BLOSSOMS MODULE
THE SCIENCE OF SOAP BUBBLES, Part 1
By Paola Rebusco

Hello. My name is Paola Rebusco. I am a post-doctoral fellow here at MIT. I'm a theoretical astrophysicist. This means that I spend my day trying to understand the behavior of nature in the vicinity of black holes, neutral stars, and clusters of galaxies.

However, today I will tell you about something that is much more common and present in everyday life, and I'm sure you are familiar with. We will talk about the mysteries of soap bubbles. Soap bubbles have attracted the attention of many painters over the years, painters such as Bartolome' Murillo, _Jan Steen, Jean Simeon Chardin, Eduard Manet, Rembrandt, and many others. You can see now a couple of examples. This is a famous painting by Chardin, and this one is by Eduard Manet. And you can notice how the painters really got to catch the details of the soap bubbles themselves.

Soap bubbles are really fun and beautiful but they're also complex and mysterious. Did you ever wonder, for example, why soap bubbles are spherical? And where does the color of soap bubbles come from? Why do we have to add soap to the water in order to get some bubbles? Today and in the next module we will try to answer these questions and much more. This first module focuses on the shape of soap bubbles, and the next one will explore the colors. So now you can stop the video and try the first activity in class. You will be exploring different solutions, different recipes to make soap bubbles. See you soon.

Welcome back. So it's not a big surprise. You found out that in order to be able to make soap bubbles and soap film you actually had to add soap to the water. Is it the same in micro-gravity? Well, you can try to discuss this in the classroom and then watch this video that was taken by an astronaut named Don Pettit at the International Space Station.

[start of film]

This subject is working with stretched thin films of water. And what we have here is a baggie, which makes a nice two-dimensional beaker for use in zero gravity. And here I'm filling a small Ziploc up with water, and it makes a real handy way to handle an open container of water. And it's basically two dimensional. And there you see a little wire loop that I made from stainless steel safety wire from the _______ kit and that's just our de-ionized water that comes from the _______. And so I'm going to stick this wire loop in the baggie and there's no soap or anything in that water, it's just our pure drinking water. And you pull the water loop out from the baggie which makes that two-dimensional beaker, and lo and behold, you have a stretched thin film of nothing but water hanging onto your loop. And so it's like a soap film only it's just water. And we've never seen anything like this before where you can make a thin film of pure water.

And it has some rather unusual properties which you'll see here. It's thin. It's about half the thickness of the wire and that's a 25-thousandths wire so that puts the film at about 300 microns thick. It's thick enough that it doesn't exhibit the interference colors that soap-bubble films do. Soap-bubble films are a lot thinner. But it's quite a tenacious film. As you can see there it kind of acts like a rubber film or a drumhead. You can sit there and shake the loop around and you can collect these fairly large lenses of water induced from the flow and it just sits there and hangs onto the film. (end of film)

Hello again. In order to understand what is going on at the space station, we first have to introduce the concept of surface tension. So let's consider a liquid. Here in this bowl I just have some plain water. In the liquid there is some part that's in the bulk and other parts that stays on the surface. We can look at the sketch here. This is a sketch of the forces between molecules on the surface and in the bulk of a fluid. Each dot represents a water molecule and the arrow represents the forces. These are electrical forces that keep the molecules close to each other. Water molecules tend to stick to each other, to stay closer. When we consider a molecule in the bulk it is surrounded by molecules of the same type. It swims in a bath of molecules of the same type. So it feels the same force, the same attraction in every possible direction. As a consequence, the net force that it will feel is zero. Nothing happens. At the surface this is different. As you can see, at the surface the molecules still feel the attraction towards the bulk and towards their neighbors, but they feel much less attraction toward the air that is much less dense, 1,000 times less. As a consequence the molecules at the surface feel a net force that is directed toward the bulk. And what it tries to do, it tries to reduce the area of the surface itself because it wants to have the water molecules as close as possible. And as a result, the surface is a little bit elastic, like the rubber of a balloon.

There is a scientist named Charles Boys who wrote a beautiful book about soap bubbles, and he actually called this effect on the surface of water "the skin of water." The skin of water is the thing that allows some insects to be able to walk on the water. And as you will see it's strong enough to support a clip without letting it sink. Here I have a paperclip and a piece of paper towel that I'm using just to do things gently. I first put the paper towel in the plain water, then I place the paperclip and I try to get rid of the paper towel. Here it is. And as you can see, the skin of the water supports the clip, it doesn't let it sink. Isn't this amazing?

Now what happens if I add some soap in the solution? Ready? I'm going to do it now. I do it here so it doesn't perturb the clip itself. I add just a single drop and as you can see the clip sinks immediately. Why is this happening? We first have to give a look at the structure of soap molecules. You can see again from this sketch that soap molecules look a little bit like tadpoles. They have a head and a tail. The head is attracted by the water while the tail is repelled by the water. This is why the head is called hydrophilic It's from the Greek from *hydro*, that means water, and *phylos* that means to like. The tail is hydrophobic, from *hydro* that means water and *phobos* that means fear. The tail are fearful of water.

Let's go back to our bowl with the water and the paperclip. Here I made a sketch of the bowl, the water and the clip. When there is no soap the skin of the water is strong enough to support the clip. However, when we add the soap, the soap molecules tend to stick their head towards the water because they like the water, they are hydrophilic and they try to point the tail as much as possible away from the water. As a result, they concentrate on the surface and all the water molecules on the surface cannot stay so close to each other because in between there are soap molecules. The result is that the skin of the water weakens. It becomes so weak that it cannot support the clip any more and the clip sinks toward the bottom. Here it is.

Now what happens when we actually create a soap bubbles? Here we have an enlargement of a soap bubble. The bubble itself is constituted by a thin film and this thin film has two surfaces and a bulk in the center. We can think of it a little bit as a sandwich. The two soap surfaces are the bread and the bulk in the center is the filling. We already know that on the surface the soap will tend to stick their head in and the tails out and this reduces the surface tension. In the bulk the soap will tend to create configurations like these. These are called micellae and all the tails stay away from water at the center of these configuration and all their heads point towards the water itself. Since the soap weakens the skin of the water, it gives it enough elasticity to be able to blow the bubble itself. By the way, this drawing is clearly out of scale. Indeed the real size of the molecules is 100 times to 1,000 times smaller than the thickness of the film itself. And the film is less than 1 million times thinner than a human hair. It's really tiny.

Molecules like soap are called surfactants and they all have this characteristic of having one part that is attracted by the water and the other that is afraid of water and wants to stay away. Surfactants play a really important role in life. Let's have a look here at you lungs. The last part of the respiratory tree is composed by alveoli. The alveoli_ here you can see a bigger image, they're like little balloons. They inflate and deflate and they are the main place where the exchange of oxygen and CO_2 in the blood takes place, so they're really important. The walls of the alveoli_ is covered with a surfactant. This surfactant can reduce and vary the surface tension of the alveoli______ themselves and this is what allows the __alveoli_____ to inflate when we breathe. In case of some sicknesses or when there are some premature born babies, it can happen that there isn't enough of this surfactant on the wall of the ___alveoli__ and as a consequence the lungs tend collapse. They cannot be really inflated and this makes respiration really difficult.

Now that you know what surface tension is, you can try to cut out some paper models of a boat something like this and find a way to power them using your knowledge about surface tension. See you soon.

So that was easy! It was too easy maybe. You just had to put a little bit of soap on one side of the boat and actually the boat was pulled towards the other side. This is because the soap is reducing the surface tension. There it is.

Now we are ready to understand what is going on at the space station. At the space station we are in a situation of microgravity. The electric forces are the same, which means that the attraction between molecules is the same and the surface tension is the same as on earth. What is different? Let's consider this circular frame and imagine to be here on earth and to create a film of water. Now what happens is that a little amount of water will drop in the center of the ring. The film sags a little bit and the water starts to drain from the edge toward the center. This makes the center of the film heavier and heavier and it will create kind of a little pool. At some point the surface tension cannot win gravity any more and the weight of the water will make the film break. And in the competition between gravity and surface tension, gravity wins.

What is different at the space station? As you have seen, the astronaut was able to create film that was really stable, thick, and it could last up to twelve hours. This is what he noted. Well, the difference is that the film there is weightless. Being weightless the surface tension doesn't have anything to fight against. It holds the water together, all the molecules can stick together and there is nothing that tries to break it, pulling it towards the bottom. This is it for now. In the next section we will investigate the shapes of soap bubbles.

Welcome back! Now we are going to find what is the energy of a soap film and how it is related to its area. In order to do that we're going to use a metal frame with three sides that are fixed and one side that can slide. Let's give a look here at this sketch of the frame. So here we have three sides that are fixed, one side that can move and this side is long, l let's say. And we try to create a film in the middle, applying a given force F. This sounds more complicated than it really is. Because what you're going to do in practice is just to take this frame and dip it in soap water. Then we pull the two sides apart and in between them there is a thin soap film. We will see it better soon. Let's first write down what are the important equations here. When we create a film we actually apply a force. This force is related to the surface tension. The surface tension is indicated by the Greek letter gamma and is equal to the force that you apply which is parallel to the film, divided by the total length of the film itself. You remember that a soap film is actually a sandwich of two soap layers and water in the middle. So we don't have just one surface but two. Here is the second one. And this is its length. So when we apply the force, we apply it to two surfaces. This means that the total length will be the sum of the two lengths of two different surfaces. L = 2 times the side of the film l. So the force which acts in this direction parallel to the surface is equal to the surface tension gamma times two times l. When we apply a force to move an object, what we are doing is we do some work and this mechanical work is equal to the force times the displacement. In our case we move the side that could slide over distance X. So X is our displacement. Let's substitute the force and we will get that the work is equal to gamma times two times l times X. But _l times X_____ is the area of the film. So the work is equal to gamma times two times the area. Gamma is constant for a constant and better and in equilibrium _____ conditions so we end up with a relationship between the work that we apply to make a film and the area of the film itself. They are proportional. This work is actually the energy that is stored by the film and it's available to the film itself to do something else.

Let's go back to our frame. We can look at it closer. Now here there is no film, there is nothing. You see these are the sides that cannot move and this one can slide. If I put here this side and I let go, nothing happens because there are no forces involved. Now I'm going to create a film. I take this frame and I dip it in the soapy solution so that I have a soapy film in the frame. Now when I let go, you see that the energy that was available has been used to pull back the film. This is the surface tension at work.

Now I would like you to use a similar frame to try to measure the surface tension of different soapy solutions. See you soon.

Nature works in the greatest possible economy or we can say nature is relaxed. This statement was first introduced by the Frenchman __Maupertis______ and then it was started in different contexts by a series of mathematicians such as ___Leibnitz___, _Euler,________ Fermat. Nowadays it is widely used in physics and it's well understood. It's known as the least action principle. In simple words we can say that nature will tend towards configurations of minimum energy. Here I have a bowl and two ping pong balls. One at the bottom and the other one at the on the edge. Which one has the higher potential energy? You can discuss this and then see you back.

I am sure that you got the right answer. The ball at the edge has a higher potential energy than the ball at the bottom simply because it's in a higher position. Now what happens if I perturb it? It's easy to forecast. After a few oscillations both balls end up at the bottom of the bowl simply because nature is making them evolving towards the situation of minimum energy. So this is true for a mechanical system. This is true for soap bubbles. We already know that in the case of soap bubbles the energy of the soap bubble is related to the area of the soap bubbles. So if nature wants to minimize the energy it seems that it also wants to minimize the area. Is this really true? We're going to verify it using a metal frame. I need an assistant. Walter could you please help me? I'm going to dip this frame in soapy water so that we can create a film. I want you to take the needle. (some back and forth here not transcribed.) So Walter it finally worked. It was a bit tricky but we managed to do it. So try to do this now in the classroom and see you in a while.

Welcome back. So I hope that you managed to create your little circle with a thread. Do you know why that happened? Well you should know that once you take a given perimeter, a two dimensional figure that encloses the maximum area is the circle. So when we make the film pop in the center of the thread, the film wants to minimize its area because this is what naturally it wants to do, minimize the area, minimize the energy. In order to do that the hole has to take the maximum possible area. This maximum area is the circle. The circle, the hole, is bigger then all the film around it is smaller. Problem solved.

Actually this is really fun but it has also some practical applications. You can give a look here at this sketch from the computer. There is a problem that is known as the motorway problem or also as _Steiner-Fermat-Torricelli-Cavalieri________________________ problem from the name of the scientist who first introduced it. This problem concerns to find the answer to this question. You have different points on a plane. What is the shortest path that connects all of them? You can think of each point as a city and the path can be a motorway. That's why we call I the motorway problem. I'm not going to explain this in detail right now. You will see it in the activity paper how to proceed. Essentially you will have two plates parallel to each other. You will put some pins, one for each point, for each city. You will dip this in a soapy solution and the soap film will find the best configuration that connects all the pins. This is a really complex mathematical problem but with soap bubbles you can solve it really easily. So if you want to try the activity you can stop here. If you want to continue, stay tuned because now we are moving to other surfaces.

We all know soap bubbles. Soap bubbles are spherical but why? In principle if we take some air it can have any possible shape. We can have soap bubbles, you can see the image here. We can have soap bubbles of any shape you can imagine. However this is not happening. Well right now you know enough to imagine that this is has to do with the area, with the energy of the soap film itself. Indeed what happens is that for a fixed volume the two dimensional surface that minimizes the area is a sphere. So this is not a big surprise. It's quite difficult to demonstrate it mathematically. I'm sure that you will be able to do it once you learn a little bit of calculus but for now you can just get it from the intuition of soap bubbles. We blow in a given amount air. In order to enclose it we have to find the shape that minimizes the area and this is a sphere. Now a sphere will form because we don't have any other constraint but we can try to create bubbles that are different from a sphere.

Let's see here for example I have a kid's pool and a hula hoop. So essentially I have two rings. Can you imagine what is the shape of the film that will be formed once I pull the hula hoop here. DO WE KEEP THIS TWICE?

Here we have a kiddy pool with some soapy solution inside and the hula hoop. So we have essentially two rings. We want to know what happens when I dip the hula hoop in the soapy solution and then I pull it out. Before I pull up the ring, stop the video and discuss in the classroom what shape you expect. I will see you in a couple of minutes.

OK. Here it is. It's not a cylinder, it's a _catenoid______, it's bent in the center. Eh Voila! Here we are. This surface is called a _catenoid______. A _______ is the surface that you obtain when you revolve a line that's called the catenary. Well this is a catenary. It's the shape taken by a chain when it's free to hang out and all the forces are uniformly distributed. A catenary is very common in nature. You can see for example here this image of this nice mammal called the sloth that is hanging from a branch. And it's spine actually makes a catenary. Catenary is also used in architecture. This is because again it minimizes the energy, it's very stable. Inverted catenaries make very nice arches. And here you have for example the Gateway Arch in St. Louis. Maybe you were surprised to see that when I pulled the hula hoop we obtained something that was different from a cylinder. I was expecting a cylinder myself. We can explain this a little bit intuitively. Let's give a look at this glass. This is a cylinder. If I want to cover it with stripes of paper, I have to take stripes that all have the same length. So there is one, here is a second one and so on. Here I have stripes all of the same length. However, a _catenoid______ is thinner in the center. So if I want to cover a _catenoid_____ with stripes of paper I will start with stripes of the same length here but then I will need stripes that are shorter and shorter. This explains a little bit why when we have two rings the surface in between is not the cylinder but it is a _catenoid_____. The _catenoid____ has a lower surface area. Again, you can make a precise mathematical demonstration but to do that you need a little bit more math. So maybe you have to wait a few years. That's it for now. See you soon.

Hello again. Now we know almost everything about the shape of soap bubbles and we know that soap bubbles are actually useful to study surfaces with a minimum area and in principle they are good physical models to try to create communication systems. I hope you tried the motorways problem. However bubbles are useful also in different contexts. For example in architecture. You can see on example here. Here we have a frame that has a spiral shape and once we dip it in a soapy solution the soap films takes a very _characteristic________ shape surface whose name is helicoid. The helicoid has been used for centuries in architecture to create winding stairs. And here we have an example. This is the stair located at the Vatican.

There is a famous German architect named Frei Otto__________ who creates really beautiful and daring structures with soap bubbles. You can see here an example. This is the roof of the Olympic stadium in Munich in Germany. And here there is another building by the same architect. And you can have an idea of how he used the soap bubbles to create it. On the top left of the image there is a soap model. Here we have the wires that he actually used to create the model. He then dipped the model in a soapy solution, took it out and saw how the soap film would configure. What soap would the soap film take? This was tested because of course it has to be stable not to break when there is wind, when there are all kind of perturbations. And then the architect was projecting this model, making a real design and here on the top right there is the network of the building. Here it is. And at the end we have the final building. Soap films minimize the energy, we already know this. And so it's really convenient to try to create some buildings that mimic them that are following the same shapes.

Finally, soap bubbles have been used in biology as a good model for membranes and for the partition of cells. On the left here you have an image of the wings of a dragonfly and on the right there is a model of these wings. This model was created using just a frame and soap bubbles. And you can see that it mimics pretty well the wings of the dragonfly itself.

And we will finish with frog eggs. Frog eggs form in a solution which is clearly different from a soap solution or from water. However the shape is really similar to that soap taken by a soap foam or by the water bubbles. In this image on the top you can see frog eggs. Here on the left there is a soap foam and on the right there is an image from the video that was taken at the international space station when the astronaut was actually putting alka seltzer inside the film of water and this was creating bubbles. These bubbles will compete and will divide and interact all in the same way. That's it for today. There are many more applications of soap bubbles in physics of turbulence, in astrophysics, in chemistry, in materiel science and I hope that you will continue to explore the world of soap bubbles because there is a lot of fun. We just barely touched the surface. In the next module we will discover where the colors of soap bubbles come from. Good bye for now. Caio!

Hello teacher. This module is designed to explore the science of soap bubbles. We first start with the concept of surface tension. If you want to talk a little bit more about it you can maybe expand talking about intermolecular forces. In the next segment we make a connection between the energy and the area of the soap film and this gives the possibility to talk more about mechanical work and energy. And it gives the possibility to understand something about the geometry of soap bubbles without entering into too many mathematical details. Finally we are just studying some applications of soap bubbles mainly in architecture and in biology. Once you make your soap solution you can try to actually change the proportion from the basic recipe that's written in the teacher guide. This is because the proportions change depending on the weather, depending on the water, depending on the soap itself that you are using. So you should really try to experiment. It can be a little bit frustrating because every time that we try to make a demonstration we had to repeat it many times. But once it works it's really rewarding so I suggest you be patient and try to do it until it works.

To make the frames I was using a copper ring. You can use any metal, any wire that you can deform and you can also try to create different frames. There are some examples on the book by Charles Boyce that is listed in the reference. And finally, Walter and I will show you how to make a ________ in your classroom. You can see it in detail. Have fun! Goodbye!

So now Walter and I are going to show you how to make your own ______ without needing a kiddy pool and a hula hoop but just with two circular frames. You can take an needle and then here I'm dipping the frames in a soapy solution. Now I pull the two rings apart and you will want to pop the circle in the middle. There it is! You can see now that in between the two rings there is a surface that's the _________.

END OF MODULE