

The Physics of Boomerangs

By Darren Tan

Segment 1

Hi! I'm the Science Samurai – and glad to have you here with me today. I'm going to show you today how to make your own boomerang, how to throw it and even how to understand the physics of a boomerang.

Now I hope today you have with you the equipment necessary to make your own boomerangs. You will first need some cardboard, either in the form of postcards or boxes. A ruler, a pencil, a pair of scissors, a protractor and a stapler. Now there's only one criteria for a good boomerang, it must come back to you.

OK, how do we make our boomerang? First, the easiest way is to use a postcard because it has all the right dimensions. You need three strips about this long, so use your ruler and measure the width of the postcard and divide it into three pieces, three equal pieces. So I'm going to make some markings on my postcard and use the pencil to draw lines down the length of the postcard to get my three pieces. So I'll get the scissors, cut along the lines, so I'll have three equal strips of cardboard. You want to do this as accurately as you can.

The next thing you need to do is put the three pieces together. So you put the three pieces together like this, and use the scissors and cut a slit through the middle of all the pieces. You just want to cut a short slit like this. You see the slit is about 2 cm long and with this slit you can then proceed to fit the pieces together like this. The third piece is a bit tricky in that you have to go under this piece and get the other slit, the other arm to come out on top of this other piece. So you have a very symmetrical setup after that.

The next thing to make sure is that the angles between the arms are all equal. So for this you will need a protractor. If we want three equal angles, we will need to get the angle up to 120 degrees. So I do this for one of the angles, hold it carefully. Go to the next one, do the same. And the third one should be 120. Then you get a stapler and staple the pieces together. One staple like this actually holds the three pieces together, but I like to put a bit more just to make sure that the boomerang is stable. There you have it.

Now it's time to test the boomerang. There you have it! So now I'll leave you some time to construct your own boomerang with your teacher. And please feel free to replay this video if necessary. Thank you.

Segment 2

Good to see all of you ready with your boomerangs. Now we're going to learn how to throw a boomerang. First thing, you hold a boomerang vertically and hold it between your fingers like this, between your thumb and fingers like this. Hold it at the end of one blade. And if it's a bit flexible, let it flop slightly inwards, towards your body. So if you're holding it in your

left hand, you let it flop this way as well. When you throw the boomerang it's important to have a wrist action, so you want to make the boomerang spin. You want the boomerang to spin this way, spin forward. You want the boomerang to spin this way.

So the next thing for you to do is really practice, but just look how I do it. Right? Observe again. And if you do it right, and your boomerang is good, it should come back to you.

Now some questions for you to think about and to experiment with, really have fun with this. Instead of making it turn left, could you make it turn right instead? Do you think you can change the turning circle? Meaning to say can you make the boomerang go further before coming back or do a smaller circle when it comes back? What do you think will happen if you throw your boomerang like a Frisbee, if you throw it in this manner? Can you compare and contrast the performance of your friends' boomerangs. I'm sure they have different flight characteristics. Try to pin down what do you think is making them different?

Notice how you must do a quick flick of the wrist. And I won't hold you back any longer, so see you in a bit. Have fun!

Segment 3

Welcome back! I'm sure you all had fun throwing your boomerangs. Now you must be wondering what makes a boomerang come back. You will have noticed there are a lot of factors that affect how a boomerang flies. It could be the stiffness of the cardboard, the type of cardboard you use, the mass of the cardboard, the width and the length of the blades. You would have some guesses as to how some of these factors affect the flight of a boomerang. Science is really about that – the process of making guesses, testing and explaining how the world works. And that involves observation.

Now, did any of you try throwing a boomerang without it spinning? I don't think that would have worked. Now when a boomerang spins, that's really very essential to what we call the precession of angular momentum. And that is actually the concept that allows the boomerang to come back to you in a circle. For this, let me try to explain on the board because you need some equations to understand how this works.

So the boomerang looks something like this. Before we talk about the physics of a boomerang, there's this thing called the moment of inertia. Now moment of inertia is a concept of how easy or difficult it is to spin something. Take this sword, for instance. When I want to spin this sword around the long end, it's relatively simple, right? I can just spin it quite easily. But if I wanted to spin it this way there's much more resistance to the motion. It's not so easy to spin the sword this way, it takes more effort, it takes more strength.

Likewise, the boomerang has a moment of inertia. Now we say that the sword has a low moment of inertia when it's spinning this way because it's easy, so the moment of inertia is low. And it has a higher moment of inertia when I spin it this way. So there's a certain moment of

inertia associated with the boomerang when it spins this way. We normally call that I . We use I to symbolize the moment of inertia. And there's this formula:

$$\mathbf{L} = I \boldsymbol{\omega}$$

This is a critical formula for the boomerang. Now L is the angular momentum. If you know what momentum means, angular momentum is actually how much momentum it has in the spinning center of the word. $\boldsymbol{\omega}$ here is actually the angular velocity. And finally I is your moment of inertia. We can take this as a definition – this is a definition of what angular momentum means. It means the moment of inertia multiplied by $\boldsymbol{\omega}$, the angular velocity. And angular velocity is basically how fast something is spinning, how many angles per second.

You will have noticed that I drew these little arrows on top of L and $\boldsymbol{\omega}$. This is because these are vector quantities. So when the boomerang is spinning this way, the direction of the vector... we use the right-hand grip rule. It's just a sign convention, meaning to say you put your fingers in the direction of the spinning, and the direction that your thumb is pointing is actually the direction of the vector. So in this case, $\boldsymbol{\omega}$ and L , both of them, are actually pointing out of the paper. Like this. So use your right-hand to “grip” the direction.

Now we have to make a comparison with Newton's laws. Most of you will know that Newton's laws say that $F = m$ times a , where F is the force and a is acceleration. Another way of writing this, which we will do, is write this m times a as dp/dt , the rate of change of momentum. In this case p , what we call the momentum, and you have m here, the mass, which is also called inertia. So notice the similarity – this is the moment of inertia, this is the inertia, and v is actually the velocity.

So we see that:

$$F = dp/dt$$

where

$$p = m v$$

This p , momentum, is mass times velocity. Angular momentum is moment of inertia times angular velocity. So very similar to Newton's second law – we have this thing called the torque $\boldsymbol{\tau}$, the symbol is “tau”, equals to dL/dt . I hope you can see the similarity there. This $\boldsymbol{\tau}$, the torque, is behaving like a force. The torque actually means the turning effect of forces.

These are the two main equations that I've introduced now. The four main quantities – moment of inertia, angular velocity, angular momentum and torque. And these three are vector quantities.

I'll give you some time now with your teacher to clarify any questions you have about all these things that I've introduced. But when you come back, I want you to tell me what happens to the angular momentum, L , if I have a constant $\boldsymbol{\omega}$ – that means I keep the angular velocity the same – but I increase I . I want you to think about that and we'll come back after the break to finish up the explanation of the boomerang.

Segment 4

Welcome back! I hope by now you have some familiarity with the concept of torque and angular momentum.

Now regarding the question I asked you at the end of the previous segment – what happens to L when I increases and ω is constant? I believe you can see from equation (1), that L is actually proportional to I , which means that if we keep the angular velocity the same and we increase the moment of inertia, the angular momentum should increase proportionally.

Now I'm going to wrap up the discussion and really put together the pieces of the puzzle that we have to solve, like how the boomerang comes back to you. I'll begin by drawing something. I'll give you a hint – this is my nose. This is my hand. And this is the boomerang. And so we are now doing a top view. In the top view remember when I throw the boomerang like this, it actually spins this way. So if you imagine you are looking from the top. When I throw the boomerang like this, what is the direction of the angular velocity? What is the direction of L and ω ? Should be pointing to the left. Because you see, as I spin the boomerang like this, it spins this way. Right-hand grip rule, it points towards my ear.

Now another piece of the puzzle is actually what happens to the boomerang when it spins. If you really think about the boomerang, if it's moving forward like this and it's spinning at the same time, moving forward and spinning, what this actually means is that the top blade is moving much faster. First it's moving forward and spinning. Whereas the bottom blade, if you look it's actually spinning backwards while the whole boomerang is moving forward. So the real speed of this blade is actually much lower than the speed of the top blade. This also means that the lift forces, the aerodynamics forces that the boomerang experiences are much larger at the top here than at the bottom. So as the boomerang spins, the top part experiences a larger force than the bottom part. And so there is a tendency for the boomerang to turn this way, to turn inwards.

Now if you think back to your right hand grip rule again, this turning effect, this torque – turning effect is actually torque – this turning effect causes the boomerang to spin this way, and so if I put my fingers this way, turning this way, the torque is actually pointing behind me. I would draw that on this top view diagram. The angular momentum is to the left and the torque is pointing behind me.

So what is torque? Remember, torque is the rate of change of angular momentum, dL/dt . So torque changes angular momentum. When I just release the boomerang, the angular momentum is pointing this way, at time zero. The torque backwards will cause this angular momentum to change. So I add these two vectors, at the next instant in time, the resultant... this new angular momentum will actually be pointing somewhat backwards. So if you visualize this, what's happening is that, at the next instant, the boomerang is tilted to the left because the angular moment is pointing this way. So repeating this argument, we will see that the boomerang will go in a circle and come back to us.

So we've just shown that the spinning motion of the boomerang, this particular "spin plus motion", this effect actually causes a torque, which then causes the angular momentum, the \mathbf{L} vector, to do what we call precession, meaning to go around in a circle, and to turn round. And this really is the explanation for why the boomerang comes back to you.

Now I want to leave you with a little challenge problem so you can work on it. What do you think will happen, if let's say I use some blu-tack – some adhesive putty – and stick it to the blades of the boomerang? Just a little bit. If I stick an equal mass on all three sides, this will increase the moment of inertia of my boomerang. Now what do you think will happen when I throw the boomerang? Think about that and discuss with your friends, check with your teacher and I'll come back in the next segment to round things up.

Segment 5

Now wasn't that a fun problem to think about? Did you manage to figure out that the boomerang with the added masses will actually go in a larger circle than before? What we said is we keep ω constant. We keep ω unchanged, but we added the masses, so the moment of inertia is greater. This means that therefore the angular momentum would have increased since $\mathbf{L} = \mathbf{I} \omega$.

What about τ – what about the torque? Well, we know that torque is $d\mathbf{L}/dt$, that's equation number (2) over there. And if you think about it, actually this is unchanged, this is also constant. Because what we said was that the boomerang will spin in the same way as before, same ω , the only difference being that the \mathbf{I} is increased. But the air doesn't know that, so the forces don't know that, the lift force will be the same. And so the torque acting on the boomerang is the same.

Does this mean that the circle is unchanged? No! Quite the contrary. In the initial case, we have our angular momentum of the boomerang pointing to the left. With the blu-tack, the angular momentum is now larger, but the torque is the same. That means in the same time, there's the same change in the angular momentum. So when we do this same argument, the change, the $\Delta\mathbf{L}$ – the length of this blue arrow and the length of this blue arrow should be the same. This $\Delta\mathbf{L}$ should be the same. So because these $\Delta\mathbf{L}$'s are the same, when I have my resultant, we see that this angle here, the original angle θ , as compared to this angle where you add the mass, θ will be larger than θ' . Meaning to say that in the original case, the boomerang will fly in a smaller circle, because it will turn faster. And so in the case without the masses, the circle might be something like this, but with the masses added on, the circle will be something like this. And this is something that we can see in real life as well. You should try it out. The boomerang goes much further before coming back. It doesn't come back quite exactly to my hand, but it still goes further.

I'm sure you'll agree with me that it takes time and effort to understand such theories. After all, science is not built in a day, and scientists and mathematicians have been doing research and experiments, lots of thinking and dreaming to come up with such theories. And I'm sure you have lots of time to think about such things further when you play with your boomerangs at home.

Now the concept of precession is actually applied in gyroscopes, and we actually use these concepts in applications such as navigation for aircraft and ships, as well as if you observe what happens to a top when it spins around the table. You'll notice that there is actually some precession going on.

At this point I'd like to invite my two assistants, Dawn and Ming Hui, to actually show to us today, demonstrate to us today, the wonderful science of precession and what wonders it can create. As you can see, they're holding onto a samurai sword, and suspended from it is a bicycle wheel. The bicycle wheel is attached by two strings to the sword, and what I'm going to do now is actually to spin the wheel and cut one of the strings. Right, amazing as that might sound, I'm going to just do it. Spin the wheel... there!

Isn't it amazing how the wheel doesn't fall? But really it's just like the boomerang. See the wheel is spinning so fast it's got a high angular momentum, so the torque due to gravity causes it to precess rather than fall. Thank you to my two assistants, Ming Hui and Dawn.

I hope that today you've had fun learning about how to make a boomerang and to understand the physics of a boomerang, and I hope that I've got you started thinking on this bizarre notion of precession of angular momentum.

To end off, I'd just like to say, that as the Science Samurai, what I do is not magic. My power comes from... the wonders of science.

END OF LESSON

Teacher Segment

Hi, this is a note for the teachers and I am so glad that you're considering using this BLOSSOMS module in your lessons. The focus of this lesson is to encourage hands-on exploration of physics and not just the theoretical kind of "laws and equations". And hope that this can really inspire students to be interested and excited about science, because I think the attitude is much more important than all the actual concepts and theories introduced.

We've provided some links to resources, additional resources, and you can further explore these links on the website.

In terms of prerequisites, think all students can take away something meaningful from the lesson regardless of their background, but for the lesson to work best I think they would need three things. Number one, a basic understanding of forces and vectors. Number two, the understanding of Newton's laws, $F = ma$, dp/dt , that kind of thing. And number three, time derivatives and vector addition. So these are the three main things that the students would need to know.

I have deliberately kept the discussion more qualitative rather than quantitative, because the actual movement of the boomerang is much more complex than I've made it sound.

The materials, I'm not sure if you would have difficulties getting them. They're quite straightforward – stapler, pencil, ruler... I think the hardest part is the cardboard. I think for this you really have to just try to experiment a bit with different kinds of cardboard. What works best is I think something rather stiff, yet still being somewhat flexible. And these kinds of material have the best performance. And I strongly advise that you do try making your own boomerang before class, because students will definitely ask you for troubleshooting advice and tips during the lesson.

There's one thing that would be nice if you had – I don't have one with me right now, but if you had a gyroscope, you could actually bring that to class. That could be a possible extension to the lesson.

Now I'll run through some of the suggested activities for each of the segments, for the breaks after each of the segments. After segment one is for students to construct the boomerang. So just help them out with this. You might want to replay the video so that students can dwell a bit longer on some of the steps that I took. I think one focus might be to be sure to get them to be more focused on accuracy and doing things properly.

After segment two is for them to throw the boomerang. This is probably the most fun part of the lesson because it's really hands-on. You want to make sure of course that they're safe. Maybe set some rules as to not to try to retrieve their boomerangs if they do get on top of some building or in some area where there is significant danger. And keep them safe from traffic, do decide on what would be a possible place before you use this lesson. And really encourage them to have fun and experiment during that break.

After segment three we start the first part of the theory, which is to introduce the variables and to sort of introduce the relationships between the variables. For this segment it would be really useful to take a look at what Walter Lewin has done. He has another BLOSSOMS video on angular momentum, I think called the “Ice Skater’s Delight” (the link is provided below) and you can really consider using that video in your class before this current video. In segment three another tip would be to, as you saw in my explanations, to link the actual physical boomerang with the theory that we are presenting. This will help them also link with their practical experience, with what they have observed as they’re throwing the boomerang, if they use the boomerang to sort of visualize what’s happening. It is a bit complicated in three dimensions.

For segment four, after segment four, that question about what happens if you add the mass, the blu-tack to the ends of the boomerang. That one you might try to lead them towards the answer, perhaps by asking them questions such as what variables are unchanged? If the spin is the same, how is the moment of inertia affected? And you might also want to let them try it out after they’ve thought through the argument and see whether their boomerangs actually behave that way.

At the end of segment five, actually you can end there, the lesson is pretty much done. However, there are some options you can consider if you want, if you have a bit more time or you want to take this further. One way would be to explain how the bicycle wheel setup works, what are the vectors involved – to really draw it out on the board. Maybe get them to draw it up, get them to identify the angular momentum, the torque and all that kind of thing. Precession, what if the wheel spins the other way, all these kind of questions can be explored. Another way, which is when I mentioned the gyroscope just now, would be to show them a toy gyroscope, or in fact if you could, you could even bring in a bicycle wheel yourself and show it to them, although it’s a little bit dangerous. So you would want to caution them on that before letting them experiment a bit.

Once again, thank you for considering this module. I hope you have lots of fun with it. I certainly did in producing this video. My email is now shown on the screen (darren.tan@gmail.com), so just drop me a note if you have any further questions. Once again, thank you.

END OF TEACHER SEGMENT