TINA SRIVASTAVA: All right. So as we discussed, we're going to start off with the most basic question-- how do airplanes fly? It's a very critical question. I think everybody should know the answer to this.

Going back to the comic that Minachi had with Calvin and Hobbes, and not knowing how airplanes fly, and thinking that it's magic is not the way that any MIT student should be. So we're going to cover how airplanes fly. And we're actually going to go beyond what the FAA requires you to know. Because frankly, you should know how airplanes fly.

So just so that we have a common vocabulary with which to discuss, we're going to talk a little bit about airplane parts. So here in my little airplane, it's kind of a model there so you can see that at the front you have your propeller. And so the engine and the propeller in this little plane is up here at the front. Who knows what a fuselage is? Just shout it out.

AUDIENCE: The middle part.

TINA SRIVASTAVA: The middle part. The body. It's where the passengers sit. Yeah, so that whole middle part where people sit. So if you're thinking about a big jet engine, it's where all the rows of seats are where everybody sits. That tube in the middle is called the fuselage. And the wings stick out the sides. So the middle part is the fuselage.

And then one thing that's interesting is the tail actually has a lot more components. People kind of casually refer to it as the tail. But there's a vertical part that comes up in the back of the vertical part of the tail can actually tilt side to side. And then you have a flat horizontal part. And that actually has a back part that can go down and up. And so we're going to talk about what all of these are.

So the back vertical part when it goes side to side is your rudder. The flat part is your elevator that you can move up and down, allows you to control the airplane. We also have, of course, the wings. Sometimes, there are struts that support the wings. So they go from the wing down to that fuselage.

And then you have landing gear. In this case, you have these wheels down at the bottom. We're also going to talk to you during this course about sea planes. So they have slightly different landing gear. But this is a good place to start.

The other thing that we need to talk about are just the main four forces that are on an airplane. So they're pretty straightforward. So the force going up is lift. And that force is opposed by the downward force of weight. And then when you're moving the airplane forward, that's thrust. And it is opposed by drag.

So what we're going to talk about is that in order for an airplane to go up, the lift has to exceed the drag. In order for the airplane to go forward, the thrust has to exceed the-- excuse me. The lift has to exceed the weight. And the thrust has to exceed the drag. So those are the main four forces we're going to be working with today. So now I'm going to spend a little bit of time over here on the blackboard.

AUDIENCE: Hey video folks, is it easier to use that blackboard?

TINA SRIVASTAVA: They said this blackboard.

AUDIENCE: This one's better?

TINA SRIVASTAVA: Yeah.

AUDIENCE: These are all chalks of color.

TINA SRIVASTAVA: Yeah, fancy-colored chalk. All right.

AUDIENCE: Chalks of color.

TINA SRIVASTAVA: Chalks of color. All right. So I will preface the discussion about lift with the fact that there are a lot of theories of lift out there, some of which are wrong. So if you spent some time googling lift before coming here, you might have actually found a couple scenarios that are completely false. So we're going to focus on what's true, but I will cover least one of those false theories to make sure you guys don't get hung up on that.

So in order to talk about it, we're going to think about an airplane. And we're going to do a cross-section of the airplane. So if you took a saw, and you cut off the wing, what are you left with? And I'll do it this way. So if you cut off the wing, at the front of the wing is the leading edge. The back of the wing is the trailing edge. If you did it-- if you cut that off, what does it look like?

So it looks like this. And this shape is called an airfoil. And we'll get into the specifics later. But first we'll just-- we'll talk about a simple way to understand how lift works. So if this is the wing, and you have air coming in, the air is pushed down by the shape of this wing. So that means is as air flows by, it gets pushed down.

Now what is air? Air is not nothing. Air has molecules. It has mass. So if you think about conservation of momentum, this is I think the easiest way to think about lift. So conservation of momentum, you have a bunch of air molecules. And those air molecules are pushed down. So you have mass being pushed down.

So if mass is being pushed down for conservation of momentum, something must be pushed up. And that's the wing. So that's the easiest way to think about it that if you're deflecting the air downward in order to have conservation of momentum, the mass of the wing is lifted upwards. We're going to break that down, but I think that's a good place to start.

I'm just going to take one moment to talk about an incorrect theory of lift. So let me emphasize it's wrong. One of them is called equal transit theory. Has anyone heard about this? Getting a lot of head nods. It's wrong.

Equal transit theory, which is incorrect, says that basically a molecule of air that's coming over that starts over here at the front has to go around the bottom and meet the tail at the same time that a molecule that goes over the top has to meet it at the back.

There is no physical principle that says that. It is false. And in fact, we have measured that they don't. The molecules that go under the bottom of the wing versus the top of the wing don't actually reach the end at the same time.

But in this false theory, equal transit theory, they say that you have to reach the bottom at the same time. They also say that there is more distance basically to cover because of the shape of the airfoil. So in order for the molecules going over the top to reach at the same time as the molecules over the bottom, they have to go faster. And so since the air is moving faster over the top and the bottom, that's what creates lift.

So that's false. And there are many reasons why it's false, the biggest one being that there is no physical principle that says that two molecules starting at the same time, one going over the top and one going over the bottom, reaches the end at the same time. That's just not true.

And we'll show you some more diagrams that show in fact it doesn't happen, that molecules don't reach at the same time anyway. So please despite that being very widely propagated, that is not true. And please don't spend time on that theory.

So let's focus on what is true, how does it really work. Actually, let me give you one more reason why that's false. The real reason that equal transit theory is trying to tell you that that generates lift is that because of the shape of the airfoil, the shape of the wing, that's why the distance that it has to travel is different over the top versus the bottom.

But one reason that's wrong-- can you pass me that paper airplane please? Who has built a paper airplane before? I see at least two people who didn't raise their hand. Do we need to do a class exercise? If you have not built a paper airplane, it's really important that you do just as a general childhood experience.

Here's a paper airplane. Thank you, Minachi, for building it for me. If we took this paper airplane instead of this fancy airplane, and we did a cross-section of this wing, what would it look like? Yes. You demonstrated with your hands, but shout it out.

AUDIENCE: It's going to be the same at the top and the bottom. It's just a piece of paper.

TINA SRIVASTAVA: Yeah, it's going to be the same at the top and the bottom. It's just a piece of paper. Exactly. It's just like a little flat rectangle. So instead of this fancy shape that you have here-- we're going to use red for wrong-- it's like a little rectangle. That's what a paper airplane's cross-section of its wing looks like.

Well, surprise. Surprise. As you said, it's the same at the top and the bottom. So the distance that a air molecule would have to travel over the top and the bottom is identical. So really, the equal transit theory completely falls apart.

Yet, a paper airplane still flies. So why is that the case? Again, remember the actual reason is that if this paper airplane is inclined, it is pushing air down. So air that's coming up is bumping into it and being pushed down. And therefore, as you deflect air molecules down, conservation of momentum-- the wing is lifted up.

So now we're going to break this down in a little bit more detail. And I'm going to go back over here to the slides. So one thing that's important, as I said, a really detailed mathematical description is not really necessary to fly a plane or become a pilot. The FAA doesn't require some of this detail. But it is important to know it to the extent that it helps you control the airplane and fly it. So here's a good reference in terms of that.

But one of the biggest things is just that for lift, you have to increase that downward momentum of the air. And airfoils are-- the shape which is called an airfoil is a type of shape that is very efficient at increasing that downward momentum. Now, who knows what Bernoulli's principle is? Who's heard of Bernoulli? Good. Everyone's heard of Bernoulli. Can anyone articulate Bernoulli's principle? Yes.

AUDIENCE: I think it's like p plus one half of mv squared equals constant the difference squared. So when the pressure goes down somewhere, the speed of the particle has to go up.

TINA SRIVASTAVA: Yes. Absolutely. Absolutely. So what Bernoulli observed was the case that when there is a decrease in pressure, there's an increase in velocity. That's the core concept that you have to understand. And so when we think about an airfoil, when we see that-- and I'll draw another airfoil for us to talk about.

When we have air that's moving very fast over the top of the wing, that means an increase in velocity means there's a decrease in pressure. So this is the extent to which you really need to know it for the FAA exam. So which statement relates to Bernoulli's principle? I'll let you read those answers. So is it A, B, or C? Shout it out.

AUDIENCE: C.

TINA SRIVASTAVA: C. Good job. Well done. We're going to discuss a little bit more details though. In order for any wing to generate lift, it has to be in a fluid. If this airplane was in space or in a vacuum, and there wasn't any fluid passing by it, then there wouldn't be any molecules to deflect downward. And therefore, you couldn't push the wing up. But the fluid doesn't always have to be air. You might see similar designs underwater for underwater drones. It just has to be a fluid that's passing by the object.

So when you have this airfoil in a fluid, when the fluid is not moving, when it's stationary, then all of the fluid is exerting pressure on the airfoil. So you get all these little normal forces exerting pressure.

When the fluid is not moving, and the airfoil is stationary in the fluid, then all of those pressure forces, all those normal forces or forces perpendicular, sum to zero because there's no net force. It's just sitting in the fluid. But when that fluid is moving, it generates a force.

So that's the force it generates generally when the fluid is moving forward. And a force is a vector. So it has direction as well as magnitude. So there is a vertical component and a horizontal component to that. So we call the vertical component the lift. Does anyone know what we call the horizontal component?

AUDIENCE: Drag.

TINA SRIVASTAVA: Drag. Good job. Now, here's a dumb question. What part of the aircraft generates lift? Yes.

AUDIENCE: The whole aircraft.

TINA SRIVASTAVA: The whole aircraft. Good job. So a lot of people might be under the misimpression that it's only the wings that are generating the lift. Well, actually, the whole aircraft is generating lift. And it's not just aircraft. Any objects that are moving through fluid have this phenomenon. And sometimes, it's not a good thing. So what is this a picture of? A race car. Come on, guys. I know we're in an airplane class but-- who can tell me what is that thing sticking up at the back of the race car?

AUDIENCE: A spoiler.

TINA SRIVASTAVA: A spoiler. What's a spoiler?

AUDIENCE: It spoils the airflow.

TINA SRIVASTAVA: It spoils the airflow. So when a race car is driving on a race track, and it's going through the air-- the fluid is air-- actually just the race car itself is generating lift. And that lift can cause the race car to kind of lift upward and not be as much in traction with the ground.

And when you're a race car, and you want to go really, really fast, you want to have very good traction with your wheels against the ground so you can go as fast as you can. So the reason that you have a spoiler at the back is actually to counteract the lift that's being generated by the race car. So it's not just airplanes and wings that generate lift, but really anything moving through a fluid can generate lift.

So we're going to talk a little bit about equations. Don't get scared here. We'll just dive into it step by step. So we have f equals ma. Hopefully, this is not the first time you're hearing about that equation. So can somebody just shout out what is acceleration?

AUDIENCE: Change in velocity with respect to time.

TINA SRIVASTAVA: Change in velocity over time. Very good. So velocity again is also a vector. So velocity being a vector has both a magnitude and direction. So you can change the velocity either by changing the magnitude or the direction. In the case of an airfoil, we're changing the direction of the air. So the air has velocity. It's coming in. We're changing the direction of that air. And that's generating the lift.

So because we changed the direction of the velocity, that creates a force. That's our force f. So f is actually here representing the rate of change of momentum of pushing those air molecules down and generating a force, creating the airfoil to be lifted up.

So that's why we discussed again that equal transit theory is false. Because even an paper airplane with a completely flat cross-section of its wing, as long as it's inclined upward such that the air is being pushed down will fly.

So here's another question. Which moves faster-- the wing through the air or the air past the wing? Wow, you're very quiet. Which moves faster? Yes.

AUDIENCE: The air over the wing.

TINA SRIVASTAVA: The air over the wing. We have one for the air over the wing is moving faster than the wing through the air. Anyone else? Yes.

AUDIENCE: Depends on where on the wing you're talking about.

TINA SRIVASTAVA: Depends on where on the wing you're talking about. Yes.

AUDIENCE: Because if you define air to be the air that's immediately next to the-- that is in contact with the wing or the general air as in the air space.

TINA SRIVASTAVA: Yes.

AUDIENCE: If it's the air that's in contact with the wing, they're going at the same speed.

TINA So it depends on which air you're talking about. True. Actually, what we're discussing is about

SRIVASTAVA: frame of reference. So depending on your frame of reference, if your frame of reference is the airfoil, you can take it to be that the airfoil is stationary. And you see the wing to be stationary and the air to be moving past you.

If your frame of reference is out here, you might see the air to be stationary and the airplane to be moving through it. So depending on what your frame of reference is, you can actually have the identical result. So the answer is actually that it's the same. So depending on your frame of reference, it's exactly the same the speed of the air moving past the airfoil versus the airfoil moving through the air.

And the reason-- so does anyone want to dive more into that? Are you guys familiar with this concept of frame of reference? Yes. A lot of head nodding. Great. So the reason that's significant is that as we learn about lift and as we study this, we actually could create a whole bunch of different airfoils, and then build airplanes, and then fly them through the air, and measure them. But that's very expensive.

So instead, what we do is we basically take the airfoil. And we put it on a stick, and then we put it inside a wind tunnel. Has anyone been in a wind tunnel? Got a couple people. Hey, we saw that like over 60 of you guys were aero-astro. You need to go to your Wright brothers wind tunnel. It's being upgraded actually right now over in your building 33.

So because it's exactly identical, the air moving past the airfoil or the airfoil moving through the air, it's a lot cheaper to put the airfoil on a stick in a wind tunnel, and then shoot air past it, and then do your measurements rather than continuing to take off airplanes and fly them through the air. So we're going to be talking about that a little bit.

So the question is, what factors affect lift? So there are a lot of things that affect lift. So one has to do with the object itself. So I was talking about the shape of the airfoil. So we talked about a different shape, which is just a flat piece of paper or a rectangle as a shape. You can have a more slender shape. And the way that you modify the shape can significantly impact your lift.

So for example, one of the modifications can be back here at the end. If you made your airfoil longer like this and point even farther down, then it would push the air in a slightly different way. So that would affect the lift that that airfoil could generate. It would also affect the drag that it induces.

Another aspect is just the size of the wing and the shape of the wing. So we see a lot of different kinds. So this is a big rectangular wing. In a jet, you might see a swept wing. There are different types of shapes.

And then there's also just the area. So regardless of whether-- if this is your-- if you're looking down at an airplane-- so this is kind of the broad, flat wings, or you could have very thin, skinny wings that you might see on a glider. Regardless, there is a surface area of the wing. That area also impacts the lift quite a bit. And the aspect ratio as we just discussed in the shape can affect lift.

The other thing other than the object itself, other than the wing itself, motion can affect lift, so the velocity of the air. And the very importantly is what's called the angle of attack. So it's the angle with which this airfoil has to the air. So if you had one airfoil that was pointed up like this versus one, the same one but it was not tilted up, this airfoil would be having a higher angle of attack or angle to the wind than this one.

Now, this might seem like a very fancy description, but who has been in a car driving down the highway, and you stuck your hand out outside? And if you tilt your hand up a little bit, you'll see that the wind kind of pushes your hand up. And if you tilt it down, your hand pushes up. And you kind of glide your hand out the window. So I'm getting a lot of head nods.

So that's really all that angle of attack is talking about that if you angle your hand up, it gets pushed up a lot more. If you angle it down, it gets pushed down. That's the angle of attack. And we're going to define it more specifically when we talk about the terms associated with an airfoil in the shape, but it's good to get the general concept first.

And then another factor affecting lift is the air, the fluid that it's in, so the actual mass of the airflow coming around you. So there are a lot of aspects to that. We talked about whether you're in water, whether you're in air, or the density of the air. Another component of that air is the viscosity. Does anyone know what viscosity is? Yes.

AUDIENCE: Resistance to flow.

TINA SRIVASTAVA: Resistance to flow. The way I like to think about it is if you've ever baked brownies, and you have your mixing bowl and your spatula in there, and if you just have the water and the oil and eggs, and you're mixing it around, you can mix pretty quickly. And it doesn't stick to the spatula that much.

But if you were mixing molasses or once you get all that brownie batter in there, it's harder to do it. And it sticks to the spatula. So that's what we're talking about when we're talking about viscosity. So it's the tendency for these molecules to stick to each other and to stick to the object that's moving through them.

So with the case of the airfoil, we're talking about-- and we were discussing this just a moment ago about which air were we talking about. So some air that might be very close might kind of stick to that airfoil or stick to the wing versus just moving smoothly past it. So viscosity has a big impact. And then compressibility also affects lift. So the compressibility of the air-- did I turn off my mic?

So certain types of fluids are compressible. So you could take a balloon of air. And you can move it into a cold environment and have it shrink or in a hot environment and have it expand while having the same amount of mass inside the balloon. So I'm getting a lot of head nods. So that just shows the compressibility of the air, whereas some types of fluids are not compressible. They're incompressible. And they affect lift in a different way.

So although I've told you all these things that affects lift, one thing I will admit to you is that calculating lift is difficult. It's very difficult. In fact, we don't really know how to do it properly. This is a snapshot from Wikipedia of all the different theories of lift. So there are a lot of different ways that people go about trying to calculate lift. And it turns out that it's very hard to do.

So one that you see up there is Navier-Stokes. So Navier-Stokes is a set of equations that does a really good job of predicting lift. And it really takes into account a lot of things. It takes into account conservation of energy, conservation of mass, conservation of momentum, viscosity, even a lot of things like thermal conductivity and a whole bunch of considerations.

But the problem is that solving those equations is very hard. We try to use supercomputers to estimate every little aspect. And it's very difficult to do. And we're not really able to solve those equations to determine precisely what the lift is going to be. Let me talk about some of the limitations that we have in solving these equations.

So first of all, it has to do with how the air flows over the wing. If the air is moving very smoothly past the airfoil, then it's very easy to come up-- not easy, but it's easier to approximate. We can predict what a particular air molecule is going to do.

But as you see there, when it starts spinning around and becoming turbulent-- so if you start seeing a particular air molecule that's moving around, and becoming turbulent, so not doing laminar flow but turbulent, and moving around, and bumping into other air molecules, then predicting what that molecule does and what all the molecules do around it become very, very difficult. In fact, we have a very hard time doing that.

And so instead, we basically assume that that doesn't happen. And we impose some limitations or conditions on the airflow which are not actually true but help us with approximating lift. So one of those is the Kutta condition that you see at the bottom left, which is this smooth flow off.

So basically, you say that none of this turbulence is happening. And the air moves very cleanly off. And you also have a couple other specific requirements such as that no air molecule from the top comes over to the bottom, and no air molecule from the bottom goes around to the top. And you just assume that they move smoothly off.

And so that Kutta condition is actually very helpful in approximating lift. We also make other assumptions that there's no viscosity or that the fluid is not compressible. Sometimes, these assumptions are appropriate. And sometimes, they're not.

Another thing that's really critical about our ability to estimate lift is that as I've been talking to you here on the blackboard, I have talked about a cross-section, that you just-- you cut off the wing. And you're only looking at one cross-section. So since we're talking about a cross-section, we're talking in two-dimensional space.

Well, we can actually do a pretty good job of estimating lift in a two-dimensional environment. But the fact of the matter is wings are not two dimensional. And the wing comes out into the classroom and back into the blackboard. And to estimate actually how all these air flows work at the edge of the wing is very difficult. Has anyone heard about tip vortices? Couple head nods.

So we have a picture there that shows a jet to just show a little bit about what the air does when it comes off the edge, the end of the wing. We're going to talk about tip vortices a little bit. But the problem is that it no longer is adhering to all of our conditions.

Now, we don't have smooth flow. We definitely have turbulent flow. We have spinning flow. And we have air molecules hitting other air molecules. And it becomes extremely difficult for us to model all of those air molecules. We really can't do it. So going from two dimensions to three dimensions is really a limitation of a lot of the equations that we have to approximate lift.

So what do we do? Well, first of all, we go back to our two-dimensional surface. And we talked about all of these normal forces, so when you have all the fluid going past, and it has pressure, and it's supplying all these forces perpendicular to the airfoil all around.

So how do you approximate lift? Well, you say, oh, that's fine. You just sum all those forces around. Well, that's great if you know what all of those forces are, but it's not great if you don't know what all of them are.

So what is the solution that we-- what we do? Basically, we calculate what we can, and then we measure the rest experimentally. So in this equation of lift, for example, so we have L is for lift. Some of the other terms that you have there-- rho is the one that looks like a p. So rho is talking about the air density. You have velocity. And A is the wing area we talked about. And then we have this fancy little symbol there C sub L or the coefficient of lift.

And basically, we say that I don't know how to come up with characterizing all those complications about viscosity and some of the effects like that have to do with turbulence and shock waves, Mach number, Reynolds number, all these types of things.

And so we say we'll measure what we can, and then we'll-- or we'll calculate what we can, and then we'll actually, in a wind tunnel where we put this guy on a stick, we'll actually measure the coefficient of lift. And that's how we really calculate lift these days is using a lot of measurement to inform what's actually happening because it's just very complicated.

AUDIENCE: Tina, that velocity is squared, right? So if you go twice as fast, you get four times as much lift.

TINA SRIVASTAVA: That is the relationship. Absolutely. And the other thing that's really important is that that coefficient of lift is measured for a given angle of attack. So we talked a little bit about angle of attack with your hand outside the window. So let's get into defining it a little bit more in detail.

So in order to describe it, I have to come up with a few more terms that have to do with the airfoil. So we talked about the very front of the airfoil or the front of the wing is called the leading edge, and then the back is the trailing edge.

And we talked about the trailing edge a little bit when we were talking about the Kutta condition that no air molecule-- we're assuming no air molecule can cross the trailing edge to the other side. So then the camber is in there. So that's just talking about really representing the curvature of that airfoil and then a chord line that goes in between so you can measure how that is. So try and do your little zoom in fanciness that you were doing.

AUDIENCE: I think I set-- yeah, maybe it went to sleep. Giving up?

TINA SRIVASTAVA: I'll just point at it. So this is the chord line of the wing. So you can see that this is a full airplane. The airfoil is right here. And you see this chord line going from the back to the front. Is somebody trying to come in the door there? Great. And then we'll talk about some of these terms. Basically, the most important thing to think about is the angle of attack. Thank you for checking on the door.

So talking about how we can control the lift, so some of the things we can do have to do with the aircraft design. So we can build an airfoil. And we can talk about how curved that airfoil is, the curvature on the top, how curved it is.

We can design the wing area. When we're flying, we can control the airspeed. And then the angle of attack is something that you can control when you're in the airplane by pitching down or pitching up. And we'll describe pitching and how you control an airplane in more detail.

Another thing that's relevant is flaps. So I talked about in this drawing right here where I added this white part of the trailing edge that moves down, that really is kind of similar to flaps. So when your flaps are up, they're sort of in line with the rest of the wing.

But when your flaps are down, it's the effective thing like pushing-- pulling a piece of your trailing edge downward, which causes again more of that air to be deflected downward. So it increases your drag, but it also increases your lift because you're deflecting more air molecules down. And then we also talked about spoilers, for example, as something that can, like on a car, that can actually disrupt the lift by disrupting the airflow.

And when we talked about the four forces of flight, if you're doing steady flight, you're not climbing or you're descending, but you're just flying straight, that means that your lift and your weight basically cancel each other out. If your lift is greater than your weight, then you can climb. And if your weight is greater than your lift, then you descend. But if you're just flying straight, you're in an equilibrium where those two forces cancel out.

So good. I have a more detailed diagram of angle of attack. So you can see here the chord line. You can also see the relative wind and same things that I drew here-- the lift and the drag and then that resultant force vector.

So you can actually control the angle of attack in a number of ways. One of the ways that we talked about is pitching down. So pushing your yoke forward causes the airplane to pitch down. And it does that by changing the elevator at the back of the airplane. We'll describe that in more detail.

But the other things that can affect the angle of attack, you can actually affect before you even take off. So it has to do with your aircraft weight, for example, and the center of gravity, as well as your airspeed when you're flying.

So here are a couple of diagrams that show you how the lift changes with the effective angle of attack, and then there is a critical angle of attack. So that's when you can keep climbing for a while. But if you get too steep, what happens? Who knows what happens when you go to steep?

AUDIENCE: You stall.

TINA SRIVASTAVA: You stall. That's right. So the air can't really effectively go over the wing. And it starts separating. And so you're no longer effectively pushing the air down. And you lose the lift that you were generating.

And one thing I also want to point out here in these diagrams is you see with these little colored lines the air that's coming in. And it's going out. And you can see that in this case, the blue lines are showing that the air that went over the top of the airfoil went faster and actually got to the back faster than the air that went from the bottom. So again, please don't fall for the equal transit theory. So practice question. A, B, or C?

AUDIENCE: A.

TINA SRIVASTAVA: A. Good. So the angle of attack is defined there. And one thing that I would like to point out is that this is also the case for a propeller. So your propeller also looks a lot like an airfoil or like a wing that's sideways and spinning around. And so also the angle of attack for a propeller is defined basically the same way is the angle between the propeller's chord line and the relative wind.

So let's define the center of pressure. So it's basically the point on the wing where the lift is centered. And so that can actually move as you can see in this figure. Based on the angle of attack, the center of pressure can act in a different location.

And that's really important to understand also that it's not that the lift is always coming right at the front. Depending on where you are, it might be pulling you in different directions. And that can affect the maneuverability of your aircraft. And we'll get into that in more detail.

So we talked a little bit about flaps, that flaps actually can increase the lift that you're able to produce. But it's a trade-off because it also increases the drag. So when in the course of the flight, takeoff, cruise, or landing, when do you use flaps? Does anyone know?

AUDIENCE: Takeoff and landing.

TINA SRIVASTAVA: Takeoff and landing. Landing. Yeah, the reason that you, especially on landing-- many times people use flaps on takeoff as well. But the reason is just that you like to have your aircraft configured that in case you didn't take off, you can land without making a lot of dramatic changes.

The reason that you do that is basically that by increasing your lift but also increasing the drag, drag affects how fast you're moving forward. And so you can actually have the airspeed be higher with the ground speed being lower.

What it does is it allows you to go very slow without stalling. And so that really helps you land an airplane. So basically, it allows you to come in at a kind of steeper angle to land, maintaining the airspeed that you need in order to do that.

And you'll notice that there are different flap settings. So you can either have flaps at 10 degrees, 20 degrees, 30 degrees. We'll discuss that in more detail. And Phillip will talk about it in terms of performance I think as well.

Thrust-- so we talked about that forward force thrust. In this type of an aircraft, a single engine propeller aircraft, it's the propeller that's rotating that is really producing the thrust. And it's really, as I said, the propeller blades are kind of like an airplane wing-- it's a good way to think about it-- that are just spinning round and round and generating lift. But in this case, it's moving air molecules front to behind your airplane.

And then although this is also just a force, instead of talking about it in pounds, we usually talk about the horsepower required to drive the propeller.

So let me also talk about drag. So there are a couple different types of drag. So one drag is just what's called parasitic drag or parasite drag. It's basically when the aircraft is moving through the air that you get some kind of resistance to that. That's parasitic drag, whereas this drag is induced drag, which is the drag that's created by the lift, so this backwards D. And so you can see in this figure that the total drag is a sum of that induced drag and the parasite drag.

AUDIENCE: Do we also call the induced drag just lift in an unwanted direction?

TINA SRIVASTAVA: Lift in an unwanted direction. Sure, whatever can have you associate induced drag with lift. That's the drag created by lift. Ground effect-- does anyone know a ground effect is? Only a couple of you.

So let's talk about it a little bit. So basically, when you're very close to the ground within one wing span of the ground, you actually have some of the airflow going on with your airplane is blocked by the ground. And so your induced drag decreases.

Now, with the induced drag decreases, it's actually the case that your airplane can become airborne at a lower speed than it's supposed to. So what you might notice is that when you're on the runway taking off-- this is probably the first part of your flights. After you did your pre-flight, your engine runup, you pulled out onto the runway. And you'll have determined in advance what is the air speed at which you should rotate.

Now, that's really important. With a Cessna 172, for example, it's around 55 knots. And you want to look at your airspeed indicator. Because if you just feel yourself, you might notice that much lower, like 40 knots, that the plane has already taken off. You're already floating. You're flying. And you might be very excited about that. And you might want to just pull back on your yoke to take off.

Well, you won't be able to sustain flight. And so this is what why ground effect is really important is that you can kind of float over the ground because you're so close to the ground that the ground is blocking some of the effects of the air.

And so what you want to do is really make sure that you continue your ground roll, continue. Even if you're a little bit airborne, stay close to the ground until your airspeed comes up to that rotate speed, so in this case, 55 knots, and then you pull back on your yoke to take off. So again, so when does ground effect happen? When you're close to the ground-- when you're within one wing span of the ground

So let's talk a little bit about stability. And we'll start by just talking about the three axes of flight. So there is a longitudinal axis, which is basically from the nose to the tail of your airplane. And there's a lateral axis, which is from wingtip to wingtip and then vertical going straight through the plane. So you have the ability to control all three of those axes.

So the elevator, which I keep talking about is like your yoke where you push it forward or you pull it back, that allows you to pitch the airplane. So pitch nose up, pitch nose down-- that's you controlling the back part of this tail, the elevator, which allows you to have motion in this direction, so pitch nose down. So you might hear that a lot. In case you're getting close to stalling because your angle of attack is getting too high, they might say, nose down or pitch nose down.

You also have ailerons, which are out on the side of your wings. And those ailerons control the roll. So that's rolling along the longitudinal axis. And then your rudder, which is at the back of the tail, the vertical part of the tail-- that controls yaw. So this is called yaw, this type of motion. So when you're turning, you actually kind of do a roll and yaw usually to enact a turn.

There are some cases where you actually want to have adverse yaw or you actually-- adverse yaw means basically you're using the yaw direction in maybe the opposite direction at which you're trying to turn with the roll or other angles of your plane. And so this just talks about an adverse yaw is when you're not turning the rudder in the same direction that you're using your aileron.

And so this is where you talk about coordinated flight or uncoordinated flight. When you're actually in an airplane, the rudder or the yaw is controlled by your feet. So you have feet pedals that control the rudder. And the yoke that you're holding onto or a joystick that you're holding onto front and back controls the pitch. And then turning it like in the steering wheel of a car is only controlling the roll. So you actually also use your feet for that third direction of the yaw.

So just talking about stability in general, this isn't going to dive into a whole diffy q discussion or anything. But just in general, something that's stable-- so it's just talking about like a little bowl if you have a ball in a bowl, even if the ball gets jostled around, it'll return to the center point. Unstable would be the opposite. So if you have a convex surface, then if the ball moves even just a little bit, it'll really get moved out of control.

So the reason that we talk about this is basically when you're flying in an airplane, and you're talking about stable aircraft, for example, the reason I really love flying a Cessna 172, even though it's kind of the training airplane, is that the-- as people call it, it flies itself. So if you notice the plane's doing something weird and turning, almost the best thing you can do is just let go. And the controls will normalize, and then the plane will fly straight and level, which is really great.

There are other types of aircraft that are inherently unstable. So we have Minachi and Oxsana over here who do aerobatic flights. And Mark will be talking about that tomorrow. So that's where you actually want an airplane that's not so stable so that you can cause it to do all kinds of crazy maneuvers and turns and twists very easily. You pretty much can't get a Cessna to do that. It really wants to fly straight and level.

So then there are also other aspects that can affect stability, such as your center of gravity, so how you load the airplane. We'll have a specific lecture that just talks about weight and balance. But one thing to keep in mind is that as people sit in your airplane or as you put bags in the baggage compartment, you're loading the airplane.

And so if you have too much weight aft of the CG or behind the center of gravity, you can cause the plane to basically go like this, which isn't very helpful when you're flying. If you have things a little too forward, it actually pushes the nose down. In general, the nose down is a little bit more stable from the perspective of lift and getting air to fly over. You don't want something that keeps trying to stall whenever you let go of it.

And then similarly, you can talk about the stability in the lateral direction in the roll direction. And some of these things like swept-back wings like you see on a jet can affect that type of stability. And then finally, there's stability about the vertical axes. Generally, this is going to be kind of fixed for the given aircraft that you're in. But you can affect it as you design an aircraft.

So we started talking about stall already. So when you have your angle of attack past its so-called critical angle of attack, it can cause the air to basically no longer be able to flow over the top and no longer be able to effectively deflect air down. And so the air kind of separates. And you can stall.

So it's really important to know that you can actually stall at any airspeed. Even with full power, you can stall. In fact, one of the maneuvers you'll have to do in order to get your pilot's license is a power on stall. So you can stall both where your engine is idle, like you're coming in for a landing, and you get too steep, but you can also stall with full power. And you just made your angle go too steep. So it's really affecting that critical angle of attack.

And again, once you have that angle of attack too steep, then there's a very significant loss of lift, which is not good when you're flying an airplane. So when can you stall? At any airspeed and any power setting, and it's really based on the angle of attack. So if you-- yes, go ahead.

AUDIENCE: So what happens after the end of the graph? Does it just plunge zero? Is it not like any solution? Like why does it stall?

TINA SRIVASTAVA: Yeah, basically, it's not generating any lift. Right. You can see this like with a paper airplane. Sometimes, if you-- it kind of stops and kind of crashes. We'll see how Minachi's paper airplane does here. Well, that one-- I definitely had a low angle of attack, so it flew very well.

Let's see if I can get it to stall or if it's too stable of an airplane. That one-- basically, after it stalled, it basically went nose down, which is good. It has a little extra paper folding at the front so that the nose will go down. But it's really bad basically. If you stall, it can go that way.

The other thing that can happen after you stall a lot usually is you can enter a spin, which is actually the next case. So this is when you're uncoordinated in your stall. So what I mean by uncoordinated? So that's what I was just talking about before, where your roll and your yaw are not going in the same direction.

And here you can have a situation where both of the wings have stalled. So the airflow has separated over both of the wings. But one may be more stalled than the other. And it causes the airplane to have a very, very hazardous condition or an intentional condition if you're Oxsana over there, and you're trying to spin your airplane to do a fancy trick.

This is very dangerous close to the ground. As you'll hear, you only intentionally do this in certain types of aircraft when you're wearing parachutes in certain airspace when you're very high above the ground. You don't want to do this. And in fact, if you're just getting your private pilot's license or your PPL, you're not going to practice a spin because it's pretty dangerous thing to do in many aircraft. But you do have to learn about it and make sure you don't get into a spin.

So let's talk a little bit about maneuvering flight. So basically, that means when you were flying straight and level, that's kind of when you're at an equilibrium where your lift and your weight kind of cancel out. And the plane's just going straight and level at the same altitude. But climbing is when your lift temporarily exceeds the weight so you can actually climb.

So once you are in a steady climb, then you can actually still have your forces be in equilibrium. So remember f equals ma. So a is acceleration, which is a change in velocity. So if you're not changing your velocity, and you're just in a steady climb, then you're also not accelerating.

Now, this is a little bit complicated, so I will say this is a little bit tricky. There is a tendency for these airplanes to turn left. And there are actually multiple things that contribute to this left-turning tendency. And when you're in an airplane flying, you might hear your instructor say right rudder. And it is really to counteract some of these left-turning tendencies.

So we're going to break them down and talk about them. But this can be a very in-depth subject, so I will definitely refer to the PHAK, which is the *Pilot Handbook of Aeronautical Knowledge.* Chapter 5 goes into all of these.

So the first one is torque. So basically, the thing is when you're-- if you're sitting in the airplane, and you're looking forward at your propeller, most US engines actually have the propeller rotating clockwise. So and you can see that arrow that says action. That's the propeller rotating clockwise.

And so because of Newton, we know for every action, there's an equal and opposite reaction. So because the propeller is turning to the right, the whole airplane is trying to roll to the left. So that is the first left-turning tendency. Before we move to the next one, are there any questions on this left-turning tendency?

Great. So the next one is p-factor, which is an asymmetrical thrust. This happens when the airplane has a high angle of attack, so either when it's climbing or in this condition called slow flight, which is where it's kind of an uncomfortable thing. You have to do this in your flight training.

So basically, you have your power setting pretty high, but you've kind of pitched the airplane up. And so you're not getting as much airflow over your control surfaces like your ailerons and your elevator. So they call your controls mushy. So it's hard to kind of coordinate your airplane. But you kind of sit in that environment to basically understand how it's difficult to control the airplane in that environment.

So if you're pitched up, and you have a-- so you have a high angle of attack, and you're either climbing or in slow flight, you have this tendency where the-- because you're angled to the wind, the right propeller blade, which is descending, is kind of cutting into the air as it's coming in. So it's actually generating more thrust, whereas the ascending left propeller blade, so the propeller blade that's going up on the left side is kind of coming away from the wind that's coming at it.

And so it's not generating as much thrust as the right propeller blade. So that causes the center of thrust to move towards the right. And that creates a little bit of a yaw tendency of the airplane. Does that make sense? Great. Lot of head nods. P-factor was one that both Phillip and I spent quite a bit of time getting our heads around. And Professor Hansman helped us out there.

So another one is called the corkscrew effect. Sometimes, it's called slipstream or spiraling slipstream. It basically has to do with the fact that that propeller remember is just kind of like a wing that's spinning around. And so it's basically pushing the air back. And since the propeller is spinning around, that air that's coming back from the propeller is spinning around the airplane.

And as it spins around, when it comes up to the back, it pushes on the vertical stabilizer, that tail piece, and causes the plane also to do a left yaw. Does that make sense? Some good head nods. Yes.

AUDIENCE: Why doesn't it also cause it to roll?

TINA SRIVASTAVA: Why doesn't it also cause it to roll was the question. And it could, especially if it's hitting the wing. But in general, what we've seen is that it can depend on whether you're in a high wing or low wing. But the biggest thing that it sort of hits is here. Now, in general, when you get to a left yaw, you sort of kind of roll. These are connected angles.

But I think just what we've observed is primarily that the air, when it hits the vertical stabilizer, is the biggest surface that's kind of pushing it and the angle that it's at. So if you sum it all together, yes. I'm actually quite confident you'll get some roll, but the biggest thing that you notice is the yaw. So let's see if we understood p-factor as well as we think we did. A, B, or C?

AUDIENCE: A.

TINA SRIVASTAVA: A. Good job. I actually have my little hint there that the B is actually talking about torque, which is a different left-turning tendency. And then finally, we're going to talk a little bit about gyroscopic precession. It's a little bit complicated if you're not familiar with the gyroscope. But when Phillip talks to you about all the different controls in your airplane, you'll have to learn about gyroscopes all over again in a little bit.

But in general, what do you need to know about a gyroscope? What is a gyroscope? A gyroscope is something you can hold. It's spinning. You can play with them. What they allow you to do is have rigidity in space. And they also have this concept of precession. And precession is basically that the resultant action of a spinning rotor when a deflecting force is applied happens 90 degrees ahead of that rotation.

And so because of that, you can consider that the-- you have the propeller spinning, and that causes this gyroscopic precession. And that basically causes 90 degrees out of that sink is this force which causes a yawing movement, a pitching and a yawing in this case.

Once we talk more about gyroscopes and how they work, you'll also learn different flight controls that you look at in the plane, leverage these gyroscopes. And we'll come back and circle back to making sure we understand the key fundamentals of gyroscopes. Yes.

AUDIENCE: So why is p-factor a left-turning tendency and not a pitch up tendency?

TINA SRIVASTAVA: Sure. So let's go back to p-factor. So what we're talking about is the difference in the center of thrust. So the thrust, when you're straight and level, the thrust is just forward. But what we're seeing is that when the right blade, because when you're in a high angle of attack, the right blade is generating more thrust than the left blade.

So the center of thrust is slightly to the right. So that is why because it's to the right and not up or down. Up or down would cause a pitch up or down. But since it's to the right, that's why it's causing the yaw action.

AUDIENCE: So it is not 90 degrees ahead because of precession.

TINA SRIVASTAVA: So precession is separate. It is generating its own factors and dynamics. So both of these things are acting at the same time. So precession does in fact affect pitch just like you correctly recognized. But this is an additional factor that's happening is that since the center of thrust is actually moved to the right, it's causing the yawing. Did that answer your question?

AUDIENCE: No, but that's OK.

TINA SRIVASTAVA: You want to chime in, Phillip?

AUDIENCE: It's an external force, as opposed to generating by the propeller.

PHILLIP GREENSPUN: It's a little bit tough. I think, yeah, we should table it and refer you to that physics book *See How It Flies,* which has some of it. But the one thing I would add on p-factor is another thing to keep in mind is whether the propeller is advancing or retreating into the wind.

So if you think about it, when the airplane is level, the propeller is not moving relative to the oncoming wind. But if you tilt the airplane up, as the propeller goes down, it's actually advancing into the wind and getting a little bit of an efficiency boost that way. Whereas when it's coming up, it's going from the front of the airplane towards the back of the airplane. So it's retreating

TINA SRIVASTAVA: Yeah, so what Phillip's describing is why the right propeller blade is generating more thrust than the left propeller blade, which is what's moving the center of thrust. So I think the real thing to answer your question is that there's more than one effect happening simultaneously. Yeah, so the--

PHILLIP GREENSPUN: I'm not sure that you get gyroscopic precession from that action here because it's generating lift by pushing air. I'm not sure that all the thrust really has to go through, for p-factor at least, through the center of the spinning propeller. Also, I know in helicopters, the physics 101 answer is 90 degrees. But the real answer for engineering it is 72 degrees. So it does get complicated. Fortunately, it's beyond the scope of what the FAA tests you on because they themselves, I'm sure, don't understand it fully.

TINA SRIVASTAVA: Yeah. How about we come back after we've talked about gyroscopes in excruciating detail and then we have a set of terminology to talk about, let's come back to discussing that more. Thanks.

AUDIENCE: I have a simple question for you maybe.

TINA SRIVASTAVA: Yes.

AUDIENCE: Just to help me remember, why is it called p-factor? What is the p for?

TINA SRIVASTAVA: Power or propeller. So the p is referring to that propeller, right propeller more than the left. It also usually happens when you're at a higher power. So some flight instructors like you to think about when you have higher power in the airplane, you need to put on more right rudder to counteract that left-turning tendency.

PHILLIP GREENSPUN: We're a little bit behind. Should we take our bathroom break now and then--

TINA SRIVASTAVA: I'm actually almost done, so I think we can finish there. So one thing is to talk-- so we talked about with climbing flight, f equals ma. So once you're done changing the velocity, and you don't have a change in velocity, your forces are in equilibrium. So the same is the case with a descending flight. When you're actually turning, your forces are not in equilibrium because you're having this change in velocity.

And so you actually have a number of changes happening. And it's basically considered accelerated flight, which is same as when you're driving if you're turning. So when you're flying, when you're doing a turn, you're accelerating because you're constantly changing the direction of your velocity.

You also have load factor, which we'll get into in more detail when we talk about performance of an aircraft and how the load affects your performance. But another thing to think about back when we were talking about that zero gravity flight and a plane flying in a parabolic trajectory or a roller coaster when you're at the top. But when you're at the bottom of the roller coaster, you really feel like you're being pressed down into your seat.

In fact, when we run that zero gravity flight, although at the top, we had 30 seconds of weightlessness so we could do our experiments, when you go to the bottom of the parabola, you basically get 2G or twice what you normally feel. And so you have to kind of lay down and let that happen before you come up again. And so when you think about load factor, just think about you being at the bottom of your roller coaster and really feeling a kind of twice that force on you.

And then just to kind of end, we want to talk about most of the time we're talking about the planes that you'd be flying, but another type of aircraft altogether is a blended wing body aircraft. So just like this is one example of that.

So what it means is that that fuselage or that kind of tube in the middle that you sit in is blended into the wings so that the whole body is generating more lift because the whole surface is kind of designed that way. It's really kind of cool. And from an aerodynamic perspective, it's got a much better lift to drag ratio because the whole thing is really deflecting the air molecules downward and generating that lift.

So I just asked kind of a thought question. If this is so much better, it's more efficient of an aircraft and aerodynamically has much better properties, why do you-- it actually-- we've also found that it's better in terms of fuel efficiency because it has less drag and more lift. Why do you think that JetBlue and American Airlines don't fly aircraft that look like this?

AUDIENCE: They don't have routes with a thousand passengers.

TINA SRIVASTAVA: They don't have routes with a thousand passengers? Well, you could make a smaller blended wing body aircraft. Yes.

AUDIENCE: Passengers like windows.

TINA SRIVASTAVA: Passengers like windows. That's actually a big-- it's a big reason truthfully. Yes.

AUDIENCE: It's very different from what's currently made, so the development would be expensive and risky.

TINA SRIVASTAVA: So it's very different from what's currently made. And then you said so the development would be very risky. Actually, I think it's more than just the development. Because it's different from what's currently made, the entire infrastructure supports the current format of an airplane with a tube and wings.

So we're talking about airports, jet bridges, the way that people load food carts onto a plane, the way that passengers get on and off, the fact the passengers don't have as many windows on this type of aircraft. It's unfortunately that whole infrastructure that surrounds it that is a big contributing factor to why, even though there's a better design, why we don't move towards that.

So this was a big, big thing for me when I was an undergrad at MIT aero-astro. I'm thinking I'm going to design the next best amazing airplane. But even if you do design the next best amazing airplane, it may not be widely deployed because of these other infrastructure aspects, which really got me into systems engineering.

But enough with that thought exercise. For time, we'll just summarize what did we learn today. So we talked about how does an airplane generate lift? And we talked about different factors that affect lift. We also discussed that lift is very hard to calculate. And so we experimentally measure a lot of aspects of it.

And we discussed the different forces on an airplane-- stability, and kind of this left-turning tendencies, and some of the different aircraft configurations. So are there any questions about that?

PHILLIP GREENSPUN: Yeah, Tina, what do you think about let's do questions, let's take a bathroom break, and then--

TINA SRIVASTAVA: Yeah, so you can think about it.

PHILLIP GREENSPUN: People with questions talk. I'm going to call the pizza people and give them my credit card.