Engineering Mechanics
Prof. K. Ramesh
Department of Applied Mechanics
Indian Institute of Technology, Madras

Module – 01
Statics
Lecture - 18
Friction - I

Let us move on to our next chapter on Friction. See in common usage of the word friction even in the relationship when we say if there is friction, we use it in a negative connotation, we are not using in a positive connotation. If you ask the question whether friction is a bane or a boon you find friction is needed in certain applications.

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Even for you to walk you need friction I have shown it on a glass floor if somebody walks, you have to walk very carefully that is what you see here without friction you cannot walk.

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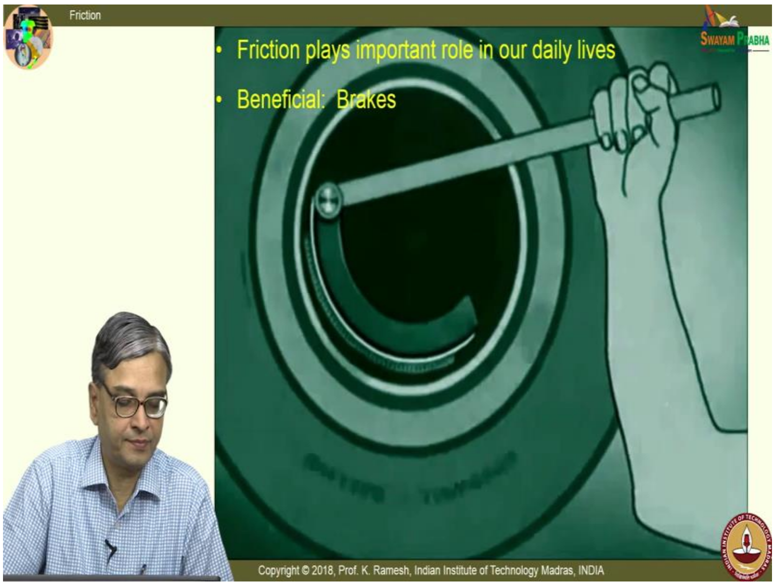
And if you go to well simple 'atta chakki' this is driven by belt drives and these belt drives employee friction; so, in such applications friction is beneficial.



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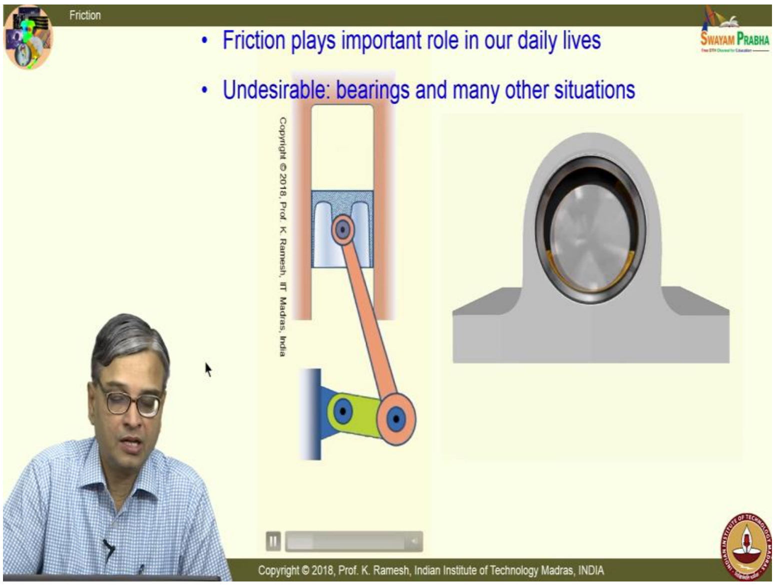
Friction is also a beneficial in another application that deals with braking system. So, when you apply the break because of the friction the wheel comes to a stop. So, there are many applications where friction is needed for our own good.



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There are also many other situations where friction is undesirable you know lots of money spent on lubrication. This is the IC engine which is used in automobiles and you have millions of automobiles, they all use oil to minimize the friction between the cylinder and the piston, and you also have several applications of general bearing where oil separates metal to metal contact between the shaft and the bearing.

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And if you go and see a machine in the workshop you would see lot of oil is used to lubricate the systems involve and here you also have a system where this is pumped like this and you have a worm and worm wheel that assembly is literally flooded with oil to remove the frictional effects this is one example. You also have another example, this is a quick return mechanism of a shaper is literally in oil, it is a pool of oil here. We will also have an occasion to solve this quick return mechanism when we see dynamics. So, in all these applications you find you need to minimize the effect of friction. So, you achieve this by having a medium of oil to solve your frictional issues.

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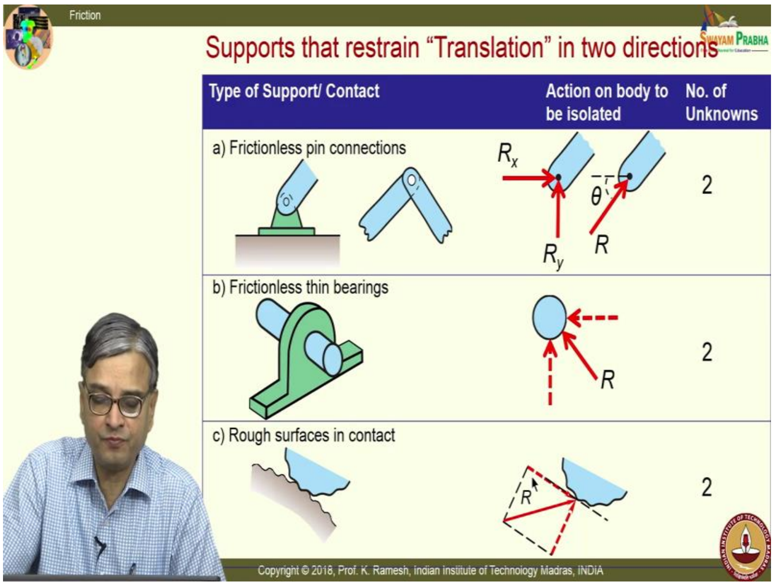
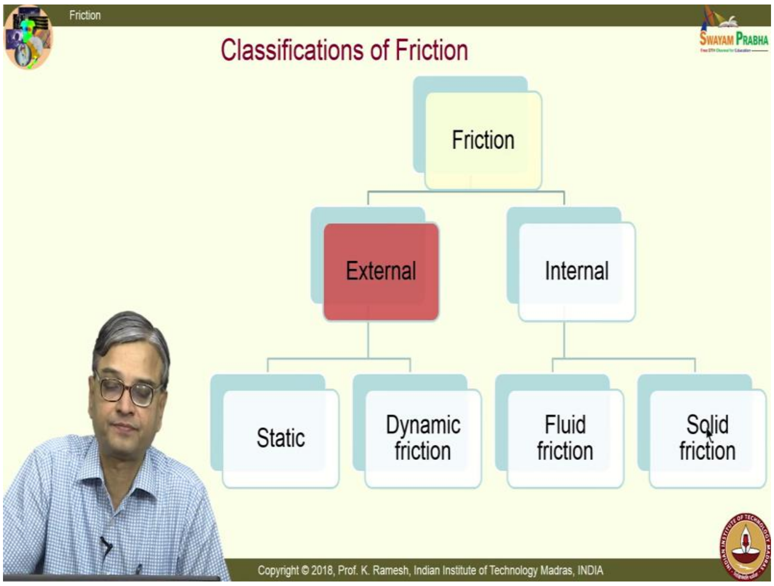
And we have also seen earlier when we studied support conditions when I have a pin joint it restrains translation in two directions and you have two reactions the force is unknown and the direction is unknown. So, you have essentially two unknowns. We also saw frictionless thin bearings, here again the direction as well as the magnitude are not known you have two unknowns.



Extending this you have in the case of rough surfaces in contact, the rough surfaces are shown highly exaggerated. You have two forces a normal force and a frictional force. In all problems dealing with friction one of the challenges is to find out what is the actual direction of the frictional force.

And from the loss of dry friction when the motion is impending; it is possible for you to write the frictional force from the equations of friction. In all other cases you will have to determine these forces only based on the free body diagram of the component under consideration which we will emphasize and see later also.



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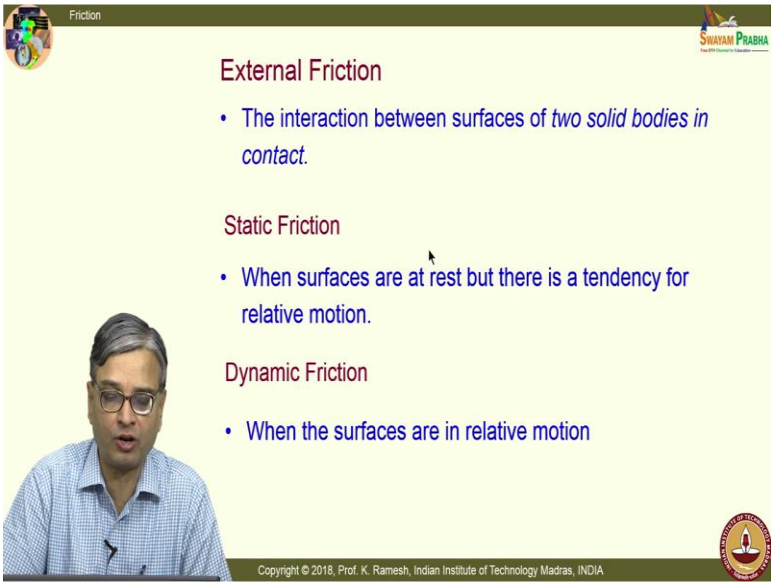
And what are the classifications of friction it can be broadly classified as external and internal. In external friction I will have static friction I will as also have dynamic friction and internal friction I have fluid friction as well as solid friction.



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What you call as external friction? The interaction between surfaces of two solid bodies in contact, this can be static friction or dynamic friction. In static friction, the surfaces are at rest, but there is a tendency for relative motion. See only when there is a tendency for relative motion frictional forces come into play, until then frictional forces do not come into play. And in dynamic friction, the surfaces are in relative motion.

See in earlier books you would also find the term called kinetic friction, the current practice is to do away with kinetic friction and embody all that what we have discuss under the ambit of kinetic friction as dynamic friction that is the new terminology that is accepted.

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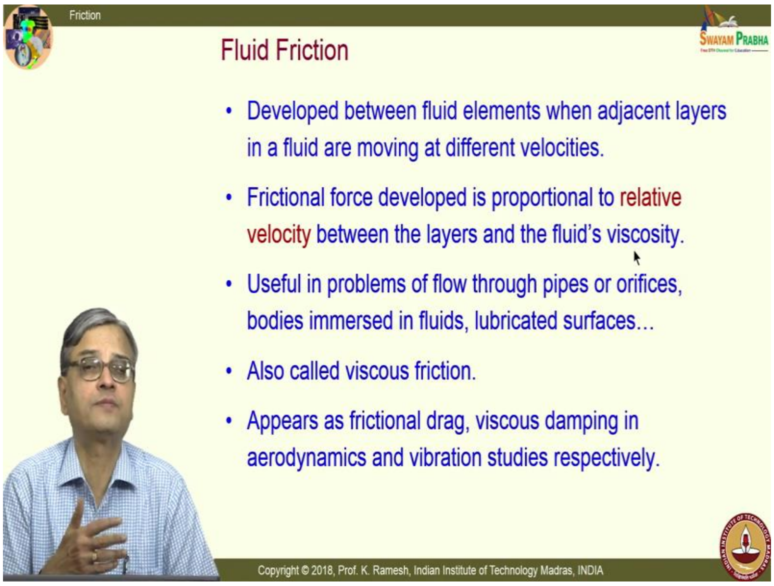


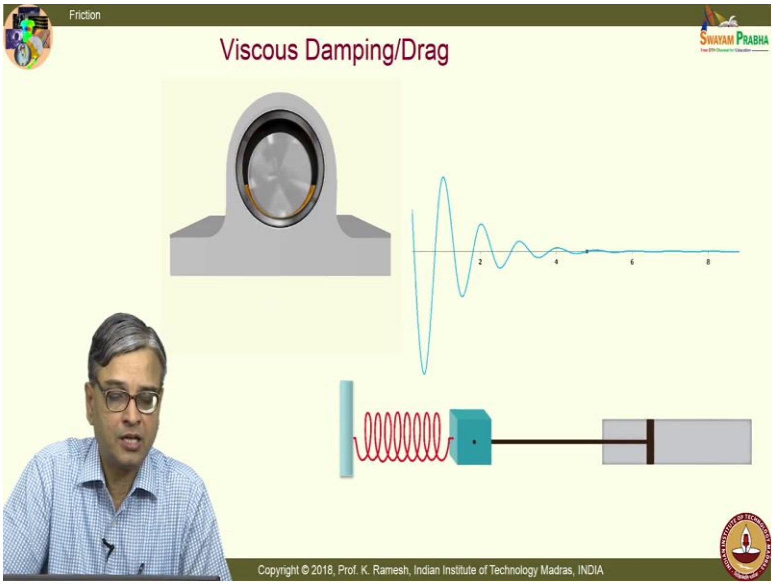
And before we get into the details of external friction let us have some brief discussion on fluid friction as well as solid friction. This is developed between fluid elements when adjacent layers in a fluid are moving at different velocities. This is possible only when you have the metal to metal contact is completely separated by your lubricating oil.

And what is interesting here is the frictional force developed is proportional to the relative velocity between the layers and the fluids viscosity. It is also interesting to note in your course related to physics you are already exposed to certain aspects of friction and you might have also heard the frictional force is proportional to the normal reaction. From Newton's third law you also learnt force is proportional to the acceleration related to the acceleration. So, in a case of a dry friction you find the frictional force is directly proportional to the acceleration.

In the case of fluid friction, it is proportional to relative velocity and we would see later in the case of solid friction the frictional force is related to displacement this is very interesting. And fluid friction is useful in problems of flow through pipes or orifices, bodies immersed in fluids, lubricated surfaces and so on this is also called viscous friction.

And you know fluid friction appears as a frictional drag which is seen in the design of a automobiles and India is also going in for a high-speed train, if you look at the stream lined body counter of the engine, this is essentially done to minimize the frictional drag.

And also, in the case of sports, if you look at the cycling in Olympics the participants are competing with each other and they can have an edge over the competitor if he or she wears an appropriate clothing. The dress is design based on frictional aspects and if they reduce the frictional drag from that they may have an edge of the order of 0.1 one seconds compare to the competitors.



And another interesting aspect is in the case of vibration studies, you use the damping as viscous damping and this is also used in aerodynamics the frictional drag in the as frictional drag in aerodynamics and as viscous damping in vibration studies.

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And this is what you see here in the vibration study I have a spring and dash pot, and dash pot has viscous fluid and you find the amplitudes reduce rapidly because of the viscous damper. And this is the case of a shaft running in a general bearing completely separated by a fluid film and this develops a maximum pressure slightly to the left. This is where it develops a maximum pressure; there is no metal to metal contact, fluid completely separates it.

In such a case in well lubricated applications you have to employ only fluid friction for analysis that is what is again seen here, I have the lubricating oil is pumped on to this you find this is the contact point where you have a flood of a viscous oil. So, in this has to be analyzed based on fluid friction you also have the other application. This is the quick return mechanism of a shaper; this is almost in a bath of the oil.

In fact, it is a very big subject by itself tribology is a name of the subject and you have engineers who have trained how to circulate the viscous oil to all the components in the engine, and with space application how to handle microgravity; zero gravity applications are also becoming very important. You also have journals that deal with where so, it is not a trivial aspect one has to handle friction very very carefully.

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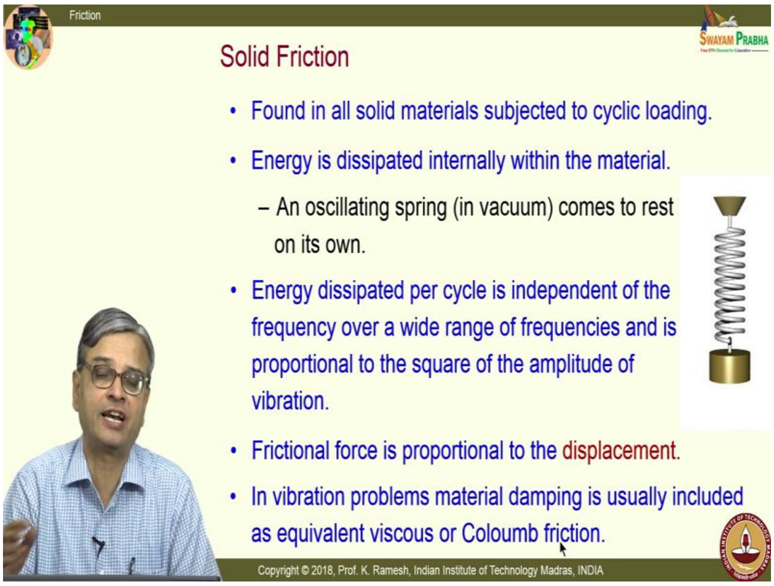

And it is also surprising when solid materials are subjected to cyclic loading one comes across the impact of solid friction. Energy is dissipated internally within the material that is why it comes under the category of internal friction. For example, if you put an oscillating spring in vacuum it comes to rest on its own, the moment you put it in vacuum you make sure that there is no frictional drag because of the surrounding air. So, that is eliminated when there is no retarding effect visibly you imagine if you disturb the spring it would continue forever it does not happen.

Even in vacuum this spring comes to rest and the energy dissipated per cycle is independent of the frequency over a wide range of frequencies and is proportional to the square of the amplitude of vibration. So, it is interesting to note frictional force is proportional to the displacement, this is what I mentioned you also earlier; in one case frictional force is proportional to displacement, in another case frictional force is proportional to relative velocity. In the case which you normally come across frictional force is proportional to the accelerations. So, you have all the three possibilities.

And this spring comes to rest after a long period of time and in vibration problems material damping is usually included as equivalent viscous or Coloumb friction. Either it is related in terms of fluid friction or it is related in terms of dry friction to simplify the analysis. See even in friction experiments are played a very important role in understanding the concepts.

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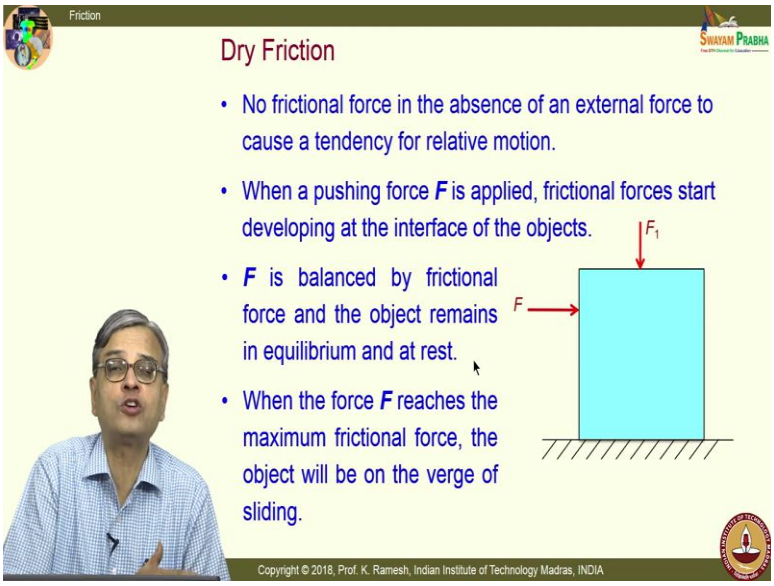
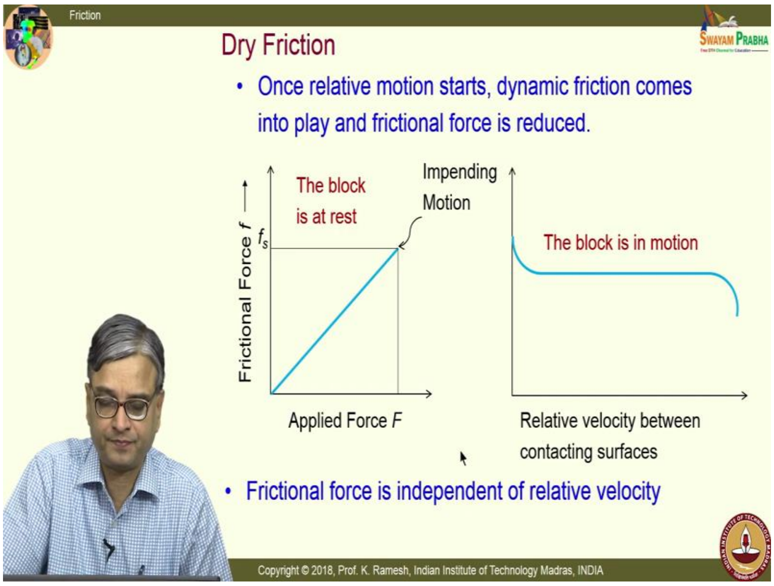
Let us get on to dry friction. Suppose, I have a block and I have a force F_1 acting on it; are frictional force is developed? Frictional forces are not developed. In the absence of an external force to cross a tendency for relative motion no frictional forces are developed, only when a force which is try to dislodge when there is a relative motion possible between these two surfaces you have frictional force is developed.



And frictional forces are developed and the object continuous to remain rest until the force applied reaches a threshold value; this is a common experience I have a table in front of me. Suppose, I want to push this table common experience is you go and try to push it, after you apply sufficient amount of force suddenly you find the table picks up an acceleration and it also becomes easier for you to push it further. And when the F reaches the maximum frictional force, the object will be on the verge of sliding.



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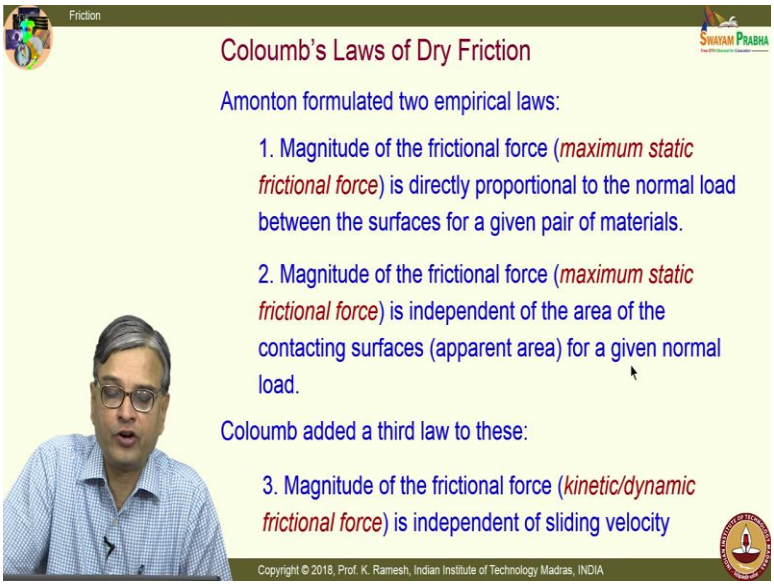
And this is what put in the graph it is plotted between applied force and the frictional force. It is remains linear as the applied force is increased frictional force is also increase, it cannot indefinitely increase it reaches a maximum value dictated by the frictional coefficient between the surfaces. And this happens reaches a maximum value when the motion is impending; that means, if the forces are slightly increased further the block or the object will tend to move.

Under this situation, the block is at rest; suppose, I increase the force you also plot between relative motion starts when I increase the force, dynamic friction comes into play and frictional force is reduced. This is the common feeling experience, if you take a if you have to push a table you find at some point in time you have reach the maximum force.

Then the block or the table whichever you are trying to push picks up an acceleration, why it picks up an acceleration? There is a drop in the force there is documented in the form of a graph like this. There is a reduction after that it remains constant it is also an idealization; frictional force is independent of relative velocity up to a limit beyond that there are changes it drops down.



And in this situation the block is in motion, it is always desirable that you plot this graph as two graphs as it is shown in this slide. Because the first graph is between applied force and the frictional force, second graph is between relative velocity between a contacting surfaces and frictional force. Many books simply combined these two as one graph which is strictly not correct.

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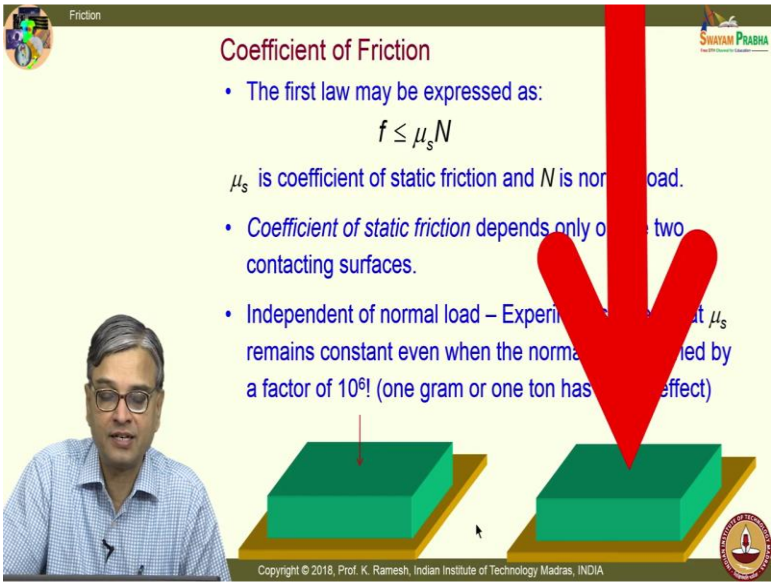
And what are Coloumb's laws of dry friction, though they are attributed to the scientist Coloumb the first two laws are formulated by another scientist call Amonton and these are based on experimental observations they are empirical laws.

And the law states magnitude of a frictional force is directly proportional to the normal load between the surfaces for a given pair of materials what you need to understand is the coefficient of friction is always given for a pair of materials it is not given for one single material. Between the two materials what is the coefficient of friction and what is said here is magnitude of the frictional force when we mean, we mean the maximum static frictional force.

And the second law is this maximum static frictional force is independent of the area of the contacting surfaces which is known as an apparent area for a given normal load. It is a very subtle point because normally you associate when you bring in you are intuition if I have a larger object it has a larger surface, you may think that it would offer larger resistance because of friction this is not so, we will also see some of the details as we go by.



To these two laws Coloumb added a third law which says magnitude of the frictional force when we say this, we always mean the maximum static frictional force when the object is at rest and the object is moving kinetic or dynamic frictional force is independent of sliding velocity. This is an experimental observation we also have situations where this is violated and what happens in such a case.

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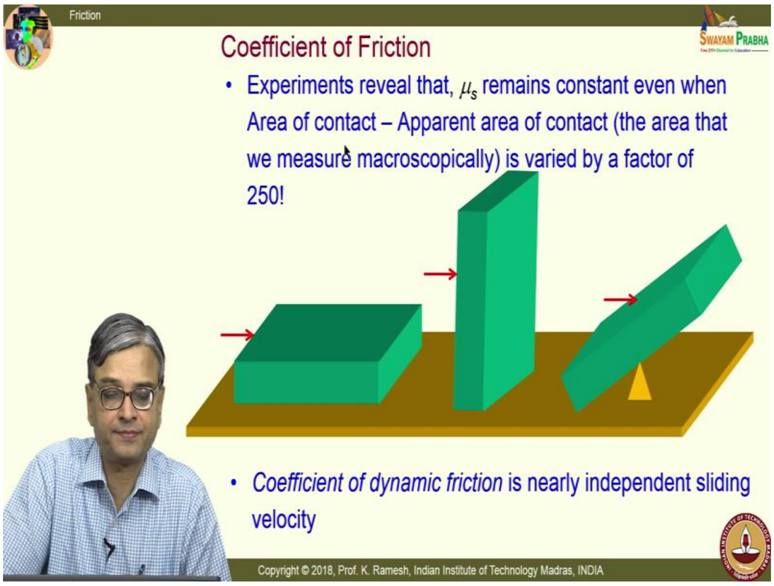
The first law maybe expressed simply as the frictional force is $f \le \mu_s N$. Please note down the mathematical inequality written here normally, people write this equal to μ_s N, but you should recognize from the way we have learnt what happens when the frictional forces are developed. In the initial stages, the frictional forces are dictated by the conditions of equilibrium and it reaches a threshold value when the motion is impending, when there is impending motion takes place only at that condition, I have $f \le \mu_s N$.

This is the coefficient of static friction that is by the symbol s is used and *N* is the normal load and you should note here when I want to denote this as a force. These are written in terms of italic font one may confuse this with the Newton as the force unit that is always written as a normal font without this italic so, see the distinction. And you know it depends only on the two contacting surfaces I have one surface shown as in this color another surface in this color.

Suppose, I apply a smaller load here and I apply a larger load here. The experiments reveal even if the load is varied by a factor of 10^6, the force is shown by a thin arrow indicating 1 gram of load and this is shown by a very thick arrow indicating one ton separated by a factor of 10^6. The coefficient of static friction between the surfaces in both the cases remain same they do not have a change.



And this is based on experiments; without experiments one can never appreciate this concept, intuitively may feel more frictional forces would be developed, but the coefficient of static friction that remain same that does not change. So, that you will have to make a distinction μ_s is independent of the normal load.

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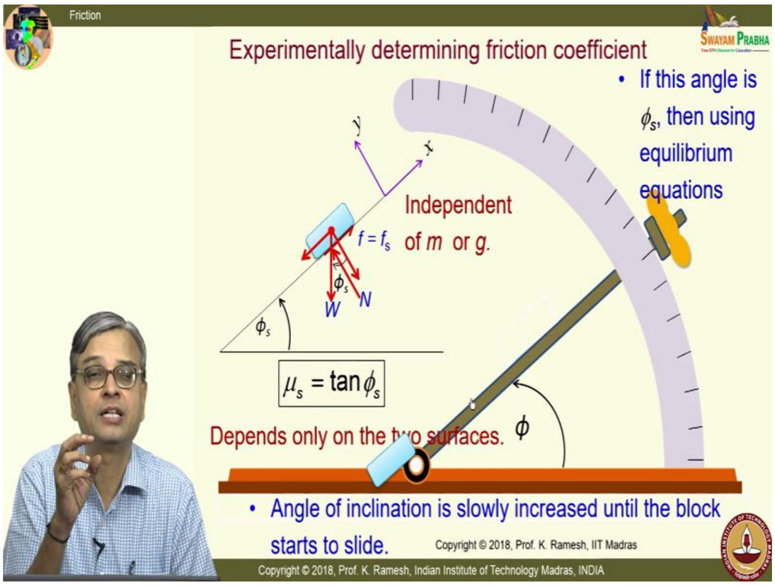
And another aspect is experiments also reveal that μ_s remains constant even when area of contact is varied by a factor of 250 times. What we normally see is only is an apparent area where is nothing but the area that we measure macroscopically And I show an example here I have the surface on this I have an object supported on a knife edge, I apply a force to displace this and I have another situation where the block is resting on an one of the edges, the third situation where the block is resting on an edge like this. In all the three cases the coefficient of static friction remains same; it does not change at all. The experiments reveal, if the apparent area is increased by 250 times there is no change is observed.

For all practical purposes we can take that this is independent of the area of contact and also the load that is acting on the object. On a similar way we also find coefficient of dynamic friction is nearly independent of sliding velocity and what is the best way to find out the coefficient of static friction. We would see a demonstration and we will also see that by in animation.

See one of the simplest experimental methods to find out the coefficient of friction is the inclined plane. In this you make the plane made of one material or you put the material for which you have to find out the frictional coefficient as the base. Then you have a sample in this case, I want to find out of the same material I have a block made of this I put it on this and slowly increase the orientation and find out at what angle the block slips. What is the angle? 22^o ok. Now, I have the same block instead of putting it like this, let me put it this way the surface area is less and this also happens more or less at the similar angle. So, this indicates that surface area has no role to play on determining the coefficient of friction and if I have to find out for another material I have this is aluminium, I put the aluminium here and rise it and slowly rise it and you have to see at what angle this slips, its slips at angle 26^o.

This is happening at an angle 26^o. And what you have to appreciate here is you have to appreciate that the motion is impending only at a stage where this is about the slip if I slightly rise the plank it will start slipping. So, you have to correctly identify that portion that position and you have to employ that for applying your frictional laws. When I say frictional force is proportional to μN, it happens only when the motion is impending that is very important to see. The first case I have Perspex on Perspex, the frictional it is very smooth I have a smaller angle that is about 22^o and for aluminum between aluminum and Perspex it is found to be 26^o.



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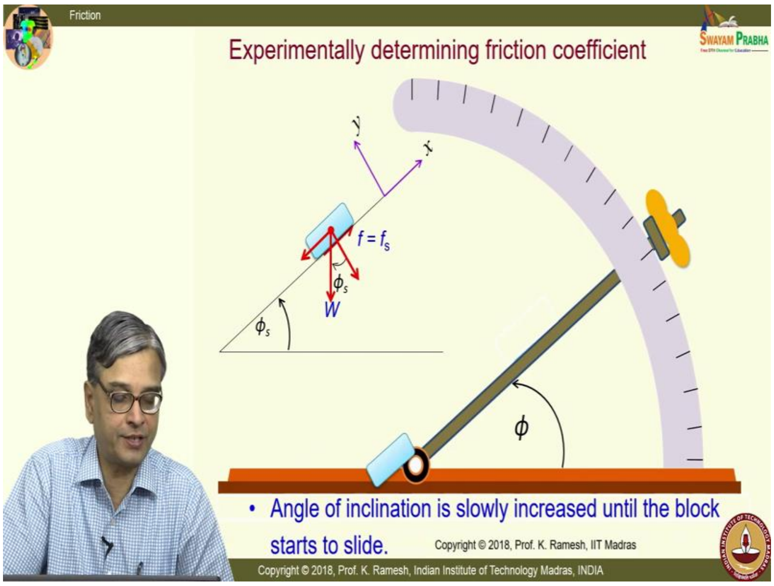
So, now I have this animation and you find the block is sliding I will repeat this animation again. And what is drawn here is I have the free body diagram of the block weight is acting downwards, friction is opposing the motion and your normal force is shown slightly displace is a good practice to put in this way. And from this experiment, if we measure the angle at which the block is about to slide you call that as angle φ_s which is known as a friction angle based on the equilibrium equation. This is related to the coefficient of static friction as $\mu_s = \tan\phi_s$.

I will repeat this animation. The important point what I want to see is if I displace slightly at the stage the block slides. So, you have to understand what is the meaning of impending motion only when slight angle is modified the block is going to slide that moment is impending. You know in the game of tug of war when you are pulling the rope when the rope is about to slide out of your hands; that is the time the motion is impending and you should know how to identify whether the motion is impending or not. You understand whether the motion is impending only the actual slipping takes place.

But we are talking about the situation where slipping has not taken place, but any slight modification with precipitator sliding of the objects concerned.



So, that is what is illustrated in this. And when you look at the mathematics, I get the expression $\mu_s = \tan\phi_s$, this is not dependent on the mass *m* or the force of gravity *g*; acceleration due to gravity g, it is not a function of these two and in fact, if you go and see in many places where they store sand or where they store some of the construction materials or also in the place where they have grains in large markets where they put it in a pile depending on the material that you have they will automatically form a cone of a particular angle.

And this is also known as angle of repose that is dictated by the friction this is also known as angle of repose.

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And you again see what is the meaning of impending motion when I slightly change it the block begins to slide. So, the situation just prior to this is the condition for impending motion.

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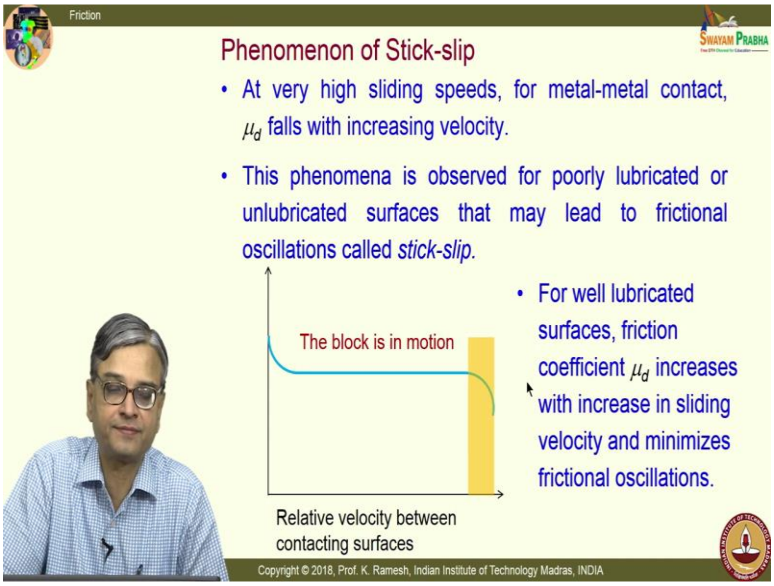
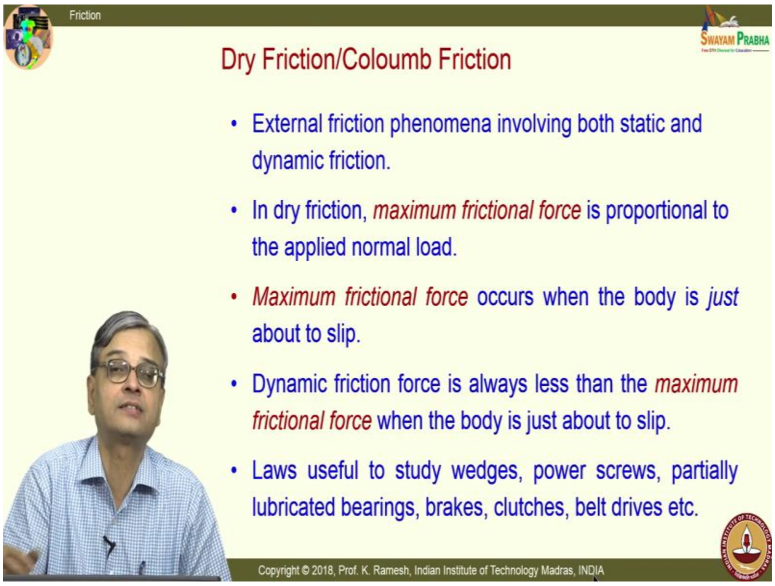
What happens at higher relative velocities, when I when the block is in motion it is dictated by the coefficient of friction which is known as dynamic friction indicated by the symbol μ with the suffix d. At very high sliding speeds for metal to metal contact μ_d falls with increasing velocity this is what is observed. What is the consequence of it? These phenomena are observed for poorly lubricated or unlubricated surfaces that may lead to fictional oscillations called stick-slip.



In fact, in some of the movies where they want to show a very eerie condition in midnight the you would enter into a bungalow where there will be a door which will be oscillating like this and generating a creaking sound. You feel the situation is very uncomfortable for you to feel; the creaking sound what you here is mainly because of the phenomena called stick-slip.

So, it is seen even in simple doors if they are poorly lubricated, and what happens when the objects under consideration of well lubricated, friction coefficient μ_d increases with increase in sliding velocity and minimizes the frictional oscillations. So, it is always desirable that you should have well lubricated surfaces.

So, normally that is what you will do, if there is a creaking sounds from your door you take a drop of oil and put it, you essentially lubricate it, you do not even need to study mechanics to do this you are not comfortable with the sounds. So, you simply put an oil and manage the situation. So, from a scientific prospective you have to lubricate it well so, that you can increase the coefficient of the dynamic friction. So, that you minimize the frictional oscillation.



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And how do I select the appropriate frictional laws. Three possible states of the surfaces are identified, one can be dry, greasy or partially lubricated, film or completely lubricated. For the first two cases when it is dry or partially lubricated, laws of Coloumb friction are applicable that makes our life very simple. On the other hand, when I have a film completely separates the metal to metal contact, even though I do not see visibly here there is a film available in between the two; it is very small in thickness with a very high pressure. In such cases you have to apply laws of viscous friction for the analysis of a problem.

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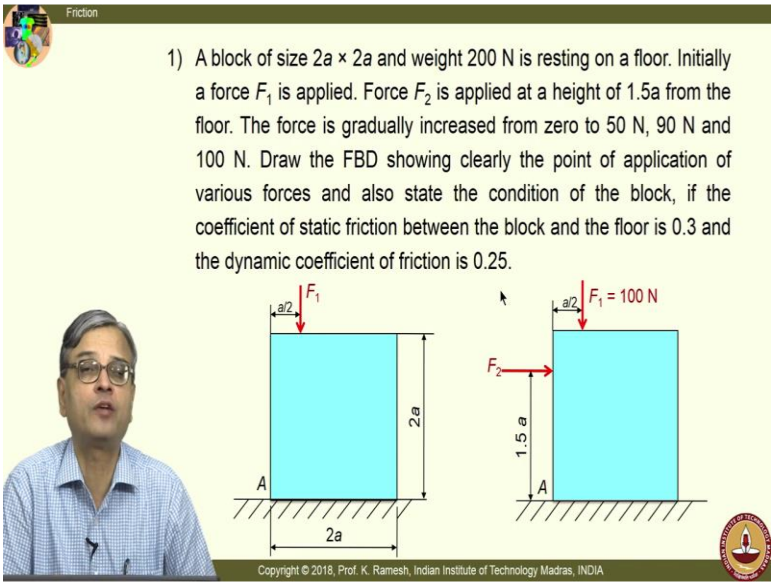
So, in dry friction or Coloumb friction it is essential external friction phenomena, you have both static and dynamic friction. In dry friction maximum frictional force is proportional to the applied normal load, the concept is re-emphasized. And this maximum frictional force occurs only when the body is just about to slip that is a key point to note for any frictional problem you cannot simply replace the frictional force as μN. Only when you investigate and find out relative motion is possible or motion is impending then only you can say frictional force equals μN.

And you will also have to note dynamic frictional force is always less than the maximum frictional force when the body is just about to slip. And you know this is very useful to study wedges, power screws; power screws are nothing but wedge wrap around a cylinder. And you have a square threaded screw which is used in many mechanical engineering applications, partially lubricated bearings, you have an important application of brakes, clutches and belt drives. In all these cases you can apply laws of Coulomb friction and get your parameters calculated.



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And you know it is better that you learn the concepts by solving a simple problem. I have a block of 2a × 2a weighing 200 Newtons and in this case, you will have to find out for different forces F_2 starting from zero, 50, 90, 100 Newton. Find out the condition of the block and also determine the reaction forces and it is given in the problem statement that the coefficient of static friction between the block and the floor is 0.3 and the dynamic coefficient of friction is 0.25. You can note clearly here the $\mu_s > \mu_b$, please ponder about this problem and we will try to solve it in the next class.

So, in this class we had a brief idea about what are the classifications of friction we classified as external and internal friction. In external friction you have further classified as static and dynamic, in internal friction we looked at fluid friction as well as solid friction.

And the interesting point I brought into focus was in one case frictional force is proportional to displacement that is what happened in solid friction, in the case of fluid friction, frictional force is proportional to relative velocity and in the case of dry friction frictional force is proportional to the acceleration. And I have a cautioned in problems dealing with friction, you should recognize frictional forces develop only when there is tendency for relative motion.

Further in initial stages the frictional forces are dictated by the equilibrium condition. The frictional forces increase as the external forces is increased; it reaches a maximum value when the motion is impending. Only at that condition you can replace a frictional force as mu times the normal force.

Thank you.