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Toward a Conceptual Approach to the Coriolis Force: Cataloging Intuitive Knowledge Elements in Intermediate Physics Learners

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TOWARD A CONCEPTUAL APPROACH TO THE CORIOLIS FORCE: CATALOGING INTUITIVE KNOWLEDGE ELEMENTS IN INTERMEDIATE PHYSICS LEARNERS

by

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ABSTRACT

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by

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Traditional instruction on the Coriolis force is primarily mathematical and conceptually simplistic. This approach alienates casual learners, confuses experienced learners, and often fails to achieve the desired conceptual understanding. While developing a novel, conceptual approach to the Coriolis force, I conducted semi-structured interviews with eleven intermediate physics students to identify elements of intuitive or prior knowledge which contribute to or interfere with their learning in the domain of the Coriolis force. The students reasoned within a set of thought experiments designed to elucidate the origin of the oblate shape of the earth and emphasize its critical role in the Coriolis force as seen by objects moving across the surface of the earth. The students utilized a wide range of previously documented knowledge elements while navigating the conceptual approach, including a large collection of elements related to balance and equilibrium. Additionally, students displayed confidence when discussing how rotating objects bulge around their centers, possibly indicating a novel element of “bulging”. I observed an intermediate knowledge structure when students discussed isolated systems, frictionless idealizations, and inertial motion. I call the novel structures belonging to this class “instructional landmarks”. Instructional landmarks originate from formal physics teaching and embody axiomatic principles which students rely on to orient themselves in conceptual spaces and resolve cognitive disputes between competing solutions. Areas of cognitive conflict were identified, though most were resolved through simple cueing from the instructor. Most students expressed an increased conceptual understanding of the Coriolis force after participating, suggesting that conceptual approaches should be investigated further.

(79 pages)

PUBLIC ABSTRACT

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Jared Arnell

In Physics, the topic of the Coriolis force is often confusing and difficult to teach. I conducted a series of interviews with undergraduate physics students to understand how they would use their prior knowledge and personal experiences to interact with and navigate through a new conceptual teaching approach for the Coriolis force. Many students applied their intuitive understanding of balance to interpret and make predictions about the Coriolis force. Some students displayed a strong conviction that rotating objects will naturally get pulled outward, which suggests that this impression may be a useful tool for novice physics learners to use in other contexts. The students also demonstrated how their experience in previous physics classes had taught them to prioritize certain physics concepts in order to guide them through the problem-solving process, showing how classroom learning can help develop and enrich students' intellectual skills. These findings indicate ways in which educators can adapt or restructure current Coriolis force teaching method to utilize these productive knowledge resources in a more efficient manner.

CONTENTS

Page

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Since it was first observed affecting trade winds and sailing ships in the 17th century, the Coriolis force has been a locus of confusion and misinterpretation (Persson, 2005). This apparent force deflects objects moving across the surface of the earth to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. It seems easy enough to understand on its surface, but the true richness and complexity of its origins and mechanisms have spurred a host of cognitive and pedagogical challenges. These hurdles are not unique to novice physics learners; even renowned physicists such as Pierre Simon de Laplace and Richard Feynman have been caught making blunders when exploring the intricacies of the topic (Persson, 2006; Tiersten & Soodak, 1998). Coriolis force mistakes are also not limited to the classroom or the laboratory; numerous myths and misconceptions about the effects and applications of the Coriolis force have permeated popular culture as well, muddying the waters even further (Grof et al., 2020; Kearns, 2010; Stommel & Moore, 1989). This high prevalence of errors surrounding the Coriolis force is especially worrying due to the massive breadth of its relevance: the Coriolis force can be seen not only throughout meteorology, climatology, and oceanography, but also within astrophysics, aerodynamics, ballistics, optics, and even atomic physics and chemistry (Bliokh et al., 2008; Chandrasekhar, 1953; Chu & Han, 2008; Farrel, 2008; Hastenrath & Lamb, 1978; Jardin & David, 2015; Neumann, 1984; Persson, 1998; Polton et al., 2005; Thompson, 1972; Walker & Dracoulis, 1999).The scientific literature has no shortage of investigations of the Coriolis force and its numerous implementations, and yet the published works seem to have been ineffective at preventing myths and misunderstandings from invading discussions (Shakur, 2014). Due to the myriad of issues permeating this critical subject on multiple levels, it is necessary to address the problem at its origin and investigate the manner in which the Coriolis force is being taught.

Conventionally, formal Coriolis force instruction has relied primarily on a complex, calculus-based derivation in which intermediate physics and engineering students are guided through the transformation and re-writing of Newton's Laws of Motion into a uniformly rotating reference frame (Meriam & Kraige, 2012; Stommel & Moore, 1989; Taylor, 2005). In response to the pervading confusion, some researchers have proposed alternative mathematical solutions which could provide an easier method for deriving the Coriolis force while remaining just as rigorous (Dolovich et al., 2012; Gallardo-Alvarado et al., 2018; Kageyama & Hyodo, 2006; Renault & Okal, 1977). Unfortunately, even if these mathematical methods succeed at discovering an effective substitute for the derivation process, they might not make much of an improvement to Coriolis force discussions on the whole. The wide variety of learners who would benefit from improved Coriolis force instruction often have significant mathematical disparities between them, which means that a reliance on overelaborate mathematical solutions may actually alienate some learners (Grof et al, 2020; Shakur, 2014). What's more, students who are guided through these calculations may simply be accepting the truth of the equations even when they don't really grasp the material, relying instead on their trust of the experts who developed the derivation to not lead them astray. As such, those who receive the rigorous mathematical explanation for the Coriolis force may find themselves unable to adequately explain its fundamental principles when pressed beyond the comfort of their mathematical framework, which would make their communication with more naive learners who lack the same background all the more challenging (Stommel & Moore, 1989). While these derivations have their usefulness in the upper division curricula, the solution to improving Coriolis force teaching and communication will likely not be found in a predominantly mathematical intervention.

Instead of tackling the problem from the mathematical side, a conceptual understanding of the Coriolis force could provide a portal to learning which is accessible to students of any background. Regrettably, the inclusion of conceptual descriptions of the Coriolis force in common textbooks is painfully inadequate. In some cases, conceptual discussion is excluded in its entirety (Taylor, 2005). When it is present, conceptual aspects of the Coriolis force are often conveyed using simplified models such as the 2-dimensional rotating disc or the 'carousel' example (Grof et al., 2020; Schmidt, 1986; Wagner et al., 2006). These reductionist approaches can make for helpful illustrations, but without careful implementation, they can create erroneous heuristics which lead to even more incorrect predictions (Persson, 1998; Persson, 2014; Taylor, 2005). Another common conceptual shortcut is to attribute the Coriolis force solely to the conservation of angular momentum: as objects move away from the center of rotation, their tangential speed decreases and the rotating reference frame 'overtakes' them (Herrera & Morett, 2016; Schmidt, 1986). While this explanation is valid, it fails to explain the presence of the Coriolis force on objects whose motion has no radial component, such as objects moving directly east or west across the surface of the earth.[1] This highlights a deficiency found in nearly all conceptual descriptions of the Coriolis force, namely a hesitancy to explore the Coriolis force in its most germane setting: motion across the surface of the earth. In the rare cases where the 3-dimensional earth is considered, it is usually approximated as a sphere. While this sort of approximation is usually sufficient for other purposes, it neglects the integral role that the oblate shape of

[1] It also fails to explain why objects moving directly north or south in the inertial frame (which have no angular momentum along the axis of rotation of the earth) still experience a Coriolis force.

the earth plays in determining the motion of bodies across its surface (Edwards & Edwards, 2021). It is clear that the conventionally available conceptual methods for teaching how the Coriolis force affects motion across the surface of the earth are too infrequent, inaccurate, or incomplete to construct the desired conceptual mastery.

Any novel teaching method which attempts to address these current educational deficiencies must be derived from and informed by up-to-date educational research. Early science education research predominantly believed that students' prior knowledge composed a coherent but inaccurate naive theory. These misconceptions hindered instruction, and educators were tasked with rooting out and replacing the naive theories with expert knowledge (McCloskey, 1983). This viewpoint has been thoroughly criticized for its dismissal of useful prior knowledge and its problematic assertion of confrontation and replacement as a viable educational strategy (Smith et al., 1993). Contemporary theories on science education instead recognize the productive role which prior knowledge can play and the variety of forms which that prior knowledge can take (Hammer, 2000; Niedderer, 2001). These theories acknowledge that many misconceptions which may appear as incorrect prior knowledge are actually misapplications of prior knowledge, which may be otherwise productive in another context. From this perspective, the role of educators is to help students categorize and reorganize their prior knowledge into forms that match scientific knowledge (Chi & Roscoe, 2002; Vosniadou & Brewer, 1987). Theories which view prior knowledge as an accessible resource for promoting conceptual change have already begun to influence the educational research of many physics domains, such as kinematics, buoyancy, circuitry, thermodynamics, and astronomy (Apaydin, 2020; Clark, 2006; Ding et al., 2020; Koponen & Huttunen, 2013; Prather et al., 2003; Roschelle, 1998). It is time to apply these same principles to the domain of inertial forces and the Coriolis force in particular.

Scientific educational research has also begun stressing the importance of conceptual understanding as a pivotal component of scientific knowledge. Cultivating conceptual understanding allows students to construct deeper meaning rather than simply regurgitate memorized information with little to no ability to apply it to circumstances removed from the classroom (Konicek-Moran & Keeley, 2015). In the realm of physics, teaching methods which explore the causal mechanisms behind physical phenomena are especially useful in developing students' conceptual understanding without compromising their ability to solve related computational problems (Hung & Jonassen, 2006). Model-based reasoning, in which students create a mental representation of a physical system and its interactions, has also been suggested as a useful tool in aiding conceptual change, especially with counter-intuitive topics (Vosniadou, 2013). Thus, current education theories suggest that successful physics teaching methods will focus on conceptual understanding which builds on students' prior knowledge, explains causal mechanisms, and constructs mental models.

The purpose of this study was to advance the development and implementation of a robust, conceptual approach to understanding the Coriolis force as it affects objects in motion on the surface of the earth. For the past two years, I have worked with professors in the Physics, Computer Science, and Instructional Technology & Learning Sciences Departments at Utah State University to create a novel conceptual approach to the Coriolis force. Through our collaborations, we assembled a series of thought experiments which could intuitively explain the real-world, physical phenomena which compose the causal mechanism for the Coriolis force as seen on objects which move across the surface of the earth. Alongside these thought experiments, our team developed an online module called *CorioVis* which could display the paths of objects moving across the surface of the earth from multiple reference frames. After we had finalized a preliminary draft of the conceptual approach, my role was to present it to intermediate physics students and observe their real-time construction of new Coriolis force knowledge during this novel instructional experience. My intent was to catalog any intuitive knowledge elements which the students used as they navigated the thought experiments and explore how their prior knowledge was contributing to or hindering their overall learning. By identifying the intuitive knowledge elements which were activated in these ways during this conceptual instruction on the Coriolis force, I hope to not only further the evolution of our own method, but also provide a scaffolding from which future conceptual approaches can build to ensure that their instructional design makes the most of their student's prior knowledge.

Theoretical Framework

This study's data were analyzed according to a constructivist theory called Knowledge in Pieces (KiP), which postulates that knowledge is a complex web of individual elements with context-dependent connections which can be computationally modeled (diSessa, 1993). As novices advance to expertise, they refine their network by adding new elements, purging erroneous connections, and reinforcing useful pathways. As the network becomes more reliable, clusters of related elements fuse into more developed structures which can influence sense-making. By examining learners at various stages of development and across a broad range of topics, researchers can catalog the various available resources, understand the relationships and interactions between them, and explore their evolution and development over time.

KiP expects that the foundation of an individual's knowledge structure will be composed of discrete knowledge elements. These elements can be created or collected in a variety of ways (e.g., physical experience, cultural interaction, schooling), and their genesis will often influence their role in the knowledge structure. One type of knowledge element that is particularly relevant to physics education is the phenomenological primitive, or "p-prim". P-prims are intuitive explanations of causal mechanisms and are developed by interacting with and observing the physical world. They are phenomenological in that they describe the causality of common events, and they are primitive in that a) they are the smallest divisible unit of thought in the same way that coding primitives are the smallest building blocks of code, and b) young learners treat p-prims as "how the world works" with no deeper explanation required. P-prims are often abstract in nature, describing the underlying relationship between agents rather than context-specific or superficial characteristics. This flexibility means that a single p-prim can be used to describe a wide range of scenarios. One example is the p-prim *bouncing*, in which a moving object rebounds off of a stationary object. When young learners first observe this common interaction, they will obviously lack the deeper understanding of material science and kinematics necessary to explain the mechanism in the manner that an expert would. The young learner will only see that some objects tend to bounce when they impact a surface. If asked to explain why *bouncing* occurs, they would likely state that it is "common sense" or "just what happens"; a deeper explanation is not necessary for them to make sense of the world. As these young learners explore and investigate their world, they will amass a robust set of p-prims to describe the cause-and-effect relationships they encounter.

The p-prims which are activated (or not activated) will drastically influence the way naive learners perceive the causal mechanisms in novel circumstances. If a naive learner were to observe an unfamiliar phenomenon which has elements that remind them of *bouncing*, they may "activate" the *bouncing* p-prim to guide their predictions in the new scenario. In some cases, p-prims may be activated which an expert would not apply to the event in question. These misapplied p-prims can explain many common errors or misconceptions. Naive learners may not lack the necessary knowledge or be incapable of understanding; instead, their knowledge structures may just be disorganized or prone to errant connections. For example, when young children are asked about what causes the earth's seasons, they may recall the intuitive explanation that *closer means stronger* (lights are brighter and sounds are louder when they are nearby). The children may then predict that the earth must be closer to the sun during summer and further from the sun during winter. This misplaced connection can be addressed by reminding the children that the Northern and Southern Hemispheres don't experience summer and winter at the same time (Hammer & van Zee, 2006). Through this "cueing," naive learners can activate productive p-prims and establish reliable connections, resulting in the development of a more expert-like knowledge system. By identifying helpful or relevant p-prims which apply to a particular topic, instructors can adjust their lessons, activities, discussions, or experiments to intentionally direct the students' observations toward the desired p-prims and away from p-prims which may muddy the waters.

KiP's ultimate goal is to create a computational model for cognition. By mapping out the structure, behavior, and development of knowledge structures across varying topics and stages of development, a theory could be constructed which would provide educators with a roadmap for understanding the trajectory of their students' understanding. If successful, instructors could make detailed inferences about how learners might interact with cognitive challenges based on their relevant knowledge structures. This would allow for the adaptation and customization of educational material to utilize the students’ available resources while navigating around expected cognitive pitfalls. Cataloging the list of knowledge elements and the contexts in which those elements are used is vital for creating this computational model.

This study explored an intermediate stage in physics learners’ development by capturing a snapshot of how their knowledge structures appeared at this transitional stage in the domain of the Coriolis force. By documenting the observed knowledge elements in this context and their perceived implementations, I aim to contribute to the larger body of cataloged knowledge elements which will be necessary to construct a complete computational model of physics cognition and learning.

Methodology

A Conceptual Approach to the Coriolis Force

As mentioned previously, the impetus for this study was the attempted development of an alternative method for teaching the Coriolis force in upper-division physics classrooms without resorting to complex mathematics or relying heavily on manipulating equations. This approach consists of a set of thought experiments that incrementally introduce key concepts to ultimately explain the origin of the Coriolis force and how to predict its effect on objects moving across the surface of the earth. The conceptual approach was developed alongside an interactive digital module called *CorioVis*, which would provide visual approximations for the thought experiments, though the visuals were not strictly necessary to the instruction. Here, I provide a summarized version of the thought experiments which constitute the conceptual approach for later reference.[2]

1. Imagine that the earth was perfectly spherical, motionless, and frictionless. If an observer who was floating motionless in space some distance away from the planet (whom we call Isaac) was to place a puck on the surface of the earth and release it from rest, the puck would remain motionless, both relative to the surface of the earth and to Isaac. If Isaac were to then kick the puck in an arbitrary direction at an arbitrary speed (though not fast enough to leave the surface), the puck would travel in a straight line across the surface of the earth at a constant speed. Eventually, it would circumnavigate the globe and return to its starting location, tracing a circular path which divides the globe into two equal hemispheres. This path is known as a “great circle”.
2. Imagine that the spherical, frictionless earth was allowed to rotate as normal. If Isaac were to repeat the action of placing a puck on the surface and releasing it from rest, it would again remain motionless relative to Isaac. The earth would rotate beneath the puck, but because it is frictionless, it would not impart motion to the puck. If Isaac were to kick the puck, it would still trace out a great circle from his point of view. However, this time the earth would rotate beneath the puck as it traveled. Thus, when the puck arrives back at its starting location relative to Isaac, it may not be at the location on the surface of the earth at which it started.

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[2] The thought experiments outlined here constitute a primitive version of the conceptual approach.

3. Imagine a second observer (who we call Rachel) floating in space like Isaac, but rotating with the earth rather than remaining motionless. From Rachel's perspective, the earth is motionless while Isaac and the distant stars rotate in the opposite direction. When Isaac places the puck on the earth and releases it from rest, Rachel would say the puck is moving directly to the west (as she and the earth rotate to the east). To compare how Isaac and Rachel describe a moving puck, a specific location, direction, and velocity are chosen. Isaac places the puck in the Northern Hemisphere and kicks it directly east at the same speed as the ground beneath it. As stated before, Isaac will see the puck travel in a great circle, which would be a circular cross-section which dips down into the Southern Hemisphere on the opposite side of the earth from where Isaac released the puck. However, the motion looks entirely different to Rachel. Initially, the puck appeared to be motionless as it was moving in the same direction and at the same speed as the earth beneath it. However, Rachel sees the puck begin to drift southward toward the equator. Eventually, it would reach a southern latitude that was equal and opposite to its original starting latitude. There, Rachel would watch the puck come to a stop and begin traveling north. Thus, on a spherical, rotating earth, objects that are initially motionless begin to move toward the equator as they follow their unobstructed great circle trajectories.[3]
4. To investigate the consequences of this conclusion, imagine that the earth was fluid, being composed of many infinitesimally small particles which can each move about according to their own motion. If this fluid earth was rotating as the real earth does, every particle would originally be moving to the east. However, as the particles in the Northern Hemisphere follow their straight-line great circle

[3] This equatorial drift can also be recontextualized as the centrifugal force if appropriate.

trajectories, they will begin to drift toward the equator. Likewise, the particles in the Southern Hemisphere will begin drifting toward the equator from the opposite direction. When these opposing particles meet at the equator, the north/south components of their motion will negate each other, causing them to pile up and accumulate at the equator. This will cause the cross-section of the earth (when cut from pole to pole) to change from circular to elliptical.[4] For a particle on the surface of the earth, this bulging will have the same effect as elevating the equatorial edge of the ground. This will introduce an effect which will push the particle toward the nearest pole. Initially, when the equatorial bulge is negligible, the push is not sufficient to prevent the particles from continuing to drift toward the equator. But, as more particles drift and arrive at the equator, the bulge will increase continuously until a point of equilibrium is reached where the tendency for the particles to drift toward the equator due to their great circle paths is exactly counteracted by the tendency to drift toward the pole due to the bulged shape of the earth. This new shape is dependent on the rotation rate of the earth; the earth would bulge more if it were to rotate faster, and it would bulge less if it were to rotate slower. For the earth, the shape is very nearly spherical as the earth is only completing one rotation every 24 hours, but it is oblate nonetheless. At this exact shape (which is determined by the rotation rate of the earth), objects which are motionless on the surface of the earth will remain motionless, neither drifting toward the equator or toward the poles. We may now freeze the earth in this new corrected oblate shape. Now, if Isaac kicks the puck directly east at the

[4] In more rigorous settings, this equilibrium state can be described as the point at which the gravitational, normal, and centrifugal forces sum to zero in the rotating reference frame.

same speed as the earth beneath it, Rachel will observe that the puck is motionless and remains so indefinitely, regardless of its position on the globe.

5. We can now understand how Rachel will observe objects which are moving across the surface of the earth in her perspective. If Isaac kicks the puck to the east faster than the ground beneath it, that puck will have a greater rotational speed and thus an increased tendency to drift toward the equator. As the shape of the earth is fixed, the bulge will not be sufficient to prevent this, and Rachel will observe that the puck (which she originally viewed as moving directly eastward) now changes direction and begins moving toward the equator. Likewise, if Isaac kicks the puck to the east at a slower speed than the earth, the puck will have a smaller rotational speed and thus a decreased tendency to drift to the equator. The bulging of the earth will remain constant, so the polar drift will now be larger than the equatorial drift. Thus, Rachel will see the puck (which was originally moving directly westward in her reference frame) begin to change direction and move toward the nearest pole. In addition to these deflections, Rachel will also observe deflections in pucks that move north or south in her reference frame; as a puck moves away from the equator and towards the poles, it is getting closer to the axis of rotation of the earth. Like a skater pulling her arms in, the puck's rotation rate will increase (a consequence of the conservation of angular momentum). Conversely, if a puck is moving toward the equator, it is moving away from the axis of rotation and will see a decrease in its rotation rate. The combination of the deflection on east-west moving pucks from the bulge of the earth and the deflection on north-south moving pucks from the conservation of angular momentum create a cyclical pattern which deflects them clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. As

Rachel would measure the speed of the pucks (their kinetic energy) as constant, it appears as though they are being acted on by a force that is always perpendicular to the velocity of the pucks.[5] This apparent deflective force is what we call the Coriolis Force.

This study served as a maiden voyage of sorts for this conceptual approach, both acting as a proof of concept as well as allowing actual physics students to provide commentary and feedback. Although the conceptual approach was ultimately envisioned to be used in tandem with *CorioVis*, it was decided that this study would investigate the thought experiments in a vacuum without accompanying visual resources to determine if the conceptual approach was viable on its own.

Data Collection

Undergraduate students at Utah State University who had completed the Introductory Physics course were invited to participate in a 1-on-1 interview (via Zoom due to Covid-19 restrictions) to investigate how students reason about Coriolis force phenomena. As the Coriolis force is primarily covered in the upper-division PHYS 3550 Classical Mechanics course, our initial sense was to invite only students who had taken the Introductory Physics course but had not yet taken Classical Mechanics to participate. This would have given us a sample of students for whom the Coriolis force was novel (at least in an academic sense). Ultimately, we decided to also invite students who had completed the Classical Mechanics course to participate in order to increase our sample size; while the Coriolis force would not be novel to these students, the input from those who had received a traditional instruction on the Coriolis force would likely be useful.

[5] While Rachel would view the puck's speed as constant, it is important to note that Isaac would instead see the puck slow down as it approached the equator (as it "climbs" up the bulge to a higher potential energy and thus loses kinetic energy).

In total, eleven students volunteered to participate in the study. The students have been assigned pseudonyms for anonymity. Five students had taken the Introductory Physics course but had not yet taken Classical Mechanics: Joshua, Diane, Hilda, Kayla, and Gina. The remaining six students had completed both the Introductory Physics and the Classical Mechanics courses: Bailey, Felix, Ian, Adam, Ethan, and Caleb. The students were guided through a semi-structured protocol which began with a few background questions regarding their prior knowledge about the Coriolis force and some related topics. They were then introduced sequentially to the thought experiments and asked to predict the motion of the pucks under the various circumstances. The students were instructed to think aloud as they reasoned their way through their predictions. At the end of each thought experiment, the instructor verified the accuracy of the students' predictions and discussed any corrections before moving on. This was done because the thought experiments were designed to build upon the conclusions of the previous thought experiments, meaning that erroneous predictions early on would compound if left unaddressed. At the conclusion of the interviews, the students were given an opportunity to express their thoughts on the conceptual approach, including areas which were easy or difficult and their overall experience with the instruction. Afterwards, Otter.AI (an automated transcription software) was used to create a transcript for each interview, though the transcripts needed to be reviewed and edited as the AI was unfamiliar with many of the physics-specific jargon.

Data Analysis

The analysis of this study was conducted using Knowledge Analysis, which places the structure, genesis, and evolution of knowledge within an individual's mind as the primary focus of investigation (diSessa et al., 2015). To be more specific, this study's goal of identifying the resources being cued and activated by the participants in real-time qualifies it as a microanalytic analysis. This methodology was informed by the techniques found in Grounded Theory, which allows patterns and interpretations to emerge from the data rather than looking at the data to find already existing components of a theory (Corbin & Strauss, 2008).

The interview transcripts were coded using the qualitative data analysis software NVivo. The students' responses were coded by basic physics concepts such as "reference frames," "friction," "equilibrium," and "gravity". In total, 16 coding categories were designated. As the students discussed the same physics topic, it was predicted that they would activate similar or related resources due to the highly context-dependent nature of the connections. Thus, once all eleven transcripts had been coded, each code was reviewed independently to identify patterns within the students' explanations, questions, difficulties, and predictions when engaging with that particular topic. In total, 34 unique patterns of response were identified, with some patterns being seen across multiple related codes. The list of patterns was revised to a) combine items which appeared to be individual manifestations of a larger theme and b) eliminate items which did not have sufficient examples within the data collected to warrant confident conclusions. The remaining 16 patterns were then examined in greater detail to determine their relevance to the research questions, their prevalence among the participants' responses, and their basic identifiable attributes. Questions were posed to explore whether the relevant patterns a) referenced personal experience and/or classroom instruction, b) described tangible and/or observable phenomenon, or c) were offered as self-explanatory or required prior conclusions. From these attributes, the patterns were compared to previously documented knowledge elements and structures to explore possible identifications or categorizations.

Results

I will be discussing the observations of this study as a linear-analytical structured case study (Yin, 2018). As I discuss my findings, there will be times at which I specify the number of students who shared a particular response. The purpose of these enumerations is to provide context for the patterns and situate them relative to each other. The sample size for this inquiry was far too small to make any definitive claims about the frequency of these knowledge elements occurring in the general population of undergraduate physics students; even if an element was seen in every student in this study, it would not guarantee that such an element would be as ubiquitous on the larger scale. However, by investigating and reporting on elements observed in small case studies such as this, we can gain a better sense for the overall shape of the students' intuitive knowledge structures and inform the scope and target of future studies. When it is necessary, I will include longer excerpts from the interviews to display the patterns seen in the students' responses. However, for shorter references, I will indicate which student is being referenced with the first letter of their pseudonym in brackets.

I will begin by briefly commenting on the students' answers to the background questions. I will then discuss the previously documented knowledge elements which were observed, followed by one pattern which may qualify as a new p-prim and a set of patterns that may constitute a new type of knowledge structure. I will then cover the various areas of conflict that were encountered with the students and offer possible causes and solutions for each. Finally, I will include the students' responses to the conceptual approach.

Comparing Coriolis Preconceptions

Before beginning the conceptual approach, I asked the students who had already taken Classical Mechanics if they could explain the Coriolis force (a task which they should ideally be capable of if their formal instruction was satisfactory). While one student [F] was unable to remember enough to give an explanation, the other five summarized their understanding of the concept. All five explanations included two important elements.

1. Reference Frames: The students were aware that the Coriolis force was caused by a difference in frames of reference. One student [E] used the proper term of “inertial force” to describe this categorization, but others used more casual phrases such as “a virtual force” [A], “an imaginary force” [I], or “a perceived discrepancy” [B]. Regardless of language, the students understood that the Coriolis force only existed when participants in a system occupied separate reference frames. Furthermore, the students recognized that the Coriolis force would only be felt by the observers in the non-inertial reference frame.
2. Rotation: The students identified the rotation of the earth (and us along with it) as the source of the Coriolis force. However, their explanations of the exact mechanism through which the rotation caused the Coriolis force were far less precise (when they offered one at all). One student [B] claimed that as an object moved, “its tangential velocity would remain the same” which would result in a deflection as “it’s going towards the center of the thing that’s rotating”. Another student [A] correctly identified the relevance of the conservation of angular momentum, though this led them to a fallacious conclusion:

   Jared: *On the earth, where do you see the effects of the Coriolis force?*
   Adam: *You’d see it if you were flying an airplane, for example. If you’re going from the north pole to the south pole, the velocity of the surface of*

the earth is increasing. You have a constant angular rotation, but the diameter is increasing if you're going down… I'm not sure which way it rotates, let's say it's rotating counterclockwise. If you fly an airplane south, you would appear to be going off to the west.
Jared: *...What about a plane that was flying east or west? What would happen there?*
Adam: *There would be no… you're flying purely east or west? There's no Coriolis force.*

The conclusion that the Coriolis force exists only for longitudinal motion was also reached by another student [E], and although he did not mention the conservation of angular momentum by name, he attached angular velocity and rotational motion to his explanation in a similar manner:

Ethan: *The Coriolis force is an inertial force that's related to angular velocity… it's not necessarily a force that is caused by anything other than the inertia of an object wanting to stay in motion at the same rate.*
Jared: *Where can we see the effects of the Coriolis force?*
Ethan: *...I believe in long range shooting and applications of an object traveling over the surface of the earth at great speeds. And I believe it's only in effect when you're traveling north to south or south to north…*
Jared: *So, if that sniper were to fire the bullet directly east or directly west, what would happen to the path of the bullet?*
Ethan: *I do not believe it is affected by the Coriolis force.*

It is promising that the students had retained both non-inertial reference frames and the earth's rotation as integral components of the mechanism of the Coriolis force from their formal instruction. After all, no explanation of the Coriolis force would be complete without these pillars. However, as seen from the previous excerpts, the tight association of conservation of angular momentum in the standard explanations for the Coriolis force had stuck a little too well with a few of the students; they regarded the difference in rotation speeds as the only source of the Coriolis force and thus predicted that objects maintaining a constant angular velocity (moving directly to the east or west) would be unaffected by the Coriolis force. This conclusion stands in direct opposition to the mathematical formula these students would have been taught in the same Classical

Mechanics course, in which all objects which move relative to the surface of the earth should feel a Coriolis force (with the exception of objects moving directly parallel to the axis of rotation of the earth).

As part of the pre-interview questions, the students were also asked how they would describe the shape of the earth. All six students who had taken Classical Mechanics mentioned that the earth was close to spherical, but that its radius at the equator was larger than the radius at the poles. While one student [F] did not go further, the remaining five students specified that the bulge arises due to the earth’s rotation. However, not one student mentioned this oblate shape of the earth when describing the Coriolis force. They were aware that both the equatorial bulge and the Coriolis force were caused by the spinning earth, and yet they saw no correlation between the two phenomena, despite them being inextricable in reality. These results seem to affirm the criticisms that have been levied against traditional Coriolis force instruction; these students left their classroom without a complete conceptual understanding of the Coriolis force.

Even though the Introductory Physics students had not yet taken the Classical Mechanics course, I asked them if they had encountered the terms “Coriolis force” or “Coriolis effect” in other circumstances. Three of the students had never come across the terms, which was not especially surprising; the Coriolis force isn’t standard watercooler conversation. Of the two that had, one [G] had recently taken an undergraduate weather class where the topic had been covered briefly, though not in any rigorous mathematical sense that would’ve been comparable to the coverage in Classical Mechanics. The other [J] did not specify where he was introduced to the phenomenon. However, when the students were asked to provide a summary of their understanding, both identified the rotation of the earth as the source of the Coriolis force:

> Gina: *As the earth spins, the equator spins faster than the poles and covers more distance, so it can affect how the atmosphere's wind patterns work and it can drag them in certain directions, depending on the hemisphere you're in… the top of the globe (the North Pole) doesn't move much distance as it spins, where the equator spins really far, so it pushes or pulls the wind on the equator faster.*
>
> Joshua: *Because the Earth is spinning, water is more likely to spin one direction in the Northern Hemisphere and the opposite direction in the Southern Hemisphere, like when it's draining down a hole... I think if you have any sort of spinning object, it will take more or less energy, depending on the direction it's spinning relative to the earth, maybe even hurricanes or something like that. So tropical storms will spin one way if they form in the Southern Hemisphere and the other way if they form in the Northern Hemisphere.*

While both mechanisms are ultimately incorrect, it is noteworthy that the spinning of the earth is cited as the primary link in the chain in both cases. This indicates that casual or non-mathematical explanations of the Coriolis force are also building an association between the rotation of the earth and the consequential phenomenon. Similar to the Classical Mechanics students, neither explanation mentioned the oblate shape of the earth as a participating factor, though the exact nature of the earth's shape was much less prevalent in the Introductory Physics group. Only one student [J] correctly described the shape of the earth as "bulging at the equator". Many students had a vague sense that the earth was not perfectly spherical, but they described it as being "thicker at the bottom" [D] or "egg shaped" due to "tidal forces" [G]. One student [K] said the earth only deviated from being spherical "in minute ways, like landmarks, hills, and valleys".

The emphasis that has been placed on the connection between the rotation of the earth and the Coriolis force in both formal and informal learning environments is advantageous; this connection is one that formal educators can and should capitalize on when creating their own educational strategies and material. However, even though a similarly useful connection between the earth's shape and the rotation of the earth appears to be commonplace, it appears that the relevance of the earth's shape in the Coriolis force has been entirely overlooked. With revised teaching methods and materials, these previously established connections could provide a scaffolding to support a conceptual approach to the Coriolis force which highlights the relevance of both the rotation and the shape of the earth.

Documenting Knowledge Elements

The primary purpose of this inquiry was to document the prior knowledge elements exhibited by undergraduate students as they attempt to understand the Coriolis force on a conceptual level. On a broad scale, the elements that were observed can be sorted into one of three categories: helpful elements activated within the correct context which should be reinforced, resources which may be helpful elsewhere but are activated beyond their relevant context, and unhelpful or disruptive activations which should be avoided or corrected.

I will begin by reporting on the helpful knowledge elements that I saw on display during the interviews, starting with the small-grain p-prims and moving up the ladder to the larger-grain knowledge structures. Afterwards, I will discuss specific areas in which elements were causing confusion or conflict; the incidents of misapplied resources and unhelpful activations tended to occur concurrently, so it will be easier to address them simultaneously according to the contexts in which they arose.

Upon reviewing the various knowledge elements utilized by the students throughout the interviews, I found no significant difference between those used by either group of students. The Classical Mechanics students had a more expansive and precise lexicon for describing their analysis and predictions, but the frequency and prevalence of any individual knowledge element showed no bias toward either group. I believe this is due to the conceptual approach being a sufficiently novel experience for all participants, regardless of prior instruction. Thus, I feel it is warranted to treat the participants as one group going forward as few other distinctions between groups will be worth mentioning.

The Balance/Imbalance P-prim Cluster

The p-prims which students use to understand the basic mechanisms of balance and equilibrium (as well as their opposites: imbalance and re-equilibration) have been well-studied and documented (diSessa, 1993). These p-prims are most commonly activated when students identify two agents attempting to achieve results which are mutually exclusive. In abstract battles such as these, there are two possible outcomes. The first is that the opposing desires of the warring agents will happen to negate each other entirely, *canceling* out any result. This leads to a state of *dynamic balance*, where neither agent's wishes are fulfilled despite their continued assertion. The second option is that one agent will overpower the other and achieve its goal against the behest of its opponent. This *overcoming* leads to a state of *dynamic imbalance* where the system is perturbed and will only *re-equilibrate* if the disparity is corrected. In either case, these p-prims are easiest to activate when an interaction can be abstracted as a pair of agents battling each other, as opposed to a single agent trying to surmount an apparently agentless obstacle (which may cue a p-prim called *blocking* which will be addressed later).

There were two key places in the conceptual approach where the students instinctively represented the phenomena as a pair of agents battling each other. Both occurred in thought experiment #4 as the students were pondering the mechanism responsible for the earth's oblate shape.

Northern Particles vs. Southern Particles

At the beginning of thought experiment #4, the students were asked to consider the consequences of the equatorial drift that was observed on the rotating spherical earth in thought experiment #3. They saw that the particles of matter that make up the Northern Hemisphere of the earth will have a desire to move south and cross over the equator as they attempt to travel along their natural path of a great circle. However, the particles in the Southern Hemisphere have the same desire, only mirrored across the equator. In this case, the symmetry of the particles helped the participants activate *canceling* to predict that neither set of particles would win out in the conflict:

> Jared: *What's going to happen in the middle where [the particles] meet up?*
> Hilda: *I imagine that they would bump into each other and just stay in that area.*
>
> Joshua: *If they can bump into each other, then that's going to balance things out. Because theoretically, for every particle in the Northern Hemisphere there's going to be a particle in the Southern Hemisphere that's going to be at an opposite trajectory.*
>
> Bailey: *The ones in the north start to head south, and the ones in the south start to head north, and they all collate towards the equator. And then, if all those particles are interacting with each other, they're gonna bump into each other... And so even though the great circle path takes it across both hemispheres, they get in the way of each other at the equator and probably cluster there.*

Upon arriving at this *dynamic balance* conclusion, all eleven students easily concluded that the opposing particles would pile up and create the equatorial bulge. The ease of this logical transition may have been due to the oblate shape already existing in their prior mental representations of the earth, meaning the students knew it must arise eventually. Had the *dynamic balance* proposed a more counterintuitive circumstance, it is unclear whether or not the students would have exhibited greater resistance.

Equatorial Drift vs. Bulge

From the perspective of any single particle on the rotating spherical earth as seen in thought experiments #2 and #3, there had been only one guiding agent that had governed their motion: the inertial tendency to follow a great circle, resulting in an apparent slide toward the equator according to Rachel. However, as soon as the perfectly spherical earth was allowed to bulge outward at the equator, a new agent with an antithetical desire was introduced: the ground itself. Where previously the earth had not stood in the way of the particles' motion, it now acted as an antagonist; the equatorial edge of the ground was "uphill", and so the ground would push anything on it "downhill" toward the poles. The lack of common origin between these agents gave the students a much stronger intuition that one of the tendencies would *overcome* the other:

> Hilda: *I feel like it's going to make it a little bit harder for [the particles] to drift towards the equator. I wouldn't say that it's going to stop them completely, because I don't think it would. I do think it would make it a little bit more difficult for them to get all the way into the southern equator.*

At this moment, the students were proposing a *dynamic imbalance* where the equatorial drift would still assert itself above the effects of the inadequate bulge. As such, the students predicted that the particles would continue to collect at the equator. Most students were able to foresee that this imbalance could not exist indefinitely:

> Jared: *As the equator bulges out, what does that do to the slope of the earth in the Northern Hemisphere?*
> Gina: *I guess that would make it an upward slope, upward against gravity. There's probably some point where the upward slope the bulge creates cancels out the puck trying to make a great circle.*

This is a timely activation of another p-prim called *Ohm's p-prim* which states that a greater action should achieve greater results (along with the corollary that a lesser action should achieve lesser results). As the students had correctly associated the strength of the bulge's deflection with the size, slope, or steepness of the bulge, they gathered that there must come a time where the bulge had grown enough that its influence would be on par with that of the equatorial drift (whose strength was proportional only to the rotational speed of the puck and independent of the size of the bulge):

> Jared: *Why doesn't it keep bulging out? Why does it reach a certain bulge and then stop?*
> Diane: *I'm not sure. It could be because particles only have so much force driving them north or south, and the middle of the equator reaches a certain density where that northern and southern pushing force isn't enough to compress the middle and push it out any further.*
>
> Ian: *There's going to be some component that's pulling it towards the north, from the gravity or from the normal force… These particles are traveling along the great circles, and then because of that extra component, it needs to bulge outward to keep things nice and tidy. The bulge will stop where that component is matched with gravity, I would say where it reaches some static equilibrium.*
>
> Bailey: *It's reached a point of equilibrium where things are balanced out. The bits of the earth, the fluid bits of this theoretical earth are no longer drifting up and down and all over the place, they've reached a point where they just sit. And that makes sense, because if they've reached that equilibrium, then there's no more forces pushing them further north or south, and so they stay stable.*

At that point, the students reactivated *dynamic balance* as the oblate shape of the earth *canceled* the desire to drift toward the equator. This new equilibrium attained at the end of thought experiment #4 provided an explanation for the causal mechanism behind the earth's oblate shape in the real world (the presence of which most of the students had been previously aware). Again, this fulfillment of expectations may have been partially responsible for the competency displayed by the students at manipulating the mental model to arrive at such a precarious balance.

This equilibrium was then perturbed in thought experiment #5 when the puck was kicked such that it was moving east according to Rachel. In this scenario, the bulge of the earth was fixed and so its effect was constant. However, by changing the rotation rate of the puck (it was now rotating to the east faster than the earth beneath it), the students activated *Ohm's p-prim* once again, this time associating the strength of the equatorial drift to the rotational speed of the puck:

> Kayla: *I'm wondering if the speed of the puck is greater than the speed of the earth's rotation, if it could break through and then add to the bulge. Like, if the speed can increase so much where it messes up the equilibrium?*
>
> Joshua: *[The puck] is going faster, so it has more energy to overcome the bulge than the rest of the particles on the planet do, and so that slope isn't going to deter it, that slope isn't enough to keep it stationary, like with the pullback from the poles and the push towards the equator.*
>
> Bailey: *It takes a certain amount of force to hold an object in a circular path... When [the puck] is stationary with the earth, we said it was balanced, that southern pull was balanced with the slightly tilted normal force from the ground pushing it back north a little bit. But if it's moving faster, then the normal force trying to keep it further north may not be enough to hold it in that tighter circle, keeping it from the equator. So, if it's not enough to counteract that, then it would start to drift south.*

These intuitions were mirrored when the students were asked about a puck kicked to the west according to Rachel (which would still be moving east, just slower than the ground beneath it). In this case, they activated *Ohm's p-prim* in an inverse fashion, predicting that the puck's slower rotation speed would decrease the strength of the equatorial drift, allowing the bulge to *overcome* the equatorial drift in this case:

> Jared: *Why would the puck move north instead of south this time?*
> Adam: *Because the bulge of the earth is exceeding the slope necessary to keep things from drifting southward, so that northward force is suddenly greater than the southward force from gravity. And so, it'd begin to drift northwards.*

In thought experiments #4 and #5, the students were asked to imagine a system that starts in imbalance, becomes balanced, and then is disturbed once again to arrive in a new, distinct imbalance. The students were remarkably adept at alternating between these complimentary p-prim clusters when prompted. This plasticity may have been enhanced by the relatively direct guidance of the semi-structured protocol and the prior knowledge relating to the shape of the real earth. If so, it would support the predictions made by KiP researchers who emphasize the importance of cueing to reinforce helpful activations and the importance of contextual connections with prior knowledge.

The strong prevalence of these balancing p-prims and the students' ability to fluidly activate, deactivate, and reactivate them according to new context are incredibly encouraging. The earth's equatorial bulge is the centerpiece of the conceptual approach; the first half of the method explains the necessity for its inclusion, while the last half investigates the consequences of its influence. It is integral to a complete understanding of the Coriolis force and has not been included in either traditional or alternative Coriolis instruction techniques. It is clear that the students have the intuition and prior knowledge necessary to understand the bulging phenomenon on a fundamental level, not only acknowledging that it occurs but also how it impacts the motion of objects across the surface of the earth.

Bulging as a Phenomenological Primitive

Of the eleven students interviewed, ten had already been taught that the earth is slightly oblate, and eight of those mentioned that this was a consequence of the earth's rotation. Looking closer at these explanations, I noticed that the students who had taken Classical Mechanics provided detailed deconstructions involving "centripetal forces" [B], "rotation and inertia" [E], and "the centrifugal force" [A]; this was not remarkable as the centrifugal force is another inertial force discussed in the Classical Mechanics curriculum alongside the Coriolis force. In contrast, when the students who had only taken Introductory Physics offered a reason for the shape, the rotation was used as a self-evident description that required no further dissection:

> Joshua: *It's not a perfect sphere. I know that because of the earth's spin, it bulges a little bit at the equator, but it's still very spherical.*
>
> Hilda: *Based on stuff that I've seen (like pottery wheels), usually when something is spinning around, no matter how fast, things tend to make an almost diamond shape… there's a point that most of the clay starts to gather just based on how it's spinning.*

Later, when asked to predict how the shape of the earth would be affected if the earth were to rotate faster or slower, all eleven students (even those who had not previously mentioned the oblate shape of the earth or the rotation as a cause) intuitively answered that the earth would bulge more or return to a more spherical shape respectively. These responses were given quickly and confidently, as if the answer should be obvious.

Together, these two observations led me to wonder if the students might be drawing upon some naive sense or rule that spinning objects are "supposed to" bulge outward. This intuition seemed at first glance to match many of the expected properties of a phenomenological primitive (diSessa, 1993). I gave this intuitive knowledge element the preliminary name "*bulging*" and took a closer look at how it compared to descriptions of p-prims:

1. Elements: Since all of the students interviewed had received some form of formal physics instructions, it is impossible to state with certainty the grain size of the *bulging* primitive. That being said, I believe that the contrast between the two student groups suggests a knowledge element that is at least somewhat basal: the students with the least instruction were the only ones who offered spinning as a de facto mechanism for the shape of spinning objects and the perceived outward force. This may indicate a "principle of obviousness" and/or "principle of

impenetrability" (diSessa, 1993) which existed in the naive learners and was refined into a more formal understanding of the centrifugal force during the Classical Mechanics course. To be sure, younger and more naive participants would need to be examined to see if the *bulging* primitive preceded formal physics instruction.

2. Cognitive Mechanism: P-prims tend to be abstract concepts that have no specific tie to the superficial or immediately observable structure of a phenomenon. When the students mentioned *bulging*, they did so in multiple scenarios. In most cases, the spinning object was either the earth or themselves, but some students brought up pizza dough [G], pottery wheels [H] and water balloons [K] as other objects that exhibit the same behavior. This shows that the *bulging* primitive was not associated with any particular physical object or material property, but rather with the abstractions of "rotating" or "turning". It would be necessary to investigate if *bulging* occurs consistently through a wider range of circumstances which involve these same abstractions, but I am confident that the pattern observed here would persist.
3. Development: One principle for identifying p-prims is the "principle of body" (diSessa, 1993), which predicts that p-prims will likely have strong roots in physiological experience and will be justified by novices using their bodily sensations as evidence. Within this study in particular, students cited cars [G], buses [B], and carnival rides [J] as places where they had personally experienced this outward pull. I suspect that the physical sensations of *bulging* would not be merely limited to locomotion; on the most basic level, you merely

have to spin in a circle to feel your arms rise away from your torso.[6] I would also expect that similar personal narratives would be found regarding swinging or throwing small objects like baseball bats or buckets. The ubiquity of these experiences could fulfill the “principle of unproblematic genesis”, showing a common root for the intuitive understanding of bulging. Similarly, these early origins may fulfill the “principle of functionality” as the bulging primitive would help young learners anticipate and respond to the relevant scenarios.

4. Systematicity: As stated earlier, each student interviewed intuitively predicted that an object spinning faster would experience more *bulging*, while an object spinning slower would experience less. This result indicates a very strong cueing priority between the *bulging* primitive and *Ohm's p-prim*. It has also been previously documented that students explaining circular motion in orbits will claim that the orbiting body is trapped in place by the opposing forces of gravity and the outward centrifugal force (diSessa, 1993). This was interpreted as an activation of the *clamping* p-prim to reach *dynamic balance*, but it may also indicate the primitive nature of the centrifugal force itself and might suggest a connection between *clamping* and *bulging* within the context of orbits.

Overall, it appears that the *bulging* primitive might be a good candidate for a phenomenological primitive, but it would ultimately require more targeted scrutiny than this study was able to provide to be conclusive. If the *bulging* primitive is shown to be consistent and pervasive, it may shed light on the difficulties that many educators have experienced when teaching about the centrifugal force and rotational motion in general.

[6] At first, this may seem more like a “lift” than a “bulge”, but anyone who has spun in a circle with their arms raised above their head will have felt an equally mysterious force tugging downward on their arms, as if the natural state for your spinning arms is directly outward.

The internal conflict that students have when trying to resolve their formative intuitions about the centrifugal force and their proper physics instruction was voiced by one student during the study:

> Joshua: *This is something that did confuse me in physics because we talked about how the centrifugal force is illusionary, it's not a real force. But then, where is it coming from? Why do I feel it? When I'm put in a carnival ride, why do I feel it? Or when I swing a bucket of water around, how does the water stay in? I get conceptually the idea that the velocity is in one direction, so if I'm swinging the water up, the momentum of the water, the velocity of the water is going to be tangent to the circle I'm making, but then the path of the bucket curves and that catches the water, same thing with the carnival ride. But on an object that's just floating in space, that's a bit harder for me to understand, because then it does seem like there would be some sort of force pushing it out.*

Demonstrating the primitivity of *bulging* could provide a means for improving centrifugal force instruction: instead of fighting against the primitive by labeling the centrifugal force as “imaginary” or “illusory” (which implies that the students are incorrect in their own perception and memory), educators could instead acknowledge and reinforce the bodily experience of students. The *bulging* primitive could then be situated within a more refined context by cueing knowledge elements or structures from the domains of reference frames and perspective to demonstrate the contextual uniqueness and intrigue of inertial forces.

Instructional Landmarks

According to Knowledge in Pieces, knowledge is a complex structure of interconnected elements; P-prims form the foundation of this as the smallest grain size knowledge element possible. Novices tend to have scattered, arbitrary, reflexive structures, whereas experts have refined the connections to create a reliable, meticulous, consistent network. The stages that lie between the novice and expert are of great importance, and the participants of this study were situated at an important middle stage: they had received an initial amount of formal physics instruction, but they still needed significantly more practice before they could be considered experts. In this transitory stage, we would expect to see the first precursors of large-scale expert knowledge systems beginning to emerge.

Throughout the interviews, I noticed a common heuristic pattern in the way the students interacted with several intermediate physics concepts. As will be shown, these structures appeared to have strong roots within the students' formal education, and their primary function seemed to be orienting the students within a conceptual landscape during problem solving. I named these structures "instructional landmarks" and began documenting their common traits:

1. Central Node: Instructional landmarks have a focal point that is a common physics term, phrase, or rule. The highlighted term is one that would have little importance to a lay person but is instantly recognizable to anyone with an introductory level of physics education. This demonstrates that instructional landmarks are not intuitive knowledge elements, but rather are constructed in the same environment where novice physics learners are introduced to proper physics jargon.
2. Loose Organization: Concepts, rules, or terms which share a contextual association to the central node are cued when learners activate the instructional landmark. The strength of the cuing is proportional to the frequency at which the associated concept was relevant to problem solving involving the central node during physics instruction. The connections surrounding the central node are still unrefined; students may mistakenly use the wrong associated term when

describing the parameters of the central node even when their understanding of the central node is correct.

3. Authoritative: Instructional landmarks form around central nodes which were taught in an axiomatic manner: within a specific context, the rules imposed by the central node are assumed to be unquestionable and of the highest priority. Due to this assertion, students grant these structures an enormous amount of trust, rarely questioning their presuppositions. The reliable nature of the central node also gives students a tool to achieve a higher degree of credibility than they may be used to; students cite the central node as they discuss relevant problems and propose solutions to demonstrate the validity of their arguments. Oftentimes, they will do so confidently, definitively, and repetitively.
4. Orientation: When exploring the cognitive space around an instructional landmark, students will use the central node to orient themselves as they attempt to determine the range of acceptable solutions and weed out irrelevant or unsatisfactory ideas. Before brainstorming, students will try to verify that the problem space is within the contextual boundaries which pertain to the central node. Once confirmed, they branch outwards from the central node, working through related concepts while maintaining their view of the central node; they may reiterate the central node during the cognitive exploration to assure it has not been neglected. If the students get lost or become unsure, they will try to reestablish their view of the central node before continuing.
5. Conflict Resolution: As the students arrive at potential solutions, they will measure the proposals against the central node to determine if the suggested answers are acceptable; in cases where multiple instructional landmarks are relevant, the rules of all visible central nodes will be applied. If the solutions

> disagree with the postulates of any relevant central node, they must be relinquished (even if the solution is supported by the students' intuition). When multiple ideas clash, preference will be given to whichever best aligns with the nearby landmarks. If the students fail to discover a solution which meets these requirements, they will abandon the search rather than suggest an answer which knowingly conflicts with the central node.

As can be expected, some of the landmarks observed in this study exhibited certain traits more strongly than others, and in some cases did not exhibit a trait at all (though this was usually due to the interviews not providing an opportunity for the trait to be seen). During my observations, I noted three distinct instructional landmarks built around the central nodes of isolated systems, frictionless environments, and the law of Inertia.

The Isolated Systems Landmark

At the beginning of the interview, the students were asked to give a brief summary of some of the conservation laws that were covered in the Introductory Physics course. Each student was able to give a basic explanation of the conservation of energy and the conservation of angular momentum, and six students mentioned that these laws would only apply to a closed or isolated system (without such language being prompted or cued by the interviewer):

> Jared: *Would you be able to give a brief description of the conservation of energy?*
> Diane: *Let's see if I can remember all the little caveats. I would say in a closed system, all energy is conserved.*

This strong association between conservation problems and isolated systems is a valid connection taught in traditional introductory physics instruction. What was most interesting was the frequency at which the hallmark phrases and terms arose during some students' answers:

> Ethan: *Conservation of energy is like, in a closed system, energy isn't spontaneously created or destroyed, it's only transformed into different forms of energy... as something falls in potential energy, it gets kinetic energy and thus the system is equal in the amount of energy it had...Angular momentum is just like energy, it's conserved… some outside force needs to interact with an object for it to change, just how the earth will remain at the same angular momentum until an outside force acts on it... even with subatomic particles, its angular momentum is always constant, unless acted upon by something else.*

> Jared: *...How well do you understand the conservation of angular momentum?*
> Bailey: *Relatively well… In a closed system, angular momentum is conserved, so if something is rotating and either the radius of that rotation changes or the direction somehow changes (where its angular velocity vector is now pointed in a different direction), then something else about the system will change to conserve that angular momentum.*

This repetitiveness highlights the importance of the isolation landmark in the minds of the students when the conservation laws are brought up. This connection was likely hammered into them by their instructors and now acts as a contextual signal to cue one subject when the other is mentioned. However, the conservation laws weren't the only landscape where the relevance of isolation came up; one student attempted to use the isolation landmark when discussing inertial reference frames:

> Jared: *Do you remember what [inertial reference frame] means?*
> Hilda: *It means that you're observing what happens in a system from outside the system and following it around, right?*

The strength of the isolation landmark's connection to conservation made this reference intriguing. Due to the heavy contextual association, I had been suspicious that the landmark's central node may actually be conservation itself, with isolation instead being a correlated landscape. This association to reference frames prompted me to ultimately side with isolation as the landmark, though more rigorous study of this particular landmark (in the context of work or entropy, perhaps) could shed more light on its structure and support a renaming. Unfortunately, I was unable to gather enough data over the course of the study to confidently resolve the issue, primarily because the conceptual approach does not incorporate scenarios in which the isolated system of the earth is intruded upon by outside forces. Without those conflicts, there was no reason for the students to utilize the landmark beyond its initial declaration within our limited discussion. Further study would be necessary to confidently identify the internal structure of this landmark, explore other contexts in which the landmark might be cued, and determine the manner in which students rely upon it during conceptual problem solving.

The Frictionless Environments Landmark

As is the case in many thought experiments, the conceptual approach asked the students to disregard friction for the duration of the interview.[7] This idealization is one that the students showed a great deal of familiarity with, to no surprise; frictionless idealizations are a staple of introductory physics problems. Unlike the isolation landmark, the frictionless landmark didn't show any strong connections to other concepts. This may have resulted from the frictionless status of the environment being overtly assigned by the instructor, rather than being cued from context or proposed by the students independently. Likewise, the extent of the inherent trust placed in the frictionless landmark was difficult to ascertain due to the rule being an imposition from the instructor (which placed it beyond dispute). Despite these difficulties, the frictionless landmark

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[7] The purpose for this neglect is to allow the puck to move large distances across the surface of the earth without stopping so that the long-term effects of the Coriolis force could be seen.

appeared to play an incredibly important role in the students' conceptual decision making. One way this manifested was when the students repeatedly checked in to verify that the landmark was still applicable during our thought experiments:

> Bailey: *Over a long enough period of time, it would basically form a perfect circle, with the earth being perfectly spherical. You said it's frictionless, right?*
> Jared: *Correct.*
> Bailey: *Yeah. Then it would continue to slide in whatever direction all the way around the earth forming a circular path, because there would be nothing to divert in any other direction.*
>
> Jared: *How would Isaac describe the puck's motion over a long period of time?*
> Caleb: *Is there a frictional force?*
> Jared: *All these thought experiments will be neglecting friction.*
> Caleb: *Friction and air resistance? Okay.*

Another indication of the importance of the landmark was the way students would precede their responses by reiterating the assumptive clause:

> Jared: *How would Isaac describe the path of the puck over a long period of time?*
> Joshua: *With the planet being frictionless, the rotation underneath shouldn't matter, so it should still make a great circle.*
>
> Jared: *Would the puck go all the way around the earth?*
> Diane: *Because there's no friction, there's not gonna be a force that inhibits the motion of the puck, so it should just keep going.*
>
> Jared: *How would Isaac describe the motion of the puck over a long period of time?*
> Felix: *Well, if it was completely frictionless, it would just continue at that same initial velocity forever in whatever direction he kicked it.*

These conditional clauses demonstrate how students can utilize the authority of the frictionless landmark for their own benefit: they reiterate the landmark to emphasize that their answer agrees with the rules established by the landmark, giving their answer additional credibility. Another expression of the students taking advantage of the frictionless landmark was seen when one student proposed two mutually exclusive answers to a question (one considering friction and one neglecting it) with the implication that the ‘correct’ answer would depend on the relevance of the landmark:

> Jared: *If we marked the ground with an X underneath where we placed the puck, would the puck stay on the X?*
> Caleb: *It wouldn't if there's no friction. If there was friction, it would be, say, ‘glued’ to the ground, and it would be moving with the earth.*

Where the frictionless landmark really excelled was in its ability to resolve internal cognitive conflicts; as the students were working through the thought experiments and stating their predictions, there were several instances of students immediately walking back their predictions as soon as they realized that the answers would be incongruent with the frictionless landmark:

> Jared: *Why would the puck be moving with the earth if Isaac wasn't?*
> Caleb: *Because the earth is rotating, or at least from Isaac's point of view, he's not moving at all, but their earth is and because the puck is on the earth... Actually, if we're still negating friction, I would say the puck still is in the same stationary spot.*

> Gina: *I think it would look like it was curving to the right, because the earth is spinning and pulling it that way...*
> Jared: *You said that earth would be pulling it? What do you mean by that, could you clarify?*
> Gina: *Since the earth is spinning… is the earth still frictionless?*
> Jared: *Yes, the earth is still frictionless*
> Gina: *Well, I'm not sure if it would work that way then. If there was zero friction, maybe it would ignore the spinning globe beneath it and it would just go straight. But I'm not totally sure about that.*

> Jared: *When Isaac releases the puck, what happens?*
> Felix: *Because the earth is spinning… is it still frictionless?*
> Jared: *Yes.*
> Felix: *...The puck should stay at the same place on the earth, but it would be spinning from where Isaac is seeing it.*
> Jared: *...If we placed an X on the ground where Isaac placed the puck, would the puck stay on the X?*
> Felix: *My first thought is yes. Actually, if it’s frictionless, it probably would move off the X.*

These real-time corrections exemplify one of the primary uses of instructional landmarks for intermediate students: because the rules and parameters associated with each landmark can be reliably assumed by the students to be true within the declared conceptual space, they can serve as a litmus test for detecting flawed ideas or uncovering contradictions. Interestingly, the frictionless landmark encompasses a ruleset that technically does not translate to the real world, but the usefulness of instructional landmarks does not seem to depend on their objective truth. Rather, their usefulness is specific to the context in which they can be “seen” and treated as axiomatic. If this context is a purely idealized space that does not exist in reality (as is the case with frictionless environments in introductory physics), the landmark can still be treated as reliable within that space. The students appeared to have a great deal of experience navigating using the frictionless landmark, and I have no doubt that the Introductory Physics curriculum in particular would provide a plethora of data for researching students’ relationship to the frictionless landmark further.

The Inertia Landmark

The conceptual approach repeatedly asked the students to predict the motion of pucks that were either released from rest or kicked, and these predictions allowed the students to display their intuitive sense for how objects respond to pushes (or a lack thereof). Each time they were prompted, the students unanimously activated a p-prim called *force as a mover* (diSessa, 1993) to predict that the pucks would move in the direction of the push; conversely, when there was no perceived push, the students usually proposed that the puck would remain stationary:

> Jared: *What direction do you think it would move?*
> Diane: *In whatever direction that he gives it momentum.*
> Jared: *If Isaac didn't give it any push and just released it without pushing it in a direction, what would happen to the puck?*

Diane: *He didn't apply a force, so it's not gonna move.*

Similarly, when the orthogonal influence of the Coriolis force was introduced later in the conceptual approach, each student activated the p-prim of *deflection* to predict how the puck would move when acted upon by a force that was perpendicular to its current direction of motion:

Jared: *How would Isaac describe the path of the puck?*
Gina: *I think it would look like it was going in the direction he was kicking it, but it would have a curved path because the spinning of the earth is pulling it one way, which kind of curves its trajectory.*

The frequency of these activations was not surprising; the students had spent a significant amount of time solving kinetics problems in the introductory classes which require a thorough understanding of how forces (in the direction of motion or otherwise) influence the behavior of a moving object. On a larger scale, though, the combination of the *force as a mover* and *deflection* p-prims, along with the inverse assumptions that a lack of forces will result in a lack of change in motion, seemed to form a larger structure that provided a set of rules for motion in the presence or absence of forces. This landmark acts as a conceptual combination of Newton's first and second laws of motion: it predicts that objects will remain in a constant state of motion unless acted upon, and that the direction of the action will influence the direction of the change in the state of motion. I refer to this structure as the "inertia landmark", although the central node of this landmark had a far weaker association with proper terminology than any other observed landmark. In fact, across all eleven students, not one used the word "inertia" when predicting the motions of the released and kicked pucks in thought experiments #1 and #2 (even though they were unquestionably using the concept to inform their predictions). Despite the weaker jargon, the landmark still proved decisively useful: it reminded the students to habitually identify and consider the forces acting on the puck before they attempted to anticipate its movement. The students tended to vocalize which forces were (or weren't) relevant to the question as they started to formulate their predictions:

Jared: *Why doesn't the puck move with the earth?*
Ethan: *If the surface is frictionless, then there's no force that is changing where the puck is, other than gravity and the normal force once again. So now, it's only the two forces, actually.*

Jared: *What would happen to the puck?*
Joshua: *The puck would stay stationary where he left it on the surface, unless there was some sort of force that he didn't intend to put on it because it is a frictionless surface. So, if there was some amount of force, it would move in that direction probably, and because of gravity it would move just along the surface of the planet.*

Caleb: *The puck will be pulled towards the center of mass on the earth, but there'll be a perpendicular normal force keeping the puck on the surface, so it wouldn't move.*

Jared: *How would Isaac describe the path of the puck over a long period of time?*
Kayla: *So... the earth is perfectly spherical and it's frictionless, so you would continue in like a balanced pathway. We just continue at the same speed, which is the same initial velocity that he kicked it with, and continue around the surface of the earth… it would eventually come back to where he was.*

Jared: *If Isaac kicked the puck in a random direction, where would it go?*
Adam: *It would slide along the surface of the sphere in the arc of a great circle and pass through the same again because there's no friction, so there's no other force.*

Jared: *Isaac reaches down and places the puck on the surface of the earth and releases it from rest. What happens to the puck?*
Ian: *…I'd say it just traces out one of the latitudes wherever it was placed, because there's no force to keep in specifically at that spot, but that's what my brain would say it does. There's just gravity pointing down, there's no friction keeping it in place… technically according to Isaac, it would stay in the same spot, but if you were on the earth like the fixed observer, it would look like it's sliding along that latitude because the puck wants to stay at rest, but the earth is rotating underneath it.*

Even though the word "inertia" wasn't being offered as a part of these propositions, it was clear that the students had formed a habit of enumerating forces as a preliminary step when predicting motion during their Introductory Physics education. What's more, this structure then appears to have been refined further in the students who took the Classical Mechanics course: three of the Classical Mechanics students mentioned the term "inertia" when the tangential issue of centrifugal forces came up in their discussions:

> Bailey: *Growing up, we were on a bus ride, and as the bus turns, you get pulled towards the outer edge of the turn. And really, that's just the effect of inertia, your body trying to continue a straight path, but the object is moving. And we would call that the centrifugal force... that's not technically a real force, because really, it's just inertia is trying to keep us along this path, but the objects around us are moving.*
>
> Adam: *As the earth is rotating, the inertia of each particle is going to be changing, because if you were to let go of a piece, it would just go off in a straight line. So, the tendency is for those bits to pull out of the earth a little bit. And the parts of the earth which are going faster (namely those of the equator) have a greater inward acceleration, so that's a greater inertial effect.*
>
> Ethan: *When an object turns or makes a change in its direction of velocity, things about that object experience a force from its changing direction. It's not necessarily a force that is caused by anything other than just the inertia of an object wanting to stay in motion at the same rate.*

Interestingly, the mentioning of inertia seen here activates the same landmark as before: in the context of moving objects, the students recognize that a state of motion will remain unchanged according to the inertial observer unless acted upon by a recognizable agent. Here, the strong contextual association of inertia with the centrifugal force (which is covered in the Classical Mechanics course but not Introductory Physics) demonstrates that the connection has been reinforced and developed further during the advanced instruction; the same conceptual framework that applied in kinetics is now relevant once again in the new territory of inertial forces. To put it another way, the conceptual landscape from which the inertia landmark was visible had been increased as a direct result of instruction. This is a prime example of the continuous nature of knowledge as it is refined from a naive state to expertise: existing knowledge elements and structures are repurposed and expanded to facilitate complex understanding and enable more advanced problem-solving.

It appears that all three landmarks have a strong central conceptual node, though the association of that node to specific terminology or neighboring concepts varies. The landmarks display a wide range of connections which vary in specificity from broader physics topics to specific problem-solving scenarios; this interconnectivity supports a strong possibility of cueing as a reliable method of utilization for both students and instructors. The connections displayed by all three landmarks bear a significant resemblance to traditional instruction methods, suggesting that these structures rely highly on student-teacher interactions to shape and refine. These landmarks occupy an elevated status in the students' minds, where they are given priority over other intuitive or instinctual knowledge. Once built, the landmarks serve the students during conceptual problem solving, providing a yardstick with which the students can measure possible solutions, eliminate erroneous suggestions, or differentiate among competing hypotheses.

Given the similarity in traits between the trends documented here, I believe that the framework of "instructional landmarks" could provide education researchers with an interesting perspective from which we can deconstruct and analyze intermediate students' knowledge structures. The three landmarks chronicled here are merely those which pertained to discussions about the Coriolis force and as such are not at all a comprehensive list. I would expect to find similar landmarks on conceptual nodes throughout physics. The nodes will most likely be those which have high experimental confirmation (which results in axiomatic teaching) or wide-reaching conceptual utility (such as idealizations or simplifications). The high degree to which context determines activation will mean that instructional landmarks will most easily be identified by examining students' cognitive decision-making within specific conceptual neighborhoods. Instructional landmarks should also develop into more refined models as the students pursue deeper and more complex guidance from physics experts throughout their formal education (and perhaps even beyond). Ultimately, these instructional landmarks could prove to be a precursor to larger, more systematized structures that provide support and context in complex problem solving. As with many postulates of KiP research, the best method for determining the accuracy and usefulness of instructional landmarks as a theory will be to take a leap of faith and see if the framework yields reliable and repeatable conclusions when applied to the breadth of physics education (diSessa, 1993).

Areas of Conflict

So far, we have seen the variety and complexity of the intuitive knowledge elements and structure which the students used to support their reasoning and make predictions about the Coriolis force. The students were mostly successful at navigating the conceptual hurdles of the conceptual approach, but there were places where they experienced some difficulty. These areas tend to be unique and nuanced, and each deserves its own exploration. Some areas involved the untimely activation of p-prims, while others arose from the proximity of neighboring concepts and the blurry delineation between them. As I address each area of concern, I will provide my theories on where these incongruities may have originated and strategies for pre-empting or resolving them. It should be noted that these theories are my own conjecture and will need continued investigation to understand completely. At this time, my intent is primarily to document my observations and secondarily to provide commentary which may inform future discussions.

Friction and Clamping

In thought experiment #2, the students were asked to predict what would happen when Isaac released a puck from rest on the surface of a rotating spherical earth. Six students initially answered incorrectly that the puck would begin moving with the earth as soon as it was released:

> Jared: *When we had the earth that was not rotating, when Isaac placed a puck on the surface, what did we say would happen?*
> Felix: *It would stay still. And so, it wouldn't be rotating or anything.*
> Jared: *...If we repeat the same action, but this time the earth is rotating, would the rotation of the earth affect the puck?*
> Felix: *It would.*
> Jared: *And how would it affect the puck?*
> Felix: *The puck would stay on the X... but it would be rotating while the earth was rotating, just at the same angular velocity.*
>
> Jared: *When Isaac released the puck from rest, was the puck moving from Isaac's perspective?*
> Joshua: *From his perspective, yes. Right?*
> Jared: *Why was it moving?*
> Joshua: *Because the planet it's on is rotating. So, in the first case, he puts the puck down and it stays stationary. Then in this case, it would stay stationary relative to the planet, but the planet is rotating, so from Isaac's perspective (where he's still relative to the stars), he would see that the rotation and the puck's rotation become the same.*
>
> Jared: *Isaac is going to reach down, place a puck on the surface of the earth, and let go. What happens to the puck?*
> *Hilda: From Isaac's perspective, the puck is going to start moving from the left to the right in circular motion around the earth. But from the puck's perspective, it's going to be in the same place, right?*

This tendency to assume that objects in contact with each other will move together is fairly predictable. The real world is full of phenomena which demonstrate this principle: a book resting on a table will come with you if you drag the table across the room, toys placed in a wagon can be toted along even if they are not touching the walls of the wagon, and anyone unfortunate enough to have stepped onto a treadmill already at speed will discover how quickly relative motion can be transferred between contacting surfaces. These interactions are all caused by the friction between the two touching surfaces, and students should not be chastised for reflexively making the same assumption. This phenomenological observation is so pervasive, some students may even note that they have experienced it themselves:

> Gina: *It's kind of like when you're in a car: you and the car are both moving, but when you're inside the car it feels like you're not moving because you're both moving at the same time. So, it would stay on the X, because they're both moving through space together.*

It is possible that this is indicative of an untimely activation of a constraint p-prim called *clamping*, though that particular p-prim usually involves an object sandwiched between two surfaces. In these cases, the abstraction appeared to be more of a “stickiness” which one student clarified had arisen from their assumptions in the prior thought experiment:

> Jared: *You originally had said it'll stay on the same point on the earth and rotate with it.*
> Joshua: *...I think it's more of a carryover of the direction I went in the first thought experiment, where it's like, ‘If there's any little tiny force that he accidentally puts into it, then it's going to move in that direction.’ So, when you said, ‘Let's say that he's careful enough’ my brain switched to ‘Okay, so it's going to stick to the earth.’ And so, then that carried over to the next experiment.*

When the students provided these responses in the conceptual approach, they had most likely just forgotten about the frictionless idealization or had not yet realized the consequence of such an idealization. As seen in the quotations provided earlier when discussing the frictionless landmark, several students realized the error midway through the discussion without any prompting and corrected their own responses. In the cases where the students did not recognize the discrepancy themselves, cueing from the interviewer had the same corrective effect:

> Jared: *Why does the puck start moving?*
> Hilda: *Well, because the earth's axis looks like it is moving to Isaac. So, any point on the earth is going to look like it's moving from the perspective of Isaac.*
> Jared: *Now, when Isaac placed the puck on the earth, he let go and didn't push the puck in any direction. So, if this earth is frictionless, will the puck slide with the earth?*
> Hilda: *It will not, you're right! Since it doesn't have the force of friction, it'll just stay in the same spot as the earth rotates under it.*
>
> Jared: *When Isaac reached down and placed the puck on the earth and let go, did Isaac push the puck in any direction?*
> Kayla: *No.*
> Jared: *At that moment, was the puck moving? Was the puck rotating with the earth?*
> Kayla: *I think the moment he lets it go, it assumes the same velocity and motion as the earth because it's now in contact with it.*
> Jared: *If the puck is in contact with the earth, but there's no friction, can the earth get the puck to start moving?*
> Kayla: *No, no, I don't think so. So no, the puck is not moving.*

In this context, it was also important to recognize that the puck was not initially moving: the frictionless landmark explains why the puck would not gain motion from an idle state, but the student would need to acknowledge the idle state to begin with. For a few students, a cue from the interviewer to consider the puck's initial lack of motion was enough for them to reconsider their responses:

> Jared: *Was Isaac moving with the earth?*
> Gina: *I guess he wasn't. Okay, so if Isaac never got any of the same direction as the earth did, the earth is moving towards the right, you put the puck down, it would look like he was going to the left.*
> Jared: *From Isaac's perspective, does the puck look like it's moving?*
> Gina: *I don't think so. It probably looks like the sphere is moving underneath the puck.*
>
> Jared: *I should clarify, when Isaac is releasing the puck from rest, I mean that Isaac is releasing the puck from rest in his perspective…*
> Joshua: *Oh, so in that case, because the planet doesn't have friction, the puck would just glide along the surface. It wouldn't move relative to Isaac's*

> *perspective, but that's only because the planet is frictionless, but the planet would continue to move.*

This conflict is one that fortunately appears to be easily rectified by reinforcing the frictionless environment or the initial lack of motion. A stronger emphasis of this idealization at the beginning could preempt some of the confusion.

The Earth's Bulge and Blocking

Previously, I reported on the many equilibrium p-prims that students activated when working through the balancing of the equatorial drift and the earth's bulge in thought experiment #4. In some cases, the students had difficulty reasoning through the following step proposed in thought experiment #5 in which the bulge is fixed and the puck is given either a greater or lesser rotational speed (such that it is moving east or west according to Rachel). In these cases, some students correctly identified that the strength of the equatorial drift would change in size, but incorrectly concluded that the puck would situate itself at a new equilibrium state:

> Hilda: *Eventually, there will come a point that the earth will have bulged enough that it's nearly impossible for the Northern Hemisphere particles to get into the Southern Hemisphere. So even if they do rotate down just a little bit, they won't quite get into the Southern Hemisphere. Same with the southern particles into the northern one.*
>
> Jared: *What will that tilt do to the path of the puck if it is now too sloped?*
> Caleb: *If it's too sloped, then the puck wouldn't have enough kinetic energy to overcome that slope, so it'll have the same path that it started out.*
>
> Joshua: *I guess either it would hit some sort of equilibrium before it gets to the equator, or I would imagine... I guess it also depends on how fast he kicked it. But it would either go back to circular rotation with no southern or northern element once it hits the equator, or if we hit it very fast then it would continue to bounce between the poles.*

The students were envisioning the equatorial bulge like a wall that needed to be climbed over, and even when the puck's desire to move south was increased, it could fail to climb the wall if the increase was insufficient. In their mind, the equilibrium established at the end of thought experiment #4 could be likened to a ball resting at the bottom of a bowl; if the ball was pushed one way or the other, it may attempt to leave the bowl but would ultimately be unable to do so unless the push was strong enough.

This shift in perspective can be seen as an activation of the p-prim *blocking* (diSessa, 1993), where one agent's actions are halted by an insurmountable obstacle. *Blocking* differs from the *dynamic imbalance* p-prim discussed earlier in two key ways:

1. One Agent: Instead of envisioning two actors at odds with each other, *blocking* tends to occur when one side of the imbalance seems to have no agency (in this case, the bulge). It is often described as pushing against a wall: you may push harder or softer, but the wall's resolve is fixed and unchanging. The wall is not personified in the same manner as the actor and thus exhibits a different behavior.
2. Overcoming Requires a Threshold: In a true *dynamic imbalance* scenario, even a small discrepancy in the strengths of the agents will cause one to usurp the other (like adding one more participant to a team during a tug-of-war). However, *blocking* occurs when the obstacle is given a discrete size which will impede small actions but lose to large ones. The obstacle is conceptualized more like a hurdle: you either jump high enough to clear it, or you don't. Effort that does not meet the criteria will result in failure.

By understanding the differences between these p-prims, we can outline how to best avoid the aberrant activation of *blocking* during the conceptual approach. The first strategy would be to emphasize the opposition of the equatorial drift and the bulge as a pair of actors with antithetical goals. This means that the equilibrium at the end of thought experiment #4 is not caused by a forfeiture or a removal of opposition; the two agents are continuously fighting in order for objects to remain stationary in the rotating reference frame. This duality also highlights the precarious nature of the equilibrium: the two forces have matched each other exactly, so if either agent were to gain even a small amount of strength, the balance would be disturbed, and the stronger actor would begin to *overcome* the weaker actor.

Additionally, a reinforcement of *Ohm's p-prim* regarding the factors which contribute to the strength of each agent may help the students reach the proper conclusion. Both the equatorial drift and the bulge have strengths which are proportional to rotation, but the subtlety lies in the rotation to which they are proportional: the equatorial drift's strength depends on the rotation rate of the individual particle, puck, or object that is in motion, whereas the bulge's size and strength depend on the rotation rate of the planet as a whole. When initially asked what would happen to the equatorial bulge if the earth were to rotate faster or slower, all eleven students correctly responded that the bulge would increase or decrease respectively. This application of *Ohm's p-prim* was so easily and intuitively understood by the students, I would expect that applying it to the equatorial drift and the rotational motion of the object would be co-opted equally as well. Thus, when an object rotates at the same rate as the planet, the two competing effects have the same strength and achieve dynamic balance resulting in the object remaining in place on the surface. But, if the object begins to rotate faster or slower than the earth, the strength of the equatorial drift will react accordingly while the strength of the bulge remains exactly the same. These drives will remain imbalanced for as long as the rotation rates of the object and the planet do not match, and so the *dynamic imbalance* will persist and the stronger force will achieve its desired result until that equilibrium is reestablished. Framing the interaction in these terms should help students avoid the erroneous idea that the unbalanced forces will push the puck to a new latitude before mysteriously rebalancing and creating a new equilibrium location.

Latitudes and Great Circles

When considering the path of a kicked puck as viewed by Isaac, the students had very little trouble understanding that it would form a great circle regardless of the frictionless, spherical earth's rotation. In thought experiment #1, ten of the eleven students correctly predicted the great circle path for the kicked puck, with the lone student [C] saying that it would follow a great circle if it was kicked north or south, but not if it was kicked east or west (an indicator of issues to come). In thought experiment #2, nine students asserted that the kicked puck would again follow a great circle even though the earth was now rotating. As for the dissenters, one simply said they were not sure [C], while the other [D] was fairly close in saying the puck's path would trace out an "orange slice" on the earth with respect to the equator (but admitted they were not sure what would happen when the puck reached the equator).

This consensus waivered noticeably when the students were asked to consider Rachel's perspective in thought experiment #3 when the puck was kicked directly east at the same speed as the ground beneath it. Despite the properties of the kicked puck and the hypothetical earth remaining the same, only seven students maintained their argument that the puck would travel in a great circle. The remaining four students answered that the puck would instead continue traveling east, tracing out a line of latitude and remaining stationary relative to Rachel. In each of these cases, the students were able to correct their answers quickly with a small prompt from the interviewer, but the similarity between their responses hinted at a potential area of confusion that should be addressed.

For one student, a simple question comparing latitude lines and great circles was enough to prompt reflection and a retraction of their previous stance:

> Jared: *If the puck started in the Northern Hemisphere, and is following a great circle, will it stay in the Northern Hemisphere?*
> Diane: *Yeah, if you kick it directly east, it's just gonna trace out a latitude line, right?*
> Jared: *Is a latitude line a great circle?*
> Diane: *No, it is not. So, I suppose it wouldn't. Because if it's kicked directly east, it's gonna trace out a great circle. Right? So, it has to start dipping down eventually. Yeah. So no, it would not stay in the Northern Hemisphere*

Another student admitted that the puck and the X would not follow a great circle in their proposed outcome, and when pressed on that conclusion, they reconsidered:

> Adam: *If he kicked it eastward at the same tangential velocity as the surface of the earth, then it'd be taken in a circle, but wouldn't move out of Logan. It would just sit in the same place.*
> Jared: *So, if we placed an X on the ground where the puck originally was, would the puck leave that X?*
> Adam: *No.*
> Jared: *...does that X travel in a great circle?*
> Adam: *Yes, yes, the X and the puck, they both travel... no, not a great circle. They move in a circle, but not a great circle because the cross section does not pass through the center of the [earth].*
> Jared: *When Isaac kicks the puck directly eastward, should the puck travel in a great circle?*
> Adam: *No. Well, I suppose it should. Oh, you're right, I think. Yeah, it should travel in a great circle… that means it would leave Logan.*

One student recognized that she had two competing ideas, but no way to confidently determine which one was valid. Once she was reminded that the state of the earth and the puck had not changed, she was able to work out which idea was correct:

> Jared: *So, from Isaac's perspective, when he kicks the puck, how would he describe the motion of the puck?*
> Bailey: *From Isaac's perspective, it would be traveling to the east…*
> Jared: *Would the puck follow a great circle?*
> Bailey: *If it was directly to the east, I don't think it would. But hold on, that doesn't make a whole lot of sense to me. Because before, we were saying that no matter which direction you move it, it should travel a great circle.*

But maybe I'm thinking of east wrong: I'm thinking of east as exactly perpendicular to longitude, and so it'd be cutting a circular piece above the equator. But before, we said that no matter which way he kicks it, it always follows a great circle. I'm thinking of something wrong, I'm not sure what it is.
Jared: *...when we let the earth rotate, did that change anything from Isaac's perspective?*
Bailey: *As far as what the puck was doing, no.*
Jared: *So, if the puck started in the Northern Hemisphere and was moving east, what would a great circle look like?*
Bailey: *A great circle would start in the Northern Hemisphere and eventually get closer to the equator, enter the Southern Hemisphere, and eventually come back. Okay, I think I see the logic that was missing: for it to cut a smaller circle just across the Northern Hemisphere, there would have to be something that angled it towards the north pole.*

The last student said the puck would travel in a great circle, but motioned with her hand to show a puck traveling in a level path around the northern latitude. When asked to clarify this answer, she immediately saw the contradiction but had a bit of difficulty discerning how it would be resolved.

Jared: *And so, if Isaac kicked the puck to the east from Logan, Utah, where would that great circle take the puck?*
Gina: *It would go east around the globe and back again, cut a great circle that way across... I think, yeah. So, it looks like to him it was going right all the way around the globe and back to the same place, the same X if you could see it.*
Jared: *Now from the way you trace your finger, would the puck stay at the same northern latitude? Would it stay in the Northern Hemisphere?*
Gina: *That's a cool question. Well, great circles you said have to cut through the center of the earth. So, it wouldn't really make sense that it would be a great circle if it stayed at the same latitude and just cut the top off the earth. So, I'm guessing yeah, it would have to make a great circle, I believe, which would make it probably be more diagonal looking.*
Jared: *...Right at the moment when it was kicked, from Rachel's perspective, what does the puck look like?*
Gina: *Hmm. Well, my initial thought, to her it would look like it was not moving; it was just staying still on a planet rotating with her. But that wouldn't really make sense if it has to make a great circle. So then maybe it would look like it was heading south, perhaps. But my initial thought was that it would not move at all. So, one of those two.*

Each of these cases played out slightly differently from one another. Some students recognized their competing ideas without intervention, where others did not see the contradiction until it was pointed out to them. Some were able to arrive at a confident final answer while others were still unsure even after some internal discussion. However, in all four cases when the students were challenged, they reiterated the conclusion that had been reached in the first two thought experiments: a kicked puck on a frictionless, spherical earth must trace out a great circle regardless of the direction of motion. This shows that the students had not failed to grasp the earlier instruction. Instead, it seems they were considering thought experiment #3 as its own context rather than recognizing the connections between the two setups.

There are several likely reasons why the students were unknowingly neglecting the previous thought experiment's conclusion. According to Rachel, the puck that was kicked east by Isaac appeared to be unmoving (this perspective was mentioned both by students who gave correct and incorrect predictions), and it is possible that this consideration activated the inertia landmark; as the students did not perceive any force acting on the puck that would push it tangentially across the surface, they surmised that it would remain stationary indefinitely (the error here being that Rachel is not an inertial observer, so the inertial landmark does not apply to her reference frame). It is also plausible that this was an activation of the same *clamping*-type knowledge element discussed previously, leading to a mistake similar to those made by some students in thought experiment #2 regarding the puck released from rest according to Isaac. It could also be that the students intuitively believed that latitude lines were straight lines (possibly from observing the straight latitude lines on 2-dimensional maps) and so did not see any contradiction in the kicked puck moving along them indefinitely. Ultimately, the exact source for this misunderstanding was not made clear in this study given the brevity of the interactions with the students, but further investigation could prove enlightening.

Thankfully, this particular conflict was also easily resolvable. In each case, a prompt from the interviewer to consider great circles, their relation to latitude lines, or their role in the previous thought experiments was enough to activate the proper knowledge elements in the student to sort out the mix-up.

Rotational Speed at Varying Radii

The conceptual approach relies on the students' understanding of the conservation of angular momentum in order to predict the deflection of the puck as it moves north or south along the surface of the earth. This conservation law states that the radius of rotation and the tangential velocity of the rotating object will be inversely proportional in an isolated system: its velocity will increase if it moves to a smaller radius, and its velocity will decrease if it moves to a larger radius. This relationship was well understood by most of the students as they had often observed it for themselves in a variety of phenomena:

> Jared: *Once it's moving north, is it getting closer or farther away from the axis of rotation?*
> Hilda: *It's gonna start getting closer. So then, like the ice skater that brings in her arms or fists, it starts rotating faster.*
>
> Jared: *What's going to happen to the puck's rotation rate as it gets farther away from the axis?*
> Joshua: *From that perspective, the velocity would decrease, its speed would decrease, kind of like if you're spinning in a chair and you put your arms out.*
>
> *Bailey: In the case of radius changing, then the velocity will change so that the total angular momentum is the same. Just like the little playground toys that, you sit on them and they spin, you pull yourself in, you're gonna start spinning a whole lot faster.*

During the course of one particular interview, the student accidentally reversed the relationship several times and offered the opposite answer:

> Jared: *As the radius gets smaller, what's going to happen to the tangential velocity?*
> Caleb: *The tangential velocity would have to get smaller as well.*
> Jared: *If we're trying to conserve angular momentum, keep that total amount the same, the radius gets smaller, but we want to keep that amount the same...*
> Caleb: *Oh, the velocity would be bigger.*
> *...*
> Jared: *As it moves to the north, is it getting closer or farther away from the axis of rotation?*
> Caleb: *It would be getting further from the axis of rotation. So, the radius will be increasing.*
> Jared: *What is that going to do to the tangential velocity of the puck?*
> Caleb: *It would increase the tangential velocity of the puck.*
> Jared: *...If we're trying to keep the amount of angular momentum the same, if the radius, the distance away from the axis, is getting bigger, what's going to happen to that velocity to keep the total angular momentum the same?*
> Caleb: *Oh, if you want to keep the total angular momentum the same, the velocity would have to decrease.*

While this reversal was only observed in one student, the problem was persistent throughout the interview, which warranted further consideration. In examining what may have been the cause, one interaction showed that the student believed the velocity of a rotating object and the radius should be directly proportional:

> Jared: *As we get farther away from the axis, the radius is getting bigger. But we want that total [angular momentum] to stay the same. What else is going to change?*
> Caleb: *Its velocity.*
> Jared: *What will happen to its velocity?*
> Caleb: *It would increase because they're literally proportional.*
> Jared: *As the radius got bigger, would the velocity also get bigger?*
> Caleb: *Oh, sorry. Sorry. If the radius got bigger, the velocity would get smaller.*

The student understood the concept of proportionality, but was confident that velocity should rise as the radius increases. While this is the opposite of what is predicted by the conservation of angular momentum in an isolated system, there is another related physics relationship that does have velocity and radius being directly proportional: the angular velocity of a rigid body. For any solid object rotating around a pivot, a point that is further away from the pivot will be traveling at a faster linear speed compared to a point that is closer to the axis of rotation. The proportionality of rotational velocity along rigid bodies is technically not necessary for navigating the thought experiments devised for the conceptual approach, and so it was not brought up by the interviewer. Even so, it was mentioned by several students as they discussed related topics within the conceptual approach:

> Bailey: *Every part of the earth follows... you know, because it's attached to the earth, it follows whatever tangential velocity it needs to for the entire earth to have the same angular velocity.*
>
> Adam: *You'd see it if you were flying an airplane, for example, if you're going from the North Pole down to the South Pole, the velocity of the surface of the earth is increasing, right? You have a constant angular rotation, but the diameter is increasing as you go down.*
>
> Jared: *Regardless of where he sets it down, will Rachel always see the puck move west?*
> Joshua: *Yes, unless they're at the poles, in which case, the puck would just appear to spin opposite of the earth's rotation.*

The proximity of rigid body rotation to the topics discussed in the conceptual approach means that it is possible that the befuddled student may accidentally recalled the wrong proportionality when trying to consider how the tangential velocity of a puck will change as it moves north and south along the surface of the earth. I would posit that the best approach is simply for instructors to be aware of the potential confusion so that they can identify it and correct it as soon as possible if it arises. Due to this only being observed in one student, I doubt that this would be a common enough occurrence to justify adding a discussion about the competing proportionalities to the conceptual approach; such an addition might actually increase the number of occurrences by activating the rigid body proportionality when students would have never considered it otherwise.

Post-Interview Feedback

The last observation I wish to address is the students' parting reactions to the conceptual approach. At the end of the interview, I gave the students an opportunity to share their feelings about the experience and to summarize how they felt as they went through the instruction. I was elated to see that all eleven students responded positively overall to the conceptual approach for teaching the Coriolis force. Many of the students expressed that certain steps within the process gave them trouble personally, but in each case, they were able to overcome the hurdle eventually and understand the concepts by the end.

One student who had taken the Classical Mechanics course remarked on how our conceptual approach (specifically, the inclusion of the earth's shape as an influencing factor) had improved his understanding of the Coriolis force as a whole:

> Adam: *Getting started was tricky, the stuff with the great circles and moving eastward, and why is it staying to the east? That was all pretty difficult conceptually because I had never really thought about that before… but I think that the explanation was very on point. Introducing the idea of why something would continue to move eastward in a circle (that's not a great circle) as a consequence of the bulge of the earth was pretty conceptually demanding, but after that, it started to fit together, the whole picture that you're drawing. So, very well done! I feel smarter!*

Several other students from the Classical Mechanics group compared the conceptual approach to the course material in which they had participated. In both cases, they remarked that their understanding of the Coriolis force when they left the classroom had been incomplete and that the conceptual approach had enhanced their perspective:

> Caleb: *I was very pleased with this whole exercise… it taught me more about what was going on physics-wise. In Classical Mechanics, even though I had a fantastic professor, I learned more about how to manipulate the equation and get the numbers that I needed. But with this exercise, it was easier to describe what's going on with the Coriolis force and why it is the way it is. I definitely learned something new.*
>
> Ethan: *I feel like I learned a lot, I actually gained a better understanding... I remember in Classical Mechanics, we derived the formula for rotational motion… but I never really understood what it meant. This gave me a physical interpretation.*

Several students appreciated how the conceptual approach relied primarily on conceptual, step-by-step segments instead of relying heavily on mathematics or equations. For them, this made the instruction much more accessible and straightforward:

> Gina: *I really liked the foundation you built off of that started really simple, just knowing the basics. That was helpful… I feel like I understand it a lot more now… I was kind of nervous because I haven't taken physics in such a long time. I was like, "I'm probably going to be the worst student ever!" But I really liked how even if someone didn't have much of a physics background, they'd be able to understand this the way you explained it. So, thank you for that. I really enjoyed it!*
>
> Hilda: *The easiest part for me was definitely at the beginning when we started talking about the puck just on the earth and it's not moving, and then imagining how the puck would move. I feel like that was the easiest part to conceptualize, and then I really liked how you were able to expound upon that, just build upon that initial understanding, because it wasn't super hard to understand.*

Among the other responses, one student [K] likened the conceptual approach to other popular instructional tools by saying "it could have been a Khan Academy video". Another student [I] admitted "you opened my eyes to the conceptual flaws I had". Hearing so many of the students express that they learned something new from participating in the study is promising. The prevalence of these types of responses indicates that a purely conceptual approach to the Coriolis force has legitimate merit; the students have the cognitive tools necessary to capitalize on and internalize these visualizations, and the students feel like they can successfully grasp the ideas presented in the instruction.

As for trouble spots, the most commonly cited difficulty in the conceptual approach was visualization; a few students mentioned that imagining the complex paths of the puck as it moved across the surface of the earth was the most difficult part of the interview for them, especially when trying to imagine it from Rachel's perspective:

> Ethan: *I'd say the hardest part for me was visualizing how the puck moved with respect to the surface.*
>
> Joshua: *My brain just wanted to flip back to Isaac's perspective, like, "Okay, what am I going to see happening looking down at the surface?" ...I think that was the hardest part.*

Two more students independently commented on how a visual element would be a helpful inclusion in the future, even though they did not personally struggle with it:

> Felix: *I think the visualization you gave of it, just putting something on the earth and seeing what happens, I liked that. It helped me definitely understand it better… If there's some pictures or something, I think that would help too.*
>
> Gina: *I thought it was cool that we didn't do it with any visual things, it was just all in my head. I think if there were visual things, I'd get it faster.*

While the conceptual approach employed within this study proved relatively successful even without visual implementation, I believe these responses should encourage future efforts to explore how the addition of visual elements such as *CorioVis* may complement the thought experiments and potentially improve the accessibility of the conceptual approach.

Conclusion

Modern techniques for teaching the Coriolis force are severely lacking; their insistence on a primarily mathematical approach alienates casual audiences and often fails to accomplish the principal goal of promoting conceptual understanding in students. Too often, available conceptual teaching methods for the Coriolis force rely on 2-dimensional abstractions or the conservation of angular momentum without engaging with or including the earth's 3-dimensional oblate shape (which is necessary to accurately predict the horizontal deflections seen on the earth's surface). Given the importance of conceptual understanding in the physical sciences and the range of disciplines affected by the topic, we set out to construct a series of thought experiments which would utilize students' intuitive reasoning to build a functional mental model which correctly describes Coriolis deflections on the surface of the earth. In the course of presenting this novel conceptual approach to intermediate physics students, I witnessed the breadth of intuitive knowledge to which students had access and the myriad ways in which it influenced their cognitive processes in the moment.

To start, the association of the Coriolis force with the earth's rotation had been successfully established both within students who received upper division physics instruction and students who encountered the Coriolis force in less mathematically rigorous environments. Just as well, most students were aware of the effect the earth's rotation has on the overall shape of the planet, creating a slight bulge around the equator. However, in spite of these two valid connections, none of the students interviewed saw the oblate shape of the earth as a relevant component of the Coriolis force, including those who had completed the Classical Mechanics course. In time, I hope that this relationship can become a staple of Coriolis force instructional methods so that students can appreciate the beautiful (and deceptively simple) interplay which the earth's rotation, the earth's shape, and the Coriolis force share.

Throughout the instruction, the students showcased a remarkable proficiency for navigating conceptual spaces related to balance and equilibrium. The students' intuitive understanding for opposing forces successfully guided them through the non-trivial dilemmas proposed within the thought experiments more often than not. I would hypothesize that the robustness of this primitive knowledge cluster may be a result of the immense number of physical phenomena which it exemplifies; even the infantile act of taking our first steps involves a bold foray into the territory of equilibrium. Childhood toys, sporting activities, locomotion, architecture, geology, and countless other facets of our experience provide a cornucopia of phenomena from which we can derive a sense for these fundamental concepts. If instructional methods make an effort to capitalize on this wealth of intuitive knowledge, I believe they will find a solid foundation to build deep and lasting understanding.

In our interactions, I was surprised to find how primal the idea of "spinning objects will bulge in the middle" was among the students interviewed. It showed such a presumptive acceptance that I believe it could qualify as a new phenomenological primitive. It could very easily originate from the physical interactions which young learners have with their own bodies and the objects in their environment, and it would provide them with a functional understanding of rotation without necessitating deeper explanation. This *bulging* primitive needs more investigation to understand entirely, but it could explain why instruction around rotational motion and the centrifugal force is notoriously counter-intuitive. Naive physics learners have experienced *bulging* within their own bodies in a way that is indistinguishable from any other force; yet, when they enter their physics classroom, they are commanded to relinquish the experience in favor of a string of abstract symbols which they are told are the “real forces”. This confusion could be significantly mitigated by understanding the role this *bulging* intuition plays in the minds of novice physics students and utilizing it as an example rather than demanding that the students cast it aside. Further investigation of *bulging* as a phenomenological primitive could provide physics educators with a useful theory for addressing a particularly troublesome subject.

When examining the patterns across the students’ responses, I noted the pattern of “instructional landmarks”. These large-grain knowledge structures appear to originate from formal physics instruction on topics which have a high priority when engaging in problem-solving. Students co-opt these strategies from their instructors and use them to navigate conceptual spaces. These landmarks act as a guide to orient the search for cognitive suggestions and a measuring tool to judge the merits of proposed solutions. Students will use instructional landmarks to settle disagreements between competing postulates when their own adjudication skills are insufficient and will grant supremacy to the landmark over their own intuition. I have described the “isolation”, “frictionless”, and “inertia” instructional landmarks observed here as completely as the collected data would allow, although all three could benefit from deeper inquiry. Going beyond the realm of the Coriolis force, I would expect that similar structures would be observed in intermediate students who have participated in instruction which houses other apodictic concepts. My supposition is that the laws of thermodynamics, general and special relativity, and the standard model of quantum mechanics may be among the areas which could yield fruitful results in the search for instructional landmarks. I would even go as far as predicting that instructional landmarks would not be limited to the realm of physics; given that these knowledge structures merely required a strong central concept which is authoritative in nature and conveyed through instruction rather than intuition, there may be topics such as the theory of evolution in biology or the atomic theory in chemistry which could serve a similar utility to students in those fields.

The difficulties encountered by the students while traversing the conceptual approach were mostly trivial and easily resolved. The confusion about frictionless surfaces imparting motion, latitude lines' deviation from great circles, and the neighboring rotational proportionality relationships rarely caused more than a few moments of uncertainty before being clarified and overcome. In most of these, simple reminders from the instructor were enough to cue realizations which illuminated any discrepancies. The one area of conflict which did not dissipate as readily was the disagreement on what would happen when the two competing effects on the puck were not equal. Several students represented this inequality like a spring which would compress to a new position when disturbed rather than the unstable equilibrium which will accelerate continuously until balance is restored. Through our theoretical framework, we can understand this characterization not as a useless idea which requires expunging, but a misplaced connection which can be adjusted. I theorized about possible intuitive knowledge connections that could be the culprit, but the scope of this study did not facilitate identifying which (if any) was the source of the error. For now, considering a future iteration of the conceptual approach which places increased emphasis on the instability of the balance between the two effects (and the agency of the two actors) is sufficient.

Overall, the students appeared to gain a significant improvement in their conceptual understanding of the Coriolis force through participation in the study. The students were more than capable of engaging with the mental visualizations to deconstruct the causal mechanisms; they employed a host of intuitive knowledge and cognitive tools to navigate the conceptual spaces and demonstrated an adept skill set for resolving counter-intuitive struggles. On the subject of student experience, every participant expressed positive sentiments about the approach, and many of the students specifically stated that they felt they understood the Coriolis force better after considering the thought experiments (including those who had already passed the Classical Mechanics course which includes the Coriolis force in the curriculum). These positive responses demonstrate a proof of concept for this novel approach and suggest that it could be an effective teaching method for explaining the mechanisms of the Coriolis force on the surface of the earth. Determining the actual effect of the conceptual approach on student outcomes was not the goal of this study; such an exploration would undoubtedly require a much larger sample size, quantitative data collection, and a comparison to other traditional and alternative Coriolis force instructional materials. This study has demonstrated that intermediate physics students have the cognitive tools necessary to comprehend the Coriolis force on a fundamental level, and that these conceptual instructional methods have the potential to expand student understanding in ways which traditional teaching methods have failed to achieve. Developing and implementing conceptual instructional designs for the Coriolis force is crucial to facilitating comprehensive, multidisciplinary understanding and putting to rest the pervasive misconceptions which continue to surround the topic.

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