Zachary Putnam (00:14):

Today, I'm going to talk with you about Planetary Entry, Descent, and Lending, which is one of my favorite topics. I'm going to reintroduce myself because I made this slide, just really quick. There's maybe a slightly better picture of me. My career path, I went to Georgia Tech as an undergrad and got my master's degree there. Then, I went off and worked at a nonprofit R&D lab called Draper Laboratory where I was at the field office at NASA Johnson Space Center working on the Orion Project. There's a picture of me down here on the right in front of the Orion seaworthiness test article. They basically plopped it in the ocean and see how it did. They brought it on a truck for people to see. I did that for about four years. Then, I went back to school and got my PhD. And, here I am at UIUC now. I run a research group that works in space and hypersonic systems, in guidance, navigation, and control and also in flight mechanics and modeling and simulation.

I've got to do a lot of fun stuff over the years, like go see the space shuttle and all kinds of stuff like that. It's been a lot of fun and continues to be that. So, what is planetary entry, descent, and landing, or as we typically call it in the community, EDL? Because, it's aerospace and we like our abbreviations and acronyms. Also, maybe, why should you care about it? I'll caveat this with entry, descent, and landing actually happens typically within an atmosphere. So, we're not really in space. But, we're coming in from space. So, we usually get [inaudible 00:01:52] from the space folks and frequently we're landing things on other planets. So, that's sort of considered space as well.

So, why should you care about it? Well, one reason you might care is if you were say, a crew member on the International Space Station, like the current Expedition 64 crew, someday you might like to come home, back to the surface of the earth, where you can walk outside without a spacesuit and all these kinds of fun and pleasant things. EDL is how you get from being in space, they had the space station, back down to the surface of the earth without burning yourself up. I would like to add that Mike Hopkins who's on the space station right now is actually an Illinois AE Alum. That's pretty awesome. He's up there right now. Another thing is, maybe we'd like to explore another planet. This is Mars. If we want to explore a planet, we can stay in space. Maybe, we can send an orbiter, goes around in circles. We can look at the surface from a distance. But even with really good cameras on board, there are certain things we can't do. We can't look at it in as much detail as we might like.

All these pictures, believe it or not, are from the surface of Mars. The way we get to go look at them in more detail is by going there, getting something on the surface, whether it's a rover, maybe someday actual astronauts. And, we can start answering some of those scientific questions that are impossible to answer from orbit. We like to be able to bring things home, especially people, sometimes payloads as well. We like to be able to explore the surface of other plants. That's why entry, descent, and landing is really important.

To provide some context to start off, if you want to go to space, you need to get on something we call a launch vehicle, so a big rocket. The rocket is 80% fuel, propellant, and you burn up all that propellant and throw it out the back and significantly increase your kinetic energy. You get going high enough and fast enough, mostly it's about the speed, not so much about altitude to go into space and to stay there. Depending where you're going, it might take more or less. But, you're adding lots and lots and lots of kinetic energy.

I don't know if you're taking physics, like 1/2 MV2. Your V is getting really big, and that's great. But now, if you want to come back, you have this really high speed, and you need to slow down. So, if you're in low Earth orbit where the International Space Station is, you're traveling around the Earth at approximately 17,000 miles an hour. If you're a rover on your way to Mars, when you get to Mars, right at the top of the atmosphere, like the Perseverance rover was just the other week. That was traveling about 13,500 miles per hour.

If you go to the moon and want to come back to the earth, when you get to the top of the atmosphere at Earth, coming back from the moon, you'd be going to whopping 24,600 miles per hour, approximately. If you wanted to send people to Mars and then bring them back, they'd be going even faster. Just to give you a feel for how much energy this is, if you're driving down the highway in your car and going the speed limit, say 65 miles an hour, your specific energy, so the amount of energy per unit mass of your car is about 0.45 kilojoules per kilogram of mass.

If you then decide, you're in Montana somewhere out in the middle of nowhere and where they have really high speed limits and so you're going 90 miles an hour, then your specific energy is about 80.8 kilojoules per kilogram. But, if we look at the kinetic energy associated with arriving at Mars, this 13,400 miles per hour, then that's 18,000 kilojoules per kilogram. If we look at coming back to the earth from the moon, like the Apollo missions and maybe some future missions coming up here soon in the Orion capsule, then that's 60,500 kilojoules of per kilogram. So, it's a lot of energy you've got to dissipate. Just for reference, the heat of vaporization of titanium is about 8,700 kilojoules per kilogram. So, this is way more than that. So if you just put this much energy into a piece of titanium, it would vaporize instantly over and over again, actually. And, that's a challenge.

But, if we're going this fast, and we're out in space, and we'd like to go down to a surface to land, and we don't want to land these speeds because we'd just make a big crater. We need to slow down to essentially zero velocity. We could use a really big rocket engine, a really big rocket, just like we used to get into space in the first place. The trouble is we'd have to carry that whole thing to space and that wouldn't work. So, what we like to do instead, when we can, when there's an atmosphere, we can then fly into the atmosphere on purpose and get our energy removal, our energy reduction, deceleration for free, just from drag, from flying through the atmosphere at really high speed. That is entry, descent, and landing. And really, the energy dissipation part is mostly entry. So, it's atmospheric entry, descent, and landing. We leave the atmospheric part off. That's sort of implied.

Now, when you're in space, these are various spacecraft. On the top left there is Soyuz. On the bottom left is an artist concept of Orion. And on the right side there is the Mars Science Lab or Mars 2020, Mars missions with a rover packaged in that capsule. Because of those high energies, we have to package what we want to send into some kind of a capsule shape. So, for the Soyuz, this middle gumdrop old fashioned headlight shaped component. For Orion, it's just a cone here on the front with the little windows. And for the Mars rovers, it's just this sort of rounded aerodynamic looking part in the front.

But when you're in space, you need a whole bunch of other things to keep your spacecraft alive. You need radiators. You need solar panels and all these other things. Those things are attached like a service module that you can see here. So, if you're going to go perform EDL and land on the surface, the first thing you need to do is get rid of that service module or crew stage. Depending on what you're doing, that's what it's called.

I'm going to just narrate an EDL sequence here. We might jettison that cruise stage here. Then, all we have left is our space capsule with our payload, whether it's people or rover or whatever nestled safely inside and protected from the intense heat and aerodynamic loads that you experience when you try to fly through an atmosphere at 13,000 or 17,000 miles an hour. Because, when you enter the atmosphere, you're going something like mock 30, so really, really fast. That speed comes down pretty quickly. The way it comes down is through drag, so friction with the atmosphere. Only gas molecules through the atmosphere are rubbing on your spacecraft, and you end up with something like this. It gets really hot. It glows. There's a whole bunch of plasma and things going on. That's why there's a heat shield in front to protect your vehicle. There's actually some heat shielding all over the whole thing, but the big one's in the front. Think like temperatures in the thousands and thousands of degrees.

But, the protective shell called the arrow shell protects the vehicle as it decelerates, and it slows down and slows down and slows down. And eventually, you get going slow enough that you can deploy something like a parachute. So, if you watch the Mars 2020 landing for the Perseverance rover, you might have seen, they have a parachute. For Mars, typically we use a super sonic parachute. So, the parachute is deployed around like mock 1.2 or mock 1.3, above the speed of sound. It slows the vehicle down even more. At Mars, at least the last two times, this is actually an old one from Mars Science Lab, but they got a similar picture for the Perseverance rover. They actually captured a picture with one of those orbiter looking down as the vehicle descended on the parachute, which is really cool. So, you can see the arrow shell down here and the parachute here on the back, really fun pictures.

At Earth, this is a picture of the Crew Dragon under these parachutes. We do things a little bit differently. The atmosphere is much more dense than at Mars. We typically fly bigger heavier vehicles that have people in them, instead of a Rover. So, we don't need supersonic parachutes. We can just use subsonic, so we can wait to deploy them until later. Then, we can use more of them to help hold up a bigger vehicle, but still descent under parachutes is typical.

Then, the last thing is landing. And, landing... There's all kinds of different ways to do it, depending on what you're trying to do with your system. We might have a propulsive of soft landing. I like the InSight lander here on the upper left. We might splash down in the ocean. Here on the top center, which is what Crew Dragon does. It's what the Apollo missions did. Mercury, Gemini, Orion, all these kinds of vehicles plopped in the ocean.

If you're lucky enough to have wings, like this space shuttle, you can actually land on a runway, not common. We might land on some inflated airbags like Mars Pathfinder and the Mars Exploration rovers did about 20 years ago. We might do something really nutty like the sky crane. It's actually not that nutty, which is another type of soft landing where we use thrusters to set our vehicle down very, very gently. Or, we might do what the Soyuz does, which is descent on a parachute and right at the last second it actually does fire some little retro rockets and then smack, right into the ground. It's apparently a pretty bumpy landing. But, there's lots of different things you can do. You need to design your system around those types of things.

The landing bit usually is just considered to be the last part. As you can imagine, you can see there's still parachutes here. There's still rocket engines firing. There's a fair amount of overlap when we say entry, which is the sort of hypersonic acceleration phase. Descent, usually under a parachute or something like that and then landing, which is our final touchdown or impact. So, there's a lot of overlap and sort of what's considered part of each phase. But, take them all together, it takes us from space with a very high energy down to the surface of a planet with a very low energy without destroying our payload.

If you watch any of the Mars landings... This is fascinating. There's all these pieces that come off. So, there's a parachute. At some point it jettisons the heat shield off the front, the back shell comes off. The rover descends with this propulsive descent stage, like shown here, on the right. Then, that flies off and you end up leaving this trail of debris and stuff all over the place. They actually get pictures of it. There's a new picture that just came out for the 2020 rover. This is for the Mars Science Lab, which landed about, almost 10 years ago now. But, these pieces, the back shell and the parachute, the descent stage goes off and crashes somewhere. The rover itself, on the heat shield. You can pick out all these things on this picture, which is really cool.

That's EDL in a nutshell, sort of what happens. Let's talk a little bit about entry vehicles and what they look like. Here's some examples. The space shuttle here. This is a Soyuz capsule after it landed. It looks kind of burned to a crisp. SpaceX Cargo Dragon here floating around in the ocean. Down here on the bottom right is a concept called the HL-20, which actually hasn't flown, but it may someday is The

Dream Chaser. You look at these shapes, and they don't look... pretty lumpy. It's a space capsule. It looks like a bowling ball. Who picked these shapes? There's actually a really good reason for why they look like this, but it's a little bit counterintuitive. It took people a while to figure this out. So, I mentioned that entry vehicles into the atmosphere, even like mock 30, which is really, really fast. If you think about fast airplane, it's nowhere close to that, not even close.

But, let's start with airplanes that don't fly that fast. These are airplanes you might actually ride on at some point. They have wings, and they have nice rounded edges. Generally, they've had very smooth air dynamic shapes. They look streamlined. The reason is and if you look at a cross section of a wing here, it's shown in... I guess it's tan or orange. You have nice, smooth flow lines going over that shape above and below. Everything looks great, nice and flat. That is what a low speed or a subsonic aircraft looks like.

If we go up to super sonic aerodynamics... So as people started building planes in the early 20th century, they got faster and faster. Eventually in the forties, we were able to break the sound barrier and start building super sonic aircraft. We learned more and more about how to do that. It turns out for super sonic aircraft. You actually like your shapes to be very pointy instead of nice and round and smooth. We like them to be very pointy, very sharp edges. That resulted in an aircraft, kind of like you see here, like the SR-71 or the F-104 Starfighter here on the upper left. If you look at the airflow for a supersonic plane of the cross section of the wing, it has a very sharp leading edge. Because, it's super sonic [inaudible 00:15:09], you end up with shock waves hanging out all over the place and expansion waves. This is what it looks like.

So, when people started to design faster and faster and faster aircraft, aircraft SR-71. And, they wanted to go into hypersonic aircraft. So, aircraft to fly say above mock five, or they started thinking about space vehicles that were going to come back from orbit going really high mock numbers, really fast and thought, "Well, we should just make it as sharp as possible." Makes sense, we went from blunt to sharper to sharper to sharper to sharper. We want that to be really razor edged. Even with these kind of vehicles, they're actually anecdotal stories of the F-104 Starfighter.

But, the ground crews actually had to be careful that they didn't injure themselves on the sharp leading edge of the wings. So, I thought we're getting sharper and sharper, but that's not what these hypersonic entry vehicles looked like. In fact, they're really blunt, even more blunt than our slowish, like assessed in a general aviation aircraft. You see the big fat rounded nose on the space shuttle. If you ever go get a chance to see a space shuttle in a museum, you absolutely should. They're enormous. But, it really is like a giant bus. It's like a huge box. It doesn't look very sleek. It's not. But, it's designed that way for a reason.

If you look at the space capsule, usually the blunt end is what goes first. The back end here and the white part is the backs shell. The nose here is on the... I'm going to call it yellow golden heat shield in the front. It flies blunt end first, which seems kind of counterintuitive, seems not very aerodynamic. But, there's a really good reason for it. Remember, I mentioned how fast you're going, how much energy you get to dissipate. NASA did some work. Actually, it started out as the NACA, before NASA existed. The precursor to NASA, did some work looking at, "How do we fly vehicles this fast?" The initial concept here in the upper left was a very pointy nose kind of missile thing, very sharp edges.

What they found is, when you do that, these are schlieren images from experimental testing. These dark lines are shock waves. What they found is, you get an attached shock wave right at the nose and over a shock wave there's a whole bunch of heat and things involved. When it gets really hot, your vehicle tends to melt. So, if you start with a sharp edge, it will not stay sharp very long. In fact, it will melt and disintegrate and your whole vehicle will basically fall apart. So then, they looked at something, "Well, what if we did something a little more blunt," like this hemisphere here at the top. What that does is instead of having a shock wave that touches the vehicle, it pushes the shock wave out in front of it. It's called a bow shock. There's this space between the vehicle here and this big thick shock wave out in front. They looked at some other concepts and turns out that's true. It holds up even for slightly less blunt shapes.

So, this bottom right here, manned capsule concept, 1957, is what eventually became the Mercury capsule with a nice blunt fore body. What this allows us to do, I mentioned before that we have 60,000 kilojoules per kilogram of energy we have to dissipate. But, even titanium vaporizes at 8,000 kilojoules per kilogram. So, the reality is, the vehicle doesn't see that much energy. Most of that energy and friction is actually carried away by the shock wave, which doesn't even touch the vehicle. So, it's like magic. The shape of the vehicle allows you to have this bow shock that doesn't touch the vehicle, that carries most of that thermal energy away. So, your kinetic energy, your speed of your vehicle is converted into heat through friction. Most of that thermal energy, that heat, is carried away by the bow shock. Only about 10% is left. That's still a lot. We still need a heat shield, but that's something we can do and a problem that we've solved fairly well.

So, that's why capsules look like capsules, and they don't look very cool, quite frankly. Although the Dragon and SpaceX Dragon starts to come close to that. And, why you see a space shuttle looks like it should... It goes really fast, faster than anything else, any other airplane. It's not really an airplane, but why it has such a blunt nose and really big blunt fat wings, is because of this. So, because we're going through all that heat, I just wanted to show up before and after picture here. This is the Apollo capsule.

The command module here on the picture on the left, you can see the command module on the front with the silvery cone. That's where the crew lived during the Apollo missions while they're in space. This whole thing in back is just the service module. You can't actually go in that part as a person. It just contains fuel and consumables and water and stuff like that. So, before they entered, they jettison that part, just like we talked about earlier and this silvery cone enters. And after it enters, this is what it looks like. It's totally charred and cooked. That's because of all that heat. Even with the bow shot carrying away that much energy, there's still a lot left that the vehicle has to absorb or deflect or get rid of to keep your payload or your crew safe.

Then, the last thing I want to talk about here, just briefly, is how we steer things during entry. If you look at a capsule, it's like a cone with a rounded bottom. How do we steer these things? How do you steer... It's like trying to steer a baseball or something like that. I'll tell you. So, if you take a space capsule like this, and it's flying in this case to the left. So, it has some velocity vector in black here. I'm going to generate some drag. We'll mark the center of mass of the vehicle here with this circle with a cross in it.

If you do that, there's really not much you can do to steer. You can just sort of let it go. We do this sometimes. When we don't need to do any steering and that's okay. But, if we do want to do steering, we can steer the same kind of shape, but what we do is we move the center of mass off the center line of the vehicle. When you do that, it essentially doesn't fly straight anymore. It flies canted. It flies at some angle, which we call the angle attack, relative to its center line. So instead of flying straight, it flies at some angle. When it does that, now all of a sudden, the flow going over the top is different than the flow going over the bottom. And, we end up some lift, and it could be up or down, depending on how you do things. We could get a little bit less drag, but not a lot. And, we want drag. We're trying to slow down.

So, drag is very good, which is different than how you would normally design an airplane. Normally airplanes are designed to minimize drag. But, when we do EDL, we want lots of drag because we're trying to slow down. But, we get a little bit of lift, and it's not much. But, it's enough we can use to steer. Here's a picture. Actually, this from a press kit from one of the Apollo missions. You can see here, that it's generating some lift. It has some drag. Their picture is better than mine here. It's got a lot more drag than lift, which is typical. The way they get the center of mass of this symmetric vehicle to being off center is they cleverly package things. Sometimes, they just literally stick some lumps of inert metal on one side and help weigh it down on one end.

So, we generate some lift. And, the way we steer is actually just by rotating the vehicle. We can't usually change the magnitude of the lift, but we can change the direction it points. We can sort of steer this way. Then a little while later, we can bank over and steer the other way. This is called bank angle steering. So, this angle, when you change the lift vector's direction by some angle, that's the bank angle sigma here on this picture. That's how we steer a space capsule.

Now, interestingly enough, that's actually also how we steer the space shuttle. When it's flying hypersonically. It doesn't actually use its wings and its flaps and things like that until it gets down to a pretty low velocity in the supersonic regime. So same thing, so all of these vehicles here on the right, Orion on the top left, Soyuz, Mars Science Lab, bottom left and the x37b here on the bottom right, all steer in the same way. In fact, with maybe one exception, every entry vehicle that has done any steering, not all of them are steered, has steered this way.

So, what's next in entry, descent, and landing in terms of technology. I'm just wanted to give you some things to think about. One of the places we're really focused on right now is a community that is landing things on Mars. I'd say there's sort of two things people are working on. One is trying to send smaller things. Maybe, you've read about the Ingenuity helicopter that was tucked underneath the Perseverance rover. Well, what if we could just land an Ingenuity helicopter anytime we wanted. We don't have to wait for a rover, which only launches maybe once every 10 years. So, how do we land smaller things on the surface of a planet to allow us to do targeted science investigations and technology checkout and that kind of thing.

The other thing, particularly on Mars, is how do we land bigger things? We can land a one ton rover. We've done it twice now. That's very cool. But if we want to send people, we're not landing a one ton rover. We're in like a 20 ton house. We probably need to land more than one. We'd like them to be right next to each other. We don't know how to do that yet. We're working on it. But, there's a lot of challenges there. So, if you're interested in going to this field, these are the kind of things that you might work on someday.

I just wanted to finish up with some upcoming EDL missions. Tianwen-1, the Chinese mission to Mars has an entry vehicle on it. It's in orbit right now. It'll send the lander down here in the next month or two or three. I don't know exactly what the date is. They probably haven't decided yet. In 2023, the European Space Agency is launching its own rover to Mars called Exomars. Also in 2023, the OSIRIS-REx mission, which is a U.S. mission is going to return an astroid sample to Earth. So, this one will be at Earth. This is the picture of the capsule here. That's actually taken in space on the vehicle. It's waiting around to come back. Then, this year, in 2021, we should have launches from the SpaceX Crew Dragon. Then, hopefully also the Boeing CST 100 Starliner. So, those will both be earth entries too. So, there's lots of fun upcoming EDL missions to keep an eye out for in the news, if you're interested and sort of see how they go. And, we wish them all the greatest of success, of course. I'll stop there and see if anyone has any questions.

Speaker 2 (25:17):

Hello, professor. I had a couple of questions, one of them was about the parachute. For supersonic travel, I was wondering, what has to be considered for designing a parachute for supersonic travel versus subsonic versus for the regular space shuttle?

Zachary Putnam (25:37):

The space shuttle didn't actually... It used a drag shoot to slow down on the runway, but it didn't really have a parachute for descent, like we would normally think. One of the major differences is the inflation loads. You're going much faster on [inaudible 00:25:55] and aerodynamics. The force you get from a parachute is the dynamic pressure, which is one half times the density times the square of your velocity. So, when you're going fast, your inflation load goes up with the square velocity. Those are much higher. So, you have to have a stronger system. Predicting the inflation of the parachute is pretty fiddly. It can be difficult. So, there's lots of difficult things they got to do with parachutes, and parachute dynamics are notoriously difficult to model. Because, the parachute itself was pretty large, but the material it's made of is really thin. They're really lightweight, which is great. But, it's hard to model at the same time, really big things that are made up of really tiny things. It's a difficult challenge.

Speaker 2 (26:46):

Thank you-

Zachary Putnam (26:46):

I hope that answered your question.

Speaker 2 (26:46):

Yes it did.

Speaker 3 (26:51):

[inaudible 00:26:51]. We do have a question in the chat. "What's the main goal, objective you have with your research at the moment?" That's from Isaac.

Zachary Putnam (26:59):

Oh, the main objective I have with my research at the moment. I'd say, overall, the main objective is... I work mostly in guidance control so that bit ahead about how we steer these vehicles is pretty important, and we're looking for ways to improve the way we do that so that we can land more accurately. Also, better understand what our flight path is going to look like in advance and which can help us with vehicle design and things like that.

Speaker 3 (27:26):

Thank you.

Speaker 2 (27:27):

I had one more question if you don't mind?

Zachary Putnam (27:30):

Sure.

Speaker 2 (27:32):

I was wondering, "What would you have to consider for entry to Mars versus to the Moon or to Earth?" There's like different gravity of course and then air resistance in drag, but what else would you have to consider?

Zachary Putnam (27:50):

Those are the big ones. So, the gravity is different at all those places. At the Moon, there's no atmosphere, so all of your deceleration has to be done with propulsion, so with rockets. So, that's quite different. Luckily the gravity's smaller so you don't have to decelerate as much. The big difference between Earth and Mars is the density, the thickness of the atmosphere. Mars' atmosphere is really thin. The density and the pressure of the surface are like 1/100th of what it is at the Earth's surface. So, that makes it a challenge at Mars to slow down before you hit the ground. You just don't get as much drag out of it because it's so thin. So, that's a big challenge. At Earth, you can typically deploy parachutes, and you'll have plenty of time to drift down to a nice soft landing. On Mars, you have to be really careful. In fact, you can't really land things on Mars with only parachutes once they get above a certain size.

Speaker 4 (28:44):

Can I ask one more question?

Zachary Putnam (28:46):

Sure.

Speaker 4 (28:47):

So, you said you worked on the Orion, right?

Zachary Putnam (28:50):

I did.

Speaker 4 (28:51):

What was the best experience working on that or most memorable experience you had?

Zachary Putnam (28:56):

It was a lot of fun. I got to work with a lot of great people at NASA. It was a really exciting program. It was really interesting too. If you go off to be an engineer someday, typically you work on something pretty narrow, especially when you're kind at the bottom of the totem pole, which is where I was. But, when I worked in guidance and control and trajectory design, we got to sort of interact with all of the other bits and pieces of the vehicles. The people doing the heat shield. The people doing the aerodynamics. The people doing packaging, so where things go in the vehicle. The folks doing navigation and mission design. That was really a lot of fun.

Speaker 4 (29:34):

Cool. Thank you.