Section 2 Falling balls

Today's topic is about falling balls. Falling balls are everywhere. They're in most sports, many toys, and they're even in Times Square on New Year's Eve. Whenever a ball isn't touching anything, whether you dropped it or tossed it or kicked it, it's a falling ball, and it moves according to physics of falling objects. A falling ball is experiencing only one force, its weight.

That is, the force exerted on the ball by the Earth's gravity. We've talked about forces in general up to this point, but we have never identified a specific one. So, our first specific force is weight, the balls weight and it's going to play a leading role in this episode.

If falling balls don't catch your fancy, then you can think of anything else that is experiencing only its weight. Whether that's a coffee mug, or a handful of coins, or a coconut falling from a tree any time an object is completely on its own, except for gravity, it's a falling object and it descends according to the rules of falling objects.

http://www.grc.nasa.gov/WWW/k12/airplane/newton1a.html

http://physics.info/falling/

The one notable exception, or at least one I have in mind, is a sheet of paper. It doesn't quite fall like everything else. That's because it's experiencing a second force that we can't ignore, air resistance. Air resistance is another one of these nuisances that makes our lives more difficult. So, for this episode, we can ignore air resistance and I save it for another episode further down the road.

For now, all these objects that we will drop, whether it's a basketball, a tennis ball, a golf ball, we're going to ignore air resistance and treat only the influence of their own weight on their motion. As you toss a ball around, you'll find that there are some recurring features to its motion.

For example, if you drop the ball from rest, it moves downward faster and faster with each passing second. Now, your head might not be sure that it's really picking up speed, but your gut is and I'll show you, that you know it, too. For that, I need help from my assistant, Katrina here. Hi, Katrina. Hi. So, what I'm going to have Katrina do is put her hand right here on the table, okay? Mm-hm and now, I'm going to drop the ball on Katrina's hand.

First from this height, it doesn't hurt. Okay, not too bad, and we're not going off to in an ambulance yet. But now, let's try it again. Yeah. Thanks, Katrina. As, as you can tell, so, like Katrina knew that the ball will have picked up a lot of speed on its route to her hand because it will have had a lot of time to fall and it does, indeed, go faster and faster with each passing second.

So, you know, out from under it. She doesn't want to be there when the ball arrives. Now, as the ball is going down faster and faster, that means it's descending ever more distance with each passing second. So, its height is going down by bigger and bigger increments as time goes by. Showing you that is going to require a little work, and we'll save that for later in this episode.

As a second example, if you toss a ball straight up, it rises quickly at first but then more and more slowly as it reaches greater height and you can see that just by looking at the ball hit my hand. It's going fast at first, but less fast and less fast still and at very top, it is momentarily motionless. The ball rises to a peak at which point it's not moving at all, for an instant, and then it drops as though
from rest. It's as though at that moment when it was motionless, someone had been holding it, and let go and down it comes, faster, and faster.

So, in this episode, we'll look at the dropping from rest and we'll look at the rise to peak height, and then drop essentially from rest and, we'll also look what happens when you don't throw the ball straight up, but instead throw it up at an angle similar to a tossed ball, like in most sports. As we explore the behaviour of falling balls, we'll take a close look at the connection between weight and mass.

Two fundamentally different physical quantities that are related to one another in interesting ways and that work together to give us the motion of falling balls. Moreover, falling balls are a wonderful example of the laws of motion I introduced in the episode on skating. It's a simple, yet elegant example, and a good step along the path to the more complicated objects that we'll examine as we continue to look at how things work.

At this point, I'm going to pose a question. I won't answer it yet, but I want it to be in your mind as you continue through this episode. If I take a ball and throw it upward, toss it straight up, during the time when it's above my hand, not touching my hand, and heading upward, is there a force pushing upward on the ball? You should neglect any effects due to the air in thinking about this question.

So, it's just as the ball is on its way up, not touching my hand, is there upward force acting on the ball? To help guide us through the science of falling balls, we'll pursue the following six how and why questions. Why does a dropped ball fall downward? How differently do different balls fall? How would a ball fall on the moon? How does a falling ball move after it is dropped? How can a ball move upward and still be falling? How does a ball's horizontal motion, affect its fall? There's a video sequence for each of those 6 questions, and a summary video at the end.

Why does a dropped ball fall downward? The short answer to that question is that it's pulled downward by its weight and it accelerates downward in response to that force. In other words, when you let go of the ball, its weight dominates its motion and it plummets. Well, weight is associated with gravity and gravity is a physical phenomenon that produces attractive forces between every pair of objects in the universe.

This ball is exerting an attractive force on me by way of gravity; I'm exerting an attractive force on the ball by way of gravity, every possible pair but gravity is a very weak phenomena, and as a result, the only object big enough to produce noticeable gravitational effects, that is once we, we are routinely aware of is our earth.

The earth exerts a downward gravitational force on every object in its vicinity. It pulls this ball downward with a gravitational force, it pulls me down with a gravitational force, it pulls you downward with a gravitational force, and we give a name to these individual gravitational forces.

This ball's gravitational force, due to the earth, is known as its weight and, this ball is experiencing its weight due to the earth, as I'm experiencing my weight due to the Earth, and you're experiencing your weight due to your earth. To observe the ball's weight in action, let go of the ball, and let it accelerate. The force that's causing that acceleration is the ball's weight it's a force exerted on the ball by the earth's gravity and it, the ball, the ball itself responds to that weight by accelerating, by falling.
Since the ball’s weight is the force that the earth’s gravity exerts on the ball, the only way to observe it directly is to let go of the ball and watch it accelerate. The weight pulls down on the ball and according to Newton’s second law, the ball accelerates downward in response.

Well, what determines the ball's weight? It turns out that the ball's weight is exactly proportional to the ball's mass and that's a remarkable result. Remember, that a ball's weight is a force exerted by gravity, whereas the ball’s mass is its resistance to accelerations. How hard is it to make it change velocities? There is no fundamental reason why weight and mass should have any connection to one another, and yet they do.

It turns out that, before observation, that every kilogram of mass here near the earth's surface weighs about 9.8 Newtons. So, the weight of an object is 9.8 Newtons per kilogram of its mass. Now remember a Newton, 1 Newton is the SI unit of force, and it's about the force that a small apple, conveniently enough given that it's Newton a small apple exerts on your hand when you hold the apple there steady. There are about 4.5 Newtons in 1 pound force for people who are more familiar with pounds. So this ball, oh, it's probably about 10 Newtons, maybe something like that.

The fact that there’s that relationship between the object’s mass and its weight is convenient, but what to call that 9.8 Newtons per kilogram, what's known as a constant of proportionality. What do you call it? Well, it’s conventionally represented by the letter g, the lowercase letter g, and it carries a mysterious name, it’s called the acceleration due to gravity. In the next video, we'll take a look at why that name is appropriate.

How differently do different balls fall? The simple but remarkable answer to that question is that all balls fall at the same rate. Now remember, we're neglecting air resistance, which is a pretty good approximation for balls that you just drop in front of you but don’t try to apply the same story to a sheet of paper because the sheet of paper is really affected a lot by air resistance.

So, returning then to the balls and this question whether it's a basketball, a tennis ball, a handball, a golf ball or a baseball, if you drop them together, they all fall together. So here, we have a tennis ball and a basketball, we’ll see whether they fall together. Ready, get set, go. Exactly together, not only do all balls fall together, but if you were to begin falling with them, you would keep pace perfectly.

You would all fall together well, we can do that. Now, I'm not going to take you and drop you with a bunch of balls, but I can allow you to take that trip with this gadget. So here, I've got a frame with a camera mounted on it, and Catherine and I are going to let this frame fall down a pair of strings. So, it'll plummet down to the ground in a somewhat controlled way, with springs at the bottom so that it, it comes to a safe a safe stop near the ground and you'll be looking out that little window at the world in front of you and the balls that are dropping as you drop with them.

Here are you guys and there's Catherine down there. Hi down there, Catherine. Hi. You ready to have some balls and the camera drop at you? We're ready. Alright, everyone, here you guys go. Ready, get set, go 3, 2, 1. You’re probably wondering whether one of those falling balls ever hit the camera down below where Catherine was standing.

The answer is, yes, and it wasn’t pretty that’s one of the reasons why I didn’t drop a bowling ball. Why does that happen? Why does a bowling ball and a baseball fall together and hit the ground at the same time? After all, the bowling ball weighs much more than the baseball. So, from a weight point of view, the bowling ball's pulled downward much more strongly by the earth’s gravity than
the baseball, and so the bowling ball should accelerate faster. It should clearly outpace the baseball and hit the ground first.

What’s wrong with that thinking? Well, there’s another difference between the bowling ball and the baseball apart from their difference in weight. The bowling ball has much more mass than the baseball, which is to say that it’s an awful lot harder to shake a bowling ball, to make it accelerate first away from me, toward me, away from me, toward me.

Much harder than just shaking a baseball, right? This, this guy accelerates very easily in response to small forces. So, from the point view of mass, the baseball is the more responsive one, less mass. So, when it’s pulled downward by the earth’s gravity, it should accelerate faster, it should clearly outpace the bowling ball and the baseball should hit the ground first.

We’ve got two opposite predictions from the weight point of view, the bowling ball should hit first but from the mass point of view, the baseball should hit first and actually from observation, we know that both of those predictions are just wrong, the two balls hit together.

So, what have we done wrong? Well, you can’t separate the weight point of view and mass point of view, you have to combine them. We have to have one point of view which we take into account both the higher weight of the base, bowling ball and the greater mass of the bowling ball and when we put those altogether and do the analysis more carefully, we discover that the bowling ball has more weight.

It’s pulled downward harder and that alone would make it go, accelerate faster but it also has more mass, so it resists accelerations more, and that alone would slow its acceleration. The two together, more downward force, more mass resisting that force. Those two increases, cancel perfectly, so the bowling balls response, that is its downward acceleration caused by gravity, the earth’s gravity, is exactly the same as the down response of the baseball to the earth’s gravity.

The two balls accelerate downward at exactly the same pace and hit the ground together. When you’re carrying a ball at constant velocity, the ball is moving at constant velocity, you’re most aware of the balls weight because you have to support that weight. Without your upward push on the ball, the ball would fall and so, you have to push up just enough to balance the ball’s weight and you know it, I mean, you feel that you are pushing up.

So, you are detecting gravity as you walk along at a constant velocity. When you push a ball back and forth on a table, you’re causing the ball to accelerate first one direction then the other. You’re changing its velocity and as a result, you’re quite aware of the ball’s mass. It’s resistance to acceleration or the measure of its inertia. The table on the other hand is supporting the weight of the ball, so you are completely oblivious to that weight, it could be large, it could be small, and that’s the table’s responsibility.

Yours is the acceleration and therefore, the mass of the ball. Now, this course is about the objects of everyday experience and the physics concepts that make them do what they do. In other words, it’s about understanding how things work more than it is about calculating how they work. That said, however, there are times when looking at the Quantitative Physics, opening up the hood and staring at the Mathematics that underlie the concepts is a useful activity and will give us insight into how the machinery of our universe works. This is one of those times. So, bear with me as I do a little bit of Algebra to look at why all balls when draw from rest, fall together.
When a ball is falling, the only force acting on it is its weight. So, the net force on a falling ball is the ball’s weight. Well, Newton’s Second Law of Motion tells us, that the acceleration of any object is equal to the net force on that object divided by the object’s mass.

The second law states that the net force on an object is equal to the rate of change (that is, the derivative) of its linear momentum \( p \) in an inertial reference frame:

\[
F = \frac{dp}{dt} = \frac{d(mv)}{dt}
\]

The second law can also be stated in terms of an object’s acceleration. Since Newton’s second law is only valid for constant-mass systems, mass can be taken outside the differentiation operator by the constant factor rule in differentiation. Thus,

\[
F = m\frac{dv}{dt} = ma
\]

where \( F \) is the net force applied, \( m \) is the mass of the body, and \( a \) is the body’s acceleration. Thus, the net force applied to a body produces a proportional acceleration. In other words, if a body is accelerating, then there is a force on it.

Consistent with the first law, the time derivative of the momentum is non-zero when the momentum changes direction, even if there is no change in its magnitude; such is the case with uniform circular motion. The relationship also implies the conservation of momentum: when the net force on the body is zero, the momentum of the body is constant. Any net force is equal to the rate of change of the momentum.

Any mass that is gained or lost by the system will cause a change in momentum that is not the result of an external force. A different equation is necessary for variable-mass systems (see below).

Newton’s second law requires modification if the effects of special relativity are to be taken into account, because at high speeds the approximation that momentum is the product of rest mass and velocity is not accurate.

So, in this specific case of a falling ball, the acceleration of a falling ball is equal to the net force on the ball, which is the ball’s weight. So, it’s the ball’s weight divided by the ball’s mass. That’s pretty simple. The falling ball’s acceleration is equal to the ball’s weight divided by the ball’s mass. Well, we can make it simpler, we can make it simpler because we know something about the ball’s weight.

Here, near the surface of the Earth, a ball weighs 9.8 Newtons for every kilogram of mass it has, that is its weight is proportional to its mass and the constant of proportionality is 9.8 Newtons per kilogram. For those of you who prefer to talk about pounds, because Newton is kind of an esoteric concept, that’s about 2.2 pounds force per kilogram of mass. Alright, so we now know something about the weight, we can substitute in this version of the weight, that is that constant of proportionality times the mass of the ball.
When we do that, we discover that Newton’s Second Law becomes quite simple. It’s the acceleration of a falling ball is equal to that constant of proportionality times mass divided by mass, the ball’s mass divided by the ball’s mass. That cancels, the ball’s mass disappears from this Newton’s Second Law and Newton Second Law says that the falling ball’s acceleration is simply the constant of proportionality, which is to say, a falling ball’s acceleration is 9.8 N/kg or equivalently 2.2 pounds per kilogram.

Done, well, that’s a strange result. It’s, it’s kind of cool, what this says is the ball’s mass doesn’t matter. The acceleration of this ball is the same as the acceleration of this ball. The mass was unimportant and this is consistent with our observation. You drop all these balls, they all go down together, they all accelerate downward together but what remains to be done and it’s bizarre, is, that constant proportionality has wacky units.

9.8 Newtons that is a unit of force, per kilogram, that is unit of mass. That doesn’t sound like acceleration. Recall that the SI unit of acceleration is the meter per second squared. So, where, is the connection? Well, it turns out that the unit, this unit’s Newton per kilogram is exactly same as this unit, the meter per Second Square, they’re the same and how does that even happen?

Well, it turns out that the Newton is defined in an interesting way by Newton’s Second Law. One Newton is the force that causes a one kilogram mass to accelerate at one meter per second ^2. That defines the Newton and as a result, Newton's Second Law written out in that way says, that one meter per second squared of acceleration is equal to one Newton of force divided by 1 kilogram of mass.

Get rid of the ones and you have the meter per second squared is equal to the Newton per kilogram, they’re the same unit. As a result, that little g constant of proportionality is an acceleration, it is 9.8 meters per second squared and that is the acceleration of any falling object here near the Earth’s surface, as long as air resistance can be neglected.

How would a ball fall on the moon? The answer to this question is simple. The ball would fall much more slowly than on Earth. Every aspect of the ball’s fall would be slower. It would pick up speed in the downward direction more slowly. It would cover distance toward the ground more slowly, and it would take longer to hit.

To understand why that’s the case, however, we need to revisit the issue of gravity and take a look again at the relationship between weight and mass. Up until now, I’ve talked about falling near the Earth's surface and I’ve told you that every kilogram of mass, near the Earth’s surface, requires a weight of about 9.8 Newtons and if you drop an object near the Earth’s surface, it accelerates downward at about 9.8 meters per second squared.

You’ll notice that I keep saying, near the Earth’s surface, and that’s because those two statements are dependent on the Earth’s gravity here, the local strength of gravity. Now, as we'll see in the episode on rockets, does local strength of gravity is local? It varies from place to place and the details, we’ll save for that episode but, for the moment, it’s important to know that the strength of gravity, that is how much weight is produced for each kilogram of mass, depends on two things. It depends on the mass of the object producing that gravitational force, and it depends on your distance from that object.

In the present case, here near the Earth’s surface, the object that’s producing the gravity is the Earth and so, we care about the, the mass of the Earth and the distance that’s involved. That is the distance between the object in question, namely the Earth and us, is about the distance between us
and the centre of the Earth. Quite a distance away so, the Earth is very massive and in fact, quite distant from us, and together, that leads to a strength of gravity that gives every kilogram of mass a weight of 9.8 Newtons, and causes falling objects to accelerate downward at about 9.8 meters per second squared.

If we go somewhere else, that relation, those relationships may change. For example, if we go to the Moon where the strength of gravity locally on the surface of the Moon, is about 1/6th that on the Earth. Well, every kilogram of mass will acquire a weight of only about 1.6 Newtons, and if you drop a ball or any other object there near the surface of the Moon, it will accelerate downward at about 1.6 meters per second squared.

You might think this is all very hypothetical and unimportant to everyday life but actually, where you are in the Earth surface matters. When I say that a kilogram of mass weighs about 9.8 Newtons, here in the Earth's surface, it's really in about but, there are places you can go on Earth that have stronger, local gravity, and places you can go that have weaker local gravity.

Every time you go upward, for example, into the mountains or into a plane and get farther from the centre of the Earth, the strength of gravity, the Earth's gravity weaken slightly, and you weigh a little less. You don’t actually have to go up or down, you can move to different locations on Earth.

The Earth, it turns out, is not perfectly spherical because it's spinning, it is in effect flung outward, around its equator. The diameter of the Earth is larger around the equator than it is across the poles. So, you can get closer to the centre of the Earth by going to the North or South Pole and you can get farther from the centre of the Earth by going to the equator and that will affect your weight by about half of a per cent.

So, you will actually weight, about half a per cent more on one of the poles, than you do on the equator. Half a per cent is not trivial, and so, that 9.8 meters per second squared acceleration of a falling ball. Don’t trust the next digit all that much you have to, to be careful about it. So, the relationships between mass and weight depend on where you are, and the acceleration of a falling ball also depends on where you are.

If you visit the grocery store, you’ll find items being sold by weight, and items being sold by mass, and some items that are sold by both. This chocolate bar, for example, is labelled according to both weight and mass. It says here, net weight 3.5 ounces. That’s a weight listing. The ounce is a unit of force which is equal to 1/16th of a pound force. So, that's the weight of this chocolate bar as, as promised by, by the manufacturer and a second label here says this chocolate bar has a mass of 100 grams.

A gram is a unit of mass equal to 1/1000th of a kilogram; we have this bar labelled according to its weight and according to its mass. The same is true of this bag of cookies. We have a weight listing. It says net weight 16 ounces or 1 pound, those are both units of those are both force amounts, so we have a weight and we also have 453 grams. That means that this bag of cookies has a mass of 453 grams, and again, a gram is a unit of mass. So, these two items are labelled and sold by both weight and by mass.

Which brings us to a question, if I take these items to the Moon, are they still labelled correctly and if they’re not labelled correctly, what has gone wrong with the labelling? Their labels still accurately specify their masses. But those labels are way off when it comes to weight. Mass, after all, is the measure of an object’s inertia. It has nothing to do with gravity. So, the mass of say, this chocolate
bar is the same on the Moon as it is on Earth, as it is in deep space. It's, it simply reflects how difficult it is to make this chocolate bar accelerate.

So, the mass is 100 grams here, it's a mass, mass of 100 grams on the Moon, mass of 100 grams anywhere you like. On the other hand, weight depends on the local strength of gravity. So, this bag of cookies weighs 1 pound here on Earth, where the strength of gravity is a certain amount. But if we go to the Moon where the strength of gravity is only 1/6th that on Earth this bag of cookies is no longer one pound it's about 1/6th of a pound, it's no longer accurately labelled.

Long and short of it is, if you're going to be selling items on an intergalactic basis, you do best to label them according to mass because they'll always be properly and accurately labelled, regardless of where they're shipped to. If you label them according to weight, you're likely to run into trouble with the authorities for selling under or possibly over weight items.

The bottom line is that a ball's weight and its acceleration due to gravity both depend on the local strength of that gravity. In most cases, however, we don't notice that dependence, and that's because the Earth's gravity is so nearly the same anywhere we can go that the variations in weight and acceleration of gravity are very subtle. Whether you're playing baseball at sea level or in the mountains, or on the North Pole or on the Equator, the game is essentially the same.

It's very hard to notice any changes in the ball's weight or its acceleration due to gravity as it falls but if you go and play baseball on the Moon where the local strength of gravity is only about 1/6th that on Earth the game is going to change significantly. The ball will weigh only 1/6th its Earth weight and as it falls; its acceleration due to gravity will be only about 1/6th its value here on Earth. The game would be a very different game.

How does a falling ball move after it is dropped? This question asks for a careful analysis of the ball's velocity and position as it falls. In a nutshell, the ball's velocity increases steadily in the downward direction. But its position shifts down further with each passing second. Now, to help you understand these positions and velocities, let me suppose initially that gravity has vanished, and let's look and see what happens.

To a falling ball in the absence of gravity in a live class I can make that supposition, but only in my head. In video, I can show you that possibility. Now, this is a class about how the real world works. It's a science class it's not about science fiction. So whenever I do this sort of thing, when I show you how things would happen if I changed the rules slightly, I'll let you know.

So, off goes gravity let's see what happens to a ball that's released from rest in the absence of gravity. Gravity has been switched off now; the acceleration of the gravity is 0 and what happens when we drop a ball from rest. Ready, get set, go. There's no acceleration due to gravity, so the ball's velocity starts at 0, which is when I release it, and it stays at 0. The balls inertial and it does nothing. It just remains there in space, gravity is still switched off and I'm going to drop the ball from rest again.

This time, I'm going to plot the ball's velocity versus time. Now velocity is a vector quantity, and plotting a vector quantity is difficult. After all it has an amount and a direction. So what I'm actually going to plot. Is the vertical component of the ball's velocity? That is, the portion of the ball's velocity that lies along the vertical direction, and therefore that affects the ball's altitude or height above the ground.
So if it's moving downward that contributes a downward component of velocity. If it's moving upward, that is an upward component of velocity? Ready? Again, no gravity here we go. Ready? Get set. There you have it. The ball's velocity starts at 0, and as time passes, the velocity stays at 0. It's inertial.

The acceleration due to gravity is 0, in the absence of gravity and so, the ball's velocity is constant. Well, this is getting tedious. We need some action. Gravity's still switched off, though. So, if we want some action, we want some motion, I've got to do it myself. So I'm going to drop the ball again, but this time I'm going to give it a push before I let go of it. I'm going to make sure that it has a downward velocity from the moment I let go. What it does with that velocity is up to it, but I'm going to give it that starting velocity in the downward direction and as it moves I'm going to plot two things.

First I'm going to plot the vertical component of the ball's velocity, as before, but I'm also going to plot the vertical component of the ball's position. What's the vertical component of position? Well, it's the altitude of the ball. Relative to some starting point, some 0, and I'm going to make the 0 the point at which I let go of the ball, so if the ball moves downward relative to the point where I let go of it, that's downward, a position that's down, below where it started.

Those'll be the negative values for my component, vertical component of position graph. If it moves upward, which it won't this time, those'll be the positive values of my vertical component of position graph. So here we go. I'm going to release the ball, not from rest, but with an initial downward component to its velocity, and we'll watch the ball fall in this gravity-free environment. Are you ready? Get set. Go.

It was inertial, the ball coasted downward after all, it has 0 net force acting on it, here in the world of no gravity and so whatever velocity it started with it retained. So as time passed, the velocity didn't change. The position of the ball did change however. The ball used its velocity to cover the distance and with each passing second, it went lower and lowers, until it finally drifted out of view.

Without gravity the ball becomes inertial after you let go of it. It's experiencing no external forces, and so it travels at constant velocity, in accordance with Newton's first law of motion. Whichever way it was heading when you let go of it, it'll keep heading in that direction.

Finally, it's time for some gravity, but just a little. If I turn on the full earth gravity, the ball drops so fast that I can't show you what's going on. So I'm going to start with just a little bit of gravity, 1/100th of the full earth gravity. That means that the full acceleration of the gravity here in my special video world is going to be 0.098 meters per second. That's 1/100th of the real-world value. What you'll see then is the ball accelerates downward. It will go faster and faster as time passes. At the same time, its position will change.

It will cover distance in the downward direction. I'm going to drop it from rest, make things simple, and you'll watch it accelerate downward and travel downward in response to a very weak version of gravity. Are you ready? Here we go. Ready, get set, go. How about that? It started very slowly. In fact, from the moment I let go of it, it was at rest and then it went faster and faster and faster as time passed and it used that downward velocity to travel more and more with each passing second.

So in the first second, it didn't go very far because it was traveling very slowly on average. The 2nd second, it travelled farther. The 3rd second, farther still, and by the time 5 seconds have passed, it had pretty much drifted out of view. So, that's life with weak gravity. To show you full gravity, the whole earth's gravity, to return to the real world. I need more height. I can't work in this tiny
laboratory. We have got to go use the entire Physics building at the University of Virginia and that's what we're going to do. The earth's gravity is strong enough to make things happen fast and that's why I need more height to work with. I'm going to drop this bowling ball out of the 3rd floor window of the Physics building and let the ball fall all the way past the basement but even with that amount of height to work with, the ball's going to be over in a little more than 1.2 seconds.

So we'll do it initially at full speed and then because this is video, I'll slow down the video and begin to mark it up, so that you can see how a falling ball moves downward. Here's a bowling ball, ready, set, go. I told you that fall would be quick it's hard to even see the bowling ball as it plummets. To make it easier for you to follow the bowling ball during its descent, I'm going to highlight it with a red dot.

So here's the same fall, but with a red dot marking the position of the bowling ball as it falls. Ready, set, go. Because I'm trying to explain how a falling ball moves after is dropped I need to be able to show you how the ball's position and its velocity change with time. But recall that while it takes only a single glimpse to absorb the ball's position, it takes 2 glimpses to determine the ball's velocity and if you go as far as looking for acceleration, it takes 3 glimpses.

It would be helpful therefore, if we had more than the 1 glimpse of the ball's position visible simultaneously. Since this is a video, I can do that the camera records 30 frames per second, that's 30 glimpses of the ball's position every second. What I can do is cause the whole video to remember all the previous glimpses of the ball up until the current moment.

That means that every 30th of a second, we'll have a glimpse of the ball. So, here's that same falling bowling ball, marked by a red dot, and all the previous red dots will linger on the screen so you can see the, the evolution of the ball's position, and from that. Take a look at its velocity and acceleration. Ready, set, go, that trail of red dots tells us a great deal about the bowling ball's movement after I dropped it.

At first, the bowling ball was moving downward very slowly, and it remained close to my hands. It had a small downward velocity, so its position was shifting downward slowly. But that slow descent didn't last after about a second of falling, the ball had accumulated a much larger downward velocity. After all, it's accelerating downward rapidly, at the acceleration due to gravity. So, there near the bottom of the fall, the ball had a large downward velocity, and so its position was shifting downward rapidly.

To help you observe the motion I just described, I need to slow the video down. So here's the same fall again at 1/10th of normal speed, slow motion, and I'm going to mark out the ball's position every 5th of a second, so five times a second. I'm going to draw a line, to indicate where the ball is. Let's choose as the 0 of position, the point from which I dropped the bowling ball, that's 0. I can then measure the ball's position every 1/5th in a second in indicating on the video. I can also measure the ball's velocity every 5th of a second, and indicated as well. But to do that, to make the measurement of velocity, I have to compare two positions at different times. After all, velocity is the rate at which position is changing with time. I need to look at the change in position to observe velocity.

So, here is the same fall, once again in slow motion at 1/10th of full normal speed, with approximate values for the ball's position and its velocity indicated every 5th of a second. As you can see, the falling bowling ball's velocity is increasing in the downward direction by about 2 meters per second every 5th of a second. It's a steady increase in downward direction, so this corresponds to a steady
acceleration downward. Over the course of an entire second, the bowling ball, ball's velocity increases by about 10 meters per second in the downward direction.

That’s an acceleration of 10 meters per second, per second, or equivalently about 10m/sec^2, in the downward direction. That’s not a coincidence. This is a falling ball, and falling balls accelerate downward, at about 10m/sec^2, the acceleration due to gravity. So this is a falling ball, its velocity’s increasing steadily in a downward direction at a rate of 10 meters per second per second or 9.8 meters per second per second if you like, physics works.

http://en.wikipedia.org/wiki/Equations_for_a_falling_body

Well, you may find it helpful if I graph that falling bowling ball’s position and velocity, each as a function of time. So here, here in this next version of the same video, I will give you a plot of the bowling ball’s velocity versus time and the bowling ball’s position versus time. Here we go ahead, slow motion, a tenth of normal speed, the bowling ball falling out of the window.

The ball’s steadily increasing downward velocity is the hallmark of constant downward acceleration. After all, this is a falling ball, and falling balls are always accelerating downward at the acceleration due to gravity. That steady downward increase in the ball’s velocity causes the graph of the ball’s position to arc downward, for some thoughts on the shape of that arc, let’s return to my laboratory.

The bowling ball survived its fall just fine, but the ground outside the Physics Building has a pretty good dent in it. So where do these motion curves come from? That is for falling ball drop from rest, its velocity plotted versus time gives you a straight line and its position plotted versus time gives you a curve that bends downward. Where does that come from? To answer those questions, we need to look at how the falling ball dropped from rest, how its acceleration depends on time, how its velocity depends on time, and lastly, how its position depends on time.

The first of those, how the following ball’s drop from rest, acceleration depends on time is simple. It’s a falling ball, its acceleration is constant. It’s the acceleration due to gravity, approximately 10m/sec^2 straight down, and we represent that by the little letter g. So, the falling ball’s acceleration is just equal to little g, nothing else.

Time is out of the picture, second issue, the velocity of that following ball dropped from rest as a function of time. Well now time does matter because the following balls. Velocity starts at 0, but because it’s accelerating downward, the velocity gradually accumulates more and more downward, aspect to it. It goes faster and faster. After 1 second, the falling ball, dropped from rest, is heading downward at, ten meters per second, approximately. After 2 seconds, it's a 20m/sec, approximately, and so on.

What’s the formulaic relationship, then, between the velocity and the time? It turns out that the velocity of the falling ball dropped from rest is simply the acceleration, which is little g, times time, nothing else. So that is the formula for a straight line. When you plot the falling ball dropped from rest at velocity versus time there in a straight line. The slope of that line is little g, the acceleration due to gravity.

That brings us to position the falling ball dropped from rest; position is more complicated, because to determine how far the ball has moved from where we started we have to know the average velocity of the ball over the time we're considering. From start, from the drop moment, to now, and we have to know its average velocity over that period, and we also know, the length of that period because the ball will move using its average velocity to make progress, to go somewhere.
To change its position and the, the new position of the ball will be its average velocity times the time over which it’s used at average velocity, namely the time between the drop and now, the moment in question. That passes, that begs a new question.

Okay, so what’s the average velocity of this ball dropped from rest, in many cases in physics calculating an average velocity is difficult. This is a very simple case where you can do it pretty easily; the average of a ball if dropped from rest is simply the average of its starting velocity times 0 and it’s ending velocity, the moment in question. Just take those 2 values and average them because they’ll be times early on when the ball was traveling more like the starting velocity, they’ll be times later on when the ball is traveling more like the final velocity and it all averages out.

The middle, the middle point, in terms of velocity, is the average and so, we know, what the velocity of a falling ball is, as a function of time its \( g \cdot t \) (time), so the velocity at the start of the drop is 0. The velocity at the end of the drop is \( g \cdot t \), when, not necessarily the end of the drop, but the moment in question, the moment we’re paying attention to.

So the average of 0 in \( g \cdot t \) is \( g \cdot t / 2 \), halfway between the two. So that is the average velocity of a falling ball dropped from rest, \( g \cdot t / 2 \), the falling ball uses that average velocity to make progress and it has time, amount of time to work with so we multiply \( g \cdot t / 2 \), the average velocity, \( g \cdot t \), we get the new position of the falling ball dropped from rest.

Its \( g \cdot t^2 / 2 \) and that is the formulaic relationship between the position of this falling ball dropped from rest and the time it’s had to fall.

The, the relationship between acceleration and time, is simple, it’s a constant. The relationship between the falling balls velocity, and time, is a straight line. It is, that the falling balls velocity, is proportional to time; \( g \cdot t \) and finally, the falling ball dropped from rest position is proportional to time squared its \( g / 2 \cdot t^2 \) and that kind of a formulaic relationship between position and time gives you an arc, if you plotted against time, time squared.

http://www.physicsclassroom.com/class/1DKin/Lesson-1/Speed-and-Velocity

If you plot time squared or anything proportional to time squared against time, it gives you an arc and the shape of that arc is parabolic, so this is the mathematicians would identify that and go, oh, that’s a special kind of arc. It’s a parabola and parabolas show up all the time in falling objects, and will see more of them later on in this episode.

During the first second of its fall the stone is moving down relatively slowly on average and so it doesn’t travel very far from your hands, but during the second second of its fall The stone is moving downward much faster on average, and so it covers far more distance during that second second than during the first second. That’s why, after only 1 second of falling, the stone is much closer to your hand than it is to the water.

So we’ve seen that when you drop a ball from rest, all of its motion occurs along that vertical coordinate direction and that motion is relatively simple. The ball’s acceleration is that of a falling object. It accelerates downward at the acceleration due to gravity. The ball’s velocity is also pretty simple. It starts at 0, because we’re dropping it from rest, and then it increases in the downward direction in proportion, to the time, over which the ball has been falling.

Lastly that brings us to position, the balls position, we can define as starting at 0, and then that position, increases in the downward direction, in proportion to the time it’s been falling squared.
That's because as the balls moves faster and faster, it covers more and more distance with each passing second. So, its velocity increases in proportion to time, its position increases in proportion to \( t^2 \). Well, this is the simplest case of falling, falling from rest. In the next video we'll take a look at what happens if you have a ball that's not falling from rest but it's actually falling, from a start in the upward direction.

How can a ball move upward and still be falling? The answer to that question is that a falling ball is accelerating downward at the acceleration due to gravity, regardless of its current velocity. Recall that a falling ball is one that’s experiencing only a single force, its downward weight and it is accelerating downward in response. The ball's acceleration then dictates how the ball's velocity is changing with time. After all, that's what acceleration is, the rate at which velocity is changing with time. What the falling process doesn't determine is what the ball's velocity was when it started to fall. That's a completely separate issue.

When I drop a ball from rest, I'm choosing the initial velocity for the ball to be zero. I let go of it, and for that one moment, I have control over the ball's velocity. I choose it to be zero. After that, the velocity is out of my hands, literally. From the moment I let go of it, acceleration, the acceleration due to gravity takes over, and the ball's velocity, which started at zero by my choice, begins to change with time and become more and more downward and the ball develops 10, roughly 10 meters per second of downward velocity for every second it has had to fall. But, I didn't have to choose an initial velocity of zero.

I could choose, for example, to let, let go of the ball with an initial velocity downward. I can throw it downward. Like this, in that case, at the moment I let go of the ball and it became a falling object, it already had a large downward velocity. In effect, I gave it a head start on the falling process. But once it left my hand, it accelerated according to the rules of a falling object and it picked up speed in the downward direction at the usual rate of 10 meters per second per second. Well, for the purist, 9.8 m per second per second.

Well, that leads to another possibility what if instead of dropping the ball from rest or throwing the ball downward with a downward initial velocity, what if I start the ball with an upward initial velocity? I throw it upward. In that case, it's rising upward but it's still accelerating downward; it's still a falling ball and so, it continues upward for a while but as it goes higher and higher, it's being pulled downward and is accelerated downward, and so it's slowing down. It eventually comes to a stop, and then it begins to descend faster, and faster, and faster.

To look a little more carefully at all the properties of a ball that is falling but heading upward, we need some more room. So, let's head outside and start throwing a ball around in the open spaces. Before we examine that ball toss carefully, here's a question about the balls travels. At the moment that the ball reaches the peak height on its way up, it comes to a peak and then it comes down.

Right at that peak, what are its velocity and acceleration? At the peak of its travel, the ball has momentarily come to a stop. Just before that instant, it was heading upward. Just after that instant, it'll be heading downward. So, at that point, it is in transition from heading upward to heading downward, and it's neither, it's doing neither. It's neither rising nor descending. So, it's motionless, velocity zero. But that doesn't mean it's not accelerating. Like any falling ball, it's still accelerating downward at the full acceleration due to gravity. So, let's return to the ball that I tossed straight up. I'll show it to you again to remind you what it looks like.

The basketball took just 2.2 seconds to complete its journey; it spends half that time heading upward and half that time heading downward. To help you see how that movement occurred, I can
now begin to play with the video of that basketball toss. The first thing that I'm going to do is I'm going to show you where the basketball was at each moment in time prior to the present. Now, the camera records 30 images per second so I'm going to have the images of the basketball linger on the screen, each one separated from the next by 1/30th of a second.

Here then, is that same basketball toss but with all of the previous basketball images still visible on the screen. That trail of basketball images provides us with enough information to determine the basketball's velocity and position at each frame of the video. Now, I'm going to graph those values, velocity and position, as a function of time.

So here, it will be the, the graph of the basketball’s velocity versus time, and its position versus time. Now, in showing you how they evolve over the course of time, everything happens pretty fast in real life. So, I'm going to slow the video down to 1/10th of its normal speed. Here then, is the same tossed basketball with its velocity and position graphed as time goes on. The graph of the basketball’s velocity versus time is a straight line.

We've seen that straight line before. When I drop the ball from rest, its velocity versus time is another straight line. In that case, the velocity started at zero when I released the ball and then increased steadily in the downward direction. In this case, the ball started to fall while it was heading upward with a large upward velocity. So, it began its fall with a large upward velocity but it finished its fall with a large downward velocity and the transition from large upward velocity to large downward velocity was smooth, steady, and seamless.

The velocity change formed a straight line when plotted against time as its downward acceleration, the acceleration of a falling object, gradually reduced, and gradually caused its velocity to shift more and more in the downward direction. The effect of that downward acceleration early on was to slow the rise of the ball. The ball started out after I threw it upward with a large upward velocity, so its velocity was upward. But its acceleration was downward and that causes what we often refer to as deceleration i.e.: acceleration opposite the velocity.

So that if you are moving forward but accelerating, you slow down. The same thing happened for the ball, the basketball. It was heading upward, velocity was upward, but its acceleration was downward and it was a constant downward acceleration so the velocity in the upper direction gradually decreased, steadily, steadily, steadily until at one instant in time, one moment, the velocity was reduced all the way to zero. After that moment, which occurred halfway through the travels, the ball's downward acceleration cause its velocity to become more and more downward, it steadily increased in the downward direction.

So, the 1st half of this trip, the upward part of the trip, is the ball having an upward velocity that decreases steadily towards zero. The second half of the trip is the ball dropping from great height with the velocity that's downward and steadily increasing from zero. Right between these two, these two portions of the motion is that instant in time where the velocity is neither upward nor downward, it’s zero. The ball is momentarily motionless but, it's still accelerating there.

So, it continues its, its transition from velocity upward to velocity downward, and shortly returns to my hands. The graph of the ball's position versus time is a smooth arc that curves downward. It starts rising swiftly at first, then arcs over to a flat top and then, arcs downward more and more steeply. That reflects the motion of the ball that starts rising quickly at first, then more and more slowly as the downward acceleration of the falling ball saps its upward velocity. It momentarily stops rising altogether and then begins to descend faster and faster, covering more and more
distance each second. and so, we get this rapid rise at first and then slower and slower than not at all, then slow descent, slow descent, faster, faster, faster until down it comes at high speed. The moment at which the basketball reaches peak height is an interesting moment up until that point, the ball had an upward velocity that was gradually decreasing, but it was still rising upward to greater and greater height. After that moment of peak height, the ball's velocity was downward and gradually increasing. So, the ball was descending away from peak height that's why the moment of peak height is the moment at which the ball's velocity stops being upward and hasn't yet been downward. It's just hit zero exactly, that's the peak moment and the ball's motion is remarkably symmetrical around that moment of peak height. If you look at where the ball was one second before the moment of peak height and one second after the moment of peak height, it's at the same altitude.

The ball is the same distance below the peak on both sides of time, one second before, one second after. Not only is that, but the speed of the ball the same. Before peak height, the speed was directly upward. It was an upward velocity. After peak height, that speed was directed downward, it was a downward velocity. But the speeds were the same. So, there's wonderful symmetry around the peak. Because of that symmetry, the rise and fall of the ball looks the same if I play it forward as if I play it backward. You pretty much can't tell the difference between the video of me throwing the ball up and down, played forward, or played backward.

The bottom line here is that a falling ball is falling no matter what its velocity is at the start of the fall. It can start from rest, it can start with me throwing it downward a little bit, or it can start with me throwing it upward. It doesn't matter. Once the ball leaves my hands, the only force acting on it is its weight, and it accelerates downward at the acceleration due to gravity. All the rest, the initial velocity issues, how I started are details that we can deal with. So, the formulas that I gave previously for a ball dropped from rest still, still apply, they're still relevant. But, we need to spruce them up a little to take into account the possibility that the ball started to fall with an initial velocity that wasn't zero.

To take a look at that, those slightly revised formulas, let's go back to my laboratory. To describe the motion of a falling ball that begins its fall with an initial velocity different from zero, we have to make some modifications to the equations I gave you to describe the motion of a falling ball dropped from rest. We have to incorporate the possibility of an initial velocity that's not zero. So, let's look at the ball's acceleration, then its velocity, then its position. Well, the ball's acceleration doesn't change because of any initial velocity.

The ball's acceleration has nothing to do with its initial velocity. It's simply the acceleration due to gravity. It's a falling ball and whether the ball is going up, or down, or sideways, or any which way, as long as the only force acting on it is its weight, it's accelerating downward at the acceleration due to gravity. End of story, so that was easy acceleration's unchanged.

Okay, that brings us to velocity. Now, velocity does change. In the old relationship, we had for a ball dropped from rest that the velocity at any given time is simply the acceleration due to gravity multiplied by the time over which the ball has been falling. That product of the acceleration due to gravity multiplied by time at time zero, at the moment the fall starts, that becomes zero. So, the velocity at time zero is zero.

Well, if we allow for the possibility of some initial velocity that isn't zero, we have to add it in. So, at time zero, when the ball hasn't had any time to fall and therefore hasn't undergone any acceleration due to falling, the velocity of the ball is the velocity it started at. So, we simply add it in. The
formula that gives us the velocity of a falling ball that started with an initial velocity is the ball’s initial velocity plus the acceleration due to gravity multiplied by time, that’s all there is to it. Finally, that then brings us to the ball’s position. This one’s a more difficult calculation. First off, we should really allow for the ball to start its fall at a position other than zero and if we do that, we add in the starting position. So, the position at any given time is equal to the starting position, that’s the beginning, plus additional substance and what is the additional stuff we have to add in there?

Well, it’s the, once again, it’s the average velocity of the ball over the course of its fall from the moment we let it start falling until now, the moment in question. So, it’s that average velocity multiplied by the time between the start of the fall and now. It’s the same product as before, but now the average velocity is more complicated because the velocity didn’t start at zero. It started at something else and if we work through that carefully, and this is simply an algebra work. It’s not very difficult but it’s enough that, I’ll leave it out of this, out of this video.

The final result is that the position of the ball during its fall at, at any given time where, where time zero is the moment the fall began, that position is equal to the initial position of the ball, where you let go of it, plus the ball’s initial velocity times time. Plus, 1/2 of the acceleration due to gravity times time squared. So, the three terms that are present in that relationship that give you the ultimate, the position of the ball overall. The first term adjusts for the fact that you might want to start the fall, the ball’s fall, at a position other than zero.

The second term accounts for the fact that the ball might start with an initial velocity other than zero and the third term recognizes that a falling ball is accelerating downward, the acceleration due to gravity and it experiences this evolution of position that goes in proportion to the square of the time, that is time to the second power. So, whether you, you care about these quantitative relationships that, that, that actually tell you specifically where the ball is in space, how fast its moving, and, and what its acceleration is, or when you simply want to watch the ball fall, its motion is still very simple.

The ball starts with its initial velocity, and once it’s falling, it, it accelerates downward. So, its velocity is changing in the downward direction. If it’s heading upward at a given moment, well it’s becoming less and less upward as time goes on. If it’s heading downward, it’s becoming more and more downward as time goes on. So, so it makes use of this velocity then to cover distance, and so you see these rises and falls, or simply fall, they’re all dictated by this constant downward acceleration, the downward acceleration of a falling ball. It’s time to ask the question I asked you to think about during the introduction to this episode.

Suppose I throw a ball straight up during the time that the ball is above my hand and heading upward, is there a force pushing the ball upward? In answering this question, neglect any effects due to the air. The ball moves upward not because of any force pushing it upward, but because of its own inertia. The ball left my hand with an upward velocity and even though it begins to fall the moment I stop supporting it, it takes time for that ball’s downward acceleration to change the ball’s upward velocity into a downward velocity.

By now, you should have a pretty good idea how balls move if you drop them from rest or toss them straight up. But, most ball sports involve motions of falling balls that are not vertical. If the only thing you could do in baseball, or basketball, or football, or soccer, or volleyball was make the ball go straight up and down, those would be pretty dull sports. They still involve falling balls, but those balls have room to move and, in the next part of this episode, we’ll take a look at motions that aren’t strictly vertical.
How does a ball's horizontal motion affect its fall? The trivial answer to that question is that it doesn't. But a more complete answer is that the ball's horizontal coasting motion has no effect on its vertical falling motion. The ball is doing two things at once. It's falling vertically, while it's coasting horizontally. The space we live in is 3-dimensional, and so motion occurs in 3 dimensions. Up until now, I focused only on the vertical dimension, the ball altitude or its height above the ground. In more general cases, the ball can move horizontally as well as vertically and if I throw it up at an angle, it does two things at once. It falls vertically. It goes up and down like a falling object, but at the same time it coasts horizontally at a steady pace.

Geometry tells us that in three dimensions, we can describe a ball's position, or any other vector quantity for that matter, in terms of coordinates along three separate directions. Now, we have some flexibility in choosing those directions, but the best choices are three directions that are perpendicular to one another. So, for example, I have this box. Boxes are made in such a shape that if you put sticks along three sides, you have three mutually perpendicular directions pointed out. So, here's one direction, a second direction that is at right angles to the first, and a third direction that is also at right angles to both the previous directions.

So, this is a system that is three perpendicular and mutually perpendicular directions and any of these is a pretty good choice of coordinates, of coordinate directions, along which to describe any vector quantity you like.

When describing the motion of a falling ball, there is one particularly simple choice of coordinate directions. In that choice, one of the coordinate directions points straight up. The second points horizontally along the path that the ball is taking I call that direction the down-field direction because if you're playing American football or soccer, then you're trying to make progress along with that down feel direction. The third coordinate points to one side or the other, and it actually doesn't matter in this situation.

So, here are the three simplest coordinate’s one of them points straight up, one of them points horizontally along the downward direction, and the third points to the side. Well, with that description then, we can look at how a ball falls. If I drop it from rest or toss it straight up, then all of its motion is along that vertical coordinate. But if I throw it up and at an angle, it moves both along the vertical coordinate direction and along the downfield direction and now, for something more remarkable.

A falling ball's motion separates perfectly into two parts, a vertical falling motion, and a downfield coasting motion. The ball's vertical motion, that is the component of its motion that lies along the vertical coordinate direction, is that of a falling ball and the ball's down field motion, that is the component of its motion that lies along the down field coordinate direction, is that of a coasting ball and the ball is doing both of these things simultaneously and they have no effect on one another.

To give you an idea of why this works, before I set out and show you that it works, let's look at how the ball accelerates. The ball is being pulled downward by gravity and so its acceleration is straight down, perfectly along the vertical coordinate direction. The acceleration of the ball is entirely along that vertical core direction, and so the component of the ball’s acceleration along that direction is the entire acceleration. Therefore the ball accelerates along the vertical coordinate direction perfectly. It's a, you know, it's a falling ball along that direction everything relating to falling is taking place along that coordinate direction.
On the other hand, there is no gravitational force component pointing along the down field direction. That down field direction is horizontal and gravity is a vertical effect. So, the ball has no acceleration due to gravity along the down field coordinate direction. Gravity has no effect on motion along the down field coordinate direction, and so the ball simply does what it was doing in accordance with Newton's first law it's unaffected and therefore it coast, it travels.

The component of its velocity along the downfield coordinate direction is constant. So, the ball’s motion vertically is that of a falling object. Its motion along the downfield coordinate direction is that of a coasting object. Well, let me show you this. I need more room so we're going to go up to the third floor again and throw things out the window. Now, I want to make the, the ball head horizontally fast so that you can see that downfield motion and because a bowling ball has a pretty big mass, I can't throw it sideways very fast, that's an inertia issue, right?

I'm going to stick with a basketball, here we go. I'm going to throw a basketball out the 3rd floor window of the Physics Building at, at UVA and I'm going to get it going horizontally as fast as I can so that you'll see that down field coasting motion at the same time. The ball experiences the vertical falling motion. Here goes a basketball; I'm going to throw it as horizontally as possible. So, it'll start with no vertical component to its velocity. Ready, get set, go, the basketball's fall and its subsequent bounces took a few seconds but it's still hard to see what happened in real time.

I'm going to use the fact that this is video to show you that same arcing descent, but with the images of the basketball lingering on the screen. So, recall this camera takes 30 frames per second, so the images that you'll see in a moment are separated in time by 1/30th of a second. So, here again is that, is the, the ball thrown horizontally out the window and arcing downward in the arc of a falling ball. That trail of basketball images allows us to determine the basketball's position, velocity, and even acceleration at each moment during its fall. Now, I'm going to concentrate first on the vertical motion of the ball.


That is, the component of its motion that lies along the vertical coordinate direction and I'm going to show you the same video, slowed down to 1/10 of, of normal speed so that you can see what's happening, and I'm going to mark the ball's vertical component of position and vertical component of velocity every fifth of a second as it plummets. So, here again, same basketball fall, but with slowed down and with the, the vertical components of velocity and position there for you to see. As you can see, the vertical component of the basketball's motion is that of a falling object.

There's no difference between the vertical component of motion of this basketball, which I threw sideways to start with, and the bowling ball that I dropped previously from rest out the same window. In both cases, the ball is accelerating downward at the acceleration due to gravity. Its vertical component of velocity is increasing in the downward direction by about 10 meters per second every second and the ball is covering more and more distance with the passing time. So, the vertical motion of a falling ball is that of falling regardless of what its horizontal motion is. So now, I'm going to show you the same video again at tenth, at 1/10th normal speed. But instead of worrying about the vertical component of motion, I'm going to worry about the downfield component of motion.

That is, the portion of the motion that's occurring along the down field coordinates direction, which will be towards your left. So, here's the same video in slow motion, with the, the horizontal component of position marked off every fifth of a second. As you can see, the downfield component of the ball's motion is that of a coasting object. The ball moves steadily downfield, equal distances in
equal times. So, the down field component of motion is that of an inertial object. The ball is experiencing no force along that down field coordinate direction, so it's not accelerating along that down field coordinate direction. It's simply coasting horizontally. So, the ball's doing two things at once.

It's falling vertically, it's coasting horizontally, and that gives you the arc that you saw as the ball descended out this window starting horizontally then arcing downward, until finally it hit the ground. Well, that was a basketball falling out the window. The story will be identical if I throw a bowling ball out the window and of course, it's fun to throw bowling balls out the window.

So, you wanted to see it, I'm sure here we go. Ready? [LAUGH] Here goes the bowling ball didn't bounce much. Well, that was fun, I think I'd better go repair the dent. Now, bowling doesn't have much to do with falling balls, but basketball does. Still, tossing basketballs out the window isn't how the sport is played. Instead, it's played on a court by people throwing the ball, either between themselves or toward the basket and once the ball is free from anybody's hands; it's a falling ball, so basketball is all about the motion of falling balls.

To see that, let's go over to the gym and watch some people shooting hoops. Once the basketball leaves the hands of the shooter, it's experiencing only one force, its weight straight down and so it's a falling ball and the arc that it travels in is the arc of a falling object. Every time a player takes his shot and the ball leaves his hands, the ball begins to fall and it travels in the arc of a falling object. I could take any one of these shots, show you the trail of basketball images, and then show you that, that trail is the arc of a falling object. Here are a couple of those curves. I will show you the arc that's formed by the basketball images, and then I'll show you both the vertical motion, and the horizontal motion. So you can see if the vertical motion is that of falling, then the horizontal motion is that of coasting.

Now, depending on the perspective we have on a particular shot, some of the distances get compressed as the ball gets farther away from us and so the evenness of the horizontal motion maybe not perfectly visible. Nonetheless, this, this basic behaviour of falling vertically and coasting horizontally is everywhere in the game of basketball. Here is a beautiful three point shot right through the basket and here is that same shot again with all the previous basketball images lingering on the screen and here is a still photograph of that same shot showing you all the basketball images and I've marked it up so that you can see the ball's vertical component of motion and it's down field component of motion.

The ball's vertical motion is that of a falling object the ball rises quickly at first, then more and more slowly. It's momentarily neither rising nor descending, and then it descends more and more quickly as it approaches the basket. The ball's horizontal motion, the motion along the downfield coordinate direction, is that of a coasting object. The ball is moving steadily downfield at you at a uniform pace and, it looks like the, the vertical yellow lines are getting closer and closer together only because the ball is getting farther and farther from us, and because of our perspective on this shot then, the lines that are far away from us appear closer together because the space out there is compressed. It's, it's just off in the distance.

So, this really is the arc of a falling ball thrown up at an angle and basketball has lots of these arcs, every single shot is like this. Here's another nice shot through the basket and here is that same shot with a trail of basketball images lingering on the screen. Lastly, here is a still photograph the same shot marked up to show you that the basketball is falling vertically and coasting horizontally. It's time for a question. I have an orange ball and a black ball, and I'm going to roll them off the table side by side and let them hit the floor.
The black ball weighs twice as much as the orange ball, but the orange ball will be moving to your right twice as fast when the two of them leave the table. The question is which ball will hit the ground first, and which ball will hit the ground farthest from the table? Here we go. Ready? Get set. Go. Both balls left the table with the same vertical component of velocity, namely zero. In effect, they began their fall from rest. They dropped together; it hit the floor at the same time. But the orange ball was traveling sideways faster. It had a greater down field component of velocity than the black ball, and so it used its time to travel farther from the table, it hit the ground farther from the table.

The arcs of falling balls are part of nearly every ball sport, including football, basketball, baseball and soccer. Effects due to the air modify those arcs somewhat, and we'll deal with those air issues in later episodes. But even if we continue to ignore air, we can make some interesting observations about how ball sports work. Whenever you throw or kick or hit a ball, there's usually a limit to how fast you can make that ball move. For example, I can only throw a baseball so fast. Let's suppose that you throw the, a ball as fast as you can, what path does that ball take? Well, that depends on the direction in which you throw it. I've set that upper speed for the ball but I haven't selected yet its velocity.

Remember, velocity is a vector quantity and it has a direction to it. So, when you throw the ball, you're choosing not only its speed, and we'll choose the maximum. But you're choosing the direction of that ball’s velocity when it leaves your hand. Well, when you choose the ball’s velocity, and particularly the direction of its velocity, you’re choosing both the vertical component of the ball’s velocity and its down field component of velocity. If you throw the ball straight up, you’re putting all of that speed into the vertical motion and giving the ball its maximum vertical component of velocity. At the same time, though, you’re giving the ball zero down field component of velocity. So, straight up, it distributes all of the speed in the vertical direction.

On the other hand, you can throw it straight horizontally and give the ball, put all the ball’s speed into the down field component of velocity, not into the vertical and everything in between. Well, that choice of angle, and we'll measure angle relative to horizontal. So, this is zero degrees on up to 90 degrees. That choice of angle at which to throw the ball has a big effect on the ball’s path. It, it determines both how long the ball stays above the ground and how far it travels down field during its time aloft. Let's start by throwing the ball straight up. That is, 90 degrees above the horizontal. Here is a plot of the ball's position, both its vertical component of position and its downfield component of position at times, at equal times during its travels.

By throwing the ball straight up, you’re putting all of the ball's initial speed into its vertical component of velocity and none into the downfield component of velocity. That ball has the maximum vertical upward speed, and so it rises to it’s the greatest height it can go to and takes as long as possible to return to the ground. But, of course, it makes no progress down field at all because you haven’t given it any down flow component of velocity. It hits you on the head, which isn’t typically very useful in most ball sports. Let’s try something else. Let's lower the angle at which we throw the ball to about 70 degrees.

In this case, we're putting the ball speed mostly into its vertical component of velocity, but still somewhat into its down field component of velocity. At this point then, the ball doesn’t stay above the ground as long. It simply doesn't have as much upward component of velocity, but it uses the time that it's above the ground to make progress down field, and it lands somewhere down field, this is good, you didn't get hit in the head again.
Alright, let's go to a lower angle. Let's go down to 45 degrees. 45 degrees is special because at that angle, you're distributing the ball's initial velocity equally. So that the vertical component of velocity and the down field component of velocity are the same. They're different direction but they're equal in amount. So, the ball has a perfect balance between the vertical motion which keeps it above the ground, and the down field motion which causes it to travel in the direction you want it to go and with this perfect balance, at 45 degrees and in the absence of air, air changes this somewhat. The ball stays aloft long enough and travels down field fast enough to travel as far as you can make it go from where you threw it.

So, if you throw it from this height, it will pass through this height again as far as possible down field. Alright, let's lower the angle still further from 45 down to about 20 degrees. At this point you're putting most of the ball's initial velocity along the down field direction so that the down field component of velocity is quite large. There isn't all that much vertical component of velocity left. The ball doesn't stay above the ground very long, but it uses what little time it has to travel very fast down field.

Finally, if we go all the way down to, to, to horizontal, the ball in principle doesn't stay above the ground at all. I mean, depends on the fact you throw the ball from up here and the ball, the ground is down there. But if you threw the ball from ground level horizontally, you hit the ground immediately. So, a totally level throw is, is often not very valuable if you're, if you're low. But, for baseball for example, it's not bad because you are far enough above the ground that the ball can stay above the ground by the time it gets to home plate. All of these possible paths are potentially useful in ball sports.

For example, if you're going for maximum distance with a football, you probably want to throw it about 45 degrees above the horizontal because that gives you the best balance between vertical component of velocity and down field component of velocity to maximize its flight distance down field. But sometimes, maximizing that distance isn't your goal, for example, a punter kicking the ball to the other side may want to keep the ball out of the hands of the opponents as long as possible while still achieving some amount of downfield distance, and so, a punter will often kick the ball above 45 degrees, more like 70 or 80 degrees, so that the ball has a longer time above the ground, even if that costs some amount of downfield distance.

On the other hand, if there are players all over the field in football and you want to throw the ball to someone as quickly as possible, and they're not all that far from you, distance isn't the goal, it's speed down field. In which case you want to throw the ball below 45 degrees, more like 20 degrees or maybe even 10 degrees, to put as much of the speed in the down field component of velocity as possible to get it there fast. So, in all the sports choosing those angles matters, it gives different flights and many of them are useful.

In this episode, we examined what it means to fall and what happens to a falling ball when you drop it from rest, toss it straight up, or throw it upward at an angle. We encountered our first force, weight. A ball's weight is the downward force exerted on it by the Earth's gravity. That weight, it turns out is exactly proportional to the ball's mass. So that, for every kilogram with the ball's mass there is, the ball acquires a downward weight of about 9.8 Newtons.

That constant proportionality 9.8 Newtons per kilogram is called the acceleration due to gravity because not only does it does, does it describe the proportionality between mass and weight, it also tells you how a ball accelerates if you drop it, if you allow it to experience only its weight, and therefore accelerate in response to that weight. The 9.8 Newtons per kg has other units, it's also 9.8 m/s², which is explicitly an acceleration.
Well, that 9.8 Newtons per kilogram or meters per seconds squared are true here near the Earth’s surface, but if you go to the moon, the value changes because the strength of gravity on the moon is different from here near the Earth’s surface. Returning back to the [LAUGH] to, to, to the Earth then, we saw how balls move when they’re falling. They accelerate downward at the acceleration of gravity regardless of which way they’re going, but that downward acceleration causes their velocities to evolve with time and you see different behaviours, depending on what the balls initial velocity was.

If you drop it from rest, the velocity simply evolves into more and more downward speed. If you throw it upward the velocity starts upward and so it’s accelerating opposite its velocity. In other words, it’s decelerating, so it slows gradually to a stop, momentarily comes to a true stop and then descends as though you dropped it from up there and if you throw it up at an angle, well, it’s accelerating straight down, which affects the vertical component of its, of its velocity and ultimately its position. But it’s not accelerating horizontally along a downfield direction so it coasts downfield and we saw how a lot of ball sports then make use of this dual behaviour.

The falling in the vertical direction and the coasting in the downfield direction and when you play a ball sport, you’re, you’re working with that motion, that dual motion, the rising and falling, and also the coasting down a field to get what you want, to put the ball where you want it to be. Well, that’s it for balls, for falling balls.

Go play some sports and watch the balls fall or, or become one yourself by diving off a diving board, into the water, of course, which is nice and safe and, you know, relatively soft and we’ll be back for another episode of “How Things Work”.