**Introduction to Launch Vehicle Analysis and Design**
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**Lecture - 31**
**Lifting and Other Reentry Modes**

Hello and welcome. In the last lecture, we had looked at the basic procedures for generating the ballistic trajectories and in that context, we had considered two cases, one of the steep ballistic trajectories, which was by and large a straight line and an orbital or a shallow ballistic trajectory and we also arrived at some broad features of these two solutions.

In this lecture, we will now look at the option of using lift to perform the entry mission and we will look at some broad aspects of such trajectories. So let us begin.

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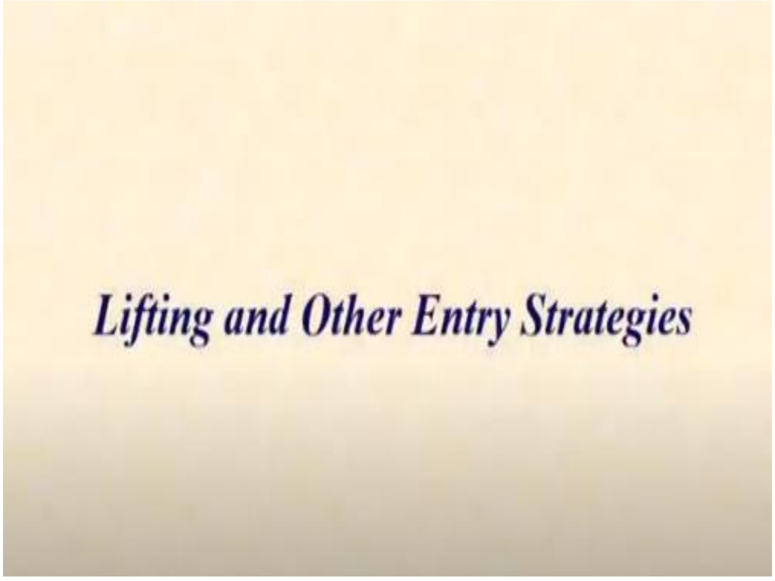


In this context we will not only look at the basic lifting trajectory, but we will also look at other possibilities of having an entry mission.

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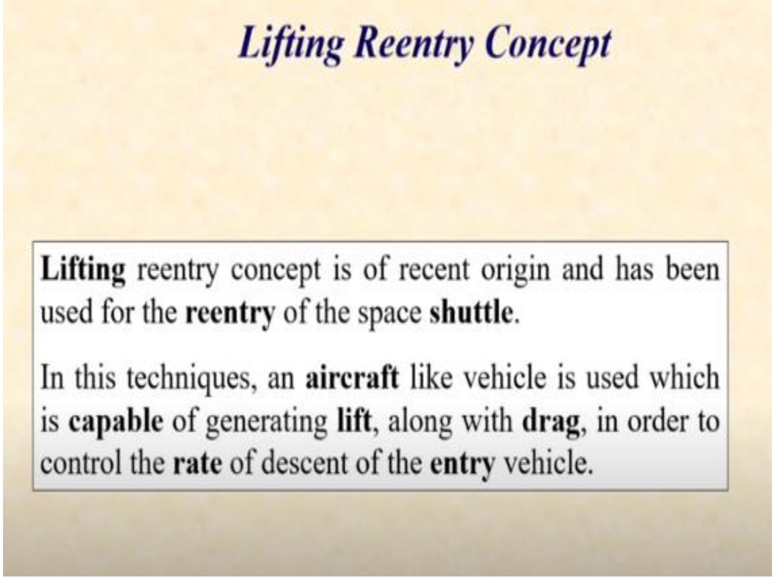


Let us first look at the basic concept of lifting reentry. This concept is of comparatively recent origin and has been actually used for the reentry of the space shuttle which was the first object to make use of lift to manage both the drag and the heating requirements. So, in this technique, typically an aircraft like vehicle is used, which is capable of generating lift along with drag in order to control the rate of descent of the entry vehicle.

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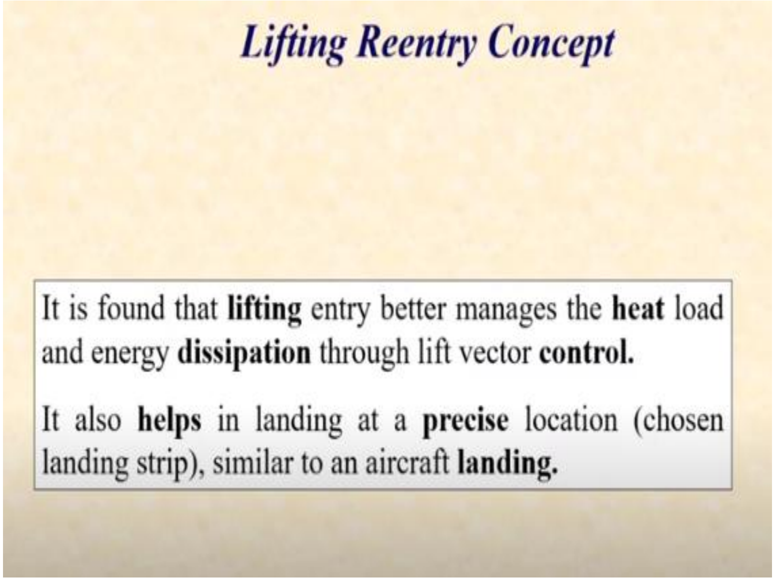


It is found that lifting entry better manages the heat load and energy dissipation through lift vector control. That is the primary mechanism that is used for lifting reentry. It also helps in landing at a precise location similar to an aircraft landing. I am sure you would have seen many pictures of Space Shuttle landing upon reentry to understand the implication of these aspects of an entry and return mission.

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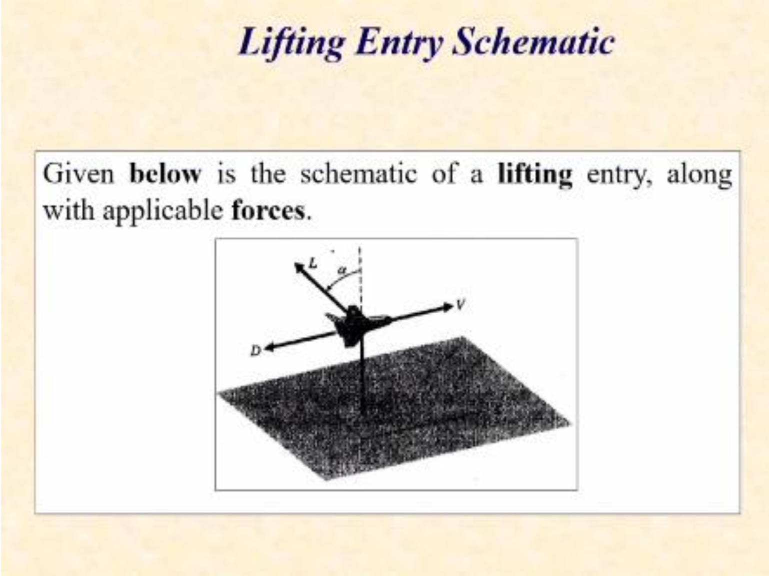


Given below is a schematic of a lifting entry along with the various forces that act on the vehicle during this phase. So, you have an aircraft like vehicle that has a velocity V and has a drag which is opposite to the velocity vector and we have a lift which is normal to the velocity vector. In addition, the weight acts along the downward direction or the gravitational direction.

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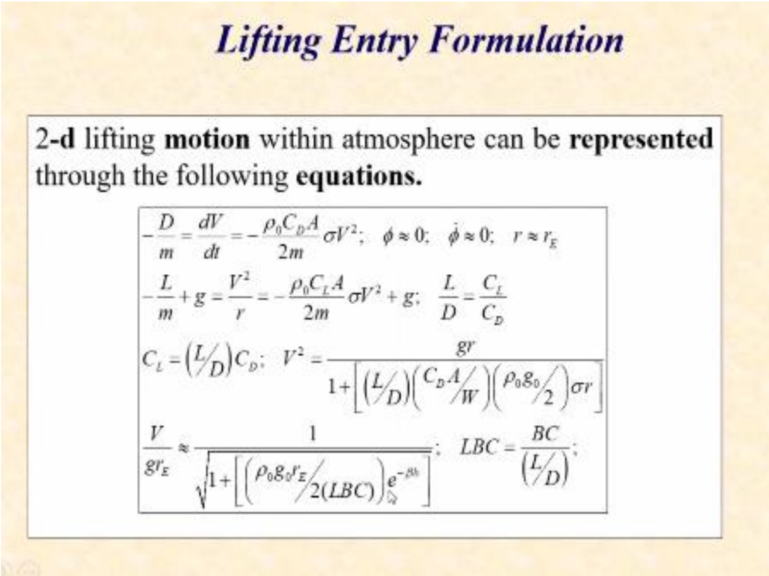


As the trajectory is primarily a two-dimensional motion, this motion can be represented in atmosphere through the following equations. So again, we have the same set of equations for the equation in the direction of velocity that we have already seen for our ballistic entry with specific assumptions that the flight path angle is nearly 0.

Of course, in the case of the lifting reentry of an aircraft like vehicle, this is also called the glide path angle as the vehicle by and large executes a gliding type of trajectory on the reentry. We also assume that the rate of change of this angle is so small as to be negligible and the distance above the surface of earth is nearly same as the radius of earth itself.

Which means, the addition of the altitude of 50 to 100 km to the radius of earth, which is about 6400 km is what we are neglecting. However, there is now a change in the normal equilibrium equation that we have seen in the context of shallow ballistic trajectory, that now we have a lift term along with the gravitational force and that brings in the idea of a parameter what we call the lift to drag ratio or lift coefficient to drag coefficient ratio.

This is an important configuration parameter of the vehicle and is normally frozen during the design process. As $C_D$ is our primary parameter for dissipating the energy, it is useful to also express $C_L$ in terms of $C_D$ through the $L/D$ ratio which is also is a constant. So, we can say that $C_L$ is a constant multiplier of the $C_D$. With this it is easy to show that the $V^2$ solution in the present case using the second equation would be given by the expression which contains the $L/D$ the $\frac{C_D A}{W}$ and the weight term.

We already know that $\frac{C_D A}{W}$ is inverse of your ballistic coefficient. What happens in this case is that we combine $L/D$ along with this and define what is called a parameter $LBC$ or what is called the lifting ballistic coefficient which is the ballistic coefficient divided by the $L/D$ ratio. So similar to the ballistic entry even in the context of lifting entry, we have a similar parameter that gives us a velocity solution as a function of the lifting ballistic coefficient.

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## *Lifting Entry Solution*

Solution for **deceleration** 'n', & **time** 'Δt' are as follows.

$$\frac{L}{m} = g - \frac{V^2}{r} = g - \frac{gV^2}{gr} = g\left[1 - \left(\frac{V}{V_{cir}}\right)^2\right]; \quad \frac{D}{m} = \frac{L}{m\left(L/D\right)} = -\frac{dV}{dt};$$

$$n = \frac{1}{g_0}\frac{dV}{dt} = -\frac{\left[1 - \left(V/V_{cir}\right)^2\right]}{\left(L/D\right)}; \quad n = \frac{-1}{\left(L/D\right) + \left[2\left(W/C_D A\right)e^{+\beta h}/\left(\rho_0 g_0 r_E\right)\right]}$$

$$n \approx \frac{-1}{\left(L/D\right)}; \quad dt = \frac{-\left(L/D\right)dV}{g\left[1 - \left(\frac{V}{V_{cir}}\right)^2\right]} \rightarrow \Delta t = \frac{1}{2}\sqrt{\frac{r_E}{g_0}}\frac{L}{D}\ln\frac{1 + \left(V/V_{cir}\right)^2}{1 + \left(V/V_{cir}\right)}$$

With this, we can now obtain the solution for the deceleration and that is number of g's and the total time taken for the trajectory as follows. It just involves solving the applicable differential equation. Here what we have done is to convert the $D/m$ which is the deceleration due to the drag in terms of a real number $n$ by dividing this by $g_0$.

And after a little bit of algebraic manipulation and making certain assumptions regarding the magnitude of various quantities, we can show that this $n$ obviously is negative because it is a deceleration and is inversely proportional to $L/D$ or lift to drag ratios. Now that is an extremely important result.

The implication of this result is that one can choose a deceleration factor directly at the design stage of the vehicle by designing an appropriate $L/D$ ratio. Here let me also make a mention that this $L/D$ ratio also in some way is related to the slenderness ratio or the wing aspect ratio for this class of vehicle.

So, by choosing an appropriate aspect ratio and the fuselage fineness ratio, it is possible to fix a particular lift to drag ratio and the moment we do that, the rate of deceleration can be fixed. And as we see, the rate of deceleration once it is fixed, it will automatically fix the value of drag and hence the value of the heat generated and, in that manner, we realize that indirectly we can also manage the heat load during the design itself.

Then of course, we can generate the time solution, the time taken to complete. And as we can see, larger the $L/D$ ratio smaller will be the deceleration. And hence longer will be the time spent in the trajectory. If you recall, this was the point that we had mentioned even in the context of orbital or shallow ballistic trajectory, where we said that if we want to reduce the drag and the rate of deceleration, then we must spend much longer time in the orbit before we come to the ground.

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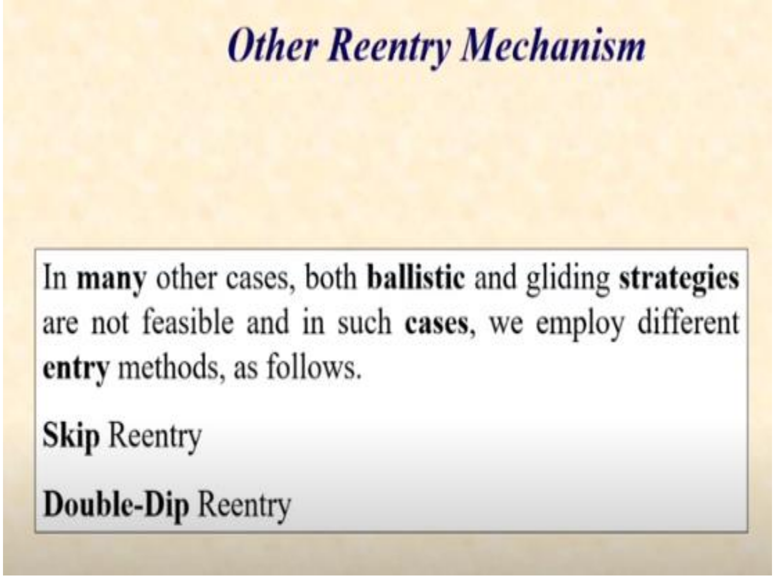


Of course, apart from this methodology, there are also other reentry mechanisms that exist and have been employed in different contexts. One of them is the combination of the lifting and the ballistic trajectory, which means you could design vehicle such that they could have good features of both of them. And we can also look at scenarios where both of these may not necessarily be feasible.

In which case, there are two more types of reentry mechanisms that have been employed. One of them is called the skip reentry. Other one is called the double-dip reentry.

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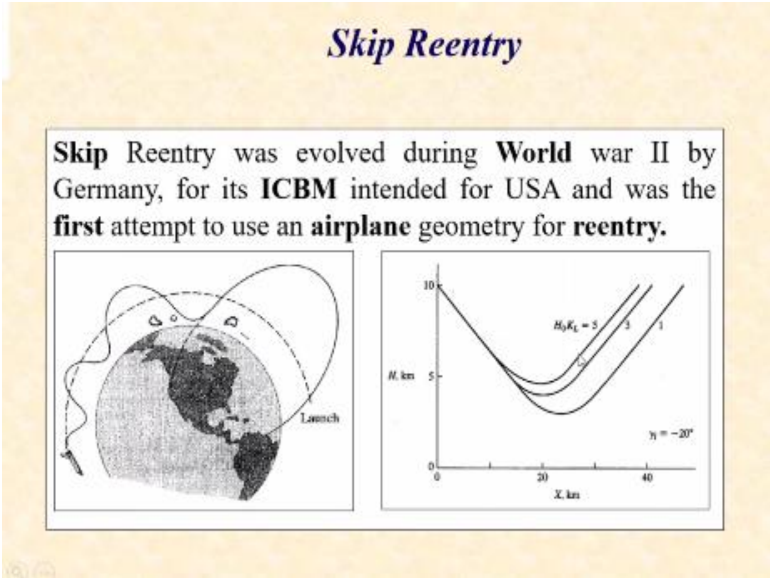


If we look at the skip reentry its history is somewhere around the Second World War where Germany evolved this methodology for its ICBMs, the intercontinental ballistic missiles, which were intended for USA and this was the first attempt to use an airplane geometry for reentry. The figure below schematically shows the basic idea of the skip reentry. So, as you can see, it starts as a ballistic missile.

And you can see the ballistic missile trajectory in the boost phase, the ballistic phase. And then at the reentry point, instead of directly impacting, it is allowed to skip out of the atmosphere which is shown by the dotted circle. So, it will skip out and execute another small ballistic segment and then reenter and again skip.

You will immediately notice that every time it enters the atmosphere there will be a drag acting on it and there will be a deceleration and the heat would be generated and it will lose certain amount of energy. Then as it would skip out the heat load would reduce until it was in a condition to reenter the atmosphere when another amount of drag and deceleration would happen along with a bit more of heat load, which again would get dissipated through radiation once it is out of the atmosphere.

As you can see, it is an efficient way of managing the heat load without having to explicitly make use of any thermal protection and just by changing the lift it could be achieved. What you see on the right-hand side are the typical plots of altitude versus the horizontal distance, the trajectory, for a reasonably steep ballistic entry and that for different values of an equivalent of a ballistic parameter we could create different kinds of skip motion.

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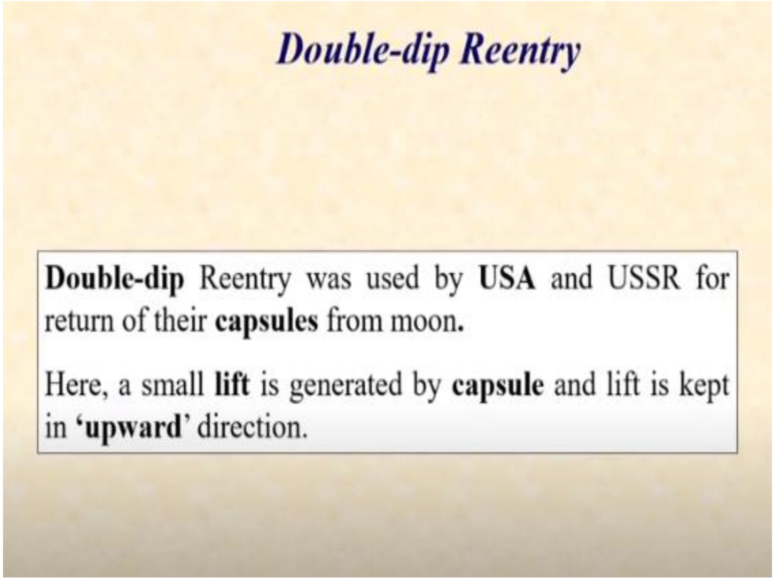


In contrast to the skip reentry, the double dip reentry was used by USA and USSR for return of their capsules from the moon when they were synthesizing the Apollo missions and similar moon missions. In this case, we generate a small lift by the capsule, there was no wings basically. So, this lift is actually quite small. And typically, initially it is kept in upward direction.

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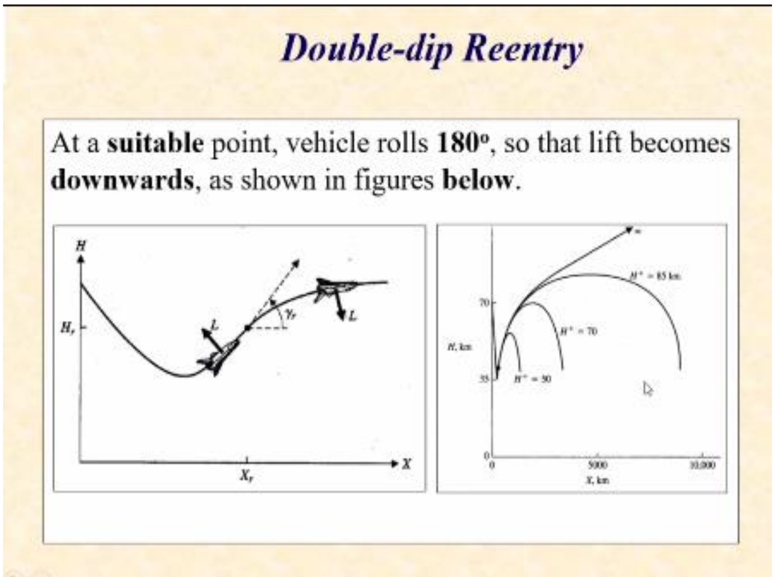


At a suitable point based on the requirements of the trajectory, the vehicle is allowed to roll by 180° without making any other changes to its altitude, so that the lift vector flips by 180° and it acts downwards along with the weight as shown in the picture below.

So, as it enters, it has a ballistic entry until the lowermost point at which you generate the lift such that vehicle starts increasing in altitude.

At a point which is typically chosen to be an inflection point, you roll the vehicle by 180° so that the lift becomes downward direction. So now, while the trajectory continues to gain altitude, but because of the lift, the increase in the altitude is limited so that vehicle continues to remain within the atmosphere, it does not skip out of it. And in the process dissipates a significantly larger amount of energy and hence can dissipate energy in a shorter time.

The picture on the right-hand side again shows altitude versus horizontal distance plot for different altitude values. And it can be shown that depending upon the requirement, you start from a 70 km altitude, come down to about 35. And then you can choose any one of these motions to do the landing while in the process dissipating the energy.

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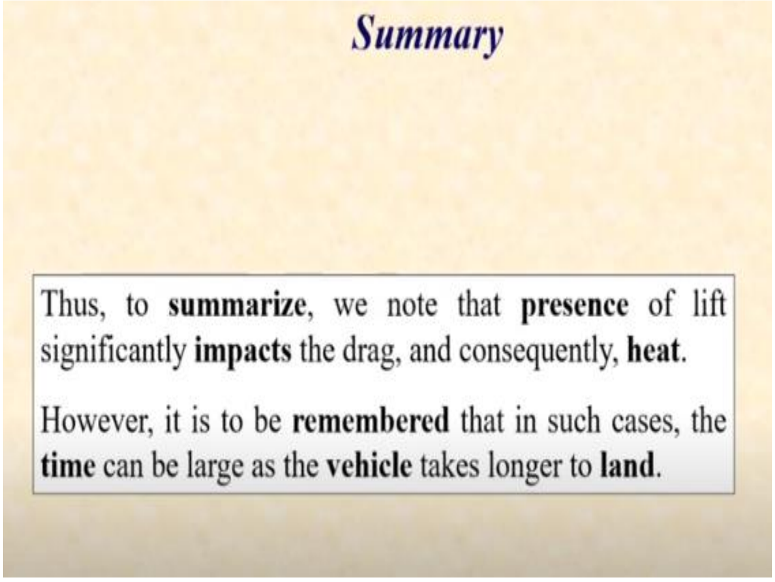


Thus, to summarize, we note that presence of lift significantly impacts the drag and consequently the heat. However, we should also note that in such cases, the time can be large as the vehicle takes longer to land. Hi, so in this lecture, we have seen the use of lift vector to arrive at different types of reentry trajectories to manage the heat load and the deceleration of the vehicle.

And in the process, we have also seen that it directly impacts the time taken for the mission to complete. With this we have concluded our discussion on the reentry missions. Though there are many other aspects that we have not been able to touch upon, but due to paucity of time I will be stopping at this point. And with this, we have also come to the end of the content that is planned to be delivered as part of this course.

And we will conclude the course in the next lecture. So, bye, see you in the next lecture and thank you.