Neural Science for Engineers
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Lecture - 42
Human auditory system - III

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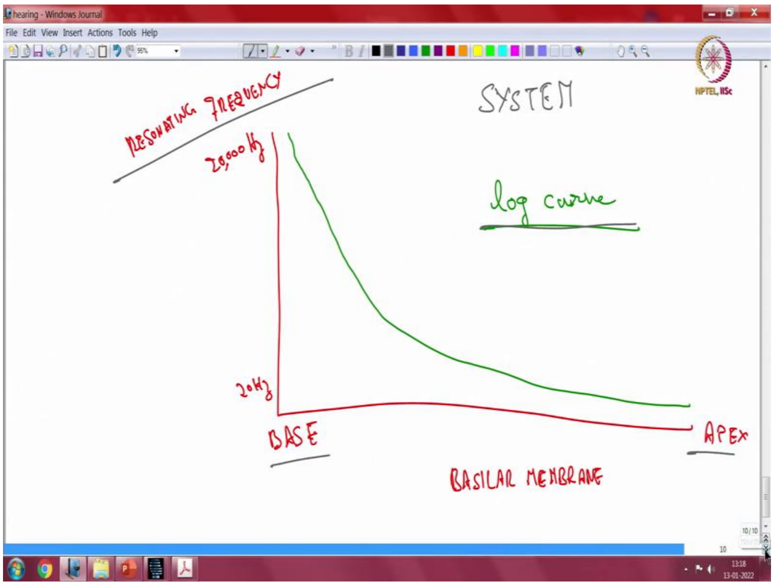

So, the membrane what you call gets excited by very different frequencies at very different parts of the membrane. So, that is the part of the story to which we have come down. A couple more people would have the aha moment at this time because there is a lock and then there is a resonating frequency and then there is a base in the apex.

So, we go to the next part of the story. So, we have gone through different parts of this membrane and how it is very peculiar. So, it is transmitting information to the cells.

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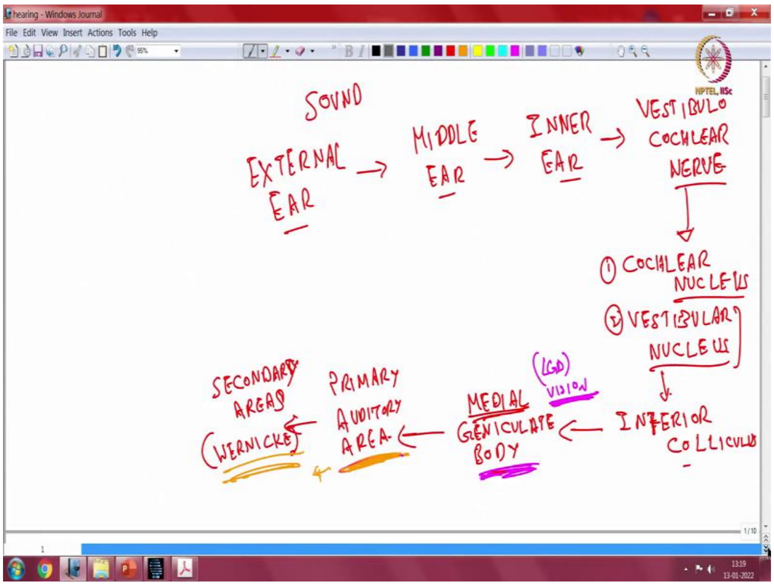

But before it is transmitting information to the cells, it is doing all this stuff.

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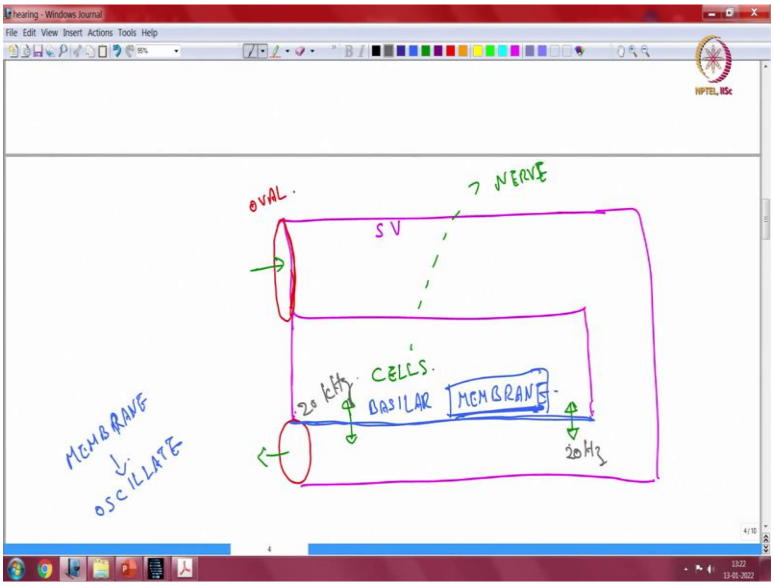

So, this to reiterate the story back again oval window, this is the oval window.

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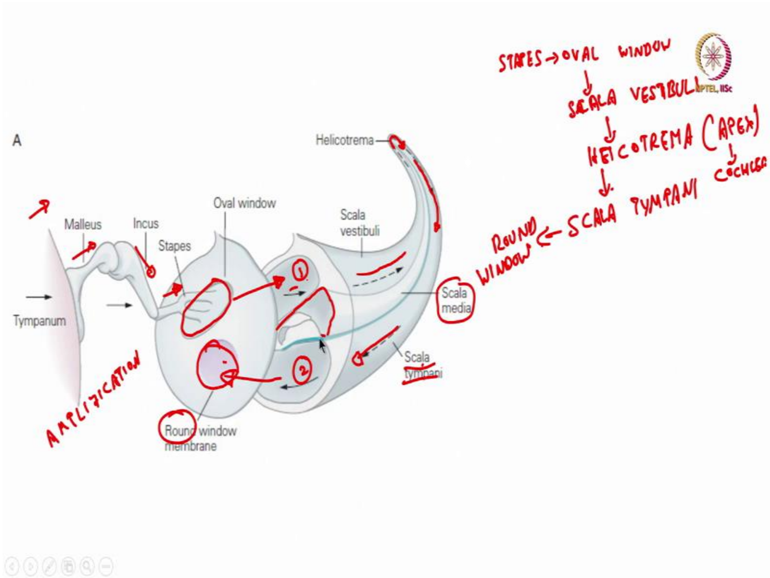

I think I should go back to the slide and then the picture becomes little more clearer now, tympanic membrane, malleus incus and stapes, a bones. So, then this membrane over here which goes into a smaller membrane over here, there is the amplification over here that there is air to liquid transfer over here of sound. So, then maybe because the air to liquid you know there might be a dampening.

So, that is the reason this mechanism exists, the exact causes are not known of course. So, then the sound gets transmitted through this membrane, all the way up to the apex and then remember the apex there is one membrane over here.

So, this is the more rigid membrane, its rigid. I am not sure of the material properties of the Reissner's membrane vis a vis. But let us say that you know it is it has minimal contribution, but for the purpose of discussion we will focus only on the basilar membrane, for important reasons which I am about to tell you.

So, the sound goes all the way over here and then comes back over here in the scala tympani at which point of time the basilar membrane is in direct contact with this sound wave which is coming from here. So, as the sound wave comes through the scala tympani different parts of the basilar membrane gets stimulated, stimulated in the sense its mechanical stimulation that is because each part of the basilar membrane is responsive to a specific set of frequencies.

Now, frequencies itself is different, it is a log scale across from the apex to the sorry base to the apex. Base has a low frequency sensitivity, the base has high frequency sensitivity and this entire 33 millimeter covers about 20 to 20000 kilohertz range. So, that is the story which I have conveyed.

Now, we will come back to our discussion. So, this is the nice picture which conveys the same thing without the 3D, box shape sound goes in sound comes out, basilar membrane oscillates. So, the oscillation is different.

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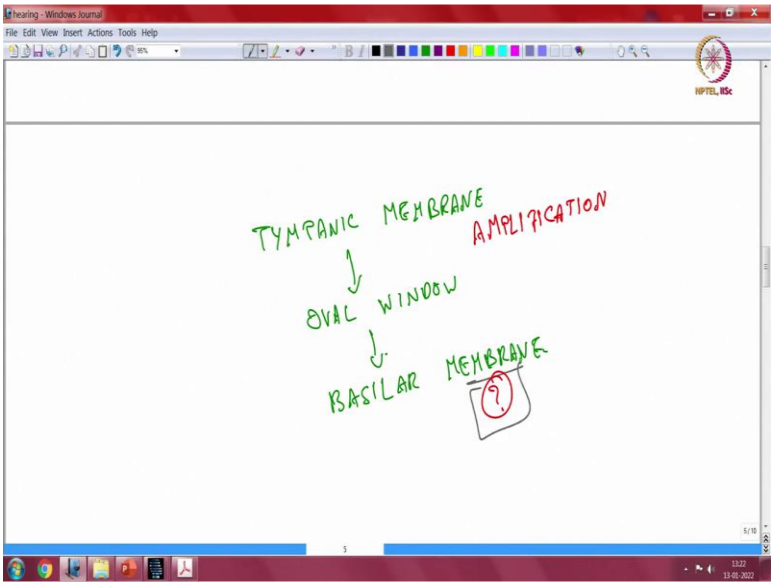

So, now we still have this idea of what is the basilar membrane trying to do. So, we go back a bit and try to see what actually happens with this. So, this is the log curve which is there. So, the basilar membranes function is what we are analyzing.

Now, let us see what happens to stimulus and how that goes out through the basilar membrane and then what is actually happening to that. So, for that we need to draw the basilar membrane.

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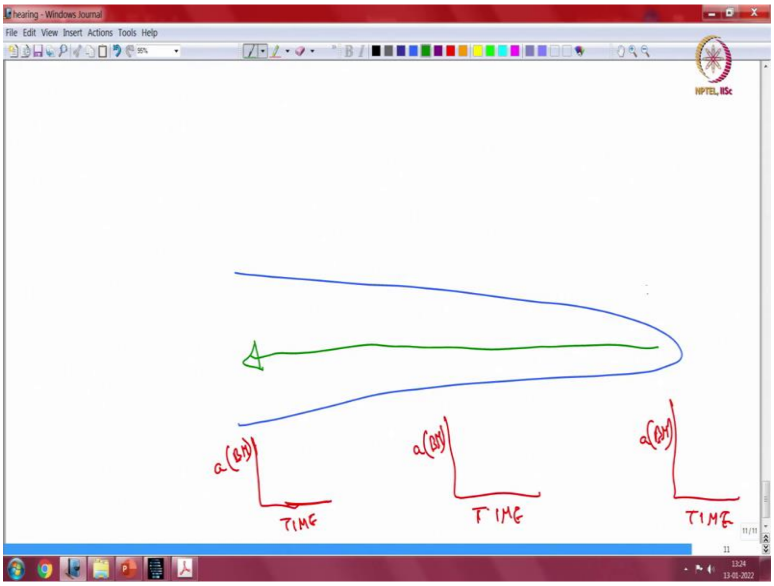

And, then we draw 3 nice graphs over here. So, this is amplitude of the basilar membrane; amplitude of the basilar membrane and this should be time series. So, the input to this membrane, it is a travelling wave, remember it is a travelling wave.

So, travelling in this direction. So, travelling in where do I put it? The travelling wave is coming in this direction. Why is it coming? Because this is the helicotrema, the travelling wave.

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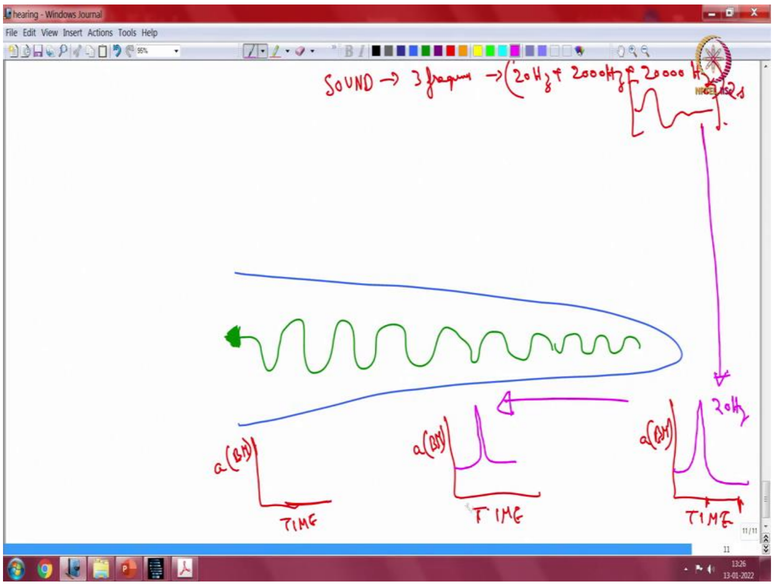

So, this is the travelling wave coming through the scala tympani and it is going across the basilar membrane. So, what we do is we run a thought experiment and then we see what happens with that. So, we give a sound wave which contains 3 frequencies complex sound wave. So, 3 frequencies are 20 hertz plus 2000 hertz plus 20000 hertz 20 kilohertz.

So, the signal consists of about say 2 seconds of this complex sound which contains these 3 sets of frequencies. So, we are looking at a waveform which has been sent through, sent into this membrane and what happens with this waveform. So, 0 and 2 seconds. So, when this particular wave reaches this particular area. So, when the signal reaches this area the 20 hertz signal is picked up.

So, 20 hertz there is a spike, 20 hertz spike and nothing else. The wave comes over here, there is a spike. So, I should have put frequency over here, sorry I think I need to redraw this.

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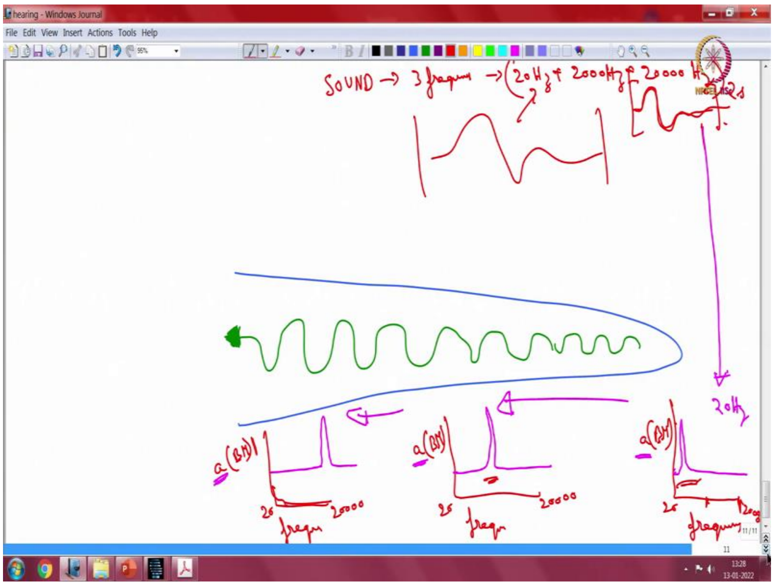

So, this is frequency, frequency we will put it as 20 and 20000, 20 and 20000, 20 and 20000. So, what happens over here is we have a spike in the 20 hertz and then there is a straight line. When the signal comes over here, we have a signal in the 2000 hertz and then there is a straight line. And finally, when the sound wave reaches the base, we have a spike over here and spike over here.

So, remember this is amplitude, amplitude of the basilar membrane. So, how much does the basilar membrane move when there is a complex sound signal such as this. So, a complex sound signal is this. So, you have got a complex sound signal which contains 3 frequencies. So, 3 frequencies modulated comes to the basilar membrane and this is the picture which you get.

So, this 20 the maximum amplitude for this part is the 20 because, that is that is the area which is of the basilar membrane which is getting maximum stimulated. Then there is the middle part of the basilar membrane where there is the frequency is 20 2000 and so, that part gets stimulated and in the end the wave reaches the base of it where 20000 signal is perceived it is mechanical. Please remember that it is mechanical.

So, what is happening? I should be meaning we in a Riemann manifold, I should have been hearing ahs and uhs and all that.

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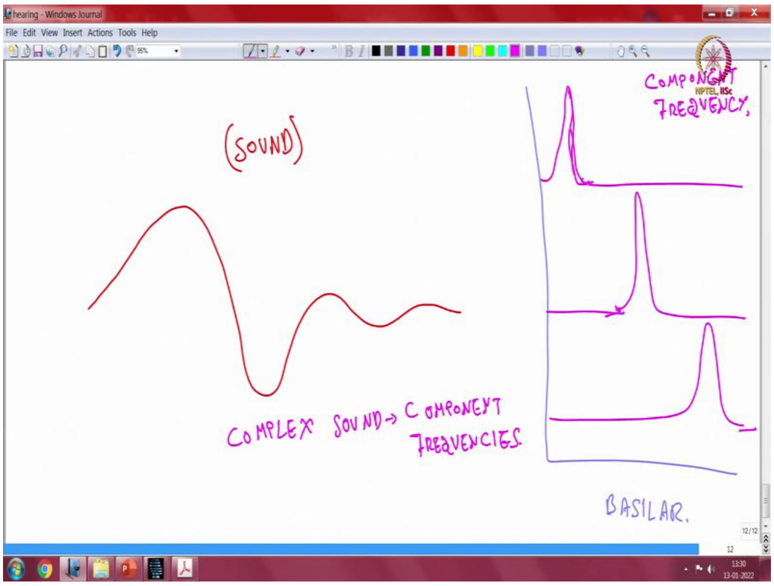

So, what has happened is the basilar membrane took this very nice complex waveform which is sound and split it into its component frequency. So, complex sound is split into component frequencies and that is the function of the basilar membrane.

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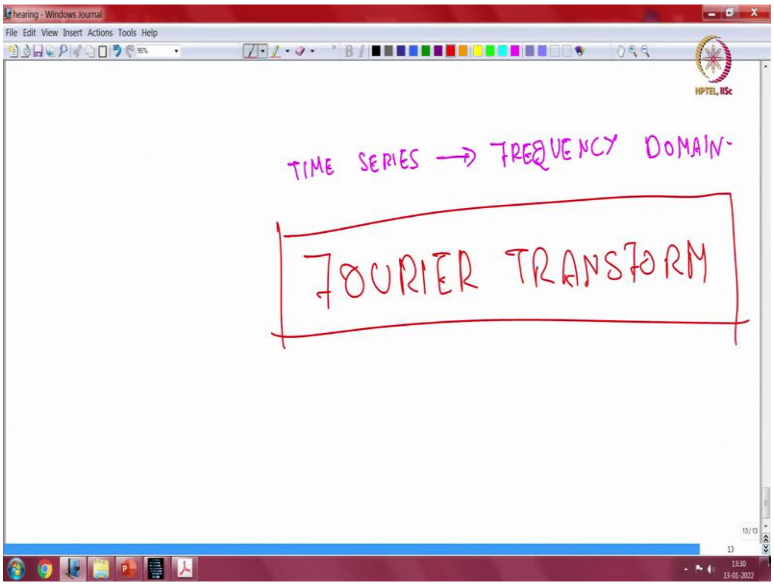

To put it in another terms, what I would like to say is that a time series has been converted into the frequency domain. And, that I think is for apparently 2 millennia people did not know how to process sound.

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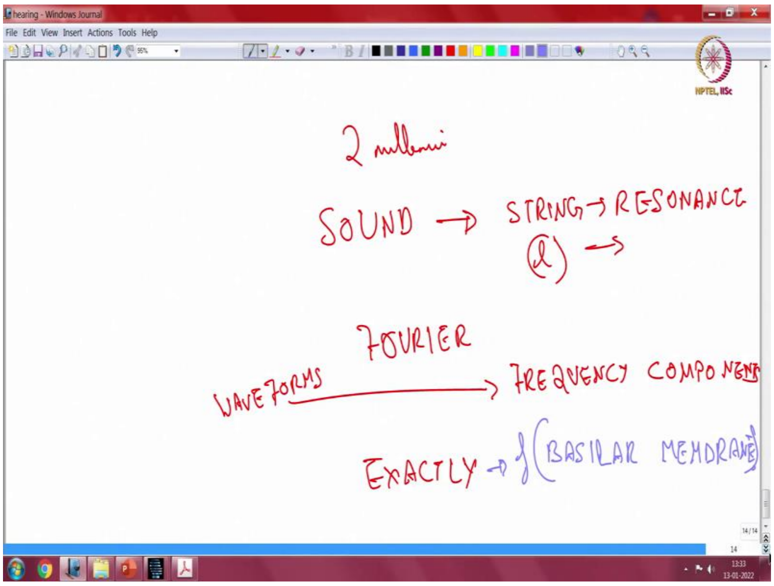

So, I read something on history, and they had this string and it had resonance and you changed the length of the string and it changed different things and so much stuff was there. Until the notion of Fourier of analyzing as analyzing waveforms in the in terms of frequency components and that is exactly what. So, that completes the aha part of the story.

So, complex sound with multitudes of frequencies is split into its component frequencies across the basilar membrane starting from the apex to the base and from and it is on a graded scale, it is a log scale. It is a log scale between 20 hertz to 20000 hertz and each individual frequency of the sound elicits, specific response due to the material properties of the basilar membrane.

And, based upon the sensitivity of the basilar membrane a different part of the basilar membrane oscillates, sort of resonates with that particular frequency and the amount of oscillation would in turn depend upon the intensity of the sound. So, frequency of a frequency-based component analysis is done by the basilar membrane. We can go to the next part of the story where we see how this is further translated along the nervous system.

But yes; so that is the rest of the story is actually sort of simpler once this concept is understood and so, we go with the back to the diagram of the hair cell.

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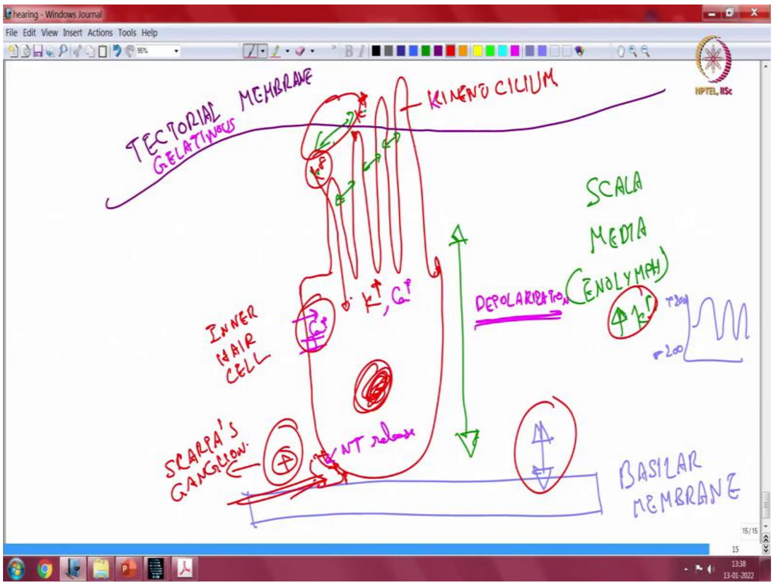

So, hair cell is somewhat like this, and it has got these funny structures called cilia I think these are too small. So, the biggest one is the called kineto celium. So, hair cell then below this is the basilar membrane. So, basilar membrane oscillates. So, that oscillation causes this hair cell to oscillate.

Now, the hair cell does not oscillate in free space, remember this is the whole thing is called scala media containing endolymph which is high potassium, that is one thing. The second and most important thing is, there is another this funny membrane over here, you know that is the tectorial membrane which is gelatinous and this cilia actually within the tectorial membrane.

So, when there is movement over here, the cilia move like this. So, because it's embedded within a firm structure and the basilar membrane oscillates and that causes movement within that. Now, at the apex of this the cilia are potassium channels. So, when movement happens potassium channels open, k+ opens, potassium enters into it, causes an action potential at the base; remember there are synapses over here, synapses which go.

So, I am just drawing an inner hair cell. So, synapse there are signals over here, it is not so simple. So, potassium actually goes into the cell and then it also causes calcium channel to open. So, calcium channel, calcium gets into the cell causing depolarization I am confident that people now do understand what a depolarization happens.

There is no action potential which is generated, remember these are sensor cells in general do not generate action potentials. So, there is a depolarization, the depolarization is more in the context of plus 200 minus 2 some other there is about a 200 change in potential. The potassium first comes in, potassium is in and calcium comes in and that causes depolarization and that in turn causes neurotransmitter release.

And there is the signal which is generated within the nerve which goes to the Scarpa's ganglion. So, that is what happens within the cell, how signal mechanical energy is transmitted to electric ionic charge and that ionic charge is responsible for an action potential. So, that is what is happening. Basilar membrane movement causes activation of the cells, the cells in turn cause general depolarization like which happens with many of these things.

The channel which is responsible is movement dependent. So, movement of the kineto cilium and the other cilia cause these potassium channels to open. Potassium remember, it’s a potassium-based dynamics as opposed to sodium based dynamics which I described in the earlier classes. So, potassium-based dynamics produces this current into the cell making the cell come back towards 0 potential which is the phenomenon of depolarization.

Depolarization causes neurotransmitter release at the synapses. The synapses produce action potentials, and the signal is transmitted onto the cochlear cells, bipolar cells, from there it goes on to the central nervous system. We will discuss that in the coming this one. So, one thing which I wanted to showcase over here is this is very interesting phenomenon which I thought I should discuss with you.

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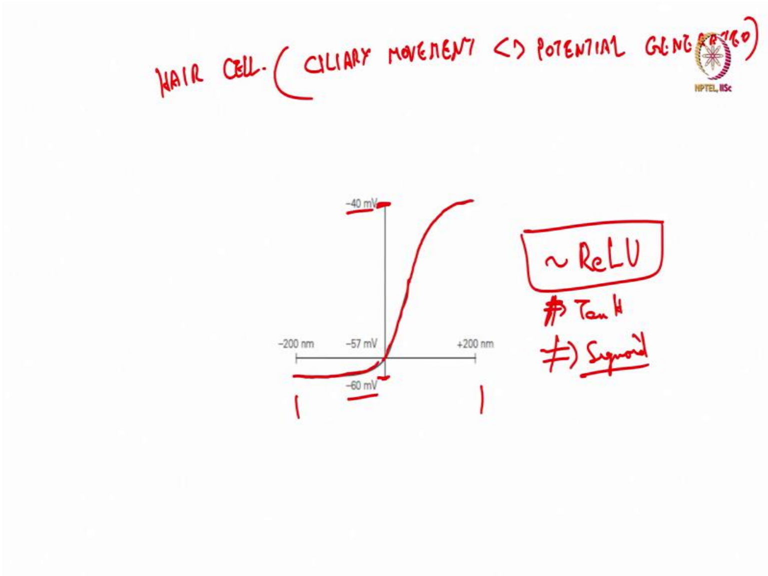

So, somebody has done some analysis of ciliary movement to potential generated that is in hair cell. Hair cell ciliary moment, how much of ciliary moment is between minus 200 nanometers to plus 200 nanometers and how much is the potential which is generated minus 60 millivolts to minus 40 millivolts. What I would like you to appreciate is you know the activation function; the activation function is what caught my eye.

So, its deliciously close to ReLU, it looks to be approximately ReLU, but it is not a tan H, not sigmoid. So, for all of the ML enthusiasts, you have biological proof of validation, you know otherwise you have to spend I think it would have helped couple of people get couple of PhDs on how these functions, I do not know how it works.

But you know if ReLU is popular because they have demonstrated results that indicates that ReLU is the better one. But I think maybe somebody should try out this function, it’s not exactly a ReLU, but it sort of encompasses the principles which are there in the development of ReLU vis a vis tan H and sigmoid. So, biological systems have generated their own you know activation functions..

These activation functions if you recollect my original first set of classes, they are protein based. And, somehow over periods of several millennia maybe you know they have developed this activation function which is so nicely mimics human intellect in the 21st century. So, that is the point of showcasing that. Now, what happens with the pathway is something which I have to show in some case.

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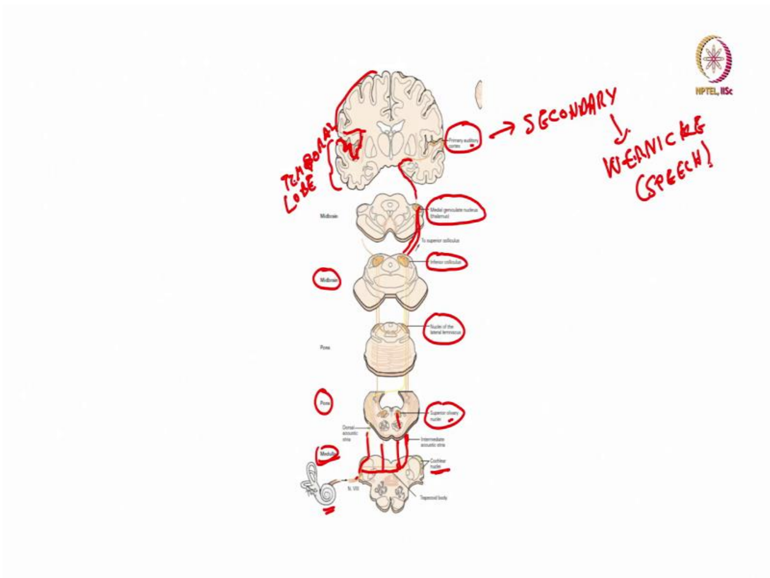

So, this is the inner ear and that is the cochlear. So, cochlear goes into the medulla. So, medullary section, it goes into the cochlear nuclei. Now, from the cochlear nuclei you should notice that the further pathways are superior olivary and the superior olivary nucleus. There are some fibers which go from the cochlear nucleus into the olivary nucleus, majority of the fibers. Please do notice another thing that it is bilateral.

So, there are fibers which are going same side which are fibers which are going opposite side. So, that is the phenomenon which is fairly different from the stuff which we have told, you know in optic apparatus in the motor system you have got 80 20; you know 80 20 or 50 50 in the case of optic. Optic is half the nasal fibers go to the opposite side;

temporal continue on the same side. In a motor 80 percent of the fibers go to the opposite side, 20 percent come down on the same side.

So, here you see that the split is sort of uniform, they got so many fibers going to the opposite side, very early in their pathway through the brain. So, that is happening over here. So, this is pons over here; so, in the pons there is some fibers going to superior olivary nucleus. Then there are multiple other way stations over here that is not the point of interest, the point of interest is the inferior colliculus.

Inferior colliculus, if you remember my anatomy classes in the back of the midbrain. I think I tried to show exaggerated versions of it if, people do not recollect it; I invite you to go back and check those videos. So, inferior colliculus then there are some fibers which go to the superior colliculus over here. But, sorry superior colliculus and more than superior colliculus, the next way station is the Medial Geniculate Body.

So, MGB and from the MGB, it goes all the way into this is the temporal lobe. So, this is the temporal lobe, the upper part of the temporal lobe is the primary auditory cortex. So, upper part of the temporal lobe which is in conjunction, close location to the insula and to the frontal lobe, frontal lobe is this one, insula is this one and that is the primary auditory cortex, from there it goes to secondary auditory cortex which is somewhere in that location. Then it goes to Wernicke's, Wernicke's is basically speech.

So, that is the kind of pathway which is there. Now yeah so, I jumped a lot, I jumped a lot between hair cell function to so many other things.

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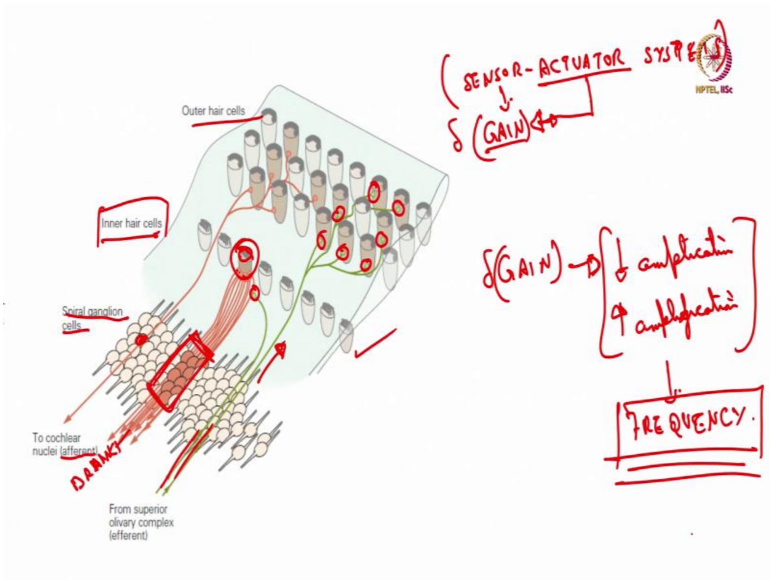

So, I come back to this slide at this point of time. So, I did speak about this sensor actuator systems and how you know you can fine tune your response to stimuli. So, what actually happens is you can change this sensitivity to the cells. You can ensure that they you know you send an input data and change the gain. A change in gain can you know reduce amplification or increase amplification; what I mean? So, what I mean is amplification of a specific frequency.

So, these things can change the sensitivity of these cells and you can change the information which is coming back into these neurons over here. So, that is the idea. So, you can actually change the gain and then you can select certain frequency, you know you become deaf to something. So, it has got a biological concept as a biological construct.

So, you become deaf to something, you play pay attention to some part of speech, you do not you filter out something in the background. You can talk to people in a crowded place, you can select music when you are talking to somebody, and you know cut out the person speaking to you. So, all that is possible at a biological level because of this, you know you can tune the cells.

Now, what does tuning actually mean? Ok. There is another thing which I would like you to notice is this one too many configurations. So, one inner hair cell; so, these are inner hair cells, one inner hair cell synapses to a bunch of a nuclear cells and that goes back to that. So, there is an overlap and then there is you know you can have a specific information in a particular frequency range. So, let us refresh our global concept once again.

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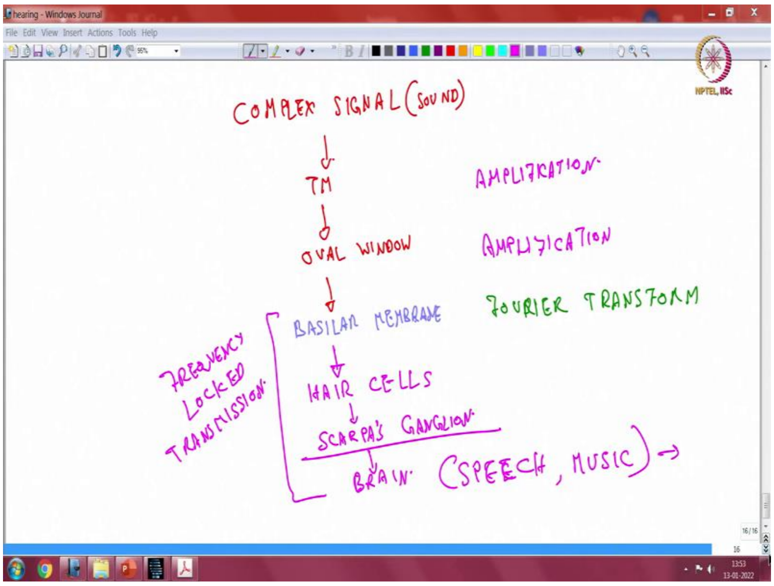

So, complex signal which is sound through the tympanic membrane and through the oval window, oval window. So, what actually happens is everything here is amplification, then it goes on to the basilar membrane. Yeah, I do not know if somebody gets offended by my using Fourier transform over here, Fourier transform because there is no imaginary number in this.

So, the basilar membrane is a very decent mechanical construct, it does not care about math to a great extent. But it efficiently does its job for which reason we as human beings hear all the stuff which we hear. Now, from there on it goes on to the hair cells Scarpa's ganglion and to the brain. Now, these are all frequency locked transmission.

So, the data which is actually conveyed to the brain is that how frequently is a particular frequency of voice heard in the input data. So, yeah input data has a set of frequencies, it is split into its component frequencies. You have amplitude of these individual frequencies, and that amplitude is coded in the signal strength which comes to the Scarpa's ganglion, it is hardwire. The frequency is hardwired into the pathway. So, from the basilar membrane on to the entire neural pathway up to the head you have frequency which is encoded in nerve, not in rock in nerve and what changes is the amplitude; how often is this amplitude which is changing in time.

So, time series converted into frequency series and then transmitted onto the brain, the brain analyzes all these things and then outputs data to you know that is where it's converted to speech, music. And there goes that goes to secondary cortices again like in vision it is not that you know every kind of speech is not an end entity. So, you pick put in a lot of other context you know.

So, when you speak to somebody, there is a lot of memory in play on the topic, there is attention in play on the topic. If it is a song, you know there are mirror neurons which get activated, if you are happy with the song with you get irritated with the, with some other part of the brain. The limbic system if you do not like the song and all this happens in parallel with the sound acquisition and processing.

So, a difference here which I have to mention in terms of vision is that vision is based on the second transmission, second transmitter pathways. So, if you recollect light, rhodopsin, cyclic GMP pathway and that there it goes in the sensor cell. Here it is directly you know movement causes potassium channel and then that its faster, ionic gateways are much faster than biochemical pathways.

Because biochemical pathways usually are the series of molecular reactions which have its own KM and things like that and KM because most of them are reversible reactions. So, they go from one set of reversible reactions, there is a lot more amplification which happens in a second neurotransmitter pathway, biochemical pathway as opposed to ion. Because ions there is a potential change and that causes neurotransmitter release.

So, mechanisms are much faster in auditory as in comparison to vision. So, that is the contrast which is again there between that. In vision you have light which is which causes chemical reactions, here sound is converted into mechanical energy and the mechanical energy is what is reflected on.

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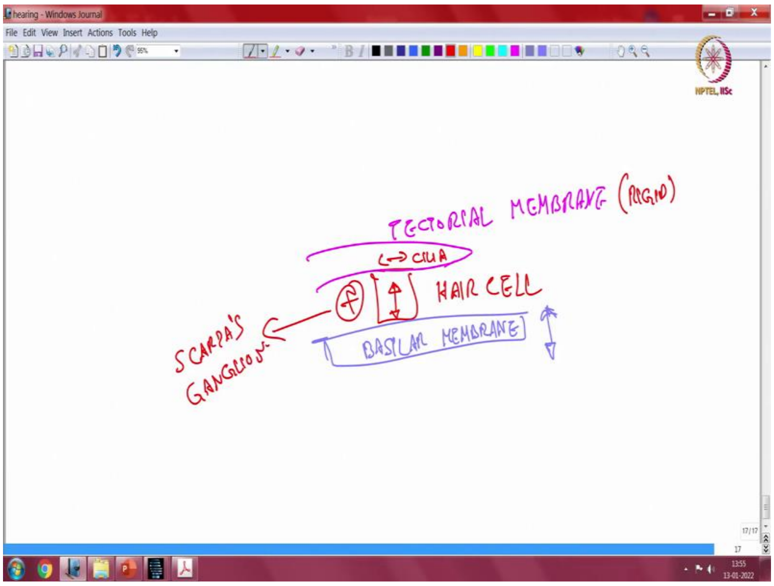

So, that is something which I have not explained, I think we will put it in context like this. So, you have hair cell, tecto membrane and basilar membrane. Basilar membrane oscillates, hair cell oscillates, the tectorial membrane is rigid say sort of rigid. So, rigid and that causes the cilia to move and that causes the signal to go to the Scarpa's ganglion.

So, I think that is the message conveyed here is these are the fundamentals of hearing. There are lot of other stuff on the how the hair cells are tunable, and you can change the hair cells in specific have something called as a tuning frequency, where the response; it is something like the it is something like the cones and vision.

So, you have different three sets of cones which are sensitive to different frequencies of input light. Similarly, hair cells here are encoded because on the location on because of the location on the basilar membrane. So, specific parts of the basilar membrane respond to specific frequencies and that frequency is hardwired into the hair cell and thereon into the central nervous system. So, that is how frequencies are coded.

So, hair cells in themselves they contain frequency data which is sound frequency data which is conveyed all along up to the brain. So, with that I think I can safely conclude the story on hearing, and I think an important thing, I would love to hear your comments on what I think about Fourier transformation in the hearing. I have done fairly an extensive search and not found that correlation it's obvious, meaning somebody who is had anything to do with Fourier transform, they should understand the importance of frequency-based analysis. And, the year for all its it does exactly the same, much before Fourier thought of the idea of doing frequency analysis on sound waves.

So, with that I conclude this.

Thank you.