Physics of Biological Systems

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Lecture – 16
Introduction to fluids, viscosity and reynolds number

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So, we have been talking about how things move and in particular we have been looking at how things move passively by diffusion over the last few lectures. So, today what we look at is sort of starting to describe the environment in which these things move and how do we describe the laws of physics in these environments.

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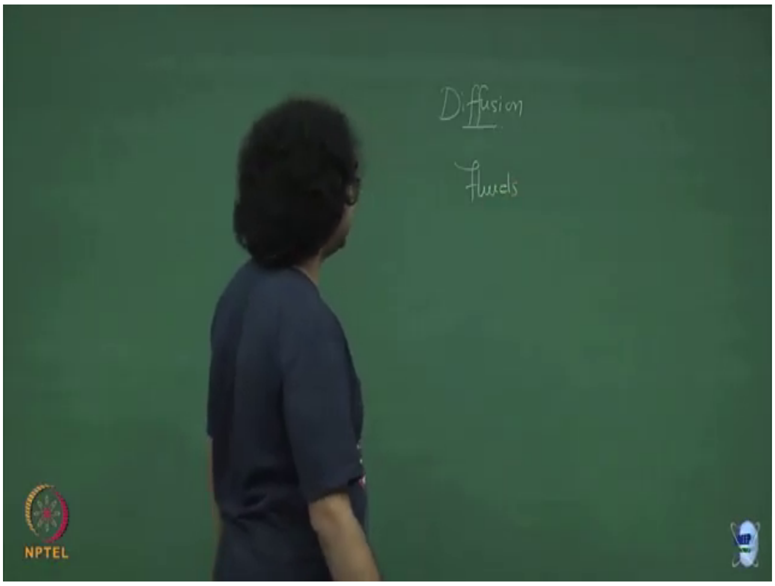

So, we will describe the fluids, we will develop the equations for the fluid flows in biological context. So, water is basically everywhere right; cells are swimming in water organisms are swimming in water inside of cells is also mostly water with proteins and so on and so forth mixed in. And therefore, its so, all of this diffusion, transport, transcription, translation all of this is happening in this fluid background.

So, it is good to understand it is important to understand how to describe these fluids in the biological context. When I say its water, there is a biological protein or a cell E coli or paramecium or whatever which is swimming in water does is it experience or would its description of water be the same as how we experience water. So, that is sort of the thing that we will try to describe; what are the properties we can use to describe fluids and what they mean at these biological length scales and this biological time scales ok.

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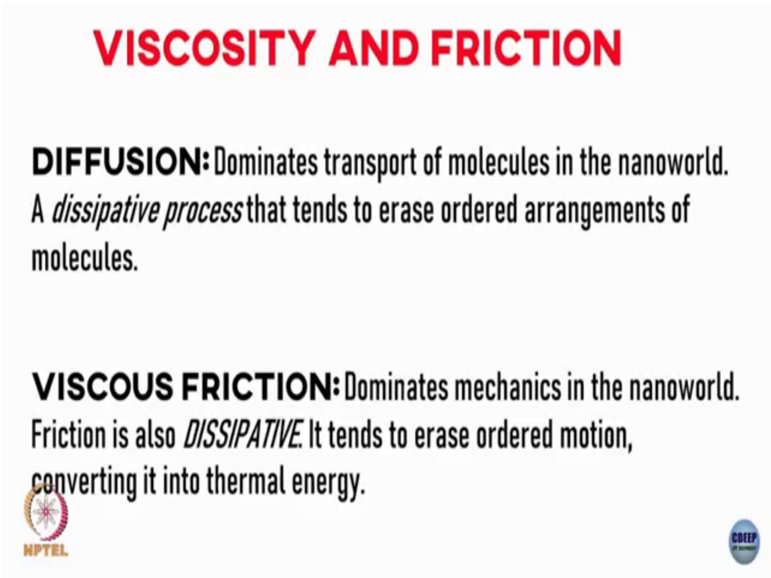

So, we have been looking at diffusion and as we saw; so diffusion is a major driver of transport of molecules in this nano or this micron sized world of biology; it is a dissipated process in that it tends to raise ordered arrangements of molecules. So, if you started off with a delta function like we saw; eventually we will go to a flat peak through a Gaussian and so on. So, it tends to erase any order that you might have; eventually tends to raise any order that you might have in the system.

Similarly, a viscous friction that dominates mechanics in the nano world; this is also dissipative it tends to again raise ordered motion and it converts it into random energy or thermal energy ok. So, this viscosity of this viscous friction is what we will try to talk about today, how to characterize it and quantify in terms of (Refer Time: 02:29). Underlying this is this sort of idea that how does; how to fluid flows, how do these fluid environments or these fluid backgrounds differ depending on this biological scale.

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So, for example, if I have a bacteria which swims in water versus this fish with swims in a water; it will turn out that the strategies that it uses in order to propel itself; will be very different for this bacteria as opposed to this fish ok. And that is because if you write down the equations of motion for this fluid, you will see that the terms which are important will be very different whether depending on whether it is a bacteria or depending on whether it is a fluid.

So, if the terms in these equations are very different; the terms which play an important role are different although the underlying background equation is the same, relative importance of the different terms varies. And it will turn out that because of these differences these organisms which are at very different length scales; this is at the micron scale, this is at centimeters or whatever meters if you have big fish or humans whatever.

The strategies that they have evolved in order to transport themselves in this fluid background they also turn out to be very different. So, eventually over the next two or three lectures; we will sort of try to see what sort of strategies these biological organisms which live in this micron scale; micron tens of microns whatever at scales such as these what sort of strategies they have evolved in order to propel themselves in this fluid background.

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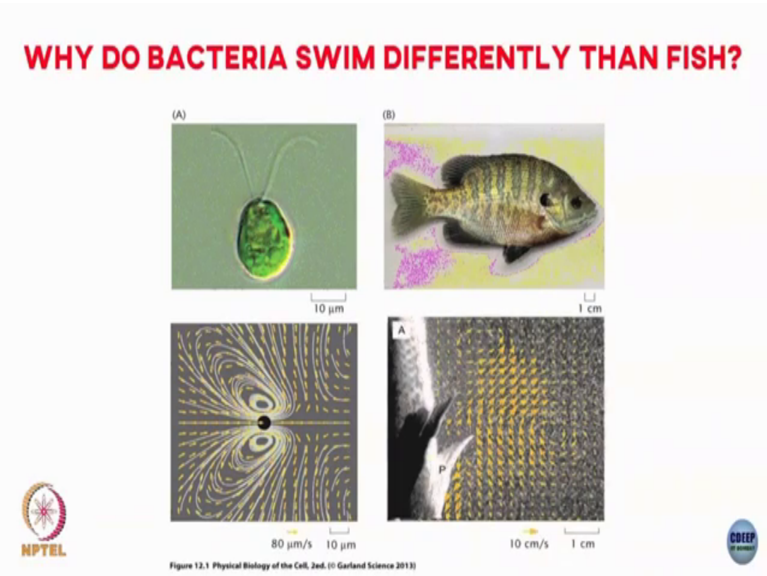

And again at the back of all of this is a lot of experiments for example, you can track how fluid flows behave around this; so this is if I am not this is plasmodium over here on the left and that is some fish; I forget what fish some sunfish it is called and you can map out the fluid flows around this organism this or that as it moves through water ok. So, for example, here are the vector fields; so fluid I would characterize it by a density and a velocity so as a fluid. So, you have some fluid or whatever that is say flowing.

So, as it is flowing; it has some velocity field which might depend on space and on time. So, it can depend on space and it can depend on time and what these arrows show you are these velocities; so this black dot over here ok. So, this is black dot over here is this algae and it is moving I think in this direction and this arrow show the velocity; on the velocity vector field of the fluid as it moves through the fluid.

Similarly, for the fish again you can do this. So, basically you fluorescent beads and track their motion fluorescent beads in this fluid; we track their motion and again you can construct velocity vector vector fields of the velocity as this fish swims through the water. So, this fish is like swimming in this way and what you will notice is that the scales are very different. So, for example, for this algae; the scale is around 10 microns. So, this scale bar over here is 10 microns; for this fish that scale bar is 1 centimeters. The velocities with which they move is also very different; this is roughly of the order of 10s of microns. So, these are on 80 microns per second that is of the order of centimeters; so that is around 10 centimeters per second ok.

And we will what we will try to do is that we will try to come up with properties of the fluids. So, for example, viscosity and combine them with the properties of the object that are moving in this fluids. So, for example, the length scales or the velocities of this bacteria or algae or whatever and try to come up with a way to sort of quantify what sort of terms will be important when we are looking at the physics of this swimming.

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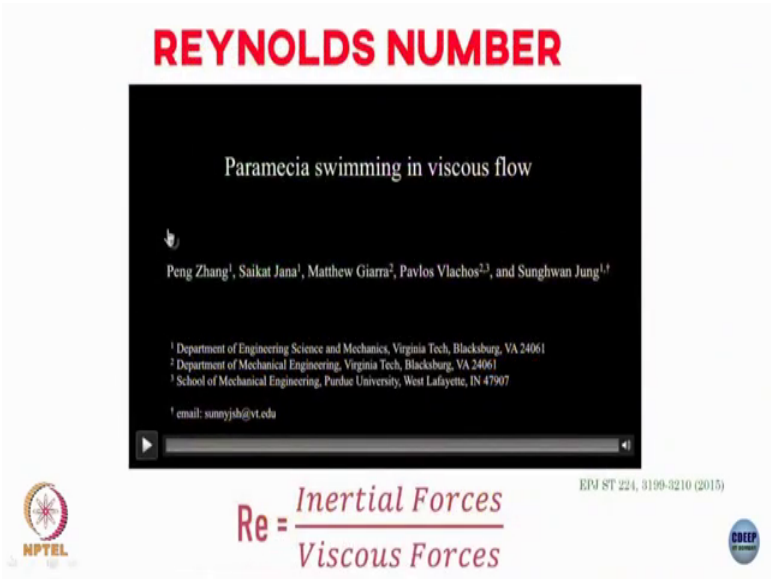

So, what we will basically first try to do is that we will first try to derive the equations that govern fluid flow and that equation as you may know is called the Navier Stokes equation; called the Navier Stokes equation.

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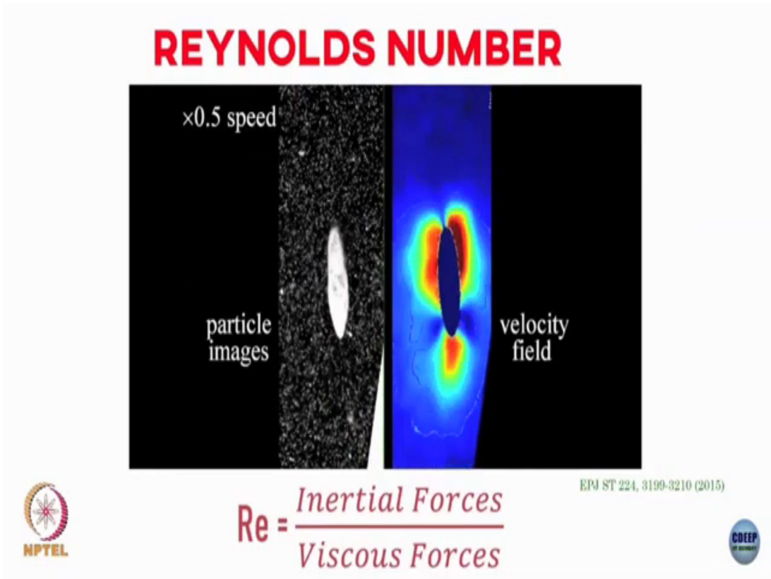

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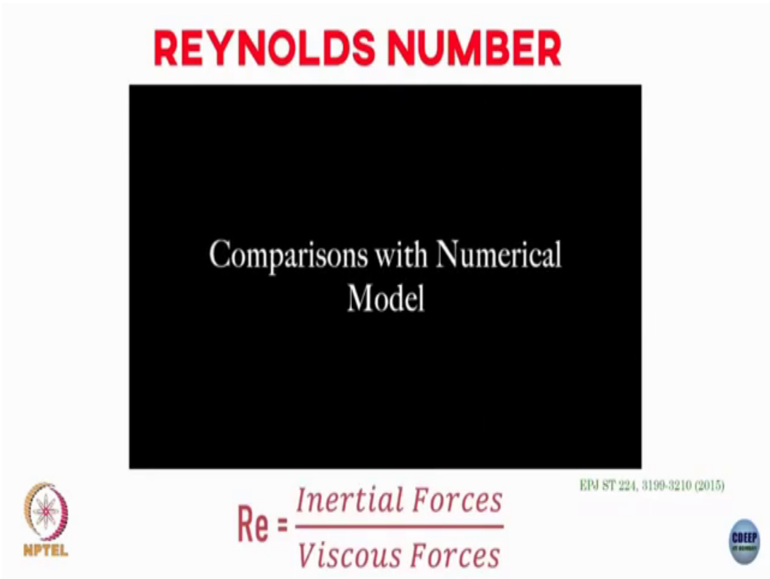

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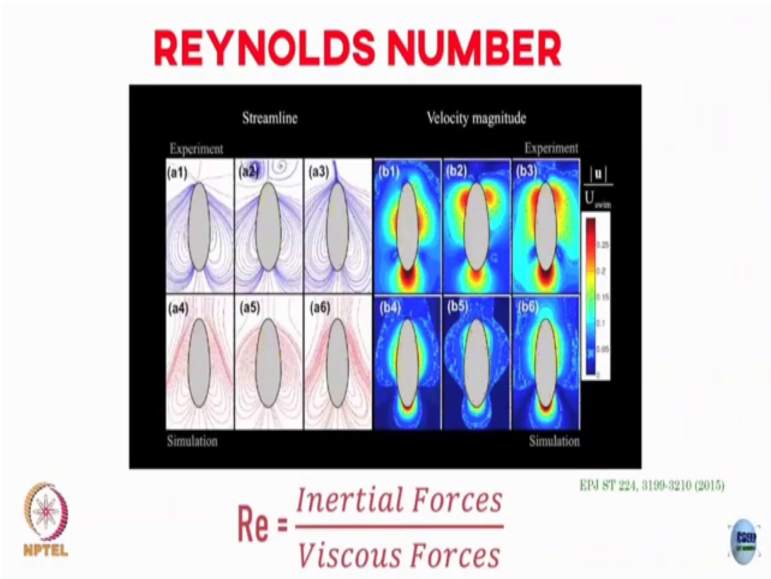

So, firstly I will try to derive that solving the Navier Stokes equation is a very difficult task in the most general case and I will explain why later on, but at least you can do some sort of numerical; you can do numerical simulations. So, this is one particular case of a paramecium which is swimming in some viscous flow. These are actual experiments where you can construct the velocity field of this paramecium as it moves; you can then solve these solve these hydrodynamic equations and you can compare with.

So, for example, let us forget the streamlines; if you look at this velocity contour map, these are the top panel are the experiments; the bottom panel are the simulations based on this Navier Stokes equation and you can reproduce the lot of the effects it lot of the observations that you see in these experiment.

So, the key sort of quantity that tells us what sort of terms will be important in this Navier Stokes equation is what is called this Reynolds number; which is a measure of how strong the inertial forces are compared to how strong the viscous forces are. And I will deal with this a lot I will go into more detail about what I mean by this after we have done the Navier Stokes equation. How many of you have done some amount of hydrodynamics before ok; continue your mechanics ok? Alright, the rest fine; so, I will do a very loose derivation.

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But it should hopefully be instructive.

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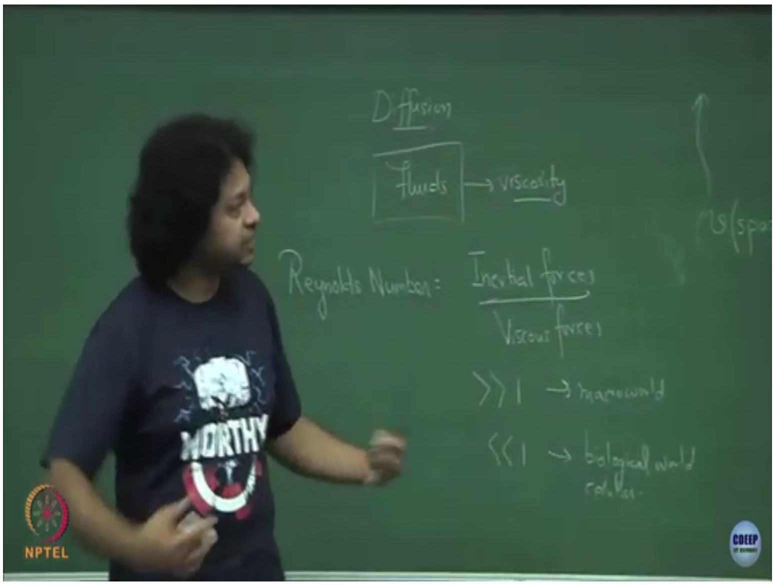

The thing is that; so we have this Reynolds number we have this Reynolds number which tells us the relative magnitude of the inertial forces; inertial forces to the viscous forces. So, if inertia dominates then you have this; if you are writing the Newton's laws of motion you would have that MDADT term which would play a dominant role.

So, the physics in the regime where inertial forces dominate is the physics of the macro world; it is the physics of Newton's laws that we are sort of more familiar with ok. So, when Reynolds number is much much larger than 1, that corresponds to the macro world in some sense and still keeping this very loose; I will make this a little more rigorous as we go along. On the other hand, if viscous forces dominate then you get to water the environment that you see is what the environment that these biological microorganisms swim in. So, this is the biological world in some sense; I should not say may be biological, I should say cellular something.

So, the scales of these microns the Reynolds numbers for this fluid flows will be turn out to be much smaller than 1. And, the physics at these scales at these low Reynolds number will look very different from the normal physics that we are more generally used ok. So, here for example, is this very famous experiment; it is called the pitch drop experiment. This is one of the world's longest running experiments it was started in 1927 and it still goes on.

The person who started the experiment has died; I think the second person is also died, somebody else is carrying on the experiment. So, this is an experiment where you just let you this person fill the jar with pitch and he allowed the pitch to drop.

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And roughly one drop of pitch falls at the rate of I think 10 to 20 years. So, every 10 to 12 years you have one drop of pitch falling from this upper conical thing to this lower beaker ok. So, in this 1927 to current today 9 drops have fallen. People are waiting to see the 10th drop which is why this website is called the 10th watch; it has a live stream where you can watch if you are completely bored out of your mind, you can go and watch nothing happened right. I think the 10th drop is scheduled to fall sometime in 20, 22 or something; if all goes according to plan.

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So, these are extremely viscous objects. So, this is pitch its; it forget what exact kind of pitch it is, but these are extremely viscous um. If you were going to travel through pitch, you can imagine as opposed to air for example, if you are trying to watch walk through a thing a medium which was this viscous is this; you might guess the strategies that we used to sort of walk around this room may not be very suitable to the strategies you would need to deploy if we were living in such an environment.

And as it turns out the biological environment is closer to this than to air. So, microorganism which is swimming inside a cell or whatever in water or something feels it is an environment is something as if its moving through this blob of pitch um. So, that is the sort of qualitative difference.

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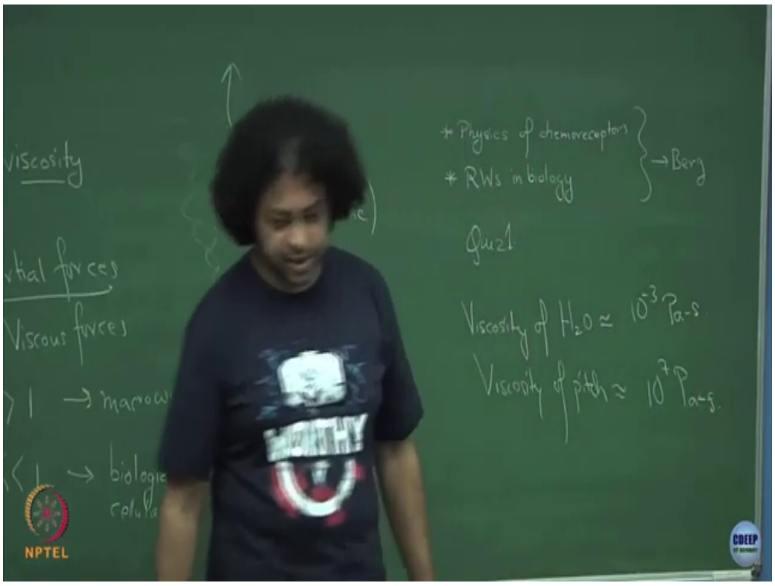

If you look at the viscosity of pitch; I think from these experiments I might be wrong say the viscosity of water; the viscosity of water is around 10 to the power of roughly around 10 to the power of minus 3 Pascal seconds. And the viscosity of this pitch that they are measured from this pitch drop experiments is something of the; if idle number correctly was something like 10 to the power of 10 times that of water; it is around 10 power 7 (Refer Time: 12:55) 7 ok.

So, these are extremely; extremely viscous it is of almost unimaginable for us to map; to think about or to contemplate about moving in environment that looks like this, but that is precisely what cells do ok. To show another fun experiment and again many of you may have seen this before.

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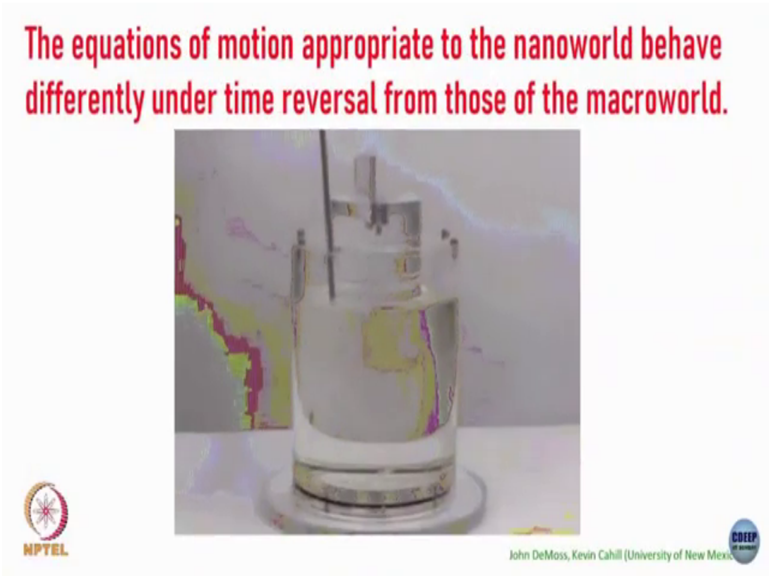

So, here is an experiment where they have a beaker filled with some viscous substance; I think this was corn syrup and the place the dye; how many of you have seen this experiment?

Student: Yes.

Good most of you. So, you place the dye in it and you rotate the inner cylinder with respect to the outer cylinder in a circular motion and so you places many dyes I think three colors so on. And as you rotates the you rotates these two cylinders with respect to one and other; what you see is an apparent mixing of these dyes as you would normally expect. So, you rotates the cylinders with respect to one another and these three colors the red, blue and the green this sort of mixed one and other; at some point he will stop and he will start to rotate it in the reverse direction ok.

So, this is the well mixed sort of limit where all the three colors apparently mixed into one and other and now he stops any (Refer Time: 14:32).

Student: (Refer Time: 14:34).

Ha.

Student: (Refer Time: 14:36).

Because they want to make sure that the forward motion and the reverse motion are as closely a opposite to one another as possible. So, they do not want to set up itself to sort of rotate; they do not want to disturb the setup itself.

He is doing it very slowly in a controlled fashion. So, as you rotate it in this reverse direction; what you will see as opposed to this normal mixing that one might be familiar with is that the colors those blobs of dyes will come back to their original position; these sort of unmixed from one and other. So, this is not something that you would expect if you were to mix, if you were to take three; this is not something that you would expect if you were to take three random drops; so dry in water and you do this no matter how we do this is in a very nice way and you reverse it you will never get this sort of a very clean on mixing.

So, what is going on here from those of you who have seen the video; is this violation of the second law of entropy?

Student: (Refer Time: 15:42).

Yes, Krishna.

Student: (Refer Time: 15:46).

Generally, I say that you know when things have mixed up together; I have increase the entropy I everything is sort of well mixed. And I would expect that the second law of thermodynamics tells me that you know once I have achieve this high entropy state I should not be able to come back to this well separate its or unmixing sort of unmixed sort of state.

So, what is the; what is going on over here? The thing that goes on is that this is not really a true mixing in that sense because this fluid is so viscous; what happens is that all this rotation does is that it stretches this blob.

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So, for example, you had this blob and you had another blob and as you rotate it; you are sort of sharing this. So, it sort of stretches this blob and it stretches this blob ok. So, it is still a single blob even in this limit where it looks like it is completely mixed; even here what you are basically done is that you have taken this blob and you have stretched it and stretched it, but it still a single blob which is not really mixed with the other dyes ok.

So, and this is possible because this is such a highly viscous liquid; then when you on mix it you are slowly reversing back the shear that you have given and eventually you will come if you do it slowly enough and controlled enough fashion; you should be able to come back to this original initial condition that you started off with ok.

So, its although it looks to be mixing this is sort of apparent mixing in that what is happening is what is called a laminar flow is called a laminar flow; where you stretched out this blob without truly mixing the different colors. So, again this is something that is characteristic of this low Reynolds number flows; it is very difficult to mix it is difficult to mix highly viscous liquids ok; it is easier to makes liquids which have low viscosity for example, ok.

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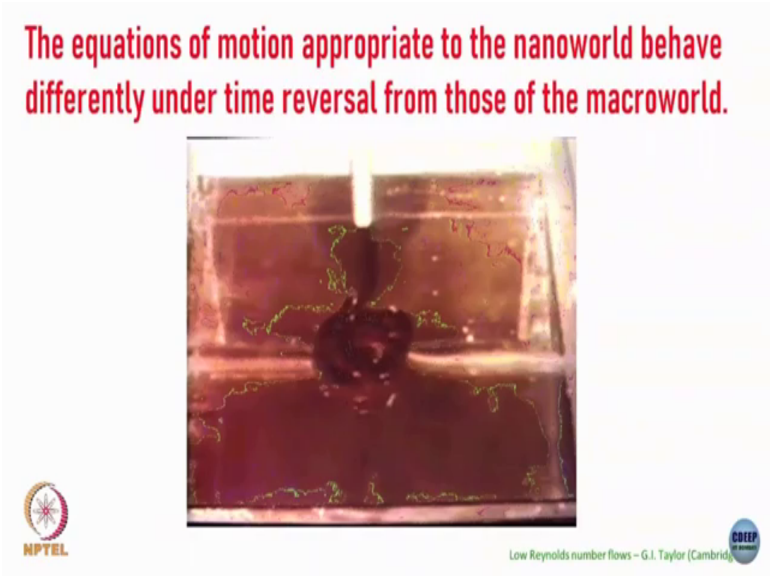

Another example this is again a very classic example done in the 1950s by this famous person called G. I. Taylor from Cambridge and this is actually small part of a movie that he has on this low Reynolds number flows; not movie, a documentary let us say; it is an hour long documentary you can watch it if you are interested.

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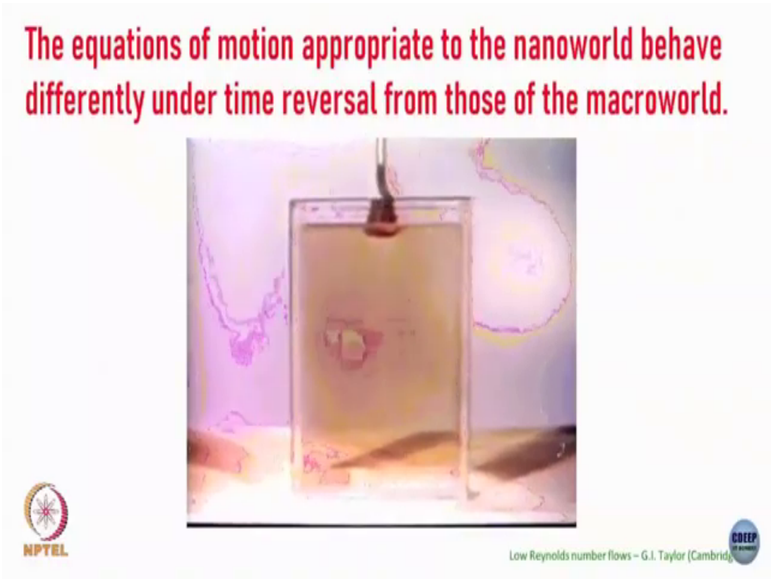

So, here is again a dye which is being injected into a syrah ok; this is again a very highly viscous syrah because the viscosity is so high; the dye does not even penetrates too. So, generally if I just put it would get mixed, but because this viscosity is so high and or rather what is the more relevant quantity is this Reynolds number; the Reynolds number for this is very low; this dye does not mix it all, it sort of gets into this blob and just sits there ok.

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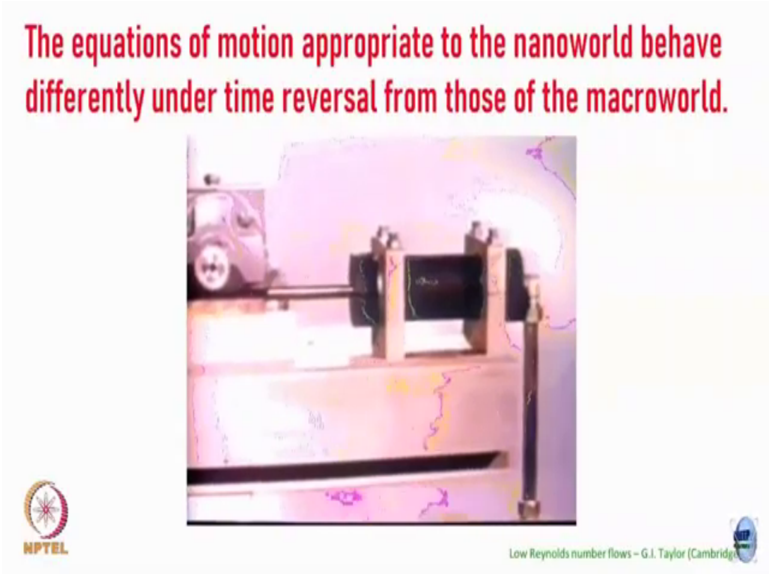

So, this is I am sorry for the quality; so this is the syrup, then he has a bunch of other beakers which has glycerine which is slightly; which is slightly higher Reynolds number. So, the Reynolds number is Reynolds number of syrup is smaller than the Reynolds number of glycerine which is the second beaker.

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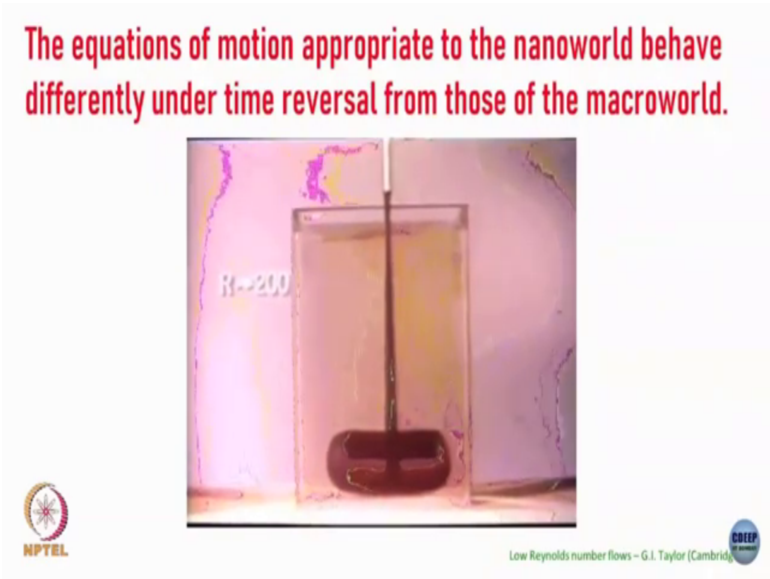

And then I think he has glycerine plus water glycerine plus water and that the fourth beaker has water. So, this is the lowest Reynolds number; this is the third law right yeah; so, this is glycerine plus water where it sort of penetrates the whole depth, but it does not really disperse and this is a Reynolds number of around 200. Again, I will come to what this Reynolds number is exact definition, but this is a higher Reynolds number than this glycerine.

And finally, he will do it for water which has even higher Reynolds number and this is something that we would expect based on a normal macro world sort of an experience ok. You throw in a jet it sort of gets turbulent; it mixes almost immediately.

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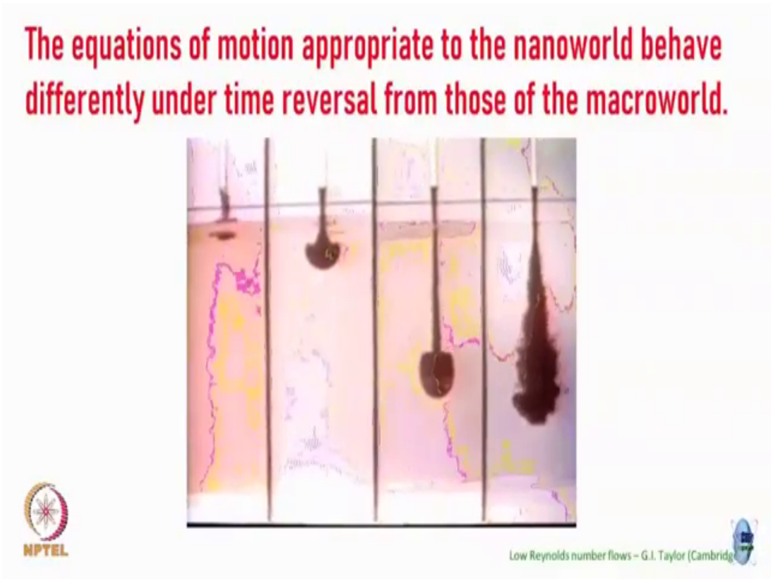

So, it depending on the viscosity of the fluid or more accurately depending on the Reynolds number of; so which depends on the velocity as well as the size of this of this jet you will get mixing two completely different aspects.

So, if you would simply look at the movie over here and this movie for corn syrup was this movie for water; you would say that the physics that is going on is very different in these two cases right. And that is what we will sort of try to quantify as we go along that what are the terms in this Navier Stokes equation that will dominate the description of this corn syrup versus what are the terms that will dominate the description of this water.

Student: (Refer Time: 20:37).

Student: Why is the (Refer Time: 20:39).

Why is the?

Student: (Refer Time: 20:42).

This one? So, this is because I am not really very sure, but it also as it sort of accumulates; it also exert some force back because of this viscous friction. So, it has not fallen a large enough amount and the exert some force back that force is not necessarily perpendicular to the surface. So, that; so I would assume; so this is a guess I would assume that sort of plays a role in the fact that that over there, but it does not penetrate a lot; it seems to go a bit wobbly over there.

But at the nozzles; so basically he controls the experiment such that at the nozzle the velocity is exactly the same; for then the for all the four cases and the nozzle is also of exactly the same radius in all the four cases. So, the initial conditions for this dye are exactly the same; all that differs this liquid.