

The Physics of Pool  
By Joseph Formaggio and Jose Machuca

My name is Joseph Formaggio. I'm an assistant professor of physics at the Massachusetts Institute of Technology. Today, I hope to explain some very basic concepts of physics that we might see in our everyday lives.

Now, to help me with this, I have asked the help of my friend, Jose Machuca, who teaches computer technology at Regis High School in Manhattan. Hello, Jose.

How you doing, Joe?

Good. I see you have pool stick ready to go.

You know I can't resist a good game of pool.

That's actually perfect, because it explains exactly what I want to do today, the very basic rules of physics.

Oh, really? With pool?

Yes. It's an ideal framework to explain some very basic laws while having fun. But before we get into the physics of it, maybe we should talk a little bit about the rules of pool for our audience, in case they're not familiar with it.

OK. Well, in pool, you're trying to sink the colored balls into the pockets at the corners in the sides of the table. In eight ball, one player tries to sink the solid colored balls, and the other tries to sink the striped colored balls. All of these you do by striking the cue ball with the cue stick and sending it at the colored balls. And then, finally, once one player has sunk all of his colored balls, he'll try to sink the eight ball to win the game.

Do you want to break first?

Sure.

That was a nice break, Jose. And it looks like you got a solids in, so it's still your turn.

OK.

This is a perfect example of the concept of linear momentum and Newton's laws in action.

This straight shot.

It's an example of Newton's third law.

Every action has an equal and opposite reaction.

That's right. And in this particular case, one of the consequences of that law is the conservation of momentum, or, more specifically, linear momentum.

You might want to start from the beginning. I don't know that everybody's familiar with linear momentum.

You're right. And let's look at, first, the set up. Now, in our pool set up, we have two very nice simplifications that make our lives a lot easier. The first is that the objects on the table are all spheres. They're all identical. And so this makes things a lot simpler to think about.

And the other is everything's happening on the surface of the pool table, so this is a nice, two dimensional set up. And we don't have to worry about complications that you might get from a more involved system. Now, in the case of momentum, or linear momentum, which really stems from Newton's third law, we have first, to define what linear momentum is.

Now, very simply, it is the object's mass-- in this case, it's our ball-- times its velocity, how fast it's going. So if you have an object that's very massive, then it will have more momentum than a less massive object. And if you have something that's going faster, then that object will have more velocity, and thus, more momentum.

Now, one of the consequences of Newton's third law is that momentum, in a simple system like this, is conserved. So when you set up your shot, you set up your cue ball. You hit the ball. And then, the ball went into the pocket. So that's a perfect example of this conservation concept.

You took all the momentum from the ball that you gave it when you hit it. Now the ball stopped, and all the momentum was transferred over to the ball, continuing its line of motion, until the ball shoots into the side pocket. So that's a perfect exchange. There was something happening, but again, you have conservation of momentum when you look at the before and the after.

All right, Einstein. How do you make sense of this shot?

Well, linear momentum is still conserved.

But how? The two ball went right, and the cue ball went left.

Well, maybe this is a good one for our audience to think about. Do you think the linear momentum was conserved in this case? Why don't you discuss it, and we'll be back.

We're now back at one of MIT's classrooms in order to help explain some of the concepts we've been talking about in our game of pool. Let us begin, at first, with the definition of linear momentum. As we said before, it is what we define as the mass of the object times the velocity of the object. That's how we define momentum.

Now, I've been very careful about the concept of velocity, instead of, for example, speed. That's because velocity doesn't just incorporate how fast something goes, but also what direction it's going. Now, we've been talking about this conservation of linear momentum. What do we mean by conservation?

Well, to a physicist, conservation involves looking at the state of things before and after some interaction. So let's look at, for example, just our straight shot. In our straight shot, we had this one billiard ball, which had some initial momentum, about to strike its other billiard ball, which wasn't moving. If you look at the total momentum of the system, you would have to add up the momentum of the moving ball, the cue ball, and the momentum of our target billiard. And that momentum would add up to some number.

Then, in the second half, after they've collided, you had the cue ball stand still and the target ball shoot off in some direction. In that process, then, all the momentum before is the same as the momentum after. Just the objects that are moving are different. We can actually write this process down in terms of equations, or sometimes it's helpful even to draw a particular example.

So let's, for example, look at our initial head-on collision. We had the cue ball coming forward. It has its momentum. And you had the billiard that's standing still.

And if you sum up the momentum, OK, you've got the mass of the first object times its velocity. And you have the mass of the second object times its velocity. Happens to be zero. And that is the momentum before, the total momentum before.

Now, let's take a look at what things look like after the two particles collided. Well, again, you now have your cue ball standing still. It has zero momentum because it's not moving anymore.

And the second one is moving forward in the same direction as the original. And then we'll have a momentum that's proportional to its mass times its velocity. And the bottom line is that, even though things have changed around, this basic relationship of momentum before equals momentum after is the physical principle at stake. This is basically the idea of the conservation of linear momentum.

Now let's take a look at a slightly different example, the one where the two balls strike each other, but one is going off in a different direction. So again, here are our two balls. And the cue ball is moving toward the second one, which is standing still. And now, here they are colliding.

One thing to note is, look, if they're not right head on, if they're slightly offset from each other, there is one point where they interact, just one. If you look at where the overlap of these two spheres are, they just contact at one point. Let's draw a line between the centers of one billiard ball to the other.

The direction in which the second billiard ball is going to travel is going to be pointed along this direction. And in order to conserve linear momentum, what has to happen? Where does the second ball need to go?

It helps to remember that conservation of linear momentum involves velocities, so directions matter. If you're thinking that the second ball needs to counteract the direction of the first one, you would be correct. Sometimes it helps to draw a simple triangle to illustrate this concept, just as I have shown here.

It is this very principle of conservation of linear momentum that allows us to predict what's going to happen when two objects collide in a somewhat ideal world. Think about where the second ball is going to go. And we'll be right back.

Welcome back. Now, some of you may have studied that last shot in more detail. It's true that the two ball flew off at a different angle when I struck it with the cue ball. But observe what happened to the cue ball. It, too, flew in a different direction. In fact, it is going forward and to the left, while the two ball moved forward, just like the cue ball, but to the right.

The left and right directions essentially canceled out, while the forward directions add up to the total speed of the cue ball before the impact. This is because momentum deals not just with speed, but with direction, as well.

So if I want to send the ball in a certain direction, I have to be careful about where I strike the ball. The point of contact between the two balls is what matters. I want to make sure that my cue ball strikes off center. The further off center I strike the ball, the wider the angle the ball will fly off at.

What?

The 10 ball's in my way. I'm going to need a bank shot. There's something I don't understand here. In a bank shot, the ball bounces back at the same angle that it hit the side of the table, like a mirror.

Yeah, that's right.

So how does that conserve momentum? Where did the momentum go?

You know, that's a good question, a good question for our audience, too. So where did the momentum go? Talk about it with your peers, and we'll be back.

Welcome back. As some of you may know from looking over the video, the pool table, now, is playing part of the game with us, as well. You see, when the ball strikes the side of the table, it imparts some of its momentum to the table itself. But the table has a much greater mass than any of our pool balls, so it gets a much smaller velocity.

That's right, and in fact, because the table is anchored to the floor, when you impart momentum to the table, it gets passed down to the entire earth, really. Now, if we somehow could put the table on, say, rollers, or wheels, and we did the same trick, the same bank shot, then when the ball strikes the side of the pool table, then we should see the pool table shift slightly, have a tiny bit of velocity to the right, conserving the momentum principle we talked about. So all the while, while we're playing this game, Newton's third law of physics comes into play. And this idea of conservation of linear momentum is maintained.

When we discuss this idea of linear momentum, we're always trying to figure out what the system we're describing is. For example, in the case where we had two billiard balls colliding, it was very simple to say, well I just have two billiard balls, one standing still and one moving. So it was very easy to describe the sum of their momenta in order to help describe the motion after they collided with each other.

When we got to the bank shot and had to bring in the table, then things got a little bit more complicated, because all of a sudden, now, a different object was at play when we were describing momentum. And some of you may have thought, well, what if I start adding more and more systems into my momentum description? Let's take the example of the pool player about to engage in the game of pool.

So here I am, about to take a shot. And I raise my cue stick, and I strike my cue ball. And now, my cue ball goes forward.

By the principle of conservation of momentum, if I take my system to be not just the ball, but the ball, and me, and the floor, and the entire earth, well then, the total change in momentum remains the same. The ball goes forward, and as a result, I, along with everything that I'm attached to, must go backwards. You can even show this, again, in terms of arrows, or in terms of a very simple equation.

Let's say that our ball now strikes the side of the table, like we did before. Well, the ball bounces back like a mirror, reversing its velocity. And as we explained in the bank shot, the table, along with me and the entire earth, is also affected. We get another recoil push as a ball goes forward.

Now the ball goes into the pocket and comes to a stop. Well, in order to come to a stop, it has to hit the side of the table, again, imparting the momentum it had until it is standing still. Now, let's just draw, in terms of arrows, each step of before, and then after, at each collision.

Here we have me, and the entire earth system, and the billiard ball. I strike it. Boom. I go one way and the billiard ball goes the other way.

Then it strikes the table, which, remember, I'm indirectly attached to through the earth. The ball recoils in the opposite direction. So does the table-earth-me system.

And then finally, here, it goes again. It hits the side of the table, comes to a stop, and so does-- and the momentum, again, has to be added up. When you look at all the arrows, before and after, you realize that at each step, the total change in momentum is zero. That's because I made my system really big.

I incorporated not just what's going on on the table, but also what's going on with me and the entire earth. So if I incorporate a large enough system, the total change in momentum remains zero. And yet things move around.

OK, so far, we've concentrated on what happens when a ball hits another ball, or the side of the table. But that's only half the story. We also need to think about how the cue stick hits the cue ball.

That's right. And that brings up a whole new set of concepts, such as angular momentum and friction.

OK. What about just the simple shot, where I strike the cue ball at the center of the ball? It seems like it begins to slide, at first. But then it catches and begins to roll. What's going on here?

Well, there are a couple of concepts at play here. First is the concept of friction. Whenever you have an object rubbing against another, Newton's third law is at play, and you get this equal and opposite reaction demonstration we talked about before.

In this case, the ball feels a force at the point of contact with the pool table. That's due to all the roughness at the surface of the table. In fact, friction is eventually responsible for the ball coming to rest.

Now, whenever one applies a force to the edge of a sphere, or something that turns, one is introducing torque, which are responsible for making the thing spin or turn. One example of this idea is seen every time you push a door open. You never open a door by pushing on its hinges. Rather, you push the door as far away from the hinge as you can. With minimal effort, you're able to swing, or rotate, the door to open.

And when you strike the cue ball at the center, or just above it, initially the ball is moving across the table without spinning. But at the bottom of the ball-- this is where it's making contact with the table-- friction is at work, pushing the ball in the opposite direction. And eventually, friction wins, and the ball begins to roll.

That makes sense from my experience playing. Sometimes I want to strike the cue ball closer to the bottom. And sometimes, I want to strike the ball closer to the top.

Let's think about that. What happens when you strike the ball just below the center? Which way does the ball want to spin? And when would you use such a shot in the game of pool? Why don't you discuss it amongst ourselves, and we'll be back shortly.

Welcome back. Now, Jose will demonstrate what happens when you strike the cue ball just below the center. As you can see, the ball slides a lot more at first, and eventually starts to spin in such a way as to come back to me. This is useful if I want the cue to come back to this side of the table. Likewise, if you were to strike the cue ball just above the center, then the ball will want to continue rolling away from you.

All right. Well, looks like you've set yourself up for a nice line shot to the eight ball corner pocket. Can you remind me which law of Newton's we're illustrating in this shot, Jose?

Oh, it's not Newton's law. It's Jose's law.

That should pretty much do it for today's lesson. Thank you, again, for participating in today's session. And thank you, Jose, for showing us some of the tricks of the trade.

My pleasure.

At the risk of getting some of the parents mad at us, I hope the next time you look at the game of pool, you'll realize there's a lot more to the game.

So do you want to play another game?

Yeah, sure.

You know, for a physicist, you're not actually that good at beating me.

Well, that's because I'm thinking about the quantum mechanics of the problem.

Oh. Or maybe I'm just better than you.

How about we just play?

Hello. We wish to thank you for considering this video as part of your teaching lesson. I will now discuss a few of the basic concepts that we hope to have shown in this small video. We wanted to basically show some of the few laws of physics that come about in everyday life. And we chose pool as a way to demonstrate this.

There's a few concepts that we went through that you may want to discuss with your students. In the first part, we talked about linear momentum, which is basically a idea of conservation. For the more advanced students, you may want to go through an exercise where it shows the actual conservation of linear momentum. For students that are just taking physics for the first time, or are not introduced to advanced mathematical concepts, you may just want to install the idea of direction and motion playing a role in predicting how the balls will behave when they're struck.

In the second part, we talk a little bit about different concepts, such as friction. In the friction portion, you may want to have students experience some different surfaces that have different friction properties. For example, having accessible surfaces that are smooth, and surfaces that are rough, and then seeing how various objects, such as balls or even blocks, move when they slide across them. This will give them more of a intuitive feel for what friction is like.

And then finally, we talked a little bit about torque, without going into much detail. This is the concept of having things move and spin when subject to a force. There, I would have the students really to look at systems that can turn. I mentioned a doorknob and sliding door as an example. If you have balls available, you may also want to have the students observe what happens as objects move and are pushed in different ways.

We hope that this very simple video shows the basic concepts of physics, especially to introductory students, and at the same time, having a little bit of fun in the process. Again, thank you for your attention. And we hope to see you next time. [MUSIC PLAYING]