RANDY GORDON: Well, guys, you have picked the coolest independent activities period class you could ever do at ground school. This is the most awesome thing possible when I saw the course offerings. So kudos to Tina and Phil for teaching this. This is a good, good. Gig. I go by Laz. It's a fighter pilot thing. All fighter pilots have call signs. They're not like what you see in the movies.

By the way, *Top Gun* is the worst movie for any fighter pilot to watch. It's terrible, drives you crazy. No one is called Maverick because they're the most awesome thing on the face of the planet. Never happens that way. You're always named for something silly. So the previous discussion about crew resource management, if you're a single seat, you still have air traffic control, you have other guys, I am living proof that that's 100% true. So I won't get into it too much, but suffice to say, if you know the biblical story of Lazarus, you know a lot about how I got my name, and I'll leave it at that. Normally that's over a beer afterwards.

So we're here to talk about F-22 flight control stuff. I'm going to give you the punch line right at the start. I'm here to tell you that everything you're learning-- so who's actually flown airplanes here already, like sailplanes? So a lot of guys. So a lot of guys. So first time then for probably the other half of the class or so. So here's what I'm here to tell you. The same stuff that you're learning with respect to Cessnas and all this stuff with respect to the ground school, there's no difference between this and between my beloved Raptor. It's the same thing.

So there's great relevance. And you as MIT guys have the ability to derive and figure out what makes the Raptor look the way that it does, and we can talk a lot about the flight controls. It's not cosmic. We can go through that. So with that, they always have the standard personal background slide. Here's the gig. I'll keep it really simple. I am a test pilot, which means I am a fighter pilot and I'm also an engineer. It means I like *Beavis and Butthead* greatly, and I read Carl Sagan. It's the same thing to me.

So as a fighter test pilot, you live in the world of being a fighter pilot, but you also have the ability to understand Matlab and to be able to do cool neat MIT-ish kind of things. Because all of the stuff that you're working with as a test pilot are brand new things-- new weapons, new avionics, new airplanes, in some cases. And that's not the world of a fighter pilot. Fighter pilots are exceptionally good at taking this airplane to combat and doing the normal kind of missions with it. But when there's something new on board, that requires an engineer.

So I have a deep, deep connection with this institution. I finished up here last year in 2018. I've done a whole bunch of other kind of funky stuff along the way. Two combat tours. That was a lot of fun. I'll tell you, flying is one of my great passions. Flying and getting shot at and missed is my second great passion. That's much cooler. And then when you can fly and you can use that airplane to actually protect people from bad guys, that's life-fulfilling to go get a chance to go do that. So we can talk a little bit more through that as well.

Test pilots, we get a chance to fly a lot of different stuff. So you'll see this 76 different airplanes. That might sound weird to the rest of the world, but in the world of flight test, that's pretty normal. And the reason that's there is it's just like-- look, by the way, warning to the class, I talk a lot in terms of movies, *Game of Thrones,* or whatever, television shows and sports because no matter where you come from, those three topics always tend to bring everybody all together. So it is just like what you-- when you've gone car shopping and you sit in this car and go, oh, man, I really like the way this steering wheel feels but I hate the way the radio is set up, and you go to another car and you go, oh, man, this is great from the sunroof or whatever but this stinks.

That same kind of discernment that you have when you're shopping for cars, this airplane is a couple hundred million dollars. You don't want to be wrong about that, and so you want your test pilots very, very experienced in a lot of different airplanes. So I've got a chance to fly helicopters-- spectacular. In pilot training, I don't know why, but we send our worst pilot training students to helicopters. It's the dumbest idea because helicopters are really, really challenging to go fly.

But we've had a chance to fly helicopters. Your discussion, Tina, earlier about right of way, I was laughing with that because I've flown a Zeppelin, an airship. It's quite spectacular. It's a big Lab-Z-Boy couch with a big trim wheel and big engines that actually pivot on the outside, so you can turn the whole ship based on that. That's pretty normal for being a test pilot, is getting a chance to fly a lot of different airplanes, more so than just one particular airplane your whole life.

Most of my stuff is in fighters. So I've flown every frontline fighter with the exception of the F-35. Hopefully I'll fix that soon, shortly, in a few months. But a lot of stuff. So MIT guy, Harvard guy. Did some stuff. It's been a good life. Really, at the end of the day what I want to impress on you is I am 100% zero different from anybody in this room. I just have more battle scars on me just from a lifetime of doing this. I started off flying Cessnas. I did that for several years of my life. I still do it. I love it. Fly sailplanes. Still do it, love it.

And all the stuff that you learn with this has direct applicability to the more advanced fighter airplanes. In fact, I'll tell you, this is actually harder to fly than the Raptor, and we'll talk a little bit more about that as we go through. All right. So more fun and games. All right. So now comes the class participation part. My talks are very interactive. I love hearing what you guys think. So we'll do a quick thought exercise. I'll try and keep a mental note because I stink at writing on a chalkboard. But we'll chat through this just so you can understand that there's really not that much difference from what you're learning now to go off to do something like that.

So why does a Cessna look the way that it does? And why does a Raptor look the way that it does? What were the engineers trying to do? And just call them out. No real-- go ahead, just shoot.

AUDIENCE: [INAUDIBLE] Raptor.

RANDY GORDON: OK. So explain.

AUDIENCE: You have way more area that's clear [INAUDIBLE]

RANDY GORDON: So you brought up two things. One is the position of the wing, right. So in a Cessna, the wings are obviously-- well, in a lot of airplanes, really, not just Cessnas. But in the Cessna, the wings are directly above you, big Hershey bar wing. Why did they put the wings this way in a Cessna?

[LAUGHTER]

You're doing great so far. Keep going, man.

PROFESSOR: I'm going to answer that. Get in or out of a Cirrus in heavy rain, and you will immediately see the value of that Cessna wing.

RANDY GORDON: Yeah, they did this so that my wife doesn't yell at me in bad weather conditions, so that you can get inside the airplane with not getting completely wet. The other part about the high wing is it's great for visibility, looking down. Where this is terrible is if you're turning and you have to be able to see through the wing because you're kind of doing the old-- looking over the side to see out the outside. So that's one advantage over Raptor. It's not a high wing or a-- it's kind of a mid wing, if you will. But that wing is well after the cockpit for what reason?

AUDIENCE: Visibility.

RANDY GORDON: Visibility, yeah. That's the big, huge reason why. And then you also brought up the idea of the swept wings. Why the swept wings compared to, say, straight wings?

AUDIENCE: Well, wouldn't they have an aerodynamic advantage?

RANDY GORDON: OK. What's that advantage?

AUDIENCE: Something that [INAUDIBLE]

RANDY GORDON: Close. I'll stop picking on you because you're bold and went first. Go ahead.

AUDIENCE: Mach.

RANDY GORDON: Yeah, Mach. So explain Mach.

AUDIENCE: The closer you get to the speed of sound, the more compressibility is important.

RANDY GORDON: Yep.

AUDIENCE: Aerodynamically, the wing really behaves like it's going at the speed normal to leading edge.

RANDY GORDON: Yeah. So you ever see those old, the first jet airplanes that came out? The wings on the jet airplanes had wings that looked exactly like this, and that was a problem. I'm going to do something I said I wouldn't try to do, but I'll try to do it. So here's your swept wing. Here's the arrows that come over the wing. And then what ends up happening is, really what you care about is the air that's going over top of the wing, that's normal to the chord line of the wing itself.

You know what I mean when I say chord? Just like this imaginary line. So on a Hershey bar wing, all of that air hits the wing and it goes directly over top of that chord line of the wing. So like when we talked about over here, the wings have camber. So what happens to the air as it goes over top of any wing? Doesn't matter if it's a fighter wing or whatever else. But what happens to the velocity of the air as it goes over top? It goes faster, right.

So if I'm already going fast and air hits my wing and goes over top of my wing and goes faster than the rest of the airplane, that's going to cause a problem when you get to very high speeds approaching Mach because what ends up happening is you'll get a shockwave forming on that wing. And the moment you get a shockwave form in there, that's like a big brick wall to the wind and that causes all types of drag downstream, slows down the airplane, all types of things.

So what they found is I can sweep the wing. When I sweep the wing, some of that air is normal to the chord line. So if this is the fuselage over here, and here's the wing and it comes back over here, some of that air is going to be that way, and some of that air is going to actually go out and go span-wise, if you will, like this. So I'm trying to draw this correctly to get the right angles. But you get my point. So some of that air goes span-wise.

Some of the reasons why you have wing winglets, right, to prevent some of that drag that happens at the winglets. But then also what you're worried about is rather than the full component of this wind, you're only worried about the wind that's normal to the flow of the way the chord line is set up. So that's why they sweep the wings.

OK. So what else? Why does a Cessna look this way? Why does this look like that? Go ahead. Yeah, go ahead, both.

AUDIENCE: Stealth and payload and [INAUDIBLE].

RANDY GORDON: OK, so stealth. Payload is an important thing. Let's talk about the payload for a second. Actually, we'll talk about stealth since you brought it up. So look at that plan form, and what do you notice with regards to stealth?

AUDIENCE: It's all angles.

RANDY GORDON: All angles, right. That angle, that angle, that angle.

AUDIENCE: No right angles.

RANDY GORDON: Yeah, no right angles. So the reason is-- and I'll do my high tech pizza aid here. So who's Double E in here? Anyone Double E for MIT? OK. So if you're a beam of radar energy, you love this. You love when you have a nice flat thing directly that reflects. All that radar energy you put at me goes right back at you.

Now what happens if I take that panel and I go like this a little bit? So yeah, there's not so much. Now I'll really mess up your mind. What happens if I do that? And now you have to start dealing with angles and edges. The Raptor is this constant fight between the Double E guys and the aeronautical engineers. When you make an airplane like this and you make angles like this, and you make it there's no right angles or whatever else like that, you're exactly right, it greatly reduces the stealth.

Now, this is not Wonder Woman's airplane. It's not like you just become invisible and no one can see you. But it's very, very hard to see on radar. But there's a challenge in that because when you make an airplane that looks like this, which the Double E guys tend to like, the aeroengineer guys tend to hate because it makes the airplane unstable. So we'll talk about that. This airplane, very, very stable, very, very stable.

OK. What else? A couple other things. So why is the Raptor look this way? Why does the Cessna look this way? Go ahead.

AUDIENCE: I feel like the Cessna is designed to be produced with cheap commodity materials. The Raptor uses exotic metals.

RANDY GORDON: Yep, titanium, whole types of stuff, right. So this is an airplane people buy commercially. If you were Jeff Bezos, you would never purchase this airplane because it is hyper expensive. My jets were test jets, which means they were very different, almost like hand-built custom F-22s. Each one, $300 million to $400 million a piece. Scary in terms of how much it actually costs.

The canopy on this thing, probably worth more than about 10 of these all put together. The payload part-- you brought up payload, too. So the other part about the stealth, if you can see here, I've got doors. So there's a big main weapon bay door, big 17-foot doors, if you will. And then there's doors on the side that come open here. Unlike a Cessna, we talked about-- where did Tina go? Oh, she disappeared. The dropped object, dropping pumpkins.

My pumpkins are 1,000 pounds, come off the airplane just like that. Different missiles and different bombs or whatever. The center of gravity of the airplane is right about where my finger is. And so these weapons that are here, when I release them, it's suddenly like dropping a car off the front end of your airplane. And so there's a huge center of gravity shift that happens just like that.

And so the flight controls need to be able to compensate for something like that. Last piece I'll give you just for sake of time is, what's the speed envelope, if you will, that this airplane operates?

AUDIENCE: [INAUDIBLE]

RANDY GORDON: What's up?

AUDIENCE: [INAUDIBLE]

RANDY GORDON: Oh, I wish 200. Man, I wish 200. I would buy one right now if I could go 200 in this thing.

AUDIENCE: About 160.

RANDY GORDON: Yeah, on a good day. You might get, if you get a really, really high end general aviation airplane, 160 knots or so, something like that. You can get more than that, but then you start getting into some real, like, Mercedes Benz exotic class, general aviation planes that are like the Cirrus that go beyond there. In general, you're talking somewhere between 80 and about 140, 150 for most of them, or something like that.

Believe it or not, this airplane can actually fly as slow as a Cessna, but it also can fly two times the speed of sound. And it does that pretty easily, believe it or not. Also, this airplane, 60 degrees of bank starts to get really extreme, a little bit uncomfortable. This airplane, fully aerobatic, doesn't care. Pulls 9 g's. You guys know what g's are? The accelerations of gravity.

So my human head-- well, MIT heads weight about 20 pounds or so, a little bit more than the norm. So at 9 g's, everything on your body weighs nine times as much. So that's 180 pounds. Your neck has to be able to support that. Imagine everything on this airplane has to be stressed such that it can tolerate that load and more. Also, it can go negative g as well.

Altitude-wise, I think the highest I've ever had a Cessna was about 14,000 feet. And it was wheezing. I mean, it was really, really hard for it to get up there. This airplane goes 0 feet all the way up to about 60,000 to 65,000 feet. So it flies twice as high of what you would see on your commercial airliners. What I'm trying to impress on you is it's a huge flight envelope with a very different solution set compared to what you might have on a Cessna.

The only other thing I would say with Raptor is-- and this was something that took me a while. My first combat mission, I really understood this. In a Cessna, if I have a problem, I can land and most likely people will come out to help me and call home and let everybody know I'm OK. In bad guy land, if people are coming to get me, they really are coming to get me. So you're in very hostile territory where you do not want to leave the airplane if you can avoid it.

So there is a tremendous amount of redundancy that's built into this airplane. We'll talk more through that a little bit. So anyway, you've essentially derived all of the challenges that a flight control engineer would have to deal with. Let's talk a little bit about-- I'll put this here just for sake of making it easy to rest. This airplane has what's called reversible flight control system. What does that mean? You guys talk about that yet? Go ahead.

AUDIENCE: I think it's basically [INAUDIBLE] or when you move [INAUDIBLE]

RANDY GORDON: Yep. So not only when you move the stick. What happens if you go outside the airplane, grab the aileron, move that up and down? What happens inside?

AUDIENCE: The stick--

RANDY GORDON: The stick moves, right. So it's reversible. I move the stick, and the flight control surfaces will deflect. Or I move the flight control surfaces, and the stick will deflect. So they are directly connected with pulleys and cables to one another. For the guys who have flown, what does the airplane feel like when you get to 100, 120, 130, 140 miles an hour? I mean, what does it feel like on the control surfaces?

AUDIENCE: Heavy.

RANDY GORDON: Yeah, so it gets heavy, it gets real stick kind of heavy. Same thing if you're slow, everything gets kind of sloppy, if you will, because you are directly feeling the air loads on the airplane as transmitted to the stick. In this airplane, these flight control surfaces, this tail surface back here is about the size of a lot of fighter wings. It's huge. And you can imagine at 120, 130, the airplane is really hard to really move.

Well, what happens if you're going 1,000 miles per hour? You could be Arnold Schwarzenegger. You do not have the strength to maneuver these controls around. So this airplane has a very, very exotic hydraulic system and a computer system and an electric system that allows all that to operate. From the hydraulics, I'm not kidding, there's like 4,000 psi of hydraulic fluid that moves this whole thing around, swings it back and forth.

From the electric standpoint, now, again, this is a reversible flight control system, all manual. The flight controls in this airplane don't work unless the electrics are turned on to go do it. So your flight controls are electrically controlled-- hydraulically powered but electrically controlled.

Which is a little weird when you think about it because now all of a sudden, electrical problems in this airplane start impacting your ability to fly the airplane, which gets a little bit strange.

You guys ever hear of a thing called a permanent magnetic generator? Do you know what that is? A little bit of a technical term. Who knows? You know a lot. Go ahead.

AUDIENCE: Is it a type of generator that uses permanent magnetic energy?

RANDY GORDON: Outstanding! Yes, you have correctly derived the definition of a permanent magnetic generator. No. The way it works is this airplane has six permanent magnetic generators. They are the primary source of flight control power. All that has to happen is the engines have to rotate. That's it. So even if the engines are shut down, I can just keep wind going through the engines and they rotate, they will rotate sufficient to generate power from the permanent magnetic generators.

If those fail, the airplane also has electrical generators on board. There's two of them-- there's actually three of them on board. They can power the flight controls as well. Worst case scenario for a Raptor pilot, the engines seize up, I lose my electrical power. The only thing I have left is a battery. And just like anything else with a battery, the more you use it, the more it depletes. So at that point, any deflection of the flight control surfaces depletes the electrical energy and you don't have that much left to actually control it.

OK. One last thing here and we'll move on to the next slide. We'll talk a little bit-- just some definitions. The wing has this thing on the front. Do you know what that's called?

AUDIENCE: Leading edge.

RANDY GORDON: Leading edge flaps, right. OK, perfect. All right. What's that called?

AUDIENCE: Ailerons.

RANDY GORDON: Ailerons. What did I hear? I heard something else.

AUDIENCE: Flaperon.

RANDY GORDON: Ah. Who said that? OK. Explain.

AUDIENCE: It's a combination of both flap and aileron. Flaps are on the outside, ailerons are on the inside. And-- no. Did I get that backwards?

RANDY GORDON: Yep, other way around.

AUDIENCE: Other way around. And depending on which [INAUDIBLE] of flight you're in, you either have full use of those control surfaces or part of it is dedicated to the flap and part of it is dedicated to being the aileron.

RANDY GORDON: Yeah. Outstanding. That's good. And this airplane-- this airplane has what? Ailerons, right. So if I want to go right and I move the yoke right, what happens to the ailerons here in this airplane? Sorry, I'll put it that way. That way, you're setting up. So I'm going this way. So this aileron is doing what?

AUDIENCE: It's going that way.

RANDY GORDON: Going that way, right. This aileron is doing what?

AUDIENCE: Up.

RANDY GORDON: Up, right. So I'll cut to the chase. These are ailerons, these are-- so these are the flaperons here on the inside. These are the ailerons. In a Raptor, those aileron deflect differentially. So just like you have in a Cessna, they can also both deflect up, they can also both deflect down. The flaps on the inboard are flaps and ailerons-- flaperons. So they can deflect up and they can deflect down. We'll show why that brings up some neat stuff.

OK. Rudder, obviously back here. In this airplane, when I push the rudder left, the rudder deflects left, I deflect right. This has two rudders. Both rudders can deflect one way, they can deflect the other way. They can both deflect in, and there's some reasons why you'd want to do that. And they can both deflect out. The last piece I'll give you is back here, normally this would be called an elevator, but on a supersonic airplane we call these horizontal stabilizers.

If you guys have read the story of the Bell X-1, so Chuck Yeager when he went supersonic-- we talked a little bit earlier about supersonic shockwaves forming on the airplane as you start going fast. What Chuck Yeager discovered is that the elevator, like in a traditional Cessna, that horizontal stabilizer does not move. So the elevator at the back moves, but this part stays fixed.

That shockwave that would form right here would actually blank the air back to the elevator, and they wouldn't have any pitch control. So when they talk about this thing called Mach tuck, which was a scary, scary thing that happened to a lot of World War II fighter pilots when they got into a dive-- they would start forming shockwaves on the airplane. They didn't have the elevator authority to pull up, and so they would actually nose dive all the way in because they go faster and faster and faster heading down. The answer was rather than the back end of this thing maneuvering, the entire surface moves.

So as a fighter pilot, especially when you got people walking underneath the airplane because they're maintainers, they're working on things, you always, always, always, you show them your hands. Because if you tap that stick, again, the stick is not directly connected just like it is, the stick's connected to a computer. The computer votes and it allows things to happen. It then commands a 4,000 hydraulic psi system to deflect basically this big old wing. You can actually take a guy's head off with the flight control surfaces. So you always, always show your hands whenever you have people walking underneath the airplane for that.

So it's got a very, very advanced flight control system on board. We'll talk through a little bit about what advantages that gives you. The last piece I'll give you is the engines at the back, which are a thing of beauty. I was a propulsion guy, aeronautics engineer kind of thing. It's almost like modern art masterpiece to me. Those engines have the ability to call what's called thrust vectoring. They'll swing up and they'll swing down. Where would you want to use that? Why do the engines have thrust vectoring? You've answered a lot today. You're smart, though. You know what's going on. Go ahead.

AUDIENCE: Very low speeds.

RANDY GORDON: Very low speeds. Outstanding, yep. Where's another regime? Think of the flight envelope of the airplane.

AUDIENCE: Yeah, very high altitude.

RANDY GORDON: Very high altitude. So why high altitudes?

AUDIENCE: A little lift from the wings, or the wings could be small so--

RANDY GORDON: Yeah, yeah. Density goes way down as you go up in altitude. So if I deflect-- I mean, I have to get more deflection to move that air to be able to move the airplane if I'm relying just on the aerosurfaces alone. The way I get around that is I put two 35,000 thrust pound engines, if you will, on board the airplane. And just like a fire hose, if I grab a fire hose and I move it, you would feel that torque on your body, the same thing here with the thrust vectoring on the back.

So with just the movement of my hand, I can deflect 70,000 pounds of thrust way at the back end of the airplane. So we talked about center of gravity being right about here. So that moment arm of that thrust force is all the way back here, and I can deflect that up. And at very, very low speeds, where the flight control surfaces might not be doing well, I can still move the airplane just by using the thrust alone. At high altitude, where I don't have a lot of density, same thing, I can maneuver the airplane just by using the thrust alone.

So where that helps you-- because, again, this is a dog fighter. Here's what happens, and you'll see this from time to time. So I'll do this with a side look. When I get to high angle of attack, so the wind is coming like this and it's hitting the bottom surface of the airplane, I don't have the ability to really maneuver a lot because sometimes some aerosurfaces are blanked by just the size of that fuselage coming right out into the wing. So I cheat, if you will, by using the engines to get that final little pitch rate.

We'll see later on in the Raptor demo video where the airplane will go-- it's called a high alpha loop, high angle of attack loop. It'll go vertical-- rather than doing a loop where you see it prescribed this whole path over here, the airplane will go vertical. I'll engage the thrust vectoring, and it'll pivot. So the velocity vector is still heading straight up, so the airplane is still moving up. But it kind of does this gymnastics thing where I've now turned the airplane using thrust vectoring, even though the airplane is still heading straight up. It's wacky. It's totally cool.

All right. Let's talk through a couple other things. OK. So that's the flight controls. How we do in timeline? OK. We're looking pretty good. Anyone recognize the cockpit on your left?

AUDIENCE: F-15.

RANDY GORDON: F-15, yeah. Outstanding. Good. This was my very first airplane. I didn't know any better. I sat down I said, wow, what a cool cockpit. Look at all this cool stuff. Buttons everywhere and switches all over the place. This is an airplane of the '70s, designed when Richard Nixon, Jimmy Carter, that kind of era, if you will-- very, very first intro to solid state electronics. Really wasn't fully fleshed out at this stage. This airplane had a hydro mechanical system, which meant that just like in this airplane where there were cables and pulleys, a similar kind of flight control system in it there.

This picture is the Raptor's cockpit on the inside. Some pretty dramatic differences between the two. So again, just call them out. What do you see?

AUDIENCE: Glass cockpit.

RANDY GORDON: Glass cockpit. Where does that help you?

AUDIENCE: I say the glass is cooler.

RANDY GORDON: Go ahead.

AUDIENCE: It can be display.

RANDY GORDON: What's up?

AUDIENCE: It can be multi-display. You can change it to--

RANDY GORDON: Oh, yeah. It's great. You can see these new digital cockpit Mercedes Benz and BMWs or whatever, where in the old days you just had speed and tack, if you will. Now you can configure it however you want. Now, the moment you start putting that in there-- no, got it. Yeah, the moment you start doing stuff like that, you start creating a software airplane, which gives you a lot of flexibility and a danger. We'll talk about that one a little bit later on. What else do you see flight controls-wise since we're talking mainly about flight controls today?

AUDIENCE: Side stick.

RANDY GORDON: Side stick, yeah. So right there is the control stick in an F-15. Sits directly between your knees. In a Raptor, that is your control stick. It's on the side. Why would you ever want to put something like that on the side? Go ahead.

AUDIENCE: [INAUDIBLE]

RANDY GORDON: That's part of it. That helps. And there's actually-- you can't see it. Here it's partly there, but this little section here, it's a foldout armrest. So your wrist is on the stick. Your elbow, if you will, it's resting on an arm rest. So it gives you a lot of leverage from there. That's one reason. What's a couple other reasons why you'd want to go side stick versus center stick?

AUDIENCE: Your legs get in the way on the center stick.

RANDY GORDON: Legs get in the way. That's a big deal because in this airplane, you actually got pretty good after while of flying it, where if you really need to maneuver the stick, you kind of do the leg up and kind of move over that way to get everything out of the way. The other side about it, too, it might not be quite so obvious, but you see how that stick-- that's about where your eye height would be. You see how that stick kind of gets in the way of seeing some of the instruments? It's just sitting right there.

In a side stick, that's completely off to the side and all of this real estate is completely open. The other thing I'll give you, again, just for sake of time, it's a little bit of a thought change. When you have a center stick, it's like when you're driving a car. And when you're parking-- you're trying to park your car, you want to be able to maneuver that wheel around a lot. But when you're at highway speeds, if you were to take the wheel and maneuver it that much again, you're going to roll the car. So in a center stick, you move the stick around to be able to deflect the flight control surfaces.

There's a physical displacement of the stick to make that happen. On a side stick, that stick, initially when they first put it in, did not move at all. So imagine if you were in your car and you wanted to steer, and rather than the wheel actually moving, you just put pressure on the wheel itself and that was enough to transmit to the computer in the car to turn the wheels. That was a problem initially, which we can talk about after the presentation. That's a little bit of a sidebar discussion. This is a human factors thing.

It's a side stick. Initially it didn't move. Eventually they decided, I'll put in some deflection. So I can go a half inch left, a half inch right, about a quarter inch forward, I go about a half inch back because normally I really want to get the nose going this way. If I had that much deflection forward, I don't want to fly the airplane this way. So you have the ability to do that. But it gives you a little bit of the best of both worlds. There's some deflection to give you feedback that you've input something on the stick, but not so much deflection that it gets in the way of everything else you're trying to do. So there's a little bit of real estate in the fighter cockpit.

The last piece I'll give you, and it's a little bit hard to see here, is all those buttons there on the stick. What you have the ability to do-- so it's exactly like modern car steering wheels right now. You can control volume, radio, everything else like that, you can do it from the steering wheel. Same thing in a fighter. It's called hands-on throttle and stick, HOTAS. And it allows you to control everything that you would want to do on the airplane with never having to leave your hands from the throttle on the stick.

The other piece I'll give you is that in a Raptor-- so in a fighter like this, this is your stick, this is your throttle. In a Raptor, because the flight control modes can change so much, this is your right inceptor and this is your left inceptor. It's all considered part of the flight control system. All right. Let's keep going. So just like on your car where if you want to go to XM radio, you go to media source or whatever and go XM satellite radio, you have buttons because it's a software-driven jet, just like we saw before, and I can pull up a flight control display that shows me the position of all my flight control surfaces.

Again, the pilot is way forward on the front end of this airplane. As I deflect things, sometimes I can't actually see them. And so initially, this was a flight test display so that I don't have to do the old poltergeist thing and try to rotate all the way around to be able to see to the back end of the airplane to see if the elevators moving. I basically instrument everything and I can see it here. Now, some of the human factor stuff that's kind of cool with how they did this-- so again, this tells you, at the top, rudder deflection surfaces, ailerons, where the horizontal stabilizers are at, how the engines are doing.

This is a little weird. I don't really like how they did this one, but this is the leading edge flaps, LE flaps, the leading edge flaps. So it just shows you how far they're deflected, dug in, dug down. On the lower left-hand corner, it shows you center of gravity. So there's limits. Just like what you would normally do on flight planning for your Cessna-- hey, I can only put this much fuel with this much passengers, and I've got to be within this limit for takeoff, for landing and everything else, the airplane tells you that.

Now, what's cool about some of the things they've done in Raptor is that if it's out of limits, again, it doesn't expect you to get out the piece of paper with the whiz wheel and the E6B. It just changes color. It goes red and it gives you a warning that says, hey, idiot, you are beyond the aft center of gravity. No gauge tells you it's just having a hard time seeing where all the fuel is and everything else. That's a different story. But it tells you what percentage of mean aerodynamic chord that you're sitting at and it's able to adjust stuff around.

So I'll give that to you because what this allows is-- oh, by the way, the last part here is flight control-- so in other words, this tells you where you moved your stick and it tells you trim. So you know where the trim is set, and it also tells you where the stick is set. So you know your inputs that go through there. When you have a software-driven machine, you can customize things and make it very simple.

You guys have seen that terrible, terrible awful movie *Top Gun,* right? It's just awful, right? So that scene where Maverick loses his engines and they go through this, engine one is out, engine two is out, and they go on this flat spin to sea, which is a bunch of BS. When you're in a spin, you don't translate over the ground, you fall straight down. So this whole flying out to sea thing is ridiculous. It doesn't happen that way.

If you don't have a software-driven airplane, when you lose engines like that, then you've got to go through this whole-- for instance, in the Cessna, if you lose the motor, what do you got to do? Establish your glide, get everything set up, check to see am I my left, right, or both on the fuel source, what's my whatever, blah, blah, blah, and everything else. In the Raptor it's the most awesome thing possible, you literally do nothing. You sit there and the computer goes, oh, you've lost a motor. I've noticed that you have a problem. Let me see if I can help you, and it will restart the motor for you if it can.

If it can't restart the motor, chances are it ain't going to restart and you can leave it shut down, if you will. It allows some neat human factor designs because in this airplane-- in the Raptor, believe it or not, when you're flying the Raptor, you're not thinking about flying the Raptor. You're thinking about employing the Raptor. So you're trying to find where all of your wing mates are, where the bad guys are, et cetera, et cetera. Flying is secondary. Whereas in this plane, flying is everything. So they tried to as much as possible alleviate the pilot from as much burden of responsibility of thinking about flying the airplane by doing neat little tricks like that.

The other thing I'll give you too about the flight controls is, again, we talked about how ailerons can go up, ailerons can come down, flaperons go up, they go down, rudders come out and go down. On takeoff mode, I'll show you something kind of cool. So here's the nose look on here. On takeoff mode, without any input from the pilot-- so there's no flap switch in the cockpit, there's no leading edge, there's nothing like that. It just knows, based on the fact that you've got the gear handled down and that you're on the ground, that it senses the weight on wheels, it thinks, this guy wants to take off. So the rudders will both deflect inward. Why would you do that? Go ahead.

AUDIENCE: [INAUDIBLE]

RANDY GORDON: So not quite. There is a tie between the flight controls, though. So in other words, if I take the rudders and I tow them both in, so both rudders are deflected in, what does that do from an aerodynamic standpoint? Which way's the nose going to go if these rudders are deflected in?

AUDIENCE: Up.

RANDY GORDON: Up, right. So it makes it easier to rotate the airplane on takeoff because the rudders are deflecting in. Both of them go in. The other part about it too is-- so we talked about this. You guys ever see a competition aerobatic, one of those extra 300 kind of airplanes? See how the aileron runs the entire length of the whole wing? So the pilot, all they got to do is just tap the wing and the airplane is going to do corkscrews and spirals. On a Raptor, that's part of the reason why the aileron and the flaperon can move together as one surface. And so the leading edge flaps will dig in. The trailing aileron and the trailing edge flap, that will dig in as well.

So on takeoff, with no input from the pilot, whereas the wing normally would look like this with a little bit of camber on it, on takeoff the wing looks like this. It's kind of cool like when you look at from the side. So if you're looking at it from directly side on, that leading edge flap comes down, these come down. That puts in a whole bunch of camber on the wing, and it generates a lot of lift. And again, that's completely independent of the pilot. The pilot has done nothing other than just tell it, I'm on the ground because the gear handle is down.

PROFESSOR: Laz, what would be a typical rotation speed?

RANDY GORDON: Yeah. So that's a good question. What do you guys think? So I start on the runway. By the way, I need 8,000 feet of runway. This whole 2,500 feet is not for a Raptor, unfortunately. 8,000 feet of runway. But by the time I actually get ready to pull back on that stick to rotate, how fast do you think it's going?

AUDIENCE: [INAUDIBLE]

RANDY GORDON: Little close. 150 is the usual-- so about take off-- which, by the way, this airplane is about 34, 35 tons on takeoff, compared to 2,500 pounds or whatever. So it's a very heavy airplane. It's got to get a lot of speed to be able to get that rotation. But it's about 150, 160 knots on takeoff, which is faster than the never exceed speed of the Cessna, as it goes. But yeah, so the flight controls are there to help you. The other thing I'll show you too is there is-- so sailplane guys-- where are my sailplane guys? Anyone fly sailplanes?

So on the left in a sailplane cockpit, you typically have a lever for the speed brakes, spoilers, so these big surfaces that pop up on the wing to slow the airplane down to just glide slopes and those sorts of things. We talked a little bit earlier about how the electrical engineer guys want this thing to be completely stealthy and whatever else. The last thing you want to do, based on the discussion we just had, is I don't want to have a big board stick up in the middle of this airplane because that's going to make my radar reflection go very, very large. So they did something kind of remarkable. They used the flight control surfaces themselves as the speed brakes.

So if I need to slow the airplane down, I hit a little switch on the throttle. And immediately what happens is the leading edge flaps will come down a bit, the ailerons will both go up, the rudders will go out, so they'll both tow out. And it's using that to help slow the airplane down. It's actually quite effective, which is pretty cool. All right. A couple other things we'll go through. Landing mode. Pilot's done nothing. Touchdown, throttles are back, gear handle's down, and all of this stuff happens. Here, let me get this zoomed in here.

So that's the aileron. It's up. Holy crap. The other one's up, too. The flaperon goes up on either side. The rudders, you can see how they're both kind of towing in there a little bit. The reason it's doing that is it's trying to transfer all of that weight from the wings and put it into the gear. So it's trying to kill all of the lift on the wings and transfer that to the landing gear so that you have the maximum traction on the wheels as you hit the brakes as you slow down. Also, on refueling-- so when you go air refueling, there's a little switch that you open in the jet. That opens up this door. That tells the jet that I'm getting ready to refuel while I'm airborne.

When it does that, it says, this guy isn't trying to dogfight the airplane anymore. They're trying to get gas. So therefore I don't need all the full roll capability and everything else, and really, what I really want is an airplane that's really responsive with its lift. And so, again, no input from the pilot, but the leading edge flaps will deploy down, the trailing edge flap and the ailerons will also deploy down. Again, they're trying to create camber on that wing. This is all digital flight controls. No input from the pilot whatsoever.

PROFESSOR: Laz, what would a typical airspeed be when doing this air refueling?

RANDY GORDON: This is about-- oops, sorry. Let me go back one here. This is about 300 knots or so, something like that. You've got to be able to fly-- so for a Raptor, that's kind of slow. For the tanker airplane, that's somewhat fast. So you're trying to find that marriage where both airplanes have good flying qualities so that one's not about to stall and the other one's in full power trying to catch up to him. By the way, the most unnatural act I've ever done as a fighter pilot is to connect up my airplane to another airplane. I just never got used to it. I can do it just fine, but the whole notion of this big boom connecting my airplane to a big airliner was just really strange and weird to me. Never got used to it.

OK. Some of the limiters. So in an F-15, because we talked to that a little bit earlier, you can get up to 500, 600 miles an hour. You can take both hands on the stick, you can pull that stick all the way back, and you will rip the wings off the airplane and you will turn it into a big ball of metal cascading down to the ground because you have over-g'ed the airplane. Again, that awful, terrible movie *Top Gun* in which Tom Cruise departs the airplane and gets into a spin, again, you've exceeded some capability of the airplane and the airplane departs controlled flight and gets into some type of uncontrolled situation. On a Raptor, there used to be in the pilot operating manual a little blurb that said quote you can maneuver this airplane with quote reckless abandon, and you will not over g the airplane, you will not depart the airplane from controlled flight.

They did a spectacular job allowing this airplane to get right to the edge of performance but not going over the top. So one of the neat things that they did-- airplane is in a left-hand turn. Look at that aileron. It's up. Look at that aileron. It's up. What the crap is going on there? And if you know this one, you really do get the model because I didn't know this for a long time. So again, just for sake of time because I know we've got guys coming in afterwards, center of gravity of the airplane sits right here. In your engineering classes you always talk about forces acting on the center of gravity. And you take this whole airplane and you model it down to a point mass and you say that's-- for sake of all the sum of forces analysis.

Well, in real life this airplane's about 43 feet wide. Yeah, you can sum the forces through there, but there's forces acting all over this airplane at different spots. Think about here on the wingtip. I put g on the airplane. And this wing tip, it's almost like the wings want to bend up as I'm coming down. So you put a lot of stress out on the wing tips. So their answer, quite ingeniously, was to deflect the ailerons down when you're at high maneuvering. The way you know you're at high maneuvering is you can kind of see these little wispies forming off the wingtips.

So you are creating low pressure. That's another one, too. You can see the clouds forming on the front edge of the wing. Low pressure causes that air to condense, and so you make clouds. So you know the airplane's really maneuvering up. And an answer to reduce stress at the wingtips was to deflect the ailerons up. What happens to the lift out at the wingtips with the ailerons up? Goes down, right? So it helps to push those wings back down again so you're not trying to overstress the airplane. There are limiters like this all over the airplane, such that you won't over g the airplane. Literally, you can do anything you want to this airplane.

That's what I'm telling you, it's easier to fly a Raptor than it is to fly a Cessna because you really have to pay attention to what you're doing in a Cessna. In a Raptor, I could put my kid in there and he can do this all day at whatever speed, and nothing bad will happen to the airplane. It's really quite spectacular how they did that. The other part I'll give you here is some of the command systems. So if I'm in a dogfight and I'm trying to shoot the other guy, I'm going against a maneuvering target. And so the flight controls transfer over to what's called a g command system.

So if I'm maneuvering at 4 g's and I let go of the stick, the airplane will stay at 4 g's. And if I see that the target's maneuvering and I need to go to 6 g's or 7 g's, I'll put that in and the airplane will keep that. So in other words, again, it's a vote. I'm not physically connected to anything. I talk to the computer and I say, I want 6 g's. And the airplane does all types of black magic and sorcery behind me, and Lo and behold, the airplane gets to 6 to 7 g's. That really matters when you're in a high maneuvering kind of situation, so it goes g command.

When you're slower, i.e. on landing, and I want to put that flight path marker right on that edge of the runway because that's where I want to touch down, right at the 1,000-foot markers, then in that scenario, I'm not really caring so much about g command, I care about pitch rate. And so it transitions over to a pitch rate command. And if I put no input on the stick, it says zero pitch rate, again, black magic and sorcery will happen behind me. The flight controls will do whatever they need to do to make sure that my pitch rate stays at zero. So it transitions from one type of light control system to the other. No pilot input whatsoever. It's just based off of flight command system.

All right. So let's talk through a couple of the implications of that, and then we'll go to questions at the end. Can you do the flight control video Raptor at the top? It's about a minute. And then bring it up to full screen and hit pause.

[VIDEO PLAYBACK]

[MUSIC PLAYING]

Got to love that music. Stop.

[END PLAYBACK]

Thank you.

PROFESSOR: OK. This one is full speed and pause.

RANDY GORDON: OK. And can you go back to the beginning on it real quick? OK. So video in cockpit facing out to the display screens is a big no-no because you could see stuff. So we won't even bother with that. But what they did, this is the Raptor Flight Demonstration Team. This is out of Langley Air Force Base Virginia. They mounted a camera in the cockpit facing aft. What I love about this is, again, you can see real quick what's going on with the airplane. So again, the leading edge slats, there's no input from the pilot other than just maneuvering. They'll deploy wherever they need to. You'll see the horizontal stabilators And if you're close, you can actually see what the ailerons are doing and what the flaperons are doing.

A neat trick, and we'll see this as they go into this high g demo. Do you guys know about-- this gets a little bit advanced, but a thing called static margin, which is a stability thing about this airplane. Again, this airplane, in its bare airframe configuration, no hydraulics, no computers, nothing on board the airplane, totally unstable. What keeps it stable is the computer itself. What you'll see is you'll see this maneuver where he'll go into a g turn and you'll see all those clouds forming on the back end of the airplane. Pay attention to what the leading edge flaps are doing. They're digging in.

The horizontal stabilators, you'll see them initially move to get the turn going, but then once established in the turn, the way it's controlling things is it's moving around the aerodynamic center and the center of gravity. It's doing that by dorking around a bit with the lift on the wing, and it's doing that by deflecting the leading edge flaps. So that flight control surface display I showed you earlier, the horizontal stabilators would be completely streamlined. And all of the maneuvering is coming from the wing itself, which is pretty amazing.

PROFESSOR: Next video?

RANDY GORDON: No, no. Go to flight controls. We'll watch that.

PROFESSOR: Go back, then?

RANDY GORDON: Yep, and then we'll just watch as it goes through, this time without the funky club music, I guess, hopefully.

[VIDEO PLAYBACK]

[MUSIC PLAYING]

[INAUDIBLE]. The horizontal stabilators are streamlined. [INAUDIBLE] Incidentally, watch the flight controllers in the back.

AUDIENCE: Oh, man. We need somebody better here.

RANDY GORDON: I know, totally.

[LAUGHTER]

So at that speed, again, it's the g command system. The pilot is commanding a certain g rate. And miner deflections are happening all the way here back along the back edge of the airplane. The pilot has no input on that. The system is doing everything possible to command that g that the pilot has asked for. You'll see one other maneuver here. Pause for a second. So what this maneuver is is-- and again, slow speed. Airplane's going straight up, and what they're trying to do is basically pitch forward completely and get the airplane-- so it's almost like you're flying an L, like you're going straight up and then you want to pitch forward and then accelerate out horizontally that way.

The way gets that is through that thrust vectoring that happens. But as that maneuver happens, again, all the pilot is doing is just doing a direct push forward on the stick. Watch what happens to all the flight controls in the back of the airplane to keep that airplane going exactly where the pilot wants it to. Play. So you'll see huge deflections out of that horizontal stabilizer. It's kind of neat. You can keep playing.

So what you're seeing there is, from the outside of the airplane-- we'll see this more on the demo-- is the airplane is essentially pirouetting in the sky. So it's falling straight down, but it's very controllable. It's flying at speeds about 60 to 65 miles an hour, but very, very controllable. And you'll see every bit of flight control surface on the back end of this airplane deflecting to do what it needs to do. So don't think of it in terms of aileron, elevator. It's a little bit fluid when it comes to a Raptor's stuff. Stuff happens back there.

PROFESSOR: Touch and go video?

RANDY GORDON: OK, so this shows a little bit of-- yeah, you can go ahead and play that. And hit pause for a second. We'll just do the setup. OK. So very quick, the setup for this video, this is the downside of a digital flight control system. Because on this airplane, again, it's pure cables, pulleys, it's ratios and gears and stuff like that. On this airplane, it's software code. It's zeros and ones, and you better get it right. And everything is interconnected. We talked about how moving the gear handle tells the flight control system something different. If I open the air refueling door, it tells the flight control something different.

In this case, the power setting of the airplane tells the airplane something different. One of my good friends, test pilot, outstanding guy. So don't think of this as he's a bad pilot. He's not, he's awesome. But the jet believes something that wasn't really true because there was an error in how the software was coded. And you'll see the first approach-- he'll take off again on what's called military power, so they're not using afterburner, and the airplane behaves just fine.

The next time around, he goes around using afterburner power, so you'll see fire come out of the back end of the airplane. And that changes something in the flight system for the engines, which tells the flight control computer a different condition. And what ended up happening is that the gains, if you will, of the stick were completely off. So again, this would be like if you were on a highway speed and that same wheel deflection you would use to park your car in your garage, now that little deflection of your wheel makes that same turn of the tires up front. So you get into what's called a pilot-induced oscillation, PIO, which basically says you're out of phase with the airplane.

If I'm driving my car and I turn the steering wheel right, the car is going left. As it's going left, I'm trying to correct, I go right, and now the thing goes right. And so you get out of phase with the airplane, and you'll see what happens. Go ahead and play. By the way, you see all the flight control surfaces deflecting in the back? This is now in a pitch rate system. So he's just trying to land the airplane. The back of the airplane does whatever it needs to do to keep that flight path marker exactly where it needs to go. And again, all the flight control surface is deflected. Military power because the engines are black, if you will, on this one.

On the next time around, you'll see him maneuver with afterburner, and you'll see him get into this pitch-induced oscillation. That's the chase airplane, by the way. It's an F-16 that follows them around. So same thing, getting set up to land. The camera goes out of focus here for a second, comes back in. Again, just notice everything that's happening on the back end of this airplane to keep that pitch rate where the pilot has commanded it to.

Two things will happen here. He selects afterburner and he raises the gear. That changes the flight control laws. And the gains were not set correctly. There's the afterburner. And now you see where he's out of phase with the airplane. And he's doing everything to keep the airplane from hitting the ground, and can't avoid it. He's OK, but the airplane was fairly well scraped, as you can imagine. So it's just a danger. The digital flight controls allow a lot of flexibility and creativity.

There used to be a term, eh, it's only software, we can figure it out. Not true when you're dealing with vehicles like this, where small changes in software code can have dramatic implications on the ability of the airplane. So it takes an amazing amount of--

PROFESSOR: Demo?

RANDY GORDON: Yeah, you can go ahead and do Raptor demo. And with that, we can go questions because I'm a little bit over.

PROFESSOR: No, it's fine.

RANDY GORDON: OK. So we can play this full screen, if you will.

PROFESSOR: You want to take questions while it's running?

RANDY GORDON: Yeah. So this is from another good buddy of mine, a guy name Zeke Skalicky, who was the Raptor demo pilot. Outstanding guy. But this is the Raptor demo if you've never seen it. So we'll take some questions while this is going. Go ahead.

AUDIENCE: Is there a thrust to weight ratio on an F-22?

RANDY GORDON: Yeah, greater than one to one. So the airplane, about 63,000, 64,000 pounds. Normally a strong takeoff. The thrust coming out the back is 70,000 pounds. So on a nice cold day, like if you're close enough to sea level, you will actually go faster than the speed of sound while you're climbing up, which is cool. Yeah?

AUDIENCE: What is the thrust vectoring while taking off?

PROFESSOR: Laz, try to-- oh, yeah. Try to repeat the question if you can.

RANDY GORDON: Oh, sorry.

PROFESSOR: Because he's not mic'ed.

RANDY GORDON: So the question was-- well, one, the question was the thrust to weight ratio. It's greater than one to one-- a little bit greater than one to one on takeoff. By the way, watch this maneuver here real quick. So that's the thrust vectoring kicking in to really get the airplane-- so initially it has the flight control surfaces. And then as things slow down, the thrust vectoring kicks in to basically turn the airplane into a flat plate. Second question was about the thrust vectoring on takeoff. So it'll put it a little bit up, not much, just a little bit up to help the nose rotate just a tad.

This is that high angle of attack maneuver, if you will. Keep going. It's all good questions. Yeah?

AUDIENCE: You said all the software is written basically so the plane can't damage itself. Does the pilot become a limiter? Can it put you in situations where it can hurt you?

RANDY GORDON: Yeah, very much so. In fact, we've kind of achieved that spot now, where the pilot very much is limiting the performance of the airplane itself because the airplane could do so much more. So this is what's called a fifth generation fighter. The first generation was like an old Korean War, like F-86 kind of airplane. And then successively through the generations, you arrive at this fifth generation, which to me is the pinnacle of what you could get with a human and an airplane together.

Sixth generation is going to involve teaming this airplane with unmanned airplanes, and the unmanned airplanes are going to have a lot more capability from a maneuvering standpoint because they don't have the limitation of the pilot and all the life support systems that come with it and everything else. So all that weight you would normally devote to that, you can get away with putting other stuff in there. When I was telling you it flies at about the same speed as a Cessna-- I mean, this is those types of maneuvers there where you can get away with that.

Again, watch the flight control surfaces in the back and what's going on. Later on they'll do a pass where he'll open up the doors and you can see the main weapon bay, which is underneath the airplane belly. And then you'll see the side weapon bay doors, so you can kind of see where all the weapons are carried inside the airplane. Again, a huge center of gravity challenge. So here's that maneuver there. You can see the doors open.

One thing I didn't really tell you about is, so in that such situation, because missiles weigh a couple hundred pounds a piece or so, some of the bombs are about 1,000 pounds apiece, when you lose all that weight immediately, it's literally like dropping a car off the front end of your airplane. The way that it fixes that center of gravity issue is by changing fuel inside the airplane. So it sloshes fuel forward or back to keep the center of gravity. Again, there's no fuel control panel where I go, well, move this and click this and whatever. It does it all completely automatically. Go ahead.

AUDIENCE: What kind of sensors can you use to detect the center of gravity?

RANDY GORDON: The sensors that you can use? So all of the fuel tanks are instrumented, so you know the status of fuel in terms of where things are set up. You tell it-- well, actually, it has the ability to know what's on the airplane. So when you load a missile, it goes, oh, it's this type of missile and it weighs this much, and it knows the mass properties of it and so it sets it up from there.

AUDIENCE: [INAUDIBLE]

RANDY GORDON: So it actually identifies that all by itself. So like in a Cirrus, you have to actually pull up a screen in the Cirrus and go, my passenger weighs this and I've got this baggage on board, and then it gives you the picture of where the center of gravity is. This thing, because it's all digital, the missile has a little connector rod that connects it and it says, behold, I'm a missile.

AUDIENCE: What about the pilot weight?

RANDY GORDON: Oh, the pilot weight? Doesn't matter because they spec'ed it-- well, it matters but for a different reason. It matters for the ejection seat, predominantly. Because the ejection seat-- I think it's like 135 pounds is the lightest, something like that, 115 to 135 to, like, 220 or something. It's something around that spot. So to be able to be within the safe envelope of the ejection seat, that's where the weight of the pilot matters. But they spec the center of gravity such that so long as really anyone can sit up front and you're not going to throw off the CG of the airplane, even though you're way far forward of the CG and there's a moment arm there.

But between everything else in the cockpit, that ejection seat is ridiculously heavy. And all the avionics that sit up front, the radars up front, all these things that sit up there have far more of a contribution to the center of gravity than you do, unless you're, like, Shaq or something like that. But go ahead.

AUDIENCE: [INAUDIBLE] on the helmet screen?

RANDY GORDON: So in this airplane, not yet. That's coming along soon. Some of the older airplanes, believe it or not, have that. Like the F-15 that I flew, you had a special helmet that had all of the information displayed on the visor itself. So in addition to that hands-on throttle and stick so I don't have to take my hands off of anything to touch anything in the cockpit, I also don't have to look in the cockpit to see altitude, air speed, heading. It's all displayed to me upfront. This airplane eventually will get that. This is a programmatic discussion now. They only had so many dollars to spend, and they said, this airplane is so awesome that it shouldn't need a helmet-mounted display system because it should be able to see all the bad guys from far enough away and not be a problem.

We fielded the airplane that way. The first batch of pilots, they all transitioned from airplanes that had that helmet-mounted system. And they came to this airplane where it didn't have it, and they were pissed. They were like, we've got to have that back. So that's kind of where a lot of the efforts now are going to modernize the airplane a bit. What else? Good questions. Go ahead. Yeah?

AUDIENCE: Why is there a need for humans in the cockpit? Why not just go for unmanned systems?

RANDY GORDON: Yeah, it is the great debate of the fighter community right now. You're really touching on something really, really deep. The best answer so far is that the greatest-- I mean, we talked a lot about the hardware and the systems on board the airplane. Really, the greatest piece of capability on the airplane is the mind of the person flying up front. If it's a very dynamic and changing environment, to be able to tell a machine to be able to incorporate all those inputs and make the right decisions based on that, kind of hard to do right now. I'm not saying we're not going to get there, just right now, it's difficult.

Where we use unmanned systems a lot now is in surveillance missions, where you can just launch the thing. And it's got a pre-programmed navigation, and it knows what it needs to do and it can set things up. Those are somewhat bounded problems, is probably the best way to describe it, where you could use an unmanned system for that. Where it gets difficulties is in combat situation, it's extremely dynamic. It's battle royale, WWF, mosh pit, any possible chaotic situation you can put, that's kind of what it looks like. And so having a human mind attached in that environment, to be able to adapt and do what the mind does better than a machine does, at least right now, that's the main argument to keep humans in the system for now. Yeah?

AUDIENCE: [INAUDIBLE] operate these planes [INAUDIBLE] to remotely operate them, is the [INAUDIBLE]?

RANDY GORDON: It is.

PROFESSOR: Can you repeat the question?

RANDY GORDON: Yeah, the question is that if you operate these things remotely-- so even if you had-- classic example, we'll use Sully Sullenberger because we talked about Sully in the previous one. You take off out of LaGuardia, you lose both engines. If you could have a remote pilot sitting somewhere else that could take over and decide land on the Hudson, because a machine most likely wouldn't have made that choice, is there a time lag issue? The answer is 100% yes. There is a time lag issue between getting that information displayed down, make the input, that input goes back up and comes back over.

A thing we've done at test pilot school is-- remember we showed earlier that flight path marker, where as a pilot you put the flight path marker and that's exactly where your airplane's going to go? If there's a time lag, that will actually mess you up because there's some second or two delay between what you're seeing and what the airplane's actually going. At test pilot school, they actually built a flight path marker that accounts for that time delay. If it knows that time delay, it will actually count for it.

So you could fly the airplane remotely even with the time lag and still be able to do very high gain tasks, like land the airplane, for instance, where things are changing very rapidly. So it's a new science, not fully fleshed out here. But the proof of concept has been demonstrated, to control an airplane remotely even with the time lag. Who really cares about that right now are the airlines because, to be very frank, the pilots tend to be a pain in the butt for an airline company. And if you can remove the pilots and just have a remote operated system or even an autonomous system, from a business standpoint, the company really likes that from an aviation standpoint.

It triggers all types of discussions in a lot of other issues, but that's one question. Go ahead.

PROFESSOR: Let me jump in for a minute with that. I think actually to me, one of the holy grails of GA safety would be to have a human co-pilot, perhaps, on the ground. So if you had that kind of telemetry that you have in a drone, a human somewhere else could say, you're running a little short on fuel or you forgot to change tanks, all the things that a human co-pilot could do right in the cockpit. Most of that safety running checklist could be probably enhanced remotely. So that would be a great add to a Cessna, or a Piper, even.

RANDY GORDON: And you see a little bit now in some of the more advanced airplanes, like we talked a little bit about if I have an engine problem in the Raptor, I literally do nothing. I just sit there and stare at the clouds and go, wow, what a lovely day, and the computer fixes it for me. There are other scenarios where the jet will tell me, hey, you've got a generator problem and then immediately pull up the checklist for the generator failure to allow me to fix it. So you see some basic automation right now already in play. A couple other questions. I know we're running short. Go ahead.

AUDIENCE: How much of flying a Raptor is seat of the pants that you would miss by not being in the cockpit?

RANDY GORDON: By not being there?

AUDIENCE: Or is it so automated at this point that it's the same whether you're sitting there or at a computer screen?

RANDY GORDON: Yeah, if it's a-- so we have two terms. One is called beyond visual range, which means I can't see the other guy with my eyes, but my sensors can see him. And if I'm shooting missiles long distance like that, I don't lose any seat of the pants by being remotely. It's like a video game. Literally, it's exactly like a video game. If it's a maneuvering environment where I see the guy and we're in a dogfight, then yeah, you lose a lot in terms of seat of the pants, eyeball, just things that are hard to automate. So it's half and half.

In a drone scenario, would a drone dogfight? I don't know. It's a good question. I'm not really sure. Go ahead.

AUDIENCE: [INAUDIBLE]

RANDY GORDON: You could, but then I'd have to have some way to represent the physical environment that the drone is seeing. I've got to be able to represent that to the guy in the simulator on the ground. I have to be able to relay that real time. It matters. So who play sports? Guys, any of you? Whenever you're playing sports, you've got an opponent. If you play it a lot, like if it's racquetball or football or something like that, you get very good at looking at your opponent and being able to see micro movements before the actual big movement happens, so that you know, oh, they're about to swing this way or they're going to throw this way.

So you can read your opponent and make a decision about what's about to happen a second or two from now. In a fighter jet, the exact same thing. If I'm fighting a guy and I see a control surface deflection, even before the airplane is gone, I know the person is going this way, I can position myself to be there before they arrive. I would need some way to represent that if I'm in a simulator on the ground, and it would have to be transparent to the guy in the simulator what that feels like. Go ahead. Lots of good questions. This is a good class.

PROFESSOR: Let me ask, actually, who's here from the Flying Club? Sebastian.

AUDIENCE: Yeah.

PROFESSOR: Yeah, actually, I wonder if, Laz, can you stay another 10, 15 minutes?

RANDY GORDON: Sure, absolutely.

PROFESSOR: Why don't we have Sebastian jump in, give his Flying Club spiel, and then both of them will be up front for questions right afterwards. Thank you, Laz.

RANDY GORDON: No worries.

[APPLAUSE]