I'm honored to be here to talk a little about how we build a body of understanding about our surroundings, and how we come to know what we know, and how it is that we contend with the truly alien, as seen primarily through the lens of my scientific research.

So to begin… for most of human history, the planets were no more than points of light. But the ancients did know that there were five "wanderers" that moved separately from the fixed stars. Of those, only one had a distinct color, and at times its red light blazed as the third brightest object in the dark sky.

It wasn't only this planet's color that made it perplexing, but also its motion. Mars drifted eastward, night after night, in relation to the other stars, but every couple of years, it suddenly turned and backpedaled against the zodiac, wandering west for several weeks before resuming its normal course. Sometimes the size of the loop was smaller, sometimes larger. From this, Plato concluded that the planets had souls, for what could these retrograde acts be, he reasoned, if not expressions of free will?

Truly, we knew very little about Mars before the dawn of the space age. Some of it was right, for instance the fact that Mars had polar caps and a length of the day similar to our own. A lot of it was wild speculation, as there have been so few data points to cabin our inquiry or limit our imagination. In 1965, when NASA's Mariner 4 spacecraft arrived at Mars, for the first time, humans saw the face of another planet. That moment, actually, was hugely disappointing. Even the scientists struggled to believe what they

That meant there were no oceans. No waxing and waning of forests as the seasons progressed. None of the photographed terrain showed evidence of resurfacing, meaning there was no weathering of any kind resembling the Earth. A few days later, the *New York Times* declared that Mars was probably a dead planet.

Fortunately, we returned on subsequent missions, and we discovered more completely unexpected things. For instance, everyone thought was Mars flat, it was this tiny planet, it didn't have as much heat of accretion, so far from the sun… how could it have generated vigorous geologic activity? And by 1971, NASA had flown by Mars three times and hadn't seen a single significant shadow, not a single contour on the horizon. But the spots shown here, emerging from the top of a dust storm, turned out to be mountainous volcanoes, far larger than any volcano on Earth. Nearby Nix Olympica was soon reclassified as Olympus Mons, as its escarpment alone was as high as Mount Everest.

As the dust cleared, the spacecraft revealed a much more dynamic world filled with, among other things, tons of ancient river valleys, which meant Mars must have been warmer and wetter in its ancient past. Eventually minerals that only form in the presence of water of liquid water would be discovered as well. Water had left its mark all over the surface of Mars.

A few years later, in 1976, NASA's Viking landers touched down on the surface of Mars for the first time. Because no one knew what the surface would actually be like, the first image was of the lander's foot, simply to make sure the ground was solid. The next image was of the terrain… you'll notice something, how the sky looks like the sky here on Earth. This is the image that was released to the public. But in fact the image-processing laboratory had made a mistake. The color on the lander's cameras had to be calibrated because the color diodes were also sensitive to infrared light. Soon the engineers realized was full of light and the color of butterscotch light reflecting off billions of tiny dust particles in the air.

One of the most exciting things about that mission was its life detection package of instruments it carried along, called by some "the greatest experiment in the history of modern science." The results were enigmatic, however. Some of the readings flashed and then died away, as if something in the soil was a chain of powerful chemical reactions. Then the chemistry instrument team announced that they had found no organics. It was just so weird, because even the moon contained some organics: simple molecules that had rained down from space on comets and meteorites.

But when NASA's Phoenix mission landed in 2008, we figured out why. The Phoenix lander was built with a sensor that detected perchlorate, a reactive compound in the Martian soil. We know now that this salt, when heated, will simply destroy organic molecules on Mars.

And when the Opportunity rover landed at Meridiani Planum, the first Mars mission I had the chance to work on, it found not only these bizarre little rounded blueberry-like spherules, like the ball bearings Fred Flintstone would slip on, it also found minerals that could have only formed in acidic water—water the pH of battery acid. Water that acidic wouldn't be so friendly to life.

But a decade later NASA's Curiosity rover, found just the opposite, smooth mudstones that formed in neutral pH waters, the kind of water that you might have been able to drink had you been standing on the planet's surface all those years ago… Curiosity found not only evidence for lots of water but also all the essential elements we need for life as we know it, as well as lots of those missing organics, the building blocks of life as we know it.

This beautiful nearby planet, the closest thing to Earth we've ever found, is a world just as complex and enigmatic as our own. It's a world that keeps surprising us. What I want to talk about next is how I think places like Mars, as well as the outer moons of the Solar System, to say nothing of the planets around other stars, may also surprise us when it comes to the search for life.

As astrobiologists involved in that search, we typically start with what we know. There's a large set of well-established and widely accepted features associated with terrestrial life and signatures of biologic processes; for example, particular classes of molecules and isotopic signatures, patterns within the molecular weights of fatty acids or other lipids, biogenic structures and textures, and biogenic minerals.

We've gotten pretty good at looking for these things. We do this in extreme environments here on Earth, places where there's not a lot of life, and we do this in the ancient rock record.

Since we're starting from what we know, it's easier to interpret the data, and signals may be rich in information. We also have a better understand of what's happening through time. We've been able to find biomarkers, or molecular traces of life, in rocks that extend billions of years into our own geologic history, -- even when the molecules have begun to break apart. Paleontologists don't go looking for dinosaurs, they go looking for dinosaur bones. It's the same with molecular fossils. Even after the original molecule degrades, even if some functional groups fall away like fingers and toes, if you still have the molecular backbone, you can understand a lot.

Mars is also as similar to Earth as it gets. We had very similar pasts, especially around the time life was getting started billions of years ago. There's also a chance that life on Mars and life on Earth share a common ancestor, that life might have been "caught" from the next planet over. Research has shown that meteorites weren't necessarily heated above sterilization temperatures, and that some arrived on quick trajectories. A billion tons of rocks may have been exchanged between Earth and Mars early in our histories—and in fact far more of those rocks were coming from Mars to Earth because of the gravitational well of our sun. So perhaps, in the end, we'll discovered we're all Martians.

So those are some of the good reasons to look for life as we know it. It's a great place to start. Like if you were to lose your keys at night, a sensible first place to look would be under the light post, where the ground would be illuminated. But as the history of space exploration has shown us, we also really need to be cognizant of the limits of analogy. And when I say the limits of analogy, I mean that in two ways. First, we're somewhere on a spectrum of understanding life, even life as we know it, and that understanding has advanced tremendously in the last few decades and will likely advance tremendously in the coming decades. We think about where we were in terms of our understanding of life when we first tried this in the 1970s. One of the most famous of the Viking experiments was Vance Oyama's "chicken soup" experiment, premised on the idea that life would grow rapidly in nutrient-rich media, but that was before we understood that vast majority of microbes couldn't be cultured in the laboratory. With the advent of genomics, we realized that the vast majority of the diversity of microbial life on Earth was, in fact, unculturable. So I would argue that if we designed those experiments now, we probably would design them differently. We also need to be open not only to the possibility that our understanding of life here is far from complete, and that especially that our understanding of life elsewhere is limited, that there could be life beyond the confines of our current thinking.

We're also beginning to explore worlds very different from our own. These include worlds like Europa, a moon of Jupiter. For a long time, it seemed impossible that there could be liquid water in such a cold part of the Solar System, so far from the sun's heat. But underneath its ice shell, Europa has a liquid water ocean. This is because it's constantly contorted by Jupiter, which is 300 times more massive than Earth. The tidal tug and pull causes Europa to flex, creating a great deal of friction and heat.

We suspect that the underwater ocean on this moon is approximately two to three times the volume of all of Earth's oceans combined, and also that the ocean may have persisted since the origin of the Jovian system.

Another ocean world is Enceladus, orbiting around Saturn. It's tiny, only 1/7th the size of our own moon, about the size of England. There are over 100 cryovolcanoes on the surface, spewing more than 500 pounds of salty water up from its global subsurface ocean. Most of this material falls back to the surface as bright snow, but part of it forms the diffuse and wide E ring, one of Saturn's beautiful rings. One of the best things is that we don't necessarily need to drill or melt our way through all that ice to access the subsurface ocean, a spacecraft could just swoop by and catch some briny water to analyze.

We see spectral evidence for silica in the plume material, indicative of hydrothermal activity. There may be active hydrothermal vents at the rock-water interface on both Europa and Enceladus, similar to the hydrothermal vents deep in our own oceans.

The ocean floor is a place that no one used to think could be home to life. Despite toxic sulfide gas and temperatures hot enough to melt lead, we now know that hydrothermal vents are teeming with microbial communities. In some, there are even thickets of two-meter-long tube worms tipped with feathery red plumes, which were seen for the first time as the lights of submersibles cut across the seafloor.

Also orbiting Saturn is Titan, its largest moon. It has pale hills and dark rivers. Titan also has clouds and weather, and it's the only moon we know of with a thick atmosphere.

What's so fascinating about Titan is that it's ocean world but the seas and lakes are made from hydrocarbons, not water. -- It's a gasoline world, filled with ethane and methane, as shown in this Cassini radar image—which prompts the question, what might the molecular and polymeric building blocks of life look like in such a place?

These moons of the outer planets are far from what we often consider the "habitable zone," the region around a star where planets could have liquid water on their surfaces. Yet there might still be possibilities for life. If only we had a tricorder, for those of you that catch the Star Trek reference, some way of determining what it is we might have in front of us.

We don't have a tricorder yet, but with a $7M recent grant from NASA, a team of colleagues and I are asking the question, how can we search for indicators of life without presupposing an underlying biochemistry or particular molecular framework? Methods that don't require DNA or even carbon-based life.

In some ways, it's an enormous big challenge, almost like trying to imagine a color we're never seen. But it's a lot of fun. Our team includes biologists and chemists, computer scientists and mathematicians, planetary scientists and veteran instrument developers. Some of tools and techniques we've developing rely on high heritage spaceflight technologies, like mass spectrometers, and others require all new instrumental approaches.

I'll briefly walk through a few of the ideas to give you a sense of what I'm talking about. One really exciting approach is the idea of looking for chemical complexity, regardless of what the basis of that complexity is. As my colleague Lee Cronin likes to say, if you find a 747 on the surface of Mars, or many of them, you might have no idea how it got there, but it probably wasn't random. Now imagine the molecular equivalent of that.

So what does it mean to be a complex molecule? You can't just use something like molecular weight because there are all kinds of heavy molecules that are simply polymers with repeating subunits. But using graph theory, we're figured out a neat way to quantify complexity, and it turns out that all the molecules requiring 15 or more steps to make, with each step adding things like a new element or type of bond, all the molecules are the result of biology. There may be a lot of simple biological molecules we miss, but everything about the threshold of 15 appears to be made by life.

And here's a nice animation showing this in play, and what the fragmentation pattern for this molecule might look like in terms of the kind of data we can collect with a next generation spacecraft mass spectrometer, like the one that will fly on NASA's upcoming Dragonfly mission to Titan.

Another really interesting approach that we've been working on at Georgetown and the University of Texas at Austin is what we've been calling molecular complementarily, which uses miniaturized sequencing technology alongside libraries of millions of randomly generated short strands of DNA or RNA, which will naturally curl up and have secondary and tertiary structures. These oligos will bind to a lot of things like minerals, peptides, small organics, metals, etc., a huge array of different ligands.

Now imagine the vast amount of information patterned on the surface of even the most primitive cell here on Earth. There would be far more potential binding targets on the surface of that cell than say, a mineral grain. A very small percentage, far less than 1%, of this library of oligos will bind to the surface ligands in a sample. We have techniques for amplifying those binding oligos millions to billions of times. This is helpful because life -- relying on chemical sources of energy without sunlight may have less biomass than life on Earth.

Again, we're using these short nucleic acid strands as reporters and looking at patterns, not requiring oligos to bind to other nucleic acids, not requiring a lifeform to be based on DNA or RNA. We've also recently refined this method to also tell us about what kind of chemistry is present-for instance, if the binding sites are, say, aliphatic or aromatic-by using what are called oligourethanes with different R groups attached.

We are also exploring new technologies, including one called NanoSIMS, that allow us to explore chemical fractionation, in other words whether elemental and isotopic accumulations, regardless of what those elements or isotopes are, detected in compartments separate from the environment could serve as a potential biosignature.

We see concentrations of elements at the microscale when it comes to life, distinguishing a cell from say, the abiotic precipitation of calcite from seawater. -- What's also interesting is that we may be able to detect this at the macroscale too. There's this interesting fact about the ratio of carbon to nitrogen to phosphorus in the ocean, it's 106:16:1. We see that same geochemically distinct signature at the bulk level, in marine biomass but also after the death and decay of marine biomass. It's called the Redfield Ratio, and perhaps we'll one day be able to detect and understand "Redfield" ratios in exotic fluids on other worlds, as a bulk biosignature at the level of a whole planet or moon.

I'll end with one more idea, and that's the idea of energy transfer. There's a lovely quote from a Nobel-prize winning physiologist that "life is nothing but an electron looking for a place to rest." One of the other things we're -- investigating is whether the current density or are other electrical attributes produced by microbes are notably distinct from abiotic oxidation? It turns out yes. We've been working with colleagues from Harvard University on the idea of designing new probes, the kind of thing you could perhaps utilize at the rock-water interface of an ocean world, searching for evidence of extant, or still alive, simple life by looking for the transfer of energy.

Now these "agnostic" methods may trade definitiveness for inclusivity. But, fortunately, we typically get to send a package of many instruments together on a space mission, not just one. Our group has been working closely with computer scientists and statisticians on how we can use integrative and probabilistic approaches to data analysis to help convert measurements into likelihoods and thresholds. We're hoping to move away from a "yes-no" framework into more of a conceptual spectrum of certainty, something like "this is three sigma, or three standard deviations, away from what we would expect of abiotic processes alone."

I want to end with four quick thoughts related to this work that I think are particularly relevant to the workshop at large. When the sun rises and sets on Mars, the sky glows a baffling and incandescent blue … I used this image at the beginning because it's so poignant, not something we would have ever expected. Time and again we've been bowled over by the utter foreignness of other worlds.

I think it's important to remember how challenging it is to make sense of what's around us, especially given the limits of human perception. I've always loved this passage by Blake, from The Marriage of Heaven and Hell, about how we can only see through the chinks in our cavern. That's how I often think about the universe.

Next is that we may still be toddlers when it comes to understanding what life even is. A colleague of mine, Carol Cleland, a philosopher, argues that it’s premature to even try to define life. We have only one data point, this DNA-based life we have on Earth, which is all the same, which can all be pinned onto the same phylogenetic tree. For example, how we would define water without truly understanding chemistry? We could describe some attributes, but would purple water be water, would ice? We couldn’t really say until we began to understand the molecule that forms from two hydrogen atoms binding to one oxygen atom, and began to understand the van der Waals forces that exist between those separate molecules. Maybe with a second or many additional data points, we will see similar underlying constraints on biology.

Third is that we are ephemeral. That small dot is Earth, next to the little arrow, it’s a picture of our planet from 900 million miles away. The Cassini spacecraft took it from orbit around Saturn in 2013; here’s our home, our pale blue dot. I love this image because it reminds me of what Carl Sagan once said about a similar image, shot in 1990 from the Voyager 1 spacecraft. He said, “That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. The aggregate of our joy and suffering, thousands of confident religions, ideologies, and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, every corrupt politician, every "superstar," every "supreme leader," every saint and sinner in the history of our species lived there—on a mote of dust suspended in a sunbeam.” I just happen to like this image even more than the Voyager self-portrait, because it gives you a better sense of the neighborhood. Our planet will survive the Anthropocene... the question is just whether us humans can last long enough to experience what comes next.

The universe is also vast. We have now confirmed over 5000 exoplanets, or planets around other stars, where the neighborhoods are certainly even stranger. What if life evolved somewhere without Darwinian evolution, perhaps without death? Or imagine somewhere there is life but no clear separation between life and its environment? Or perhaps there’s life everywhere, perhaps life is simply the byproduct of energetic systems? There could be as many as forty billion planets that could support life in the Milky Way alone, belted with moons and moonlets—potentially an entire solar system for every person on Earth. The idea of knowing these places intimately, of one day touching their surfaces, may seem ludicrous. These worlds seem impossibly far away, like what could we possibly know about them besides maybe a few details about their orbits, perhaps some spectrographic measurements of their atmospheres. The distances are immense, and the universe has a speed limit, and it’s slow. These may be points of light and shadow at the very edge of our sight, far beyond our grasp.

But then again, that is exactly how Mars seemed only a century ago, when telescopes had run up against the limits of our atmosphere. That’s just one human lifetime away, and I can’t help but wonder how much more could still change and what we might learn about who we are, where we came from, why there is something and not nothing and whether that something from nothing happened once or time and again. Thank you.