WATER - Curated Transcript of BBC In Our Time podcast
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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

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Hans Rausing Professor of History and Philosophy of Science at the University of Cambridge

Andrea Sella
Professor of Chemistry at University College London

Patricia Hunt
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Transcript:

[Melvyn Bragg] Hello. Water is one of the commonest substances on Earth. It covers 70 per cent of the planet's surface, including the vast amounts of water in our atmosphere, in organisms and in the Earth itself, we're surrounded by more than 330,000,000 cubic miles of the stuff. It's the second commonest molecule in the universe, after hydrogen. Water is one of the simplest chemical compounds we know, but it's also one of the most intriguing, perhaps because it's all around us. We tend to think of water as normal, but it's quite an exceptional molecule. It dissolves more substances than any other liquid and it's essential for all life. Since the 19th century, it's been known by the formula H2O. And today, scientists are still discovering new things about water. We now know, for instance, that there are at least 15 different types of ice. With me to discuss the chemistry of water are

Hasok Chang, Hans Rausing Professor of History and Philosophy of Science at the University of Cambridge,

Andrea Sella, Professor of Chemistry at University College London,
and

Patricia Hunt, Senior Lecturer in Chemistry at Imperial College London.

[Melvyn Bragg] Hasok Chang, it wasn't until the chemical revolution of the 18th century that we began to understand the nature of water. Who were the first scientists to make progress and what were they progressing from?

[Hasok Chang] Well, we associate the idea that water is a compound made of hydrogen and oxygen with the Frenchman Antoine Lavoisier, who was the chief architect of the chemical revolution that you just mentioned. And until his work, it was centuries and centuries during which people thought water was an element. Nobody dreamt that it was made up of anything else. I mean, nowadays we take it for granted that every school child knows that water is H2O. But for many centuries, people lived perfectly good, intelligent lives without knowing that.

[Melvyn Bragg] When you talk about the chemical revolution, can you be more specific and tell our listeners when about that happened and what it involved?

[Hasok Chang] The peak of the chemical revolution was in the 1780s, and interestingly coinciding with the French Revolution. Before then, water was commonly considered an element, people did not know about oxygen. And in fact, Lavoisier also named the element "hydrogen", meaning "water maker", having discovered that water was made up of hydrogen and oxygen. And before his work, people also commonly believed in the element of "phlogiston", the element of fire. So Henry Cavendish, for example, who actually first made hydrogen gas and studied his properties, discovered that it was inflammable, he could explode it with oxygen, and he actually made water before Lavoisier. He thought hydrogen was full of phlogiston, therefore it was combustible.

[Melvyn Bragg] You're talking about as if Lavoisier cracked the whole thing. But as I understand it, from reading the notes from the three of you? He didn't. He was the beginning of a daisy chain that went round Europe from one country to another, involving a lot of people in this country, people in Italy, people eventually in Sweden. So can you give us some idea of how the debate developed after Lavoisier's early discoveries? Because he discovered these things, but he didn't really ... nail this as water, did he?

[Hasok Chang] Yes. I mean, the chemical revolution itself was a very controversial affair, rather than Lavoisier just discovering the truth and everybody lying down and admitting it. But even after Lavoisier's views were generally accepted, it's not the case that people were thinking about atoms and molecules, because the chemical atomic theory, which we associate with the name of John Dalton, didn't come in until the first decade of the 19th century. And even so, if you look up Dalton's original publication of 1808, he has the water molecule as ho, one atom of hydrogen and one atom of oxygen and it took chemist half a century after that to come to an agreement that water was H2O.

[Melvyn Bragg] And what is unusual about this, Andrea? So I said in my actual question, it's a substance that's all around us. We count on it every day, but it's unusual. Can you give us some idea of its unusual qualities? Some examples would be better, actually...

[Andrea Sella] Well, water is a funny material ... because it's so common. We find it in bottles in front of us, in our refrigerators, and we assume that liquids, and, of course, solids like ice are very typical, and it's not. So the first thing is the fact that it is able to store enormous amounts of energy. So the amount of energy you need to actually warm it up or that it will release when you cool it down is huge by comparison with other liquids. And this is the reason why it makes it so effective in our heating systems, for example, is that we can store vast amounts of energy and move them around our houses and thereby keep warm. But the second thing is that as we cool water down, it does something very, very peculiar. At a temperature of about four degrees... it contracts down until you get to four degrees, and then suddenly it starts to do something different. It expands again, and its density actually reduces. So the result is that by the time it actually freezes to ice, you have a material which is less dense than the liquid that it's sitting on. There is no other molecular material that I know of which will actually float on its melt. So if, for example, you go into your supermarket later today and you go and take a look (it's quite a cold day) uou look at the olive oil shelves, for example. You'll see that at the bottom of the olive oil, there's sort of an offwhiteish deposit, and that's actually olive oil ice. Olive oil is a normal liquid, right, which when it freezes, it contracts and so the stuff goes down to the bottom. And somehow or other instinctively we get brainwashed from when we're age two that when you freeze a solid, it should go to the surface. And water is completely unique in that respect. So there are a whole series of things. Its boiling point is completely anomalous. If you compare it with other molecules of similar size. All of them boil way down at -40 -90 -200 or whatever. Water on the other hand boils at 100 degrees. And that really points to the fact that water is a very, very special material, which is held together in a completely different way from others.

[Melvyn Bragg] How come given that the sun is so near comparatively ... that we have any at all?

[Andrea Sella] Well, that's an interesting point. I mean, first of all you might think that the sun would essentially boil it away. But there are two things. The first thing is that the sun could have... its first effect would simply be that the light will split the water into hydrogen and oxygen. And that's something that will happen on planets without an atmosphere. Now we are fortunate that through a combination of luck and life, we have an atmosphere which contains a whole series of molecules which are actually able to filter out the most harmful rays. And that in a sense protects the water from being essentially destroyed and converted into its elements.

[Melvyn Bragg] Hasok Chang began the story of the discovery of H2O but didn't complete it. When did it become known that there were two parts of hydrogen and one part of oxygen? ...

[Andrea Sella] The story really is a 50 year long one, because shortly after Lavoisier there started to be the first experiments with electricity in which people passed electric currents through different materials. And of course we always remember Humphrey Davy discovering potassium and so on. But there was actually an Englishman called Nicholson who passed electricity through a sample of slightly acidic water. And what he found was that he got two different gases off which he identified as hydrogen and oxygen. And when you measure the volumes of that you find that they are in a two to one ratio, two parts hydrogen, one part oxygen. In spite of the fact that that observation had been made, there were still concerns about what the actual weight. And I use "weight" sort-of deliberately because back then people weighed things, they used balances to determine the amounts. There was still a lot of controversy over how much hydrogen weighed and how much oxygen weighed. And so this remained controversial until, really the middle of the 19th century, and and it was a crucial experiment that was carried out by a man called Alexander Williamson, who was actually a professor at University College London. And what he was able to do was to show that water was really the parent of a whole class of molecules in which you can include alcohols and ethers. And if we think of water as being HOH, you can replace one of the hydrogens with a carbon containing thing. We'll call that R. So an alcohol is ROH. And if you replace the other hydrogen, then you get an ether, R-O-R. And in many ways, that sort of cemented the unity of water with organic chemistry and the idea that, in a sense, this structure, OH_2 connected in very nicely with the rest of organic chemistry.

[Melvyn Bragg] Patricia Hunt, could you describe in detail the water molecule for us?

[10:02]
[Patricia Hunt] Okay, so we know that water is H_2O. If you think of a triangle sitting on your desktop and you put the oxygen at the apex, at the top, you can think of the hydrogens as being below them at the other ends of the triangle. But that's not just all of what water is. It also has what we call lone pairs, some little bunny ears of electron density, which sit perpendicular or 90 degrees to the orientation of the hydrogens. And this makes the local environment around the oxygen atom tetrahedral. Now, these small bunny ears of electron density, they are kind of negatively charged, and the hydrogens become slightly positively charged. And this creates a dipole for our molecule, a positive and a negative end. And one of the most important things about water is that our hydrogen bonds - and this is where the bunny ears of electron density of our water molecule interact with the positively charged hydrogen atoms of the next water molecule along. And actually, water can form four of these kinds of interactions two with its bunny ears and two with its hydrogen molecules. And when you put all that together, water forms these quite highly structured networks. And this is why the water boils at a very high temperature, because it has all these hydrogen bonds around it, holding it in place.

[Melvyn Bragg] When you say "hydro", please go on, I'll ask you...

[Patricia Hunt] Okay, so, well, hydrogen bonds... are what we call 90% ionic - so this is this plus-minus interaction - and about 10% covalent - and this is about the electrons mixing together.

[Melvyn Bragg] What do you mean by covalent?

[Patricia Hunt] Covalent is where two atoms share their electrons to form a bond. So the oxygen and the hydrogen have a almost completely covalent bond. They're sharing their electrons, one from the hydrogen and one from the oxygen. But the bunny ears are two electron pairs, and they don't contribute as much to this hydrogen bond. So it's a weak bond, much, much weaker than a normal covalent bond. So it can be formed and broken relatively easily compared to a major bond, which, when you break it, you are undertaking a chemical reaction. And it's this hydrogen bond that's very important for water. So in ice, we found that the density of ice is less than that of liquid water. That's because these hydrogen bonds form and they structure the liquid and push the water molecules apart a little bit. In a liquid, what happens is some of these break down and the water molecules can come closer together. Another very important thing about liquid water is the dynamics of these hydrogen bonds. So you can think of them as flicking on and off hundreds of thousands of times a second.

[Melvyn Bragg] A second?

[Patricia Hunt] It's a picosecond. They flick on and on in a picosecond which is ten to the minus twelve times a second. So it's really fast, faster than you can imagine, the faster than we can see. And this is one of the problems with understanding water is that we really don't know how this process is occurring right at the atomic scale. And this process is

[Melvyn Bragg] So what you've been saying is just a guess then?

[Patricia Hunt] That the hydrogen bonds flick on and off? You can monitor them indirectly. There's been some recent spectro chemical studies where you can fire a laser at a water molecule - a femtosecond laser so it's ten to the -15 [pulses per second] - and you can monitor the formation and breaking of these hydrogen bonds. But what you get back is an average picture. So we don't understand the individual changes that occur and that's where you want to use calculations, which is what I'm a specialist in. And so we use quantum mechanics to study what's happening. But even then it's very, very difficult to use quantum mechanics and study them, something that occurs over time in this way. But this random forming and breaking of these hydrogen bonds is incredibly important for water because it introduces something called entropy - disorder. So now we've got something about energy, the forming and breaking of hydrogen bonds and something about entropy, the order and disorder in a system. And for water this is really important.

[Melvyn Bragg] And as people are well... That was very, very clear. So at the moment I understand it, how long I'll retain that is a different matter. But that that's fair. Is this molecule, is it different from other molecules the way it behaves? Or is it like lots of other molecules?

[Patricia Hunt] It has aspects that other molecules have. So for example H2S - and sulfur is the next element down on the periodic table from oxygen that can form hydrogen bonds as well, but they're not nearly as strong and so the melting point is very low -85 degrees and the boiling point is very low -61. And we can think of something like ammonia; so that's nitrogen with three hydrogens; so that's the next kind of thing you might think of. But that only has one lone pair to form hydrogen bonds and it's much weaker. H2S and NH3, ammonia, are gasses at ambient temperatures and pressures. So [at] the pressure and temperature of everyday life, water is a liquid that makes it very special.

[Melvyn Bragg] Hasok Chang, can... you tell us why this bonding that Patricia has been talking about, this hydrogen bonding, makes such a difference to the property of water?

[Hasok Chang] To put all the learned things that Patricia just said, in a crude way, hydrogen bonds make water very sticky, right? I mean, people may imagine that water is just a disconnected heap of H2O molecules, but because of the hydrogen bonds, water molecules grab onto each other quite strongly, and that makes all kinds of differences. For example, in the boiling point.

[Melvyn Bragg] Now, can you just continue that? What sort of difference does it make?

[15:48]
[Hasok Chang] So Patricia mentioned the boiling point of water being very high, and that's in comparison to other similar molecules, as Andrea said earlier, and that's because the water molecules are attracting each other with this additional force that you would otherwise imagine. So you have to give it much more energy for the molecules to fly off away from each other, which is what needs to happen in order for it to boil.

[Melvyn Bragg] Andrea, you want to come in? Andrea Sella?

[16:20]
[Andrea Sella] Well, I think the additional thing about water is this fundamental stickiness, and it's not simply stickiness towards each other. And that, of course, is driven by the fact that the oxygen is negative, the hydrogen is positive, and these molecules pull each other together. But in fact, it's sticky towards all kinds of other materials. On planet Earth, for example, when your finger touches the table here, it turns out that it's not really your finger touching the table, but it's the water molecules on your finger which are touching the water molecules on the table.

[Melvyn Bragg] As we do it now, like that?

[Andrea Sella] Absolutely. And that creates enormous problems for chemists, because water turns out to be an extremely reactive molecule. And in the sorts of chemistry...

[Melvyn Bragg] What does reactive mean in this context?

[Andrea Sella] Reactive in the sense that it can take part in chemical reactions with a very very wide range of different things. Now, an extreme example is the old sort of school experiment where you take sodium and you throw it into water and it fizzes, and if you're lucky, it goes bang. But actually, there are all kinds of other chemical reactions that it takes part in. And one of the consequences, for a chemist anyway, is the fact that often we have to keep water away. We have to go to incredible lengths to keep water away from our reactions and to dry things, to remove water from material. It turns out to be an extremely difficult process.

[Melvyn Bragg] Hasok Chang?

[Hasok Chang] Yes. And another very important fact for our lives is that water is a liquid in our ambient temperatures because of its high boiling point. Because without liquid water, obviously life as we know it couldn't exist.

[Melvyn Bragg] And so is this?... How do you account for that? Is there an accounting for it? It's just one of those things?

[Hasok Chang] Well, it all does stem from the facts about the microstructure of the water molecule which we've been discussing, which then gives rise to its high boiling point, which allows water to be liquid at these temperatures that we're used to.

[Melvyn Bragg] What is an excellent solvent, Patricia Hunt? Can you tell us what happens when it works as a solvent?

[18:32]
[Patricia Hunt] Okay, so we...

[Melvyn Bragg] Take salt as an example, and let's work from that.

[Patricia Hunt] Sodium chloride is what chemists call salt. It's like table salt.

[Melvyn Bragg] Pass the sodium chloride. Put a bit of a ring about it, doesn't it?

[Patricia Hunt] And that's because it's made out of sodium ions, which are positively charged, and chloride ions, which are negatively charged. And when you put them together, they form a solid - table salt, nice white crystals, and it's a solid at room temperature. And actually, to melt sodium chloride, you need about 800 degrees C to turn it into a liquid. However, you can put a teaspoon of salt into a cup of water and your water doesn't boil up because there's 800 degrees worth of heat coming out of the system released as you break down the sodium chloride. This is because the water is able to surround each iron. And so for the positive iron, you have the negative part of the water surrounds it, and for the negative ion, you have the positive part of the water surrounds the iron. We say that the solute, or the ion, has a solvation shell - some special waters that have come out of the bulk and sort of attached or stuck themselves onto the ion. And these water molecules are actually very special because now they don't behave like normal, ordinary, free water. Suddenly their motion is retarded. They're not interacting as much with other water molecules. And this solvation shell can just be one set of water molecules wide, or it can extend out further two or three shells of water molecules. And actually, it's quite hard to know exactly how many shells of water an individual ion has. And so we can take ionic things and dissolve them in water. This is really important for life. So, potassium, sodium, these are all ions for life. Chloride.

[Melvyn Bragg] Can we just take that on a bit? Why is it such a good solvent though?

[Hasok Chang] Part of the story there is this polarity of the water molecule, right? So one side of water, the oxygen side, is slightly negative, the hydrogen side, is positive. And that helps water break down these other substances by pulling them apart on their positive and negative sides. So that's what we talk about when we talk about ionic solutes.

[Melvyn Bragg] So, furious activity going on all over the place with water all the time?

[Hasok Chang] Yes.

[Melvyn Bragg] Andrea alluded to this earlier on, but the fact that water in its solid form ice, is less dense than its liquid form, could you develop that a little? Because it's sort of counter-intuitive, isn't it?

[Hasok Chang] Yes, it is. That's a very interesting fact that we love to talk about in science. And as Patricia was saying earlier, this is because when water freezes, more of these hydrogen bonds form between the water molecules and the result is that it really turns into a crystal, right? When all the hydrogen bonds you can form have formed, you have these hexagonal structures in water, which is the kind of thing that's manifested in snowflakes. Everyone's seen these hexagonal shapes of snowflakes so imagine that sort of micro structures all over the place in water and that sort of structure has holes in them, right? And that means that the water molecules are not able to get as close to each other as they are able when in the liquid state.

[Melvyn Bragg] Andrea Sella?

[Andrea Sella] One of the striking things about ice is the fact that essentially each water molecule is surrounded by four neighbors and each water molecule is essentially pinioned in place by these four sort-of hydrogen interactions. When you actually get melting, one of the curious things is that this structure effectively collapses and you start to have slightly more sort-of neighbors. So on average you have close to four and a half neighbors at any one time. So this is what kind of accounts for this change in density that we observe. But the intriguing thing, of course, is the fact that water actually has these, these kinds of channels running through it.

[Melvyn Bragg] Now you're going to have to explain that.

[Andrea Sella] And within the structure, as the ...

N[Melvyn Bragg] o, the channels you're talking about the channel...

[Andrea Sella] We're coming back to the channel...

[Melvyn Bragg] okay.

[Andrea Sella] When we when we look at ice and we look at the way in which the water molecules are arranged. As I said, they have four neighbors, and there is essentially this hexagonal pattern which is set up with the oxygens arranged in a way that you can think of analogous to how you arrange oranges in the supermarket piled up in in stacks with hydrogens sort of sitting in between them. And the structure is actually quite open. In other words, the oranges are held rather apart and so there are channels running through in which you can trap molecules and within the actual ice structure you can embed molecules which have to be relatively small. These include things like air molecules, nitrogen, oxygen. But the other thing also is methane. And these structures are referred to as clathrates. They're not true chemical compounds in the sense that what you have is a bonding handshake. It's rather more like a cage but like a prison in which the molecules are essentially the right size to fit within this sort of chicken wire array, if you will, of hydrogen bonds, but they can't escape. And this has all kinds of, sort of intriguing consequences, certainly for environmental ones, but also ones in terms of our understanding of ice.

[Melvyn Bragg] Can we turn to another aspect, Patricia Hunt, the water surface tension? Can you tell us how that comes about and why it comes about?

[Patricia Hunt] Okay, so we can imagine let's think about our water air interface and at one end you've got air, and the other's end you've got water. And there is a series of water molecules sitting on the surface and they really want to have hydrogen bonds all around them, but they can't.

[Melvyn Bragg] Why?...

[Patricia Hunt] They've only got hydrogen bonds below them and nothing above them because it's air now, so there's essentially nothing above them. And so they become quite high in energy. And one way to think of surface tension is an energy per unit area. So the high energy water molecules on the top contribute to this high surface tension. Another way to think about this is that the hydrogen bonds down into the rest of the water are slightly stronger because there's only two of them, or one of them instead of four. And so you can think of this as pulling them or like a pressure. So you have a surface tension, something is tense and holding it in. Now, systems in nature want to go to the lowest energy possible and so you want to minimize your surface area. And so the smallest surface area that you can have, you've seen it, it's a droplet, it's a perfect sphere. And then you can have other environmental things that impact on that to maybe make it spread out a little bit or to change its shape. But water, if it had its way, would exist in little spherical droplets if you divided it up enough that it had that kind of surface exposure.

[Melvyn Bragg] But the tension is palpable when you see insects and walking across carrying them, isn't it?

[Patricia Hunt] Yes. So you can think of this strong hydrogen bonding sort of holding the top of the water together much more strongly and it can't fall in or you can think of it as a pressure or a tension, like a trampoline. If you're on a trampoline, you're a bit like a water skater on the top of the water.

[Melvyn Bragg] Is this also seen graphically, Andrea Sella, in bubbles?

[Andrea Sella] Absolutely. One of the consequences of this very high surface tension is that it's very, very hard to stretch water. It's like a very, very tense trampoline. And in order to be able to blow a bubble, what you really need to do is to stretch the water out to make a film. And the way in which you can do this is essentially by changing that surface tension. The way you do it is by putting molecules actually onto the surface of the water. Now, you've probably ... All listeners, I'm sure, have seen this. When you do the washing up, you have a bowl of dirty dishes and you put your soap into the bowl and you suddenly see all of the oil droplets on the surface of the water in the sink suddenly rush off to the sides. And the reason is because what you're doing is you're putting your soap molecules. And the soap molecules are quite interesting. They look a little bit like sperm, if you will. They have a charged head at one side, and then they have a long wiggly tail, and the long wiggly tail kind of extends up into the air. And so they're able to bridge this junction between the water and the air above. And what they do is they make the surface much more amenable to stretching. And so, at this point, any small child or adult in touch with your inner child can pull up a little bit of soap solution with a plastic ring, blow, and effectively what they're able to do is to stretch the surface of the water out. And then what it does is it forms these beautiful bubbles that we all know and love.

[Melvyn Bragg] Hasok Chang, it's been mentioned already that water boils at 100 degrees centigrade. But can you?...Of course, there's more and more research. There's several research programs going on into water, including many by the three of you around the table. It isn't as quite as simple as that, is it?

[Hasok Chang] No, actually not. And this is something I, in fact learned in my historical research by reading reports from 200 years ago. And we already spoke about the high boiling point of water. But there is more to it, because when you think about the mechanics of boiling, in order for water to boil, it basically has to blow bubbles within itself. Andrea talked about blowing bubbles, and that's what water has to do - make a bubble of vapor inside the body of liquid water. And that's only possible if the pressure of that vapor generated is matched with the external pressure of the atmosphere so the bubble doesn't collapse. Now, that vapor pressure is correlated with the temperature of the water. And when the water is 100 degrees, that vapor pressure is equal to the normal atmospheric pressure that we have around us. So that's what we call the normal boiling point. But if you look at the mechanics of the bubble formation, there's another factor, which is the surface tension that we've just been speaking about. Because in a bubble of vapor inside liquid water, the water molecules on the surface, the inner surface of that bubble, will tend to attract each other with the effect of closing up that bubble. And that force is actually quite strong, and it gets stronger the smaller the bubble is. J.J. Thompson actually calculated that 100 years ago - that it was inversely proportional to the radius of the bubble. So if you start from nothing with zero radius, the surface tension force is infinite, and you can't start a bubble. So you have to start from a preexisting bubble or even vacuum of a finite size. So when you look at water boiling normally or when you look at a glass of champagne or beer, you notice the bubbles only come from certain spots on the surface, not everywhere. And those are the places where there are little microscopic pock marks or little holes where air gets trapped or there's a pocket of vacuum. And from those places, water is able to grow bubbles. And when the surface is so smooth, microscopically, as it happens with various types of glass, or even better with ceramic, there aren't enough places where the bubbles can form, which means heat can't be carried off at the normal rate, so the water gets superheated. If you try to boil water in your ordinary mug, it'll easily go 102 and 103 degrees before it boils.

[Melvyn Bragg] Patricia Hunt, I mentioned it's essential for life and so on, but why is it such an important molecule for life?

[Patricia Hunt] Okay, I'd like to come back a little bit and talk about ... some kinds of molecules that don't dissolve into water,

[Melvyn Bragg] I'd rather we moved on, I'm sorry. I don't mean to be rude, but there's quite a bit of territory to cover....

[Patricia Hunt] It relates to what we're going to talk about...

[Melvyn Bragg] Right, right, absolutely.

[Patricia Hunt] Okay, so you have these non-polar molecules that don't dissolve into water like oil. So oil and water don't mix. And what happens here is the water, because it can't form hydrogen bonds, it wants to exclude the oil from its local environment. So this allows us to compartmentalize water. So you can have something like a cell membrane, which is formed from these polar molecules, and they can separate areas of water. So water dissolves things. It dissolves ions. So now you can have on one side of your cell membrane a higher concentration of ions than you have at the other and this is one of the things that allows life and biochemistry to work. One of the other things is that water can solvate biological molecules, so molecules can dissolve in the water system. So your blood is carrying around lots of things inside your body. So you need to have a fluidity. And that's very important, that water isn't too fluid, but it's not too sticky in the sense of it's like honey and it's trying to pump around your body; it's not really going to work. We've talked about heat, so we need to regulate the temperature in our bodies. So this is really important for life as well. You need to be able to evaporate water off so you can cool your skin. And we need to be able to hold our heat. If all our heat dissipated off straight away, we'd be freezing cold and we couldn't sustain life. One of the really important things about water for life is it helps proteins fold. Proteins can form enzymes, and these are the things that undertake the chemistry of life. And you must have them in very precise arrangements and it's the stitching together via water molecules and hydrogen bonding that allows these things to form the right structures that they need for this.

[Melvyn Bragg] Well, I'm glad that you interrupted my question. Your answer is better than my question by a long way. Andrea Sella, there's been some discussion - a lot of discussion, a lot of research - into ice and the notion that hot water appears to freeze more quickly than cold water. Can you talk about the different sorts of ice? We've said that there are 15 different sorts of ice...

[33:45]
[Andrea Sella] Well, there are two questions that you're asking here and I'll answer the second one, which is the sort of mysteries of ice itself. One of the things is that the ice that we encounter in everyday life is what we call ice one, it's a hexagonal type of ice. But if you start changing the temperature and the pressure under which that ice is sitting; so imagine that you were to take the ice and you put it in the freezer and you cool it down, and then at the same time you place your ice cube into a kind of vice; so you squeeze it very, very hard. One of the things that you start to do is to rearrange the structure. And ice has been found so far to form in 15 different phases - 15 different arrangements...

[Melvyn Bragg] Is there any way you can indicate ... what these different arrangements are so people can visualize them? There's this sort of ice that sort of ice ... ... give us at least three [examples]?

[Andrea Sella] Now, the crucial thing is that there are two parts to the structure of ice. Now, I said before that the oxygen is regularly arrayed a little bit like oranges, sort of stacked up with hydrogen bonds between them. The intriguing thing is that the hydrogen bonds in normal hexagonalize are completely disordered. In other words, each oxygen must have two short interactions and two long ones. In other words, two hydrogens directly attached and two hydrogens attached through hydrogen bonds. And if you were to turn each one of those molecules around, you can essentially rearrange the hydrogen bonding network completely. So ice one, the typical ice, has an exceptionally complex structure because while the oxygens are ordered, the hydrogens are disordered. Now, when you start squeezing the ice or changing the temperature, you can do one of two things. Either you can start to order the hydrogens so that they become much more regular and appear like guardsmen on parade so that all the hydrogen bonds are pointing in the same direction, or alternatively, you can actually rearrange the oxygens so that they stack in a different sequence. And it's this extraordinary complexity and richness which makes life so fascinating to so many researchers.

[Melvyn Bragg] Hasok Chang, what's going on now in research into water? What are the areas that are being tackled by people like yourselves and your colleagues?

[Hasok Chang] Well, my own research is historical. Mostly I think I should defer to my chemistry colleagues here about what scientific research is going on.

[Melvyn Bragg] Over to you, Patricia.

[Patricia Hunt] I've sort of alluded to one of the problems is understanding exactly how these hydrogen bonds reform and change themselves. There's lots of different ideas. Do they flicker on and off? Does a water molecule rotate slowly? Is it assisted by another water molecule? So there's a lot of very intense research in this area at the moment. Another one is how ions interact with water. So ions are important for life. We need to understand how water surrounds these ions. And it's really interesting that in some cases, you can have, for example, a protein in an aqueous system, a water system, and you can add an ion, and that can force it to precipitate. So adding ions changes the structure and the nature of the water surrounding it. And we don't really understand this particularly well.

[Melvyn Bragg] Is there any way you can summarize, Andrea Sella, how research into the properties of water is likely to benefit people?

[Andrea Sella] Well, let me give you one very pedestrian example which is appropriate for today. When it's so cold. One of the real mysteries about ice is why it's so slippery. We're in a moment when everyone's terrified of slipping on ice because it's so cold. And one of the things we don't really understand is why it is that ice is as slippery as we find it to be - how ice skating works. And one of the things that we're interested in is finding out what happens on the surface of ice. It turns out that well below the melting point, the water molecules are actually disordered in an almost kind-of slushy like arrangement, which is called pre-melting, that we don't fully understand. And so it's through a kind of combination of experimental, on the one hand, and then computational approaches that we can start to get insight into how this actually works and why it is that ice is so wonderful and so completely infuriating at the same time.

[Hasok Chang] I should probably just add one thing. There seems to be a great deal of research going on today about these very fast changing, temporary structures that form even within the liquid water due to this transience of hydrogen bonding. And I think there are all kinds of interesting things we can expect from that research.

[Melvyn Bragg] Well, we look forward to them. Thank you very much. Thank you very much Hasok Chang, Patricia Hunt and Andrea Sella.