Bumper Cars

Introduction

Hello. I'm Lou Bloomfield and welcome to ***How Things Work*** at the University of Virginia. Today's topic: Bumper Cars. Like many amusement park rides, bumper cars involve almost as much physics as they involve fun. A bumper car is a small electric vehicle that is surrounded on all sides by rubber bumpers. Those bumpers are essential because collisions are unavoidable in bumper cars. In fact, the whole point of driving a bumper car is to crash into as many other cars as possible. If you've never seen bumper cars, picture a rectangular or oval floor surrounded on all sides by a padded wall with bumpers on it. That's that arena for bumper cars. And driving around this arena are about 20 little electric cars, each just big enough to hold one or two people. Every car has a steering wheel and a motor that's controlled by a pedal. So, it resembles a little car, more like a golf cart or something. And the drivers drive around that arena wildly and smash into one another frequently. It's a blast.

Not surprisingly the bumper cars are designed to move relatively slowly and their passenger compartments have lots of padding. Still, you can experience some pretty intense impacts. And it's those impacts that I'm going to be talking about in this episode. When two bumper cars collide, they typically exchange some energy. So, that we've seen. But they also exchange two other observed physical quantities: **momentum** and **angular momentum**. Those conserved quantities are new to us--and they are so important in bumper cars that they won't be so new by the end of this episode.

As great as it would be to have a bumper car arena at the University of Virginia, I didn't manage to make that happen this semester. So, I'm going to have to make compromises. But don't feel too sorry for me. To start with, I have these great little miniature hovercrafts. I actually have four of them, and they can zoom about the table and bump into one another. Boing. Boing. Collisions galore. They're perfectly good bumper cars. If you happen to be a gerbil.

I also have a miniature bumper car arena. Ha, ha, ha. Look at this. Okay. It's actually a small air hockey table. But there's no real difference. I can send discs around this arena, and have them crash into one another. Look at that. Woo-hoo. And there's pretty much everything there that you would see in bumper cars, except for laughing children. So, using these cars, these guys, and my little arena, we can examine the important roles that momentum and angular momentum play in collisions. And we can study the processes whereby those quantities are transferred from one object to another. And, although, we'll examine them in the context of bumper cars, momentum and angular momentum will reappear in everything from roller coasters to rockets as we continue to look at how things work.

At this point, I'm going to post a question and ask you to keep it in mind, as we explore bumper cars. So, hopefully, you have seen or ridden on a playground merry-go-round--one of these surfaces that you can spin and whip yourself around in a circle. The question is this. If you're riding a playground merry-go-round and you climb to the center of that merry-go-round (from the outside edge to the center) how will that affect its rotation? To help guide us through the science of bumper cars, we'll pursue five how and why questions.

- Does a moving bumper car carry a force?
- How is momentum transferred from one bumper car to another?
- Does a spinning bumper car carry a torque?
- How is angular momentum transferred from one bumper car to another?
- How does a bumper car move on an uneven floor?

There's one video sequence for each of those questions and a summary video at the end. Now, on to the first question.

Part 1

Does a moving bumper car carry a force? The answer to that question is no. The moving bumper car carries momentum, but it cannot carry a force. A force is exerted by one object on another object. So a single object can't carry a force. But we intuit that a moving bumper car carries some physical quantity of motion with it, some capacity to make other objects move in the direction of its motion. That physical quantity of motion does exist. And the bumper car is in deep carrying it as it moves. That physical quantity is called momentum and **momentum is the conserved quality of moving**. As required by conserved quality, momentum cannot be created or destroyed but it can be transferred between objects. So when I bump these two bumper cars into one another, they transfer some of their momentum, and you can almost see that. If I make one of them move and hit the other, one stops; the other goes. They're transferring momentum.

Now momentum differs from energy another conserved quantity that we've already encountered in a number of crucial ways, two of them in particular.

- First unlike energy, momentum cannot be stored. There's no such thing as potential momentum. Potential energy exists because energy isn't about moving, it's about doing. So moving objects have kinetic energy but even a stationary object can have potential energy. Right now the bumper car has gravitational potential energy. Momentum however is really about moving, so without motion there's no momentum. A moving object has momentum, a stationary object does not. Or, to be more technically accurate, a stationary object has zero momentum.

- The second way in which momentum differs from energy is that momentum is a vector quantity; it has a direction. To show you this, along with the fact that momentum is truly conserved, I need more room.

So, here I am in a bigger venue, a classroom, and I have a wheeled cart. It's kind of like a skateboard for real beginners, like me. And, I need the wheeled cart because friction tends to give away my momentum to the earth. And I don't need that. I mean, as it is, air resistance, (there are many ways in which my momentum can leak out of me, not because I'm destroying it but because I'm giving it away). So, the wheel cart makes that effect relatively small. I can show you momentum going in and out of me. Back in the lab I use air cushions to move around the objects without letting them retain their momentum. Here it’s wheels, so to start with I have no momentum. And because momentum's conserved unless something gives me momentum, I'm never going to move. I need to get some momentum. And where we're going to get from is the wall. I'm going to have the wall give me momentum to the right.

Momentum has a direction. It’s a vector quantity, so the wall's going to give me momentum to the right. Now that will cost the wall--the wall will be giving up momentum to the right. This is actually meaning that it ends up with momentum to the left. We'll deal with that a little bit later on. But imagine right now, when I push on the wall, (we'll talk about how the transfer occurs later, next video) the wall pushes on me, giving me momentum to your right, and I'm going to carry it with me. Are you ready? Here we go. I have momentum; I can't stop until I give my momentum away. When I got over to this wall I gave it my rightward momentum and came to a stop.

That's great, now I can do the reverse. But this time I don't want the wall to give me rightward momentum. I want the wall to give me leftward momentum. Here we go… I'm going to push on the wall the wall is going to push on me, it's going to give me a nice dose of leftward momentum… and I got it… I can't stop until I give it away again. So I can do this all day. It's kind of fun, and a little dangerous, but not too bad. Off I go. I'm carrying it back and forth. And each time I do this, I'm exchanging momentum with the wall and therefore the whole earth, carrying whatever I end up with, with me, eventually giving it back to the wall and the whole earth.

Let's start that again, but now I want you to watch when I encounter the wall on the right. So, I'm going to obtain rightward momentum. I'm going to head toward the wall on your right, and when I get there I'm going to do two transfers of momentum in sequence. Here we go. First, I'm going to get the momentum to the right, out of the wall. I got it. I'm carrying it with me. I give it all to the wall. And then I give more momentum to the right to the wall, and that costs me. I end up missing momentum to the right, which is to say, I have momentum to the left. A negative amount of momentum to the right is momentum to the left. And when I encounter that wall on the right I can do it again. I can do this over and over (as long as I don't get injured). Off I go. I'm going to give it my rightward momentum and extra rightward momentum. I gave it more rightward momentum than I had. And I ended up with a deficit of rightward momentum, less than zero rightward momentum. This is to say leftward momentum. That's what you do when you bounce off something.

So when you bounce, you might want to bounce something other than yourself, off of a wall. Unless you’re a small child having a lot of fun and bouncing off walls. So when I encounter that wall and I give it more rightward momentum then I ever had. Here it goes I'm going to give it all one my momentum and extra. I end up with leftward momentum until I give it away to the wall again. As you can see, to go from having momentum to the right to momentum in the left, I have to make a huge exchange of momentum with something else. I can't just simply turn my momentum around.

Rightward momentum and leftward momentum are very different. And therefore when I'm heading to your right I can't simply turn around and head to the left without help. I need some other object like this wall to exchange momentum with in order to reverse my direction of travel. And that's one of the reasons why objects that are all by themselves just keep going in a straight line at a steady pace. This is Newton's first law of motion again but with a more sophisticated twist.

One way of looking at why objects that are left to themselves keep going at a constant velocity is that they have a certain momentum. And without help, they can't change their momentum and they have to keep going. Well, for me here on this cart, when I'm out in the middle of the room I have to carry my momentum with me. I've got no choice, but in a bumper car arena there are lots of other objects around with which to exchange momentum and that's part of the fun of bumper cars. So we'll go back to the lab and start playing with bumper cars.

So here we are back in the lab, I am going to save the exchanges of momentum between bumper cars for the next video and concentrate for now on the momentum of a single bumper car. So here we are bumper cars solitaire - it's boring, but instructive. You can think of momentum as the currency of motion. And the momentum of our lone bumper car reflects how much of that currency had to be invested into the bumper car to bring it from rest to its current motion.

It turns out that a bumper car's momentum, like that of any object, depends on only two things:

- its mass, and
- its velocity.

Let's start with mass. **Momentum is proportional to mass**, and I can show you a simple reason why that should be true. Let's start with one bumper car that's moving. It has a certain momentum, in this case to the right. If I take a second identical bumper car, and make it move exactly lie the first bumper car, then it has the same momentum, again, to the right in that case. Suppose that these two bumper cars are being driven by people who are friends and they hold hands. Doing that turns this pair of bumper cars into one single, larger bumper car. And if we get it moving exactly as it was before, it's now a single bumper car with twice the momentum of each bumper car individually. All I've done then, is double the mass of a bumper car and I'm evidently doubled the momentum of the bumper car as well. Well this is a typical physicist analyst where you look at the situation, the two cars by themselves each one has one portion of momentum. And when you do something that has essentially no effect on the situation, you just have the people just touch hands; they become a single bumper car with twice the mass and twice the momentum. That analysis is typical of what physicist would do. But the bottom line is quite important.

The momentum an object has is proportional to its mass. It turns out that a bumper car's momentum is also proportional to its velocity. To start with momentum and velocity have the same direction. But even the amount of the bumper car's momentum is proportional to the amount of its velocity. To see that momentum should be proportional to velocity, I'll put away the double bumper car and bring out two bumper cars that have Velcro bumpers. These bumper cars don't bounce off one another when they hit; they stick. And now, I will give a usual portion of rightward momentum to the first bumper car and let it collide with a motionless second identical bumper car. When that collision occurs, the first bumper car will have to share its momentum with the second identical bumper car. What will happen to the velocity of the first bumper car when it's got half the momentum it started with? Its velocity drops by a factor of two. It travels only with half its original velocity.

So, decreasing the momentum of the first bumper car by a factor of two decreases its velocity by a factor of two. Showing that it's exactly a factor of two requires a calculation that I won't do, but that's really the case. Momentum really does drop by a factor of two. So, overall then the momentum of a bumper car is proportional to its velocity. Combining these two observations, the momentum of a bumper car is equal to its mass times its velocity. That relationship gives us some interesting insight into what happens with bumper cars. Let me turn these guys off. The vehicles themselves have relatively little mass, so the riders contribute significantly to the total mass of a bumper car, and thus to its total momentum. The bumper car’s behavior changes depending on who's riding in the car. When the only rider in a bumper car is a little child, the car carries relatively little momentum.

We'll see in the next video, when I start crashing bumper cars into one another. The low mass cars can't transfer much momentum to whatever they hit, and don't affect other cars very much. In the world of a bumper car arena, the cars with the little kids in them are like bugs zipping around a lawn party. You barely notice when they hit you. At the other extreme is a bumper car that's carrying a couple of couch potatoes. I'm thinking in terms of really big people. In a car that's filled with really big people has a truly enormous mass. That car carries considerable momentum, even when it's moving slowly. And it can transfer large amounts of momentum to whatever it hits. Its effects on other cars then, are substantial. It's like a big hammer in a box of nails or a bowling ball in an alley full little bowling pins. It knocks everything for a loop.

So, how about velocity issues? What insights can we gather from the fact that momentum is proportional velocity? Well, the faster a bumper car is moving, the more momentum it carries. Carrying a huge momentum is fine. But huge transfers of momentum can be a problem, even dangerous.

So, think about dropping a melon off a tall building. Near the bottom of its fall, the melon has enormous downward momentum. And that alone isn't a problem for the melon. Hey, says the melon. Wow. This is kind of cool. The whole world is rushing up at me really fast. It's not the fall that's the problem; it's the ground. When the melon reaches the ground, it transfers its enormous momentum to the ground, and the melon stops having fun. So because of the associated lawsuits, the people who run bumper car arenas limit the speed of bumper cars. Bumper cars are supposed to be fun and exciting, not death defying. So the masses of the cars themselves are small. Everybody who sits in the cars has a big influence on a car's mass and therefore the momentum the car carries with it. The velocity of the car, the faster it's going, the more momentum it's carrying in the direction of the velocity, but they limit that maximum amount, so that you're not transferring huge amounts of momentum when you collide with things.

So now for a question that's easiest to answer if you think in terms of momentum. Suppose your spaceship is coasting forward through empty space at constant velocity. You decide to get rid of the trash by throwing backward out behind the ship. In other words, you give the trash backward momentum. What affect, if any, does that actually have on your ship's velocity? By throwing the trash out backward, you're giving the trash backward momentum. You have less backward momentum as a result. You've given it away and it's a conserved quantity so you have less backward momentum which is equivalent to more forward momentum because a negative amount of backward momentum is a positive amount of forward momentum. So the remaining ship has more forward momentum than it had before. It also has less mass than it had before.

With more forward momentum and less mass, you’re traveling at a greater forward velocity. Your ship is traveling faster. This whole process of throwing stuff out the back is how a rocket engine works. Now, you threw trash out the back and you're possibly in trouble with the galactic police. But if you throw gasses out the back, as you would with a rocket engine, you're not going to get arrested, and you're going to propel the ship forward at a greater velocity. The act of throwing gases out the back of the ship at great speed causes them to carry away backward momentum and leaves the ship with additional forward momentum. And so it picks up velocity. That’s how rocket engines work, as we'll see in the episode on rockets. At this point you could picture a bumper car arena as filled with vehicles, each carrying its own momentum equal to its mass times its velocity. The stage is set for big things to happen. But that's going to require collisions, which is the subject of the next video.

Part 2

How is momentum transferred from one bumper car to another? The answer to that question is that the first bumper car does an **impulse** on the second bumper car. Just as you can transfer energy by doing work, you can transfer momentum by doing an impulse. So what exactly is an impulse? And impulse is a force exerted for a time. For example, I do an impulse on this bumper car by pushing on it as time passes. The product of my force on the bumper car times the duration of that force is the impulse and corresponds to the amount of momentum I transfer to the bumper car. Since an impulse transfers a vector quantity, namely momentum, that impulse is also a vector quantity. An impulse points in the same direction as the force responsible for it. So, for example, if I push the bumper car to the right, the impulse points to the right and transfers rightward momentum to the bumper car. If I push the bumper car to the left, my force points to the left, the impulse points to the left, and I transfer a leftward momentum to the bumper car.

Of course, at an amusement park, people don't usually transfer momentum to bumper cars. Bumper cars transform momentum to bumper cars. So, here's one bumper car. And it's going to do an impulse on a second bumper car and I'm going to make it so that this bumper car is going to hit that one, like this and it's going to do a rightward impulse on a second bumper car. Here we go. Ready. So, this guy transferred momentum to that guy. But actually, there were two impulses occurring during that collision. We've seen one. This one did impulse on that one; it exerted a force on that one over a period of time. But simultaneously, the second bumper car did an impulse back on the first bumper car in the opposite direction. It had to--this is Newton's third law. As this one pushes on that one, that one pushes back on this one equally hard in the opposite direction. So there were two impulses occurring simultaneously. That bumper car did a rightward impulse on the second bumper car, but at the same time, the second bumper car did a leftward impulse on the first bumper car.

That means that the second bumper car transferred leftward momentum to the first bumper car. But leftward momentum is the same as a negative amount of rightward momentum. So as this bumper car was transferring rightward momentum to that bumper car, the second bumper car was taking away rightward momentum from the first bumper car. That's how the transfer works. The bumper car over here transfers right where momentum the second bumper car and gives it up. It comes out of this one into that one. And you can see that where the collision occurs. The original bumper car basically has lost its rightward momentum, and the second bumper car carries it away. You can see, this one almost stops, and the second bumper car carries away the rightward momentum that had started in the first bumper car.

The transfers of momentum that are occurring as these two bumper cars collide have to be perfect, because momentum is a conserved quantity. Whatever momentum the second bumper car receives, the first bumper car has to loose. Let's return to the fact that an impulse is proportional to both the force that's responsible for it and the time of which it adds. That's a rather interesting result. I'm going to go back to pushing a single bumper car by hand. Now, of course, I can increase the amount of momentum I transfer into that bumper car. Either by pushing harder or by pushing for longer duration, but that's not surprising.

What is somewhat remarkable is that I can transfer the same amount of momentum to the bumper car with different pairings of my force and its duration. As long as the product of my force times the duration doesn't change, I'd do the same impulse and transfer the same amount of momentum to the bumper car. For example, I can start by exerting a medium force for a medium amount of time. Here we go. I pushed it medium hard for a medium amount of time and off it goes. But I can do the same impulse by pushing hard for a short amount of time.

Same thing, or I can go back and transfer the same amount of momentum by using a gentler force for a longer duration.

I have some choices here. Are there any consequences to changing those pairings of force and duration? Oh, yeah. The faster the momentum transfer occurs, the shorter its duration and the larger the force must be. Big forces can break things. For example, here's a hammer. And I'm going to invest some downward momentum in that hammer, before it encounters a nail on a piece of wood. And when the hammer reaches the nail, it's going to transfer all of its downward momentum to the nail by way of an impulse. The hammer will exert what is known as an impact force on the nail as it transfers its momentum to the nail. And that transfer is going to occur in the blink of an eye--short duration, so the force has to be huge. The hammer exerts such a large force on the nail that it pounds the nail right into the wood.

I'm going to try that again, but this time, I'm going to tape a rubber stopper on to the tip of the hammer before I hit the nail. Now, there we go. I'll pull the nail back out. Now, I'm going to try to pound in the nail again--doesn't work. I'm giving the hammer plenty of downward momentum before it strikes the nail. The hammer is still. Transferring all of its downward momentum to the nail, but somehow that doesn't cause the nail to enter the wood. The problem is that the impulse that's occurring when the hammer hits the nail involves a much longer time now. The softness of that rubber stopper prolongs the impact. So, there's a long impact. Consequently, there has to be a smaller force, and so there is.

The force that develops, the impact force of this rubber hammer hitting the nail is too small to push the nail into the wood. I occasionally insert what I call public service announcements into my how things work course and here's one of them. This type of baseball used in professional sports is mounted here on a handle so that it looks like a hammer. The baseball is extremely hard. It's so hard that it transfers its momentum to whatever it hits extremely fast. Because the duration of that impulse is so short, the force of the impulse can be huge. You could pound a nail in with this kind of baseball. In contrast, a somewhat softer ball, so this ball has the same mass, carries the same momentum, with the same velocity as a professional ball, but it's got a somewhat softer surface. And it takes a little longer to transfer its momentum with a longer duration for its impulse. The force of that impulse is smaller.

So these softer balls are soft strike, or reduced-impact force balls, because the longer impulse involves a smaller impact force. This type of ball can’t pound in a nail. In fact, you can hit your own hand with it. Don't try that with a professional sports ball. My advice is this. Be careful with the professional hard balls. Or consider switching to a softer ball. A fast-moving hard ball is effectively a loose hammer, and it can cause serious injury or worse if it hits you in the wrong place.

So the trade-off between forces and durations is also important with bumper cars. You've seen these bumper cars with their rubber bumpers. Without those bumpers the steel frames of the cars would hit and they would transfer momentum way too fast. I can show that because the bumpers come off these guys, and I've already removed the bumpers from this pair of bumper cars. So, if I turn them on and bump them into each other, this kind of bumper car, a bumperless bumper car, wouldn't be very fun. The transfers of momentum are so fast, involve such big forces, that the cars will get damaged by them. And you, as a rider in one of these cars, will also experience unpleasantly large forces in rapid accelerations. It's not going to be good. So, if you have the option of going and riding bumperless bumper cars or bumperless cars, skip it. Go for the bumper cars.

It's time for a question. We've seen that it's entirely possible to use a hammer to pound a nail into the floor. So the question is this, can you use a hammer to pound a nail into the ceiling? You'll have no trouble driving a nail into the ceiling with a hammer. That's because the impact between hammer and nail occurs over a very short period of time and transfers the hammer's momentum, the upward momentum, to the nail so quickly that it involves an enormous force. A force that's capable of pushing the nail right into the ceiling. You might worry about gravity during this upside down hammering process, but the force of gravity is so small compared to the force of the hammer on the nail during the impact that it just doesn't amount to anything. You can pretty much ignore gravity when it comes to hammering.

Bumper cars obtain their initial forward momenta from the floor. Like ordinary cars, bumper cars have powered wheels. And they use frictional forces between those wheels in the floor to propel themselves forward. As the floor pushes the bumper car forward the car gradually accumulates forward momentum. The impulse that it's experiencing as it picks up speed involves a relatively weak frictional force from the floor exerted for a long period of time. During collisions however, things happen so fast that there's very little momentum transfer to the floor. The frictional force between the wheels and the floor are just too weak. And there isn't enough time for any significant impulses. So, when two bumper cars collide, they're pretty much on their own during that collision. As though there's nothing else in the universe. And for the sake of simplicity, I'm going to assume that they're completely on their own. Ignore the floor. Since momentum is conserved quantity, the collision can redistribute their momentum, their total momentum, but it can't change that total. Their total momentum before and after the collision has to be the same.

The same is true for energy. The collision between two bumper cars can redistribute their total energy, but it can't change that total. Unfortunately, the collision between bumper cars can and does grind up some of their ordered energy into thermal energy so that we don't see it after the collision. But that wasted energy is relatively small for bumper cars and so for simplicity, I'm going to ignore it. For the experts, perfect collisions, ones that waste no energy are known as **elastic collisions**. Those that do waste energy are said to be **inelastic**. Elastic collisions are somewhat simpler to understand then inelastic collisions. So pretend the bumper cars bounce perfectly and waste no energy. We'll make our lives a little easier without really changing the story.

A collision between two bumper cars has two important constraints:

- their total momentum can't change, and
- their total energy can't change before and after the collision.

Together, those two constraints determine how the cars bounce from one another. The simplest case is two identical bumper cars, and that's what I have here. These bumper cars have the same mass, they're basically indistinguishable. And the need for them to have the same total momentum and total energy after the collision as before the collision really constrains how they bounce. And you get these very interesting effects, like, if they have head-on collisions (collisions that are entirely along one line) they exchange motion. So if I have one of them at rest and I slam the second one into it, they trade their motion. The second one continues on as though it were the first one. And the first one continues on as though it was the second one.

It works like that. It works if I slam then both like that…all of these variations. They trade places--in effect in their motions. If they hit off center, if they're not riding this rail into each other and apart, then you get more complicated motions, but still they're all related. Very highly constrained bounces--and this is how bumper cars the bumper car arena will behave if they have identical masses. Actually, you don't even need bumper cars to see some of these effects. Any objects that are identical and that bounce almost perfectly off one another will work. For example, coins. Here are a bunch of US quarters. And if I bump one of them into another quarter head on, perfect shot, they'll trade motion. The first one stops, the second one continues on as though it were the first one. Actually you can line a whole series of these quarters up and if I hit the first one head on, the last one will go on as though it were the first one.

It's all about conserving momentum and energy during a very complicated collision. That causes the first one to stop and the last one to continue on. Actually, people have made toys that use this principle called either Newton's cradle or the executive toy, which doesn't say much about executives, but that's the name under which it goes. This has a set of very elastic balls. They're made of steel and they bounce almost perfectly off one another and if I take the first one and I make it smack into the entire row of balls the last will come off. It's a series of collisions in which energy and momentum have to be conserved, and the only way that can work is if the motion propagates through the entire row of balls and the last one continues on as though it were continuing the work of the first one.

It's time for the full glory of bumper cars, and that means having bumper cars with different masses. So, I brought the little bumper car arena. And first I can show you things you've already seen before. I can take two bumper cars that have identical masses. They differ in color, but otherwise, they're identical. And if I smack the green one into the red one, the red one continues on with the green one's motion. They exchange motion. So far, so good. But the real interesting stuff starts when I bump different bumper cars into each other. That is, ones with substantially different masses like this green one and this little red one. When these collide, different things happen. I'm going to make the green one hit the red one. It just swats the red one out of the way, and the green one continues on. Watch that again.

Why did that happen? Well, the physics isn't too hard to understand. When the green one collides with the motionless red one, it begins to transfer to conserve physical quantities. The right one is transferring momentum by way of an impulse and it’s transferring energy by way of work. It's using the same force to make both transfers but the impulse involves force times time while the work involves force times distance. The little red one moves easily during the impact. It's being pushed on and it's accelerating, and picking up speed, and beginning to move so the green one is able to do a lot of work on it. It's travelling in the direction of the force. So, the green one's doing work on it and it turns out that the green one is able to do enough work on the little red one to set it off in the distance before the green one has had time to transfer all of the green one's momentum. So, the green one keeps on going it only gives some of its momentum to the little red one. The little red one runs away too soon and heads off in the distance.

The reverse is also interesting. Let the little red one collide with the stationary green one. Watch what happens there. The little red one bounces backwards. I'll do it again. How did that happen? Well, when the little red one arrives at the green one, it's again trying to transfer to conserve quantities to the green one. Momentum and energy: momentum by way of an impulse; energy by way of work. So the red one begins to push on the green one. That force is going to transfer both of these conserved quantities. But the green one won't move, not very well, any way. It's massive. It's very hard to get that green one moving. So it doesn't travel very much distance during a collision. Therefore the red one is barely able to give the green one any energy. It can't do much work on that almost immobile green one.

But the red one tries and tries and tries, so a lot of time goes by during the impact. And the red one manages to transfer all of its momentum and it transfers more momentum, even than it had. So it was heading to the right, it gives all its rightward momentum to the green one and extra. And it ends up with a deficit of rightward momentum. Which as we know is leftward momentum--and it heads backwards. It tried to give the green one all its energy and momentum. And it didn't manage to give the green one much energy. But it gave it a lot of momentum and off it goes backward.

So all of these impacts, then, are making use of these transfers: energy and momentum, trying to get everything to work out right, because those two quantities have to be conserved. So this explains a lot of what you see or experience in bumper cars. The really massive cars, the ones carrying a lot of heavy, high mass occupants pretty much swap the other cars out of the way when they hit them. They transfer a lot of energy to those cars, but not all of their momentum. And so these big, massive cars just keep on going. They still have momentum after the impact--in the same direction they had before the impact. The little cars, on the other hand, bounce off the other cars when they hit them. Because they don't manage to transfer much energy to those other cars, but they transfer a lot of momentum and they bounce back. The things that I've said about bumper car collisions apply to many other collisions.

So let me ask you a question. To successfully catch a ball, why do you have to let your hands move with the ball as it collides with your hands? By letting your hands move with the ball as it collides with your hands, you're letting the ball do work on you and transfer its energy to you. In the process, it transfers its energy and its momentum and comes to rest, and that's how you catch things. If you hold your hands rigidly in place as the ball hits them, it's going to be able to transfer momentum to you, but no energy. And it will actually bounce off you like, like the little bumper cars bouncing off the big bumper cars. They bounce backwards.

So that's it for translational motion in bumper cars. We see how momentum moves from car to car during the collisions, as they do impulses on one another. But not all of the motion in bumper cars is in straight lines moving from here to there. Bumper cars can also spin. They exhibit rotational motion. So the next video is about the rotational motion of bumper cars. And the associated conserve quantity known as angular momentum.

Part 3

Can a spinning bumper car carry a torque? The answer is no. The spinning bumper car carries angular momentum, but it can't carry a torque. As you've probably guessed, the story I'm about to tell you is a rotational equivalent of the translational story I told in this episode's first video. Like a force, a **torque** is exerted by one object on another object. So a single object can't carry a torque. But there is a physical quality of rotational motion that a spinning bumper car does carry. A capacity to make other things turn in the direction the bumper car is turning. That physical quantity of rotational motion is called **angular momentum**. And angular momentum is the conserved quantity of turning. As required of any conserved quantity, angular momentum can't be created or destroyed. It can only be transferred between objects. So, one bumper car can transfer angular momentum to a second bumper car.

Fortunately for us, angular momentum has many similarities to what is called **linear momentum**. Still, those two are separate quantities and they're conserved separately. And a bumper car carries both of the simultaneously, so I can send this guy along with momentum, angular momentum, and both. Out of control, there we go. Together with energy, a bumper car can carry three conserved quantities altogether. And those three conserved quantities determine much of how the bumper car behaves.

Like linear momentum, angular momentum involves motion. There is no such thing as potential angular momentum. A bumper car that's turning around some center has angular momentum, and one that's not turning about that center has zero angular momentum. Angular momentum is also a vector quantity. It's about rotation, and rotation is a three-dimensional activity that requires direction. I can rotate like this. I can rotate like this. Not very far. But you get the idea that rotation is complicated in three dimensions. So you have to specify it with direction. And just as angular velocity has a direction, so angular momentum has a direction. And you use the same rules.

Now, I can show you the direction of angular momentum in a single bumper car by choosing as the center of rotation the bumper car center of mass that's sort of the natural center of rotation for the bumper car and I'm going to give it first angular momentum upward like this here it is. It has angular momentum upward. And now, I'm going to get angular momentum downward, like that. And it's got all the variety of a vector quantity, upward, downward. In principle, I can do toward me, there it is toward you. Not very good for a bumper car.

And finally, it has an amount--this is a little bit of angular momentum upward, and this is a lot of angular momentum upward--always about that center of rotation which is a center of mass of my little lone bumper car. Well, to show you more about angular momentum and in particular, that it's a conserved quantity, I'm going to return to the classroom, and go for a spin myself.

So here I am in a classroom. And I'm going to sit on this swivel chair, which is the rotational equivalent of the wheelie cart that I used for linear momentum. This swivel chair spins so freely, or so nearly freely, that I can't exchange any angular momentum about my center of mass with the earth and it allows me to kind of coast in terms of angular momentum. The angular momentum that's in me won't leak out very quickly into the ground. There are issues of air resistance too, but basically I can show you that my angle management's conserved. Now I'm having trouble trying to look at the camera because the thing swivels so easily, and I can't get started turning, without something investing angle management in me because I can't create any momentum. Whatever I've got, I've got. Now I've got some slight rotations going on here that have to do with the imperfections of this system, but basically, my angular momentum is zero right now. And to get some angular momentum, I need to obtain some from the ground.

So I'm going to put my foot down and I'm going to have the ground twist me. It's going to exert torque on me, and I'll get some angular momentum. Here we go, ready? I'm going to get some angular momentum. I got it. And now that I’ve got it, I can't get rid of it. I’ve got to keep going. This is a little less pleasant than coasting across a room. I'm going to get awfully dizzy, so I have to get rid of my angular momentum and the way I‘ve got to do that is by giving it to something else. So I'm going to give it to the ground with my foot again.

Ready, there we go--gave it to the ground and I wish you guys would stop moving. So that was angular momentum upward. Now, I can get some manual momentum downward by twisting the ground the other way having it twist me back and woof, I've got angular momentum it's now downward. I've got downward angular momentum. And I can't stop until I give it away. There we go. It’s got a direction and the same kind of ideas apply as with linear momentum: that if I want to reverse directions, I need a huge transfer of angular momentum, because not only do I have to come to a stop and get rid of my initial angular momentum, but I also have to reverse, go the other direction around, which requires still more exchange of momentum with the ground.

To show you that more concretely, let me get some angular momentum upward. Here we go, okay, I've got it now. A little less, so I'm not quite so dizzy. And now, to reverse my direction, I'm going to have to give all my upward angular momentum to the ground. Here we go. And, I have to give more than I had in reverse directions. So I gave the ground more upward momentum than I actually had, and I ended up with a deficit of upward momentum which is to say, downward momentum. And here I am, rotating downward. So angular momentum is a conserved quantity. Once you're isolated and you can't exchange it with anything, whatever you've got, you've got. It's trapped in you. And to exchange it, well, there's a mechanism for exchanging it, and that will be the subject of the next video.

My angular momentum depends on two things:

- my rotational mass, and
- my angular velocity.

And it turns out to be proportional to each of those quantities. That is, the more rotational mass I have, the more angular momentum I carry, or the more angular velocity I have, the more angular momentum I carry. Actually, angular momentum is equal to rotational mass times angular velocity. So if I turn, if I bring myself in close to the center of rotation and shrink my rotational mass, then I'm have a small rotational mass. And if I rotate very slowly with a small angular velocity, then the product of a small rotational mass times a small angular velocity isn't quite as small angular momentum.

On the other hand, if I increase my rotational mass by spreading myself out far away from the center of rotation, now even at the same angular velocity as before, I'm carrying more angular momentum. If I go back to my original rotational mass and spin faster, again, I'm carrying more angular momentum. Where things get interesting is, if I have a certain angular momentum invested in me by the ground, and I change my shape, I can change my rotational mass. I'm not a rigid object. If I change my rotational mass, but I don't exchange angular momentum with anything around me, my angular momentum has to say the same.

If my rotational mass changes, then my angular velocity has to change to compensate to keep my angular momentum constant. This is actually a fun demonstration, one you've seen before. I'm going to do it in a physicist version, but you've seen it as the ice skater trick if you've watched ice skaters spinning. If I start spinning with my arms out and these massive dumbbells in them I have a huge rotational mass, and even when I'm turning relatively slowly, small angular velocity, I have a lot of angular momentum. If I then shrink my rotational mass by pulling the dumb bells in, I still have a lot of angular momentum, my angular velocity has to increase to compensate. Because the product of my now small rotational mass times what will have to be a large angular velocity has to come out equal to my angular momentum, which is large.

So here we go. I have a large rotational mass and even though I'm turning slowly I've got lots of angular momentum in me. It's upward and now as I pull these masses in, I spin faster. I have to because my angular momentum is constant. Everything else can change, but not my angular momentum. So skaters do this trick where they start spinning with their arms out and then they pull in tight and they spin faster as their angular momentum stays constant, but their rotational mass shrinks and their angular velocity increases.

Well, with that then, I'm going to go back to the lab. Because I'm getting pretty dizzy. It's time to stop. Wait a second. This isn't my laboratory. What am I doing here? Is this some sort of big picture moment or something? Actually it is. I'm going to revisit Newton's first law of translation motion and rotation motion with some new insights gathered from our experiences with momentum and angular momentum.

Think about Newton's first law of translational motion. It says that an object that's free of external forces moves at constant velocity, and I'm going to make myself an object that's free of external forces so I move at constant velocity. What underlies that law, Newton's first law of translation motion, is actually conservation momentum.

Once you're isolated, free of external forces, your momentum is constant. And because your mass can't change your velocity can't, change either. After all, your fixed momentum--the momentum of an isolated object, is equal to your mass, which can't change, times your velocity, which therefore, can't change. So once I start moving along, I have a fixed velocity because my momentum is constant and because my mass is constant.
So that's the real origin of Newton's first law of translational motion, conservation of momentum. What about Newton's first law of rotational motion? Things are a little different. Newton's first law of rotational motion has underlying it **conservation of angular momentum**.

Once you're free of external torques (and I'll add the word rigid and I'll come back to it), your angular momentum can't change. So, if you're rigid, your rotational mass can't change and therefore your angular velocity can't change. So the angular velocity's constant because your angular momentum is constant and your rotational mass is constant. So, your angular velocity has to come along for the ride. It's got no choice.

But, what if you're not rigid? Remember that word rigid in Newton's first law of rotational motion. Why was the word rigid in there? It's because if you're not rigid, you can change your rotational mass. You can't change your ordinary mass. That's really, really, really fixed, but you can change your rotational mass by changing your shape. And if you do that, Newton's first law of rotational motion no longer applies to you. And what's more, you do experience changes in angular velocity, for a good reason. So I'll isolate myself again into some separate from the whole world and now my angular momentum is constant because it's conserved and I can't exchange it with anything. And my rotational mass is constant because I'm playing at being rigid. So therefore my angular velocity is constant. It's coming along for the ride.

But if I change my shape, all bets are off. My angular momentum still is constant, but because I changed my rotational mass (I increased it) my angular velocity decreased. That's a remarkable thing that you can do in the world of rotation because you can change your rotational mass. In the world of translation, you can't change your mass or you can't change your velocity all by yourself. Because you can change your rotation mass, you can actually change your angular velocity all by yourself. Just change your shape. And with that, I'm dizzy again and it really is time to go back to the laboratory.

It's nice to be back. And before I forget--it's time to pose the question that I asked you to think about in the introduction to this episode. That question was, suppose you're on a playground merry-go-round, or one of these spinning platforms. And you're on the outside, and if you pull yourself to the center of that spinning playground merry-go-round, what will happen to its rotation? As you climb to the center of this rotating disk, its angular momentum won't change because that's fixed. It's an isolated object. Spinning about its center of mass, but you will be shrinking its rotational mass. And consequently, its angular velocity has to increase to compensate to keep the total angular momentum of this spinning object constant. By now, it should be pretty clear that once a bumper car is spinning it has angular momentum. And it can't stop spinning until it transfers that angular momentum to something else.

The riders in the car do matter because they contribute to the bumper car's rotational mass. And the more mass of those riders is, and the farther they are from the center of mass of the car (that is, the center of rotation we have in mind for our angular momentum), the bigger the rotational mass of the car and therefore the more angular momentum it carries for a given angle of velocity. So, a car filled with very massive people sitting far from the center of mass (spread out widely within the car) can allow that car to carry awful lot of angular momentum. On the other hand, a single child seated right in the middle of the car doesn't contribute much of the rotational mass, so that car then can turn fairly fast and still not be carrying very much angular momentum. If people move around, they can change the rotational mass of the car. And if it's already spinning, they'll affect the rotation, the angular velocity of the car--according to all this stuff I've been talking about where the angular momentum stays the same.

But as the rotational mass for example decreases, the angular velocity has to increase to compensate. Most people don't set their own car's spinning deliberately. That is, they don't obtain angular momentum out of the ground by driving funny. Most of the time they wait for collisions to occur and it's those collisions that transfer angular momentum and start the cars spinning, at least when the cars are spinning wildly. So, we need to look at those transfers of angular momentum. And that’s the job for the next video.

Part 4

How is angular momentum transferred from one bumper car to another? The answer to that question is that the first bumper car does an angular impulse on the second bumper car. Just as you can transfer energy by doing work and linear momentum by doing an impulse, you can transfer angular momentum by doing an angular impulse. So, what exactly is an angular impulse? An angular impulse is a torque exerted for time. For example, I can do an angular impulse on this bumper car by twisting it, that's the torque, as time passes, and here we go. Okay, I did an angular impulse on that bumper car and I transfer a momentum to it. So, that product: my torque times the time over which it acted on the angular impulse, and therefore the amount of angular momentum that I transfer to the bumper car and angular impulse, transfers a vector quantity, angular momentum, so that angular impulse itself is a vector quantity. It points in the direction of the torque that's responsible for it.

For example, if I twist the bumper car downward, I transfer downward angular momentum to the bumper car. So I did downward angular impulse. On the other hand, if I twist it upward, that's upward torque and produces an upward angular impulse that results in an upward transfer of angular momentum to the bumper car. And, also like impulses, I have some flexibility in the angular impulse I'm doing. For example, I can do the same angular impulse with different combinations of torque and time, or rather duration. For example, here’s an angular impulse that involves a medium torque exerted for a medium amount of time.

Here it goes... Okay. I transferred a certain amount of angular momentum, in this case downward, into the bumper car. And I did it with a medium torque exerted for a medium time. I could also use a much larger torque exerted for a very short time. And that was the same angular impulse, but with a bigger torque for a shorter time. And finally, I can do the same angular impulse with a smaller torque exerted for a longer time. It's a little hard, but you get the idea. And, in bumper cars, many of the twisting jolts that you experience, that you feel during the motion around the arena, occur during these collisions that transfer a lot of angular momentum in a very short period of time. So they are high torque, short duration, and your impulses really spin you around hard.

Also, like ordinary impulses (the impulses that transfer momentum), angular impulses come in equal but opposite pairs. When I twist this bumper car downward, that's a downward twist. I did a downward transfer of angular momentum by way of a downward angular impulse. It does an angular impulse back on me in the opposite direction. So, I transferred downward angular momentum to it. It, on the other hand, twisted me backwards, because it has to. That's Newton's third law of rotational motion. It twisted me upward and did an angular impulse upward on me and gave me upward angular momentum, which is the same as a deficit--a negative amount of downward angular momentum. It took away the downward angular momentum that I gave it and that makes the transfer complete. I gave the bumper car downward angular momentum. At the same time, it took away downward angular momentum from me. So that what I lost, it gained. Angular momentum is conserved. And this has to happen. Whatever I give it, I have to give up.

All right, well, so far, I'm just doing all of this with my hands and a bumper car. But in the bumper car, most of the angular impulses, and certainly the ones that are most exciting, involve collisions. And the angular impulses in the collision context are kind of subtle and they often involve frictional forces. So let me show you how an angular impulse occurs in bumper cars. As I say, they often involve friction, so, having these rubber bumpers which have a lot of friction really grip each other pretty well, is important. Now, angular momentum, like all the rotational quantities, is defined about a center of rotation, so we have to pick it and stick with it. The center of rotation I'm going to pick is the center of mass of this car. This is our center of attention, too. We're going to pay attention to this car. This guy is just an interloper where it's going to come through and spin the first car.

At the start of the story, the angular momentum will be present already. It will be in the form of this cars moving around, it will effect orbiting. It's going around the center of rotation, for our story. It won't actually be travelling in a circle. It'll be travelling in a straight line as objects do when they're free of external forces. But the fact that it's moving like this means that it’s swinging around that center rotation. There's rotation in here already, and therefore, angular momentum here already. So this guy's going to come along and it's going to clip the edge of that bumper car. It's going to catch it and twist it. And the act of catching that edge and twisting that bumper car there--a frictional force exerted at a lever arm from the center of rotation produces a torque and will twist our main focus bumper car and do the angular impulse. So, as this guy comes along, heading straight and true and it grabs the edge of the bumper car, it's going to exert the torque for the time and do the angular impulse on that bumper car. So, let me see if I can pull this off. The, what you should be looking for is this thing traveling straight, that one not spinning, the collision. And after that, this guy should be spinning, because the angular momentum will be transferred from this one to our main focus. Ready, get set. There it is.

So, those kinds of collisions in bumper cars break. I'm going to hold this guy and really clip it hard. It was spinning fast before it flew off onto the floor. But those kinds of collisions occur in real bumper cars, and all of sudden, you get clipped, your bumper car gets caught on the edge by a fast moving nearby bumper car, and suddenly, whoa. You're spinning around. That's where that comes from.

It's time for a question. This is a gyroscope, which consists of a wheel on an axle. It's mounted in a frame that allows that wheel and axle to turn very freely, almost without any frictional torques at all. This particular gyroscope resides in a frame that isolates it from the external world so that it's very hard to exert any torques on this gyroscope wheel--about the gyroscope wheel's center of mass which is the center rotation of this gyroscope.

Now, there's a string wrapped around the axle of this gyroscope. And the question is this. If I pull that string while holding the frame so that axle can't move, except to just rotate, all it can do is rotate. If I pull the string while the axle is held in in orientation, what will happen to the gyroscope? When I pull that string, I will produce a torque on the gyroscope about its center of mass, center of rotation. And that torque will last for a while, good for actually a second. As a result, I will do a large angular impulse on the gyroscope and transfer a lot of angular momentum to it. And once I do, it'll be spinning fast. I'll show you. Here we go. It's now spinning quite fast and it has a lot of angular momentum.

And the interesting thing to show is that, as I try to move, the surrounding frame that holds this gyroscope in place--it tends to keep turning about the same axis. As long as I don't exert a torque on it, I transfer no angular momentum about its own center of rotation and it keeps turning as it was. Now, it's not perfect. It's pretty close, but the frame really tries to prevent any angular impulses on that spinning gyroscope. Nice.

Now, in my bumper car arena which I'll bring out in a moment, I have bumper cars that don't have rubber bumpers, they're all plastic, they don't have very much friction between them. And so, when one clips the other one, it doesn't transfer very much angular momentum. So the one it hit, I can help that by making my bumper cars not perfectly round, not circular like this, and many bumper cars aren't quite circular. And when they're not circular, it isn't just frictional forces that contribute to torque. It's also support forces, so I'm going to bring out my little bumper car arena, and I'm going to put on some bumper cars that I've made not round.

So here, we have my miniature bumper car arena again and I've modified two of the bumper cars by putting wires on them that stick out. And, those wires will allow a passing bumper car to exert a large torque on these modified bumper cars. So that makes them more similar to bumper cars that have either rubber bumpers that give you a lot of grip or to bumper cars that aren't circular--that extend outward in certain areas. So that a passing bumper car can exert support forces on that bumper car and produce torque in that manner.

So first, to show you that--a passing bumper car, let me pick a different color. The green one passing the red one will catch its wire and exert the torque on the red bumper car, about the red bumper car's center of mass, which will be our center for this story. And it will set the red bumper car spinning by doing an angular impulse on the red bumper car. So I'll start with the red bumper car as motionless as I can get it. Here it is, motionless. We're going to spin it. There it goes, and I can do the same with the little red bumper car. I only have little red bumper cars and I can set it spinning. Where things get a little more interesting though, is when I have bumper cars of different masses bumping into each other. For example, this big red bumper car has a relatively large rotational mass, so you have to pour a lot of angular momentum into that to make its angular velocity significant.

So let me smack a small one of the little red guys into that big red behemoth. Not much action. The little red one carried the angular momentum at the start. It has a small mass and therefore, had a relatively small rotational mass about the center of the big red one. So, it didn't have much angular momentum to transfer. It transferred a good fraction of what it had, but that wasn't enough to set the big red one with its large rotational mass, spinning very fast. On the other hand, if we use the little red one as a target, and take the big green one as the passing monster, it sets the little red one spinning furiously, because, the big green one was carrying a lot of rotation--a lot of angular momentum. It has a big mass, and as it moved around the center of rotation, which was the center of mass from our little one, the green one was carrying a lot of angular momentum. The little red one received a good fraction of that angular momentum from the green one and that was enough to make the little red one with its tiny rotational mass spin like crazy.

So, you've seen these effects in bumper cars if you've gone there or experienced them. And that is, the big massive cars passing you and clipping the edge of your car can really cause some serous angular response from your car. Your car receives a big dose of angular momentum by way of a big angular impulse, and suddenly, you're whipped around in a hurry. On the other hand, passing cars that are occupied by small children don't carry very much angular momentum about your center of mass. And so, when they give you even a good fraction of their angular momentum, it doesn't have much effect on you and your car. Your car receives a modest angular momentum dose by way of a modest angular momentum angular impulse, and the result is underwhelming.

Once again, the big massive cars affect the little cars a lot more than the other way around. Well, that's it for the story of angular impulses in the bumper car arena. The next and final topic is what happens if the bumper car arena isn't perfectly flat? How do the bumper cars move when they're on a surface that’s uneven? And that's the topic for the next video.

Part 5

How does a bumper car move on an uneven floor? The answer to that question is that the bumper car accelerates in the direction that reduces its total potential energy as quickly as possible. I hope you're thinking, wait a second. A bumper car accelerates in the direction of a net force acting on it. That's part of Newton's second law.

Why is Lou talking about potential energy? Your observation about bumper car's acceleration is exactly right. It does accelerate in the direction of the net force acting on it. But my observation is also right. It does accelerate in the direction that reduces its total potential energy as quickly as possible. This is another big picture moment. Forces and potential energies are intimately related. After all, potential energy is energy stored in forces. When I lift this ball upward, I'm doing work against the gravitational forces it experiences--it's downward weight, and it stores my work as gravitational potential energy. So I'm doing work against the same force that stores that work as potential energy. When I let go of the ball, and it becomes a falling ball, it accelerates downward because that's the direction of the only force acting on the ball—and because that's the direction that reduces its only potential energy, its gravitational energy, as quickly as possible. Two reasons simultaneously.

But they are two separate reasons. They're the same reasons looked at from different perspectives. The ball accelerates down because that's the direction of the net force on it. The ball accelerates down because that's the direction that reduces its total potential energy as quickly as possible. Same reason, two perspectives. The direction of the gravitational force of the ball is the direction that reduces the balls gravitational potential energy as quickly as possible.

Another example, a rubber band, if I hold one end still and I stretch the other end, in this case, the left end, outward, I do work on it, against the elastic forces of the rubber band. And the rubber band stores my work as elastic potential energy. When I release this left end of the rubber band it accelerates inward because that's the direction of the elastic force on it and because that's the direction that reduces the rubber bands elastic potential energy as quickly as possible. Once again, those aren't separate reasons for the ends exhilaration. They're the same reason from different perspectives. The direction of the elastic force on the left end of the rubber band is the direction that reduces the rubber band's elastic potential energy as quickly as possible.

Let me show you one more example. When I lift one end of the rubber band upward like this, I'm doing work against both an elastic force and a gravitational force at the same time. And it's storing that work as two separate potential energies at the same time. And when I let go of the other end, the bottom end of the rubber band accelerates, but figuring out why it chose that direction and stuff isn't that easy. How would you figure out the net force on that rubber band? Actually, the rubber band isn't even a single object. It's this big floppy thing, and each piece of the rubber band had its own individual acceleration based on its own individual net force. Things are pretty complicated. Well, rather than trying to identify the net force on each individual part of the rubber band, sometimes it's easier just to think in terms of total potential energy.

Since individual forces are associated with individual potential energies, net force is associated with total potential energy. I sum up all the potential energies that an object has; that's the total. And an object accelerates in the direction that reduces its total potential energy as quickly as possible. That is a universal rule. So you can think of it kind of as a fancier version of falling. An ordinary falling ball accelerates downward, so as to reduce the only potential energy it has, gravitational potential energy, as quickly as possible. A ball that has many different potential energies, like this one, will accelerate in the direction that reduces all of its potential energies, the sum of them, as quickly as possible. So it's kind of a fancy version of falling. I don't even know which way this things going to go.

Let's try it. Like that. Okay, well this episode is about bumper cars. So it's time to bring bumper cars into the picture. Like anything else, a bumper car will accelerate in the direction that reduces its total potential energy as quickly as possible. And that turns out to be a useful way to predict a bumper car's motion when the arena isn't flat and level. So let me get out my miniature bumper car arena and let's take a look. So here's my miniature bumper car arena again and right now the bumper cars don't accelerate at all, at least when they're by themselves. Because the arena is flat and level and there's no direction they can travel to reduce their total potential energy, quickly or not quickly.

But if I tilt the arena, something you don't normally do at the amusement park, now there is something they can do to reduce their total potential energy. The only potential energy they really have to work with right now is gravitational potential energy and if they go up to this high side of the bumper car arena they have more of it then if they're at the bottom. So if I let this guy accelerate, which way do you think it's going to accelerate?

It tries to reduce its total potential energy. And it accelerates in the direction that reduces its total potential energy as quickly as possible. Now, this is really a glorified ramp. And we know what things do on ramps. They accelerate downhill on ramps. But, if we forget that and just deal with the general rule, we notice that, wow, there are ways in which objects on this surface, bumper cars on the surface can increase or decrease their total potential energy. And, I wonder which way this bumper car will accelerate. It will accelerate in the direction that reduces its total potential energy as quickly as possible. And look at the paths it takes--these lovely arcs. These are sort of a fancy version of falling objects. It's moving sideways, falling on a ramp. And the coherent, overarching idea is this acceleration so as to reduce total potential energy.

Well, if you played bumper car on this surface, it would be exciting. You would spend a lot of time, probably, at that end of the arena. And, if the arena weren't simply tilted, as I've done here, but rather had complicated undulating surfaces, as you drove along in your bumper car you would find that it was always accelerating in the direction that reduced its total potential energy as quickly as possible. It would tend to accelerate down into the dips--the low points on the arena surface, because that's the direction it can go to reduce its gravitation potential energy. When bumper cars collide and are pressing against each other, there's also an elastic potential energy involved and the acceleration acts to reduce that total potential energy as well.

So, life on a bumper car arena, with all of its complications, and various ways in which to store energy… various potential energies have accelerations always in the direction that reduces the total potential energy as quickly as possible.

It's time for a question. This giant pendulum has a bowling ball at the bottom and it can swing back and forth as you see. Notice as I pull it away from center what happens to the height of the bowling ball because this is going to be important in the question I'm about to ask you. As I pull away from center look what it's doing--so the question is this: when I let go of the bowling ball in which direction will it accelerate? When I let go of the bowling ball, it'll accelerate forward because of that order reduce its total potential energy as quickly as possible. Off it goes.

Actually, this is a fun version of the experiment. If I hold the bowling ball like this and let go of it, it will accelerate forward until it reaches the low point. Then it'll keep going and accelerate backwards as it goes away from the low point. It will reverse its direction, continuing to accelerate back to a low point, overshoot and come back and visit me. But it won't go any farther than you see it right now. Because doing so would, would require it to create energy out of nothing. So let's watch it go, here it goes. See, it worked. It accelerates in the direction that reduces its total potential energy as quickly as possible (and you're probably getting tired of hearing me say it).

So I'll introduce one more really useful concept, gradients. A gradient is a gradual variation in a physical quantity near a particular position. You've seen gradients before and perhaps even called them gradients. This is a brightness gradient. Brightness is a physical quantity and the brightness of this rectangle here increases gradually from here to here. Don't you love video? One of my favorite examples of a gradient is a scent or fragrance gradient. If you watch a dog searching for food with its nose, you'll see that it's constantly measuring a scent gradient. Once it detects the scent of food, it sniffs the food out, trying to figure out the direction in which that scent increases most rapidly. It moves up that scent gradient and eventually reaches the source of the scent, which is the food--and it eats the food.

So a gradient is actually a vector quantity that points in the direction that its physical quantity increases most rapidly. So, if the scent of the food is increasing from here to there, that's the fastest path for the scent to get stronger--that's the direction the dog moves and that's the direction of the scent gradient. The dog moves in that direction; that is, up the scent gradient, because that's likely to be the shortest path to the food. The dog goes up the scent gradient, and finds the food and eats it.

So nature's actually full of creatures and plants that travel up or down various gradients. They go up or down chemical gradients they go up or down temperature gradients light gradients and so on. So this concept of a gradient is very useful in physics and we'll encounter gradients in many different contexts in future episodes. The gradient that’s relevant to this episode is the potential energy gradient.

For example, this ball's total potential energy varies with its position. The only form of potential energy that it really has to work with is its gravitational potential energy. Its total potential energy increases as I lift it higher and higher. This is the direction in which its total potential energy is increasing most rapidly. That’s the direction of its total potential energy gradient. So you can sort of think of the ball as kind of sniffing around. Where is its total potential energy increasing the most? Oh, it's going upward. This is the fastest increase in total potential energy. That’s the direction of the ball's total potential energy gradient. And, if I let go of the ball, it accelerates downward, opposite the total potential energy gradient. That's a general observation.

Any object accelerates in the direction opposite its total potential energy gradient. Because that is the direction which is total potential energy is decreasing as rapidly as possible. And that's also the direction of the net force on it. It all comes together. Objects accelerate opposite their total potential energy gradients because that's the direction that had force on them.

Back to bumper cars… in my crazy little tilted bumper car arena, a bumper car has a potential energy gradient. As it goes up the slope its total potential energy is increasing. So that's the potential energy gradient for it and if I let go of it, it accelerates opposite that potential energy gradient, namely down the slope. In general, in a real bumper car arena the floor is typically not perfectly smooth. It's got some undulations in it. Wear and tear, and how it was made. And at any location, the bumper car will accelerate down the local potential energy gradient. It sort of examines the local potential energy and it finds the path in which that potential energy is decreasing as rapidly as possible--that's down the local, total potential energy gradient.

Summary

By now it should be clear that your experiences while riding in bumper cars are heavily influenced by three conserved quantities: energy, momentum, and angular momentum. Energy, we've seen before, and we know that it's transferred by doing work. So, when two cars collide with one another, one of them may well do work on the other and therefore give the other car some of its energy. Now, the bumpers in bumper cars aren't perfectly elastic. They don't restore and return all the energy that goes into them during the collision. And they turn some of that into thermal energy. They grind it up and degrade it. And that actually helps to keep the motion on the bumper car arena a little under control. The cars don't get more and more energetic. As the game goes on they use more and more electric energy to get themselves moving.

Momentum is new in this episode and you can see how influential it is in the game bumper cars. When two cars collide they transfer momentum by way of impulses. Force times time and that can always occur, so whenever there's a collision, there's always a transfer of momentum. And depending on the masses of the cars involved, those transfers of momentum can have different effects. For example, two cars of the same mass colliding tend to exchange their motions. If it's a head-on collision, one of them tends to resume motion as though it were the other car. But if two cars of different masses collide, for example this green one and that red one, the low mass car tends to bounce of the high mass car--and the high mass car tends to swat the low mass car kind of almost off the arena field.

So, how many people are piled into a given car and how big those people are mass-wise, does affect their experience as they ride around the bumper car we're in. The single children in the bumper car, they're giving the bumper car very low masses. Those kids get knocked all over the place. And lastly, there's angular momentum, which is typically transferred from one bumper car to another bumper car during a glancing collision. That is not a head-on collision, but a collision in which one car clips the edge of a second car. And that first car then does an angular impulse on the second car. Actually, the second car does a reverse and opposite angular impulse on the first car. But typically it's most noticeable on the car that gets clipped and we're paying attention, if you're in that car and your car gets clipped on the edge by a passing, a massive passing car, you tend to get spun around as angular momentum is transferred into your car about your center of mass by way of an angular impulse...

So, this is life in the bumper car arena for all the collisions. And even if you're not colliding with another car, you're simply riding the hills and valleys of a not perfect arena floor. You find that energy, in this case, potential energy, influences your motion because you always accelerate in the direction that reduces your potential energy as quickly as possible. In other words, you'll accelerate opposite the local potential energy gradient. Well, these concepts came up in the context of bumper cars, all this stuff about, new stuff about energy and new ideas of momentum and angular momentum. So they're here in bumper cars, but we'll continue to use them as we continue to explore how things work.