[music]

00:06 Sarah Crespi: Welcome to the Science Podcast for April 17th, 2020. I'm Sarah Crespi. First up this week, we talk about Coronavirus phase 2. What countries can do to get back to the new normal once they've slowed their cases to a trickle? Contributing correspondent Lizzie Wade joins us to discuss how 1,400 years ago ingenious water management helped the Wari expand throughout the Peruvian Andes. But it turns out these techniques couldn't save them from a serious drought. Last up, we have researcher Yon Visell. He's here to talk about his Science Advances paper and how waves propagate along the skin of the hand and aid our sense of touch. Now we have contributing correspondent Kai Kupferschmidt. He's written a piece this week on Coronavirus phase 2. We're recording Tuesday, April 14th. So phase 2, what happens after cases slow down? How do countries come to unlock themselves? Hi, Kai.

01:06 Kai Kupferschmidt: Hey, Sarah.

01:07 SC: It doesn't seem like there's a straightforward answer to this question. It might be a lot easier to lock down than to unlock. Is there any consensus on how to do this?

01:19 KK: There isn't a consensus around this, and it's gonna look a lot more varied than the first Phase did. I mean, most countries did more or less the same thing. They instituted pretty hard social distancing measures or physical distancing measures. Some went further than others, but the basic recipe was the same. Once you have the cases down, you might be able to relax some of these measures. And then, of course, it depends a little bit on the country and the culture and also what's seen as politically more important, which ones you want to relax and also which ones you can relax without giving the virus too much of a chance to rebound.

01:54 SC: Right, the countries have to balance safety, their economy and the freedoms of the individuals, of the citizens. It's tough to solve this, especially in different contexts. And as you say in your story, a lot of researchers are focusing on the effective reproduction number. Why is that more important than, say, new cases or deaths from Coronavirus?

02:17 KK: The basic reproduction number of a pathogen just means how many people does one infected person in turn infect. We know that there's a range, measles is incredibly infectious so on average one person will infect maybe 15 other people. And then, there's other viruses like say Ebola which are a lot lower, so it's like 1.5 to 2.5. And the basic point here is if one person on average infects more than one other person you get this steep climb in cases and the outbreak is growing. Everything that we've seen so far with the physical distancing has been trying to make this value of R go below one. So trying to make sure that every infected person infects less than one other person so that the outbreak slowly comes to a halt.

03:02 SC: And there are different approaches to moving this value, social distancing. Which you talked about, contact tracing and then also you mentioned in your story monitoring orders, let's take these one at a time. How they impact this value. So for example, contact tracing this is keeping track of all the cases in the country.

03:22 KK: Contact tracing and finding cases and testing really belong together. And again, it's a very simple idea. We know that we can stop any infection from spreading if we find the people that are infected and isolate them before they can infect anyone else. Or if we can't do that, we can try to find who they were in contact with, and then take these people and before they can infect somebody else, quarantine them. The problem is that we haven't been very good at that. There's one plan from Johns Hopkins University where they say that the US needs an additional 100,000 people to be trained to do contact tracing, just to give you an idea of what a scale-up of these capabilities will look like.

04:03 SC: I saw yesterday that New York State, 1% of people are infected. Can you imagine contact tracing? It's a lot of people.

04:12 KK: Yes. We missed an opportunity at the beginning of this outbreak where maybe we could have stopped the virus from spreading if we had really jumped on the cases and done the contact tracing. But at some point the system becomes overwhelmed and I don't think anybody realistically expects someone to be able to trace all the contacts of 1% of the population of a major city. But as the cases go down again, we get another opportunity. That's what we've been working towards with this whole lock-down is to get the numbers low enough so that we can make some of these classic interventions work for us again.

04:46 SC: Let's turn to border control. So, a lot of countries closed their borders at least to non-citizens during this crisis. But is it possible to re-open borders once the cases start to decline, and how would that affect efforts to combat a second wave?

05:04 KK: What's becoming clear in this outbreak is that it really depends on the pathogen and on the phase of the outbreak.

05:09 SC: The situation on the ground.

05:10 KK: Yeah, arguably if borders had been closed earlier, then maybe the virus wouldn't have gotten to so many places. And now, we get into this next phase where the border closures might have a relevance again, because once you've controlled the outbreak and once you're on top of some of your transmission chains, then when you introduce new travelers who might be bringing the virus from somewhere. And often these are people who might not be in your national system that you're using. For instance, if you're using a certain app to track people, they might not be using that, they also are quite likely if they come to the country to meet with a lot of people and have quite a lot of contacts. So, you can see how having a lot of travelers is going to make your job harder if you're really trying to find every case and find it early. And that's why I think that in the second phase at least, we'll have quite significant restrictions on travel still.

06:02 SC: Let's go to social distancing as a measure. This is something that we are all going through. We're staying at home as much as we can. A lot of things are closed, and it's tough on people. They can't work, businesses are closing. What do we know about how to re-open? What the steps are? What to open first? Is there any evidence that we can use to make these decisions?

06:25 KK: There isn't a lot. I think the two things that we know for sure is you better do it slowly, and you better do it step-by-step. Taking the time to see whether re-opening one part of society, whether that already gets you in trouble or not. In some ways, this is the hardest one to talk about, because the border closures, to a certain extent will just stay in place, and the contact tracing and testing will have to be ramped up. With the social distancing, different parts of society are also going to have different interests. Some people will think it's the most important thing to reopen...

06:57 SC: Schools.

06:57 KK: Schools, exactly. That's going to be a large discussion. And Germany recently in a report said, "Once schools are re-opened, we should start with the youngest kids first, because they need the actual interaction with a teacher more than the older classes." There are other people who say, "Well, actually, it's easier to tell older students to keep a distance."

07:17 SC: Careful.

07:17 KK: "And be careful." Exactly. There are all these trade-offs that we have to talk about. Then of course, other people will feel that actually it's more important to open churches or synagogues or gyms or bars. I think different countries will try different things. First, Austria is now re-opening the small shops. They basically re-opened today. They're looking at this for two weeks before they're gonna open bigger shops and open malls again, and then another few weeks before they want to re-open bars and restaurants. And at every step of this, people will look very closely at this value of R, which we can track almost in real time now.

07:50 SC: Yeah. How can you track it in real time?

07:52 KK: Logically, you can't really know what R is right now, because you're always looking at infections that have already happened. But basically, you can look back and say, "Okay, how many infections did we have a few weeks ago. And how many infections came out of those infections?" So that gives you a first estimate of the R a few weeks ago. What a lot of modellers now are doing is they supplement that with some real-time data on mobility, for instance...

08:17 SC: Like how far they're going?

08:18 KK: Yeah, exactly. So for instance, in Hong Kong, what they're using is the Octopus Card, which is this card that they use to pay for public transport but also to pay for some other things. So that gives you an idea. If that ticks up, you see that your population is becoming more mobile again, probably having more interactions. They're basically trying to estimate, "Is the R that we had a few weeks ago, is that still the R we expect to see now or has there been a shift in behavior that maybe makes it tick up or down?"

08:44 SC: Then you can roll back something, or you can implement something to control that R?

08:49 KK: The hope is that you say, "Okay, let's open schools for the youngest kids." You wait a week, and then you see hopefully that R doesn't tick up too much. And then you're like, "Okay, this seems to have worked, maybe we can do something else." Or you realize that something makes a huge difference. Because the problem at the moment is most countries have implemented a lot of different measures at the same time.

09:08 SC: So they don't know which ones worked?

09:10 KK: Exactly.

09:11 SC: A lot of the researchers that you talked to were less than confident that this was gonna be an easy thing to do. They're more like, "This is going to be a long slog, and people are not going to like it."

09:26 KK: Yes, absolutely. And it's one of the things that almost surprised me a little bit. I'm quite used to people saying, especially modellers, saying, "Okay, we have these models, and if we do this and this and this, we can get this under control." Maybe it doesn't work out that way in real life sometimes. But the modeling, at least usually, shows you that it could be done.

09:42 SC: A path.

09:43 KK: Yeah. Just because it is so clear that a lot of the models require quite a lot of social distancing for this to work. After a few weeks of experiencing this, it's just clear to everyone you're unlikely to have a population in most places in the world be willing or able to keep this up for months. So the question becomes a little bit, "Are we willing to enjoy short periods of really lifting a lot of the social distancing measures, and then maybe see the virus come back, and then re-institute the lockdowns?" So have these phases of lifting and then suppressing the virus again. Or will there be some other way of dealing with it? I think most scientists at this point are very conscious of the fact that what happens in the next months probably depends a lot more on politics and psychology and how people, in the whole, react in certain societies, rather than how many percentage points they can suppress the R with certain social distancing measures.

10:41 KK: So Marc Lipsitch, an epidemiologist at Harvard University, he told me, from his perspective, we've made it to the life raft, but he's not sure how we're gonna get to the shore. And I think that's the phase that we're in now. It'll take a lot of patience and trial and error, and it'll be difficult to communicate a lot of the uncertainty around this, even for us the science journalists. But certainly in general for the public and for scientists, it'll be a difficult period, I think.

11:06 SC: Alright. Thank you so much, Kai.

11:07 KK: Thanks, Sarah.

11:08 SC: Kai Kupferschmidt is a contributing correspondent based in Berlin. You can find a link to his story and all of our COVID-19 coverage at sciencemag.org/podcast. Stay tuned for an interview with Lizzie Wade about the fate of the Wari state.

[music]

11:27 SC: When water dries up, people must move out, or they move water in or try to. But as climate change strengthens its hold on the planet and populations grow, shrinking water supplies and drought are an increasing challenge. Our special issue on drought this week tackles these big, dry problems, like the causes of drought, engineering resistant crops, and predicting droughts and famines. Also this week, contributing correspondent Lizzie Wade brings a story on the effects of droughts gone by and lessons we can learn from them. Hi, Lizzie.

12:06 Lizzie Wade: Hi, Sarah.

12:07 SC: Obviously, we're gonna go somewhere with an archeological angle here. We're gonna talk about the Wari. This is a state that was around from 500 to 1000 CE in what is now Peru, the high Andes part of the country. Is there much water up there Lizzie?

12:24 LW: No. There isn't now, and there wasn't then. [chuckle] So most of the rain in South America gets blocked by the Andes 'cause they're very high mountains obviously, and so, the clouds get pushed East, the rain falls over the Amazon. This is why the Amazon exists in part. If you're living on top of the mountains, or on the other side of the mountains towards the Pacific Coast of Peru, you hardly get any rain at all, and you're really dependent on these rivers that are fed by mountain glaciers mostly.

12:54 SC: But the Wari state was large, and part of the reason for that was how they dealt with this low water, what are some of the things they did back in the day to make sure they had enough for crops and for drinking?

13:05 LW: Wari was really good at water. Their heartland was around the modern city of Ayacucho, Peru, so their capital was sort of near there. There and in other places when they started expanding, what they did was build really, really, really, really long canals. Canals that are so long that they have never been rivaled until the last 10 years. [laughter]

13:26 SC: Wow.

13:27 LW: Engineering in Peru, it's very impressive. If you're thinking about living on a mountain, it's sort of easier to live at the bottom of the mountain. Naturally there's river valleys, you're close to the water, the higher you get up, the dryer or colder it gets, harder to grow crops. But, the Wari were really good at living up on that mid-range of the mountains. They would tap into the rivers higher up than most people could go, so they would build these very long winding canals around these mountains, aqueducts across ravines, very sophisticated engineering. And then they would feed these canals into agricultural terraces, where you sort of flatten out a mountain slope into big stair-steps, and each little stair is a field for your crops. And what that does is, it makes it so you could farm on a mountain slope. Obviously you need a little bit of flat land; it conserves water, it keeps the water where you want it to be so that the soil around the roots of your plant stays quite damp, and, it kind of allows really efficient drainage to the terraces below, so you're not wasting any water, you're really using it all very efficiently.

14:32 SC: Can you still find that canal today?

14:34 LW: They haven't all survived obviously [chuckle] for the thousand years since they've been used, but, in quite a few places they have been preserved. So, the place that my story focuses on is this place in Southern Peru, near the border with Bolivia and Chile that is called Cerro Baúl, and it's in the... A part of Peru called the Moquegua Valley, and it remains very very dry, and it's quite remote. They have really good preservation of this hydraulic infrastructure so you can still see canals, you can measure them. Some of the terraces remain in use actually.

15:03 SC: So all of this put together, helped them to have a really strong hold on the land and their territory for a long time. How big was the Wari state at its height?

15:13 LW: Basically, if you look at a map of Peru, there's Wari influence in almost all of it, all through the Andes and in a lot of places on the coast. Some people call it an empire, some people call it an expansive state, it's not quite clear. It's not exactly like Rome where you would march through different territories and conquer each one as you went. It was a little more diffused than that for sure. But there were colonies from the very south of Peru to the middle of the North Coast at least. It was a very, very big ancient state with these tentacles that expanded in many directions.

15:47 SC: Is this a very early empire for South America?

15:51 LW: People who think it is an empire think it's the first empire in South America, and actually becomes sort of a blueprint for the Inca later on.

16:00 SC: Kind of surprisingly I think the end of the Wari time coincides with a big drought. What the heck? [laughter]

16:07 LW: Yeah. Yeah. This is the big question. So, they rise during a period that seems to be relatively dry, maybe not full on drought, but it's centuries of arid climate. They seem to be really good at managing water, and then 400 years later, this big big, big massive drought comes along, and they collapse. If anyone was gonna be able to survive a really big drought it seems like it should have been Wari, right? It's still sort of a mystery, but, what seems to be happening at least in colonies like Cerro Baúl, and maybe to a certain extent in the capital. As the government is fragmenting and the ways that they maintained power and influence over the people around them seemed to be fracturing a little bit. So in Cerro Baúl, building these huge canals and aqueducts required a huge amount of labor from a lot of different kinds of people, and, they're right next to another kind of expansive state, they're basically a border town with the Tiwanaku state. Everyone seems to be getting along pretty well, living their separate lives, but have some elite interaction like diplomacy.

17:10 LW: And, in Cerro Baúl in the century or so before the drought, it seems there's more Tiwanaku people moving in, some kind of thing about their relationship is changing and maybe breaking down. Maybe it's becoming harder to live there for some reason that we're not really sure about, pieces of the Wari canal system and field seemed to be falling out of use. People would construct their houses on top of them instead of planting crops there. Something is going wrong at the level of political organization in the government, and so when the drought arrives, maybe if it had arrived 200 years earlier, when everyone was getting along and cooperating and really working to maintain this incredibly extensive and complicated infrastructure, they would have done better, but because the drought arrived at a time when they were already sort of fracturing, it really drove deep wedges, drove divisions even further into their culture.

18:00 SC: Drought isn't just about not having water. That's the natural hazard right? The disaster, the people have to help that along.

18:06 LW: Exactly. Yeah, I think, in a lot of cases there is sort of a tendency when looking at ancient people to consider environmental challenges to be like, nothing else matters, if there's a big drought it's like there's nothing really people can do about that, and they all die. Over and over again archaeologists see that that isn't true. These natural challenges of course exist, living through drought is very hard. [laughter] But, it really has more to do with the decisions that people make both on an individual and the societal level of how they're gonna deal with them. Are they gonna cooperate more, and build more infrastructure, and, get better at using the limited resources that they have, as Wari seemed to be able to do at the beginning, or, are they just gonna give up on this collective project and go their own ways as they did at the end?

18:52 SC: Do we have some lessons that we can draw from this for today when we're facing climate change and, definitely drought in different parts of the world?

19:00 LW: The engineering marvels that they accomplished are definitely worthy of emulation, and in fact, some of the canals are still visible, they were repurposed by the Inca. Some of the terraces are still being used, and, increasingly so as water becomes... It's always been sort of a challenge to improve it because of climate change is becoming even more of a challenge, and, I think that this really shows that cooperation is the key to getting through this, right? [chuckle] As someone says in my story, "The key moment is not really when the canals run dry, it's when people stop believing in the system and cooperating to keep it going."

19:36 SC: Lizzie, what made you decide to write about this story for drought issue? We know that other societies' downfalls have been linked to drought, like for example, some people say that happened to the Maya. Why focus on the Wari?

19:48 LW: It's a society that a lot of people probably haven't heard of, and they sort of have a bad reputation, [chuckle] because in some places, their takeover was quite violent, and so I thought it was interesting that they also had this water angle and hydraulic engineering that really was so impressive. And I liked that it was a story that people hadn't heard before, that hit some of these same points. And I just think it really is a big question, "Why is one drought an opportunity for Wari, and another one is, at least, coincides with their downfall?"

20:21 SC: Alright. Thank you so much, Lizzie.

20:23 LW: Thanks, Sarah.

20:23 SC: Lizzie Wade is a contributing correspondent based in Mexico City. You can find a link to her story and the drought special issue at sciencemag.org/podcast. Don't touch that dial. We still have one interview left with researcher Yon Visell about waves that propagate along our hands.

[music]

20:48 SC: This week in science advances, Yon Visell and colleagues write about special properties of our hands, how vibration kind of propagates along the skin and helps us with our tactile experience of the world. Hi, Yon.

21:03 Yon Visell: Hi there.

21:04 SC: Okay, so this was a really fun concept to grapple with, this idea that skin isn't just a series of zones that receive information, they all just sense independently, but that this information is kind of, makes a wave on your hand, and then that wave itself is read by the brain. And then, phew, okay, let's... How close am I getting here? [chuckle]

21:24 YV: Yeah, well, that's pretty close. So our sense of touch, which we also call the haptic system, comprises our skin, muscles, brain and nervous system that allow us to touch and interact with the world via our sense of touch. An important part of that is the skin itself, and it's not just properties for sensing, but also the mechanical elasticity and transmission of vibrations as waves throughout the skin, including kind of our whole hands.

21:53 SC: When you say a vibration, do you mean like if I am touching a guitar string, like that kind of vibration?

22:00 YV: Sort of. Yeah, our skin does something similar to that. So for example, if you tap a melon, that tapping action produces a complex pattern of indentation on the skin that turns out is transmitted to adjacent areas because of the elasticity of the skin, the skin motion then excites responses in a large number of sensory neurons that innervate the skin, these neurons then transmit information toward the brain about the touch event, the properties of the melon, like how soft it is, and things like that. And so in our hand, we have both a large number of these sensory neurons, on the order of 10,000 of them, but also the skin itself, which connects all of these other tissues in the hand.

22:42 SC: When I look at the figures, it really helps me understand what we mean by this wave propagation in the hand. So can you talk about how you wired up people's hands?

22:51 YV: To enable this work, we used a sensor array that we designed in our lab that could be worn on the hand while people touched or interacted with objects or surfaces in their environment in kind of a natural way. And we used this sensor array to collect nearly 5,000 recordings of vibration patterns throughout the skin.

23:10 SC: What kind of gestures, or what kind of hand movements were your participants engaging in?

23:16 YV: We selected an array of gestures that were kind of representative of the repertoire of everyday touch interactions; these included touching surfaces with different fingers or combinations of fingers, grasping surfaces, sliding the fingers across different surfaces, holding an object, a stylus in this case, and tapping a surface indirectly with that. And each of these interactions gave rise to a different pattern of vibrations, and they varied each time someone performed one of these interactions.

23:48 SC: Looking at the figures in your paper, you see these hands, and you can see if one finger taps, the waves travel up a certain distance. If two fingers are tapping, waves go further up the hand. Is this kind of the general pattern that you found?

24:03 YV: Our work, including prior work, showed that due to the elasticity of the skin itself, even lightly touching any object produces mechanical waves in the form of vibrations that rapidly spread throughout the hand. So even if you touch a very small area of the skin, it excites vibrations in larger areas of the skin, and these give rise to responses in widespread sensory neurons that transmit touch information to our brain.

24:30 SC: To take it a step further, you talk about this as compression.

24:35 YV: Yeah, so in our new paper, what we show is that this process of transmission of vibrations in the skin allows for a more efficient encoding of the sensory information that we collect through touch contact. So we used the dataset of these vibration patterns, and then used a mathematical model for the efficient encoding of these tactile signals in order to compute a much smaller number of primitive vibration patterns that efficiently captured information in the entire dataset.

25:04 SC: You were able to kind of break down these different patterns into subsets that you could combine to create these more complicated patterns?

25:14 YV: That's a great summary. So anything that was felt mechanically by the skin during these touch interactions could be represented using a combination of these primitive patterns. So they provide a kind of palette or a lexicon or a dictionary for describing tactile sensory information at a mechanical level.

25:31 SC: I have a hard question. [chuckle]

25:33 YV: Sure.

25:34 SC: So how do we know that this is important to the brain as opposed to just a nice way for a computer to describe what is happening with the hand? How do we know that the brain is viewing this as compression?

25:45 YV: That's a great question, and also an area in which further work is needed. But there are several lines of evidence that indicate to us that these processes are important for perception. There have been a number of studies that have shown that the transmission of these vibrations in the skin is instrumental to touch perception. So for example, some of our colleagues in Belgium conducted experiments in which they anesthetized people's fingers; they could still discriminate fine surface texture, because the mechanical signals were transmitted to areas of their skin that were not anesthetized.

26:19 SC: That's really interesting.

26:21 YV: And there's a nice analogy to other sensory modalities.

26:23 SC: I was just gonna ask that question. Yeah, that's great.

26:25 YV: Yeah, so in vision and hearing, which are both more widely studied than touch, similar methods have been applied and have been used to successfully deduce properties of early processing in the perceptual system. So, there's a fundamental hypothesis underlying all this work in perception, which is that the brain and body are most efficiently using the resources we have and that can be expressed through these efficient encoding ideas.

26:57 SC: So, our hands are special. They are this very important way that we gather tactile information in our day-to-day lives. But what about our legs, our faces, are they also likely to be doing the same kind of compression?

27:11 YV: That's a reasonable hypothesis, I would say, that similar processes apply to different parts of the body. So if you look, for example, at our feet, our feet are rather similar in structure and sensory physiology to our hands. Many people have learned actually to grasp or perform interesting tasks with their feet as well. So, the thought is that these general principles would apply in slightly different ways to other parts of the body, but like you said, as bipeds, we have a privileged role for our hands. We touch and manipulate things and the brain and nervous system and body really invest in these systems as high value areas.

27:50 SC: One thing that I came away with from your paper was that it seems difficult to study hands because of how much nervous stuff is going on in them and also how mobile they are, how they can move so much in space and how many different things that they do.

28:05 YV: Yeah, so in research on the sense of touch, there's some interesting similarities to, say, vision or hearing other sensory modalities, but there are important differences that actually make it harder to study in a few ways. One of those is that what we feel depends greatly on how we feel. So, I can pick up the same apple 10 different times and try to do it in the same way, and our skin captures different information each time. So, this action dependence is extremely important, and then the mechanics of the skin play an intimate role in this active property as well. In touch, we encounter a really challenging question that's also reflected in our work here, which is that it can be very difficult to reason about what the basic inputs to the body are as opposed to the eye where we might envision the visual process beginning with an image projected onto the retina.

29:00 SC: In this case in your work, you're now saying, "Oh, well, the physical patterns, the waves on the hand, this mechanical motion are also an input that need to be considered."

29:11 YV: I think this overarching idea that's super interesting to me is that this research shows how the bio-mechanics of waves in our skin can be thought of as performing computations that are useful for touch perception and that the skin actually produces a compression of tactile information. This is unusual because perceptual computations are normally attributed to the nervous system and not the mechanics of the body.

29:34 SC: Some of the mechanical properties of the inner ear are similar to this, right?

29:39 YV: That's a great point. So, the role played by mechanical transmission in the skin in this setting is in some respects similar to the role of the mechanics of the inner ear and hearing. In 1972, von Békésy received the Nobel Prize for his work in which he showed how the mechanics of the inner ear facilitate auditory processing. So, this idea of mechanics playing a role in perceptual computation isn't entirely new, and there's a really nice connection to earlier work on hearing.

30:08 SC: Now that we are starting to understand those early computation, pre-nervous system computation that our hands are engaging in. Is this gonna help us design prosthesis or VR, Virtual Reality, where we get our hands to sense stuff even when there is nothing there?

30:26 YV: It's an area that our lab and others are working on. The one challenge in designing electronic devices that provide touch feedback that might simulate what we feel in the real world is that it can be difficult to deduce what signals should be reproduced. And so, this work contributes toward elaborating that picture and filling in some of the gaps in that very challenging problem. In areas like robotics and prosthetics, there might also be interesting implications, so conventional approaches to touch sensing and, say, robotics have been typically based on capturing forces between a robotic limb and an object that's grasped. There's something like that. An alternative approach that one could adopt inspired by work like ours would be to design an array of sensors and an elastic skin for a robot that would couple those together in ways that might actually aid touch perception.

31:30 SC: Okay, well, Yon, thank you so much.

31:32 YV: My pleasure, thank you.

31:34 SC: Yon Visell is a professor at the University of California, Santa Barbara, in the Department of Electrical and Computer Engineering, and the Media Arts and Technology Graduate Program and at the California NanoSystems Institute. You can find a link to his Science Advances paper at sciencemag.org/podcasts.

[music]

31:52 SC: And that concludes this edition of the Science Podcast. If you have any comments or suggestions for the show, write to us at sciencepodcast@aaas.org. You can listen to the show on the Science website. That's sciencemag.org/podcasts. There you'll find links to the research and news discussed in the episode. And of course, you can subscribe to the show on Overcast, Stitcher, Spotify, Apple Podcasts and many other places. This show was edited and produced by Sarah Crespi with production help from Podigy, Meagan Cantwell, and Joel Goldberg. Jeffrey Cook composed the music. On behalf of Science Magazine and its publisher, AAAS, thanks for joining us.