Fixing Our Physics: Circular Motion

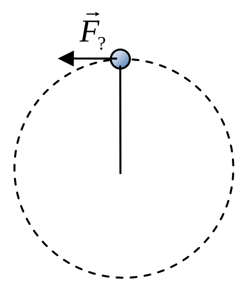
by Chris Meyer
christopher.meyer@tdsb.on.ca
York Mills Collegiate Institute, Toronto

Ah, circular motion – I get dizzy just thinking about it. Everybody is doing it (even sometimes the LHC), but who understands it? This is a challenging topic for all of us. Fortunately, physics education research (PER) has many insights to offer us on matters topical as well as pedagogical. So what does PER have to say about how to teach circular motion? Let's find out. And, for no extra charge, I will throw in my own two cents worth.

One main goal of reformed physics teaching is the development of deep conceptual understanding within a robust, interconnected framework. New ideas should not only "make sense", they should be well connected to prior concepts and ideas. This is the antidote to rote, algorithmic learning and compartmentalized, disjoint knowledge (like they say, a little compartmentalized knowledge is dangerous). This goal can be realized through the careful exploration of the two aspects of circular motion: force and acceleration - cause and effect.

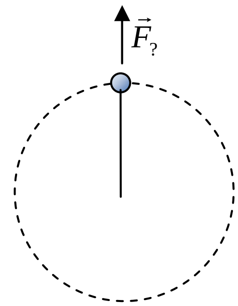
Curious Forces in Circular Motion

There are two persistent ideas that many students have regarding uniform circular motion: (1) that there must be a forwards (tangential) force that keeps the object moving in a circle; and (2) there must be an outwards force keeping it from falling inwards. These ideas can very happily coexist in the fertile student mind along with the teacher-approved notion of an inwards, radial net force. For beginners, all three possibilities can seem equally plausible and certainly not mutually exclusive. Only after repeated and explicit examination (and careful reinforcement long after the circular motion unit) will the misconceptions wither away.



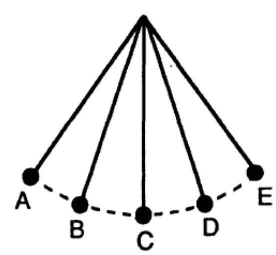
The appeal of a forwards force can stem from insecurity with Newton's 1st law and the context of two-dimensional motion. The idea that an external force is not required for an object to maintain a constant speed is strange enough. To compound things, physics suffers from very rich laws whose many consequences are not well unpacked for students. Mathematicians have theorems and their theorem's offspring: lemmas. We need these for physics! For example, Newton's Second Law should have a lemma, which I affectionately call the *Orthogonality Principle*, stating that "a net force in one direction does not affect the speed in a perpendicular direction." Obvious, right? Not for most students. This is a fundamental feature of the second law which lies at the heart of understanding circular motion. Its earlier introduction with projectiles can greatly help dispel the "forwards force" notion. Another useful lemma students should develop while exploring circular motion is "a force parallel to an objects direction of motion only changes its speed, a force perpendicular only changes the direction." Both lemmas are helpful ways of capturing the nuances of Newton's Laws applied to two-dimensional motion.

The Outwards Force



The allure of an outwards force in circular motion is very great and surprisingly persistent (even amongst a number of teachers I have workshopped). We only have ourselves to blame for this, and by "ourselves" I mean our physical selves - when we travel in a circle we feel an outwards effect of some kind. It takes careful work to reinterpret this valuable observation, a process which should begin long before the topic of circular motion is reached. The physical sensation of acceleration needs to be made sense of early on in the context of linear acceleration. The goal is the understanding that when accelerating due to any force other than gravity, our physical sensation is that of being pushed in a direction opposite to our acceleration (we feel pressed into the seat of a car that is speeding up). This provides students with a familiar tool to help understand the sensation of being pushed outwards without the existence of an outwards force.

Another rationale invoked for an outwards force is the need to prevent the object from travelling directly inwards to the centre of the circular path. Another still is to explain why there is any tension in the string at all! These proposals need to be met with a careful kinematic exploration of circular motion. I find this is easiest in the context of orbits and the recognition of the need for orbital speed. Another valuable example is a rollercoaster loop with an unattached car upside-down at the top. The car could in fact fall straight down, but with a suitable tangential speed, it moves far enough forward while it "falls" that it remains in contact with the track.

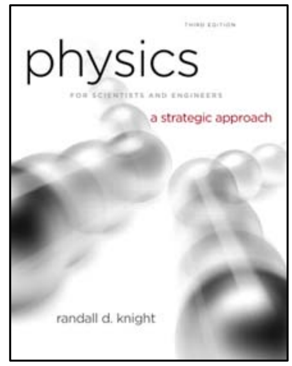


A telling example of the challenges of understanding circular motion comes from a study by Sue Allen and Frederick Reif where they give a group of students and physics professors from UC Berkeley a simple question: What is the direction of the acceleration of a pendulum bob as it speeds up and reaches point C in the diagram to the right? Only 3 out of 5 of the veteran professors answered correctly, even when prompted to clarify their responses. Indeed, the matter of forces in circular motion can be very thorny. (So what is the correct answer? Keep thinking, hah!)

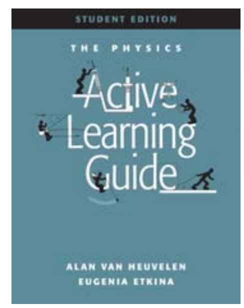
Unity and Diversity

One of the great things about physics is that a small number of ideas have the power to explain so many different things. Physicists toil endlessly, striving to reduce the number of necessary ideas - it's kind of an obsession. And teachers do a bad, bad thing when we needlessly increase that number. This brings me to a dirty trick we pull on our students. By this point in their studies, students already have a name for the idea "the combined effect of all the forces in one direction" – known as the net force in, let's say, the radial direction. But then when circular motion comes along, we introduce this new thing "F_c"

and our attempts at building a deep, robust understanding of circular motion lurches to a halt.

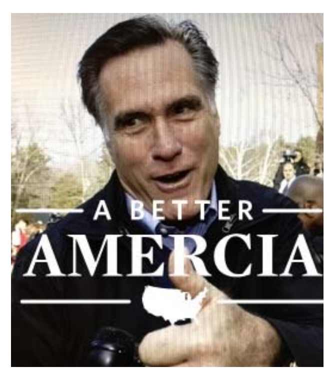


I am quite pleased to note that in Randall Knight's shiny, new textbook, which is great bedtime reading (no joking) and which is deeply infused with physics education research, the mischievous F_c never appears. There are a number of very good reasons for never using this symbol or introducing an equation like $F_c = mv^2/r$. The main reason is that there is a perfectly good idea, $F_{net} = ma$, which really has this circular motion business well covered. Besides, you would never introduce a "handy" equation like $F_{net} = m(v_2 - v_1)/\Delta t$ owing to your confidence in your student's ability to both reason about forces and find a strategy to determine the acceleration. So why sell them short with circular motion? If students don't begin their thinking about circular motion with $F_{net} = ma$, they are not making vital reinforcements between prior understanding and this challenging new topic. It is crucial to learn that there are no new laws for circular motion. Even if you preface your equation as a convenient short cut, students will memorize it and it will, indeed, cut short their thinking (which is bad).

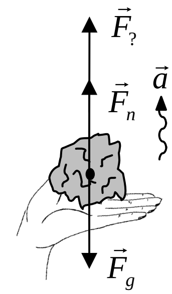


The Physics Union Mathematics program developed by Eugenia Etkina and Alan van Heuvelen at Rutgers University does a great job of emphasizing the deep connection between the kinematic and dynamic pictures of circular motion. If you email Professor Etkina and bat your eyes suggestively, you may receive a password to the website which has an astounding set of PER informed physics units. My own treatment of circular motion draws heavily upon their work. They take great pains to highlight how a velocity vector analysis of circular motion (acceleration points to the centre) agrees with a force diagram analysis (net force points to the centre) courtesy of, you guessed it, Newton's second law. These are not obvious results to be glossed over; they are pillars of a deeper understanding.

The Many Problems with F_c



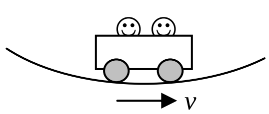
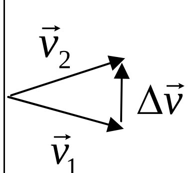
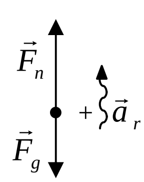
I have other concerns with the gormless F_c. Textbook authors don't really seem to use it and its namesake, the "centripetal force", honestly. The adjective "centripetal" is a valuable label when describing a familiar force that has a component responsible for keeping an object moving in a circle (my definition). For example: "When Mit Romney makes a 180^o turn in policy, political expediency is the centripetal force". Traditional texts define the centripetal force as $F_c \equiv F_{net}$, which is a problem for non-uniform circular motion. But even if we understand that, deep down, they really mean the radial component of the net force, authors seldom use it this way in their descriptions – they tend to describe single, inward forces as the centripetal force. Furthermore, this term and notation seem to be no more than an affectation of high school and introductory physics texts. In more advanced studies the term is abandoned and central forces are described or angular motion and moments are used.



Unfortunately, students are often quite relieved when you provide them with a new force, F_c, since it provides a convenient label for the mystery of circular motion. Just like students will often draw a mystery force for an object in a hand accelerating upwards, they are happy to have a brand new force to explain the peculiarities of circular motion. Perhaps you have noticed how F_c tends to appear in free-body diagrams in curious locations or in the place of other, reasonable forces. They will stop thinking carefully about how friction might be keeping the car going around the corner – why should they, it's the F_c that's responsible! Other times students seldom realize that the F_c appearing in their diagrams corresponds to no known physical interaction, but what can we expect, neither does their physical experience of circular motion! (The outwards force, that is.)

So, to briefly summarize and at risk of overwhelming the market, I would like to introduce another shiny razor which I will dub *Chris's Razor*: "If it's not necessary, don't teach it". Please, dispense with F_c.

Multiple Representations
Learning to represent the physics of a situation in a wide variety of ways is another key to developing a robust, well-connected understanding. Those in the know call this "multiple representations". Depending on the topic, there are a variety of possible representations. Shown below is an example for circular motion. A great exercise is to provide one or two of these representations and have students devise the others. This often involves quite a bit of good old know-how and also some amusing creativity!

Words and Sketch	Velocity Vectors	Force Diagram	Newton's 2nd Law	Sample Solution
A roller coaster car moves along a frictionless circular dip in the track. 			$F_{net_r} = ma_r$ $F_n - F_g = mv^2/r$	F_n – (350 kg)(9.8 N/kg) = (350 kg)(12 m/s)^2/(7.8 m)

Implementation and Invitation
All of the ideas discussed here can be used with any mode of classroom teaching – old-fashioned lecture or new-fangled group work (my modus operandi). But to be sure, your students will get the most out of their experience the more they explain their own ideas to one another. I teach circular motion over five (yes, five!) classes using a variety of investigations and activities. Don't mess around – if you're going to do it, do it well. Follow this link to my website where you can explore my circular motion lessons and syllabus, amongst all the other materials for my course. And finally, my standing

invitation: the door to my classroom is always open – just email me if you would like to drop by and see a lecture-free, reformed physics class in action.

Chris's Advice on Uniform Circular Motion:

- Use the terms radial and tangential whenever possible ($a_r = v^2/r$, $F_{net\ t} = 0$)
- Only use the term "centripetal" as an adjective for familiar inward forces
- Always start problems with $F_{net} = ma$, banish F_c to the outer realms
- Reinforce agreement between the kinematic picture and force picture
- Use multiple representations
- Provide activities that motivate the presence of an inwards net force and that help refute the existence of forward or outwards forces
- Help students explain why the object doesn't travel directly into the middle and why we feel an outwards force
- Create a lemma – name it after yourself: "parallel forces change speed, perpendicular forces change direction"
- Make sure their understanding will generalize easily to non-uniform circular motion