REVRBERATIONS: SPIDERS AND MUSICAL WEBS
MIT Museum
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Introduction by Leila Kinney, Director of CAST

[00:00:04.28] CAST is an initiative funded by the Andrew W. Mellon Foundation, which was established only two years ago in 2012. It's intended to foster at MIT the exchange among artists, scientists, and engineers, which actually has a long tradition at MIT.

[00:00:23.90] It's in our DNA. It goes back in some ways to the founding of the Center for Advanced Visual Studies in 1967. But CAST is here in part to provide a supportive framework for that kind of research and activities.

[00:00:39.00] We support artist residencies, cross-disciplinary courses, research programs, performance series, and this weekend the first of what will be a biannual series of symposia-- Seeing, Sounding, Sensing, which has been organized in part to explore the relationship between the arts and cognitive sciences.

[00:01:02.10] I'm delighted to recognize Caroline Jones from our History, Theory, and Criticism program, who is here and is one of the principal organizers of it. So Tomás Saraceno was the first visiting artists for CAST in the fall of 2012, and we're very delighted to be able to welcome him back this week.

[00:01:20.23] He will participate in the symposium along with two other artists, a major keynote by the eminent philosopher and sociologist of science, Bruno Latour, and about 20 other scholars from a whole variety of disciplines.

[00:01:38.35] Now this bad news is that we're heavily oversubscribed, so if you're not already registered, I apologize that we can't admit any more people. We are livecasting the symposium, however, and you can see the address here at the bottom-- arts.mit.edu/cast-symposium.

[00:01:56.60] There will be a live webcast of all of the events, which start tomorrow at 1:30 and go through a culminating concert with the work of the sort of pioneer musician, Alvin Lucier, on Saturday night. So I hope you will join us in one form or another.

[00:02:15.99] So we're all the more delighted that we could have this pre-symposium program here tonight, this evening, as a kind of warm-up act, or maybe spin-off is a better word given the context of what we're going to discuss-- reverberations, spiders, and musical webs.

[00:02:32.40] First I'd like to thank Brindha Muniappan, who's the director of programs here at the museum. She would normally welcome you, but unfortunately she had to attend a wake. But we have collaborated many times, and we're pleased once again to be working with her team on this CAST program.

[00:02:49.97] So this program continues a conversation and an ongoing collaboration begun when Tomás first came to MIT in the fall of 2012 and met, among many other people in various departments, Professor Markus Buehler, who is the head of civil and environmental engineering here at MIT.

[00:03:11.94] We're going to hear more about this, this evening. But first let me just say a few words about that, before I give brief introductions of our speakers. There's a very famous line from Tomás 's official biography that everyone repeats, and I can't help myself to do it again.

[00:03:30.08] Many of us who introduce him just can't help but repeat it, because it encapsulates very well the spirit, I think, of his wide-ranging, exuberant, and speculative experiments, creations, installations.

[00:03:42.55] It goes, "1973, born in San Miguel de Tucuman, Argentina. Lives and works between and beyond the planet Earth."

[00:03:53.17] It sums up a lot, really, about his work. Tomás was trained as an architect in Buenos Aires, Venice, and Frankfurt. He's also spent a summer in 2009 at the Space Studies program of the ISS, the International Space University at the NASA Ames facility in Silicon Valley.

[00:04:12.35] He does many elaborate experiments and installations. I'm just curious, did any of you visit his installation on the rooftop of the Metropolitan Museum of Art in the summer and spring of 2012?

[00:04:28.06] So this was called Cloud City, but it's really part of an ongoing series of projects, a project that's been underway since 2009-- known as Cloud City, sometimes it's Airport Cities. It's a combination of elements, drawings, prototypes, actual installations that envision a series of aggregated, floating, transparent, inflatable, bubble-like biospheres in the sky that would be propelled by wind and sustained by solar energy.

[00:04:59.84] Many of you might think of precedence for this utopian kind of vision-- Yona Friedman's mobile architecture, his manifesto Feasible Utopias, certainly Buckminster Fuller. Both of them and others were sources of inspiration.

[00:05:16.53] But his work is very wide ranging, for he makes installations that also have the morphologies of soap bubbles, foam, neural networks, cloud formations, and spider webs. And that brings us to the work that we want to focus on this evening and his common interest with Markus Buehler.

[00:05:34.03] They share a deep fascination with and research interest in spiders, or more precisely the webs that they weave, including the molecular structure of proteins in spider's silk, their use as an interesting possibility for developing synthetic building materials and so forth.

[00:05:54.45] So Markus Buehler received his Ph.D. in Materials Science from the Max Planck Institute for Metals Research at the University of Stuttgart. He also has a Master's in Engineering Mechanics from Michigan Tech and earlier had studied at the University of Stuttgart, where he's from.

[00:06:13.55] As I mentioned, he's the head of our Civil and Environmental Engineering Department. He directs the Laboratory for Atomistic and Molecular Mechanics at MIT. He leads the MIT-Germany Program, and he's a principal investigator on numerous national and international research programs.

[00:06:30.60] His primary research interest is to identify and apply innovative approaches to design better materials from less, from smaller things, using a combination of high-performance computing, new manufacturing techniques, and advanced experimental testing. His scholarly work includes over 250 articles on computational materials science, biomaterials, and nanotechnology.

[00:06:56.89] He's received many awards. I'll only mention three-- Leonardo da Vinci Award, appropriately named, given by the Engineering Mechanics Institute of ASCE; the National Science Foundation Presidential Early Career Award, it's the most highest honor that's bestowed on emerging scientists in their careers; and here at MIT he's received an Edgerton Award, which is an award that we give to teachers for teaching and research for investigators in the early stages of their careers.

[00:07:31.07] So one of his publications I'd like to mention is a book which he may refer to later, *Biomateriomics*. And what's so interesting about it for this conversation and for those of us who are interested in the arts is that it introduces a holistic approach to the study of biological and bio-inspired material systems. And he discusses in this book how art and engineering can function as mutually beneficial modes of discovery. And I think you'll hear a little bit more about that tonight.

[00:08:03.77] And I'm very pleased to welcome, also, John Ochsendorf as our moderator. John has appointments both in architecture and in civil and environmental engineering. He's a structural engineer with a multi-disciplinary research interest, including the history of construction, masonry, mechanics, and sustainable design.

[00:08:25.70] He's trained at Cornell, Princeton, and Cambridge University, and he can conducts experiments on the structural safety of historic monuments and the design of more sustainable infrastructures of various kinds. He is the author of Guastavino Vaulting, the Art of Structural Tile, having just returned from Barcelona and even more intrigued by these amazing sort of tile structural arches.

[00:08:54.67] You may know that we discovered one in Massey Hall here at MIT when it was being renovated. And I happen to know that John promises lunch, a free lunch, to anybody who discovers a Guastavino Vault anywhere in the country, and they're still being uncovered all the time.

[00:09:10.76] He has also received many honors. I'll simply mention the Rome Prize and a MacArthur. So thank you all for coming, and let me turn the program over to you.

[00:09:28.73]

Tomás Saraceno: Yes. Thank you very much. Yeah, thank you. I'm kind of very, very happy to be here.

[00:09:41.60] There is a little bit of a challenge. Leila have very kindly asked me to somehow try to make clear what I want to say, which is not so easy, because I get dispersed many times.

[00:09:54.32] This means I will try to focus and try to kind of start from some point, and then let's see if I get a little beam to some other point.

[00:10:10.38] Yeah, mostly when we talk about spiders, something which always surprises me is-- this is the type of spiders that everybody knows. And usually it's kind of an orb web. The garden spider, but there are other types of spiders. And somehow the web, you can divide it into kind of a flat web, which might have a little bit of a variation in three-dimensional space, but basically something which is very horizontal.

[00:10:37.74] But what I was all the time fascinated, somehow, is the spider which looks a little bit more like this-- which is more of a kind of a three dimensional spider, you can call them.

[00:10:49.88] This is like an idea of the type of spider which I was most intrigued. We come back later, why it was interesting. Many of them are also kind of hybrid webs, but we try not to get there in this early stage of the construction. This means I will not now describe what they are.

[00:11:13.57] This is some of the artwork, also, I have been doing before, beginning in Venice. The challenge-- we bought a black widow in Germany. You can receive it by post, still.

[00:11:27.69] And then the challenge was-- and I think so today, particularly-- that we were trying to scan these three-dimensional spider webs. Now what we find out is there is not really a machine who can scan these webs. I know that there are some soap bubbles inside there, but usually we run many times a spider web inside.

[00:11:53.62] Now the thickness of the thread is very, very thin. It's a kind of thousandth of a millimeter. This means it is very difficult to understand the emerging properties or patterns or kind of the geometry of how these spider webs are built.

[00:12:08.08] What we did, very simple-- this was the problem. Let's say we have a three dimensional spider web, and we will try to understand how much and to measure every single segment of it. Then we contact the Photogrammetry Institute in Technical University in Darmstadt. And then we set up these kind of photogrammetry-- two cameras at the same time watching one thing.

[00:12:33.67]

[00:12:34.64] I mean, it was kind of complicated, because it was very difficult to-- you had to find a method of how you could scan it. But basically, it was very simple. It was just a simple laser that you could illuminate the web. And then when you take the picture, you can see exactly the intersection of the-- here, I have to stop one second and try to get it there.

[00:12:57.95] One second, MIT. I don't need the sound yet, but if you want--

[00:13:11.45] Yes. I mean to give you an idea. This is one when the laser is moving through the house where the web has been built. The spider is not there anymore. And then you can move it very slowly, and you can see the intersection of the laser passing through a different part of the thread. Now it's moving.

[00:13:39.94] And you can see where the spider usually lives. This is a black widow's web, and this is the corner where she kind of goes to retreat. And you will start to see kind of a tunnel web in the corner. There it's getting, on the right.

[00:13:57.31] Where we are?

[00:14:09.66] OK. We got all these kind of sections of it that we have to connect together. Here are all these different types of threads. We didn't scan every millimeter. We kind of stop every two or three millimeters.

[00:14:25.21] Then we got a first three-dimensional model, where you have all the threads. You somehow have to connect them. We could not find a script to extend and make it automatically. I know that Zhao now is improving. I think we will get better and better on this idea of scanning.

[00:14:42.35] And then the other challenge was also to try to reconstruct it in three-dimensional space. We got a map where we projected all the points on the bottom and on the ceiling, and then we got a little bit messy. We tried to connect all the different links and threads.

[00:15:05.06] We were taking care, because when you have one thread here, then it's bifurcating-- two, then in three, then in four, then it makes something, which is quite difficult. Because for example, if the black widow has seven different types of threads who have different elasticity and strength.

[00:15:21.78] To keep all the time the node in space and how much tension, you have to have to every single thread to keep the node in space precise. We have these supplementary lines. This is how we were connecting point to point without cutting them and putting everything in kind of a tension. Now we're building. This will get a little bit of a nightmare.

[00:15:51.89] And then this is the construction of the black widow, when it was later claimed. We did this upside down, because it was much more easy. It has been acknowledged, always kind of complained that it is upside down, but usually the spider's also hanging. This might not so much trouble.

[00:16:12.25] Well, then, later, you know, one of the collaborators, Peter Jager-- he was one of the first-- the first three-dimensional scan of a spider web-- was presenting a conference and seminars. We also saw other papers on the scanning.

[00:16:32.82] And then when I was at NASA also at Ames, I met J Clement also. And he said, well, Tomás, now that you have found a method together with other universities, why don't we send spiders to the International Space Station to try to see how spiders might have a difference between a micro-gravity environment and here on Earth?

[00:16:55.72] We started to write together a paper, but always was missing somebody who can make sense of it and try to understand. When I got invited to MIT, and then I met Markus for the first time, I said, oh, that's exactly the person who we were missing in the team and hopefully we could start to work together.

[00:17:18.13] First we have to understand them here on Earth, but then try to see how different they are when they come back from space. And maybe-- I don't know if I want to get here. But maybe I'll go quickly to this slide.

[00:17:32.98] But basically, the major interest which also at the beginning got me into why of these kind of three-dimensional spider webs because mostly of the astrophysicists, when they refer to the region of the universe. It was the Max Planck Institute that ran something which was called the Millennium Simulation.

[00:17:52.95] And when always they talk right after the big bang, they talk about something, which is this cosmic web. And the analogy all the time they talk about it is it's similar to a three-dimensional spider web.

[00:18:03.26] And that was kind of an entry point, which was kind of funny, because everybody talks about a three-dimensional spider web, but at the same time they never measured or they never studied.

[00:18:13.54] It's kind of this very huge parallel of having something very, very close from far up, but we didn't look too much. This is a little bit some of the things that we have been talking with Markus, also.

[00:18:28.66] This is the formation of the universe, and how galaxies start to condense and get together.

[00:18:37.59] These are social spiders. Social spiders are the ones who live all together in one single web. And this is the analogy between both of them. This is the first comparison. There is the scan on the left and the universe on the right.

[00:18:56.50] Now one of the latest things that we are doing-- we are also together with [INAUDIBLE]. In October, we will try to do a live concert of spiders. We have a very sensible microphone and spider will play live in concert.

[00:19:14.60] So there is also a lot of fascination. Also with Markus then later we will see how he was taking all these aspects of the music and the spiders.

[00:19:24.80] Here we are trying to listen to them. We are recording some of them. Well, and then just quickly some of the installations-- this is in Dusseldorf at the moment, and where people could walk also suspended there. I will not get so much in detail. But then I leave to Markus now the rest of the presentation. Thank you.

[00:19:52.78]

Markus Buehler: Thank you. Thank you very much, Tomás. This is exciting. And I'll show you a few slides. And I don't know if we can take questions any time. We'd like to have a conversation.

[00:20:04.66] I actually am going to share some random thoughts with you, and maybe make you think and explore and email me or discuss here-- some lively discussion.

[00:20:17.78] We have had, really, like Tomás, parallel lives, maybe. And we had independent fascination with spider webs of various kinds. And we met about a year ago, and it's been exciting since. I'm truly thrilled. Today is special, trying to share all the ideas with you and explore.

[00:20:40.24] We've done a couple of things of inside the spider thread. And I'll share with you what is inside these little threads. These many thousand, millions of threads you've seen. But also we're going to go in the structural scale larger, and we show you how we connected his scanning experiments with the model we've development.

[00:20:59.63] And Dr. Zhao Qin is here, and he will maybe do an interactive display in the models. You can see it working live. So we'll have sort of interactive discussion and exploration here as we see fit.

[00:21:12.55] So we're fascinated, because if you look inside the spider thread-- so the web, one dimensional, two dimensional, three dimensional webs are really interesting, intriguing. And it doesn't stop there. You go inside. You take a microscope. You can see even more structure.

[00:21:29.44] So it's absolutely fascinating, the structure goes all the way down to the scale of an individual atom-- so hydrogen atom, carbon atom, and how they connect.

[00:21:40.68] And these scales of structure, from the protein to what we call secondary structures, like beta sheets and alpha helices and things, go all the way through into fibrils and fibers and bundles to the things you can see with your eyes. So what you see is not all that there is.

[00:21:57.28] There's much more inside, and we've spent many years studying those structures and understanding how they're built and how do we, as engineers, actually take the understanding we have from nature and build our own materials that are different and optimized, adapted for certain applications.

[00:22:17.58] So I'll show you a few things along those lines as well. So we have a science hat. We understand nature, but we also have the engineering hat and design new things and built them. And that's the connection with the arts, something I've been interested in and fascinated by for many, many years.

[00:22:35.84] And it's actually making sense now. We can connect these in a meaningful way using mathematics and simulation and in other ways. So there's a really exciting opportunity for us here.

[00:22:47.00] This picture, here, shows you sort of the future of engineering. Today we have chemists that think about molecular structures and we have structural engineers that look at this scale. A future structural engineer will look at all the scales.

[00:23:04.95] So the vision we have is if you construct buildings, infrastructure, we'll actually design the molecules. We'll design how the molecules assemble, how they come together at these different scales.

[00:23:17.04] And we can build, as I mentioned, we can build more from less. We can use the kind of raw materials we're not even using today. Today we use concrete and steel. They're very expensive, very energy intensive.

[00:23:29.42] In the future, we can use rocks. We can use algae. We can have plants. And they can make materials that grow buildings, that self assemble buildings, that have structures that can change dynamically.

[00:23:42.73] And the inspiration actually from Tomás is fascinating. Social spiders that live in the space, and they reconstruct the web. The web is changing. It's a living material. And so this is one of the directions that we're really excited about. And you can see where we're heading here.

[00:24:02.23] We're actually merging the biology, the structural engineering, the scales. And we're really interested in making nano big. We've all heard about nanotechnology. It's very tiny, and I'm fascinated by this idea of making nano so big you can build cities and structures and infrastructure, roads, airports, and everything from that and make them sustainable.

[00:24:26.50] So that's sort of the vision, but how do we get there? So we have discovered principles. I'm very interested in understanding not only one material, one system, but making connections between multiple areas. And we use tools of simulation. We start from simulating the quantum mechanics of atoms and molecules, and we bridge them. We connect them with other materials.

[00:24:55.28] So a beautiful aspect of starting with quantum mechanics is you can simulate any material. So you can go and simulate spider silk. You can simulate elastin protein. You can simulate steel, concrete. And we can begin to compare how these different materials

[00:25:13.28] And so this is what we put in a big box of knowledge and categorize how these materials function. And we move them into this abstract space. So we use mathematical tools to describe all these different materials, and they look very different.

[00:25:28.88] So concrete looks different from a spider web, but we have mathematical tools that allow us to identify similarities between them and commonalities and differences that define function. And so we've made these connections, not only within materials, and described how functional diversity comes from universality.

[00:25:47.65] So the idea that proteins are universal, these 20 letters or the DNA letters are universal to all biology. But then that we can make all these different functions. We can build motors from proteins. We can build spider webs. We can build adhesives and muscles. We can build the skin. We can build cells. We can build living organisms, all from the same chemical building block.

[00:26:14.29] And engineers are very far away from being able to do that. We sort of take a detour, the brute force way, by using all these different materials to create different functions. And biology has much to offer in creating different function from universality-- so diversity and function form universality and building blocks.

[00:26:34.04] And that idea is intriguing to engineers, and we are sort of pushing the limits here and scratching on that surface and trying to design new things from that principle. And the other thing we'll talk a little bit later on is this connection now to very different systems.

[00:26:50.15] And so we have this example here actually. To illustrate to you how function emerges in proteins is the idea that you take letters of DNA or letters of proteins, which are 4 to 20 different kinds, and you assemble them in patterns.

[00:27:06.66] And you create new building blocks from that pattern, which again you can connect to new building blocks again. And actually you can combine different building blocks that are actually made from the same staff but they have different functional properties when they are arranged in certain geometries.

[00:27:22.38] And we can repeat this process many times and create a web. So this web actually achieves its function from a very delicate interplay of different scales. And we like to think of scale in a geometry space, but of course function doesn't emerge in geometry space. It emerges in functional space.

[00:27:40.77] And so we, actually, in the mathematical model, remove the geometry and the physical space from the function. And we see a synergy. A simple example, simplistic way-- you have two particles. One particle is pretty boring. Two particles, they kind of interact. Three, it gets more interesting. You have 20 particles, they can do very interesting things. There are phase transitions. They can be liquids and solids.

[00:28:03.65] So that's the same idea, here. Each scale is like a particle. You interact-- one scale, two scale. Engineers have one or two scales. We want to have 20 scales, 30 scales. So nature has, biology has 5, 7, 10 scales, and we can play with them. They can resonate.

[00:28:20.61] So you create function at one scale, and you tune the knob at another scale and a third and a fourth. And suddenly you create this interaction. And so the way music emerges is the same principal.

[00:28:31.87] This is what we have here. So you have simple sound waves that you can modulate creating the sounds of musical instruments. We then combine those into melodies. And so if you think in your head how you emerge music that induces certain emotions, impressions, it's every little piece together. And suddenly you have this emergence of the feature, the property.

[00:28:55.63] And that is what happens in biological materials. The connection, actually, is quite interesting. When we create music, and this is what I leave for thought and maybe discussion later, it's really a mirror.

[00:29:10.53] Humans have this interesting demand or vision that we like to continuously portray ourselves to the world. We make paintings. We create music, and it's actually really to show others who we are.

[00:29:25.94] And in the beginning I think we made those paintings in the caves, trying to explain to others members of our species how to hunt and how to do things. And in time, we've created more complex functions and more complex pictures and paintings and music.

[00:29:41.07] And so we believe we can, and this is the thought for some out of the box thinking, can we use the existing creations of art and music to study who we are, who we are as materials? Because these structures, these complex compositions, actually are created by our brain, by our bodies that are made from these physical structures.

[00:30:04.51] And so the idea that we are trying to explore is if we can use pieces of art to understand science, engineering, and actually sort of give artists, who are experts in creating hierarchical structures-- so music is a hierarchical structure-- ask the artist to design very complex pieces of engineering, which uses a different part of our brain than if you're an engineer and you think about your CAD program or you make a calculation.

[00:30:34.53] So we're trying to think outside the box, and we need the creativity, and bring that in together. So that's one thought looking we can discuss more later.

[00:30:42.34] So let me move on to the spider web again. So this is sort of why we do this. So we have many different thoughts that we're exploring here. And in the work with Tomás we began by utilizing these really interesting three-dimensional structures that he scanned. And we like to build models. And the reason, as I explained, we build models that start from the fundamental scale of atoms and molecules.

[00:31:10.41] And we can do analyses of the model on the computer simulation that we cannot easily do on a piece of paper or by looking at things. And so we can study structures. We can study functions. We can make changes to the web in a model, in a simulation, that we can't easily do on a physical artifact.

[00:31:29.59] And so we're trying to utilize Tomás's experiment as a baseline to understand how the structure works. There's enormous complexity here. And we don't understand how these structures are created and why they are created in that way, what the spider's objectives are in creating structures, how they built it.

[00:31:48.75] Spiders build these structures in open space. Civil engineers, construction engineers, use cranes. We use scaffolding. And spiders don't have any of these. So they somehow create a space-filling construct, very high complexity with tunnels and elements and planes, without any of this help. So we're trying to learn how they do that and why.

[00:32:13.80] And so we built what we did in the work, and we'll have a little illustration of the model in a few minutes. We took the data, and using our engineering and math skills, we translated the data that Tomás generated using laser scanning into a model.

[00:32:31.42] And we've done other models of two-dimensional webs with just sort of the state of the art in modeling or in understanding. And here we're pushing from 2D to 3D. So the world sort of goes into two-dimensional graphene. We're beyond that. We're already going to the 3D. We go from 2D to 3D and trying to build this model.

[00:32:52.68] So we've created this model. And you can see, this is the installation piece that we had. And we built this model. And it's an exact replica of a computer model of this installation that Tomás did a couple years ago.

[00:33:07.71] Some interesting questions here in comparing that model, how it behaves, with the computer simulation. Potentially we thought about using a model in experiencing force through light or sound.

[00:33:23.47] If you were a spider, you have different kind of senses. And humans also, we don't sense force in a thread. So if you imagine jumping in a web, it's very hard to sit, to visualize, experience the forces, the strains, the deformations in the web.

[00:33:42.07] And so we're trying to use the model to inform media like light or sound maybe in experiencing force, which is something we don't experience through light and sound usually. So that's some of the ideas we're exploring in our discussions.

[00:33:57.37] So connecting the web, scanning the web, bringing in a computer model, using the math and the simulation, extracting new information and bringing it back to the spider web, this live web-- and you as a human or a visitor can go in and experience that. So that's one dimension of this.

[00:34:15.79] This is the model in a little more detail. And we can go and zoom in later. Zhao has some of those things in a few minutes.

[00:34:24.95] OK, so let me just show you a few more things. This is how the model looked. So one of the strengths of the model is we can analyze systematically how this web was built. So it might look actually more random than the picture you've seen before.

[00:34:39.47] But we can analyze and we found, actually, we've found these three regions-- one, two, and three-- where the web is built in different patterns, which you don't easily see when you look at the three-dimensional structure. So that's one simple way of explaining how the model can be used in extracting additional structural patterns and information.

[00:34:59.15] We can slice the web in any way we like and inform ourselves on how it works.

[00:35:04.87] There's also interesting questions on how sound translates in this web, because spiders have very keen senses in sensing vibrations. And Tomás mentioned the vibrations in the web. And so here we have a modeling that we can compare these orb webs with the three-dimensional webs, putting signals in the system and understanding how these signals travel and comparing this 3D to 2D also to a one-dimensional system.

[00:35:36.07] How we understand wave propagation typically is in a one-dimensional sense. And we know about wave propagation in a continuous medium, but in something like a web, with extreme structural complexity and different scales and fractal maybe arrangements, we don't know anything or very little about how waves propagate and sound propagates.

[00:35:53.85] And so we think that could be again a way of visualizing in an audio sense some of those vibrations in the model. And I'm going to quickly show this here. This is the web, and I'm going to play this movie here.

[00:36:15.76] It might take a few seconds. This is a simulated fly impacting this web, and that's a simple exercise the model can easily do. We can understand how this web is deformed, how forces translate, and how vibrations translate, and how that web functions. There's a lot of work we can do with this, so we're just beginning to sort of explore this very complex system.

[00:36:40.97] So do you want to show-- I don't know what we're going to do. I want to show some of the model in more detail. So Zhao, he's going to plug in. Can he connect to this computer here so I can continue talking?

[00:36:54.40] So he is going to show-- so Zhao has been working on this for about a year now and actually in a very painful way reconstructed this web in this computer model. Well, painful in the sense of developing the algorithm. We always develop the algorithms. But it was not easy, because the data that we get from this scanning is very scarce.

[00:37:17.17] So it looks like it's all connected, but actually there's a lot of defects and missing pieces. So we have to develop an algorithm to fit in these missing pieces.

[00:37:28.06]

Zhao Qin: A high school student worked with me during last semester in summer to refine the structure. So we finally built up this computational structure based on what Tomás measured and scanned in his lab.

[00:37:43.04] And so here, the advantage of this computational model is you can zoom in, zoom out, and see how the structure for this web looks like. And then you can, because this model has the physical parameters-- so we have the elasticity and the density contained in the model, so we can actually simulate if there are impacts how the web will deform in response to this impact loading at a single strand.

[00:38:14.83] So you can actually see how each of those threads get deformed. And actually we also measured how this deformation, as a wave, propagates inside this complicated structure.

[00:38:35.91] You can simulate a lot of things. You can relate the frequency to some-- maybe use this frequency to compose some music or something that relates to this. And also in this model, we have the dampening comes from the air.

[00:38:57.58] So right now it's a very short piece of the movie. So if I continue, this oscillation will get smaller and smaller, because of the dissipation of the energy in the air. So, Markus, do you want?

[00:39:13.74]

John Ochsendorf: Thank you, Zhao.

[00:39:24.25] OK, thank you so much. I'd like to invite you both up here. And I'm going to try to stay out of the way while these two brilliant gentlemen make spider music together. I don't know. Tomás, if you would like to go first and say anything in response to what Markus has shown.

[00:39:41.15]

Tomás Saraceno: I know it looked very simple, this, but it took us-- and also Markus when he said he was connecting the losing threads and the losing point, it sometimes seems very simple, but when I see it it's like I was there connecting thread by thread and now putting it back in the computer and to see this simulation in the computer-- because my imagination, when I see this, is kind of, we're pulling up galaxies. That's the relationship that I kind of feel.

[00:40:09.69] And I like Markus' approach is this kind of to push a little bit the research-- not only the bridge to hang, but also to reach to the whole universe to a certain extent. There might be something there, which we don't know how it might be connected.

[00:40:33.10]

John Ochsendorf: And I guess for me I would just like to say that this is a particularly special moment, I think. And to have it here at MIT and the combination of the creative with the analytical and simply what we're learning from you, for me, is spectacular.

[00:40:51.52] But Markus would you like to add anything in response to-- I guess maybe one question is, where to from here? Y What comes next? Now you've scanned a spider web. You've built it larger scale, painfully, because if you pull on one, five other ones go slack. And you had no model to help know how long they should be. So that was very difficult.

[00:41:16.89] Could you imagine, now that you have models like this, perhaps pushing it in some new directions? Or do you still feel like the spider is the master and they tell you what to build?

[00:41:28.16]

Tomás Saraceno: Well, I think that we enjoy, I think also Markus-- both of us enjoy more these social spiders. Because the black widow is not really social to the extent that we mean.

[00:41:46.15]

John Ochsendorf: The few that I've known have been very anti-social.

[00:41:50.08]

Tomás Saraceno: The degree of sociability also depends on how much space they have and how much food they have. Social spiders, they live all together in one single web. Up to 10,000 species, and usually they have kind of a huge web. Most of them live in Ecuador. The web could be three, four meters big.

[00:42:12.79] Even they catch huge prey. And also when they have offspring, everybody takes care of the same as would be your child. I forgot what I was saying.

[00:42:23.74]

John Ochsendorf: I think you were saying how special social spiders were, and that you wanted to consider rather than studying just the webs of a single spider, like the black widow, maybe there was more to do.

[00:42:36.31] If I could understand how your brain works, I would like to know.

[00:42:41.64]

Tomás Saraceno: Anyway, yeah-- I will come back in one moment. With Markus, what also would be very interesting, what we were thinking, is how to turn this into a kind of musical instrument. And we have been also talking with Evan [Ziporyn] and Arnold [Dreyblatt] about how also we could then, beside the spiders being the players, also how humans maybe to a certain extent we can learn.

[00:43:09.60] There is kind of a pattern, evolution, of how the instruments also have been evolved through the capability of the player. And how [INAUDIBLE] they get it. Since the beginning, the spiders were flat, in a two-dimensional world. Somehow the animals also-- and there is kind of an evolution about the instrument and how good we learn how to play and also how the instrument got more complex.

[00:43:32.14] I'm not very knowledgeable of spider anatomy, but I think spiders cannot hear. Is that correct?

[00:43:36.89] Yeah.

[00:43:37.26] They cannot hear, so when a spider, they're sensing--

[00:43:39.02] Yeah, but it is supposed to be one of the more sensible animals. One point was cockroach-- whoever know more than me, please interrupt me. And now we think the spiders are very, very sensibly, even if they are deaf.

[00:43:51.33] But all the exoskeleton vibrates. Even the hair that they have connected to their body, somehow they can perceive very, very thin vibrations, to a certain extent.

[00:44:05.52]

John Ochsendorf: So maybe one next step is in the direction of music and--

[00:44:09.60]

Tomás Saraceno: Yeah, exactly. Exactly. That's what we are trying to--

[00:44:12.94]

John Ochsendorf: Learning to play the web as an instrument.

[00:44:14.96]

Tomás Saraceno: Yeah, but also with Markus what we thought, which is very important also, is how this, let's call it instrument, is built.

[00:44:24.94] Because by tracking the animal movement, you cannot really predict also how the web is. There is kind of a non-parallel, because they build a lot of auxiliary-- For example, William Eberhard, one of famous arachnologists, he said, if you have to imagine that you have to build yourself a web as a human, you will be blind, because most spiders are blind. They don't see.

[00:44:49.15] You have to be under the water, because this is the density that they feel in space. When they move into the air it is like yourself being under the water-- blind and building the web backwards.

[00:45:02.88]

John Ochsendorf: Presumably they never went to college, so they were just born with the knowledge.

[00:45:06.70]

Tomás Saraceno: You have to imagine it's like also you are standing here, and then you start to release a thread. You reel it out of the spinneret. And then you don't see. You are backward. You are in the middle of the water. You release the thread, thread, thread, and then the wind starts to blow. You're kind of going fishing but in the middle of the air.

[00:45:24.24] And then until they feel it. It got trapped, because at the end of the line. They got some glue, and then somehow stick there. And by sticking there, they pull it back, and they start to [TING] [TING] [TING]. This is why this idea of the music all the time.

[00:45:38.69] They cannot sense it through this vibration-- how far is this-- because they don't where it is. And then somehow cross into the middle-- I describe also the orb web, because that's the only one we have been so far studying.

[00:45:50.23] So they come to the middle, go to the middle, and then they have to find the middle point, without seeing and backward. And then from there, they start to build a web. This is what we know about a two-dimensional web and the orb web.

[00:46:05.22] Now how you get to-- and this was never done. And this will be really something truly fascinating that we could explore together and try to find a way to do it, maybe.

[00:46:20.36]

John Ochsendorf: I guess I would just also like to add that as little as we understand about the natural world, the inspiration that you get as an artist and the inspiration that you're getting as a scientist and engineer are both coming from something so spectacular yet little understood I think is for me is fundamentally the kind of conversation we can have here at MIT, where we like to have artists talking to scientists and engineers. So that's actually terrific.

[00:46:49.80]

Tomás Saraceno: Now I have been very cautious, also, because otherwise I get too quickly. But most of these webs maybe in the future, step by step, I always get too quick. But what I'm mostly working now is on hybrid spider webs. That was really kind of fascinating.

[00:47:03.53]

John Ochsendorf: When you say hybrid, you mean different types of spiders working together on one web?

[00:47:07.21]

Tomás Saraceno: Well, that's-- now I come back to the idea of sociability. Exactly. Because it's very similar to the human. Social spiders, they are social because they have enough space and enough food.

[00:47:23.09] But if you put a lot of social spiders in a very tiny space, they do not became social. They eat each other. They are pretty much human. If you have enough food and all the space, then you behave.

[00:47:33.40] But anyway they have a trend. For example, there are 43,000 species of spider and only 20 are social. This means very little. And even knowing that sociability is a big trend to survive on the planet Earth. Nobody understands really how this is.

[00:47:50.44] What we do is maybe try to make them cooperate and work one to each each other. They are solitary and social, or they're semisocial, because there are some of the webs. We can go back then to certain images.

[00:48:02.02] But what we do in a lot of experiments is put first a solitary spider. She builds a web. And we take out the solitary, and we put a social colony of spiders. And they would be the web on top of the other web, kind of using the existing model to try to construct something together with different degrees of sociability.

[00:48:19.33]

John Ochsendorf: And they don't discriminate?

[00:48:21.59]

Tomás Saraceno: They don't leave at the same time. It's like me going to your apartment. You know what I mean? If you are social in the morning, well, we changed the--

[00:48:28.74]

John Ochsendorf: You're welcome any time.

[00:48:31.70]

Tomás Saraceno: How much I miss it. Some of the species-- we have been talking also with Markus, because some of the spiders, they eat their own web, because the proteins for them. Some of them, they do not eat the web. Some they come there and they say, oh, the web, it's like food. And they eat it up, and then they build all over again.

[00:48:49.20] Some of them, they say, well, that's good enough. I'll build something on top. And then you can get very intricate webs, which it's more complicated to define where somebody starts and where somebody ends.

[00:49:04.80]

John Ochsendorf: Terrific. We're going to open it to the floor in just a moment, but maybe if I could just ask a little bit of history for you, Markus. At what point did you become interested in spider silk and at what point did you learn about Tomás's work? Was it when he arrived here, really, that you learned of it?

[00:49:18.17]

Markus Buehler: Yeah, a little before he arrived. We've been interested in spider webs for a while. We became interested in proteins first. Proteins being the main building material and things that we use, that nature and biology uses to create the function.

[00:49:38.04] And spider webs actually are one of the prototypes of an extreme function, which is extreme strength and toughness. Spider silk being stronger than steel, some silks, and actually much tougher, because it's much more extensible.

[00:49:51.35] Imagine having a steel cable wire that you can stretch 1,500%. And so that takes a lot of energy to break. So we took that as a prototype in the beginning as a study in what extreme functions we can create with protein. Protein is what you usually eat.

[00:50:09.40] Actually if you have protein in a structure, it's like jello. It's not worth anything, really, in terms of mechanical strength. And so silk is one of the extremes there. But then we became more and more fascinated with larger scales and structures. We became interested in orb webs and then Tomás, when he came, looking at three-dimensional webs.

[00:50:33.42] And a lot of times, you like to expand on this. And so the ideas we have with going to space and actually looking at how structure formation in this. So in a way, when the spider creates three-dimensional webs it's like creating the universe. It's putting density fluctuations in material, and that's how we have this analogy with the early stage of the universe.

[00:50:59.24] The spider puts material down-- high density, there's low density. And out of these fluctuations emerge these complex features. So we're trying to go really big, because they're asking where we're going now. And we're going to the universe and trying to see.

[00:51:13.67]

John Ochsendorf: Two very quick things and then I'd love to hear from the audience. So think of your questions for these two researchers and designers. The first one is when you began working together, was there a real problem of language? Because oftentimes when you come from different disciplines, you speak with completely different languages. Or did you pretty quickly understand because you both are fascinated by three-dimensional webs that you could understand each other?

[00:51:39.68]

Markus Buehler: I would say so.

[00:51:41.40]

John Ochsendorf: Or is the common language German and that's that?

[00:51:45.10]

Markus Buehler: We haven't explored that, actually. I don't know. But to us it was very natural. We use the passion for the web and the structure and the intricacy. And the structure, really, was the common language, I think. And then we look at different functions-- I mean, the artistic function and for us the chemical and the biological. But yeah, it's the structure, I think that was the common language.

[00:52:12.38]

Tomás Saraceno: For example, earlier today Leila said, Tomás, don't start with the universe. You know what I mean? Start with something very practical. You want to start a web. Don't start with the hybrid spider web, because then you confuse people. Everything is simple, one step by step. It's like I mix up too much, too quickly, everything.

[00:52:33.12] And I don't know if I can really make sense. It might make sense to a certain extent, but it's like keep a little bit the peace. We can kind of work together. It's like the social and solitary, the engineer and the artist.

[00:52:51.88]

John Ochsendorf: I'm not sure which one's social and which one's solitary. And then just the last thing I wanted to ask is in terms of product of collaboration, because I find it fascinating that you publish technical articles and you have proposals to the International Space Station. So in some ways you're operating as the scientist-artist or--

[00:53:11.94]

Tomás Saraceno: Yeah, it's unbelievable I have managed to convince. I still cannot believe myself. It's like today, when Markus said, yeah. But who knows?

[00:53:22.27]

John Ochsendorf: I think the work is pioneering and therefore worthy of being published. And so my question is, in terms of products, for each of you is it important to have an installation as a result or are papers and creation of new knowledge the outcome of this? And maybe have your perspectives changed as a result of working together? I don't know.

[00:53:41.73] What do you think?

[00:53:42.54]

Markus Buehler: Well, first it's been really interesting to try to build some of the webs. We've built two-dimensional webs with 3D printing. And I didn't, I think get to this, but we've genetically engineered bacteria to make spider silk protein, and we've been trying to spin those proteins into webs and so forth.

[00:53:59.27] So it's become really important to us to build physical artifacts, two-dimensinal ones, and so we're hoping now make it three-dimensional. And having something you can go and walk inside and touch and feel is something really interesting to me.

[00:54:11.59] So an installation like that sort of puts the model and the science, engineering, within the artistic expression would be absolutely fascinating. So we have actually discussed a couple ideas in the last several days.

[00:54:24.00] I should also add that in the world of MIT, where people publish a lot, Markus publishes an absurd, you know, 40 papers a year or something. So I can imagine you're tired of writing papers and you're ready to build something.

[00:54:33.78]

Markus Buehler: That's right, yeah-- done paper writing.

[00:54:39.59]

Tomás Saraceno: I don't know what I can say, because also with Evan and Arnold, we start to talk about also maybe the capability of-- what it will take if also we build some kind of web that also we could play. But I go back the idea how I came also with this fascination, maybe to try to incorporate sound to this installation and try to understand spiders, how they feel and perceive sense.

[00:55:11.29]

[00:55:13.86] Because they are deaf, but they can sense space with a kind of a very, very refined technique. Their own body is the one who vibrates. This means it goes faster than the speed of sound.

[00:55:26.88] There is one book that is called *Where is Everybody?*, which is kind of 40 answers to the Fermi Paradox-- why we've never managed to communicate with somebody else. If you go to the Moon, Mars, or far away, and you start to hear the planet Earth, it's kind of a noise. It's kind of [STATIC SOUNDS]. You don't understand anything. It's very difficult to understand.

[00:55:50.50] And then one of the answers of this Fermi Paradox is like saying, well, because we talk all different languages and we cannot somehow agree on sending messages out to space. This means a very simple answer to this. Like, well, maybe we have to build an instrument that more than one person can play together.

[00:56:10.06] To some extent, it's this kind of instrument that spiders-- social, nonsocial-- are trying to build together. And then maybe we can start to tune ourselves to somehow start to communicate, maybe. I don't know if so far as planet Earth, but you know an exercise somehow to engage the capability.

[00:56:26.97] It's very difficult if you play one single instrument yourself, and if it's an instrument that somehow is affected by the way somebody else plays. Like a big drum-- when you go to a concert, everybody has his own single instrument.

[00:56:40.91] But you have one instrument who somehow-- if you have a big drum, 10 meters, and everybody is hitting the same, it's a little bit more something which affects how much the way you play it, also.

[00:56:56.41] Many of the installations also are something how to learn to coexist, maybe to the perception of the sound in this extent. But I don't know.

[00:57:04.59]

John Ochsendorf: I would just like to say the first time I met Tomás, I only understood about 10% of what he was saying to met, and yet what I could catch was absolutely brilliant. And so I've enjoyed learning very much from you and your work. I would like to open it up to the floor and take questions. We are recording this event, and we ask that you speak into a microphone.

And Meg has the microphone. And so you, young lady, are closest to the microphone, so you get to go first. And we'll go from there.

[00:57:35.66]

Audience: Thanks, I feel very lucky to ask the very first question. I think I figured out something that I want to say about your point you made, which is how do you take this further? So you were saying maybe social interactions and that kind of stuff. My question would be, this looks like a very kind of a complex system and yet a dynamic one, of course, because it occurred across time.

[00:57:57.48] And I'm just wondering why we have those finite discrete objects, which are those webs, and perhaps asking why you stopped looking at them at that moment, and perhaps asking whether you would see them developing over time. And perhaps what we're seeing here is an impact of a fly on this kind of system. That's fantastic.

[00:58:18.54] But how would you predict the kind of developing of that web maybe across, I don't know, 10 years or 10 months? I mean, just getting the time back into the construction-- and I think the music is perhaps addressing that point. How do you see this as a kind of dynamic, complex system, not one that's finite and ended in a way?

[00:58:39.76]

John Ochsendorf: Thank you. So not a snapshot in time, but an evolution over time--

[00:58:42.81]

Markus Buehler: Yeah, this is something we're trying to create now. Now that we have a static model at one point in time, we're actually trying to build at one of the places, either Berlin or here, the set up and then doing the scanning over time.

[00:58:58.36] And actually you raise an interesting idea when you imagine the web actually as the result, the structure, of something happening potentially. It might be a fly, and that controls how the structure is formed. And understanding this sort of maybe in a time lapse, a very rapid time lapse, thousands of different situations, understanding the drivers for how the web is formed-- very intriguing, yeah.

[00:59:21.02]

Tomás Saraceno: Also the web is something which never stops. It's not a finite element. You know what I mean? The spider is all the time fixing and repairing it and doing and doing and doing. It's a constant thing. A fly comes, breaks it a little bit, she goes and repairs it.

[00:59:38.20] Then usually you can see that it's kind of patched somehow. And she comes the next day, then she puts another patch on it. There is a moment when it is too much broken, and then she rebuilds it all again. It is something which is all the time kind of a work in progress to a certain extent.

[00:59:55.86]

John Ochsendorf: That's fascinating. Next question? Sure. Here, and then we'll come to the other side.

[01:00:05.68]

Arnold Dreyblatt: Yes, thank you. Yeah, we've been in a discussion together with Tomás and Evan Ziporyn about this question of sonic realization. And I found it interesting what you said earlier-- the sense that humans cannot sense tension maybe in kind of cables and that possibly since the spiders are blind, they cannot hear, and they're sensing obviously some movement.

[01:00:40.02] And we use words because we want to speak about music, and then we have to use a terminology like vibrations. So I'm wondering how much is known, actually, about these vibrations. I mean, when we speak about sort of a cable system or a string system then there's kind of longitudinal and transverse vibrations.

[01:01:00.52] We know that it swings. We see it gets deformed. Does it continue? Is it passing through the cable, so to say, of the web? And do we know about the obviously hyper-developed sensory abilities of the spiders to, through this movement, sense vibration and distance?

[01:01:25.43]

Markus Buehler: Yeah, I think that's a great question. We think that the spider has an ability to process all the data it generates from these thousands and maybe millions of hairs and sensors and make sense of the world around it in a way that-- we have two hands and two legs and we can touch things.

[01:01:44.68] The spider has other abilities. And so they might be able to reconstruct forces and deformations in ways we're not able to do as humans-- and actually something that we can use in engineering if we're interested in understanding deformations and breaking and repair of bridges and structures and using sensors and understanding those kinds of behaviors and patterns.

[01:02:06.90]

Arnold Dreyblatt: When you use the word vibration, is there really a vibration as we would describe it is a physical property? Has it been measured?

[01:02:18.37] It becomes more complex.

[01:02:20.95] Are there waves?

[01:02:21.80]

Markus Buehler: When you vibrate, when you excite, one of those pieces, you can see very complex combinations of longitudinal and transversal and shearing. And one of the things we've been playing with is to understand the wave, how these waves propagate, actually, in the web. Because it's not a continuum. It's not a single cable. It's this intermediate density complex structure that we haven't studied in detail.

[01:02:50.00]

John Ochsendorf: But, yes, there are mode shapes and natural frequencies and it's a dynamic system.

[01:02:54.56] Each of the elements behave like this.

[01:02:56.45]

Tomás Saraceno: But what's amazing. Zhao was showing me the other day what Markus and Zhao were working on together. The model they built, even the property of the elasticity, would be interesting for when we start to work.

[01:03:13.95] With one of the silk strings from a black widow-- it's quite precise the amount of elasticity that this model has rebuilt digitally with exactly one of the--

[01:03:30.36]

Zhao Qin: The model you have, the elastic property-- sorry. So the elastic property of every single silk thread here we constructed actually based on a very precise experimental measurement.

[01:03:50.11] We have a collaborator in Brown University, so she used the laser spectrum to measure the stiffness metrics of the silk material in different directions. And we also have a [INAUDIBLE] model of the silk, so based on every single molecular detail of the silk peptides.

[01:04:15.00] And we actually have compared those results and here, the model we have, has both a very precise description of the elastic property as well as the density. Density is easier to measure, actually.

[01:04:33.03]

John Ochsendorf: So you can compare the different types of silk. I think, Caroline Jones, did you have a question here in the front? Thank you.

[01:04:40.52]

Caroline Jones: I'm being selfish, because other people also have questions. And I'm going to break Leila's rule, because this is a question about the universe.

[01:04:51.68] About the universe.

[01:04:53.25] It's a question about the universe.

[01:04:54.29] Louder, louder-- I'm deaf.

[01:04:57.53] So in the most simple framework that a child-- if you build a web, it's an additive process. You're adding material. You're squirting out your spinneret. You're whatever. And the universe is a problem of condensation. So the filamentary structure is condensing.

[01:05:19.76] So it is a very simple question about how or why these models can be compared. Is it at the level of the quantum that you're talking about? And do you want to think about strings, like string theory, in terms of this web?

[01:05:37.33] Mostly it feels like a metaphor. Mostly it feels like, yeah, this kind of looks like that. But in art history, we call that pseudo-morphology. So I give you this word, and you think about this word. So that's a question.

[01:05:49.71]

Markus Buehler: Can I give it a first shot? So it's more than that I think, and we're just beginning to reflect on this. But actually the condensation is really what's happening. And if you look at the protein, what happens in the spinning actually is this condensation of proteins that have been loosely connected.

[01:06:04.25] And in the spider's body it's sort of in a homogeneous distribution of a liquid. The spinning is this condensation of many protein chains into very, very, high density and forming these connections, these secondary structures.

[01:06:19.34] So you create out of this more equally distributed monomaterial something that has a structure. And so now once you create a few filaments, you condense others to that. Because a spider will orient itself around this.

[01:06:32.47] And so I think they could be more than a pseudo analogy there.

[01:06:37.29]

Tomás Saraceno: And at the same time, this is what we've been discussing with-- I mean, I think so the entry point, yes. It's very simple. It's like a there is no match yet. But somehow, with Zhao yesterday when we were talking, it's really like there is some kind of more intrinsic, emerging properties. And that's what we're trying to look, which is not so much like a visual, maybe, that you can say, well, this looks like this.

[01:07:02.38] But there might be some kind of-- for example, it's like how many nodes are in space in relationship with the length of every single thread? You know what I mean, some kind of more deep mathematical relationship that you might try to understand. How is sound propagating-- two dimensional, one dimensional, two dimensional, three dimensional?

[01:07:19.97] It's something which might sound correct, or you can tune it somehow, because you have some kind of previous knowledge that you might refer to it. But at the same time, I think we're getting more and more refined, somehow, or trying to understand where we are.

[01:07:35.02]

John Ochsendorf: OK, next question, sir.

[01:07:43.25]

Audience: Thank you. Markus was commenting on this idea of looking across scales and how there can be resonances and evoking from one level to the other. One of the works that Tomás has done that we're trying to replicate now with the Red Cross, from one plastic bag, one person, one house all the way to making a solar hot air balloon at the neighborhood level, all the way to the global level when the [INAUDIBLE] travels around the world.

[01:08:09.26] In this question about individual versus social spiders, could you tell us about the human creatures that were looking at your big representations of these spiders? How did they relate to that installation?

[01:08:23.48] Was it mostly an individual looking at one segment, an individual looking at the structure and function? Was there interaction between people when looking at this? Is there room for designing an interactive endeavor of some kind next time you do something with spiders? It's just too much fun to think about it, what you're thinking.

[01:08:43.60]

Tomás Saraceno: The first thing that I could tell you is the females watch. The male's are a minority and kind of useless. They do nothing.

[01:08:53.73]

John Ochsendorf: Are you talking about the spider world or the human world?

[01:08:56.70]

Tomás Saraceno: I think we can draw some conclusion in the future if we want to survive. Usually spiders are always eight female, two males. This means that the huge majority is a female world. And the males really mostly also do not do the web. Most of them, they're very small. And you know, they studied the black widow. After mating, you can eat it up and throw it away.

[01:09:16.61]

John Ochsendorf: It's a good protein source.

[01:09:18.34]

Tomás Saraceno: Does it mean-- I don't know. That was a fine analogy, but maybe Markus can get more.

[01:09:25.52]

John Ochsendorf: But just in general, as people react to your installations, how do people tend to--

[01:09:32.09]

Tomás Saraceno: I'll tell you now. For example, in [INAUDIBLE], which is this kind of semisocial-- the male, there is a moment that they want to mate. And he comes-- it's territorial. It's a kind of orb web, but it's a little bit more complex.

[01:09:45.48] He comes from the side, and then he really starts to vibrate the web in a certain fashion that the female, she is kind of here, she recognizes it's not a fly. She is blind. She cannot see. He is a male.

[01:09:58.20] And then he comes and [BING] [BING] [BING]. He really pitches some of the strings that somehow it really-- and the female, for one hour, lets it play. And the male go there and [BING] [BING].

[01:10:11.42] He loses 60% of his own body weight-- so much exercise. After one hour the lady says, OK, come on. They mate. She eats half of the man. After he goes away, plays a little bit with a half body, and then again. And then they stop it.

[01:10:31.69] It's quite an effort to seduce.

[01:10:39.28]

John Ochsendorf: So he was thinking about how humans reacted to your webs, but that was so much better. I think we'll just stay with that.

[01:10:48.08] John Durant, and then you.

[01:10:53.04]

John Durant: So this is a very basic question, but Tomás has just made it impossible not to ask for me. I had been thinking that the missing element in this collaboration was the biology. I mean we have an artist, and we have an engineer--

[01:11:09.77]

Tomás Saraceno: Musician--

[01:11:11.07]

John Durant: But the more that Tomás speaks, the more I think that you are a biologist. You seem to know a huge amount about these spiders, so I'm interested in the back story there.

How did you get to know so much about spiders and are there any biologists in this interdisciplinary mix?

[01:11:28.80]

Tomás Saraceno: No, no, absolutely. This is what we just been talking about before we Markus, to try to kind of set up the team all together. There are two people, which mostly I work in Frankurt together with-- one is Peter Jager. He is at the Senckenberg Museum in Frankfurt. He was, at the beginning, the world leader of the Arachnology Society. And then now is Yael Lubin from Israel, and then she also.

[01:11:57.88] And both of them-- the arachnid-- mostly it's very, very small. There are not so many people who study spider webs, because also there was not really a method how you could scan the three-dimensional webs. Now it's kind of maybe-- these are the two people with which we work most.

[01:12:21.06] And also you cannot buy spiders. You really need friends around the world to-- you know what I mean. The social spiders really live-- you can only buy-- in Germany so far it's like the black widow and a tarantula. Most of them, there's no market. If you go 43,000-- now we are planning to go to Ecuador and pick it. The social spiders are more complicated. There are only 20 species.

[01:12:44.98] For example, Yale was shipping some stegodyphus spiders to the studio. Peter usually go to [INAUDIBLE] and bring us some. It is a great collaboration about-- and with Markus also, so when we think now that we would like, with Zhao, to send spiders to the ISS, to the International Space Station, the selection of the different interests each of us might have, at the beginning it's pretty much based on the arachnologists.

[01:13:20.04] Because they have to survive the journey. They have selected already some kind of a species that they think. And then we are sharing with Markus. And I'm also thinking, and we will decide all together which are the candidates, astronaut spiders.

[01:13:35.89]

John Ochsendorf: Thank you. And just here at the back.

[01:13:40.77]

Audience: I'm interested in this as like an artistic and a, like, materials type of thing. Have you considered coming up with some sort of resin or something that simulates the silk to perhaps 3D or something like that? Is that something you're looking to?

[01:13:57.87]

Markus Buehler: Yeah, I think we showed a slide. But yeah, we've 3D printed webs-- only two-dimensional webs so far. And we're trying to recreate, actually, this web that we have. We're trying to recreate and 3D print that web also.

[01:14:13.17]

John Ochsendorf: And that's with a synthetic silk that you've developed or worked with others to develop?

[01:14:18.71]

Markus Buehler: So we can do both. We have two ways of doing this. We can actually create filaments synthetically of actually real silk that we have genetically recreated in the lab, completely. That's one way.

[01:14:32.37] The other way would be what you described, using a synthetic material like PDMS or silicon, something like this. And that is easier. But both ways are possible.

[01:14:44.14]

John Ochsendorf: One fascinating thing to point out is that if we use 3D printers or other, more advanced materials that we develop, those require a large power source. And you think of the spider doing this with a few flies a week as a power source. So we're not there, yet.

[01:14:59.86] There was a question here.

[01:15:02.86]

Audience: As an architect, I'm always looking for a way to do a curve less expensively, because most building materials are straight. But people feel curves, and they're more natural. So this would obviously have a lot of application to tensile structures. My question is, in your model, are all the spider web filaments straight lines? Because it's a force diagram.

[01:15:27.56] They connect together, and there is a force at each intersection. And you've been able to model that, so you could have a fabulous time with different light intensities at each intersection related to the force of that, or color on the spectrum. You probably-- that's what you're working on, right? And think of that in a building or a tensile structure. The wind blows and you'd have these incredible lights shows.

[01:15:52.78]

Markus Buehler: That's a terrific idea. Yeah, I mean, the wind is something we've thought a lot about actually today. It goes off your question a little bit, but creating gravity-free environments on Earth by blowing wind to mitigate the effect of gravity, which pulls the spider down.

[01:16:09.74]

Audience: That was my next thing. Is gravity involved in this at all? If it's all in tension, gravity shouldn't have anything to do with it. But when you invert a web, do they sag?

[01:16:20.36]

Markus Buehler: I think there's a directionality with this. But the question about the light and so forth-- yeah, we thought about having actually humans go in the web, and they would play with the web. You would try to pull on the web and try to experience, and you would have light and colors and maybe audio signals to get another dimension in the experience which you usually don't have.

[01:16:44.12]

Caroline Jones: Then a giant spider comes out and eats you.

[01:16:53.20]

Tomás Saraceno: Maybe to add about-- the other thing which is a little bit in that direction-- spiders, how they travel, it seems that spiders are the animals who could fly higher than any other or almost there. It starts to give us some chances about that maybe we might be able to fly in the future. But anyway, you think they are not morphologically developed to have wings, to be able to fly. But the spiders do a method which is called ballooning or kiting. And then they cross all the way from the Mediterranean. They come from Africa to Europe without any visa all the time.

[01:17:37.40] They kind of release a thread on flight. They're hatching. It's like Charlotte's Web. And then the wind, it blows. And then when they strike this long enough they release themselves and [WHOOSH] they start to fly.

[01:17:49.44] They cross very, very highly. And then how they fly is like with thermics. The currents, air, the wind-- they blow. They get very, very high and then cross. It would be interesting. And there a big question, because they found out that there was a spider which was quite big. I don't know how many grams. And they measure, they say, OK, how much is the line?

[01:18:10.25] One of these threads-- how long does it have to be for this spider to take off? They ended up with 800 kilometers for one piece. All the scientists could not find out how one single thread, 800 kilometers-- because of the drag that you need.

[01:18:25.61] What they found out is actually what they do-- you can correct me. It's half fiction half-- what I say. They come up here, it seems, and then they start to release together. There is one here, one here, one here. They start to release. The air starts to blow. And then how they do, they release a piece of thread which is without glue, and then they put a small glue.

[01:18:47.90] Then again, another piece of thread and a small glue-- they make a line with glue points. You are here also, and then you start to release a thing. The air and the atmosphere and the thermics and all the wind-- they kind of start to weave a web in the air.

[01:19:03.18] And then this web, when you have a mesh and something which is a little bit like-- imagine a parachute or paragliding-- with this it makes kind of a structure and then [WHOOSH], they can take off all at the same time.

[01:19:13.96] It is fascinating, this idea of making a web that is built for in the atmosphere and became ballooning. But it's true, eh?

[01:19:21.38] That's fabulous. It's mostly true.

[01:19:25.35] Today I got my education with MIT. You should trust me.

[01:19:30.02]

John Ochsendorf: We have time for just one or two more questions-- here and then here.

[01:19:35.53]

Zhao Qin: I'm sorry, but actually I have some comments.

[01:19:40.33] Just quickly, please.

[01:19:42.81] So Tomás and I, actually we discuss about how to design those human-scale architecture. So using these kind of measures, actually we can design the boundary condition for this complex structure. So we can optimize the boundary condition, and we can actually manipulate the stress distribution in the network.

[01:20:04.09] And then we can test what kind of optimized structure can take impact force or wing loadings or any kind of those designs to have a better performance.

[01:20:18.46]

John Ochsendorf: I see. Thank you. So I think there was a question here in the front?

[01:20:23.26]

Audience: I'm just wondering, in the simulations, I get how you get the geometry from the picture. But how do you know how much tension all the strings are under?

[01:20:34.91]

Markus Buehler: In the beginning, it's purely point-based geometry. We connect the points. There's no initial tension in the system other than maybe some little pretension. But there's no other measure of tension in there. We don't have that information. You're right. But it's not in there.

[01:20:55.66]

John Ochsendorf: So they're linear springs, basically. And there was a-- OK, there was one in the back. And then we'll take one last one here.

[01:21:04.88]

Tomás Saraceno: Maybe, Caroline, one thing which I am also thinking, because there was all this thing about biomimicry. It's like a kind of a simulation. But this is what I think. So Markus is really getting to the next level, which is not biomimicry-- biomateriomics.

[01:21:19.19] I think it's really kind of an evolved step to understanding some kind of emerging properties.

[01:21:27.76]

Caroline Jones: To make it universe, or to imagine anew--

[01:21:30.55]

Tomás Sarceno: But it's a little bit more--

[01:21:35.16] I see. It's not just mimicry. OK.

[01:21:38.75]

Audience: Yes, my question begins with Tomás and then moves over to Markus. My question is, of what material did you fabricate your construction and how did you fabricate the individual joints among members? And then the next part of the question is, how does that translate, or has that been translated, into your computer model and what effect might it have?

[01:22:03.07]

Tomás Sarceno: And this is what we were discussing with Zhao and Markus. The black widow, in this case, has seven diffident types of-- and then our friends, arachnologists, might cover it much better than me, but anyway I'll supplement them, yes. But the black widow has seven different types of threads. I don't know which is the degree of elasticity of each of them.

[01:22:24.83] I know that, for example, usually the vertical ones, the model is always upside down. This is up, and this is down. For example, this one usually you always have some kind of glue in the bottom. It might have a different view.

[01:22:38.95] The model, how I built it myself, every thread was kind of nonelastic, but they join in the node, where everything connected was elastic. It gave me some margin to correct a little bit. Because if I have everything elastic, it was moving too much. I built the segments precisely. They have arrived from here to here, and the node was built with inelastic.

[01:23:02.29] With Zhao and Markus, we put only one property.

[01:23:08.41] Everything was elastic.

[01:23:09.20]

Markus Buehler: Everything.

[01:23:10.00] I mean the connections are perfectly glued together with the glue silk. So it's different than the web that you constructed. You have the elasticity in the nodes. We have the elasticity everywhere in the system, which is probably how it would be in a real web.

[01:23:27.49]

John Ochsendorf: OK, let's just have one last question here in the second row. Right here, Meg.

[01:23:32.08]

[01:23:37.82]

Audience: Yeah, I have a structural question. It's kind of a follow-up to his question. How much can the model tell you? Could you analyze it and figure out what would make it fail? I mean, it's so complex. Do you know enough to use-- have you located things in space? Or if you don't know what the tension would be on various things, to what extent could you analyze that structure?

[01:24:06.94]

Markus Buehler: Yeah, I mean in the 3D web. In the 2D web, we've done exactly this. It's a lot easier than the three-dimensional web. We've removed individual struts, and we've identified what are the conditions to make the web break very easily, versus being more resilient.

[01:24:20.91] In the 3D web, exactly one of the big questions, which are unanswered is exactly that. Is it by removing random struts? Or is it by removing them in a particular pattern? And to answer that question, in a simulation, we can do it much easier than in the real web.

[01:24:39.30] We can't do it in a real web, or in the installation we'd have to cut the cables. So the model is a great way of doing this. And we can do it using inverse algorithms, using mathematical models that would either randomly or particularly, using genetic algorithms, selectively, progressively remove particular threads that are highly loaded and deformed.

[01:24:59.65] So there are ways of doing this mathematically that we can apply to identify the failure modes, to make it fail, and conversely understand what makes it robust.

[01:25:12.21]

John Ochsendorf: Well, this has been tremendously fun, and I think it's a testament to the strength of both the arts and science and engineering research at MIT that so many of you would come out on Thursday night for-- is today Thursday?

[01:25:28.21] Yes.

[01:25:30.02] I asked the same question.

[01:25:32.06] And personally, it was a privilege for me to be here and to take part in the conversation. I've enjoyed learning from both of you. And these two rock stars, I think, will stick around for a few moments. So if you have a few other questions, please come and say hello. Thank you all so much for coming, and thank you for hosting us this evening.

[01:25:47.16] Thank you.

[01:25:47.46] Thank you.