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How Science Changes Our Lives

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I promised to give you a talk today, and I'm hoping you will find it interesting.

This is the Grand Canyon at sunset, and what I wish to say is that those discoveries that most change the way we think about nature cannot be anticipated. How then are such discoveries made, and are there research strategies which can substantially increase ones chances of making such a discovery?

And of course I have to think the answer to that is "Yes", or I wouldn't have asked the question.

Let me illustrate this with a linked chain of discoveries and inventions, starting with one of my great heroes, this gentleman here, and I presume that everyone knows who this is. This is Heike Kamerlingh Onnes, who was the first person to liquify Helium, and I daresay without his contributions I probably wouldn't be speaking here today. Kamerlingh Onnes first liquified Helium in 1908. This was Helium 4 or the commoner isotope of Helium, although Helium is not very common, and just 5 years later he received the Nobel Prize for Physics. I suppose you can imagine that he is smiling at us, but in fact I think he seldom smiled.

What happened was that there was a competition between Dewar and Kamerlingh Onnes to see who first could liquify the lightest and most inert of the atmospheric gases, and it looked like Dewar had one when he succeeded in liquifying Hydrogen, because Hydrogen is the lightest element, but it is certainly not the most inert. So there was only one element left to liquefy, and that was Helium. Helium was very scarce at this time but eventually Kamerlingh Onnes was able to gather enough Helium that he could attempt to liquify it.

Kamerlingh Onnes decided to answer some other interesting questions with this very spectacular set of refrigeration devices that he had built. People where arguing about what would happen to the conductivity of a very pure metal, if one could cool it to the absolute zero. One school of thought was that as you cool it, you eliminate the lattice vibrations that scattered the conduction electrons, and so gradually the electrical resistance would slowly drop towards zero. Whereas the other school of thought believed that at some temperature the conduction electrons, which are free to roam around the interior of the metal, would re-condense on the ions from which they had come and all electrical conductivity would cease.

So Kamerlingh Onnes obtained a very pure sample of mercury and gave it to his associate. I actually do not know if Gilles Holst was his graduate student as Kamerlingh Onnes was not of the habit of including his students names in his research papers so this is a little difficult to tell… there is now some hissing in the audience, this must be a graduate student hissing. Anyway, Gilles Holst measured the electrical resistance, those are the data points… this is a scale of resistance from 0 ohms to 2 thousandths of an ohm, a very small electric resistance, and the temperature goes from 4 Kelvin to 4.5 Kelvin. As you can see as he is cooling his sample, in fact the electrical resistance is dropping, but then at a temperature at around 4.2 Kelvin there was a nearly discontinuous drop in the electrical resistance, to a value less than 0.00001 ohms, essentially zero electrical resistance. We look at this now, and we recognize immediately that this was the onset of superconductivity. The medal that Kamerlingh Onnes had given Gilles Holst was mercury, which is a very good superconductor at low temperatures. This, in fact, was the first observation of superconductivity. I don't know if this is exactly what Kamerlingh Onnes got the Nobel Prize for in 1913, but I suppose it had something to do with that. I daresay that superconductivity has been studied at multiple places around the world ever since that time, as it’s a phenomenon that fascinated physicists for a long time.

Now you see, what I actually am is not a physicist but a photographer. This is a small part of the Iguazu Falls at the border between Paraguay and Brazil. I like to illustrate the ideas in my talks with distracting photographs in the background.

The process of advancing science often leads to inventions and technologies that directly benefit mankind. However, it is impossible to know from where the advance will come that might solve a particular problem facing mankind. Consider, for example, nuclear magnetic resonance. I don't mean to say that nuclear magnetic resonance is a problem facing mankind, but rather a solution to problems faced by mankind. Nuclear magnetic resonance was invented by 2 gentlemen in 1946, just at the end of World War II. One of the 2 gentlemen is Felix Bloch, who was a professor at Stanford University. I daresay that Felix Bloch was a rather crusty old man. Even though I am a professor at Stanford University, I never met Felix Bloch as he died by the time I became a professor there. The other gentleman, Ed Purcell, was a professor at Harvard University and a very kind and gentle person, whom I dearly loved. I am sorry to say he is not around anymore. These were the 2 gentlemen that invented NMR, and they got the Nobel Prize just 6 years after their invention. When they went to Stockholm to receive their Nobel Prizes, the press descended on them and asked these gentlemen to explain nuclear magnetic resonance, which is a very complicated process, involving the procession of nuclear spins, having magnetic moments in a static magnetic field, and after a while the press gave up, because they couldn't understand any of this, and so they asked "Just tell us what NMR might be good for." Felix Bloch is reputed to have said: "Damn little." His idea was that they were measuring the distribution of charge in atomic nuclei, and this had nothing to do with applications. Ed Purcell, who was a kinder and gentler man, said "Perhaps one can use NMR to calibrate magnetic fields." Now this is what the visionaries who invented NMR had to say about it, and now let's see what actually transpired.

Well, first of all, this is like a spinning top in a gravitational field, and this basically explains what Felix Bloch and Ed Purcell could not explain to the press. But I think we can flip over this. Now we are looking at an organic molecule in solution, probably an aqueoes solution, and specifically we are doing nuclear magnetic resonance on the hydrogen nuclei (protons), and what one finds is in fact that all the protons do not come into resonance at the same time. There are triplets and quadruplets, depending upon just exactly which hydrogen atoms you are looking at and which are involved in the bonding processes.

If you look at the scale here you see that these are frequency shifts in parts per million. These are very, very tiny effects, and it really took quite a while to be able to do this, but in fact this was a spectacular advance in nuclear magnetic resonance at that point. I daresay that the thing that really made this work was in fact not doing what is called continuous wave nuclear magnetic resonance, where you either sweep slowly the magnetic field or the frequency, but in fact this was pulsed NMR. Pulsed NMR was invented by Richard Ernst.

It used to be that there was a set of meetings, every 3 years I believe it was, and I would meet most of these gentlemen at these meetings. There I met Richard Ernst. What Richard Ernst did for NMR is rather than very gently tickling the nuclear spins, he would apply a very intense pulse of RF energy which would tip all spins by 90 degrees and then, as they processed, they would induce an alternating voltage in a pickup coil. That is how pulsed NMR works. That's in fact what Richard Ernst got the Nobel Prize for in 1991. It wasn't in physics, the original NMR Nobel Prize was in physics, but the second Nobel Prize for advances in NMR was in chemistry, because this was where NMR was mostly used, in studies of organic chemistry in particular.

Richard Ernst did not do this all by himself. He had a partner whose name was Kurt Wuthrich and the two of them had done a lot of this work, but when it came time to give a Nobel Prize for NMR as applied to chemistry, Kurt Wuthrich did not share the Prize with his Swiss colleague Richard Ernst. I would meet these guys at international NMR meetings, and I went to Kurt Wuthrich and said: "Kurt, how did you feel when Richard Ernst got the Nobel Prize, and you did not share it with him? You must have been disappointed!" He said:" No, I was not disappointed, I was mad!"

What happened then is that Richard Ernst set out as a man possessed to show that he could do things with NMR that no one else could do, and indeed he invented a very complicated pulsed NMR sequence which allowed him to determine the three dimensional confirmation of even complex molecules like proteins. So this was a real boon to NMR and eventually, in 2002, Kurt Wuthrich got his own Nobel Prize, and you can see here that he is smiling. I think you cannot accept the Nobel Prize from the king of Sweden without smiling.

So, now we have had two Nobel Prizes in chemistry for aspects of NMR and one, the original one, was in physics. But we are really not done yet. People in the early 1970's started realizing that if you applied a magnetic field gradient across the sample which contains the nuclear spins that you wished to study, then you could actually create images with very detailed structure. Here is a rather healthy human knee. My own right knee is made of titanium, and so I think you cannot do these kind of experiments on it anymore.

Anyway, for their work on developing what is called 'magnetic resonance imaging' or nuclear magnetic resonance imaging Paul Lauterbur and Peter Mansfield received a Nobel Prize in 2003, one year after Kurt Wuthrich received his Nobel Prize for determining the three dimensional confirmation of very tiny things like proteins, while these two determined the three dimensional confirmation of large biological things like knees. This is the fourth Nobel Prize for some aspects of nuclear magnetic resonance, and if we go back now to what the inventors of NMR said to the press, when Felix Bloch answered a question about what NMR might be good for he said "Damn little", and his counterpart guessed that NMR might be used to calibrate magnetic fields.

What I am trying to show you is that the visionaries that develop new techniques do not necessarily know what they might be good for, and I think that is something that's worth remembering.

So, this is Felix Bloch again and Ed Purcell, and we're back in 1952, and I would like to think that Felix Bloch is smiling a little bit in that picture as I think he should have been alive when that prize came out. Now I'm going to shift gears and talk about my own contributions to science. I suppose the person I have the most to thank was my high school chemistry teacher, shown right here: William Hock. The first large prize I got was the MacArthur Prize, and after receiving word of the prize, I called William Hock on the telephone. I haven't seen him for many years, and I said: "Mr. Hock, guess who!" and he said: "Well, that has to be Douglas Osheroff."

I think he might have read that I received a prize and thought I might call him up. So this is William Hock, and that guy, looking over his shoulder, that's me. The next three people were guys who were my partners in crime: We liked to make bombs and rockets and things like that. This is Al Close, he was my debate partner in high school. I was not a very good debater, and I didn't do my homework well, but we managed to win our share of prizes, I suppose.

I am skipping over my four years at CALTECH (Californian Institute of Technology). I actually was involved in astrophysics when I was at CALTECH, mostly infrared astrophysics which was a new field at that time. When I applied for a graduate study to several different universities, I actually only applied to schools that had good astrophysics programs. I think I applied to eight schools, and I got accepted to all of them. But then I started thinking about what I loved doing all my life, and it was not observing some objects that where so far away I could not possibly touch them, but in fact, what I really liked doing was concocting experiments to probe Nature. So, at the last moment I switched fields, and I decided to go into condensed matter physics.

I went to Cornell University for graduate study and began working for David Lee, who ended up being my Phd thesis advisor. This was just at the time when new refrigeration technologies were being developed. This is (see presentation) something called the "Helium-3 - Helium-4 Dilution Refrigerator", and I won't explain all of it. Here is a picture of my Helium-3 - Helium-4 Dilution Refrigerator, and this is where the cooling occurred, and these are heat exchangers which would use the rising cold Helium3 liquid to cool Helium3, returning to the mixing chamber. This was my device, but when I was at Cornell at that time every graduate student was building his or her own Dilution Refrigerator. Mine was one of the ones that actually worked, which was a good thing for me.

Helium-3 and Helium-4 are, of course, both isotopes of Helium, but Helium-3 is extremely rare. It essentially doesn't exist naturally. The amount of Helium-3 in natural gas wells, which is where most of the Helium-4 comes from, was vanishingly small. However, Helium-3 results from the decay of Tritium. During the period after World War II where the US and the Soviet Union were busily building hydrogen bombs, they were creating Tritium for the bombs, and Tritium decayed into Helium-3. There was a guy named Ed Hammel at Los Alamos who was responsible for keeping the U.S. Tritium supply clean, and that meant filtering out the Helium-3. Then, without getting permission from anyone to do this, he decided that he would liquify the Helium-3 and measure its vapor pressure as a function of temperature. He did that and he published the results and not only that, but he also said how much Helium-3 he had in his sample. This told the Russians something about how much Tritium the United States had. He did not lose his job. I interviewed him when he was 81 years old. It was a telephone conversation, and I wish that I'd met him, because he was a very colorful character.

Anyway, there was a Russian theorist who was a member of what was called the 'Landau school'. He had very broad interests, and when he heard about Helium-3 he started thinking about its properties. Now with

Helium-3 liquid at low temperatures the entropy or disorder drops linearly to zero as as it is cooled. Solid Helium-3 is perfectly ordered spatially at absolute zero, but each nuclear spin can point either up or down in a magnetic field. That gives the spatially ordered solid an entropy of R Log2, and at very low temperatures the entropies of the solid and liquid 3He cross. Below the temperature where the 2 curves cross you have the very unusual situation in nature that the liquid is more highly ordered than the solid of a substance. This is the only case where that actually happens.

Then Isaac Pomeranchuk, who was the Russian theorist I mentioned earlier, realized that Helium-3 has a negative melting curve because of the fact that these two entropies cross (as mentioned above), and if you start with liquid Helium-3 and you compress it, as you move along this melting curve you move to lower and lower temperatures. This was a technique that had been predicted would allow you to reach temperatures probably less that 1000th of degree above absolute zero. As a young graduate student I said: "I want one of these things."

We had enough Helium-3, and so I built a very elegant Pomeranchuk Cell, as it's called. The gold region is Helium-3, because it's rather expensive I suppose, and the idea is that you push a metal bellows in here that decreases the volume and raises the pressure where the liquid 3He resided, until some of the liquid starts to convert into solid. For every percent of the liquid converted into solid the system would cool by 0.001 Kelvin. What that meant was that if I converted 15% of the liquid to solid, I would be at a temperature very close to absolute zero. That was the technique I was pinning my hopes on in order to get a Phd out of the low temperature group at Cornell.

Here is some data, which I had taken… you have to explain these things, because young people these days do not understand what a strip chart recorder is or how it works. The paper moves underneath a pen, which moves back and forth according to what voltage is applied to it. This is the melting pressure of Helium-3 as it is cooling. I'm actually measuring a pressure transducer made with a capacitor, so this is actually the capacitance. I rebalanced the bridge, and it continued to cool, and then there was a very sharp decrease in the rate of cooling, which I later labeled "A". I was in fact quite crushed to see this, because I felt that something had gone wrong, and so I let this continue to cool. Then I saw a little tiny drop in pressure at a temperature of about 0.002K. I wasn't very creative, I didn't give these things good names. A and B is what they were called, and in fact this is the A superfluid, and this is the B superfluid Helium-3, so those names have actually stuck.

This was not the first time I'd seen these changes in the rate of cooling, so I went back and looked at my old data, and there they were. The pressures where these deflections occurred were very highly reproducible, and so I suddenly realized that there was something really exciting going on. To understand what I was seeing, I invented an early form of MRI, where I actually applied a horizontal magnetic field that was larger at the bottom of my cell than at the top. Then, if I applied an RF frequency to my NMR coil, as I show here in red, if I swept the NMR frequency upward, this resonant layer would move downward. So, I could actually measure the distribution of the solid and liquid 3He in my Pomeranchuk cell as a function of the vertical position.

These are what some early data looked like. This is all liquid. This funny feature here resulted, because the pressure transducer itself was slightly magnetic. Then we started cooling, and the solid Helium-3 NMR signal started growing as I formed more solid. It gets larger and larger, and I ultimately had to decrease the gain on the recorder. So, the liquid NMR signal appears to shrink, as if the amount of liquid is decreasing, but in fact it's staying the same in size.

This was taken on April 17, 1972, and I was looking at this data later that night, while I was waiting for things to happen. This is the liquid signal, and it should have been flat across here, and it looked rather badly distorted. Suddenly the size of the liquid NMR signal dropped by a factor of two. I knew exactly what that meant.

So I wrote in my lab-book: "Have discovered the BCS transition in liquid Helium-3 tonight"… and BCS is the theory that explains superconductivity. Bardeen, Cooper and Schrieffer are the three theorists that first understood superconductivity. People had predicted that Helium-3 might undergo a similar phase transition, but it has never been seen. So, there it was, at 2:40 in the morning, and what could I do?

I ran around the basement of the physics building to share this excited news with other graduate students. Well, it turned out, no one was there. In desperation I went up to the 6th floor. Theorists, you see, like to be as close to God as possible, so they, in fact, would normally inhabit the 6th floor, but it turns out that on that particular night there was no one around.

At 4:30 that morning I couldn't stand it any longer, and I called up my thesis advisor David Lee. To the young students in the audience, let me say that you do put your live in your hands if you call up your thesis advisor at 4:30 am. However, in this case David Lee called me back at 6 am, because he was not able to go back to sleep, so neither one of us got any sleep that night. I wanted to share this with you, because I suppose it's not typically the way science is done, but I wanted you get some feeling for the excitement associated with discoveries.

Here I have some strategies:

1. Utilize new technologies to view nature from a new perspective or a different realm. I'm talking about MRI, using the magnetic field gradient.
2. Don't give up when things are going badly, failure might be an invitation to try something new. Now, I didn't tell you this, but to do the NMR experiment I obviously needed a magnetic field. The magnet that produced that field weighed about 5 tons, and we only had one of them. Some other students had gone to David Lee and complained that I had been monopolizing this magnet for quite a long time. Then David Lee told me that I had to give up the magnet, and so then I felt really, really bad. But in fact it was that next evening that I did the experiment that led to the discovery of superfluidity in Helium-3, so: Failure might be an invitation to try something new.
3. Spend a little time doing something different. Curiosity driven research is fun and can be rewarding! Later, as a Professor of Physics at Stanford University, I would come up with "What would happen if I did this?" and then, if I thought it would be interesting, I would go to the graduate students and say: "What do you think would happen, if you did this?" and they would answer: "We don't know." Then I say: "Why don't you try?" That's, in fact, a very typical way of making discoveries.
4. Avoid too many commitments. I have to say that I was married by this time. My wife is Chinese, and she was working very hard to teach me Chinese, but I am a very bad student. Cornell University was offering a course in conversational Chinese, and we both thought it would be great for me to take this course, but….我笑自己死亡 which means 'I

laugh myself to death'. I realized that I didn't have the time to take this course. I never learned very much Chinese, but I did get a Nobel Prize.

5. Back off from what you are doing occasionally to gain a better perspective on the task at hand. I think this is absolutely true: we become myopic when we focus too tightly on our work.

Now I go back to the Pomeranchuk Cell. I add the names of the people who didn't necessarily get anything for inventing Pomeranchuk Cells or those who contributed to science in general. Without them I would not have made the discovery I did. Bardeen, Cooper and Schrieffer were the ones who developed the theory that explains superconductivity. That theory was then applied to Helium-3 by Philip Anderson, a very dear friend of mine. Of course Pomeranchuk and Pomeranchuk's cooling cell was why I was able to get cold but, in fact to use Pomeranchuk's cooler, you actually had to get to very low temperature, and I used the Helium-3, Helium-4 dilution refrigerator, which was invented by Edwards and Hall. And - I used NMR extensively in my research - thanks to Bloch and Purcell NMR had been developed. Ed Hammel was the one who gave the world Helium-3 by not throwing away this Helium-3 that he separated from the Tritium.

So it is certainly not me alone who did this work, there were a myriad of people associated with this, and this is the way science actually works. The wonderful thing about it is that the work is published, it is out there and anyone can use it, in any country that wants to use it. So science is in fact an international occupation, and it's something that is shared very easily and in a very friendly way between nations.

Advances in science are seldom made by individuals alone. Let me make that clear, it looks like I did everything, but in fact there are all those names up there, and those were people that gave contributions that I needed. They result from progress in the scientific community, asking questions, developing new technologies to answer those questions and sharing their results and their ideas with others. To have rapid progress, one must support scientific research broadly and encourage scientists to interact with one another and to spend a bit of their time satisfying their own curiosity. This is how advances in science are really made.

Question:

Do you think that the world is going to end (in 2012)?

Professor Osheroff:

No, I don't think that the world is going to end in a week or another year. Let’s face it, the word has been around for billions of years, and I see no reason to suspect it won't be around for billions of more years. Now, that said, I think that human beings by the activities that we do, in particular burning fossil fuels are having a very profound impact on our planet, and I don't think that that is making the planet go away, but it certainly has the possibility of impacting a lot of species to disappear as a result of us changing their habitat. Of course, if you put a lot of CO_2 into the atmosphere, then it’s much more difficult for the infrared radiation to leave the planet, and that’s part of global warming.

I’d like to think that we are occupants of this planet, but that we don't own it, and we have a responsibility, not just to ourselves and the planet, but to the future generations which certainly don't want to inherit a dead planet.

Question:

I would be interested to study physics, but I always fail in any test. How can I solve this problem?

Professor Osheroff:

I have been in love with mother nature in some sense ever since I was probably 6 years old, and I learned more science probably through middle school on my own than I did from the classes I took. What makes you a good scientist are curiosity and a love for the subject, and the last thing that is likely to make you a good scientist is the fear of failing in exams. What you need to do is reading on your own … There was a bunch of kids and myself who formed a loose club, and we would talk a lot about science, mainly physics. I think you learn faster and better if you ask questions rather than someone else asks the questions. To become a good scientist you should start asking yourself questions.

Question:

Before you got the Nobel Prize, did you ever think that it's possible for you to change the world?

Professor Osheroff:

Well, I don't know if anything I've ever done has changed the world. I do things mainly because I enjoy doing them and because I'm good at it. The things I am not good at, I don't do. I daresay I took art lessons when I was young, and I was terrible. So I had this choice, I could either take swimming lessons or art lessons, and that was a very easy choice for me to make.

I think each of us is the manager of our own human resources, and I think you have to know what motivates you, to begin with, what those things are that you're good at, because they are usually the same things that you enjoy doing. Then you can go from there, because the worst thing to do is to hammer your head against a rock expecting the rock is going to crack, because it is your head that’s going to crack first. What you really need to do is understand who you are, what motivates you, what you enjoy doing the most, and then find out how you can use these very powerful and very positive emotions to do something that might be useful for other people besides yourself.

We all need to be needed, and we want to do something which will benefit not just yourself, but your friends and basically mankind. As you are going through school you can see those areas where the big questions are, and you can say if this is something which you can contribute to or if it’s something that you would enjoy doing. I think we all would like to think of ourselves as contributing in ways that are non-trivial and possibly important. It is really worthwhile to look inside yourself to understand what your motivations are, what your emotions are, because we all think that emotions are not very good things and they don't have anything to do with science, but in fact they do. Because it's emotions that drive us to do the things that we do. We are asking nature the very difficult questions, and it's an emotion that drives you to do that, and so I think that those people who end up being most successful in science are the people who start out knowing a lot about themselves, what motivates them and what allows them to succeed even in the face of failure.