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NESTRALL: Hi there, and welcome to the second episode of the Talks at Google podcast, where great minds meet. I'm Nestrall, and I'll be bringing you today's great episode. Talks at Google brings the world's most influential thinkers, creators, makers, and doers all to one place. Every episode of this podcast is taken from a video which can be seen at youtube.com/talksatgoogle. Today's episode features Emily Lakdawalla, Senior Editor of The Planetary Society and self-described Planetary Evangelist in conversation with Googler, Scott Maxwell, a former NASA Jet Propulsion Laboratory Engineer. They discussed her new book, The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job, which is an in-depth exploration of the incredible design and engineering of the most complex robot ever built by NASA. The discussion covers all the details you've ever wanted to know. For example, why there are holes in the wheels or how Curiosity takes its own selfies?

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Here is Emily Lakdawalla, The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job.
>> MAXWELL: All right. So-so, Emily, this is your first book.
>> LAKDAWALLA: It is.
>> MAXWELL: You didn't wanna start with something simpler? A Brief...
>> LAKDAWALLA: Well...
>> MAXWELL: --History of Time maybe? I mean, I know that's been done, but-but-but as you write in the book, this is the most complicated robot ever sent to another planet. In fact, ever sent off Earth. Why did you-why did you wanna write about this, and-and-and why do you say that it's the most complicated?
>> LAKDAWALLA: Well, I think it's fair to admit that I didn't realize what I was getting into when I started writing this book. In fact, as-as I explained in the introduction, it's not actually the book that I meant to write to begin with. It's--I was approached by Springer to write a book about the Curiosity mission. And I wrote, and I wrote, and I wrote. And I wasn't finishing, and I couldn't--I-I wound up with a tremendous quantity of material and wasn't able to wrap it up.

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And I finally figured out that the reason I was having so much trouble was because I had accidentally written two books. And so this is actually just the first of a pair of books on Curiosity. The second one is gonna be coming out next year and will be about the science mission. So I kind of was able to partition the engineering stuff into one book, the science to another book. And, basically, this is the book that I needed in order to be able to understand the Rover well enough to be able to write about its science mission. And so now I'm writing about the science, and I'm actually--I've got a copy on my desk, and I keep on referring to it all the time. How many of this thing does it have, and how long did it--and when did this fail, and--it's all in there.
>> MAXWELL: So-so-so tell us a little more about why it is the most--what-what makes it the most complicated robot we've ever sent off this planet?
>> LAKDAWALLA: It's-it's sort of the culmination of a long history of NASA's exploration of Mars. And I think that the key to its complexity is

that as you--NASA builds from one mission to the next. You begin with a very basic broad set of questions.

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What is Mars? And you map it, and you find out some more things about what it is. And then you ask more detailed questions. Was water ever important on Mars? And Spirit and Opportunity were sent with this mantra, follow the water, try to understand how water was active on Mars in the past. Curiosity's questions are more subtle than that. We know that there was water on Mars but did they ever have a habitable environment that microorganisms might have been able to live in? And so as the questions get subtler, the investigations that you have to do to try to answer those questions get more detailed, more complicated. It's not enough just to snap pictures anymore. You have to have much more detailed kinds of data. Curiosity has these two highly sophisticated laboratory instruments that are designed to ingest solid samples and perform x-ray diffraction and x-ray fluorescence. They--performs gas chromatograph, mass spectrometry with a tunable laser spectrometer and a quadruple mass spectrometer. It's got like all of these laboratory instruments that had been miniaturized to fit inside the Rover.

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And so just supporting that hardware requires a host of-of subsystems that are necessary to keep the thing alive. You also have to have a mission that lasts a lot longer. The warranty on Spirit and Opportunity is famously only 90 days. And, of course, Opportunity is still going after 5,000 and something sols. Do you know off the top of your head how many...
>> MAXWELL: Let me check my Mars time app. Why, it's 5,107 sols today, Emily.
>> LAKDAWALLA: All right. Very good. So, yeah, Curiosity has not lasted nearly so long yet. And, in fact, it's quite likely that Curiosity will not last as many sols as-as Opportunity does. It's almost certain. But, anyway, the point is that-that the--Opportunity was only warranted to last 90 days. It was supposed to be able to accomplish its prime mission in that amount of time. Curiosity's warranty ran out after the first year. And so you have to build much more robust...
>> MAXWELL: First Martian year?
>> LAKDAWALLA: ...systems. First Martian--yeah, first...
>> MAXWELL: Yeah.
>> LAKDAWALLA: ...Martian year.
>> MAXWELL: Right.
>> LAKDAWALLA: Yes. That's correct. You have to build much more robust systems to be able to support all of that.

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And so that also made it more complex 'cause you have a lot of redundancy and other things built in to make it just last so long.
>> MAXWELL: And, famously, the-the--one of those two labs that you were talking about, the-the Sample Analysis at Mars or SAM instrument, I think it was Rick-Rick Welch who pointed out that that instrument alone is larger than the entire chassis of the Mars exploration rovers.
>> LAKDAWALLA: That's right. Yeah. And it's big--it's heavier than the Sojourner rover was. I mean, it's the size of a microwave, which, you

know, in Earth terms for a laboratory instrument, it's amazingly miniature. But in terms of what a mobile rover has to support on the surface of another planet, it's enormous. It has high power demands. It has exacting temperature requirements. And it's just--it's a very complicated piece of machinery.
>> MAXWELL: I-I think that might be the size of the entire first rover that we sent, Sojourner. It's like...
>> LAKDAWALLA: Yeah. Yup.
>> MAXWELL: ...SAM is the size of Sojourner. Bigger than the chassis of-of...
>> LAKDAWALLA: Uh-hmm.
>> MAXWELL: ...the Mars exploration rovers. So you-you did an enormous amount of research. It-it-it shows and it-it pays off really well in this book. This-this, by the way, is the first technically--or I've read a lot technically--or, technically-oriented books in my life, and this is the first technically-oriented book that I've read that uses terms like stubborn gunk.

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I think it does a very good job of, kind of, like making-making these very complicated things accessible to a lay audience. Then--and that's kind of an outgrowth of the work that you do. You are the Senior Planetary--Senior Editor and Planetary Evangelist at The Planetary Society. Do you see this as kind of an outgrowth of that work?
>> LAKDAWALLA: Oh, absolutely.
>> MAXWELL: Yeah.
>> LAKDAWALLA: So--yeah. So I see what I do at The Planetary Society as kind of a translation function. There are so many exciting things happening in science, and engineering, and space exploration right now. And while I was a grad student exploring these things, I thought, you know, this stuff is really cool but nobody learns about it. And one of the main reasons that nobody learns about it is that the-the ways that scientists and engineers communicate with each other are really, frankly, kind of horrible. Science papers are just bad. They're-they're boringly written. They're difficult to understand. But when you train as a scientist or engineer, you learn that language and you become capable of reading it and understanding it. And you learn to use a whole new vocabulary of terms that have very specific and precise meanings.

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But when you use that same language to speak to a member of the public, you are basically speaking a language that's foreign to that member of the public. So you have to translate. And it's not--one of the phrases that I hate the most in public communication is dumbing down, because you are not--you're not making things stupider. You are translating to a language that you can use to communicate with other people. And so it's perfectly possible to get across complicated concepts. You just have to use the words that people can understand. So when I need to write about stubborn gunk, I write about stubborn gunk because that's exactly what we're talking about. We're talking about material that is sticking to the sides of an instrument that you can't get off even by shaking it. And that's-that's what the-the Phoenix lander was dealing with in the section that I wrote that about. And it--you know, you've all dealt with that

problem in your own homes and lives, I'm quite sure. And-and it's just--it's better to write about it in that way. It's more exciting.

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It is just as effective at communication as saying, I don't know, high viscosity material that has adsorbed onto the walls of the sample collection device or something like that, you know? You could say it that way, but why?
>> MAXWELL: I wonder if instead of dumbing down, we could say that this is a smarting down of the rover a little bit?
>> LAKDAWALLA: Just a translation. It's a translation of-of...
>> MAXWELL: Right.
>> LAKDAWALLA: ...how everything works to make it more accessible to-to the speakers of--to-to people who are non-native speakers of science.
>> MAXWELL: Right. And you're-and you're well-positioned to do that, having trained as a scientist yourself. That's-that's also your background?
>> LAKDAWALLA: Yeah. Yeah. So I'm a planetary geologist by training. So I--as an-as an undergrad, I did field geology. I got to walk around on mountains, and whack things with rock hammers, and draw pencil and-and colored-colored pencil maps and things. And then in grad school, I studied geology on Venus using radar images from the Magellan orbiter, which is just--it's such an underappreciated mission. It's--it ended in the early '90s. It mapped all of Venus in-in radar wavelengths.

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And Venus is a fascinating-looking planet, and I-I really wish NASA would get a mission back there some time soon. But it's hard-it's hard to study because of the insanely high temperatures and the sulfuric acid clouds and the-the pressure at the surface is the same as at a mile beneath the ocean, so it's tough to build hardware that survives for very long on Venus.
>> MAXWELL: Yeah. I wouldn't wanna be the guy who has to design the rover that can rove around where temperatures will melt lead.
>> LAKDAWALLA: Yes.
>> MAXWELL: That doesn't seem like fun.
>> LAKDAWALLA: Yeah. Solder is not gonna work in Venus.
>> MAXWELL: Right. Right. Right.
>> LAKDAWALLA: And the Russians succeeded in exploring the surface of Venus by essentially building--I mean, it's an exaggeration, but they were basically clockwork spacecraft. I mean, they were mechanical spacecraft 'cause you can build mechanical components that can work at very high temperatures. Electronics, especially in the 1970s, were not ready to operate at those kinds of conditions. And the Russians, being the Russians, built these big, robust spacecraft that basically worked with these mechanical systems and were able to take measurements after landing on the surface for a matter of minutes to an hour or so before the spacecraft failed.

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And that's how we know anything about the surface of Venus.
>> MAXWELL: So-so-so returning our attention to Mars, one-one of the things I think you do well--really well in this book--which-which I greatly enjoyed reading and enthusiastically recommend, by the way. One

of things I think you wrote really well in this book is you-you-you don't just translate all of the technical jargon in terms that people can understand but you also recognized--and this is, again, part of your-your work at The Planetary Society, I think. That you can't talk about this rover just as a machine. It's not just that the rover is a machine. It's that the Rover, like, carries with it a lot of human hopes and ambitions. And I think you kind of communicate that, as well, is-is what we're-we're hoping and dreaming to explore on the surface of Mars.
>> LAKDAWALLA: Yeah. There's a--there's a book that was written actually by a sociologist by--named Janet Vertesi, who has embedded with several of NASA's JPLs operations teams on space missions. And she studies the sociology of how teams work when they work on these missions.

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And one of the most striking things that she observed that really made me sit back and go, "Huh," is the-the pronoun that-that JPL engineers and scientists use when they refer to the rover. You know, it's--sometimes some people do say it. It can be traditional to call ships of exploration she, like, you know, oceangoing ships are often referred to as she. But that's--it's not actually very common to use that pronoun for Curiosity. The most common pronoun is we. And so think about that for a-for a minute, what it means to be referring to this machine as we. It means that, you know, we are exploring Mars. We drilled today. We are driving across that hill. It's-it's not just one machine. It's the embodiment of all of the people participating together on this mission. And it's-it's such a-a team thing, especially because of the way that there are all these operational roles on the mission, and many different people who can fill those operational roles on any-on any given day.

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So it feels more like--I don't know, it feel--it feels kind of like being on a-on a ship on the ocean, in a way, where there is a captain but there's all these other commanders and everything else, and-and every person has their part to contribute to make it going. And together, you're on this great ship of exploration. And that's what Curiosity feels like. And so it-it kind of feels like there's a false dichotomy between human and robotic exploration because this is human exploration.
>> MAXWELL: Right.
>> LAKDAWALLA: We are seeing the surface of Mars. We're exploring places that humans could never go, or at least not now. And we're doing it through the eyes of robots. And I think that, you know, as-as virtual reality gets more commonplace, as we decrease the separation between humans and the machines and the software that we use, we're actually gonna see a-a merging of human and robotic exploration where we may have human exploration of the surface of Venus except that it'll be humans in an orbiting spacecraft using robotic avatars to explore the surface.

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And it sounds science fiction-y, but it's not--it's really not that far-fetched given current technology, and would be a much more efficient way for us to get human brains into-into-into environments that are really hard to-to--for humans to survive. Terrible radiation environments, terrible heat, crushing pressure, you know, all of those things. We just put robot bodies down there, and we--see if we can manage to use our

human brains effectively, then-then that's, I think, the future of exploration.
>> MAXWELL: Right. And then you haven't gone down into the gravity, well--and so you don't have to get the people boosted back off the planet?
>> LAKDAWALLA: Also that, yeah.
>> MAXWELL: So you can--you can land the humans on like Phobos or something and have them, you know, teleoperating a-a mission on the surface below them. So...
>> LAKDAWALLA: Yeah. It turns out to be harder to do aerial synchronous orbits, that's Mars geosynchronous orbits than it is...
>> MAXWELL: Right. Yeah. Sure.
>> LAKDAWALLA: ...to do Earth geosynchronous orbits because Mars' gravity field is a lot lumpier, and so it's hard to keep you--to do station keeping with your spacecraft, to keep it positioned over the one--yeah, over a-a single spot on Mars. But there are like two stable positions in longitude--or metastable positions.

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So you have to like really wanna explore the part of Mars that's underneath those two metastable positions.
>> MAXWELL: Yeah. So you were talking about that-that we embody the rover, right? That-that we are the rover and that--the-the language that's used, but another thing that Janet Vertesi pointed out was that-that, in the same way as we embody the rover, we-we also use our bodies to communicate about the rover. And so--like for example, with Spirit and Opportunity, we'll talk about the solar panels by--you bend your body forward, you splay your arms backward in this position because that's what the solar panels look like. And that's--when you talk about the solar panels, you do that. When you talk about the mobility system, you kind of move your arms in this characteristic way.
>> LAKDAWALLA: Uh-hmm.
>> MAXWELL: "Oh, I can steer the wheels like this." And-and you--when you talk about the robotic arm, you use your arm. And it's always the left arm because they are left-armed. Did you find yourself doing that when you were writing this book? Did you kind of inhabit the rover-the rover's body that way?
>> LAKDAWALLA: I did that a little bit. But I actually find myself doing it a lot less with Curiosity than I do with Spirit and Opportunity.
>> MAXWELL: Everybody else does too.
>> LAKDAWALLA: Yeah. So Spirit...
>> MAXWELL: Yeah.

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>> LAKDAWALLA: Spirit and Opportunity have this--they're much more human scale and they're symmetrical. It's much more easy to imagine them as having the body plan of a person, or a donkey, or a dog, or whatever you wanna imagine it. Curiosity is--it's a--you know, it's not nearly as symmetrical. It's not nearly as pretty. And-and, to be honest, I really didn't like the appearance of Curiosity when I first started doing the research on this book. I often feel like--you know, there's these three generations of rovers. There's Sojourner, Spirit and Opportunity, and Curiosity. And I feel like Sojourner was sort of a loyal little dog that--it couldn't ever go any farther out of sight of the lander because it didn't have its own communication skills. So it just kind of, you know,

poked around rocks. You could even see these images of it like lifting its leg on a rock because it like drives up and it kept driving, and it--and there's actually an image of the rover like perched...
>> MAXWELL: Right.
>> LAKDAWALLA: ...almost sideways on a rock like this. And then Spirit and Opportunity are much more surefooted. They're bigger. They're more human scale.

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So I--in my extended animal metaphor, they're the burrows that used to--or the donkeys that used to accompany the Western geologists as they explore the geology in-in the American West. And then--so what does that make Curiosity? Well, it's the animal designed by committee. It's a camel. It's a ship of the desert. It moves slowly and steadily across the desert landscape, you know, carrying its load--lumbering load with it. And-and that's what Curiosity is like. And, like I said, I didn't really love it when I first saw the design, but that changed, actually. The JPL had a moment--had an opportunity for the media to come into the clean room and see Curiosity before it got shipped to Florida for launch. And so I was actually able to put on all the--they call it a bunny suit. The white suit and the cap and everything else. And go in and see Curiosity fate--face to face. And I have to say that I kind of fell in love with Curiosity when I had the opportunity to sit there.
>> MAXWELL: Right.
>> LAKDAWALLA: And-and meet it face to face. But, yeah, I don't-I don't feel like I embody Curiosity nearly as much because it's-it's so ungainly. It's a different kind of creature...
>> MAXWELL: Yeah.
>> LAKDAWALLA: ...from Spirit and Opportunity.

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>> MAXWELL: And-and that-that seems to be kind of widespread on the project too. Ashwin Vasavada talks about-about that, about how people have-have--he feels like people have emotionally connected with Curiosity less than with Spirit and Opportunity.
>> LAKDAWALLA: I think also it's--it may partly be because of the way that the--Spirit and Opportunity are much more responsive, in a way. They--you come in on a morning, you plan the day, and then that's it, whereas Curiosity has to be planned by committees as well, where you have as many as four parallel planning processes that are happening at the same time, operating on different time scales. You do have a tactical operations team that is planning every day of operations, but then there is a look-ahead planning team that is planning a couple of days of operations, there's a long-term planning team that's looking out months, and then there's a project science group that is kind of keeping track of all of the-the mission requirements. And, unlike Spirit and Opportunity, most of the decisions for Curiosity get made many more days in advance.

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So it's-it's much less responsive. So it feels, in a way, a lot--more like some of the other big NASA missions, like Cassini or these other things that need to be planned much longer in advance.
>> MAXWELL: Yeah. That's--it's-it's kind of this weird hybrid, right, where...

>> LAKDAWALLA: Yeah.
>> MAXWELL: ...where--for that, and for-for--also for project management reasons because it has like lots of PIs for the different instruments instead of one PI overseeing them all as on Spirit and Opportunity. And so there's-there's this kind of council of-of monarchs...
>> LAKDAWALLA: Yeah.
>> MAXWELL: ...who are kind of in charge of it. And so it's...
>> LAKDAWALLA: And I call it the Council of Elders.
>> MAXWELL: Yeah. It's-it's-it's...
>> LAKDAWALLA: They're all the men, by the way, which I hate.
>> MAXWELL: Yeah.
>> LAKDAWALLA: It's really bad. So there's this group of like 12 PIs, and they're all men. There's a lot of awesome women working on this team, but...
>> MAXWELL: Yeah. A lot of-a lot of great engineers working on the team and...
>> LAKDAWALLA: Yeah.
>> MAXWELL: ...working on operations as well. And, in fact, that was one of the things I was gonna ask you about was, you know, you-you cite some of those women in the book, some of the-the one who designed the SA/SPaH for example.
>> LAKDAWALLA: Yeah.

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>> MAXWELL: The sample acquisition, the handling system. Are you hoping that--you know, and as-as-as-as you are well known for your, kind of, science outreach, you're also well known as being an advocate of women in science and engineering. And are you hoping that, you know, one of the many effects of this book will be to encourage women to go into science and engineering, to see that there's a role for them in this kind of work?
>> LAKDAWALLA: I don't think-I don't that that's something that I see coming as an outcome of this book. I think the book is designed to feed people's insatiable curiosity about what Curiosity is.
>> MAXWELL: Right.
>> LAKDAWALLA: And, honestly, you know, as a parent of two daughters, I don't see any problems with the number of women who want to go into science and engine--engineering.
>> MAXWELL: Yeah. Sure.
>> LAKDAWALLA: It's whether science and engineering wants to keep them there really, ultimately. It's--these missions are really hard because they operate when you first land on Mars, the amount of time you spend, just continuous hours working on these missions is just--it's kind of nightmarish. And I don't really go into that that much in this book. If you're interested in books where--kind of, the life of being on a mission is central, you can read--there's another recently published book by Alan Stern and David Grinspoon called Chasing New Horizons.

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It's about the New Horizons mission to Pluto. And at every stage of that mission, it was like, "We thought we were all in before but we had to get even more all in. And then I started working sixteen hours a day and getting by on three hours of sleep. And it's like the Four Yorkshire men sketch--

>> MAXWELL: Right.
>> LAKDAWALLA:--from Monty Python. It just keeps on getting worse and worse, and you wonder how people can last like this. And people with families can't last like that for very long, you know, so you have primarily young people working on missions, at least on tactical operations. It's just--it's difficult. Now, over time, on a mission like this, they did--they were able to change the operational structure. So, first, after about--after 90 days, they went off of Mars time. So Mars time is where you set your clock to the rotational rate of Mars which has days 40 minutes longer than Earth days. And, Scott, you're always my example of the weirdo who loves Mars time because like if you are a person who's like a night owl with no children--you have children now, of course.

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But if you are a night owl with no children and you love to sleep in, what's not to love about sleeping in 40 minutes later every day? That sounds great. But like if you have any connection with the rest of humanity, it's absolutely...
>> MAXWELL: Which I totally don't.
>> LAKDAWALLA: ...miserable. If you have children who have--or a spouse or a partner who has--who wants to like see you during ordinary daylight hours, it's absolutely miserable. It's also kind of dangerous. You know, I was on Mars time with Spirit and Opportunity for a little while, and because the schedule slips around the clock, you wind up sleep-deprived driving home after being up all night during morning rush hour or on empty highways and you fall asleep while driving and get into a wreck. And Steve Squyres was actually really concerned about this and did all kinds of training for the...
>> MAXWELL: Yeah.
>> LAKDAWALLA: ...operations team before the mission started. But, anyway, after 90 days, they knew this mission was a marathon, not a sprint. They quickly went off of Mars time. After a hundred and eighty days, they stopped working on Sundays. After another 90 days, they stopped working on Saturdays.

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And what that means is that it really builds up your Friday. You have to produce a three-sol plan, a three-day plan, on a Friday. And sometimes it means that you're not taking advantage of the full capability of the rover. But they did do--they do clever things. Like some of these instruments, like the SAM instrument, has to cook samples in an oven that is tremendously power-demanding. So you might say cook them in an oven on a Saturday and just take Sunday off to let the batteries recharge 'cause the rover would have to do that anyway. So you might as well do it at a time when you don't wanna double up on your planning. And so over time, they have actually managed to get the operations requirement down to about nine hours a day. It's still a little bit long workday. They still do kind of play with the calendar a bit. So sometimes you have to come in and work at like 6:00, 7:00 AM because that's when you need to get the commands up to the rover before 2:00 PM or whatever it is. Sometimes you have to come in late. But they still--now they allow everybody to have a good night's sleep, except for the poor ChemCam team.

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ChemCam is one of the instruments, and it's operated from France. So now that they're on Earth time, the poor ChemCam team primarily works overnight, and it's kind of misery for them. But they-they trade off. There's only--they work into operational roles over time. Like they might have two days on ops per week and then the rest of the week they're not on ops and they don't have to do that schedule. And so I find that as these missions go on, you find a lot of older, a lot more women, people coming into operations 'cause the-the work time is much more predictable and it's much easier to balance it with all the other obligations you may have in your daily life.
>> MAXWELL: So do you-your point about families on Mars time, you all remember that when Curiosity landed, there was an engineer, David Oh...
>> LAKDAWALLA: Uh-hmm.
>> MAXWELL: ...who--he and his wife and their two kids all went on Mars time together 'cause the kids didn't have to be back in-in school for a month or a month and a half...
>> LAKDAWALLA: Yeah.
>> MAXWELL: ...or something like that. And so they all just--all went on Mars time. They were all living--the whole family was living on Mars time, which was the first of those that I've heard of.

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>> LAKDAWALLA: Yeah. And they-they had a blog. They talked about...
>> MAXWELL: But-but-but your point is well taken about that doesn't work for everybody all the time.
>> LAKDAWALLA: It was actually great. They talked about what can you do in Los Angeles with two child--the young children at midnight, at 2:00 AM? And they found all kinds of interesting walk-walks they could do with lights and things like that. It was actually a pretty cool blog. Going to the beach at-at like--you know, overnight is really interesting. And so they had a good time. They saw lots of interesting wildlife.
>> MAXWELL: Yeah.
>> LAKDAWALLA: They-they went to various all-night restaurants that the kids loved. So they actually had a good time with that.
>> MAXWEll: So--so you studied all the instruments on Curiosity in excruciating detail for this book. In that process, did you come out with a favorite? What's your favorite instrument on Curiosity?
>> LAKDAWALLA: I never have favorites but...
>> MAXWELL: She-she lied. But go ahead.
>> LAKDAWALLA: I-I do have to say that-that MAHLI is pretty cool. MAHLI is...
>> MAXWELL: Yeah.
>> LAKDAWALLA: ...a really cool instrument. So MAHLI stands for the Mars Hand Lens Imager. It's M-A-H-L-I. It's the camera that's on the end of the robotic arm. And for reasons that I go into exhaustive detail on--in the book, it turns out to be the widest angled cam--color camera, also, that the rover has, so it can take the broadest views.

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And because it's on the arm, you know, they can--the-the whole point of it is to take images of targets that they do their in-situ work on with their instruments. And so they'll use MAHLI to take an image from about a foot away, and then they'll zoom in and take one from about five

centimeters away, and then another one from about two--one or two centimeters away. And that gets you a nested set of images at increasing resolution that helps you see what's going on in the rocks. But because it's a focusable camera, it can also focus at infinity. So you can take long distance views and, of course, you can turn it back and look at the Rover. And so, this is--it's the first Mars Rover to demonstrate capability of taking a self-portrait on Mars, although notably, Opportunity recently took a self-portrait on Mars. It, too, has an arm-mounted camera. Its camera is not focusable, so the images that it took of itself were very blurry. But it's still unmistakably the Rover, and it was really quite a thrill to see that.

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But yeah, it's become part of standard operating procedure for Curiosity to take a selfie whenever it's at a drill site. And so, we have these self-portraits of Curiosity across the surface of Mars. And you can see it getting increasingly dusty. The one that you're seeing on the screen up here is a special one where the first self-portrait, actually, that Curiosity took was just of the wheels on the surface. And you want to do that so that you can check and see how the wheels are contacting the surface, check and see the condition of the wheels after the landing. And they--you know, after they did that, they--in order to do that, they have to have the-the arm very low, obviously, underneath the undercarriage of the Rover. Most of the selfies are shot at an altitude that's similar to the altitude of the Mastcam cameras so that they're--it's-it's, you know, taking a self-portrait. But this one, they were actually at a drill site where the ground sloped downward, which made it, like, actually quite difficult for the drill team.

[0:27:01]
But because the ground was sloping downward away from the Rover, they were able to turn the turret and take a full selfie from that low perspective, so that's what gives you this very low perspective on the Rover. And those self-portraits are cool and it--the--some people on the science team or on-on--on the engineering team we're dubious, but when the-the Molly principal investigator and a couple of the workers on that mission simulated what it could look like and showed it to the engineering team, they were like, "Oh my God, we have to do this." And so, like with everything they have to do it on Earth before they can do it on Mars and so the first selfie was actually taken by the Earth copy, the Earth twin of Curiosity inside its little garage in the Mars yard at JPL. And you can see there's two engineers in the background, one of them is Vandy Verbank, she's, like, around the corner as the--as the camera images being taken, it's pretty cool.
>> MAXWELL: Yeah. I was-I was--I'm surprised that you said the Molly was your favorite because everybody when they-when they--when a when you asked what their favorite instrument on the-the--on Curiosity is everybody always says the laser.

[0:28:04]
>> LAKDAWALLA: Oh. Pew, pew.
>> MAXWELL: It's pew, pew, pew, come on.
>> LAKDAWALLA: It's a Rover with a freaking laser beam on it, so.
>> MAXWELL: Yeah. Exactly.

>> LAKDAWALL: What's not to love about that?
>> MAXWELL: Exactly.
>> LAKDAWALLA: And actually so the--it is kind of fun, there's-there's very imaginative artworks of, you know, Curiosity zapping various things. My favorite one actually is one that I first saw in a ChemCam team, ChemCam is the instrument that has a laser. They were doing a team presentation at a science meeting and they had a-a photo of Curiosity shooting a laser and a full-on Michael Bay explosion happening at the end of the laser. So no, it's--I just--I like pictures, what can I say? Pictures tell us stories and I really like the Molly pictures. One thing ChemCam has though is it does have a camera on it for--to take context images of where they zap with their laser. And later on in the mission they trained the camera to be able to focus at infinity so that you can take long distance photos. And the camera has this circular baffle.

[0:29:00]
So, it-it-it's the highest resolution camera, can take the most distant photos so it's just like taking a spyglass and like seeing these long distance features, ahoy, there's that, you know, Valley Network that we're going to visit in the future. And-and so I always kind of feel like a ship's captain every time I see those ChemCam pictures.
>> MAXWELL: Right. Just so it's clear I didn't mean to disagree with you about the Molly, I think it's a very strong choice. Molly also has a flashlight on it.
>> LAKDAWALLA: Yes. Uh-hmm.
>> MAXWELL: Which is-which is Kim, my wife who works on the Rovers on-on Curiosity, that's her favorite is the flashlight.
>> LAKDAWALLA: Oh, yeah?
>> MAXWELL: Attached to the Molly.
>> LAKDAWALLA: Yeah, there's-there's actually two flashlights and the reason for that is because if you're a geologist working in the field with your rock hammer you smash off a piece of fresh rock to look at the crystals inside and try to identify what minerals are present, you-you'll do this with the rock sample to try to catch glints from the Sun to see if there's reflective surfaces and what the angles are to each other. Well, Curiosity can't do that, but what it can do is take its two little flashlights on Molly and go blink-blink-blink-blink-blink-blink to-to do lights coming from two different directions. And so that's what it does to try to-to catch that crystal glints.

[0:30:02]
I don't know that it's ever worked that way, but they do use the flashlights at night because that way they have a light source of known illumination properties, and so all the night images that they've taken of all of their drill sites they can compare the color to each other because they're all taken under exactly the same illumination conditions.
>> MAXWELL: Right. So in addition to the-the laser on the Rover I-I actually learned from your book there's not a thing I realized before reading your book, but I-I learned from your book that DAN the DAN--the Dynamic Albedo of Neutrons experiment has an ion cannon.
>> LAKDAWALLA: Yes.
>> MAXWELL: So we've got a laser and an ion--
>> LAKDAWALLA: We do.

>> MAXWELL: --cannon now all we need is a Rover with a lightsaber and we've got the trifecta.
>> LAKDAWALLA: That's right.
>> MAXWELL: yeah.
>> LAKDAWALLA: Yeah.
>> MAXWELL: Another-another really cool thing I learned about the science instruments from reading the book was about the RAD which has a scintillating plastic detector.
>> LAKDAWALLA: Yes.
>> MAXWELL: Which I love that name, I've decided that scintillating plastic detector is the name of my muse cover band.
>> LAKDAWALLA: Yeah, it's--there's all kinds of fun terms and they-and they tend to squeeze all of these terms into acronyms.

[0:31:01]
And so you talk about Sam's TLS and QMS and doing GCMs and all of the samples. And-and I think it's actually a lot more fun to say gas chromatographs mass spectrometer, it sounds like--it sounds like Star-Star Trekkies, you know, and let's send those--let's fire things up in our oven and send them through the, what is it, the manifolds that there are many manifolds inside SAM and you send it with your helium carrier gas through manifold A and send it off to the tunable laser spectrometer and see what that's--it's just fun. There's-there's a lot of-a lot of fun terms so.
>> MAXWELL: Right. So-so again having studied all the instruments and like this exhaustive detail as you say, which-which of them do you think was the-the most complicated instrument of all of them on the Rover?
>> LAKDAWALLA: That one's easy to answer but the first thing I want to answer is-is I--when he says exhaustive detail, exhaustive is the most common adjectives used to describe my book and I'm just glad that it's not exhausting.
>> MAXWELL: Right. Yeah.
>> LAKDAWALLA: So yeah, so--
>> MAXWELL: It's fascinating but exhaustive.
>> LAKDAWALLA: Right. So definitely without question the most complicated instrument is the SAM instrument.

[0:32:03]
So Sam means Sample Analysis at Mars it's one of two laboratory instruments. And it's interesting that the two laboratory instruments one of them is really very simple, and that's CheMin it's a--that's the instrument that it has a--it has a laser that it shines through a little sample of powder and it-it shakes the powder so that those crystals all toss around in various different orientations, and the crystals scatter the light and you get a diffraction plot. It's the same kind of technology that Rosalind Franklin used to figure out the structure of DNA. You're doing X-ray crystallography basically. And it's--and that's all it is, you-you take a picture of the-of the diffraction and then you download that picture and you can say, "Oh, these minerals are present." And that's it, and that's one of the two laboratory instruments. But then there's SAM and SAM is ridiculous, I cannot believe they actually built this instrument and put it on a Rover on Mars. It has it--has a-a carousel of more than 70 little quartz cups.

[0:33:03]
It can rotate this carousel under two different inlets to receive samples then it rotates the carousel and lifts a cup into an oven. In the oven it can heat things up to 500 degrees, it can heat it in steps, it can heat it with a ramp, it can heat it for a little bit then hold it or not. It can heat it all the way, it can heat it part way, it can take it down and do it--bring it back up again. And then there is a little helium tank that takes all of the gases that come off of the oven and sends them into one of numerous possible different instruments. But before that it sends them into these little chambers called manifolds which are, you know, a manifold is a place where you have lots of things intersecting. And by opening and closing one of dozens of different valves they can send the material on to different getters and scrubbers which take certain stuff out of-out of the-the gases. They can turn-turn on a getter for a little while and then heat the getter to release the stuff again, and then they send that into one of three different instruments.

[0:34:01]
So there's all these valves, there's all these different ways, all these knobs to turn. They actually developed basically a programming language that they can--that the SAM team can use to send things through the SAM instrument. One of the wackiest things I think is that the-the PI on the SAM instrument was very proud of the fact that it's--that he can-that he programs it in basic.
>> MAXWELL: Right.
>> LAKDAWALLA: I was like, I know--I know very little about programming languages but I know enough to know that that's not something to be proud of.
>> MAXWELL: It's-it's not widely used at Google that's what you are, yeah.
>> LAKDAWALLA: For sure. So anyway it's-it's incredibly complicated and to most people it's just a box that you--that the SAM team asks for knobs to be turned and they turn the knobs and data comes out. And then even once you have the data you still don't have answers because the kinds of things that they're trying to figure out are so complex that the only way to be sure that you've figured it out right is to create a sample of known composition, and put it through a duplicate of the instrument in a lab on Earth, under Martian conditions so that's temperature and vacuum.

[0:35:07]
And it's--so SAM results there's actually going to be a press conference tomorrow concerning a science paper that is one of the main people on the press panel is Paul Mahaffey who is the principal investigator on this instrument. And so I'm sure that the paper concerns data that was taken at least six months ago, probably years ago because that's just how long it takes to understand the results from this instrument. Fortunately there are other instruments that produce much more rapid results and-and make things a little more interesting for those of us following along in the mission.
>> MAXWELL: So the SAM instrument has another talent if-if there were a talent show on Mars, Curiosity's entry would be singing.
>> LAKDAWALLA: That's right, SAM famously sang Happy Birthday to itself using its SAM instrument. I actually don't know the details of what was vibrating or making noise.

>> MAXWELL: Yes.
>> LAKDAWALLA: Was-was it like an FPGA or something that had like--
>> MAXWELL: I-I-I-I don't know the details, my wife is the instrument engineer for the SAM instrument and so-so she could probably tell us about that and-and exhausting at detail.

[0:36:03]
>> LAKDAWALLA: So-so anyway but this story does surface once a year.
>> MAXWELL: Yeah, right.
>> LAKDAWALLA: But it--I am here to tell you it does not sing Happy Birthday to itself every year, that once on Mars it was a cute little stunt and-and that's-that's it.
>> MAXWELL: Gosh, what time? So we've been talking for about 40 minutes let's-let's throw it out for audience questions as well, and kind of while we're getting--oh, have you seen our microphone? This is really cool. The microphone is in a little box and a soft box and they can just throw the box around the room. But while we're--while we're waiting for that let me ask you, you-you were saying the SAM instrument is the most complicated instrument. Was it also the hardest to explain?
>> LAKDAWALLA: It was absolutely by far the hardest to explain to find about 50 pages of this book on the SAM instrument. And I-I warp Paul Mahaffey out asking questions about--because, you know, when I first started writing this I envisioned, you know, you-you-you have--you heat stuff up, you get a gas and it goes through the machine, comes out, and--but that's not how it works at all. You heat-you heat it up, you get a gas and goes into one place then you open a valve and it goes into this place then you might be turning on something that pumps slightly but not too much and you get like a gradient going.

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It--it's so incredibly complicated that the-the main comment that I get from people on the mission who are not on the SAM team is "Thank God somebody finally explained this to me because I have no idea how it work."
>> MAXWELL: Cool.
>> So, I was wondering how does the delay between Earth and Mars like affect the teams that operate the Rover? Like is it a lot easier to do work when Earth and Mars are close together?
>> LAKDAWALLA: Ah, so no actually that's a good question. So Mars and Earth have widely differing distance to each other which affects the-the communications lag, but the fact to the matter is that because the lag is many minutes regardless of the relative distances, there's no real time commanding. So you are always doing a full Sol's worth of sequencing at a minimum. You send the Rover receives its commands at 10 AM every morning Mars time.

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And so, the reason that they do that is because Earth is always up in Mars's sky at 10:00 AM local time. Earth is closer to the Sun than Mars is so it's always somewhere relatively close to the Sun. And so if you're doing your commanding at 10:00 AM Earth will always be up in the sky although sometimes it can be a little low on the horizon. And so the Rover executes it's one Sol's worth of commands and then in the afternoon there are over flights by two Mars orbiters. Mars Odyssey and Mars

Reconnaissance Orbiter, and it sends its data through a UHF connection up to the orbiter which receives the data and then relays it on to Earth. And so there's also overnight passes by the orbiters. And so you wind up having the command in these at minimum once Sol increments.

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>> And so, it really doesn't matter how close Mars is, except that it is--you can get much higher bandwidth in your transmissions between Mars and Earth when Mars is closer. So you do get more data return from the orbiter because it can communicate faster. You can use a higher data rate when they're close. And so, you'll see these seasonal spikes in data rate that are not actually seasonal. They happen when Mars is near opposition when Earth and Mars are close to each other. And then, on the opposite side, when-when Mars gets into conjunction with the Sun, you actually have three weeks where you're not allowed to talk to the Rover at all because if there were a problem, you couldn't be sure that your message would get through ungarbled to be able to save the Rover. So, they--all the spacecraft kind of hunker down and go into a fairly low activity mode during conjunction.
>> I have a question.
>> LAKDAWALLA: Uh-hmm.
>> Are there pieces of the Rover that it can separate from itself? Like, in the selfie picture, I don't see how there's something attached to it that would take the selfie.
>> LAKDAWALLA: Right.

[0:39:49]
So, this--the question of who took the picture and how the selfie works is one that-that pops up every single time I post a selfie. The issue is that the--although the-the field of view of the MAHLI camera is fairly wide, it's not anywhere near as wide as the kind of camera you have on your cell phone. It's actually very narrow. So, in order to take a selfie, the Rover actually takes about 70 pictures of itself in kind of a-a matrix sort of way, and it repositions the arm to keep the arm out of view. You know, it would never be able to photograph its whole arm regardless. And so, you wind up mosaicing an image together like this out of-out of multiple different images. And they just--they do it in a way so that the-the arm is not constantly poking into view from all these different directions because when-when you do take the-the selfie, you do see--you know, you-you will see the arm in-in multiple images. And so, you have to come up with a way of neatly cutting it off. You actually see more of the arm in this picture than you see in most of the self-portraits.

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Usually they chop it off at the shoulder because otherwise it would be crossing the front of the Rover, but because of all those multiple pictures, you wind up being able to get the arm out of it and there's no real sensible way. One of the more disconcerting images that I've seen was a self-portrait taken by the Mastcam, which is the only way that Opportunity and Spirit can take self-portraits is you take a--you can get a-a mosaic of the deck of the Rover by shooting multiple images with the Mastcam. And in those images, of course, the mast is missing because it can't photograph the Mastcam. It can't photograph its own mast. And so,

you wind up--you get a great view of the arm, but the Rover is headless, and it's really kind of disturbing.
>> So...
>> Yeah.
>> This--wasn't this the one that had the, like, really difficult landing? Like, it was really complicated, and they were really worried about it? I don't--
>> LAKDAWALLA: Well--
>> MAXWELL: Ands he goes in a lot of detail about that in the book, by the way. It's-it's really fascinating.
>> LAKDAWALLA: Yeah. So it's kind of funny. It-it wasn't really complicated landing. It-it's a Rube Goldbergian landing.

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So, it's has--the problem with landing on Mars is that it has enough atmosphere to burn you up, but not enough atmosphere to slow you down. So it's easier to land on the moon. It's easier to land on Earth. On the moon, no atmosphere. You just streak in, blast with retrorockets, boom, you're on the surface, no problem. On Earth, parachute and heat shield slows you down enough where you just kind of coast into a landing. That's what the-the space shuttles did. That's what all the Apollo capsules did. On Mars you have to combine all of those things. So you have a heat shield that takes you from interplanetary travel speeds down to supersonic speeds. Then you have a parachute that takes you from supersonic to subsonic. Then you have rockets that slow you down from sub--from subsonic to still. And then you have to touch down. And different missions have accomplished this in different ways. Most Mars missions are landers. And so, what the landers typically do is they get down to--
>> MAXWELL: Lander-landers as opposed to Rovers.
>> LAKDAWALLA: As opposed to Rovers. Yeah, sorry. So they get pretty close to the surface. And then, usually they cut off their rockets right above the surface because you don't want to be blasting the surface with a lot of rocket exhaust. And so, they'll have, like, crushable legs. That's what Phoenix and Insight have. They have legs that can take up that last bit of drop or you'll have what Spirit and Opportunity had which are the airbags surrounding, and it actually bounced to a halt, which I think is nutty. I mean, take a ridiculously expensive machine and whack it on the surface multiple times. That's what Spirit, and Opportunity, and Pathfinder. And so, Curiosity's approach--Curiosity was already too big to have any extra lander hardware. And so, it said it had a rocket-assisted backpack that it lowered the Rover on a rope, and the Rover--and then gently let the-the-the Rover touch the surface and there's slack on the cables. And once the machine detected that there's slack on the cables, it cuts the cables and flies the jetpack away, which, like, you can just imagine, it's just like in a Wile Coyote character, whew, clunk.

[0:43:56]
>> MAXWELL: Right.
>> LAKDAWALLA: And then there's a big explosion and a boom and stuff.
>> MAXWELL: Which we got a picture of.
>> LAKDAWALLA: Which we actually got a picture of.
>> MAXWELL: That was amazing.

>> LAKDAWALLA: The first Curiosity image from the surface of Mars was taken by its rear Hazcam. And you see this plume of dust on the horizon, and they later figured out that that was probably the-the plume from the explosion of the jetpack when it crashed on the surface, which I think is just great. So yes, so it was--it's an incredibly complicated landing. But as I explain in the book, it's actually not really out of family from what had been done before. Hanging the Rover on a rope was actually exactly what they did with Spirit and Opportunity. That airbag thingy was descend--was hanging on a rope off of the retrorockets. And so, the landing looked ridiculous, but it was very well-modeled. And after they had the-the two-year launch delay, I have never seen engineers as confident as I saw. I mean, engineers as a rule, are not confident people. They're like, well, it might work if all the conditions are right, blah, blah, blah. You know they are this. They don't want to tell you it's absolutely going to work because, like, as they say in the rocket business, "There's a thousand ways for a launch to go wrong, only one way for it to go right."

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And so--but when they were--they had that last two years to really prepare and throw all kinds of situations at it, you know, dust storms and-and bad navigation and failure of one of the rockets and all kinds of stuff. And the machine in their simulations performed with flying colors. And in the-in the final event, it was just straight down the middle. Everything was nominal, nominal, nominal, except for one little detail that maybe I'll let you guys read the book for. Yeah.
>> MAXWELL: So, software people, while-while the mic is going to the next person, software people like us understand the concept of-of Easter eggs. The little hidden things in, you know, maybe, your web browser, you hit Ctrl Alt, Shift S, and it pops up a flight simulator or something like that.
>> LAKDAWALLA: Right.
>> MAXWELL: And Curiosity has one of those Easter eggs as well in-in the wheels. Before they--
>> LAKDAWALLA: Yeah.
>> MAXWELL: --before they had not-on-purpose holes in them, they had on-purpose holes in them.
>> LAKDAWALLA: That's right. So if you look at the-the wheels of the Rover, you can see that there are deliberately a whole bunch of holes punched in them.

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This is kind of a callback to Spirit and Opportunity, which they were connected to their lander with these bolts that were fired and separated after landing. And so, there are holes on Spirit and Opportunity's wheels that are there just as an artifact of the method by which they were attached to the lander. But they turned out to be really useful for the science team because you can see the little mark that the holes left in the wheel tracks to actually measure distances. You can also use it to see how much the Rover wheels slipped during driving. So you can kind of measure distances in one way and then in a different way, and see how long or short it was. And the-the Rover actually got to where it was using this for odometry, it could actually use its own wheel tracks to help understand how far it had traveled. So they wanted to include some

kind of odometry marking on the wheels on Curiosity to make sure that it would be easy to tell how many wheel turns there had been in the Rover tracks. And so, the first thing they did was that they actually machined the letters JPL into the wheels, into the treads. And so, there's a picture in my book of the-of the an early set of wheels that has JPL on it, so it left tracks, JPL, JPL, JPL, as it was going and NASA was like, "You guys, you can't do that."

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So they came up with another plan which was to put the letters JPL in the wheels in Morse code. So that's what you see, there's three rows there and they have, like, narrower and wider gaps, and that's the letters JPL in Morse code.
>> So this isn't actually a Curiosity question because there's something else you mentioned earlier that's been bugging me. You said the Russians landed a mostly mechanical lander on Venus.
>> LAKDAWALLA: Uh-huh.
>> And the electronics wouldn't stand up to the surface temperatures. How did they communicate the information off the planet to us?
>> LAKDAWALLA: Well, I don't actually know enough about the--about how those missions worked. I mean, they-they did have, like, a pressure vessel, a temperature-safe vessel on the inside that had the electronic--the limited electronics that there were. And they did do radio communications direct to Earth. They didn't have orbiters, so they were doing a direct to Earth. But then, Venus is actually relatively close to Earth, so you don't have to have very powerful radio to get that data back. I'm afraid I'm not an electronics person myself, so I don't really know the answer to that question.

[0:48:12]
>> MAXWELL: All right. I--we're kind of--we're starting--we're run-runing a little low on time. And it kills me that we're not going to get-get to all the questions I want to ask you. Maybe we should take one more audience question, and I'll ask you to kind of to wrap-up here.
>> LAKDAWALLA: Okay.
>> So, my question is what happens if something mechanical fails? Is there any self-repair kind of capability?
>> LAKDAWALLA: There is not. But there's a lot of redundancy, a lot of redundant capability. So there's a lot of planning done to figure out how the Rover can still accomplish its mission even if this, that, or another component fails. So like the computer systems are fully redundant, there's an A side and a B side, and various components are cross-strapped to each other. So when a computer fails, as actually happened 200 days into the mission, they can swap to the backup, and operate on the backup while they repair the prime computer. And so, they've done that with-with the main computer already. It actually took them a long time to bring the backup back online, which was kind of scary. There have been mechanical problems like problems with the wheels. And so, you get through that through robustness.

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Basically, any one of the wheels, the motors are powerful enough to-to raise the entire Rover's weight vertically. So, like, if you attached a rope to it, you could wind a rope on one of the wheels, and it would--and

the motor is strong enough to be able to lift the whole Rover. This actually became important for Spirit and Opportunity because both of them had--have had different kinds of wheel failures. And so, Spirit in particular, was dragging one of its wheels for a long time. But the Rover is still able to drive that way.
>> MAXWELL: And-and it's a good thing because we made some science discoveries because of that.
>> LAKDAWALLA: We did. Yeah. And so, the biggest problem that Curiosity has been dealing with lately is a--is a major mechanical failure in the drill. So the drill used to operate with a pair of prongs that it pressed against a rock. And then there was a feed mechanism that pushed the drill into the rock while the--everything else stayed still. And the feed mechanism failed almost completely. They--it was very sticky. They couldn't get it to-to move backward and forward, which is critical for drilling. And so, over the period of more than a year now, they've managed to get the bulky feed to extend all the way.

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So now the feed is permanently extended. And they just a couple of weeks ago, for the first time, managed to do what they call feed-extended drilling, where instead of using the-the feed mechanism, which no longer works, they're now using arm motors. So it's like taking a drill and trying to drill into a wall like this. You can imagine, it's hard, but-but Curiosity's arm is pretty strong. And so, they just kind of lean on the arm and they push the drill into the rock, and it worked. So it's taken them a long time to fix it, but these engineers are really ingenious at solving problems. And so, a lot of what you do on an extended mission, and extended extended mission, which is what Curiosity is on now, is figure out how to make the most of an aging machine that does have problems, but can still do great science where it is. And so, all these people have a lot of experience in making old, groany machines work. I mean, I'd like to write a book about Galileo, about all the things they had to do--
>> MAXWELL: Oh, yeah.
>> LAKDAWALLA --to keep that thing going after radiation fried it at Jupiter multiple times. And so, Curiosity's still got a lot of life in it.

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They'll have problems, but, you know, they wish the problems weren't there, but they-they're like, okay, here's--this is our new reality, and we'll keep going. That's how it works.
>> MAXWELL: So it's-its killing me that I've got, like, 20 more questions here and we've got three minutes. So that's not enough time, I'm thinking. But-but maybe we can end on this note--
>> LAKDAWALLA: Uh-huh.
>> MAXWELL: --by asking you, like, what do you hope that readers will take away from this gorgeous, terrific book that I could not more highly recommend?
>> LAKDAWALLA: Oh, gosh. I hope that they will--I guess I hope that people will take away the fact that they can understand this is a very complicated machine, but what it's doing, why it's there, and how it works are-are not--are not inaccessible to everyone. And that's one of the great things about space exploration I think is that it's easy to

explain why we're doing it, the fundamental questions we're trying to answer. Was there ever a life on Mars, are we alone in the universe? That kind of stuff. And it's--and it's fairly easy to understand how we're going about solving those problems.

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We're sending a robot with a drill that's like sampling rocks, and we put them into a lab. And-and all of these things you can communicate with children, you can communicate with science-interested adults as well. And it's-it's just very accessible, and everybody can kind of participate in the adventure by following along with what they're doing. They-they share their raw images straight from Mars directly on the internet so that you can see every day, you can tune in at JPL and see what they've been doing. I highly recommend midnightplanets.com. It's a--it's an enthusiast-built website that aggregates all of the images from the different Rovers and-and puts them up in ways that are easy to see. And it's a--it's just--it's a fun adventure, and-and we're all part of it basically.
>> MAXWELL: Emily, I'm so sad that we're out of time, but I-I-I enthusiastically recommend this book. The book is "The Design and Engineering of Curiosity: How the Mars Rover-Rover Performs Its Job." All the stuff you've heard us talk about today, and a whole lot more stuff is in there. It's really terrific. I highly recommend it.
>> LAKDAWALLA: It's also on my blog at planetary.org/blog.

[0:53:20]
You'll find I-I write updates about every two or three months on what Curiosity is doing. I'll probably have a new one out in a couple of weeks.
>> MAXWELL: Right on. I wish we had another hour to talk, but maybe you'll be able to come back and we'll be able to do it then. In the meantime, please join me in thanking our guest today, Emily Lakdawalla.
>> NESTRALL: Thanks for listening. If you have any feedback about this or any other episode, we'd love to hear from you. You can visit g.co/talksatgoogle/podcastfeedback to leave your comments. To discover more amazing content, you can always find us online at youtube.com/talksatgoogle or via our Twitter handle @googletalks. Talk soon.