Physics Seminar

February 4, 2019

>>DR. GARRISON: Okay. First off, I want to thank everybody for coming. You know, this is the first seminar of the 2019 session, and so I hope everybody is going to enjoy this. Our speaker today is Robert Kleinberg. I met him at the Texas section of the APS meeting we had last fall in October at the University of Houston, and he is basically the Distinguished American Physical Society Lecturer. The American Physical Society flew him out here to talk to you guys. This is part of his speaking tour.

A little bit about him, he has an undergraduate degree in chemistry from the University of California Berkeley and at the University of California San Diego, he got a PhD in physics. He studied various properties of super fluid phases of liquid helium three in the laboratory of John C. Wheatley. From '80 until 2018 he was employed by Schlumberger, where his work focused on geophysical measurements. His current work at Columbia University and Boston University centers on energy, technology, and economics and on environmental issues connected with oil and gas development.

Dr. Kleinberg has authored more than 100 academic and professional papers, holds 39 U.S. patents, and is the inventor of several geophysical instruments that have been commercialized on a worldwide basis. Dr. Kleinberg is a member of the National Academy of Engineering, and the 2018-2019 American Physical Society distinguished lecturer on application of physics, and that's why he is here today. So with that, I'll turn it over to Dr. Kleinberg.

(Applause.)

>>: Are you going to be able to control the PowerPoint? If you need help, let me know.

>> DR. KLEINBERG: Okay. Well, good evening. Boy, seminar at 7:00 o'clock. I really admire your fortitude. I don't know what time you got up this morning, but it's already a long day.

So I am your American Physical Society distinguished lecturer on the application of physics, as you've heard from David. Thank you for the introduction. And what this means is that I'm sort of going around the country basically talking about how physics students like you can make a transition from the academic world to sort of the real world of industrial applications and so on.

And I think the Society realized that there were really very few mentors for physics students. We talk about lack of mentors for women and minorities and so on, but really I think most people don't have mentors probably in the sense that every physicist you know is in the university. You probably know very few outside. So this is an attempt to at least give you a little bit of a flavor of how at least one person made that transition. And later on we can talk about the more general details how you might make it.

So the title, as you see, is mK to kM, How Millikelvin Physics is Reused to Explore the Earth Kilometers Below the Surface. What you're going to see here is a fully worked out example of how one physicist made the transition from pretty esoteric laboratory science to really practical real world inventions. By the end of this talk you'll be able to measure which way the earth was blowing 10 million years ago and how to measure the size of pores in sedimentary rock and why those things are important.

You'll also get a lesson in corporate jujitsu. It comes about halfway through the talk. I recommend that you do stay awake at least until then, because that's the most important slide in the talk. Your experiences, those of you who make this transition from the academic world to the industrial world, will be different than mine, but I adapted to my time and place and you will adapt to yours.

So this is where it starts. This is a scene from my graduate school laboratory, at the University of California in San Diego. The picture was published in 1976 in Physics Today. I'm sitting second from the right. I seem to be lecturing my much more learned colleague on some fine point of physics. This was a lab where we studied super fluid phases of helium three shortly after they were discovered in the early 70s. And this picture's probably familiar to many of you, this sort of picture.

And I must say, you know, at the time I had no inkling that I would eventually wind up developing instrumentation. That's not why I went to graduate school. I went to graduate school for the same reason probably many of you are studying physics, just out of sheer curiosity and love of the subject. But then the real world does intrude.

So as you heard, I went to into the oil industry -- Schlumberger, pronounced in the Texas fashion by our host, Dr. Garrison. And so you might wonder how I got there and why. Well, you know, in the 1970s when I was in graduate school, the big pressing societal issue was the fact that oil producing countries had embargoed the United States and cut off our supply at a time when we no longer produced enough to satisfy our own needs. And that led to lines at gasoline stations stretching around the block, and this was a traumatic experience for the country.

And at the time we weren't thinking of climate change. Climte science was still in its infancy. We weren't thinking of renewables, which at that time hadn't gained the efficiency and cost-effectiveness they have today. So really there was a general universal feeling that the only way to secure our economic security and independence from rival nations was to increase our supply of petroleum of oil and gas. So that was the pressing national need that I was responding to when I left school.

Sort of another of my influences was the fact I was living in San Diego where there's the Scripps Institution of Oceanography. Several of my graduate school housemates were Scripps graduate students and they sort of excited me about geology and plate tectonics and so on. It seemed like a really interesting subject, and so those two things came together. And I worked for Exxon for a couple of years in New Jersey. That was a post-doc.

At the end of that I was once again on the job market. And there was this company, Schlumberger. Maybe you've seen the blue trucks rumbling around the roads in Texas. I didn't know much about it at the time but I did know they were involved in the petroleum industry and geoscience and instrumentation. Schlumberger is really an instrumentation company, not a geology company. And, of course, I had that graduate school experience in the lab, and there's the old Tektronix oscilloscope shown in the slide. So all those things sort of came together in what for me was a very fortunate coincidence of influences.

So let's get into sort of the meat of the talk and the question I'm going to pose is which way was the wind blowing ten million years ago. And you might think, this is a ridiculous question. I mean, the wind is inherently ephemeral. Once it's stopped blowing, what kind of evidence does it leave? And we'll get to that in a bit.

But first, to get there, let's ask a simpler and sort of more direct question, which is once you've drilled a well that produces water, where do you drill the next well? And to understand the context of that question, I have this little cartoon. This is a typical oil reservoir. I think this may be the only campus in Texas -- you don't have a petroleum engineering department here in Clear Lake, do you? You may be the only school in Texas that doesn't have a petroleum engineering department.

So I'll give you a really quick lesson on petroleum geology. So basically oil and gas is formed deep within the earth at -- when organic matter is broken down by high temperatures. And then because oil and gas is buoyant in water and water is ubiquitous in the subsurface, the oil and gas slowly migrates upwards. And in many cases it reaches the surface, which could be the seabed or the land surface, and is oxidized in the ocean or atmosphere.

But sometimes it encounters a layer that's called caprock. It's sort of that blue gray rock at the top. And that caprock has the property that its permeability to fluid flows is really low. In other words, gas and oil can't get through it. It's kind of like cement. So it's trapped. And if there's a dome like structure, it will be trapped underneath the dome and that's all good.

Because oil and gas is buoyant, it will float on water. So gas, above oil, above water, like a jar of salad dressing. And if you drill into water and you hope that there might be oil and gas nearby, water is worthless to you because at depth it's highly saline and somewhat radioactive and really it's toxic waste. But you really want to find the oil and gas that you need to power your economy.

So the trick is you want to drill a well that's toward the top of the structure. Toward the -- you know, underneath the dome. So you can do that if you know which way the rock strata is sloping underneath the earth. Now there's usually no surface manifestation, but you've got an 8-inch borehole that's going through this rock layer and the question is can you determine which way the rocks are sloping so that you can drill what the geologists call up dip, which is, in other words, toward the top of the dome.

So how do we do that? That is the problem I was presented with in my -- during one phase of my career.

Now, making measurements in borehole is really quite different than making measurements in your physics lab. So in the physics lab, the normal procedure is you've got your machine and you put the sample inside the machine. All good. In this case we're putting the machine inside the sample, which is, in fact, the earth. So whatever you do, it has to fit inside a 4-inch steel tube. You can make it as long as you like because wells are very, very deep. They're typically kilometers deep, so you can have long equipment. But it's got to be very slender. So think long, skinny circuit boards. And inside that tube you can put any combination of signal generators, volt meters, whatever you want. But it's got to be inside. And then the whole thing goes into a 20-centimeter, 8-inch borehole into the earth. That's the basic rule of the game.

But there are more rules. And this is daunting and especially for someone coming from the laboratory world, where you have kind of more control over your environment. In the earth, you don't really have much control over your environment. You have to take what it dishes out. So among other things, the apparatus has to operate after being transported in arctic, tropical, desert, or marine environments. It will probably be subjected to a hundred G shock at some point when someone drops it, and it will be drug through kilometers of rock borehole.

Now, the apparatus must operate while being exposed to temperatures ranging from negative 25C in the arctic to 175 degrees C at the bottom of deep wells because the Earth gets hotter as you get deeper and these wells can be 10 kilometers or 6 miles deep. It's going to be in a salt-saturated water environment, which is difficult with pressures up to 140 megapascals or about 20,000 psi.

You will be moving at at least 15 centimeters a second because the clients are very impatient and don't want you wasting time making your measurements while they're spending somewhere between 10,000 and $100,000 a day to rent the drilling rig that you're using. And so because you are moving in a hot environment, your temperature conditions are going to be changing continuously. So just think about your physics experiment and how would you like your temperature conditions to be changing continuously in the 175 degree centigrade range, far above military specifications?

The apparatus must operate at the end of 10 kilometers of multiconductor cable, and autonomously and simultaneously with other nuclear electromagnetic and acoustic instruments because we screw all these measurements together. Send it down. The field engineer is a young guy, typically a graduate engineer or physicist, and he's got a lot of stuff to take care of all simultaneously and he can't be fussing with your particular instrument. It has to be really very much autonomous.

So, looking at these specifications, I'm thinking, I'm a low temperature physicist, what the heck am I doing here? And then the initial panic does subside and you think, okay, what am I going to do? This is not like helium. Those days are over.

So, you know, we all have a toolbox of things that we learned in school and experiences we had. So I thought back to an experiment I did with the helium. It's shown here. This is a heat flow measurement published in the journal of low temperature physics. I'm not going to explain this whole apparatus. Don't worry.

The only part that we're really interested in is the sort of blowup part which is circled with the red oval. And that is a mutual inductance coil sat with a primary coil energized by a signal generator, as shown in the lower left of the slide. And there's a balanced secondary, so you have two secondary coils which are wound opposite to each other so that if there's no sample in them you have zero mutual inductance or in other words zero voltage at the output when you put in a current at the input.

So a sample will unbalance --

>>: Hold on a second. I want to check something with the settings.

>>: There's a little bit of sound coming back.

>>: I think that's me, but I think I need to -- for the sharing -- it wasn't advancing. We'll have to share the entire screen. Sorry. Okay, should be good. Are we good?

>>: I hope whoever is watching didn't miss all that stuff.

So basically, this gets unbalanced when you put a sample in one leg of the secondary. In other words that lower secondary, that unbalances it and now you've got a voltage when you turn on your signal generator. And the sample we used was a paramagnetic salt serum magnesium nitrate. The magnetic susceptibility (inaudible) Curie-Weiss law, which is shown in the lower corner of the slide. So basically it connects magnetic susceptibility, which is what you're measuring, with absolute temperature T, with two calibration constants, which are, as we say, trivial to determine. Not necessarily easy but trivial.

So I thought about this and I thought, huh, well maybe we can use something like this. But I knew that it had to be turned inside out because I'm going to be inside the sample not putting the sample inside the machine.

So here's what I came up with. Again, there's a single primary coil. In this case it's a single turn loop. Energized by a current source labeled I in the figure. There's two secondaries, which are wound opposite to each other. So in the absence of a sample, there is zero voltage on the load Z and the voltage is shown in V.

Now, what unbalances the mutual inductance coil set to give you a measurement is the presence of earth nearby because the primary coil will give you a magnetic field which induces a ground current in the somewhat conductive earth nearby. And that ground current reradiates magnetic field back into your apparatus but unequally through the two secondary coils. So there's going to be more flux threading the upper coil than the lower coil. And when you measure the difference, that is directly proportional to the conductivity of the formation.

So it's not the magnetic susceptibility anymore, which we are not interested in. That's the end-phase component. We're looking at the quadrature component which is proportional to conductivity, the loss, if you will. And that's what gives us our measurement. And this -- so we built a simple one of these with printed circuit boards and it actually worked. And I think the next slide is a picture of the lab prototype.

So we have on the left there's sort of a stack of circuit boards because instead of winding coils by hand, which I had to do in graduate school, which I truly hated, I printed the coils on printed circuit board material. One turn loops much easier. Stacked up as I showed you with symmetrical secondary and primary coil. And then, of course, because the thing has to survive these horrible conditions I described earlier, it had to go into metal housing.

Now, you should be thinking, metal housing? Oh, boy. Because metal is about 10 million times more conductive -- literally, I'm not making it up -- 10 million times more conductive than a salt-water saturated rock. So you would think that your signal could be drowned by this 10 million X, you know, metal that you're putting nearby. But, in fact, the metal acts like a mirror. Depth is very shallow. You don't really see a conductive signal from it.

You do have to change the positions of the secondaries a bit, because it does disturb the primary magnetic field. But basically if you're very careful adjusting the positions of the three loops, you can get a common mode rejection ratio that's pretty respectable and then you're all set to go.

And the assembled prototype pad is shown in the lower right. Now, this thing was used in the lab to sort of demonstrate that the thing would work. It's an electromagnetically accurate model. It would not survive going into a bathtub let alone a well, but it did prove the principle.

So when we were ready to say, okay, let's try the well, then we had it really engineered -- sturdy, waterproof, all those things. And we had four of these sensors that we put on the four arms of this gizmo that we can lower into the well. And the arms are spring-loaded so they press the sensors into the four 90-degree spaced azimuths in the well. So now we've got four of those conductivity measurements.

So you might be thinking, you got four measurements. Why? And how are you going to measure the slope of the earth again?

So here is the sort of cartoon answer to all of those questions. So on the left is a diagram of sort of the earth simplified and it's stratified just like you would see in an outcrop at the surface. But instead of looking at color or texture like the geologists do, we look at electrical conductivity. That's what I can measure.

And the electrical conductivity in the earth varies from about one cm per meter to about a thousandth of a cm per meter. That's a really good dynamic range. So it gives you a lot to measure. So that's a good thing.

So let's say we have these two rock layers, the lower one with sigma 1 and the upper one with sigma 2. Two different conductivities. Now, we've got the four sensors. Sensor one is pointed to the left. Sensor three is pointed to the right. Sensor two is pointed toward us. Sensor four is pointed back into the board. And we're pulling it up at 15 centimeters a second like our customer is demanding. So what happens is that as we pull it up, sensor one is the first one to see that there's an interface between sigma 1 and sigma two, and that's shown in the line plot, the strip chart recording, you might say, of sensor one. You can see there's a little displacement from sigma 1 to sigma 2 and then back.

Later on as we pull the thing up further, sensor three encounters the same interface but at the other side of the well. And so that change at the interface is displaced upwards by a known amount, which we measure. And the other two are doing the same thing.

So I think you can see with pretty simple trigonometry, you can figure out both the slope of that subsurface foundation and its azimuth. So what geologists call dip and strike. And in this case it looks like the rock layers are sort of going up toward the right.

And so I would say, driller, drill your next well to the right. That could be north or whatever direction. And you're going to be drilling up dip closer to the top of your structure and more likely to find oil and gas. And that actually worked pretty well. It worked very well, in fact.

So -- but I told you I was going to figure out which way the wind was blowing 10 million years ago and I haven't done that yet. So to answer that question, we need to sort of look at present day landforms. This is what geologists do. And if you go to a desert, you'll find sand dunes. And I've put up a picture of a classic dune shape. It's called barkhan dune.

In this case the wind is blowing from the left, that big blue arrow. And horns are sort of forming to the right. So what's happening is that as the wind blows the sand grains from the desert toward the right, the sand grains are sort of going up the backside, the windward side of the dune. And then it gets to the top and there's a mini-avalanche when enough sand builds up at the top. So you get this avalanche down. And then that's -- that forms a sort of distinct layer that you can see if you sort of drill a hole into the dune.

Then the whole thing eventually might get buried by a volcano or what and preserved, and that becomes a really great oil reservoir. There's nothing better than sand dunes, because as you'll see in the next part of the talk, we want grains -- big grains, big sand grains are good. It gives you a lot of content to store the oil or gas that you're looking for and also an easy way for it to get out.

So, now, okay. Why do I really care about this? Okay, great, Bob. It was blowing toward the north 10 million years ago. Good. But the importance is if you drill into the dune field and you do find oil, then I recommend that you drill either upwind or downwind because dune fields tend to elongate in the direction of the wind. Cross wind, not so much. So if you drill across the wind, you're going to run out of the field sooner. So it's a better bet to drill in the direction of the wind, either upwind or downwind.

So that's how we do that and that's the importance of it. And like I say, this turned out to be quite a successful instrument that basically paid for my entire lifetime salary. So my employer was pleased.

Oops. Okay.

So now the bit about corporate jujitsu. So what I just gave you is what I call the Nobel Prize version lecture. Great project, ingenious, worked great, you know, fantastic. But the trip along the way was not quite so pleasant as you might have imagined based on that sort of sugar-coated version of history.

This electrical measurement was not the approach initially endorsed by management. They had put all their chips on something different that, frankly, I did not think would work. So I sort of snuck into the lab on nights and weekends and sort of made -- sort of followed my passion and made this little gizmo, lab prototype, and got it to work, at least crudely. And I had some initial results, which looked interesting, and the other project was failing, as I predicted it would.

So management sort of begrudgingly gave me a technician. Fortunately he was a good one. I got more favorable results, more testing, looked better and better. And one of the theorists in our department asked to join the team. I welcomed him with open arms.

Meanwhile we have an engineering group in Paris. They had their own ideas about how to solve this problem. They wanted to be the heroes. So what I did was I built a copy of their device, I optimized it so it worked better than they got it to work. And I did head to head comparisons and showed that mine was superior.

So as you can imagine, this was a lot of work. And more than a little interpersonal issues going on here. But the instrument was successful, and it saved our business in the most important oil field of the day, which at the time was the North Sea.

Now, when we were done, the technician, the theorist and I had, as I've written in a memoir -- we had time on our hands. How often do you have time on your hands? I don't see a single person shaking their head "yes." There's a number of no here, but I don't see a yes. Yeah, we're too busy.

But while we had time on our hands and we're sort of, okay, what do we do next? We invented something even more important and that's going to be the subject of the second part of the talk. So part two, how large are pores in rock 2 miles below the earth's surface? And why do you want to know that?

So, okay, so oil reservoirs -- first of all they are not big lakes. You might get that impression reading Jules Verne novels. But oil reservoirs are really just rock that has pore space in it. So you can imagine a sand dune. Really good example. River bed, beach, whatever. Sort of sand grains pressed together, somewhat cemented but with lots of space between the grains. In fact, a good reservoir will have 30 percent of its total volume as pore space, 70 percent mineral matter.

So this is a microscopic view of a good sandstone. It's actually quarried in Kentucky, but it's very similar to oil field rock. And the white are sand grains, quartz mostly. The black are clay particles, which you often find associated with sand. And then the blue is epoxy, that was injected into the sample to hold the thing together when it was cut into thin section. So all that blue is pore space that can host water, oil, or gas.

Now, the first thing you need to know about this rock is how much pore space, okay, and that's another story. The second thing you need to know is how fast will fluid flow through it? Now, these grains are what? Ten to a hundred microns? And the pore spaces are maybe one to a hundred microns, say?

And so the larger the pores, the easier it is for the fluid to flow through. And you can think about the big hose versus the small hose, water hose, but basically knowing the size of the pores is really key for you understanding the economic viability of your oil and gas field. So this was a big problem because it's really hard to measure these pore sizes in this range unless you bring the sample up, and that's slow and expensive.

So somebody, not me, but somebody had the idea that, oh, we could use nuclear magnetic resonance for this. So a very quick lesson on nuclear magnetic resonance. So there's a few things you need to do to get this measurement to work. You need a strong constant magnetic field that we called B0. The second thing is you need an oscillating magnetic field that you can pulse on and off perpendicular to B0, and we call that B1. And then the frequency of that oscillating field has to have a special relationship to the strength of the constant field, B1, and the frequency is given y omega equals gamma B0, where gamma is the gyromagnetic ratio.

So that's sort of what you need to do this measurement. It's done routinely in organic chemistry labs. Maybe those of you who have MRIs have been put into that machine. So you put the sample into the machine, could be a human being. And there you go.

But as you already know, we don't have that luxury because we've got to do it inside out. But I need to tell you one more thing before we get to the apparatus and that is why this actually gives you pore size.

So here is a four panel cartoon. This is basically all you need to know about this measurement. So we start with that constant magnetic field, B0 in panel one pointing vertically and that aligns the magnetic nuclei in the fluids in the pore space. So it could be oil or water but they all get align with B0. They all line up like little bar magnets.

Now, what that pulsed oscillating field does, that B1, it tips the spins away from their comfortable, happy equilibrium direction on B0 into a plane. And so that's why it's pulsed. You sort of keep the field on until the spins are tipped and then you turn it off. And you can figure out how to leave it on. That's somewhat trivial.

The interesting thing is now you've turned out of the B1 field and the spin remains perpendicular to B0 even when the molecule that it resides in is moving around. So it could be translating, it could be rotating, whatever you want. But the spin system is decoupled from the motion of the molecule that it's sitting in. So these are nuclear spins, remember.

And they will stay that way until they hit a solid surface that might have a magnetic ion like iron or manganese, which is pretty common in sandstone. And then that magnetic interaction at the surface allows the spin to relax in its happy equilibrium directional back along B0, and that's what happens in four.

So you can see, if you have large pores, it's going to take a long time for that molecule to diffuse through a surface and allow the relaxation to happen. In a small pore, the fluid molecule gets to a surface a lot faster. So that means that relaxation time is larger in big pores. Relaxation time is smaller in small pores.

So now we have a way of having some notion of how small those pores are. And these pores are very small, in a micron range, in rock. Miles below the earth's surface, we can't even see the pores. So that's the trick.

You probably noticed in that first slide that the pores came in various sizes. Okay, how does that work? At the upper left, I have a cartoon rock. There's three sizes of pores. There's the big pore, where it takes the spins maybe 80 milliseconds to relax. There's the medium-sized pores, where it takes maybe 20 milliseconds for spin to find the surface. And then the small pores, 5 milliseconds before the fluids get to a surface.

And each one of those populations is characterized by an exponential decay of magnetization. And given an hour talk on this, I could go into this in detail but I'm not going to. Just take my word for it.

So you have exponential decays with 5 milliseconds, 20 milliseconds, and 80 milliseconds. The measurement is linear. They all add up linearly so that the total output of the measurement are the black dots, which are the sum of those three exponential. So it's a multi-exponential decay. And the amplitude of each of those decays is proportional to the fraction of pore space of that size.

So in other words, if we have -- let's say in this case 30 percent -- how did I do this? 30 percent small pores, 30 percent medium pores. They have the same amplitude. Maybe 40 percent large pores. It has an amplitude of 0.4. So when you take that multi-exponential decay, do an inverse (inaudible) transform, you get a spectrum of relaxation times as shown in the lower center plot with a peak at 5 milliseconds, a peak at 20 milliseconds, and a peak at 80 milliseconds, with the areas under the peaks proportional to the volume associated with that relaxation time.

So this is really, really powerful. This is kind of amazingly powerful. You get a volumetrically average pore size distribution.

We're in cartoon land here, but let's look at some real data. So here is a real rock. Again, quarry rock, similar to an oilfield sandstone. The lower axis is that relaxation time, how long it takes the spins to get to the surface, in seconds. And you can see it's on a logarithmic scale from 0.01 seconds to 1 second.

By calibration, you can change those relaxation times into what you really want, which is the size of the pore. That's on the upper axis and you can see that these pores range from about three tenths of a micron to about 70 microns for this rock and that's pretty typical.

So you have orders of magnitude range of pore sizes here, and we're able to capture the whole thing. So really powerful.

So, at this point I come along and somebody says, okay, Bob, you're so smart. So go build us an inside out NMR tool. So, well, I had done squid-detected NMR of liquid helium three in graduate school, which was extremely bizarre with super-conducting electronics and definitely very crazy. And then at Exxon I had done more conventional lab NMR materials. And, you know, in the big machine that you put the sample inside and so on.

So how hard could it be to build an inside out NMR? Well, okay. Not obvious. But, you know, you've got some time on your hands, so you can think about it.

Now, again, got to remember the rules of the game. Everything's got to fit into a four or 5-inch envelope for an 8-inch borehole. You could put anything inside the tube you want. Any kind of magnets or oils. It's up to you. But, you know, magnetic fields are pretty unruly. And it's much easier to put things inside them than outside them because the magnetic field will spread out very quickly. Once they get away from the magnet or coil that it's -- it's being generated.

So, okay. So the -- putting the sample inside the machine is not going to work. So you keep in mind the physics principles that you learned in school. The strong constant magnetic field B0, the oscillating field, B1, that's perpendicular to B0, and the frequency. And that's what you have to focus on, not the picture you have in your mind.

So here's what we came up with. It's something very different than what you find in the laboratory. So on the left is a side view of the whole thing. It's four and a quarter meters long. At the bottom section there, you see a bulge. That's actually the sensor that we're going to be talking about in a minute that basically senses NMR in a volume that's about 6 inches long and about a square centimeter in diameter.

The rest of it is the power supply, the spectrometer, the telemetry. Everything's got to be going down the well with you because all you've got is that seven conductor cable, which carries nothing but power and telemetry. So the whole -- all the electronics you need has to go down into the well, 175 degrees.

So let's look at a cross-section of the sensor region. Again that's that lowest region on the left. And now the big picture is the cross-section. This thing is 13 centimeters in diameter, about 5 inches, and fits into the borehole.

And so the borehole wall is this heavy black circle and inside are two -- we have two magnets. And they're sort of slabs. They're about a foot long each. They are magnetized transversely. So not north-south, but north and south. That way. So you're projecting magnetic field out into the rock in front of you. And again, it's pushed against the borehole wall out with the spring system. So that gives you magnetic field out into the formation which is where it needs to be to make the measurement of the rock formation.

So looking at the magnetic field strength, we have -- so here we have a contour map of magnetic field strength and magnetic field is going to be the strongest right in front of the north poles. And then the field sort of goes from north to south, either around the outside or through the inside of this thing. But basically as you move from top to bottom, the field is strongest in front of the poles but it's relatively weak in between the magnets. So you have a local minimum of magnetic field strength as you go from top to bottom.

As you move out from the face of the instrument out toward infinity, the fields generally fall off. Turns out you have a saddle point in the magnetic field. And that gives you about a square centimeter, maybe a couple square centimeters, of volume where B0 is relatively constant and that's what you need. You need some sort of volume where B0 is pretty homogeneous. So that's -- that was the condition for B0.

Now, the B1 is generated by this very strange antenna. It's not a coil. It's like a coaxial cable sliced in half with a current running down the center conductor, up the outer conductor. And that generates a B1 perpendicular to B0 out there inside the rock which is where it needs to be. And that satisfies the second condition to get the frequency right. That's just getting the electronics.

So that's the basic idea. And that also worked pretty well. And it's been used for purposes that I never dreamed of and no one ever dreamed of. So this is when you know you've done a good job, when whatever you've invented gets used for things that you had no idea it would be useful for. You don't find that out until later, of course.

So, okay. So we're all happy. And then I get a phone call. So this guy calls me up from an oceanographic institute in California and says, well, I hear you've got this NMR thing that can go into remote and hostile environments like oil wells. And we got something that's really tough. We want to send it to the sea floor off Monterey, California, 4,000-meter water depth.

And I said, what's the temperature and pressure again? Well temperature is 0 degrees C and pressure is about 6,000psi. But I kind of chuckled and I said, kind of too easy. Because we devised an NMR machine that works at 175 degrees C. It turns out NMR does better and better the colder it gets. It likes to be cold. You get better polarization of the nuclei. So 0 degrees C, that sounds great. The machine will operate and get good signal. 6,000psi? Come on. It's designed for 20,000psi. This is too easy.

Well, it turned out not to be too easy. It was a three year escapade to get the thing to work. And here I am, I'm kneeling installing something. You notice the bulbous section above my head. That's the sensor section. The electronics is somewhere else. And I'm strapping it on to this remotely operated unmanned submarine that goes down 4,000 meters. And that actually worked out pretty well.

So here's the NMR laboratory. This is the big boat that is the mother ship for that submarine, Western Flier, out there in California. And we got several good publications in the journal of geophysical research. So that was fun.

Then the idea of doing NMR in strange places takes on a life of its own. So the next adventure was to the north slope of Alaska. About 13 miles from the coast of the Arctic Ocean. And here's our drilling rig. We're looking at permafrost. And again the thing functions in sort of this very bizarre environment where we couldn't possibly take a conventional machine. So all good fun.

So, yeah, I've been telling you this story from my standpoint, the standpoint of experimental -- who builds gear. But, you know, I just want to make it very clear that the theorist is an equal partner in this. So the guy that does the theory, solves the equations, runs the computer codes, designs the computer codes and algorithms, is every bit as important because as you saw, these designs are based on physics principles, which any physicist can invent. But really the theorist really understands the theory of the measurement.

And once there is a model, which is typically a computer model, then you can optimize the design. You can't really optimize the design by building pieces of gear one after another. It's just way too slow and expensive. If you can put it on a computer and look at how the measurements going to perform in various environments with various different dimensions and the different pieces, then you can optimize it very efficiently. And that's exactly what we did with the help of our theoretical staff. And then, of course, you predict the performance.

So this is an example. On the lower left is a block diagram of a simulator that simulates the NMR measurement that this instrument performed. It's pretty complicated. It's more complicated than this thing would suggest because the magnetic field at each point in space is different. There's a unique B0 and B1 at each point in space. You have to account for them all individually. You sum them all up, and then you get the sensitivity maps as shown in the lower right, which is where the signal is coming from.

Now, in this case we looked at this and thought it's not so good because what are those spidery legs, which are extending toward the borehole? The borehole is full of water which has tons of signal generating nuclei. But it turned out that when you take this model and then move it, the spidery legs get washed out.

So our theorist said don't worry about those spidery legs. Just start moving the measurement, which we wanted to do anyway, and they'll go away. And they did. And that was one reason why the measurement worked so well. So it's really a team effort with the theorist being equal members.

So, just to sum up, there are challenging and interesting problems to be solved in unexpected places. I can tell you that from personal experience. And you may not realize it, but your physics education has provided you with a toolbox of techniques and skills that might prove useful in unexpected ways in the future. And I will say that your experiences will be different, but as I said at the beginning, I adapted to my time and place, and you'll adapt to yours.

So with that I'd just like to acknowledge my coworkers at the University of California who participated in the experiments I described, and then a partial list of my colleagues at Schlumberger, there are many more but there are the people that worked on the project I described.

So with that, thank you very much and I'll be certainly happy to answer any questions.

(Applause.)

Yes?

>>STUDENT: So I'm curious, you're dropping these sensors down hanging from a cable 10 kilometers down. How are you keeping track of which way the sensors are facing? I can't imagine with all your magnets and stuff you can measure the earth's magnetic field to orient to north.

>> DR. KLEINBERG: Right. There's two different instruments I described. The one that has magnets in it, which would mess up any magnetic measurement of azimuth. It's not important which side of the borehole it's facing. It's going to be on the lower side of the borehole because of the mechanics of how it goes down.

The one where it's really important, the dip meter application where you're looking at the slope of the earth and you do need to know the orientation of those payouts, there is a magnetic compass inside. And it's in a part of the steel housing that's nonmagnetic. So that's all taken care of. I mean, that's engineered carefully as common to many, many instruments. So turns out not to be a problem. But it's important to think about it. And we did think about it.

Yes? Yeah, you.

>>STUDENT: (inaudible).

>> DR. KLEINBERG: Well, you were first. Striped shirt. Okay, if you insist.

>>STUDENT: I was going to ask how advancements in technology have affected your ability to -- how you work on projects.

>> DR. KLEINBERG: I think as time has gone on, there has been much more emphasis on the modeling and theoretical understanding part because computers have sort of gotten better, the numerical techniques have gotten more sophisticated. So these days, I would say we don't design anything without finite element codes. We're dealing with media that are very complicated, (inaudible) and dispersive in both acoustic and electrical regimes. So there's really a premium on the theoretical part, and that has only become more important.

Now, recently there's sort of been this buzz about, you know, data science and data analytics. And I'm a bit skeptical. I think it's been overhyped, but I think there is something there. And people certainly want to know if there's anything in it for them. So I think you as prospective graduates could really help yourself by at least having some familiarity with these more modern methods of data handling, because you will be asked. And as physicists we are supposed to be innovators. So you'll be expected to innovate and expected to say either yes or no in an honest way but also have an answer.

Yeah?

>>STUDENT: Well, my question is actually similar because (inaudible) a couple years back, (inaudible) in Houston in the IT area, and it used to be, like, a year of time to

investigate looking for oil sites (inaudible) I don't remember. Something like that. And so now there's big data. So many different things happened. And the biggest lab (inaudible) is coming to Houston (inaudible) computer is going to be twice as fast as the biggest computer in the world.

And so what do you expect that we can do with more big data? I mean, what (inaudible) something that you were not able to do in your time, that (inaudible) possibly because of this?

>> DR. KLEINBERG: Well, I think you're raising a very good example of what I was talking about, sort of the advance of modeling and analysis. And, you know, to take that seismic example, I'm just going to give you a little color to sort of fill out that picture. When you do exploration geophysics with seismic, so that's the sound waves that go inside the earth and reflect off those layers, which show the domes, for example, as I showed earlier in the talk. You're collecting an enormous amount of data. I mean typically 10 terabytes of data to do a seismic survey in the Gulf of Mexico. Not too far from here.

And the faster your computers run and the better your analysis, the more complicated you can make the models to match the data. So there's a real premium on efficient algorithms principally. And, of course, the bigger and more powerful the computers, then you can run those more powerful algorithms.

Now, you also brought data analytics into that picture. I think that's probably less important because certainly in the seismic regime, the exploration geophysics area, the processing of that data is very physics oriented. So it very much depends on an acoustic model of the earth. And if you just took that 10 terabytes of data and stuck it into some AI program, I can assure you, you would get garbage.

So you have to put it through the physics programs to get the more accurate interpretations that we are now able to do with better algorithms and bigger computers. So that's an example. There's no substitute for physics-based thinking and algorithms. But that's a great example.

>>STUDENT: (inaudible)?

>> DR. KLEINBERG: Yeah. You know, when you talk about subsurface geology -- I mean, oil and gas is the biggest sort of single thing. The world produces and consumes a thousand barrels of oil a second, so it's a very big industry. But certainly similar measurements are made for minerals and so on.

>>STUDENT: (inaudible).

>> DR. KLEINBERG: Yeah, well, uranium in particular, yeah, because uranium is radioactive and we have radioactive sensors. And it's also radioactive waste that we've measured, say, at places where they were producing atomic bombs and had a lot of radioactive waste that has gotten into the soil and that can be measured by instruments similar to these. Obviously not the same. These aren't radiation detectors, but we have those.

So there are other applications. And the part of the challenge is figuring out what's out there and what are the needs and how to match up what's available and how to match up with a need. Yeah?

>>STUDENT: I guess you partially answered my question but (inaudible) because you were solving a very specific problem in this presentation and I was going to ask you what the other applications of those techniques -- like, what are other applications of those techniques? And why you would use them in your work throughout -- I mean, aside from -- or if you know anyone else who is using (inaudible)?

>> DR. KLEINBERG: Yeah. Well I'll give you a little bit more detail about that experiment that I was doing in Alaska. So there, the genesis of it is sort of shrouded in the mist of time, but basically what we were looking at was permafrost. And so the mental model of permafrost is you've got soil that is filled with ice, solid ice. And that's actually not true because not all the water is frozen, even below zero degrees centigrade.

And so a big question is how much of the water is not frozen? And how fast can it convert from frozen to unfrozen? And so on and so forth. And this is important for geotechnical investigations. So for example, if you're building a structure or permafrost, which people do, it's really important to know what the strength of the soils are, and for that you have to know how much of the water is frozen and not frozen.

So this investigation, using NMR, was able to quantify that. And we related a borehole measurement to a measurement where we actually brought the measurment up to the surface, and measured them both ways with the instrument that I described. And so, you know, that gets looked at by people who are doing civil engineering. That's one example. That's one (inaudible) example.

The other example that I showed, the seafloor thing, that was an investigation of methane hydrate, which is a fossil fuel. It's really peculiar because it's a form of ice that freezes above 0 degrees centigrade. For those of you that read Cat's Cradle by Kurt Vonnegut, recognize that scenario? So this is a form of ice that exists above the normal freezing point of water. It's filled with natural gas.

And so the experiment was: What are conditions under which it's produced at the seafloor, because it does exist at the sea floor? How fast does it decompose and under what conditions does it decompose? And does hat lead to submarine (inaudible). So one of those articles in the Journal of Geophysical Research talked about the subsea slope failure mechanisms of this very peculiar kind of ice.

So, yeah, there's lots of different things you can look at. Yeah?

>>STUDENT: So this is more about the (inaudible) a physicist and an engineer? How do you compare them? Because I know engineers do almost the same thing as physicists but I don't know why -- I don't know what it would be compared to.

>> DR. KLEINBERG: You know, I'd say in many cases, certainly for what I'm describing here, they're very, very parallel professions. I mean, they're kind of interchangeable. The theorist that worked -- in fact, both theorists that worked on the two

projects, they were both electrical engineers who were basically experts in electromagnetic computation. That's one thing you get in the electrical engineering curriculum. So it's more of a difference in emphasis.

And I'd say for a physicist, a good thing to do is to pick up some of those skills, things like signal processing, which has historically served the domain of electrical engineers, but which physicists really have to understand. So in other words when you get that data, what can you do with it? What are statistical properties, noise properties and so on?

So I would say they're close enough that it's worth your time to gain some familiarity with what your friends in (inaudible) are doing. Still, I mean, physics is a grand profession and (inaudible) waves and so on, so I'm not giving that up. But I'd say that really, they're comparable tracks and both equally well prepare you for the future.

Yeah?

>>STUDENT: Yeah, these two guys in my class (inaudible) anyway, I feel like physics, you have to have imagination about what is a different universe, a different world, but not in engineering.

>> DR. KLEINBERG: Yeah, I think there's a lot about physics that's sort of more fun.

(laughter).

>>STUDENT: Yeah, like, how can you know there's a (inaudible) wave? (Inaudible) I talk with student not to study theory (inaudible).

>> DR. KLEINBERG: Well, you know, quantum computing is a great area. It's the intersection. You'll find both double E's and physicists working on it and happily together and there's no conflict. And I'd say both courses of study work equally well.

>>STUDENT: So are you optimistic about it? Because you know the super fluids -- it's different in absolute zero than normal, so they say it's too much noise, so I've been focusing on (inaudible) in quantum computing, because I don't think it's (inaudible) but quantum optimization, the more noise, the better. So we're investing (inaudible).

>> DR. KLEINBERG: That's interesting. Well, you know, I'm not really an expert on that and I'm not going to give you a definitive, authoritative position on it. But I was just at the University of Pittsburgh last week where they do have a big quantum computing effort, a very substantial one.

And I asked the same question you're asking, is there anything to this? And basically the present state of the art, it's presently a laboratory curiosity. But everything started out as a laboratory curiosity. I mean, as I said, we are the innovators. If it's going to work, we have to make it work.

So I don't know whether that quest will work or not, but it sounds like you're looking at an alternate approach, which is a great idea. So without saying yes or no, I'd say, yes, let's work on it because it looks interesting. (Laughter).

>>STUDENT: What would you say is your most successful achievement in your career? (inaudible).

>> DR. KLEINBERG: Yeah, well --

>>STUDENT: (inaudible).

>> DR. KLEINBERG: Well, beyond depth in magnetic resonance, because I showed you how it could be used to measure fluid permeability, which is important. But it turns out it's also really important for characterizing these so-called shale resources, where we do tracking. So that's something we never dreamed of. It's all -- you also use it for measuring viscosity of fluids in porous media, which there's no other way of accessing that. So it turned out to be very, very versatile. And, yeah, as far as a piece of hardware, that was my most successful project.

Within that project, I sort of strayed away from the equipment design and experimental physics and actually worked out the theory of the relaxation of fluids on solid surfaces, which I would say is probably the single best paper I've written and probably one that has more citations than anything else I've written.

So I've ventured into theory myself and that was a nice little piece of work that took me about six months. Maybe 12 months to work all that out. Yeah. So.

>>STUDENT: I have another question.

>> DR. KLEINBERG: Yeah?

>>STUDENT: How did your PhD education help you or prepare you (inaudible) research in a school or a research institution, and you went from that into industry, so (inaudible)?

>> DR. KLEINBERG: Yeah. Well, okay. One thing is the toolbox. So all the things that you learn in undergraduate, graduate school, the sort of floating around in your head that you can put together in new ways. That's one answer to the question.

The second answer is is that, you know, we go to school, especially in physics, to learn how to learn. So I never, honestly I never intend to take another class again. In fact -- (laughter) by the end of my first year of graduate school, I had had it with classes. I hated the final exams. On the one hand, I will sit down with a book and read the equations. So math is a foreign language, but it's a foreign language that I mastered during those years in school. Valuable skill.

And then, the other thing that you get, if you have a -- if you really take advantage of your graduate school education in particular, you learn how to run a show. That's what PhDs do. So if you're a PhD, you get a degree, you will be expected -- it is rare for you to be asked to do something routine. You will be asked to innovate. You will be asked to take leadership, come up with a great idea, put together a team, and make it happen.

And even if you don't think you're doing that in graduate school and I didn't because my boss was really dictatorial, and he ran it as a regimen. We all did exactly what he said.

But by the time I was done with that, I knew how to do that. And I sort of marshaled my resources. And I got everybody to work together, and I was not dictatorial. And I'm a nice guy and everybody who's ever worked for me is still in touch with me. But still, we got it done.

So you know, that's some of the intangibles you get from graduate school. And undergraduate is starting to get there.

Yes?

>>STUDENT: So you gave two examples of really successful projects that you worked on. Were there projects that failed miserably? Or successful ideas that your company didn't want to work with?

>> DR. KLEINBERG: Yeah. Oh, God, yes. Of course, I'm not telling you about them. (Laughter.) So the failures fall into several categories. And that actually is the most important question of the whole session. So thank you for asking it, and I should really make another slide about this. Okay.

So why do projects fail or what prevents you from succeeding? So the easiest case is I got distracted. So I could think of one project in particular. I came up with this really brilliant idea to measure bubble point, which is a thermodynamic property of fluids that's important. And it was really ingenious.

And then the guy from the oceanographic institute called me up and said, why don't you do that this in a submarine? And the submarine won, and the bubble point project just didn't make it. And that was just due to me not focusing on bubble point, and that's one thing I regret. I had an idea for a gas chromatograph which would have worked superbly well in a borehole environment and just never got around to it.

That's one set of things that can happen. This is a rich question, by the way. It really is.

Another thing is you invented something marvelous, it worked beautifully, and no market. That's life. I mean, research is taking a risk. And, yeah, you've got to take a risk and sometimes you're going to lose or sometimes the guy in the next town is going to come up with something 5 percent better, 5 percent cheaper. And fine. You move on.

Hopefully you've learned something, and you can do better on your next project. And the important thing when you're knocked down is to stand back up, just like in all phases of life. So, yeah. I mean, there's all sorts of things that can go wrong. You've just got to keep at it. Just go back.

So that's a good point. These projects came after other projects that failed. That's really an important point.

Yeah?

>>STUDENT: So any possibility that helium three (inaudible)?

>> DR. KLEINBERG: No. Absolutely not.

>>STUDENT: (inaudible) that super conducting (inaudible).

>> DR. KLEINBERG: No. Let me tell you something about helium. So helium is a rare gas on earth because it gets into the atmosphere and promptly escapes into outer space. Helium three is even more rare because natural abundance is about ten to the minus sixth.

So normal helium, two protons, two neutrons, is the main product of thermonuclear reactions in stars. So the universe has a fair amount of helium in it. Earth not so much because it gets away.

Helium three is a very unusual reaction product of the synthesis of elements. And, in fact, the helium three that we used in the lab and that you'll find in any lab today is actually the product of tritium, which is produced artificially for the purpose of making thermonuclear bombs. So if there were no thermonuclear bombs, we never would have done helium three research because we couldn't have found enough helium to do it. So we're actually using decayed bomb material to do these experiments. So this is exotic.

Now, we're physicists. We're really curious about helium three, but there's not much of it in -- naturally occurring. There really isn't.

So, no. No practically application whatsoever. I mean, in a way I was very naive. I always thought I was going to go to graduate school and study helium, which was very interesting in textbooks, and I really didn't think further than that. And I was naive. But, on the one hand, I had a good education.

And I bet there's a lot of people in this room who match that description exactly. All the neutron star people, by the way (laughter) match that description. And good for you. It's a good education.

>>DR. GARRISON: No questions?

>>STUDENT: Do you ever get weird calls for people who have taken your conventions and put them somewhere weird and call you up and ask for consultation and troubleshooting?

>> DR. KLEINBERG: Yeah. Oh, yeah. Well, aside from the submarine, yeah. So, I got a call from a company that made rocket engines. This was a strange one. They -- so solid fuel rocket engines. The fuel has to be very uniform. And they wanted to know whether my thing could map non-uniformities of fuel inside the engine. And if the rocket fuel is not inside of a metal casing, yeah. It would be hard, but maybe feasible. But in the end, we decided no, it had to be in a metal casing so forget it.

So things like that do come up, yeah. But if you have any strange suggestions, let me know (laughter) not yet. You'll have to think about it. Good enough. All right.

>>DR. GARRISON: All right. Let's thank our speaker (Applause.)

>> DR. KLEINBERG: Thank you.

>>DR. GARRISON: And I want to remind everybody that James Frith from NASA is going to be here next week talking about orbital debris research, so please make it (inaudible). And for the students who are taking either 1638 or the undergraduate 4372, please make sure I get writeups next week when you come..

(End of class)