



In *Recursive Worlds*, Sara Walker redefines life as a physical process that structures matter through recursive information across deep time. Challenging conventional physics, she introduces *assembly theory* to describe how complex objects—including molecules, technologies, and living systems—emerge only through informational lineages. Rather than viewing life as spontaneous or reducible to chemistry, Walker argues that living systems operate beyond a measurable threshold of complexity, constructing new possibility spaces in a combinatorially vast universe. Earth, in this framework, is the largest known object in time, hosting a biosphere and technosphere that are recursively stacked and increasingly capable of perceiving their own origins. As the technosphere grows, it becomes not merely a byproduct of biology but a continuation of planetary evolution, possibly leading to biospheric reproduction. The talk invites a shift in physics toward a model where information, history, and recursive causation are central to understanding life, intelligence, and the future of planetary systems.

[Sara Walker](#) is an astrobiologist and theoretical physicist interested in the origin of life and how to find life on other worlds. While there are many things to be solved, she is most interested in whether or not there are 'laws of life' - related to how information structures the physical world - that could universally describe life here on Earth and on other planets.

## EDITORIAL

In this talk, Astrophysicist, Sara Walker, discusses how life challenges our understanding of reality, stating that our biosphere is unique and that life is about how information structures matter across space and time.

Walker contrasts standard physics with the physics of life, using thought experiments to illustrate the differences. She highlights how humans can create elements and launch satellites into space, altering the course of nature in ways that other entities cannot. Life, she argues, exists only on Earth and allows for a unique possibility space. The fundamental unit of life is not the cell, but the informational pattern structure that transcends cellular life.

Walker explains that life emerges when selection allows objects to exist that couldn't exist without an informational lineage. This transition, marked by self-sustaining systems that build increasingly complex objects, is a phase transition in the combinatorial space of what can exist. As life evolves, it creates a virtual world where objects have a larger size in time than in space.

The concept of technologies of perception is introduced, emphasizing how our ability to perceive and understand the universe expands with our evolutionary depth. Walker and her collaborator Lee Cronin are developing Assembly Theory to understand the emergence of life and this new kind of physics. The theory posits that some material objects require information for their construction, and this information comes from other objects within the universe.

Assembly Theory defines objects as compositionally constructed and existing in multiple copies, formed via selection. The complexity of an object is measured by its assembly index, representing the minimal number of recursive joining steps to construct it. A key finding is that biological systems produce molecules with a high assembly index, indicating they require a history of selection to exist.

The universe's combinatorial space is vast, with exponentially growing possibilities. Evolution constrains this space, allowing only certain structures to exist. Evolved objects have a physical size in time, and understanding information as material is crucial to understanding life. Walker argues that we live in a virtual reality created by life's deep temporal structures and that the technosphere, the largest object in time, is driving us to further virtualization. The emergence of life and mind are key transitions in this process, with life originating as a planetary-scale transition. If the technosphere is a living structure, understanding its origins is crucial for planetary reproduction.



We live probably on the most interesting planet that we know of, because life is here. But we actually don't understand the phenomena that's architecting our world. What I'm going to do in this talk is build the story about how we're thinking about the nature of life at its most fundamental level. And what's deeply intriguing to me about this process is how much life forces us to restructure the way we think about reality itself. And so this is the exploration that we're going to be doing. Our biosphere is a pretty special place, and I think one of the things that's pretty profound for me, trained in theoretical physics, is thinking about how deeply perplexing the nature of life is.

Albert Einstein has this really fabulous quote about how physics is really primitive compared to the understanding that we might get by thinking about the nature of life. This is something that he said over 100 years ago, and obviously a lot of his theories, like many other theoretical physicists, have revolutionised our understanding of reality.. In Einstein's case, it was thinking about the properties of life that really forced us to bend concepts of space and time. And actually, if you look at the history of physics, every single theory of physics that we've come up with has forced us to change some of the basic structures about how we think about the nature of reality.

01:41

Re-Orienting What We See

And so the first reframing that I want to get our head around is to think about our planet as a self-constructing system. This idea of "recursive worlds" is really about how deep in evolutionary time our planet really is. In some sense, life is forcing us to have a different concept of space and time than the concept that we have in standard physics.

We're used to thinking about the universe as being a really large place, right? And that Earth is very small, in the vastness of space. But if we actually reorient our thinking to think more about how we exist in time than how we exist in space, Earth is actually probably the largest object in the universe that we know of.

02:43

Causation

A lot of what I'm going to do tonight is walk through how I've come to understand Earth as this giant informational structure. And it really has to do with the fact that life is about the physics of how information structures matter across space and time. Because that's been happening on our planet for 4 billion years, we are a very, very deep stack of recursive objects. And so Earth is actually fundamentally huge in terms of the combinatorial possibilities that exist on this planet, which don't exist anywhere else nor can they exist anywhere else.

This brings me to try to juxtapose what we know about standard physics right now, and how we should be thinking about the physics of life. This is one of my favorite quotes. David Deutsch has this really wonderful book called *The Beginning of Infinity*, where he imagines how explanations can transform the world and how we should be thinking about new explanations as opening up new territories in terms of what the universe can actually do through us. And so he has this quote that says "Base metals can be transmuted into gold by stars and by intelligent beings who understand the processes that power stars, and by nothing else in the universe."

Holding these two contrasting processes, where stars can transmute elements and intelligent beings like us can transmute elements, there is a fundamental difference between them. One happens spontaneously, while the other one has some knowledge of that spontaneous process and some knowledge of the regularities of our universe that allows it to control those regularities and allow new possibilities to happen on the planet that it originated on.

I'll give a couple of examples. Thought experiments are critically important in the history of physics. So if we go back to Einstein's ideas about elevators moving through space, they were critically important for him to conceptualize relativity. In my line of work, it's actually quite challenging because you're trying to understand, fundamentally, what life is, and you need to conceptualize something about the regularities that describe yourself as something that exists inside the universe. This is one of the reasons that we fundamentally need new descriptions, because the laws of physics as we formulated them to date are laws that require outside observers. They require things to exist outside the universe that they're describing. And obviously, we can't exist outside the universe that generated us. So if we want to understand the generative mechanism, how it is that we live on a planet that is generating structures like us and how we're generative structures in the universe, we need to do thought experiments that have us inside them.

The first one that I'm going to propose tonight is to think about the periodic table, the elements and the formation mechanisms for all of the elements that we understand right now on this planet. We have a pretty good knowledge of Big Bang nucleosynthesis, right? So after the formation of our universe, when it cooled sufficiently, we actually had the formation of the first elements, which were hydrogen, and helium and a little bit of lithium. And then most of the elements that we know of, the familiar ones like carbon and oxygen, are actually made in the death of stars right? We had to go through generations of stellar birth and death to build some of the heavier elements. We'll often hear that we're made of stardust, but we don't talk so much about the fact that we, as intelligent beings that have come to understand nuclear processes, we can also now generate elements that, as far as we know, can't be produced anywhere else in the universe even though they're physically possible.

Those are things like element 118 Oganesson, which is the highest atomic element that we've ever produced on this planet, and which we can make in relatively high abundance. We don't know of any other conditions in the universe that produce that element in high abundance, with high regularity, besides us. We can do that because we understand nuclear physics and because we understand engineering conditions to actually build materials that can execute chain reactions to synthesise these elements. It is permitted by the laws of physics, but it is not possible without a system that evolved and learned how to actually control that regularity of nature and generate that process.

Second thought experiment, also a very anthropocentric one, because again it's about us. One of the reasons that I like to give thought experiments about us as agents in the universe, rather than talking about DNA and chemistry inside cells, even though the physics is the same independently of what scale of life that you're looking at: I think it's much more visceral for us to think about these anthropocentric examples and how they challenge our thinking than to think about chemistry modeling its environment, right? We're doing the same thing, but at a larger scale.

If we really want to understand this physics, we have to embody ourselves in it. So when we're doing things like now in this thought experiment, launching satellites into space... we know of lots of worlds that have satellites. Mars has 2. Jupiter has over 60. Earth has one natural satellite, but we have thousands of artificial satellites. Why is it that our planet has thousands of artificial satellites? It's because over billions of years of evolution, multicellular systems evolved, intelligent social systems evolved. Those intelligent social systems extract irregularities about the natural world and devise things that we call laws of gravitation. And with that knowledge, they were actually able to harness those regularities and allow a process of building small metal boxes and launching them reliably into space. It's critically important that this is a reliable process, it's not a one-off fluke, right? Mars has two satellites. They formed artificially. They didn't form during planetary formation; they're captured asteroids. If you have a planetary body hit another body, you can have a fluke accident. That's not what's happening on our planet. Our planet is such that it's almost a programmatic process, right? We have an input. We can build a satellite, we can launch it into space, that's the output. And we can do that process over and over and over again. So it's become a law, like a property of our biosphere that we can launch satellites into space because we have the knowledge to do it. As far as we know, that knowledge only exists here. It may exist on alien worlds if life is out there, but we don't know that yet.

So life exists on this planet and this planet alone, as far as we know right now. It doesn't mean that there aren't alien worlds out there, but we have yet to be able to see them. And I mean, see in a very visceral way. And I'll get to that in a little bit later in the talk. But because life exists on this planet, we have some sense that more things can be caused to exist here than anywhere else. So cell phones exist here. TikTok exists here. The idea of neural implants exists here. The possibility of building machines on the moon exists here. There is a huge space of possibilities and

possible technologies that we can construct, possible life forms we can construct, possible hybrids between biology and technology... And this possibility space only exists on this planet right now because it evolved on this planet, and this planet structured it through its history of acquiring memory and retaining knowledge of the past in the present, where we're historically deep objects and we can encode a combinatorial space that allows these possibilities to be constructed.

It is really important to think about the fact that life actually allows some objects to exist by acquiring information about how to make those objects, because it changes and reorients our thinking about what is the fundamental unit of life. So if you look in a biology textbook, we're really trained to think that the fundamental unit of life is the cell, but a cell is an instance of a temporally structured object, right? Cells have existed on this planet for billions of years. A cell just like us and our bodies is constantly having to eat to restructure its own form. So the atoms that it's made out of when it's born are not the same atoms it's made out of when it dies. What is the continuity of these objects? The object is actually this informational pattern structure in itself over time. And that fundamental unit actually transcends cellular life and applies to everything that's happened on this planet since life first emerged.

One way that we need to think about reframing and reconceptualising the nature of life itself is to think about life as these lineages of propagating information. It's about how information is structuring matter over time, and an example of how that opens up possibility spaces are the two thought experiments that I provided about making elements and making satellites. Those require very deep knowledge of the regularities of physics which we've acquired through theoretical physics. But that's not an isolated phenomenon: in our biosphere pretty much every single living system on this planet is doing some form of that process.

The reason that I like the thought experiments I provided is they really demonstrate why current physics is insufficient, right? If we think that base metals can be transmuted into gold by stars and also by things like us and things like us have to acquire that information over time, including theories of physics, it means that we need a different kind of theory of physics to describe what physicists do as a living structure. We are these lineages.

This brings us to the origin of life itself in order to understand life as a physical process. You know, reorienting our thinking in terms of these lineages of constructive processes that are acquiring information and allowing new possibilities to exist is absolutely critical. But we don't have a physics yet that describes that process. I think we have a lot of ideas about how to talk about it, and we're learning how to frame these abstractions philosophically by actually embedding them in theories of physics that allow us to solve open questions in science is quite hard. I work a lot on the nature of the origin of life itself, and the idea of the origin of life is really about the transition to this kind of physics; really taking over this idea that something about the combinatorial space changes and allows a planet like ours to start building up complexity over time through this recursive process of construction and learning.

We can really think about two transitions in that space that we canonically talk about. What we're trying to do is actually embed that in theories of physics, not just talk about them in informal ways, but really formalise that knowledge. Life emerges when selection allows objects to exist that couldn't exist in the absence of an informational lineage. And so things like satellites orbiting a planet, artificial satellites, cannot exist spontaneously. They require 4 billion years of evolution -potentially, not clock time, but construction time- to be built on a planet. We don't see satellites orbiting other planets. They don't spontaneously fluctuate into existence. They require an evolutionary process to construct them. We can define this boundary in the space of things that can exist for things that are too complex, that require information for their construction. They exist across this boundary that only life can enter.

Living physics exists across and above this complexity boundary, and the origin of life is when you actually have systems that have enough constraints on what can be built to actually be self-sustaining. They don't dissipate back into noise. They can structure themselves and maintain a cascade of building more complex objects. That critical transition is really a phase transition in the combinatorial space of what can exist. And once you cross that boundary, the space is exponentially growing in terms of the number of possibilities. Life is carving a trajectory through that space. And it's doing it by retaining memory of the past in the objects that exist, and allowing construction of future possibilities.

That process eventually becomes so deep in time that there's so much memory or information compactified in very small volumes of space, that it allows abstraction to be possible, and a virtual world to emerge in some sense.

The framing here is that evolved objects have a larger size in time than they do in space. And as that time gets deeper and deeper, reality becomes more virtual and things look more abstract. Social structures are very abstract, culture is very abstract, language is very abstract. These are very deep objects in time that our biosphere has generated. The technosphere is a very abstract concept for us. If a cell was looking up at us, we would look very abstract to it because we're much larger in time than it is.

These two transitions are actually critically important. But the ability for us to understand the earlier phases really comes from the fact that we have to be deep in time to actually see these structures. And this gets us into the idea of perception itself and our understanding of the boundary of our reality being an evolving concept. I borrow the phrase technologies of perception from Claire Webb, I'm very inspired by her thoughts on that. If you think about us evolving, we have boundaries of our sensory perception. So when life first emerged on Earth, nothing on our planet could see. We had to evolve photon receptors and the first cellular life didn't really see all the structures that we see around us. It saw single photons, and then eventually multicellular life evolved and we evolved compound eyes: many cell types in our eyes. And because we see the world the way that we do, when we evolved into technology, we started building things that allowed us to see the world even more than we could before.

A really perplexing and interesting feature of this is that even though we emerged from cellular life, we didn't know cellular life was there until we built telescopes to see it. Our boundary of what is our perceptual horizon is constantly expanding, and that horizon actually defines the boundary of us as evolutionary objects and what we can understand. As we get deeper in time, we're actually pushing the boundaries of that horizon.

The technologies of perception of the cells are also part of a living structure. This is a decomposition of a camera. It is also an evolved object our biosphere has constructed over time.

As I said, part of the reason that we construct objects that allow us to see the world is because we ourselves have evolved technologies of seeing in our own eyes. We're trying to extend that to be able to see the deepest reaches of outer space and the microscopic world around us, and even all the way down to elementary particles... The Large Hadron Collider, for example, is a giant microscope that allows us to see a technological horizon of the small substructures that we can observe and understand.

Our planet has been evolving for billions of years, building structures like us that are lineages of information, structuring the material world into all kinds of evolving objects that are getting deeper and deeper in time, and also increasing the boundary of what they understand as recursive memories of the past are embedded in the present. I've been working on a theory with my collaborator Lee Cronin, called Assembly Theory, where we're aiming to understand the first steps of this process and how this physics emerges. What is life, and how do we actually understand the transition from non-living things to living things?

18:18

Assembly Theory

As I said at the beginning of my talk, physics is quite deep. And so, if physics is really a universal physics, a lot of the mechanisms that might fundamentally explain what we are and fundamentally explain what life is change a lot of the nature about how we should talk about the structure of reality, just like previous theories of physics before have.

I want to talk a little more about the possibility space that we exist in. I've talked about how some things are only possible if there is a construction process or a set of objects that know how to make that thing, that have learned through evolution to be able to construct that object, but I think we under-appreciate how large our universe is in terms of the combinatorial possibilities it can construct.

I was trained in theoretical physics, and I'm used to looking at Hubble Deep Field. Most of us have probably looked at these images of distant galaxies and we're told "wow, the universe is really huge". If I put my pen up to the sky and just in the size of the pen tip, there's 10,000 galaxies. And that is huge, right? We do live in a very large volume of physical space. Our universe has been getting larger over time -physically in terms of spatial coordinates- but it's also getting larger in terms of combinatorial possibilities, in particular in our biosphere.

If you take a single molecule that our planet has created, like Taxol, which has a molecular weight of approximately 853, this molecule has 47 carbon atoms, 14 oxygen atoms, 51 hydrogen atoms and 1 nitrogen atom. It's not huge. There are a lot of molecules inside the cells in your body that are a lot larger. But if we wanted to iterate over the combinatorial space of just this molecular formula and make every possible three dimensional structure that could be a possible molecule, it would fill 1.5 universes of material if you had one molecule pulled for  $1.5\text{cm}^3$ . So that's one molecule our planet has invented that exists in a space of combinations that's that large. And we're not even sure that's actually the boundary of the space.

When you go into chem informatics and the study of drug design, people actually have a really hard time estimating just how large chemical space is. You just take the periodic table of the elements and you want to say how many possible molecules there are: we can't do it. It's too big. And that's chemistry. That's not technology, right?

The space that we live in is exponentially large, and a question of interest is why something like Taxol exists on our planet and not the other 1.5 universes of possibilities. Obviously, there aren't enough resources to exhaust them all. Not every structure that is possible to exist will ever exist. The space is too large to exist as physical

objects. So an important feature here is that I can even talk about the space of Taxol because of the knowledge that we have as intelligent beings that understand the regularities of chemistry and understand the periodic table of the elements. Because what I can do with Taxol is: I can take it apart, and I can say “there’s this constructed counterfactual space of all of these molecules that could exist, that Taxol’s existence actually implicates as possible things our universe could build”. And so every object that our biosphere builds contains that kind of memory in history and constructed space of possibilities folded up in a single object.

Why do we see Taxol and not those other 1.5 universes of molecules? Because evolutionary selection has sufficiently constrained the exponentially large space through the construction history on this planet to allow Taxol to exist, and not necessarily all those other possibilities. The historical contingency at every step of building into the space of complex objects constrains the space of possibilities, and allows some things to exist and not others. Some things in that space are exponentially receding away from us and will never exist, because they’re too far away from us in the space of possibilities.

Chemistry is hard. I’m not trained as a chemist, so I don’t do a lot of chemistry. I like assembly theory because it’s more intuitive to me than standard chemistry. But for a lot of us, chemistry is not at all intuitive, and so we can think instead about Lego and improbable objects in Lego.

Probably most of us have played with Lego. There are rules in a Lego universe. You can stick blocks together only in certain configurations. I could stack two blocks on top of each other, but I couldn’t stick them together from the side unless I had super glue and I cheated the rules of the Lego universe. That would violate the laws of physics in that universe. Now, if I had this pile of Lego on a table and I started shaking it, we all have some sense that there’s a probability of a couple Lego sticking together, and maybe those objects would repeat, right? So maybe if I had a blue and a green one from here, I might see a few blue and green stuck together, but I think most of us might never expect to spontaneously form an object like this, particularly not with those Lego because they were the wrong colour.

So there’s a possibility space of what we can construct with Lego. It’s constrained by the rules of the Lego universe and what building blocks we have, and there are just some things that we expect to never spontaneously form. Current physics which say that Lego Hogwarts has a very low probability of forming. If I stood there shaking that table and we had enough patience and we could wait trillions of lifetimes of our universe into the future, perhaps we would observe this spontaneously fluctuate into existence. In assembly theory, we say “no, that’s impossible”. These kinds of objects never occur unless they’re actually constructed by a system that has set the constraints and evolved and selected the information for this particular object to exist. There is no such thing as spontaneous fluctuation of complex objects. They only emerge along lineages of information structuring matter and remembering the past structures to be able to build new structures.

So the design issue is solved. It’s not that design happens spontaneously for free, right? If you imagine a Lego castle can spontaneously fluctuate into existence anywhere in the universe - which is essentially the argument of Boltzmann brains right now in standard physics, that a brain can fluctuate into existence at any moment in space and time- that requires the design of every object to exist in every point in space and time. And assembly theory is saying “no, that’s not true”. The information has to be learned. The universe has to learn how to construct itself into these spaces of possible objects.

The likelihood of forming Hogwarts randomly in standard physics is very low in assembly theory: it’s zero, unless you have a constructed history and it becomes more and more probable the closer other objects are in the space of possibilities to Lego in terms of their own causal history and causal structure, in terms of their own construction history.

I will talk about the actual formal structure of this theory, but it’s important to keep in mind this idea that what we’re really trying to capture is that some material objects require information for their construction, and that information has to come from somewhere. It has to come from other objects. It doesn’t come from outside of our universe.

It’s important to define what we mean by an object. In standard physics, objects are defined as fundamental particles. Actually, I don’t remember ever reading in any physics textbook the definition of an object, which I find interesting just from philosophical and historical grounds. Usually, what we assume is the things that are indivisible are the fundamental structure of our universe.

As I alluded to before, when we’re talking about the structures we observe, we have to recognise that we’re an evolving boundary. The structures that we observe are defined by our technology, or the kind of perceptual apparatus that we happen to have as evolved structures at that point in time. So if there is something that we cannot resolve and substructure, it probably is an indication of a technological limitation, and not that we’ve actually realised the bottom of reality.

Atoms are a good example. Atoms, as you know, come from the Greek word for indivisible. At the end of the 1800s, when we elucidated the periodic table of the elements, we thought we found the fundamental structure of reality, and we called it atoms. Then we got to the 1900s and we realised they had substructure. They were formed of electrons, protons and neutrons. And then protons and neutrons are made of quarks. And string theory is, right? There is even further substructure. But we can't confirm that because we don't have the technology to resolve it. So the things that are "boundary" right now look like they are fundamental.

Assembly Theory, because it is a theory that's attempting to explain the emergence of things like us living structures, observers inside the universe it describes, treats as fundamental all the objects that are constructed and the things at the boundary are just the things at the boundary. So we're talking about all the things inside of our observational horizon, and how much evolution and construction in history was necessary to form that particular object within that horizon. We'll call things alive or part of the living world of physics, or life. You choose your terminology. If they crossed a threshold where it's impossible for those things to form by random chance, they require a deterministic construction history to be able to form.

These objects that live inside that boundary are therefore defined as compositionally constructed. They're made of some combinatorial arrangement of parts. In chemistry that's pretty easy. We have atoms in the periodic table so we can combine them to make different molecules. With Lego, we also understand that concept. We have a set of building blocks. We can combine them to make a seemingly infinite number of different structures. And we see some of them, we can't exhaust them all.

Hogwarts Castle has a high abundance on our planet because it's a pattern we all recognise. We can actually build that pattern again and again, because Lego sets come with instructions and we all recognise Hogwarts Castle because it's associated with a lot of other lineages of information in our biosphere, like the fact that castles exist in many cultures. And Harry Potter is a novel that many people have read, and magic is part of our cultural narrative. So we have particular structures that have evolved because of a confluence of events, but they're compositionally constructed out of all of those kinds of possibilities that have existed in the past.

Objects also have to exist in more than one copy. This is kind of a subtlety, but I think we take for granted the fact that we see reliable structures in our environment and we forget that we live in a world that is entirely constructed by life. So everything on this planet is essentially a regularity of life. The fact that things happen again and again with regularity, because there's actually a mechanism that was selected on our planet to generate that structure again, is a very telltale sign of living physics. If you have complex objects in abundance and they're similar structure things like us, many people sitting in a room, we're almost identical objects in a combinatorial space of things that could have been built. Humans are very similar to each other. We share most of our DNA in common.

That kind of regularity is a feature of living physics. You need to be able to have a process, a mechanism that was selected that can construct the same objects again with some error. They'll never be exactly the same, but they will be nearly the same, and they'll be the same for most of the temporal structure that they have. Most of the history is the same, and they actually have to be observed. You have to be able to observe the compositional construction process. You have to be able to disassemble things to learn the causation that can build them. And you have to actually be able to observe them in multiple copies. Things that we can recognise as life are complex objects that require a lot of time to construct them, and they exist in many copies.

How do we talk about that, embodying those ideas in a theory of physics that emerges at the scale of chemistry? We do this with molecular assembly theory, which is basically the same principles as Lego. I have a picture of a molecule built here on the slide, but I'm going to use Hogwarts as an example because I think it's more intuitive to us. If I smashed Hogwarts on the table -we went back to the elementary parts that make up Hogwarts- and I started constructing Hogwarts by sticking two pieces of blocks together, and then allowed myself to reuse parts I already made, I could build a pathway to getting to Hogwarts, right? There is actually an exponentially large number of pathways to build any complex object. There's a lot of them, but what we do in assembly theory is actually look at the minimal construction history. So what is the shortest pathway in that space? Actually, as objects become more complex, the shortest pathway also increases in size, and every step that you take in that shortest pathway represents an exponential increase in the size of possibilities that could have been constructed but weren't. So it's exponentially harder to construct deeper and deeper into this possibility space.

A molecule like ATP, which I'm showing on this screen, has an assembly index of 21. It's a molecule that's made by biology on Earth, but it exists in a huge combinatorial space of other possible molecules. In fact, for basic biomolecules that make up life like ATP or nuclear bases, if you wanted to construct the assembly space for them and iterate over all possible molecules on a planet such as ours, there would be so many variants of those molecules that if you wanted them all to exist on our planet at once, it would collapse into a black hole. So there is no possibility of exhausting that combinatorial space. As I said, it's too large, so selection has to start taking

effect to make choices over what things are constructed over others, and that selective mechanism allows something like ATP to be made reliably.

Other objects in our biosphere are also made reliably. So this is a light bulb. I think we all recognise this as a functional object our biosphere has generated. When Edison was going through the process of inventing the light bulb, he tried I think 100 different variants. There were obviously a lot of people trying to invent light bulbs at the time. Why is copy number important for recognising that this is an evolved selected structure? Well, we actually know because it has an evolved selective structure, has billions of light bulbs on our planet, and we don't have billions of the variants that didn't work, the ones that actually didn't become part of the constructed history. So the idea of copy number is critically important because we don't expect to find a light bulb on Mars. There's no process of evolution and learning that generates that from planetary geochemistry spontaneously, which requires 4 billion years of evolution.

One of the features that's very hard about building theories of physics is actually figuring out what kind of measurements to make. I think this is something that we take for granted. I certainly did. In my physics education, I was taught that things have mass, things have charge. And I believe that those are properties of particles and planets, while planets don't have charge, really, but they have mass. But we don't think about the fact that those are inventions of our theories. Those are the abstractions that we could measure, that we could then embed the concept that we measure with high regularity. So, with electrons, every time I go into the lab, I can measure an electric charge. And it has a reliability that I then associate with a feature of the world I call the electron. Because every time I go in the lab, that feature is reliably there. And so that becomes a good feature, a good measurable anchor to actually use to construct my theories of physics, because I know it's reliable. And then I can test my theories against that. That abstraction, very interestingly enough, becomes what we feel is physical.

Assembly theory is really interesting because it's the first complexity measure that actually provides something you can measure in the lab as far as how complex or how evolved a molecule is. So there are a lot of efforts to take a graph of a molecule like the one that's being constructed here and talk about its topology, or count the number of hybridised carbons or other features as a metric of complexity. But if you actually go in the lab and you take a spectra of a molecule, which you can do in mass spectrometry or you can do it in NMR, you can do an infrared spectrometry. You can measure the assembly index with high reliability. This process of measuring a minimal construction path is actually possible for molecules. We talk about this minimal construction history to make the molecule, but because we can measure it in the lab, it's a reliable measurement of the evolved complexity of that molecule. It now is a good abstraction to talk about as a physical attribute of the molecule. It's something physical we can measure in the lab. The amount of information, the amount of constraints our universe had to do to construct that particular molecule, is a physical feature of that molecule.

When we look at objects that our biosphere has generated, I want to make the argument that some objects cannot exist in the absence of a living process, cannot exist in the absence of living physics, and require a history for their formation. I say that there's a threshold; that threshold is actually measurable in terms of physical attributes of molecules.

We actually went and did this in a lab. It wasn't me, it was actually Lee Cronin in his lab at the University of Glasgow, and what they did was they took samples from biological and non-biological materials. They used the mass spec to infer the assembly index of those molecules, that minimal construction history, and they were able to demonstrate that there is a boundary. There is a complexity threshold in this combinatorial space. Remember that at every step the space is exponentially growing, so by the time you get just a few steps into the space, you're in this exponentially large space of possibilities. And you observe molecules with high abundance, which means there's a reliable mechanism for generating them. There's a history of objects constructing other objects standing behind that object, allowing it to exist. You can measure that in the lab. What we see is for biologic systems, they're the only objects that we have studied in the lab that have produced molecules above assembly index of approximately 15. So 15 steps into an exponentially growing space is already large enough that you require information, history, and a causal construction process to actually generate those objects. Selection had to happen in order for those objects to exist. And those objects are things like us, but they're also the molecules inside our body.

That's an empirically validated result. We have a lot more to do, but when I talk about the phase boundary of the origin of life, this idea that life is the only thing that can cross this physical boundary, what I think we're seeing in these experiments is actually evidence of that boundary, and that the origin of life happens in this combinatorial space as an abrupt transition, probably around 15 steps into the chemical space. We have other evidence to suggest why this is happening at this stage, but you can imagine a physical space now, just like we can talk about coordinate geometry and coordinate time in Einstein's theory of relativity, or we can talk about the wave function in quantum mechanics, right? We have all of these abstractions that we built. In assembly theory, to talk about the physics of life we have to talk

about the combinatorial space our universe can construct. And it's an exponentially growing space with every single step that you take to combine objects, there's an exponentially growing number of histories you could have constructed. And what life does is it chooses a trajectory in that space that becomes historically contingent, because it can only build more complex things based on the structure it's already built in the past. All of that structure maintains itself in recursively structured objects, so this idea of putting two Lego pieces together and then using a piece you already built means that the structure that you built initially is now a substructure of the thing that you built subsequently.

What happens in assembly theory is that the way that you actually build up the space is by recursively structuring objects based on the things that were created in the past. When you cross this boundary into life, every object is recursive, every object is deep in time, and it can't exhaust all possibilities.

I mentioned in the beginning about how large the space is. Actually, I've mentioned it many times. But thinking about Taxol again, I talked about the idea that Taxol actually carries with it a counterfactual space of this huge volume of chemical space that are Taxol-like molecules. They share the chemical formula with Taxol. Every object our universe constructs, but in particular our biosphere; these ones that are deep in time carry with it a counterfactual space of things the universe could have built. We use this sort of nested hierarchy of universes in assembly theory to talk about how big that space is.

So if I break my Legos down to fundamental building blocks, and I want to talk about all the possibilities that I could do sticking Lego together and I can violate the rules of the Lego universe, I can super glue them together if I want. That's the assembly universe. That's my space of imagined possibilities that I, as an intelligent agent, actually can extract from a Lego object. So if I saw a Hogwarts castle, I could infer the rules of that entire universe, or imagine that possibility space.

Assembly possible is actually conforming to the rules of that physical universe. In chemistry, molecules are made by making bonds, because our universe has certain energy considerations and ways that atoms can actually stick together and other ones are not possible. So that puts a huge amount of constraints on the number of possible objects to be actually physically realisable. There are imagined objects that could never exist, like square circles, right? They exist in the assembly universe, but they don't exist in the assembly possible; they're not possible as actual physical objects, they are only possible as virtual objects that the knowledge of exists in other objects.

Assembly contingent is an actual history that our universe can construct, or our biosphere can construct by recursively building objects up into this space. We happen to have evolved on one assembly contingent trajectory. Our biosphere has built some structures and not others, and we are completely causally constrained in terms of what things we can build on this planet by a past history. For example, transistors were invented and now we've made lots and lots of technologies based on transistors. Or LLMs have been invented, and LLMs are going to form the foundation of lots of technologies, and they exclude other possibilities from being things that are in our future horizon. That's a contingent trajectory. And that recursive stack of objects is continuing to build in there.

Assembly observed is the tiny, tiny, tiny, tiny piece of this entire universe that actually exists as physical objects we've observed. And we can infer the rest of this counterfactual structure because we can disassemble those fundamental objects, the ones that actually exist as physical objects, to reveal the structure of this larger possibility space that they exist in. All of that is rolled up recursively into those objects. It exists inside those objects as these recursive stacks. So the virtual is made physical through this recursive process.

So in terms of the structure of assembly spaces and how you build objects, and thinking about this sort of recursivity and how it builds into the structure of objects, I mentioned the assembly index. The assembly index is this minimal number of recursive joining steps or functional operations to construct an object. That's a complexity measure we use, the amount of evolutionary constraint necessary to construct that object. Copy number is evidence that that object actually was selected to exist. It really does exist. It has physicality to it because you can measure how many of those objects exist in your environment. When you're building up these spaces, it means that objects that evolve together have to be related to each other in time. So the set of graphs I'm showing here have some relationship deep in their evolutionary structure, because they were co-constructed.

Every object on our planet is part of the same construction process. We're all literally part of the same evolving structure. co-constructing together. And we are very deep in time. This is one of the reasons that as humans we can recognise each other, because we're fundamentally almost identical in time. We're just at the tip of this very large structure, generated of information patterning matter. And we're just this sort of bifurcating tips that are just recently different from each other in time.

The virtual being made physical is when things that are deep in this space become actual physical objects. For example, I can imagine things like rockets and over many generations of human thought they can become physical objects. So some

of the features of this assembly space, the ones that are deeply embedded in time, can actually become physical over time through this recursivity, as we're making more and more structures possible.

I mentioned that any theory of physics changes our notions of some very fundamental concepts. So my favourite concept to think about is time, because every theory of physics from Newton on has basically invented its own concept of time. Newton gave us mechanical time. The second law of thermodynamics gave us an arrow of time. Relativity gave us simultaneity as a concept in time. And assembly theory, I think, is giving us this idea that objects actually exist in time. They have a physical size in time; it's a physical attribute.

This also makes us reinvent some of the ways that we think about what matter is, because now I'm saying matter is informational. Matter has a size and time for evolved objects. And I feel vindicated in doing that because Roger Penrose, who is a very illustrious physicist, says he doesn't like the word materialist because it suggests we know what the material is. This again gets back to the idea that mass and charge, which we think of as material properties, are actually things that are correspondences between measurements we make and abstractions we can construct that describe regularities of those measurements.

I have to do my hair properly for this one. Sorry. Hang on a second. I've got to get my 80s hair on. All right. Madonna says, "I am a material girl, we're living in a material world", right? Social reality is real reality. It's not "fake reality". It's not an "emergent reality". It's the real reality we live in. It's just as physical as any other reality. And I think really recognising the materiality of information is critically important to understanding what life is and what life does and how life constructs that possibility space.

I want to go back to this idea of assembly theory as a theory of objects. We talked a little bit about the properties of objects: they need to be things that we can recognise as finite, distinguishable things. When we look at reality, we don't see a smear of all possible structures, right? We see a basketball and a soccer ball and not all possible balls in between. We don't see square circles, right? Not everything can exist as a finite, distinguishable object. Physical objects that we talk about in our environment are special.

They have to be breakable because they have to be things the universe actually can construct in a finite number of steps. If it took an infinity of steps or a to make something, it wouldn't actually be possible for our universe to construct it. It has to be discretely constructible.

Objects have to exist more than once. If you want to talk about something actually having existence, it needs to persist in the environment, and things cannot persist over time unless there's a selection mechanism that knows how to construct that object. So our universe knows how to make electrons, our universe knows how to make people. Those are reliable features of our universe. Some of those might go away at some point. All of them could go away at some point. But they need to exist more than once to say that selection has actually generated them.

Objects are lineages. In assembly theory, take really seriously this idea that the construction history is the object. And one of the reasons that I take that seriously is because that's the feature that we measure of evolution in the lab. We can measure the amount of evolution in a molecule in the lab by measuring how complex it is with an assembly index. So objects have a size in time. It's a measurable feature of a molecule. And objects form via selection. I think actually everything in our universe is formed via selection. Things exist or they don't. The mechanism of their existence is that the universe has to construct it, it has to learn how to build it. And that only happens over time, so time is actually a part of the generating mechanism.

In some sense we live in a physical reality, but it's also a virtual reality because every object that life builds is deep in time. That temporal structure is most of the physicality of that object. It's the reason that objects exist and objects encode their own laws. They tell you how they can be formed. That's what molecules do. You learn chemistry by breaking apart molecules and studying how they can be generated. The laws of physics don't exist outside of our universe. They exist in objects inside of our universe. So in assembly theory, you can make that very precise and very physical by talking about the informational material property of objects in terms of their assembly space.

This connects pretty nicely and pretty deeply to the concept of hyper-objects that Tim Morton has proposed, objects that are massively distributed in time and space relative to humans. Concepts like climate change are hard for us to wrap our heads around because it exists on a temporal scale that's much larger than we are. But actually I would argue that pretty much every evolved structure is much larger than what we can actually interact with and recognize, and that most of that size, for evolved structures like us, exists in time not in space.

So this gets back to the idea of why I think that Earth is huge in time. Why is it the largest object in our universe? Because it's the deepest object in time. It's the most recursively stacked object that we know of. So as a biosphere evolves, it gets deeper and deeper in time.

We have a sense of space. We can measure coordinate space, we can measure simultaneity. As I mentioned, this kind of time is very different from the one that occurs in other theories of physics. It's a construction time or a causal time or a functional time. It's about the amount of function necessary to construct the kind of objects that exist now, and all of that exists rolled up as a stack structure in the present. Because of that assembly space, I showed that you can unroll and look at the structure of a molecule that is actually stacked up in the molecule. It's a feature of the molecule that you can unroll by breaking the molecule apart, which we do when we do spectrometry. We look at the kind of construction history by breaking the molecule apart and looking at the structure of its bonds, as that molecule encodes that history. It has a size in time. So this is the picture of what life is. It doesn't have a fundamental unit, in the sense that a cell is decomposable. It's not the atom of life. Life is much more dynamic. It's actually about objects that encode their own dynamics. And so in some sense, a lot of the conjecture is that life is a process, not a thing; but it's actually both right? Because the process is encoded in the thing. Complex objects are evidence of life, they encode that history. They are that history. And they can only exist in these historically contingent, constrained spaces where they're coexisting with other objects that can construct them and mutually retain their existence. So in some sense, things are fighting to exist, and we are basically reinforcing each other's existence. As a biosphere and as a collection of objects that are co-evolving and co-constructing.

The important feature of assembly theory, the thing that it predicts about the universe, is that there is a threshold in any combinatorial space the universe builds. So not just chemistry but also things like language, or computer programs, or Lego blocks above which we shouldn't expect to ever observe an object in high abundance unless there was a selective mechanism to generate it. We can formalise the origin of life as a phase transition in these combinatorial spaces of what can exist.

The implication is that all of this exists within these historically contingent combinatorial spaces, and all of us are deep in time. So I love when I talk to my friend Michael Lockman, because when you ask him how old he is, he says he's 4 billion years old because some parts of us are literally that old. And actually, if you think about the patterns that we are, the patterns that keep imprinting themselves on atoms to reassemble things like us, that structure is 4 billion years old, and there are things in time that are also ahead of us. The things that we're constructing now, that are even bigger in time than we are. And this is one of the reasons that we're viscerally feeling at this moment in history a virtualization of our reality, because we're embedding more and more time in smaller volumes of space, building virtual realities all around us.

We already live in a land of abstractions, in terms of the languages that we use, the sensory perception that we have. We construct mental imagery of the external world. But the deeper in time we get, the more things have a larger structure in time than they have in space, and so the more virtual the world looks. When we get to an evolved structure like a technosphere, the technosphere right now is the largest object in time that we know of in the universe. It's the newest structure. It's recently evolved, but it's also the largest in time. And so it's building new ways of seeing the world. It's building new possibility spaces. And we're part of that structure. The things that we're imagining are part of this virtual to physical transition. As I mentioned, the idea of rockets. They don't exist as finite, distinguishable objects. They first emerge as ideas that we can share between us, and then we build physical artefacts and laws of physics and other things that allow construction of actual physical rockets. So this kind of counterfactual space, this space of possibilities, the assembly space that exists in every object, actually allows more structures to be built over time. Things that are deep in time are actually combinatorially large, and have a larger space of possibilities that they can build in the future. If you think about this idea of the assembly space defining the object, the object is its size in time, the combinatorial history that constructed it, that recursive stack. The deeper those stacks get, the larger the future horizon is of the things that can be constructed. And so when I say that Earth is the largest thing in time, it is the largest assembly space that we know of in the entire universe.

54:56

Virtualization

It is also because all of those combinatorial possibilities exist recursively stacked in objects that we have this huge virtual space that we're existing in. We can actually generate more structures. More possible things can exist here than anywhere else in the universe.

57:02

New Narratives: Life, Mind

These two phase transitions or horizons I talked about, about life and mind, evolve as part of this construction history on some planets like ours, on recursive worlds, that become deeper and deeper in time because of an evolutionary process happening on those planets, or at least one planet. We don't know if there are others like us. The first one is the emergence of a biosphere, which I think is a planetary scale transition. I don't think there's any sort of local pocket of life that emerges and spreads out. Life is a multi-scale phenomenon, it occurs at all scales on a planet. The natural boundary for life as a structure of information powering matter is the planetary scale. The planet transitions to allow tracing a trajectory in this high dimensional combinatorial space, constructing a space of possibilities. And eventually it gets so deep in time that it builds objects like us that are much larger in time than we are in space, and we're capable of abstracting and accessing a counterfactual space, evolving a technosphere. That technosphere has enough technology of

perception to try to reveal the structure of its own origin. And this is the point that we're at now. We're trying to solve the origin of life, and if we can do that, then we understand the life that we're creating and our technologies. We have an explanation for it. And this process can continue to cascade to build more complexity.

We have to change some of our notions about how we think fundamentally about the way that our universe works to really understand and to internalize what life is teaching us about the structure of reality. So in physics, we have a prevailing conception, as David Deutsch would say, and then we have new physics when we move into new territories of reality. We want to understand, and fundamentally life says some very different things than what the prevailing concepts in physics say.

Currently, we push all design in the universe, all information content to the initial condition. In Newtonian physics, which is all of physics pretty much because everything is built on Newton's paradigm of an initial condition and a dynamical law, if you want to design anything in your universe you have to put it in the initial condition. That's one of the reasons the simulation argument and intelligent design are also popular because they do the same thing. In assembly theory, and also just in life generally if assembly theory is the right theory, it's capturing this regularity. Design emerges along informational lineages. The reason that complex objects exist is because they're constructed by other objects. There is no pre-design. The system learns as it goes. Things are genuine. We live in a genuinely creative universe. The universe has to create structures like us. It has to invent them.

The fundamental objects in standard physics are indivisible, and in assembly theory the fundamental objects are everything that we can break apart because then we know the universe can construct those objects. In standard physics, the future is determined because the initial state is predefined and the law is predefined, so everything is determined in the future: the future has a size that's the same size as the past. In assembly theory, because the combinatorial space is getting deeper and deeper, the future horizon is also getting larger and larger. So the future is bigger than the past and actually time is a generating mechanism for that. In some sense, when I say time is getting larger and time is getting larger, it means larger objects like us can also fit inside the universe because the universe has to be deep in time to accommodate us.

The standard physics universe is deterministic. The universe is not deterministic. It's not entirely random either. It's undetermined, and structures like us actually build determinism into the universe. We are very regular structures because we're causally contingent historical lineages. Time does not exist in current physics. Time is fundamental to life. We actually are structures that exist in time. That's why it's hard to reconcile with standard physics. You cannot reduce us to our atoms because our atoms do not exist in the same temporal scale that we do.

In physics, we have a history of unification. So every major theory of physics breaks down to the unification of ideas that we understood pretty well in the past, and then we had to radically reshape when we realized that they were the same thing.

My favourite example is to think about terrestrial and celestial motion. We've been seeing the planets move across the heavens as long as we've had eyes, and a cognitive infrastructure inside our head that allows us to see the patterns in our night sky. But we didn't understand that the regularity that governs that motion is the same reason that we're stuck on this planet. It took major abstractions and conceptual leaps and many generations of evolving technology before we could take the measurements of balls rolling down along inclined planes and measure seconds on mechanical clocks, and be able to extract a regularity that we associate with the laws of motion and the laws of gravitation. And I think we've been coming for a long time on the idea that computation might be somewhat fundamental to what life is, and we understand that we live in a material world. But to recognize those two things as the same thing, and understand a deeper structure that unifies both, is critical to solving the origin of life. Really understanding information as material and the assembly space gives a framework for doing that in a really physical way.

1:01:59 Time Reproducing

Right now we're emerging a technosphere, and it's the largest object in our universe. Everything else in the universe pales in comparison to the size of this thing in time. And it is somewhat paradoxical that this is the newest thing and the largest, oldest thing in time. But this is the structure our planet is generating. The question I'm asking right now that I'm deeply interested in is: if we're large enough in time to recognize our own origins, can we see that horizon that we can actually close off, and see how this whole process -this whole cascade- originated in the first place? Did we get big enough in time to have the technologies of perception to see our own origins?

If we do that, one of the reasons I think this origin of life and coming to understand this regularity is so critically important at this stage is if a technosphere is really a living structure, and is the next phase of evolution happening on our planet, eventually it will reproduce. Having an understanding of the origin of that process is a critical part of the transition of a planet reproducing itself. And so life will cascade to not only be "cells reproducing themselves" or "a copy number of humans existing on this planet" or many copies of the same technologies, but many copies of our biosphere in the future. We have to understand those regularities and build those technologies to be able to do that.