge, and research-based instructional practices can flush out students' conceptions of forces and motion, and set a conceptual foundation for understanding uniform circular motion. *This article promotes National Science Education Standards A,B, and E, and Iowa Teaching Standards 1, 2, 3, and 4.*

Introduction

The National Science Education Standards list force and motion as essential components of a standards based education (NRC, 1996). While the Standards specify that force and motion are fundamental science concepts, they do not specify how to design or arrange instruction in ways that help students gain a deep understanding of that content. Many authors (Karplus 1972, Eakin & Karplus 1976, Rubba 1984, Bybee & Champagne, 1995, and Colburn & Clough, 1997) suggest that concrete experience should precede the use of terminology. Sequencing these experiences prior to abstract symbolism and quantitative expression are essential elements of the National Science Education Standards. The Standards identify two key outcomes of scientific literacy, including developing abilities

necessary to do scientific inquiry, and gaining an understanding about scientific inquiry. Fundamental abilities and concepts that underlie these outcomes include:

- > Identifying questions and concepts that guide scientific investigations
- > Design and conduct scientific investigations
- > Use technology and mathematics to improve investigations and communications
- > Formulate and revise scientific explanations and models using logic and evidence
- > Recognize and analyze alternative explanations and models
- > Communicate and defend a scientific argument

A more thorough review of these abilities and understandings is found in *Chapter 6* of the NSES (1996).

The majority of the suggested emphases are readily apparent in the description of the guided inquiry described in this paper for circular motion. Thus, the topic of circular motion is merely a vehicle for achieving a more clearly profound understanding of inquiry through effective science instruction.

Etkina (2005) suggests in her description of a 21st century physics instructor three essential ingredients that must be in place for effective instruction. Teachers must possess a deep understanding of the science content and a deep understanding of effective pedagogy. The third, a unique blend of content knowledge and pedagogical knowledge, what is referred to in the literature as “pedagogical content knowledge” (PCK), is also necessary. What makes PCK different, yet intertwined with the other two, is that it is specific in many regards to the particular concepts being taught and is constructed through instructional practice and reflection.

For instance, PCK includes an understanding of students' misconceptions and difficulties with particular concepts, exemplars and analogies that help students understand the concepts, specific instructional strategies such as particular questions that help students link ideas between concepts, and assessment methods appropriate to the concepts. So while PCK requires a deep understanding of science content and pedagogical practices, it is more than the two combined and requires practice and reflection to develop.

What this means is that simply reading, understanding, and hopefully trying the ideas presented in this article will not at first result in effective instructional practices. Rather, this lesson serves as a guide for what an introductory lesson on circular motion looks like as a result of integrating content knowledge and pedagogical knowledge through long-term systemic practice and reflection. While the ideas suggested here reflect the author's own PCK developed over time and do promote students' deep understanding of targeted science concepts, those who use these ideas will require time to develop their own PCK relevant to the students they teach. During any introductory lesson, many elements and decisions must be considered from a PCK perspective. The essential elements are addressed specifically in what follows.

Difficulties in Teaching and Learning About Circular Motion

Common student difficulties with circular motion can be attributed to two primary conceptual difficulties. One difficulty students have is the intuitive reason they and others give to common everyday experiences. For instance, when moving in a car that quickly turns, riders **feel** as if they are thrown away from the center of the curve. Similarly, riders on a turning merry-go-round who release their grip **feel** as if they are being thrown off. In both situations, the everyday commonsense interpretation is to explain their sensations in terms of a force pushing them, rather than the natural tendency of their body to continue in a linear path.

The second conceptual difficulty is one's commonsense idea of velocity. Prior to addressing circular motion in depth, my students have received instruction recognizing that velocity includes both magnitude and direction. However, students typically adjust their vocabulary but may be subconsciously using velocity as a synonym for speed. While they may distinguish between them in familiar contexts, they often have difficulty transferring this concept to unfamiliar or unique situations, like uniform circular motion.

Students' conceptual difficulties are clearly evident when teachers avoid superficial multiple-choice, short-answer, or recall questions in favor of assessment practices that truly get inside students' heads. Effective instruction requires that teachers understand students' conceptions (Smith, 1990), and challenge students' thinking with direct experiences (Watson and Konicek, 1990). Moreover, in order to make sound decisions that promote desired conceptual change, teachers must use effective assessment practices that target students' genuine thinking. Such assessments must be embedded in instruction so that, as Foster and Heiting (1994) note, instruction itself becomes a mode of inquiry for the teacher.

Exposing commonly held ideas and helping students understand how those ideas do not adequately explain phenomena often motivate students to consider alternatives that are more consistent with scientific thinking. Instruction must also be organized and choreographed to provide students with direct

evidence making it apparent their common-sense ideas are problematic, help them consider new options and, with teacher guidance, select and understand the best alternative. Watson and Konicek (1990) write that the teacher's role in orchestrating conceptual change is to engage students in relevant situations, have them make predictions, and stress consistency in students' ideas. In order to facilitate this, the teacher must ask effective questions, be open to student interpretations, accept student responses with an unbiased demeanor, accept student suggestions for further inquiry, effectively manage classroom discourse, and promote student thinking and dialogue by using effective questioning strategies. This is quite complex and again requires that teachers have a deep understanding of the science concepts being taught, effective pedagogical practices, and PCK.

Teachers must also be aware that simply telling students correct science explanations, and introducing science vocabulary before students are conceptually ready, interferes with promoting deep understanding of science content. Introducing science concepts through lecture, overusing presentation software, or simply assigning textbook readings does not encourage students to wrestle with new ideas and develop a deep understanding of science concepts (Smith, 1990; Watson & Konicek, 1990). Worse, these approaches often interfere with desired student learning! Such approaches breed apathy and rarely mentally engage more than a few students in meaningful learning.

Rather than focusing on and wrestling with understanding phenomena, students attend to science terminology and algorithms. Later, perhaps as a coping mechanism, students use that vocabulary to masquerade their conceptual struggles. The research is clear that students' use of science terminology often is reduced to the mimicking of words and phrases they have acquired as a result of rote methods of instruction or common everyday usage. Recitation of terms and knowing definitions does not reflect understanding of fundamental science concepts (Watson & Konicek, 1990; Smith, 1990), and students using such language often obscure their understanding with scientific jargon and

teacher-pleasing behaviors.

Promoting Deep Conceptual Understanding of Circular Motion

Exploring circular motion begins with a demonstration of a hovering puck. The puck hovers as a result of an internal fan and provides a suitable frictionless environment for many other demonstrations as well as this one. Pucks are available with a rechargeable battery pack from several supply companies. By this time in the year, students are familiar with the puck, and issues concerning the upward force have been negotiated and resolved with consensus that the *upward* force on the puck by the air particles in contact with the fan blades is a F_N (puck, air). Because the puck is in equilibrium, the F_N (puck, Air) added to the *downward* force, F_g (puck, Earth) results in a net force (F_{Net}) of zero in the vertical direction.

The words in parenthesis refer to the (*object, agent*) notation or (*on, by*) notation. It is a justification system to ensure students use correct reasoning while conceptualizing forces. By convention the identifying word is abbreviated by its first letter. Interpret the notation as follows: (The first letter indicates what object the force is on, p = puck, the second letter is justification for what object is causing the force on the object, E = Earth). Not only does this notation enforce justification for one's claims, it re-enforces the concept that forces are the result of an interaction between two objects. This convention of notation will be used in the remainder of the paper.

Tie a string to the puck. Clipping two small fishing line swivels works well. One that is permanent through the air grill on the top of the puck and another for easy detachment of string (Figure 1). Begin the demonstration by circling the puck at a constant speed. Beginning with a demonstration peaks students' curiosity, and ensures that all students are familiar with the experience and its context. Having directly observed the phenomena, students should be asked to make observations. All observations should be accepted without judgment from the teacher and placed on the board using the same words students used in their descriptions. Students will see that their ideas are valued, and are beginning points for discussion, not final answers that are to be judged right or wrong. A diversity of ideas must be exposed to help

teachers accurately diagnose students' thinking, increase the likelihood that students will be compelled to choose between their personal interpretation and an acceptable scientific interpretation, and so that teachers can begin from where students' conceptual understanding resides and scaffold to the accepted scientific explanation. Typical student responses include, but are not limited to, statements that the puck "has a constant motion," "travels in a circular path," "takes the same amount of time to go around each time," and "travels counterclockwise."

Be prepared to hear and write on the board the idea that the puck has a constant velocity. While this is an inaccurate science idea (an object in circular motion actually has a constantly changing velocity), it is an idea held by at least one student and, according to well-established research, by most individuals.

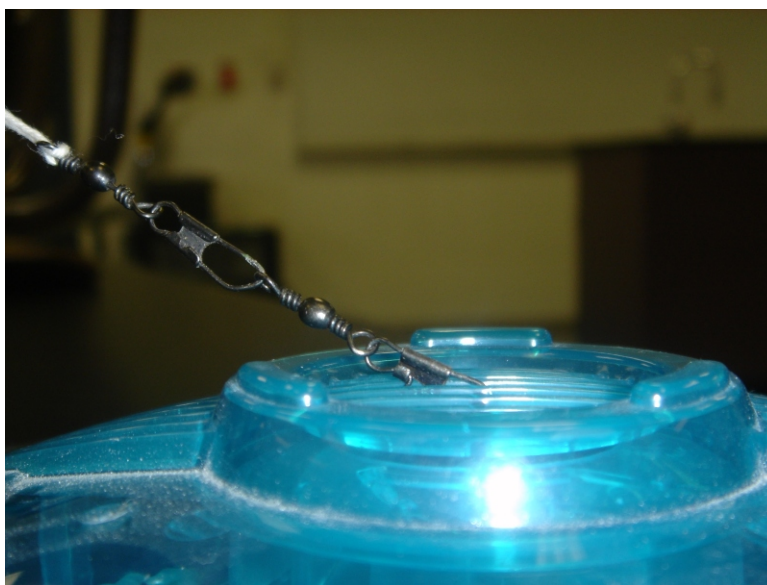
The role of the teacher is not to correct the scientific misconception at this time, but rather to generate ideas held by students. The examples provided are not accepted as correct, but rather as ideas to be investigated.

Once student observations have been elicited, the teacher now engages students by asking them to look at the situation in greater detail. Have students form groups of two and work together to draw a free body diagram for the puck at some point along the circular path. You may need to clarify your request by presenting to the students a diagram that illustrates the perspective students should take while drawing their free body diagram (Figure 2).

Having students draw their free body diagrams (FBD) on small whiteboards (e.g. 24" x 36" boards made from 4'x 8' kitchen wallboard) using dry erase markers, helps teachers quickly see students' ideas and permits easy sharing of these ideas during the ensuing discussion. Once students have completed their FBD's, students are asked to form a circle to view each group's diagram. Students are asked to compare possible options and question each group's explanation. Common student FBD's and explanations are listed in Figure 3. For the most part P in all of the parenthesis states the forces are on the puck. They are then caused by: E the earth, s the string, a the air. The question mark is simply students relying on

the impetus principle or applying general principles incorrectly. Students may think a force must be present because of the constant motion, justifying an outward force based upon personal experience. Students may also label the force as centripetal or centrifugal with no justification in an

FIGURE 1



Attachment of string to the puck using swivels.

FIGURE 2

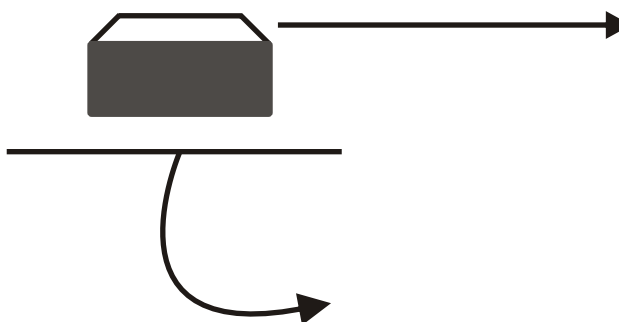
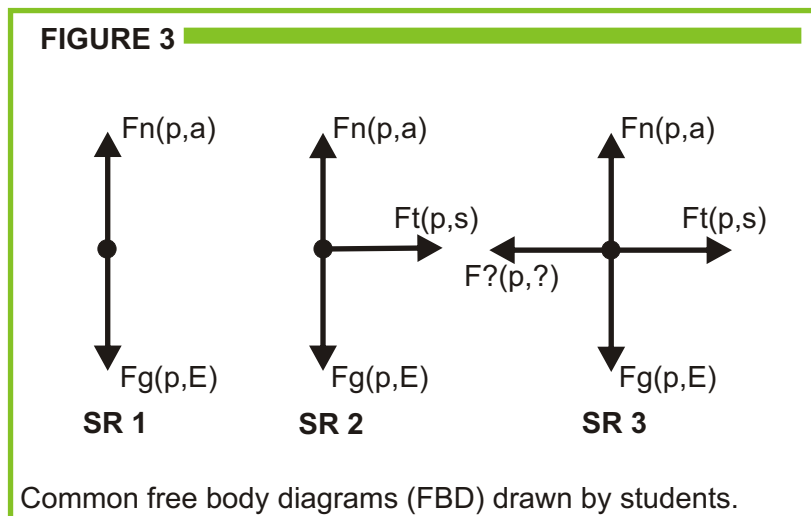


Diagram illustrating the perspective students should use to draw their free body diagram.

attempt to masquerade their understanding with terminology. Thus, contrary to many physics teacher's language, **centripetal force** should be defined as a NET FORCE towards the center, not some new and mysterious force as is often interpreted when the situation is didactically expressed prior to this kind of treatment. It is extremely important that the instructor is cognizant of the conceptual difficulties students have trying to assimilate a new term like centripetal when in cognitive disequilibrium. It is crucial for the instructor to wait until students consistently represent circular phenomena in absence of the term. Conceptual understanding must be justified with FBD's and correct expressions of NET FORCE prior to introducing the term centripetal force. *Only after the instructor is convinced students can adequately and consistently represent circular phenomena should the instructor formalize the term centripetal.*

Student responses (SR) 1, 2, and 3 are typically justified in the following manner. SR 1 is characteristic of students associating the demonstration with those earlier in the year. Most likely SR 1 is an association with a hovering puck and constant motion and the students are simply reproducing what they have remembered about the puck in linear demonstrations. Students suggesting SR 2 and SR 3 will be quick to challenge SR1 about not having a F_t . Students quickly reach consensus that F_t is an appropriate choice opting to side with SR 2 or SR 3.



Although students putting forth SR 2 are correct, many students will second guess this diagram or find themselves in a quandary with those advocating SR 3. Students are typically certain about F_t exerted on the puck by the string but realize inconsistencies between the free body diagram and their observations of the puck's motion. My students have previously investigated forces on a puck and will typically accommodate for the constant circular motion with one of the following options.

Some students, in order to account for what they interpret as constant velocity of the puck (and thus the need to

counterbalance the force exerted by the string), will put F_t in their FBD. This represents what they think is a force exerted on the hovering puck by the surface, even though their prior learning in physics has addressed that friction between surfaces requires contact. Students who understand the puck is frictionless have a tendency to propose the symbol F representing some force on the puck, but they have difficulty justifying what type of force and it's cause. Many of the brighter students will justify the proposed symbol F by saying it is a centripetal or centrifugal force, but have difficulty justifying the cause of the suggested force with *on, by* notation. This statement often initiates a reaction from students sticking to SR2 and questions are raised about the validity of some new force without proper justification.

Students sometimes claim that air friction is the proposed force represented by the symbol F. If that occurs, test the claim by setting a puck in linear motion at about the same speed it traveled in a circle in the first demonstration and ask, "How much does the speed of the puck change?" Students will note that the puck set in linear motion does not have a noticeable change in speed. On their own, or with further well phrased questions, students will come to understand that the proposed F in their FBD cannot be air friction because air friction is negligible at similar linear speeds. Students readily come to this conclusion if the situation is set up in this fashion. However, if students hold to the idea of centripetal or centrifugal force, lead a discussion that encourages students to wrestle with the rationale for and against

a new force. What typically transpires is that, lacking a sound rationale for a new force, students will reluctantly and tentatively adopt SR2 as the best alternative.

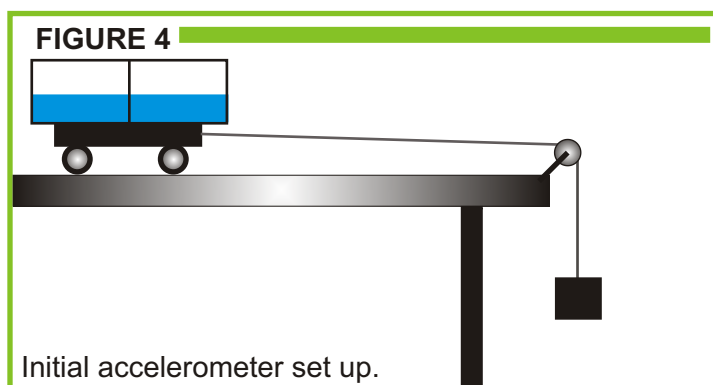
From an instructional point of view, the instructor's role during what is described above is to promote dialogue that encourages students to flush out the best alternative for the situation. The instructor must be careful during this process not to exhibit bias towards any one proposed solution. Bias is communicated through overt judgment of students' ideas, non-verbal behaviors and voice intonation that favor particular ideas. Carefully phrased thought-provoking questions, appropriate wait-time, encouraging non-verbal behaviors, and effectively playing off students' ideas in ways that encourage further wrestling with ideas are crucial for promoting discussions that help students understand why particular ideas are abandoned and what ideas need further exploration and clarification.

Once SR2 has been elucidated as the best alternative, the instructor should explicitly state the current situation. The students have a force diagram that clearly indicates a net force (F_{net}) towards the point of rotation which is the result of the unbalanced tension force. Yet the observed motion of the puck is constant. The instructor now proceeds to engage students in a deeper inquiry to determine if this situation is in conflict with what they have previously come to understand about how forces and motion are related. The instructor can initiate the inquiry with a quick dialogue to prepare for a demonstration. If a net force on an object exists, how would you expect the object to behave? Students generally respond, "it will accelerate!". The teacher can then remind the students once again of their unique situation. We have a F_{net} towards the center, but the puck has constant motion? Ask, "If we had a device that could measure acceleration, how could that help us better understand this situation?" Follow this with "Given the FBD we are exploring, in what direction would you expect the device to indicate acceleration?"

Introducing an Accelerometer

An accelerometer is basically a container filled with colored water and made of two Plexiglas plates separated by spacers and made to be watertight. They can also be purchased from science vendors but can be made for a fraction of the cost. The instructor then proceeds to guide students through an activity that appears in PRISIMS called "Stop the world, I want to get off". The activity begins by demonstrating the accelerometer in a linear situation. Ask students to predict what will happen to the water level when the accelerometer is attached to a cart being accelerated by a falling mass. Students may hesitantly answer that the water will be observed to move and accumulate at the end opposite to the direction of the accelerating cart (Figure 4). The instructor should then demonstrate this, and then do so again in the opposite direction. Now ask students to explain how the accelerometer works. The students will confidently respond that the water level is always higher on the side of the container that is opposite the direction of the acceleration.

Now ask students how the accelerometer might help address their investigation regarding the puck moving in a circle. Many students suggest attaching the accelerometer to the puck. However, the puck is quickly shown to be incapable of hovering with the accelerometer on it. The



instructor should continue to seek ideas from students, and this requires adequate wait time and encouraging non-verbal behaviors. Eventually, on their own or with hints from the teacher, students will suggest holding the accelerometer and spinning in a circle. The instructor should then ask for predictions and suggest students relate predictions to FBD options. The instructor should help students recognize how accelerometer predictions will either support or reject

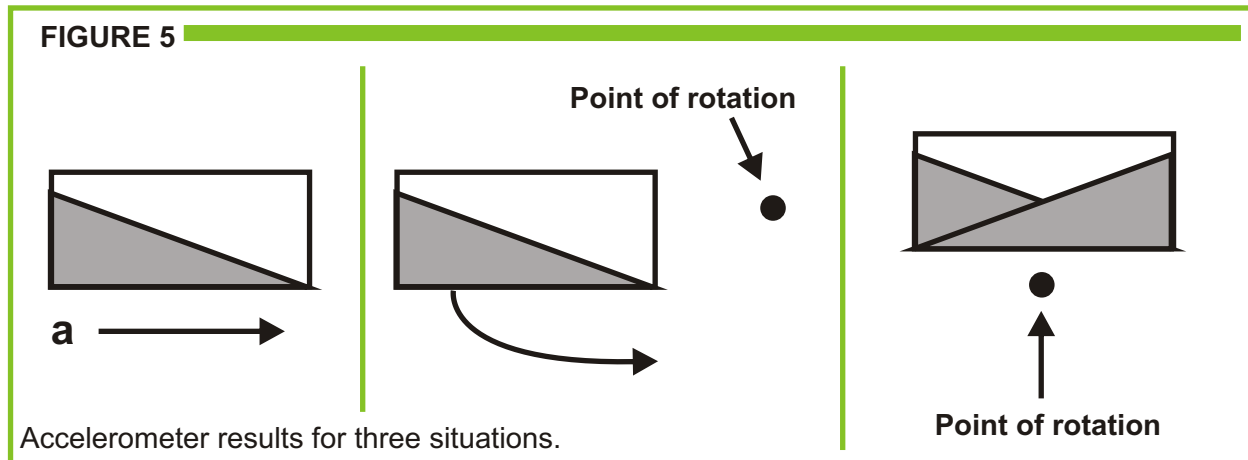
the FBD for SR2 discussed earlier.

The ensuing discussion builds suspense for the demonstration, but more importantly

encourages students to justify and seek evidence for their claims while communicating that understanding is much more than knowing what will happen. These types of interactions encourage students to reject incorrect notions that were previously held and accept that the acceleration is toward the center of rotation and the FBD in SR2 is an appropriate force representation. The accelerometer can also be placed on a rotating turntable demonstrating that the acceleration is towards the center for all points around the circular path and that the device provides consistent evidence no matter how it is used (Figure 5).

The cognitive struggles that students experience and eventually resolve indicates they are mentally engaged in the lesson, and it also throws light on how simply lecturing about circular motion rarely changes how students truly think about the phenomena. To move students towards a meaningful understanding of circular motion, or any science concept, requires that they grapple with, understand, and accept the evidence and logic supporting those concepts.

Once evidence for acceleration towards the center is established, the instructor asks, "What changes in order for an acceleration to occur?" Students should respond with "velocity", but be prepared to hear some say "speed". Even those who say "velocity" often do not grasp the significance of the concept. Once again students are confronted with thinking that is counterintuitive. How can the object be accelerating when its speed is constant? Now is an appropriate time to engage students in a demonstration that will encourage them to investigate the



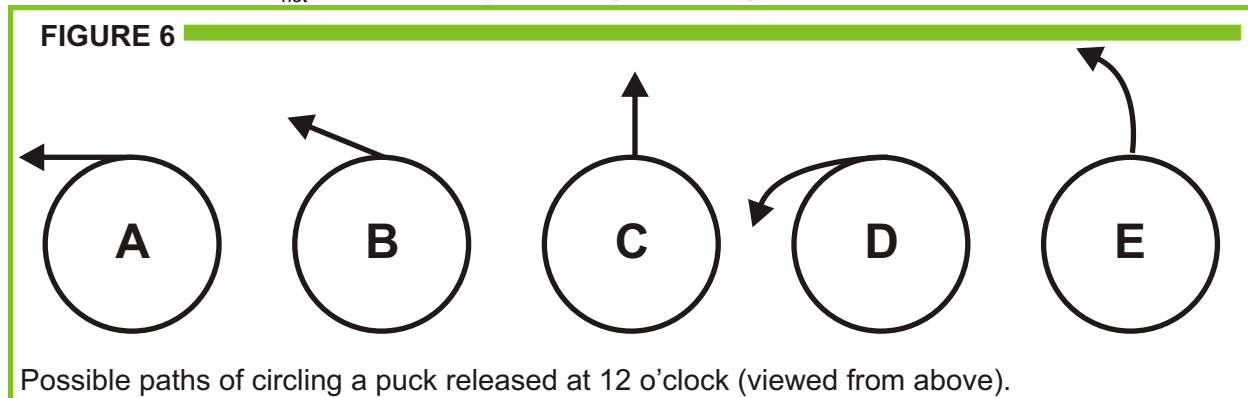
motion of an object traveling in a circular path, and develop a deeper understanding of the crucial difference between velocity and speed.

Ask the students what would happen to the puck if it was traveling in a circle and the string was released at some point along the circular path. As before, encourage many responses and draw all suggested options on the board. Encouraging non-verbal behaviors, extensive wait-time, and perhaps a think-pair-share strategy are needed to draw out all the possibilities provided in Figure 6 (drawings represent a top view and 12 o'clock release point). Only after student ideas have been exhausted should the teacher suggest additional possibilities that are sometimes put forth by individuals.

Now conduct the demonstration for students to observe. Because they have made predictions regarding the path of the released puck, they closely observe the demonstration to see if the puck behaves as they expected. The students quickly see that the path the puck takes is tangent to the release point and that the puck behaves with a constant velocity. The instructor should repeat the demonstration from other release points to provide verification. The instructor can then pursue reasons why the puck travels in a straight line at a constant velocity. A suggestion to draw a free body diagram is all that is needed. The student should quickly notice that the only forces acting on the puck are F_g and F_n (similar to FBD in SR1). These are balanced and provided a net force of zero therefore the motion of the puck will not change.

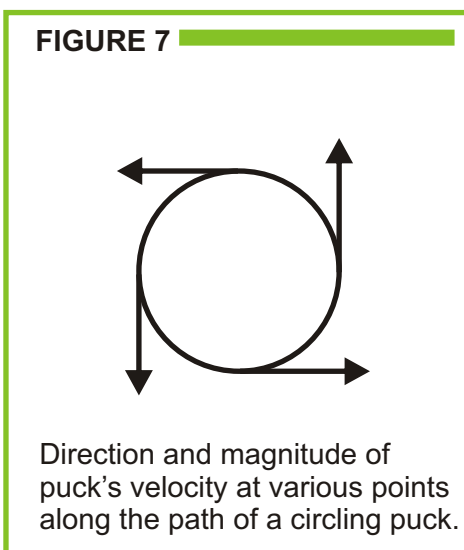
This judicious scaffolding of demonstrations and questions prepares students for the next question. Ask, "Even though the speed of the puck is the same at the different release points, what noticeable difference would be apparent if velocity vector arrows were drawn at various

release points?" Using students' answers, draw on the board a diagram like that appearing in Figure 7. The students now have all that they need to get to the bottom of their quandary. Ask students to clarify the difference between speed and velocity. Students should easily recognize the velocity is changing because, despite constant speed at the various points along the circling puck, the direction the puck moves is continuously changing. The instructor can then generalize and summarize that the F_{net} on the puck by the string is causing an acceleration, but the acceleration is



observed as a change in the velocities direction rather than a change in magnitude.

Now ask the following questions to help students consolidate and formalize the crucial conceptual ideas involved in circular motion:



- > What evidence have you observed that supports the idea that the F_{net} and acceleration are towards the center of a circling object?
- > What evidence have you observed that the velocity of a circling puck is always tangent to any point along the curved path?

Summarize the vector nature of the change in velocity with a diagram similar to Figure 8. It further clarifies for students that the change in velocity between the selected points, indicated V_1 and V_2 , accounts for a change in velocity towards the center using the definition for change in velocity and rules for vector addition. The importance of these instructional moves is that it encourages students to think about what they have observed, interpret it in a new light, and then link it to prior physics concepts. One of the beautiful aspects of science is the coherence its ideas bring to disparate events. The approach put forth in this article helps

students deeply understand circular motion and appreciate the coherence that scientific thinking can bring to natural phenomena.

Now that a reasonable conceptual understanding of circular motion has been developed, the students are in a far better position to understand a quantitative representation of circular motion. Ideally this should lead to a more quantitative inquiry, establishing the relationship between the variables F_{net} , r , m , and v .

Regardless of how quantitative representations are derived (e.g. $F_{net} = m(v^2)/r$ or $V^2 = F_{net}(r)/m$), students have a greater chance of relating abstract symbols to their observations and newly acquired conceptual understanding of the phenomena. When quantitative representations are introduced prior to a conceptual evaluation, students focus on definitions and manipulating equations. In the students' minds, this takes precedence and interferes with understanding the phenomena the equations symbolize.

Final Thoughts

This article illustrates how circular motion, an abstract and difficult concept, may be taught in a manner that begins by directly observing the phenomena, careful scaffolding to a deep understanding of scientific ideas that account for observed phenomena, and finally to a mathematical representation of those ideas. The judicious scaffolding of direct experience, exploring that experience, scaffolding to additional experiences and sense making, and continuing such scaffolds is what effective teachers do. This scaffolding requires the presence of a knowledgeable teacher who deeply

understands science content, how people learn, pedagogy, and possesses hard won pedagogical content knowledge. Effective teachers have an agenda and structure the learning environment, but they anticipate and are prepared to play off students' ideas (correct and incorrect) to help them move progressively to a deep understanding of content advocated in all science education reform documents.

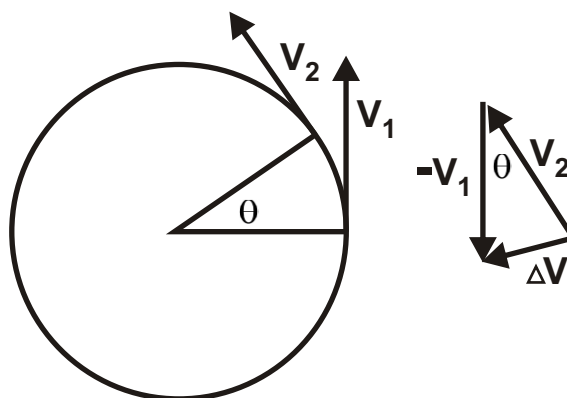
The general sequence described here for teaching about circular motion (i.e. carefully scaffolding concrete experience to sense making activities, to additional relevant experiences and sense making activities, and then to new vocabulary, abstract symbolism, and mathematical equations) reflects how people learn and has been promoted in the science education literature for decades. Deeply understanding science concepts demands critical thinking, problem solving, communication, understanding the nature of science, and other student goals sought by teachers. How to apply the general instructional sequence described in this article to the many concepts taught in science is an ongoing struggle, but well worth the effort.

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FIGURE 8



Vector change of a circling puck.