Cellular Biophysics

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Measuring Viscosity

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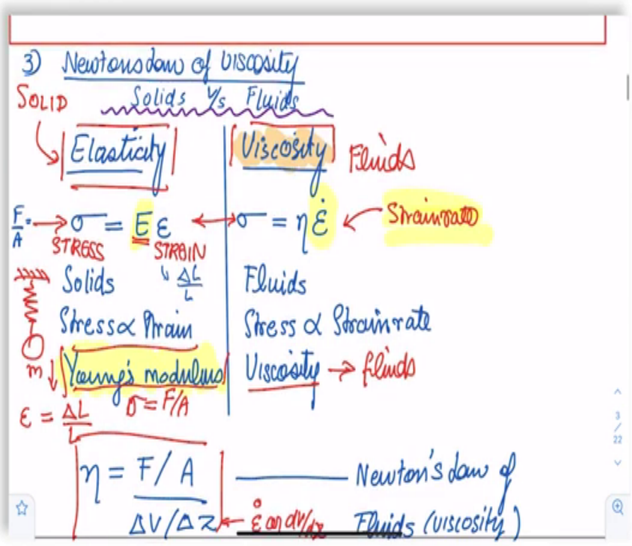

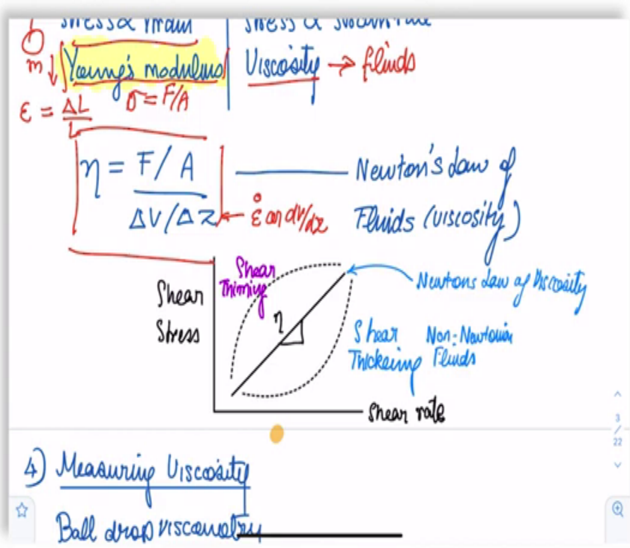

So, I want to return to the question of 'What comparison between solids and liquids phase and we talked about this earlier too. And indeed one can put these two things side by side and ask a simple question about solids and fluids. So, if you look at solids, we know, once again high school that you probably remember, that elasticity of a solid is linearly, is measured by a proportionality constant. You are familiar with Young's modulus and it relates the stress with the strain.

What is stress? Stress is nothing but the term F by A and strain is the relative deformation. If you recall when you have a spring with mass, then the strain is simply the change in length upon the length and stress is force acting per unit area. What about fluids? So, in fluids we require that viscosity is not related to strain but strain rate and this is something important. In other words, the rate of change of deformation is what we are measuring as a proportionality constant with viscosity.

So, this in some sense with a contrast between Newton's law of viscosity and the Young's modulus which relates stress with strain for solids. The reason we bringing Newton's law is that if you plot a shear rate or strain rate on the x axis or shear stress or stress on the y axis, then the proportionality constant eta is nothing but the slope of this line. However, there are fluids that deviate from this, and either the increasing shear rate needs to be a very rapid and saturating value of shear stress or it leads to a slow one.

And depending on that they are either of the two, shear thinning or shear thickening. And these indeed are deviations from Newton's law of viscosity and therefore, get referred to as Non-Newtonian Fluids. So, this is the average behavior, the standard behavior. And these deviations are then used to define what are called Non-Newtonians Fluids.

$$\eta = \frac{F/A}{\Delta v/\Delta z}$$

Just to remind ourselves, eta is F by A upon delta v by delta z, in other words, the stress upon the shear gradient, or the velocity gradient or shear rate.

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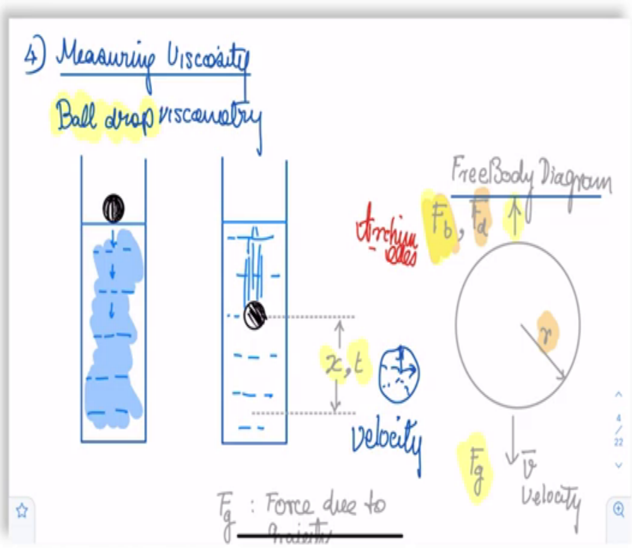
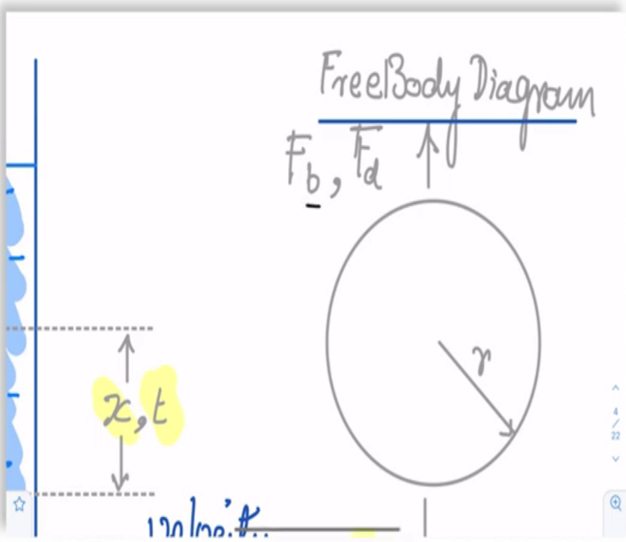
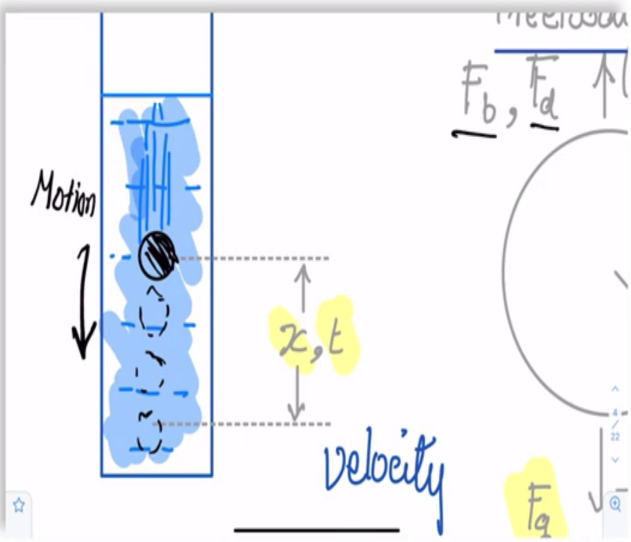
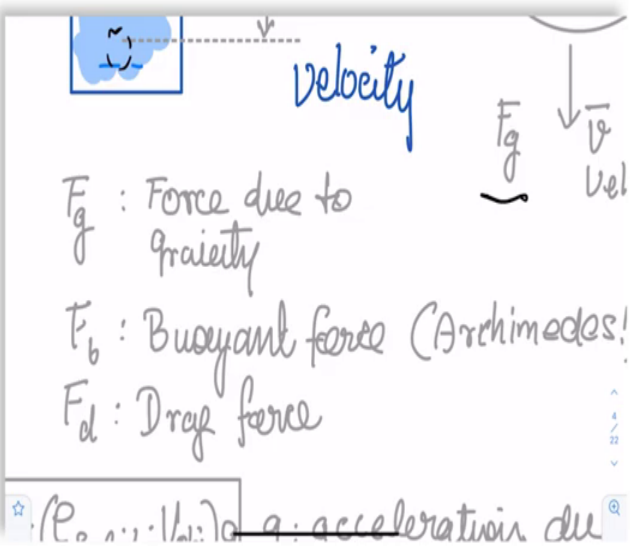
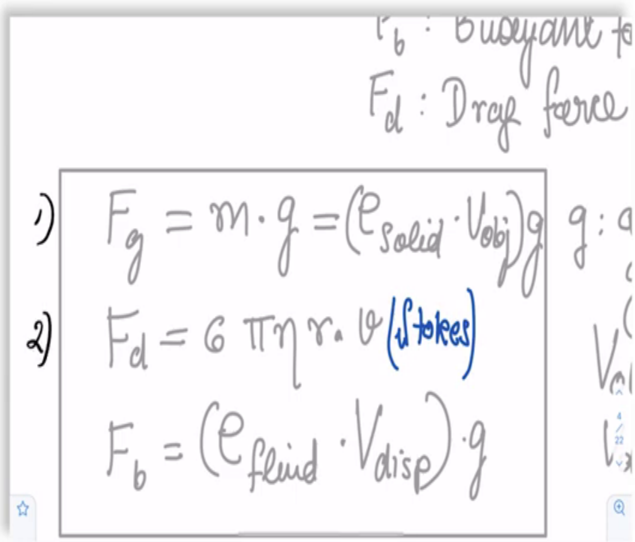
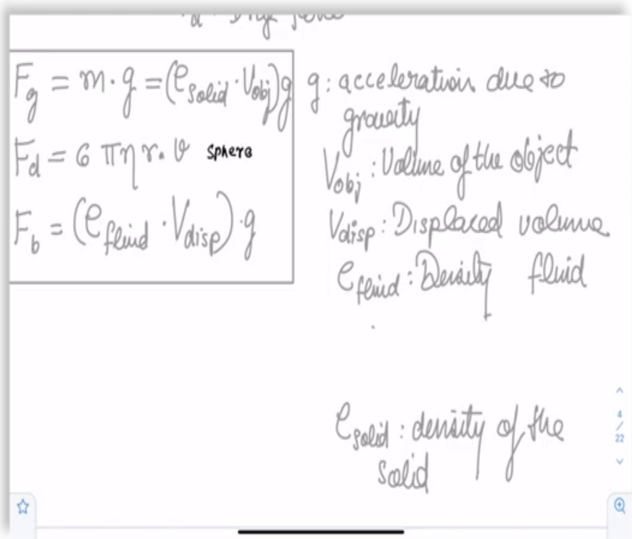



Free Body Diagram
F_b, F_d
x, t
r


Motion
F_b, F_d
x, t
Velocity
F_g


Velocity
F_g
$\bar{v}$
F_g : Force due to gravity
F_b : Buoyant force (Archimedes!
F_d : Drag force





So, I am going to sort of come back to this question of Non-Newtonian Fluids later and ask if a material is Newtonian, if it is behaving according to the standard laws then how do we measure viscosity. This is a very exciting question because after all the theories of the world are very nice, we cannot however, test them and measure them then how do we know. And one instrument, a very simple, conceptually simple instrument that is used to measure viscosity is called a ball drop viscometer and the methods is called ball drop viscometry.

As the name suggests it involves dropping a ball through a long column of the bridge, so this is your sort of fluid column here, and when you leave a ball at a point above the fluid, this one here, it is expected to fall into the fluid, it is normal expectation. So, as the ball falls through the fluid, as we know from our common experience it will increase initially in velocity and then reach a terminal velocity, meaning to say constant velocity where velocity does not change any more.

This is also if you remember your common experience with dropping a ball or throwing a ball into the air and it falling down again because gravity remember is ubiquitous on planet Earth. So, if you draw a Free body diagram which means we ask what all are the forces acting on the ball, then we expect that the ball of radius r will experience a point force that is Fb, and a drag force Fd, opposing the motion. Motion remember this way the ball is falling and overtime eventually it will get to bottom.

Obviously for this experiment to work we have to take a ball that is heavy enough. At the same time what is taking it down? This is also fairly obvious to us, is the gravitational force, which can be called Fg, and the motion is at a velocity. So, we have three forces acting on our ball, force due to gravity, Buoyant force or Archimedes force, remember Archimedes principle and drag force.

For those of you do not remember Archimedes principle please go back and look. This is brilliant ancient wisdom and by ancient wisdom I mean, the laws that ancient wisdom gave us can be written down in the simple form of an equation and that simple equation, it does not matter whether you are Greek, Archimedes was a Greek, or Hindi or Indian, Indus Valley Civilization, Egyptian, Arabic mathematician or scholar in Italy in Galileo's laboratory, the laws are still universal. This is the beauty of science, is not it?

So, the gravitational force is just simply F is equal to m g. M is your mass of the object, and g is the gravitational acceleration. Mass itself as you recall can be written in terms of density times the volume, so you have this first term, Fg is the product of the density of the solid, volume of the object and the gravitational acceleration. What about the drag force, what I called the Stokes force?

So, we call it Stokes force party because George Stokes has work the rise to this equation, for a spherical object, we can indeed say that the drag force is equal to 6 π η r. And finally Archimedes force, the Buoyant force, this is the reason why we float. Those of you who like swimming, you may go to a swimming pool or you take a ball and throw it on the top of water, not a cricket ball, that will sink, but a basketball or a volleyball or even simpler a child's plastic ball filled with air, it will float.

The reason why it floats or sinks like the cricket ball is because of this equation, number three, which is that the Buoyant force is equal to the density of the fluid times the volume displaced times the gravitational acceleration. You remember Archimedes principle was based on the volume displaced. And the fact that it depended on the density of the material which he used to decide whether the crown of the thing of Sicily was made of gold or had any additives.

Just to go over our terms, g is gravitation acceleration, v object is volume of the object, v displace is the volume of the displaced, fluid, ρ fluid density of the fluid g acceleration, this has come twice, we can get rid of it and ρ is the density of the solid.

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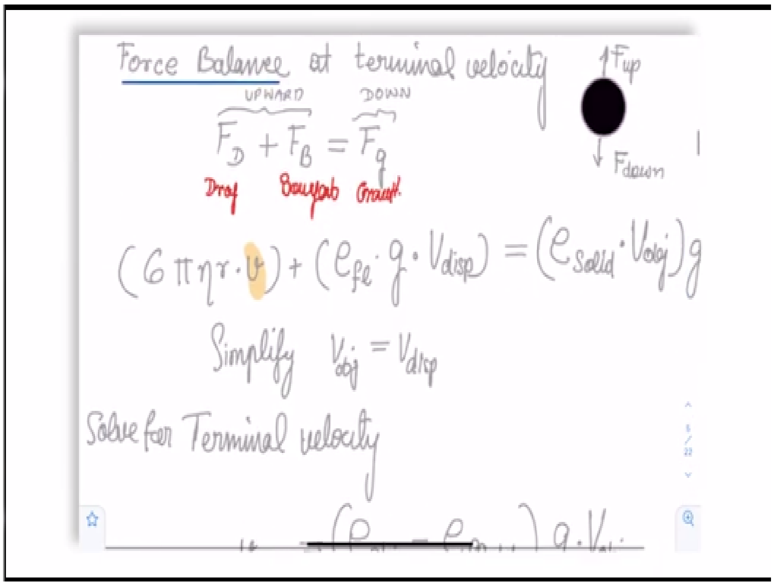

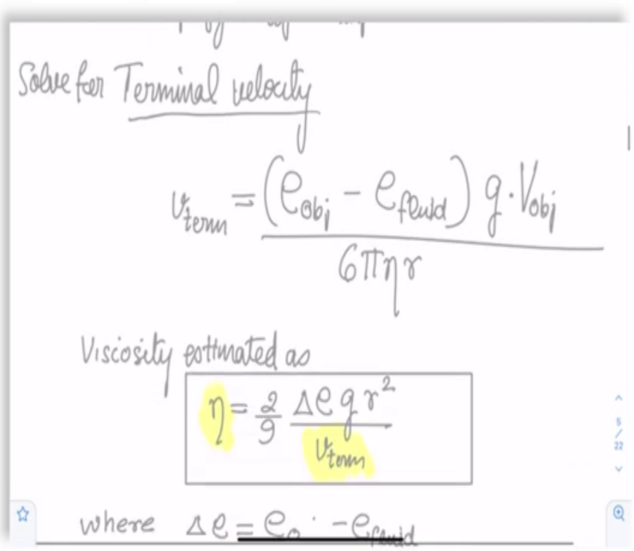

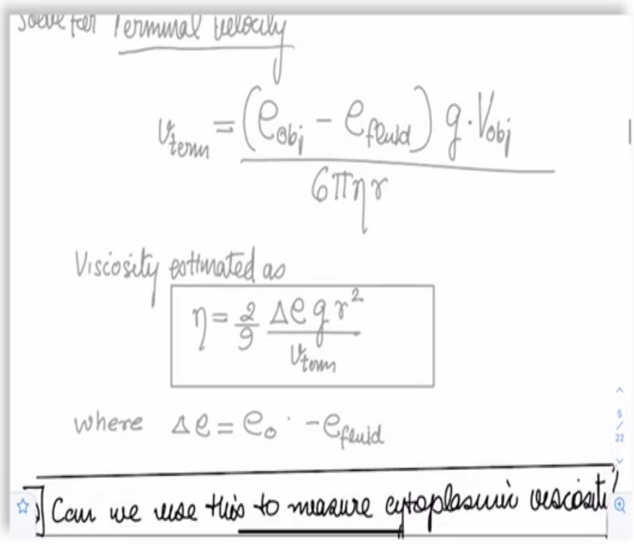

So, when we go ahead, we can write down the force balance at terminal velocity, what this means is just simply that at the time of the terminal velocity, the downward forces and the upwards forces are balanced. We call this force upwards and force downwards and therefore we can equate them, remember these are all the upward forces, the drag and Buoyant force and this is the only downward force but sufficient to take it down, the gravitational force.

Now, substituting equation 1, 2, 3 into this equation we get 6 π η r v F_d, Buoyant force being ρ fluid times gravitational acceleration times v displaced and the gravitational force being ρ solid times the object times g. We simplify by assuming that the volume displaced is corresponding to the volume of the object. In that case, when we solved for the velocity term which is what we are interested in, namely this one here, then we get a term for the terminal velocity.

This terminal velocity then becomes the difference between the object density and the fluid density as you know again familiar to your perhaps, times the gravitational acceleration g times the object upon 6 π η r. Now, remember we wanted to estimate viscosity, so we rearranged terms and we get this. We get eta is equal to 2 by 9 into delta ρ, the difference between the object and the fluid viscosity, density, into g into r square upon terminal velocity.

Important to note that at this point we can measure experimentally or know in advanced the density of the object, let us say we take a steel balance, this is well known. We know the density of the fluid, because we can measure weight for unit volume that is what density means. We know gravitation acceleration thanks to almost 200 years of physics.

We know the size of the object that gives us a r square and doing the experiment we can estimate the terminal velocity, which means, after we do the experiment and we know these parameters, we can find out the viscosity of the fluid. Wonderful, correct? Such a simple experiment, just let a ball fall in a long column of fluids, let is reach its terminal velocity, measure the velocity, substitute the values, and you get viscosity.

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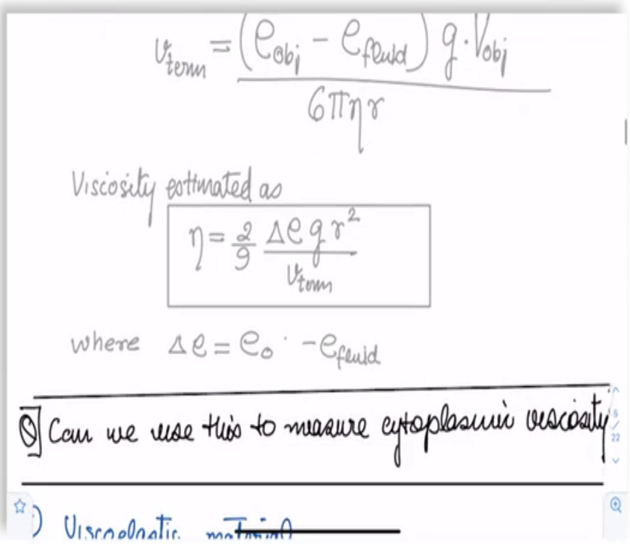

So, let us ask the next question which is ‘Can we use this to measure cytoplasmic viscosity?’ And again I have to ask you to be a little patient, and we will come back to it after we have covered some more concepts.