DENNIS FREEMAN: Hello Welcome. The good news, we're basically done. We've covered all of the theory. The only thing we're going to do, the remaining part of the course, is to think through several applications of Fourier.

Today I'll do some just really easy motivational things. I'll do another example from filtering, just because that's such an important idea. I'll talk about how Fourier transforms show up in physics. And then, starting next week, we'll talk about sampling, which is just a simple application of Fourier. You've already sort of seen it in the last lecture.

And then we'll talk about modulation, which is yet another application of Fourier. So basically you have the theory, and all we're going to do for the remainder of the course is think about applications of Fourier. So we already talked about a filter. I motivated a filter by thinking about Fourier series because it's easy. If you think about the system that's comprised of a resistor and a capacitor, and you have as an input vi and an output vo, then you can think about that system being a filter.

The filter can be characterized by a frequency response. You're all experts at that. And then if you can break the signal into Fourier components, which was easy when we had a Fourier series, if you can break the signal into Fourier components then it's easy to calculate the output as the sum of weighted and possibly time shifted versions of the components of the input.

So we can decompose the signal, the square wave, into a bunch of Fourier components. And then think about how they pass through the filter. Where if they all pass through the low frequency part of the filter, so that the gain is one and the phase is 0, the output looks just like the input. And if they all pass through the part of the filter that's sloping down with a slope of minus 1, with the phase lagging by pi over 2, you turn a square wave into a triangle wave. That was the simplest example of a filter.

We saw it again when we thought about speech production. Because there the idea was that the different kinds of sounds that we make are partially generated by the larynx, and partially generated by the throat. And it's all the musculature in your face that enables you to make the precise different sounds.

And that was what we called the source filter model of speech production. The sources down here, the filter is here. And we again, we can think about it by thinking about filtering. Filtering comes up all over the place, and it's one of the most important applications of Fourier techniques generally. And it's for all the reasons you already know.

If you can think of a way of breaking down a signal into Fourier components, then you can thing about an LTI system as a filter. And in filtering applications, in signal processing filtering applications, we usually try to think about high frequencies, low frequencies, designing systems that pass the lows, pass the highs, that sort of thing. But the key is breaking down an input, which might be complicated in the pieces. That's where the Fourier transform is so good.

And so, I want to illustrate that by thinking about a hard problem in signal processing, and that is an electrocardiogram. So first off, it's completely amazing that you can measure an electrocardiogram at all. The voltages produced by cells are on the order of 100 millivolts. That's true for all cells for extremely fundamental reasons, which if you're interested in, 6021 has a lot of information about why. There are fundamental physical limits on what kinds of a voltage a cell can make.

So the voltages are small, but they're much worse than that, they're constrained to the inside of a cell. You can't generally get access to the inside of a cell. In fact, there's a big technological breakthrough, and people figured out how to draw-- cells are little. It's kind of hard to imagine how little they are. About two to three million cells would fit in the length, in a one inch length of a human hair. And that's a skinny hair like mine.

So blonde skinny hair. The rest is not necessarily skinny, but they're skinny. So you can get about a million cells, maybe two million cells in one length, one inch of-- length of a human hair. To give you some idea of how small they are. These tiny, tiny, tiny little things. So it was a big deal when people were able to measure inside a cell. And when you put electrodes on your chest to measure an electrocardiogram, you're not inside a cell.

Cells are surrounded by an insulator. So not much of that electrical current is available to you. Furthermore, the cells in the heart are surrounded by saline. What's important about saline? What is saline?

Salt water. What's important about saline? What would be different if we were filled with distilled water? Besides the fact that we would die. Yeah.

Conducts electricity. So the fluid that bathes the cells has a very high ionic concentration. And that means that it conducts electricity, which means most of the potentials are shorted out before they ever get to the surface of the skin. Then there's another 20 layers of insulation, called your skin. So it's astonishing that you can even measure these things. And when you do, it's not surprising that there's a lot of signal in the waveform, other than the signal that you intend.

There's about 10 to the 13th neurons in your body, and they're all chattering away. So you see those. So that the idea of filtering out the part of the signal that results from the EKG is completely non-trivial. And it's very useful to think about it in a Fourier domain. And absolutely everybody does it that way. If you were to take the Fourier transform of this waveform, you would get a wave form that looks like this, which looks perhaps more complicated. except that you can make some sense out of it.

Hearts beat about 60 or 70 times a minute, depending on how athletic and how old you are, which means that it's the components around 1 or bigger that are coming from the heart. Things significantly lower than hertz probably aren't coming from the heart. Things that are up in the 10 kilohertz region probably are not from the heart. This enormous spike, what's that?

That's the lights. That's the power. That's the-- we distribute electrical power by modulating it at 60 hertz because that distributes better, but then it radiates. And so some of that can be coupled into everything, including me. So the big line is the 60 hertz that's being coupled from the power distribution network into the person whose EKG this is.

So what we'd like to do then is generate a filter that takes out the stuff that isn't EKG. So we'd like to eliminate this low frequency stuff, and we'd like to eliminate this high frequency stuff, right? So what we do is we design a filter.

Filter design Bode of course. Right? Smile? Everybody smile, you know?

There's nothing on a quiz for weeks to come, right? So Bode. So we would think about passing the high frequencies.

I didn't say that right. So we would like to cut off the very lows, we'd like to cut off the very highs. And we'd like to get rid of that one glitch at 60 hertz. So the 60 hertz thing, that's what this is intended to do. It's intended to be a very narrow filter that just wipes out the 60.

So this is a kind of filter that I'd like to design. And here is the design. Handful of poles and 0s. Your task, talk to your neighbor and figure out which poles and which 0s go with the high pass, the low pass, and the notch. Look at your neighbor, say hi, smile.

OK, so which of the poles and 0s contribute to the high pass? Rught, you can point. Like, there's up, and there's left, and there's center. So which ones are high pass?

The ones near 0. The 0 or the poles? Or one of each, or both, or what?

So what would the Bode plot look like if you only had the 0? Yeah. So the 0 alone would cancel out frequency components at 0. Which our Bode plot is a way over there, right?

What about these poles? What's the poles for? They flatten that it out. So if you think about reading off the effect of the poles and 0s starting at 0 and going to bigger and bigger radiuses, then the first thing you have to worry about going left to right on the Bode plot, is the 0s doing this. And then these poles flatten out the 0s. So what's this doing? That's the thing that's attenuating the high frequencies, which leaves us with this.

What's that? And how do you know it's a notch? There's a 0. So the 0 on the j-omega axis means there's a frequency that it completely wipes out. Why do I need to have this stupid pole here? Can't I just put the 0 there?

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: Bring it back up. So the idea is that if you put the pole close to the 0, if you get to a frequency that's pretty far away from those, their effects cancel, and there's no effect of either of them. So their effect is constrained to frequencies that are very close measured in terms of this distance. So you have to be at a frequency that's very close in order to have an effect.

And when you do that, when you design such a filter, you clean up the wave form a lot, and no one in their right mind would generate an EKG machine that didn't do this. I mean, that's just built into the preamplifier that's attached to the electrodes. So the point is that filtering is very important application of Fourier transforms. We can take an arbitrary signal and often get a lot of insight into what we would like to preserve and remove by thinking about the Fourier transform, insights that you wouldn't get by looking at the time wave form.

Next thing I want to think about is a little bit different. I want to think about physics. This isn't, of course, in physics, nor am I a physicist, but I do do optics. And the thing I want to think about is diffraction. You can't understand optics unless you think about diffraction, and honestly the easiest way to think about diffraction is Fourier transform.

So a very simple example of diffraction. So here is a diffraction grating. So if I pass a coherent beam through there, which I just happen to have, if I pass a coherent beam through a diffraction grating, what do you see? The diffraction grating split one beam. All term I've been pointing with one. Well, if I put this in front of it, now I get three.

So somehow there's something about this that's breaking one beam into three. Can you think why? Can you remember 802 where they probably mentioned this? What is this? What's in here?

AUDIENCE: Slits.

DENNIS FREEMAN: Slits. Close. Yeah. So the simplest experiment where you could illustrate this kind of a diffraction phenomenon is-- goes by the name-- yes. Shout the name. Young.

AUDIENCE: Double slit experiment.

DENNIS FREEMAN: Double slit experiment. So if you pass light through two slits, something phenomenal happens. And it's very closely related to this. What's in this?

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: Something like a slit. It's actually something like a whole bunch of slits. So, yeah?

AUDIENCE: Polarizer.

DENNIS FREEMAN: Polarizer. Close. It's one of those neat words from physics, but not quite. Polarized has to do with the fact that the light has an e field and an m field, and they are perpendicular to each other, and sources like this one actually keep them separate. So this actually does generate polarized light, but you can't really tell because if I spin the laser pointer, you can't really see anything. But if I spin the grating-- I just said something. So what did I just call this?

AUDIENCE: Grating.

DENNIS Grating. So what is it? It's a diffraction grating. It's got a bunch of little horizontal structure. So

FREEMAN: the idea is here. The grating, you can think about it as an array, big array, big compared to the size of the point that I was eliminating, big array of scatterers.

So you think about having a material that transmits light and a material that scatters light and a material that scatters light is arranged in lines. And the lines are separated from each other by some kind of a distance, here represented by a capital D.

And the reason that you see the far-field pattern, we call that the far-field pattern as opposed to the near-field pattern. If I were to do this and put it very close, then I would think about the pattern being the near-field pattern if I get close compared to D. So if the slits are D apart, the near-field is D close, and the far field is when I'm far away compared to D.

So if I'm far away compared to D, then you can imagine that the light is coming in this way, and each one of these generates scatter. So there is a spherical wave coming way out from each of these. That's Huygens' principle. Right

So the idea then is that there are contributions from each one of these scatterers out here in the far field. Each point in the far field picks up a little bit of light from each of the scatterers, but they're in different phase relationships. They were in phase when the coherent light struck these.

But now if I were to think about a point here, the phase that you get is different from the point here. So here the phase from two points would be about the same. Here they would be different because the distance traveled from this scatterer is that much longer.

So if I look at a particular angle, then each of these scatterers is a different optical path length from the source. That means that if I arrange the angle so that this is lambda, the light that scatters off of here will constructively interfere with the light that scatters off of here and here. Everybody see that? So that means that there's a funny angle, the sign of which is lambda over D in which you get constructive interference, and that's what's going on with the diffraction grating.

And you can see that. There are several illustrations of that all over the place. Here I have a CD and a DVD. Which one is which? I'm showing you the backside of a CD and a DVD.

AUDIENCE: DVD is in the left side.

DENNIS DVDs is this one. How do you know that?

FREEMAN:

AUDIENCE: Because it looks blue.

DENNIS FREEMAN: Because it looks blue. Why does it look blue? Not a clue. It's just they always do.

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: Smaller. So somehow this one reflects better, the bluer lights, so you see more of that, and this one reflects better longer lights. This one has got a greenish twinge maybe. Kind of like all colors. I like to call it green. Maybe it's because I know the answer.

So if I take these guys, I can get the same sort of thing, so I'll take the CD first. Now, of course, this has a coding on it, so if I try to shine a laser straight through it, not much will happen. I don't really want to blind somebody.

So I'm going to take this and I'm going to attempt to hit this while watching back here, which for somebody my age it's pretty hard to do. But the idea is going to be that instead of using this as a transmission grating, I'm going to use it as a reflection grating. So if I do this-- so that's kind of cute.

So my laser is green. What's lambda?

AUDIENCE: 530.

DENNIS FREEMAN: 530. So let's round off. Let's say 500. Yes. So I've got a green laser, and what will happen if I move the laser back and forth? How will the pattern change? It won't change. So if I do this, which I can't do while I'm watching it, no change.

What will happen if I move this way this way? Well, the angle is what matters. So as I move it farther away, the pattern gets bigger. So if I do this, if I were at all coordinated, which I'm not, I'm trusting that it's doing what I'm telling it to because I can't look at the same time.

So let me put this at a precise 1 meter away, 3 feet. And let me shine this in here, and let me do a very precise measurement. And those are now one-foot apart by my precise measurement skills.

So what I'd like you to do is figure out the pitch. The information on a CD is written will spirally.

That's the reason there is an apparent color. I just measured the pitch. How far apart are the tracks?

So take the data. So if I'm three feet away from the screen, the dots are separated by one foot and figure out how closely spaced the tracks are on a CD.

So what's the answer? 1, 2, 3, 4. None of the above. A very small number of votes, but about 90% correct. So what do I do? How do I figure it out?

Yeah. So we just made a big deal out of how the distance, which was D sine theta had to be an integer multiple of lambda. So all we need to do is think through some trig.

So if I think about the dots being a foot apart when I'm three feet away, then the tangent is 1/3. So the small angle approximation is about 1/3, so the sine is about 1/3. So lambda is about 500 nanometers divided by 1/3. And if I carry that out a little more precisely, I get 1,613, and the manufacturer's specification for CDs is 1,600 nanometers. So it's 1.6 micrometers. Yeah.

AUDIENCE: [? What ?] is the precision on [INAUDIBLE]?

DENNIS FREEMAN: Oh, they're pretty good. In fact, we'll talk about this a little later. They do this by an embossing process. So you make a master out of aluminum, and then you stamp it. And the stamping is actually very good.

So probably the biggest manufacturing problem is the thermals. So you stamp it in heated polystyrene, so there's a little bit of a coefficient of shrinkage as it cools, but it's not very big. It's fractions of a percent.

So what will happen then if I switch to the DVD, how many tracks are on a DVD? So we can do the same kind of an experiment. Now if I try to do the DVD, in order to get them to be a foot apart, I have to get much closer. So now to get D space at about a foot, I have to be about a foot away. So what's the spacing on the DVD, smaller or bigger? So it's smaller because the angle got bigger.

So it's the same sort of deal. If you think about the one foot, so you get one-foot spacing with about one foot. So then the tangent is about 1. It's not quite a small angle anymore. So theta is 0.78.

And so the experimental value comes out about 704 nanometers, so it's about a factor of 2.

Smaller. So we got about 700 nano, so it's a fraction of a micron, rather than 1.6 microns, and that's why they look a little different.

So we get about a factor of 2 in terms of information density in terms of track count. Of course, the information is also stored more closely within a track as well. So instead of being about a factor of 2 better, it's maybe a factor of 4 better because the track is based about a factor of 2.

You can do more interesting things. That's kind of the most degenerate case because that's one D. So here is a fancier grating from my lab, which has the property that if I shine the light through it, I get more dots. So what's inside this?

AUDIENCE: A 2D grating.

DENNIS FREEMAN: It's a 2D grating. So instead of having just lines going this way, it has lines going this way and lines going that way.

And in fact, back about 5 or 10 years ago, when laser pointers were a novelty, they became all the rage to put them right into your laser pointer. So here's another laser pointer. So here is a thing that you screw in the end, which has a fraction grating built right into it.

And so now if I mean to say some graphics reading off the cursor, so there is a cursor now in my laser pointer rather than being a dot. Or if I'm more chintzy, now I can circle things. I'm not sure why I want to do that, but in case I wanted to, I can do it. If I wanted to underline things, I guess. I'm not sure.

The point is that these things are just a diffraction grating. All that's in there is a little piece of glass that's got-- it's not actually glass. It's actually plastic that was made with an embossing process, same as they make CDs with. So if you're into--

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: Yeah. Who knows. And if you go backwards in time, they get even chintzier. So this is an even older laser pointer. They're fun. You can tell it's older because it's red and it's dimmer.

If you think the click art is kind of still-- this is my favorite. Save the favorite for the end. Dark side. I don't know. Anyway, so that's kind of the idea. The way you can think about diffraction grating, so now I want think about a more general theory. I've worked out a specific theory for a one-dimensional diffraction grating, now I want to think about the general theory.

What if I simply told you some pattern in space? What if I told you your job is to make the diffraction grating to project a dollar sign. How would you do it? Take a wild guess.

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: Take the Fourier transform, of course. So the idea. So what would happen if the target is more complicated than a grating, the way to think about this is the think about just like in the case of the grating, if you collect the light that hits the far field, the far field bit has a point in the far field, came from all over the target just like in the grating.

In the grating, the point in the far field came from every one of the lines and there was a simple relationship among the phases that came from each of the lines, and that's what gave rise to the pattern in the far field. Well, the same thing is always true. All the points in the image in the far field came from-- each point, had contributions from every point in the target.

And if you think about points in the target, now I'm going to think about just one point so this is the target space. Way out there is the far field. So in the target space, there's an x-coordinate, there's a y-coordinate, there's a z-coordinate. Let me just worry about x for the moment.

This point that is x displaced in this direction contributes a different phase to the far field than a point that's at 0. Because the point is at x, you get a different phase. And that phase relationship depends, not just on x, but also on the angle.

And this is the relationship, the phase generated by a scatterer at the point, x. Just like the one-dimensional grating, if you take x and multiply by the sine, that tells you the delay in meters, but then you can convert that into radians by dividing by the wavelength and multiplying by 2 pi.

So the phase that is generated by scattering from this point displaced a distance, x, when measured in angle, theta, in the far field, looks like that. That's supposed to be just a simple reiteration of what we just did.

Now the tricky part is that all of the light that hits a particular point in the far field, a point in the far field is characterized as theta. Where is my laser pointer? So if you go to the far field at a place, theta, the total amount of light that hits the point, theta, is the sum, the integral, of all the different scatterers. So f is x represents how much light gets scattered as a function of x. x is the target. So this is integrating over how much light gets scattered at each x, and at a particular x, you get this phase delay.

So there's a coherent sum then. So you add up all of these complex numbers by the integral. Now imagine that the sine of theta is about theta. That was true all of the examples I've done so far. So here I'm what, 15 feet away, and it's a foot, so that's small angle approximation.

So now let's replace sine of theta with theta, and let's think about this number, 2 pi theta over lambda. That's just frequency omega. So I'm thinking about now the far field, which we had previously called dependent on theta. Theta is just omega. So I've got a relationship now between how much scattering happens at each x in the target and what does the picture look like in the far field. And that's a Fourier transform.

So there is an exact Fourier transform relationship. Well, exact is a little bit of an approximation because I'm using a small angle approximation. I'm ignoring a few things. Not only am I making a small angle approximation, but I'm assuming that if the light goes straight and if the light goes up, they have the same intensity when they hit the board.

That's not quite true. That's with Fraunhofer approximation blah, blah, blah. Fancy names for a bunch of approximations. The point is that if you make reasonable approximations, you get a Fourier transform relationship between the scattering in the target and far field image.

So now we have a very convenient way of thinking about what happened whenever I shot my laser through this thing. I get a bunch of spots in the far field because-- everybody shout. This is the aha. So we've got an impulse train in the Fourier transform, which means that the thing that was down here was an impulse train. because we know that the Fourier transform of an impulse train is an impulse train.

So this is an impulse train in space. The scatterers represent an impulse train. So whenever I illuminate it, I getting impulse train in the free transform because the Fourier transfer on an impulse train is an impulse train. Well, that's pretty cool. So you all know why an impulse train is an impulse train.

So this two dimensional grating then, the interesting thing about that then is that it must be the case that the Fourier transform of a 2D impulse train is a 2D impulse train. So I want to think just a minute about that. What will we mean by a two-dimensional Fourier transform. So two-dimensional Fourier transforms. I want x j omega 1, j omega 2.

So it's a lot like a 1D transform. I am going to think about having x except now there's two time variables, time 1 and time 2. And I'm going to have to have two of these funny exponential things. So I'm going to have e to the minus j omega 1 t1 plus omega 2 t2 d t1 d t2. It's almost like a 1D transform except I have two d's now.

And the way to think about that, probably shouldn't distract you with this. That's the next slide. So the way to think about this is this separates. e to the j sum is e to the j1 plus e to the j2. So I can write this more simply as x of t1, t2 e to the minus j omega 1 t1 d t1. So then I can integrate that, e to the minus j omega d t2.

This is the integral over the t1 variable. So if I think about doing the transform in steps, this is the integral I might say-- so let's say that I had my original 2D thing was a square that I'd like to characterize as a t1 dependence and a t2 dependence.

The way I think about the 2D transform, this thing says, for each t2, treat t2 as a constant, for each t2, that's for each row. Treat t2 as a constant and just take the Fourier transform of the t1 direction.

So what I do is I take the Fourier transform of this, and I put it here, but when I've done that, I've changed the t1 axis into an omega 1 axis because the result of integrating over t1 throws away the t1, but I'm left with an omega 1. If I repeat that for all the different lines, I didn't really change this axis, which was t2, so it's still t2. All I've done now is taken a bunch of integrals in the middle.

Now, if I take the outer integral, what I need to do is integrate over t2. So if I integrate over t2, now I want to integrate this way. Now, I want to integrate out the t2. The t2 goes away. So I take Fourier transforms this way. For each column in this space, I generate a new Fourier transform over here, and I repeat.

That doesn't change this one. This one is still omega 1. But then when I take the transform this way, I had a t2. That turns it into an omega 2. So I started with t1-t2 space, take all the transforms row wise, make a new array, take all the transforms column wise, make a new array, and I end up with omega 1, omega 2.

So if I do that, what's the two-dimensional transform? What if I started with a vertical line? What if my spatial dependence had a vertical line in it? What would be the two-dimensional transform of a vertical line?

Well, the rule says transform all the rows. What's the transform? What do I call that function?

Shout. I'm deaf.

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: So let's say the line has a height of 1, and the background has a height of 0. So as I read across here it's, 0 0, 0, 1, 0, 0, 0.

AUDIENCE: [INAUDIBLE].

DENNIS FREEMAN: Exponential. Impulse. Impulse in left. So when I take the transform, I get 1. I get constant. So I get a constant over here, and then I take this one. Same thing. Same constant, same constant, same constant. I end up with a constant over here.

So this started out being delta of t1. This is a constant everywhere. So now if I take the column-wise transforms, what's the transform of a constant? It's an impulse. Where should the impulse be? 0.

So I end up when I do the omega 2, the t2 transforms. I get a delta in omega 2. So I have omega 1 here, and I have omega 2 here. So I end up with a delta function like that. Then I do it again, and I get one here. And then I do it again, and I get one here. So I end up with a line.

So vertical line in t1-t2 space turns into a horizontal line in omega 1-omega 2 space. Got it? It's all very simple. And if I do the same thing, if I did a horizontal line, it will come out vertical. And if I do a diagonal line, it will rotate 90. Very cute. Y'all got it?

So the idea then is that there's a very natural generalization from a 1D transform to a 2D transform, and that's kind of fun, but it's also kind of important. So now for the important part.

So this is a picture, a diffraction photomicrograph done by Rosalind Franklin back about 50 years ago. She had taken DNA. I can't remember. I think it was from Drosophila, but I don't really remember. She had purified DNA. And at that time, lasers were not this size.

Actually, she used x-rays. She used a source of coherent light from an x-ray, so it's not even a laser, it was x-rays. She fired coherent x-rays at DNA-- so she had just a big glob of DNA-- and took this picture. And it was pretty and pretty confusing.

By the way, just so you know, this is an artifact. This is a hole in the photographic film. So the idea was coherent source of x-rays, sample of DNA, into a photographic emotion. Develop it, you get this. So it's very similar to the diffraction grating experiment that I did except that the target was not a diffraction grating, it was not a CD, it was not a DVD, it was DNA

That cute thing is that she showed this to Watson and Crick, who were geniuses at so many different levels it's absurd, and especially Watson knew all about Fourier transforms. And so he saw that and immediately was able to interpret it as telling him something about the three-dimensional structure of DNA. In particular, if you think about our modern view of DNA, you can make an association between the structure of the DNA and this picture.

So there's a high-frequency band. So if you imagine that what you're seeing is three bright points from a diffraction pattern like I showed previously, this and this represents a high frequency. This represents DC. So the distance between DC and the high frequency is telling you something about the inverse distance between base pairs.

The highest frequency in the x-ray picture is inversely related to the distance between the base pairs. The fact that there is these closer-spaced frequencies, those are actually lower frequencies because they're closer to 0-- we're in the far field, so we're in the frequency domain. Big frequency, small frequency.

The fact that we're seeing these smaller frequency things here and there are periodic, that means there some structure at bigger spacing, which Watson and Crick interpreted as the pitch of the double helix. So the helix is twisting. This is the modern picture, and it fits very nicely with the picture that Rosalind Franklin made.

And the angles, the fact that there is an axis here, the reason for going through all this junk was to motivate the idea that there's an angle transformation in a two-dimensional transform too. In fact, angles in space get rotated 90 degrees when they're in frequency. So the angle between these solid lines tells you something about the angle that the helix makes as it's wrapping around.

So you can easily make 003 model of this experiment, and that's what this is. Here all I've taken is a trivial model. I just made a wire frame that had base pairs arranged as a rotating spiral, just like a spiral staircase. Then that was a three-dimensional picture.

Then I just flattened it, and then I took the two-dimensional Fourier transform and got that. Got it? So the idea was I made a trivial model for what DNA should look like according to a modern conception, took the two-dimensional Fourier transform, and what you can see there is all of the features that you see in Rosalind Franklin's picture.

You can see the big band that corresponds to the base pairs, you can see the smaller bands that correspond to the twist, and you can see the angle that corresponds to the angle of the double helix. So the point then is just that there's a lot of physical phenomenon. Besides the signal processing things which we're very interested in, there's actually a lot of physical phenomenon that also have intrinsic meaning within a Fourier domain, and optics is a very important example of that.

See you later. Have a good day.