“How Things Work” – Lou Bloomfield

Welcome to “How Things Work”, I'm Lou Bloomfield and I've been teaching this course at the University of Virginia for more than 20 years. It's essentially case study physics, an introduction to physics in the context of everyday objects and activities.

My goal is to make physics useful and to help you understand and manage the physical world around you, after working with almost 10,000 students, here at UVA, I'm delighted to be able to bring “How Things Work” to an even larger audience online.

I hope that you'll find this course interesting, informative and enjoyable. Moving “How Things Work” out of the classroom and onto the web is a challenge. At Virginia, my class is interactive and improvisational and I'm usually doing things. It's called “How Things Work”, after all. In transitioning to the web, I'm going to give up some of the spontaneity, conversation, shared experience, But I am going to gain time and space, time, in the sense that I can fill each explanation and example until they're as good as I can make them and space. in the sense that I can fill almost everywhere, to show you exactly what I want to show you.

In this first part of “How Things Work”, we’ll explore the physics of six objects or activities, skating, falling balls, ramps, see-saws, wheels and bumper cars. We'll see how things move, rotate, and interact with each other and watch them exchange energy and momentum as they do. It's not all of physics, but it's a good start. It will already give you many useful tools for a living. We'll cover one topic per episode.

At a suggested pace of about one episode per week, I'm breaking tradition however, by releasing this entire course all at once. Since this is a whole new adventure in education, we're not constrained to sticking to an ordinary class schedule. One week, next week, next week, anything goes.

That means if you want to binge learn, you can, you're welcome to charge ahead as fast as you like. Or take your time, as long as you finish up by December 31st. Each episode consists of an hour or two of video, and a ten question homework assignment, to help you think about and use the relevant physics concepts.

They are thought provoking questions and not easy, so I'm letting you repeat each homework assignment as often as you like. To deepen your understanding, I encourage you to read the section on the episode's topic in my textbook, “How Things Work” or in my general readership book, “How Everything Works”. I think that human interaction is an important part of learning and I hope that you'll seek out others while taking this course.

Talk with your friends or family and get them involved. Last time I offered this course; many families took it together, kids, parents, and even grandparents. I think that’s the greatest thing ever. If you have no one local to talk about, please use the forums to reach out. Moreover, I know that some of you are already experts in this content, and I hope that you'll help me teach this course using those forums. In fact, you can all enrich the course with your insights and experiences.

It's about physics of the real world, and you happen to live in the real world. So go ahead and post, or link in your own stuff. Learning physics requires careful thought and repeated exposure to the same concepts. As we shift our attention from object to object. We'll naturally revisit concepts in new situations and different circumstances and they'll gradually become more familiar and meaningful with each exposure.
Lastly, I hope you'll take the preliminary assessment; it’s not exactly a homework assignment, it's simply 21 questions about physics in the real world. Designed to see what you know right now. The fun part will be retaking that same assignment when you finish the course. I'm expecting a big improvement and now, on to the first topic, Skating.

Section 1 Skating

Today's topic, skating, whether you’re gliding across the ice, strapping old roller skates to your shoes, or cruising down the sidewalk on a skateboard. You're freeing yourself from the constraints of friction and allowing yourself to move with ease and simplicity.

Like ordinary shoes skates support you vertically. That is the ground supports the skates and the skates support you but unlike ordinary shoes the skates move freely forward and backward and you can coast.

Coasting is what makes skating so much fun, coasting is also an example of one of the most fundamental principles in all of physics that is the principle of inertia.

"An object at rest tends to remain at rest, and an object in motion tends to remain in motion."

As you skate, or watch other people skate, you'll notice a couple of common themes. If you're stationary on a level surface, and nothing pushes you, you'll remain stationary but, if you something does push you, you'll begin to move in the direction of that push.

On the other hand, if you're moving on a level surface and nothing pushes on you, you'll continue moving forward in a straight line but if something does push on you, you'll speed up or slow down or turn. My goal in examining skating is to explain those observations.

That effort will introduce us to some of the words that physicists and scientists use to characterize what they see and measure. It'll also bring up some of the basic laws of motion. Laws that date back to the times of Galileo and Newton, when we're done with skating, you'll be acquainted with some of the basic tools that we're going to need as we continue to look at how things work.

Here's a question to think about, I'm not going to ask it yet, officially, but you should have it in mind as we continue our way through skating. A rotary lawn mower is a machine that cuts the grass by spinning a sharp blade very rapidly over the grasses.

The question is whether that rotary lawn mower and its spinning blade could cut the grasses if the grasses weren't attached to the ground. To help guide us through the science of skating, we'll pursue five how and why questions. Why does a stationary skater tend to remain stationary and why is a moving skater tending to be moving?

How can we describe the fluid effortless motion of a coasting skater? How does a skater start, stop or, turn? Why does a skater need ice or wheels in order to skate? There is one video sequence for each of those questions, and a summary video at the end.

Why does a motionless skater tend to remain motionless? The short answer to that question is that an object at rest tends to remain at rest. In other words, if you leave a motionless skater completely alone, you don't push on her, she'll remain motionless and this is known as inertia and objects in our universe exhibit inertia.
Let's do some experiments so you can observe it for yourself. For our first experiment, I'm going to perform the classic parlour trick of pulling the tablecloth out from underneath the place settings. It's actually not a trick at all, its physics in action. These are objects at rest and it is their nature to remain at rest, as long as we don't bother them very much, minimal external influences and because I'm using a very slippery silk tablecloth and because I'm going to pull it very fast.

I will influence these slightly, but it'll happen so quickly and for such a short period of time that they'll pretty much be unaffected and they should stay put. Now, the whole idea of this being called a trick brings up an issue with this class. This class is not about magic, it's about un-magic. Whereas magicians try to hide from you what is actually happening, they keep their secrets, I'm trying to give away all the secrets.

It's un-magic, you should understand everything that happens and why it happens, if in doing a demonstration, this one in particular, but others as we go through the world of how things work. If I fail to convey to you why it happened, what you're seeing and why it happened, then I have missed my goal.

So, these are objects at rest it is their nature to remain at rest, they exhibit inertia and so, as long as I don't bother them, they'll stay there. So, add a degree of difficulty and I have found over the years that I have to be nervous about this, because if I get complacent and do it casually then I flip everything over. So, I'm nervous about it. Here we go. I'm going to give myself some room to get my hands moving nice and fast before the, the tablecloth pulls tight.

I'm definitely not going to pull up I'm going to pull a little down. So that I don't, fly everything around the room. Ready, three, two, one, there we go, objects at rest remaining pretty much at rest. You can try this experiment yourself, but you might want to start with unbreakable dishes. If you don't want to risk anything you could also do the experiment with a handful of coins and a sheet of paper. Just lay the coins on the paper and snap the paper off from underneath them.

The coins will stay in place. Objects at rest tending to remain at rest because they exhibit inertia too. This demonstration of inertia that an object rest, tends to remain at rest, makes use of a pencil, a wooden hoop and a glass bottle.

Alright, here we go. First, I put. The hoop on the bottle, next, I try to balance the pencil on the hoop and that is not easy. I did it and now I'm going to sneak the hoop out from underneath that pencil. I'm going to grab the hoop very fast, so that the pencil is suddenly left hanging in mid-air. It will remain in place because of inertia alone. It's an object at rest and it will tend to stay at rest, even as the hoop disappears from under it and it then begins to fall. Ready, get set, Ta-dahhhhh!

Let's take a look at that one again, in slow motion, watch how the pencil just hangs there in mid-air for a few frames before dropping into the bottle.

This brings us to the question I asked you to think about in the introductory video above, whether our rotary lawnmower can cut the grasses with its fast moving blade, if those grasses aren't attached to the ground. Inertia makes it possible for the lawn mower to cut the grasses even when they're not attached to the ground.

Each grass remains in place, not because it's held there by anything but because it's an object at rest, and it tends to remain at rest. Even as a sharp blade cuts through it. Rather than cutting grasses, though, I can show you the same effect by cutting an apple with a sharp knife.
This experiment is designed to answer the question. Can I slice through an apple, even if that apple isn’t being held in place by anything? In this particular case, I’m going to place the apple on the table and then I’m going to slice it. Horizontally, with a knife, or at least try to, now, I’m not much of a swordsman so if I try to swing that knife through the apple, by hand, sometimes I hit it and sometimes I miss. So, I have built a spring loaded, apple slicer.

This baby has a strong spring, look at that serious spring and I’ve got the knife on a swivel. So I can make it swing around here nicely and I can adjust the height. It’s all adjusted. Right there for the middle of this apple, it’s all good and, the spring is so strong I have to hold the table in place. I am going to. Get the spring, all lined up here with the apple. Notice the apple is not attached to the table. Just sitting there minding its own business, but it’s kept in place by its own inertia and we’ll see whether this knife can get through the apple.

Okay. Now I stretch the spring and get ready to let go. Here it goes. Ready? Get set. Sliced apple. Now, we did exert a little bit of external influence on the apple. The apple did finally not completely stay put, but it stayed, stayed put enough to make nice, even slices right through that apple.

So, the question is answered. Yes, it is quite possible to slice an apple that is not held in place by anything. But that is simply an object at rest tending to remain at rest. Just as a fast-moving knife can slice through a stationary apple, so the fast-moving blade of a rotary lawn mower can slice through stationary grasses. The blade sweeps so quickly through those grasses that they don’t have to be held in place. Inertia ensures that they don’t move as that sharp blade cuts through them.

Many kitchen tools take advantage of inertia. They use a fast moving blade to slice through objects at rest. A food processor dices onions, a blender crushes ice and a spinning blade coffee grinder turns coffee beans into ground coffee. So back to skating, because of inertia, a stationary skater tends to remain stationary. That’s the nature of things in our universe and while it’s not very exciting to stand motionless on your skates, it’s a relief to know that you won’t suddenly start moving swiftly in some random direction for no apparent reason.

Why does a moving skater tend to continue moving? The short answer to that question is that an object in motion tends to remain in motion. In other words, if a skater is moving and you leave that skater completely alone, you don’t push on him, then that skater will continue to move.

This behaviour is actually the other half of inertia and it’s how objects in our universe work. The complete concept of inertia then, is that an object at rest tends to remain at rest, and an object in motion tends to remain in motion.

It’s time to demonstrate the second half of inertia using a banana. This experiment is designed to test the inertia of a moving object. I’m going to throw the moving object, a banana, to the right and it’s going to have a close encounter with a very sharp knife. Now, I’m not going to be holding the banana when it meets up with the knife. So, if anyone asks you after the fact, who killed off that banana, it wasn’t me, officer, the banana did it itself.

So, the banana is going to be a moving object and it’s going to tend to continue moving, that’s its inertia. So, here we go, I’m not going to be holding the banana when it gets to that knife. It’s on its own. Ready, get set. [SOUND] Sliced banana, let’s see, can I find part of it? Well, I got half of it the rest is on the run.
So, there you have it an object in motion tends to continue in motion even if it encounters things like, sharp knives. The motion of an inertial object, that is an object that's free of external forces, is very simple. It moves in a straight line at a steady pace, but doesn't that neglect an object at rest? No, because an object at rest is just a special case of steady pace motion.

It's steady pace motion, where the steady pace we're talking about is zero. We're ready for a formal statement of the concept or principle of inertia. Because we don't know all the words for some of the physical quantities involved, we'll consider this a first draft. It's known as Newton's “First Law of Motion” and it states that an object that is free of external influences moves in a straight line and covers equal distances in equal times. Skating is full of examples of Newton's First Law.

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**Newton's first law**

The first law states that if the net force (the vector sum of all forces acting on an object) is zero, then the velocity of the object is constant. Velocity is a vector quantity which expresses both the object's speed and the direction of its motion; therefore, the statement that the object's velocity is constant is a statement that both its speed and the direction of its motion are constant.

The first law can be stated mathematically as

\[
\sum F = 0 \Leftrightarrow \frac{dv}{dt} = 0.
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Consequently,

- An object that is at rest will stay at rest unless an external force acts upon it.
- An object that is in motion will not change its velocity unless an external force acts upon it.

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How does a skater start, stop, or turn? The answer is that a force acts on the skater and causes the skater to accelerate. Once again, it's an answer that involves a new physical quantity. This time it is acceleration and it's time for me to introduce that term. As I said earlier, a skater's velocity consists of the speed in which the skater is traveling and the direction in which he's heading. If he's inertial, that is if he's experiencing no overall force, then his velocity is constant.

He has a constant speed and a constant direction of travel but if he's not inertial, if he's experiencing an overall force, then his velocity changes with time. He's accelerating. Acceleration measures the rate at which an object's velocity is changing with time.

It's a subtle quantity. It's not so easy to observe. You have to look carefully. Moreover, it's another vector quantity. It has an amount and a direction. Let me show you. I'm going to, I'll be the object, and I'm going to accelerate. But first, let me get myself some room. I'll head over here to start with and I'm about to accelerate toward your right. Now initially, I'm not going to accelerate. Here I am at velocity zero. I'm still at velocity zero, still at velocity zero. So, my velocity is not changed with time, I'm not accelerating.

But I'm about to accelerate to the right at a slow rate and my velocity will develop. Here we go towards the right and it will become faster and faster and faster and faster until I disappear from
we've. Alright, so, what you should be looking for is not mine, my movement, per se, that I simply have a velocity. You should look for my velocity changing. It goes from slowly to the right, to faster and faster and faster and faster to the right. Now, let me show you acceleration towards your left and I'm going to do a rather fast acceleration to the left. Ready, get set. Whoa, off I go. In those cases, I was accelerating in the direction of my velocity and my velocity was increasing as a result.

I was going faster and faster my speed was steadily increasing and that's how a skater starts. The skater starts from rest with a velocity of zero, chooses a direction to accelerate, and begins to pick up speed in that direction and continues to accelerate in that direction, thereby, going faster and faster and faster.

The SI unit of acceleration is the meter per second per second or meter per second squared (m/s²). Now, acceleration isn't all that familiar to anyone. So, the familiar unit for acceleration in the United States is not so familiar but it is the foot per second squared.

Well, we now have velocity and acceleration my velocity is the speed of my motion in the direction which I'm heading. My acceleration is how that velocity is changing with time and that acceleration has both an amount and a direction.

Well, let me show you a couple of examples of this. If I accelerate in the direction of my velocity as we've seen, I speed up. On the other hand, if I accelerate opposite the direction of my velocity, I am going to slow down. Let me show you. Don't watch yet. Let me get started because I, I, I can't do everything at once. So, I'm going to get started. Now, I'm moving to the right but I'm accelerating to the left, and watch what happens to my velocity.

I come momentarily to a stop and if I keep accelerating backwards here towards your left, I pick up speed and disappear off out of view on the, on the left. Well, accelerating forward, that is in the direction of my velocity, I pick up speed we, we're comfortable calling that acceleration. If I however, I accelerate opposite my velocity, so let me do this again. So, I'm going to, let me get started. So, here we go, ready, start and now, I'm going to accelerate opposite my velocity, I come to a stop, and then I pick up speed in the opposite direction.

During the stopping part of that story, so as I was heading to the right but accelerated to the left and slowing down, we have a special name that we often apply to that type of acceleration, acceleration opposite your velocity. We call it deceleration it's not necessarily a completely separate concept. It's a, just a special case of acceleration. Acceleration opposite your velocity causes you to decelerate.

There's at least one other interesting example of acceleration, what happens if instead of accelerating in the direction of my velocity or opposite the direction of velocity, I accelerate to the side. So, suppose I get started, I'll get started heading to your right, my velocity will be at the right. Here it is. Okay, I'm now moving right and I'm going to accelerate away from you. Oh, I turned and now I'm going to keep accelerating to my left, look at what happens to me. I go in a circle.

The point of this is that if you accelerate not in the direction of your velocity, and not opposite but rather to the side, you turn. So, we now can really answer the question of how a skater, starts, stops and turns.

To start, the skater, say, the skater is at rest, the skater has to pick a direction and begin to accelerating that direction. So, so here, I'll, I'll be the skater and I will start from rest and I want us, I want to hit to the right. We'll talk about what causes this acceleration surely but I am going to
develop a velocity that gets larger and larger toward the right. Here we go. Okay. So, to start, I pick a direction and then I continue to accelerate in that same direction, thereby picking up speed in the direction that I had chosen. To stop, what does the skater do? Well, the skater then starts the situation already moving and accelerates opposite the skater’s velocity. So, I’ll do it again. Here we go. So, let me get started. Okay, I’m a skater moving along and I want to stop. I accelerate backwards opposite my velocity and I slow down. Come to a stop and if the skater wants to turn and the skater accelerates in a direction neither forward or backward but rather, to the side.

So, the skater might have been heading, let me do it differently, might have been heading again to the right and now, decides to turn more and more towards you all and so, the skater is heading to the right and accelerates towards you and the skater’s velocity changes and the skater begins to turn. So, let’s see whether you got all of this. I’m going to move. And then, I’m going to ask you about my velocity and my acceleration.

Why do skaters need ice or wheels in order to skate? If you’re thinking about friction and about, more or less, eliminating with ice wheels, you’re right. Skates do a wonderful job of reducing the effects of friction. But, I’m going to go with the more general answer, that real world complications often mask inertia and Newton’s first law. When Inertia was first published by Sir Isaac Newton in his Principia Mathematica in 1687, it was a remarkable observation. Inertia underlies all of motion, but it’s largely masked from view by nuisance effects. First, there is gravity; I’ll talk more about gravity in the next episode. But here’s a preview according to Newton’s first law, if I’m free of all external forces, then I’ll move at constant velocity. I’ll be inertial, and I’ll coast. Let’s go try it! Look. No hands. Ahhhhh.

What makes skating so fun and interesting is that your skates free you from the constraints of friction, so that you can enjoy the simple pleasure of inertia. When you’re experiencing no external forces or, more generally, when the net force acting on you is zero, you move according to Newton’s first law, and travel at constant velocity. If you’re motionless, you remain motionless.

That’s a velocity of zero staying zero. If you’re moving, you move in the same direction at the same speed. That’s your velocity remaining constant and you’re coasting. On the other hand, if you are experiencing a net force, other than zero, you move according to Newton’s second law of motion, you accelerate, and your acceleration is equal to the net force acting on you, divided by your mass. Moreover that acceleration is in the same direction, as the net force. Well that’s it for skating, glide away and I will see you next time for more of how things work.