COMPILATION: Unit 3 - Newton's laws demos - conceptual confusions. Part 1

Ron McDermott, a modeler in New York state, made an important contribution to a PHYSHARE thread about common conceptual confusions in popular demos of Newton's laws.

The discussion is in two parts. Although lengthy, this thread is helpful in understanding Newton's laws and their relation to impulse, momentum and energy; and the roles of friction, stress and strain.

BACKGROUND:
On July 18, 2002, a teacher posted to PHYSHARE listserv:
>Does anyone have any interesting demos for Newton's Laws of Motion?

In response, M.H., a teacher, posted this **quarter/card/cup demo**:
...You will need a clear plastic cup, a quarter, and an index card that fits over the mouth of the cup. Put the card over the mouth of the cup, place the quarter on top, and then flick the card out from under the quarter, and the quarter should end up in the glass. Tah Dah!

THE DISCUSSION:
Donald Simanek, Ph.D, a recently retired college physics professor (40 years experience), replied:

Date: Thu, 18 Jul 2002
From: "Donald E. Simanek" <dsimanek@lhup.edu>

I'm racking my brains (yechh!, that hurts), trying to figure out what important point the cup and quarter demo is making about Newton's laws. Of course I have no doubt Newton's laws are working just fine in this demo, but nothing seems "clean" in this one. What exactly are students to get out
of this demo? Please explain that in terms my simple mind can grasp.

The difficulty is, for me, the question of force. All of Newton's laws deal with force (unless everything is at rest). Now if students are to learn anything about force from a demo they must see or experience some manifestation of a force, and have some information to give them an idea of relative sizes of the forces in the demo. About the only thing I can suppose that this demo shows is that the student INFERS that the card exerts a force upward to support the quarter. When this card (and presumably the force) is removed, the quarter falls. I know that students aren't as academically swift today, but even for today's students isn't this a bit trivial? And if it is necessary to make this point, why not have them hold a coin in their hand, then quickly move their hand down. At least in this case they can FEEL an indication of the force, which they cannot sense with the card demo.

Date: Thu, 18 Jul 2002
From: "Donald E. Simanek" <dsimanek@lhup.edu>

Judy, a physics teacher, wrote:
>The **quarter/card/cup demo** is a classic first law demo. The horizontal force
>exerted on the quarter by the card when the card is flicked out of the way
>is not enough to overcome the inertia of the quarter and thus the quarter
>does not move with the card, but rather stays put and then once the card is
>gone falls into the cup. It's the same as the magical tablecloth removal
>demo, it's an inertia thing. Does this help?

Re responses of Judy and M.H.

I was rather afraid that some justification such as this would be brought forth for the card and quarter demo. One might use the **"yanking the tablecloth" demo** also, which is similar. Also the classic **egg dropping into the glass of water**, for more showmanship. And some of you claim that this teaches something about Newton's laws? Only with a LOT of analysis and accompanying discussion might it do that.

Judy mentions "overcoming inertia". This indicates the confusion surrounding this demo, and when this language is used it's no wonder students get confused and come away with screwed-up concepts. Does not a moving body have inertia? Of course it does. It has the same inertia at rest, or moving at any speed. Inertia is a property of the body, it is in fact nothing more than what we measure by "mass". So how in the world can you "overcome" inertia? Destroy the mass? And what does it mean to "overcome" a physical quantity anyway? To exceed it? To oppose it? To convert it to something else? What with? Some other kind of inertia? This word is being used here in a very vague and slippery fashion. The use of the word "inertia" here is meaningless in this context.

Newton's laws 1 and 2 can be written F_net = ma (in vector form, of course). Newton's third is "If body A exerts a force on body B, then B exerts an equal and opposite force on A". That's the whole of this package of laws. Now what do these demos do to illuminate these laws clearly and cleanly? Nothing, they just complicate the issue, for **the behavior the students observe is due to things they do NOT directly observe, and which involve other concepts not explicit in these laws. Impulse and momentum loom large in these demos. Also friction.**

Why can the card flip out from beneath the coin without moving the coin horizontally? Simply because you do it quickly. Pull the card slowly and the coin comes with the card. So why does speed matter? Does what we've said above help the student answer that question? I think not, and the
question is crucial for it gets at what determines the outcome of the experiment. Isn't this a question that any half-awake student in physics class OUGHT to be asking? If they aren't asking such questions, why not? Is the teacher who speaks glibly of "overcoming inertia" prepared to answer such reasonable questions?

The bottom line is that **we should always be very clear what a demo is supposed to demonstrate, and be very sure we understand it before inflicting it on students.** If we don't understand it, we shouldn't do it. And we shouldn't give fake and glib "answers".

Now energy and momentum arise naturally from Newton's laws. But just as that took a long time to be realized in the history of physics, the connection isn't one we can expect students to grasp in a few minutes.

The necessary thing that needs to be said about these experiments has to do with impulse and momentum and friction. Friction depends on load on the surfaces, and is usually relatively independent of speed of surface sliding, and is usually slightly greater when there's no relative motion of the surface. The change of momentum of the quarter is due to the impulse of friction on its lower surface. Impulse is Ft. The force is nearly constant. But the shorter the time, t, the smaller the impulse, and the smaller the change of momentum. That's why knocking the card out quickly results in smaller change of momentum of the quarter, and smaller horizontal velocity given to it.

Once you see the REAL explanation, you may ask, "Why do people even mention 'inertia' in connection with these demos?

Sure, Newton's laws underlie all of this. But they underlie ANY mechanics experiment or demo, and phenomena of everyday life. To say these demonstrations "demonstrate Newton's laws" or "teach about inertia" is an outright deception and fraud. It's no wonder physics has the reputation as one of the worst-taught subjects.

I've said it before. Many physics demos are done in a manner and with "explanations" guaranteed to mislead, to form wrong concepts, and to discourage the students from doing a serious analysis of the phenomena being shown. They often do more harm than good. That doesn't mean demos shouldn't be done, but that they should carefully chosen and be done in a pedagogically sound manner.

You can read more about these demos in the demos document on my website:
http://www.lhup.edu/~dsimanek/scenario/demos.htm .
See also Arnold Arons' book *"A Guide to Introductory Physics Teaching"*. In section 3.22 "Two widely used demonstrations of 'inertia'" he addresses the misrepresentations usually made of the "yanking out" demo, and also the experiment of the block suspended by a string with a string hanging below. Pull the lower string quickly and it breaks. Pull the lower string slowly and the upper string breaks. He closes with "...students acquire no understanding of the demonstration, they simply memorize, and repeat, that it had something to do with 'inertia'." I cannot say it better than the master.

-- Donald

Date: Sun, 21 Jul 2002
From: Ron McDermott <rmcder@peoplepc.com>
Subject: Newton's Laws Demos - Again

The recent discussion, and one well-known demo given as an example, brings up an issue I seldom see or hear being discussed. I've sort of formed my own ideas about this, but am curious as to what others think...

The **hanging mass with string above and below demo**, in which a slow pull breaks the top string, but a fast pull breaks the lower string is often cited (as it was here) as a demo of the 1st Law. Donald, I believe, cited it as a demo of the 2nd Law. What seems to be overlooked is the view that it is an apparent refutation of the 3rd Law (one of several that an astute student might come up with):

We have a situation in which the force "builds up" faster in the lower string than in the upper string, despite our insistence than forces between interacting objects must be (simultaneously) equal in size and opposite in direction. Following that insistence to its conclusion in this case, the force change of the lower string on the mass should cause a simultaneously equal and opposite change of force of the mass on the lower string. At the same time, however, it should cause that same force change on the upper string with a corresponding change in the tension of that string - but it doesn't. Clearly there is something happening that we never (or seldom) touch on. A more obvious departure from theory seems to be the breaking of boards or blocks in karate. Or taking a long, thin strip of wood and laying it so that its end extends over the edge of a table (no paper on the end) and striking it sharply enough to break it in the middle somewhere. Or the "straw through the tree" type of stuff we occasionally see in photos.

At this point in the (inevitable) discussion, I invoke "propagation delay in extended objects" and the idea of a force "wave" moving through the extended object at some finite speed as explanation. The usual approach seems to be the "inertia explanation" which, frankly, wouldn't convince me of anything if I were a high school or college student. I'd like to hear a more or less full discussion/explanation of this whole idea (Donald?) and maybe a discussion of how deeply we should pursue this idea with our students (in my case, high school students). It seems to me that we shouldn't just ignore or gloss over this issue given the potential for enduring misconception?.

Date: Sun, 21 Jul 2002
From: "Donald E. Simanek" <dsimanek@lhup.edu>

I could not agree more with Ron McDermott. He asks for fuller treatment, but he already has "got it". An underlying principle of nature is that "Nothing propagates from one place to another instantaneously." Yet many student errors of analysis, and teacher's and textbook errors, too, result from unthinkingly assuming simultaneity which it is physically impossible. Many demos illustrate this, and are discussed in my demos document
http://www.lhup.edu/~dsimanek/scenario/demos.htm.

The hanging ball, two strings. A string cannot break until it stretches to a certain breaking point. This can happen quickly if only the mass of the string need be accelerated. But to stretch the upper string requires motion of the heavy mass, and under a given force, it takes longer for that mass to move the required distance. Yes, it is a nice demo of F=ma. But, the lower string must break well before the upper string stretches to the breaking point, for the inertia of the mass continues its downward motion somewhat even after the lower string breaks. It's also another example of impulse, Ft as the cause of momentum change. The impulse of a given force can be made as small as you like by decreasing the time it acts.

The dropped slinky. Stand on a platform high enough so that a slinky held at one end stretches fully, the other end not touching the floor. Ask students what will happen if you let go. Will the slinky fall as a whole, until its bottom hits the floor, then collapse? Will the lower end move upward to meet the upper end moving down? Something else? Do it. Now ask students to explain it. The principle: The lower end can't fall until it knows you've let go the other end, and that can only come from a change of tension propagating through the slinky from top to bottom. Lest students think that gravity acting over the length of the slinky is essential to the analysis, the slinky can be stretched out along a horizontal taut wire, one end fastened, and a string over a pulley to a weight at the other end. Cut or burn the string at the fastened end. The weight is observed not to begin falling until the slinky nearly collapses.

The sequence of events in the **Newton's balls** experiment. With more than two balls, the outcome we observe is only one of an infinity of outcomes which would satisfy both energy and momentum conservation. Why don't the others happen? The ball at an end of a string of touching balls can't move until it "knows" something has happened at the other end. Also, balls can't penetrate each other. These two principles, plus energy and momentum conservation, suffice to rule out all outcomes but the observed one. http://www.lhup.edu/~dsimanek/scenario/cradle.htm , an unfinished document, but useful for indicating how NOT to explain this.

I get a lot of perpetual motion machine (PPM) proposals in response to my web pages "The Museum of Unworkable Devices" http://www.lhup.edu/~dsimanek/museum/unwork.htm . It treats PMM as conceptual puzzles to test one's knowledge of elementary physics. Obviously my pages do not dissuade some of these people, so they send me proposals which clearly violate some elementary principles of physics. Sometimes it takes me a while to realize that they seriously think the device might work. As I try to think as they do, I'm struck by the fact that they are making the same errors of elementary physics that I saw in my own freshmen students over nearly 40 years of teaching. Yet some of these people hold engineering degrees! This prompted me to put together a summary of physics principles, emphasizing those often misunderstood or misapplied, titled "Physics 101 for Perpetual Motion Machine Inventors"
http://www.lhup.edu/~dsimanek/museum/physics.htm . When finished, it looks like a summary and review sheet of the things one ought to have learned correctly in intro physics, but didn't. It's

rough yet, so comments for improvement are invited. In response to the question below, two principles that ought to be emphasized right from the get-go are:

1. No body is completely rigid; all are at least somewhat deformable. This is what is responsible for contact reaction forces. It is also responsible for friction and rolling resistance forces tangent to surfaces.

2. No body or physical influence of any kind can move instantaneously between two points separated in space by a finite distance.

How much time does this take to impart to students? Not much, especially if done in the context of a few demos which illustrate these points. Yet most textbooks do not state these facts even once!

The perpetual motion proposers have taught me that we don't spend enough time as teachers trying to get into the student mind, to think as they do, and find out how and why they think and learn in unproductive ways, and how they form wrong concepts. Once we know that, we can structure our teaching and classroom activities to counteract poor concept formation, and to ensure that we give students all of the raw materials necessary for effective thinking about physics.

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Date: Sun, 21 Jul 2002
From: John Mallinckrodt <ajm@csupomona.edu>

Referring to the "The hanging mass with string above and below demo, in which a slow pull breaks the top string, but a fast pull breaks the lower string," Ron McDermott suggests that a student might object and make the argument:
>We have a situation in which the force "builds up" faster in the lower
>string than in the upper string, despite our insistence than forces between
>interacting objects must be (simultaneously) equal in size and opposite in
>direction.

Of course, this would be a misapplication of the third law. Nothing in that law can be construed to imply a simple relationship between the tension in the two strings.

>Following that insistence to its conclusion in this case, the
>force change of the lower string on the mass should cause a simultaneously
>equal and opposite change of force of the mass on the lower string.

... and this would only strictly be true if the body had zero acceleration.

In all cases (assuming we can model the body as "rigid"--an excellent approximation in this demo) we find

$$T_{top} = T_{bottom} + m(g - a)$$

with m and a being the mass and acceleration of the body and a taken positive in the downward direction.

Consider first the "slow pull": Both strings will stretch, potentially even by very large amounts. As a result the body may well move a very large distance. But since it can do so in an arbitrarily large amount of time, its acceleration can be kept arbitrarily small. In that case, the equation shows that T_{top} always exceeds T_{bottom} by about the weight of the body and, assuming that both strings have the same strength, the top one will break first.

So what is required to break the lower string? The equation makes it clear that T_bottom will only exceed T_top if the acceleration of the body exceeds g. Thus, to break the *lower* string, one needs to pull on it with sufficient force to cause the body's acceleration to exceed g. This can only happen if the upper string has significantly smaller tension which, in turn, requires it not to be stretched nearly as much. All of this happens self-consistently and automatically in the first fraction of a second if we pull on the string sharply.

I wasted an hour or two this morning putting together an Interactive Physics simulation of this demo and I have posted it on my Interactive Physics page. There is also a QuickTime movie for those
of you who do not have a copy of Interactive Physics. See
  http://www.csupomona.edu/~ajm/ip.html#jerk

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Date: Sun, 21 Jul 2002
From: Ron McDermott <rmcder@peoplepc.com>

----- Original Message -----
From: "John Mallinckrodt" <ajm@csupomona.edu>
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> the tension in the two strings.

Certainly that is true since the two strings are not directly in contact, but as we tend to present the 3rd Law, the student has every reason to think:

> >Following that insistence to its conclusion in this case, the
> >force change of the lower string on the mass should cause a simultaneously
> >equal and opposite change of force of the mass on the lower string.
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> ... and this would only strictly be true if the body had zero acceleration.

I guess I'm not following your train of thought (or you mine, perhaps)... Are you saying that the force exerted by the lower string on the mass does NOT equal the force exerted by the mass on that same string if the mass is accelerating? It seems to me that would be a clear violation of the 3rd Law. I think you mean to say that the force exerted on one face of the mass doesn't have to equal the force exerted on the opposite face (which is obviously the case whenever an object accelerates along that axis).

> In all cases (assuming we can model the body as "rigid"--an excellent

> approximation in this demo) we find
>   T_top = T_bottom + m(g - a)

You go on to talk about the relative tensions in the two strings... I agree that considering the mass as accelerating requires that the changes in tension not be equal, and accounts for what happens. Otoh, the difficulty arises in the students' trusting application of the 3rd Law to successive interactions based on the assumption that the force (in this case the change in force) propagates instantaneously "through" the mass so that it seems (to them) that the buildup in force on both sides of the mass should be equal. Yes, this is clearly wrong, and yes, the math says so, but if a student cannot "see" the reason conceptually, the misconception will probably remain firmly in place.

Since we're positing a "rigid" mass, what happens in the case of rigid strings? No acceleration of mass independent of strings, so the buildup of force in both strings proceeds at the same rate and the top string ALWAYS breaks first? What if the mass is a couple kilometers long? Longer? Good thing absolute rigidity doesn't exist!

So in reality, the bottom face of the mass accelerates before the top face and the mass stretches slightly. Perhaps what we have is a combination of net force reduction due to 2nd Law AND propagation delay in transmitting that force?

Anyone feel like tackling the **"hand breaking stone"** issue? I confess I have no clear ideas in which I have any faith on this one!