Hello, everyone. Welcome to our first Q&A about History of Science and Technology for 2026.
I see a bunch of questions saved up here.
I see one from Gary.
How would you rank 2025 in the history of science and technology? Would you say the last decade has been important, or just a small mention in the grand scheme of things?
That's harder to answer than one might think.
This year, drama.
Not so much.
That immediately comes to mind.
lost decade.
I'd like to think some of the things that I've been doing, are actually fairly significant in the overall arc of the history of science.
I think…
that the other big thing was the chat GPT surprise, and kind of the, the arrival of, kind of, certain… the sort of the next step in AI that works type thing. I think that the implications of that
For both… well, it's sort of interesting to go back and look at computation in general.
Because…
The first big effect of computation in general, starting when computers were introduced in the 1950s and got progressively more widely used into the 1980s with personal computers and so on, and then essentially ubiquitous computing in the 1990s and beyond.
The first sort of effect on, for example, science from that was
Just, you can use computers to do things.
I think the second effect that I guess I was much involved in starting in the 1980s is the concept of computation, using the idea of defining rules and seeing what they do.
Using that concept as a way to think about, sort of, the foundations of science itself.
And that's a thing that has been sort of gaining in importance, over the past few decades, and it's something where not only computers as practical things, but also computers as conceptual things.
That's been a very important thing, and there's more to run on that.
In many ways. I think it's the same story with AI and LLMs and so on. There's, oh, you can use an LLM to, you know, summarize this document or something like this. That's one sort of implication of
of LLMs and so on. The other implication is a conceptual one. If you say, well, what's really going on in brains? You know, can we tell if there has to be some new physics that makes thinking work in the brain? Well, we can kind of see that that probably isn't the case, because we know we can reproduce an awful lot
just by using things like LLMs. So I think… and I think there's a lot of, kind of, conceptual mileage
that is probably still to come from the success of LLMs in, kind of, replicating some aspects of, kind of, human thinking. We don't… we're not… you know, humans still do different things, and will always, because the only thing that's going to do exactly the same as a human does is a human.
Not, you know, a box on your desk or a thing in a cloud, you know, in the cloud or whatever else.
But I think the,

the question of… there's sort of more conceptual mileage to come from, I think, from sort of the surprise of the fact that, yes, you can get artificial neural nets to do all these things that we thought were human-only type activities.

you know, I would say in the overall arc of what's happening in science.

If we look at, kind of, the last century, let's say, the… I would say the beginning

Well, let's go back a couple of… go back several centuries. Let's talk about the bigger arc of the history of science. First question is, well, what is science?

You know, I see science as being mostly about taking what happens in the world and finding a way to make a human narrative that explains or lets one understand what happens in the world.

you see some planet going around the sun, or whatever. You just say, well, it does what it does, or you can say, I've got a story about why it does what it does. There's this force of gravity, and it's an inverse square law, and I can solve these equations, and all those kinds of things. Science is about finding

These ways to take what exists in the natural world and describe it in human terms.

Another aspect of science, which sort of somewhat connects to technology, is, well, what do we actually notice in the natural world? You know, without telescopes, we didn't notice a lot in astronomy. Without microscopes, we didn't notice a lot in biology.

Without, other kinds of, sort of, tools for noticing things, where we don't… there's less grist, there's less that we want to talk about scientifically, so to speak.

But the actual content of science ends up being typically this… this… is there a narrative that we can give from what we can see? Now, you know, even the what we can see question has advanced in interesting ways over the years. I mean, basically.

It's,

Well, let's talk about the, sort of, the general arc of these things. I mean, so, first thing is, in antiquity.

was the time when people started making lists of things. People started trying to systematize things. You know, Aristotle was making his lists of sea creatures and forms of argument.

And other people were making, you know, in Babylonian times, people were making lists of types of words, or, you know, gods for this or that, or stars, or things like this. People were sort of trying to systematize things by making lists of things.

people were also trying to introduce things like units of measure. You know, how many of these things do we have? How much of this do we have?

It was… first there's numbers, you know, you can count sheep or whatever, then there's how much gold do we have here? Well, it depends on how much it weighs, we have to have a uniform unit of measure. So, those are things which sort of start to systematize kind of describing the world.

I think at some point in the middle of that, the notion which already existed in things like Aristotle and others of, you know, species of critter. Oh, there's this kind of bird and that kind of bird, rather than just, like, we can sort of distinguish things in the world by those different categories.

Well, so, what became of science at that time?

a lot of science at that time was really mostly talking about, sort of, the structure of things. What are things made of?

those kinds of questions. It wasn't a lot of, there wasn't a lot where you could say, kind of, this is a small scientific theory, this is a small-to-describe theory, and then there's all this stuff you can deduce by going many, many steps in the theory. It was mostly pretty at the surface. It's like.

This thing does this, and that's what you know about what it does.

Now, so, you know, that was the thing that existed basically until the 1600s.

In the 1600s, well, several things happened. The I would say that… Kind of a…

One thing was mathematics had developed

further. So, I mean, the history of that was… And…

the Babylonians were the one… people we know who introduced a lot of, kind of, mathematical ideas,

And then in Greek times, kind of the notion of proofs and things like this came in. I would say that the question of… it was… it was really much more

you can work out things with numbers. Numbers were a thing that were understood. You could work out things with numbers. Then, from people like Euclid and so on, it's… we can have geometrical figures, and we can do things where we can deduce things about geometrical figures. The big advance that happened in the 1400s to 1500s was, well, was the introduction of algebra, the idea of being able to talk more abstractly about things like numbers.

not just, say, the particular number 75, but the thing that we call X that can represent any number.

Now, many of the same kinds of underlying concepts had already existed in antiquity. People like Archimedes and,

Diophantus and so on, had things that were tantamount to sort of filling in variables, but they didn't think of them that way. They didn't have a notation for describing, for setting up algebra, and so on. I think it didn't help.

That, in those days,

letters were used to represent numbers, whether it's the Roman numeral system, or whether it's the Greek numeral system, where you're actually using alpha for 1, beta for 2, things like this. And that meant that introducing another thing that was kind of a letter that stands for a number, but numbers already represented in terms of letters. It's very confusing. I think it took the introduction of Hindu-Arabic numerals

which happened in the West around 1200, to sort of have a thing where you could very obviously distinguish numbers as you wrote them down explicitly from a thing that stands for a number, but isn't itself a number.

Now, confusingly enough, some of that concept had already come in, even with Euclid. Euclid had, figures where there was represented a geometrical figure, and you would label an angle, and the angle could be labeled with a Greek letter.

and they were labeling angles with letters, even though those letters also stood for actual numbers, which weren't the numbers that were the actual angles of those… of those… in those geometrical figures. In any case, the end result of all this is 1400s to beginning of the 1500s, kind of the introduction of algebra, and the more… the sort of the development of mathematics where you could actually work out a lot more with the math than you had been able to before. You could go many more steps in doing the math.

Well, then…

In the 1600s, sort of, one of the big ideas was the kind of merger of that kind of more sophisticated math

with,

the things that you could actually, study in the physical world. So, for example, Galileo, introduced some kind of mathematical ideas, like, you know, you drop an object, and it falls, and it's, the distance it goes, goes up quadratically with the time that it's taken, and so on.

And, so that idea that you could kind of have a mathematical formula that represents something in the physical world, that was a kind of a thing that was coming in in the beginning of the 1600s with Galileo.

Then, sort of, the big advance in the late 1600s with Newton and so on, was the introduction of calculus, and the idea that you could be much more sophisticated in introducing math into, kind of, the description of the natural world. And that worked well for the motion of planets and things like this. It worked well for mechanics. It didn't work at all well for things like biology. Didn't work well for some more complex physical processes and so on.

Now, interestingly enough, in the 1600s, two other advances happened that also moved science forward. One of them was the telescope, the other was the microscope. So a telescope around 1608, was, let one kind of explore the richness of the astronomical world, or begin to, at least.

In a way that hadn't been possible before, and then the microscope let one start looking at biology, and looking at… I think the most important things that people put under microscopes were things like biological cells, and that was Van Leeuwenhoek and Robert Hooke and so on.

Starting to, examine what

These very complicated things that are, you know, the construction of biological organisms of life.

What… to tell something about what's going on there.

So…

Sort of in the 1600s, these three advances of mathematics as a formalization of science, and then the what's out there from telescopes and microscopes.

I would say that the telescope side of things, the mathematization, the formalization of celestial mechanics, was vastly more successful than any kind of formalization of things you could see under a microscope.

Later on, and actually also in the 1600s, work on crystallography, one place where you really can kind of apply math easily to microscopic things. You have crystals which have definite geometrical structure and so on. And that was another thing, I think, from about that time.

So…

you know, if we then look at, so, big, sort of, explosion of things that became possible in the 1600s in science. The 1700s.

A lot more, kind of, development of the mathematical side of things, a lot more understanding things like partial differential equations coming in, representing fluids and solid mechanics, things like this.

And…

Then, I would say in the 1800s, kind of, the… a couple of things going on. One thing was the attempt to quantify more kinds of things in the world.

The attempt to sort of put numbers on things, including things in biology, including things in sociology, not very successfully, including things in economics and so on.

That there were kind of the quantification of more kinds of things, was something that was definitely happening in the 1600s, and by that point.

kind of a certain level of mathematical sophistication, enough to do, sort of, most of classical physics had, or what could be done with traditional mathematics and classical physics, so the raw material existed in the 1800s to do that.

But I would say that the next kind of really big breakthrough period was,

The late 1800s, and the introduction of, kind of, much a higher level of formalization of things, a higher level of abstraction of things. I mean, in biology, there had been, 1859, you know, Darwin's Origin of Species.

That was kind of a zoom out and look at the big picture of biology in a more abstract way, and the notion that, oh, there are all these different species, but, you know, maybe there's something in common that we can say about all these species, and hence natural selection and so on.

Late 1800s, it's really a thing that, in both physics, and particularly in mathematics.

this notion of, let's formalize things. Let's try to have something, for example, in mathematics, let's try to understand, we've got the particulars of mathematics, you know, geometry, algebra, things like this, just as we have the particulars of mammals and birds.

But what's the zoomed-out version of what mathematics is like?

And that led to things like Hilbert's program, and this kind of notion of saying, let's just have sort of formal rules that describe what's going on underneath mathematics, and use that as the kind of thing that we situate mathematics on.

Somewhat the same kind of thing with physics, but then, sort of, the big successes of physics at the beginning of the 1900s, some of them were the result of experimental advances, some of them were,

some of them were kind of conceptual, kinds of, kinds of advances. I think that, were the three big things that came in in, well, eventually in the 20th century, statistical mechanics, relativity, and quantum mechanics.

Statistical mechanics had been sort of initiated in the mid-1800s, and it was kind of the idea of, don't just try and describe everything that's going on, just say, in the aggregate, sort of zoomed out.

what happens with all those gas molecules? Don't try and trace each gas molecule, just say, what can you say about all the gas molecules together? And that led to things like the second law of thermodynamics, and so on. And that was kind of an idea different from the ideas that had been had

in kind of the Galileo-Newton tradition of mathematical science, of just, let's figure out exactly what's going to happen to everything. This was, let's look at a whole bunch of things and statistically say what happens in the aggregate.

And I think then, I would say, in,

Both relativity and quantum mechanics were, in a sense, the greater formalization of physics. Whether it's in relativity, being able to just sort of talk about coordinates in a more abstract way, whether in quantum mechanics it's kind of talking about the states of things in a more abstract way.

Both of those advances actually had another piece to them, which was the question of Well… just what are you trying to compute in physics? Are you trying to compute something that is absolutely there, or are you trying to compute something that is relevant for what we observe to be there?

And both relativity and quantum mechanics began to bring in this idea of the observer as being something that you had to sort of account for in the science of things.

Well, the other big advance around that time was in chemistry.

And sort of the systematization of chemistry in the 1800s, whether it's the periodic table, whether it's the notion of chemical reactions, being able to identify definite elements and know what was sort of involved in chemical compounds, what was happening in chemical reactions, that was kind of a thing in the 1800s.

Where, at first, it was kind of a… a… almost a… a kind of a numerological kind of thing. Oh, we need this amount of hydrogen versus that amount of oxygen, and so on. But then, increasingly, that sort of got formalized.
And eventually it got physicalized, so to speak, of actually understanding what were these molecules and chemical elements and all that kind of thing. But chemistry got a long way without really understanding the physicalization of that and, you know, exactly what the structures and molecules were, and so on.
And so, just a huge amount of data accumulated in chemistry, and by the late 1800s, the chemical industry and lots of kinds of the work, the development of kind of, you know, actually being able to make chemicals
that, and compounds that were not naturally occurring, or make them in much larger numbers than they occurred in nature. That was a thing of the late 1800s, early 1900s. That was sort of a huge, a huge direction in science was to catalog all that stuff.
I mean, by the way, in the 1700s and 1800s, another kind of big form of cataloging that was going on was in biology, of natural history, and just, like, what are all the critters of the Earth? I suppose that had followed on from the kind of geographical efforts to kind of catalog, well, what's… what's… what is there on the Earth? Make maps of everything.
And so on. So this kind of… the natural history cataloguing of critters, the chemistry and chemical industry, kind of cataloging of different kinds of chemical compounds and so on, that was a thing from the… from the 1800s and such like.
Now.
the next sort of big thing that happened, I suppose, was the merger of chemistry and biology, and the kind of realization that
You could think about biology in chemical terms, even though the actual kinds of molecules that were involved might be different from the kinds of molecules that one had studied in conical reactions and so on.
But, by…
you know, there had been sort of numerological kinds of things discovered, like Mendel's laws for genetics. That started to become more quantitative and started to become more, more kind of chemical by the 1930s, even. But then…
By 1950, 1953, the realization of the structure of DNA, was kind of the big moment when, kind of, one could start having more, kind of, theoretical underpinnings for biology, more, kind of, much more that one could say about the mechanisms of biology.
And that, kind of, from that time on, developed molecular biology, and that has led to… in molecular biology, there have been a long series of major advances. As we understand more about this very complicated molecular computing thing that is life.
And, is what we're all running on, so to speak.
And it's been interesting that in the field of biology, there have been, if anything, sort of the… a series of… of kind of, oh, we now understand
you know, these different aspects of organelles. We now understand these different kinds of signaling pathways. We now understand this different kind of molecular mechanism, and so on. We now understand, you know, how the immune system works, things like this, or begin to, at least.
And there's been a lot to discover there. It's a… it's a kind of a long series of… you look at more stuff, and there's just more and more and more things. There's… there's an infinite

It's kind of a place where, in the history of biological evolution, just a lot of detail has been accumulated, and in progress in biology has been sort of uncovering more and more levels of that detail.

I have to say that my own efforts in recent times to understand sort of the theoretical foundations of biology kind of tell one that what biology has given us is it's harnessed certain irreducible lumps of computation, stuck them together, and made things that let us operate in the world as we do.

And if we start to get very, very obsessed with, well, why does it work this way rather than that way? There's really no answer to that. It's because

the particular history of biological evolution picked up this lump of irreducible computation and not another one. And so, one can fill textbooks talking about, kind of, the details of biology, and obviously they're very important to us for biomedicine and so on.

But they won't have the same kind of arc of principled character that one might expect in other areas. I mean, in a sense, you know, the biology textbook is a little bit like a history textbook. It's telling one, kind of, what happened to happen, so to speak.

And it's a little bit more than a history textbook, because it's kind of what happened to happen and turned out to work, in the sense that it produced a fit organism that, can be like us now, so to speak.

But I think the, so, you know, a lot of things happened in biology. Now, in physics, I would say that the overall

Kind of concepts, statistical mechanics, relativity, quantum mechanics, those were set at the beginning of the 20th century.

And the story of the 20th century has been a story of kind of using those frameworks, and then just finding more stuff that fits into those frameworks. So, big advances in the 1950s and 1960s, actually starting in the 1930s, in particle physics.

Kind of the, in a sense, ultimate reductionist approach of saying, what's everything made of? well, you know, kind of by the… in the early decades of the 20th century, where we'd learned, you know, there are electrons, that's 1897, I think, and then it's kind of, okay, there are atomic nuclei, then there are protons, there are neutrons. By the 1920s, by 1930s, that was known, and then there started to be these other particles, the muon, the pion.

And then this whole zoo of other particles. By the end of the 1950s, there were, scores of particles known that had been produced in particle accelerators. And, the… and then…

Then it was realized, well, actually, there's another level of particles, there are quarks, and so on. That was realized, then it was realized that, sort of, there are certain features of particle interactions, gauge theories, and so on, and sort of things started to fit more together there, and eventually we ended up with things like the standard model of particle physics.

That sort of emerged by,

by basically the 19… well, by the end of the 1970s, pretty much all those pieces were in place. And, but then…

You know, for example, my own personal history, you know, I worked on particle physics in the late 1970s, when it was having a very strong period as the mathematical methods from quantum field theory became applicable to study all sorts of things with particles.

But I have to say, it is somewhat shocking to me that even though there was quite a lot of advance in those times, the amount of advance in particle physics since then has been very incremental. I mean, a lot of details have been filled in, but the big picture things one new at that time are still the big picture things in particle physics.

At that time, also, I was involved in this, actually, there was sort of the effort to connect particle physics, with what happened in the early universe and with cosmology. There's actually been more experimental development in cosmology, to some extent astrophysics, but particularly cosmology, over the last few decades, mostly as a result of better instrumentation.

I wouldn't say the theories have really advanced much.

It's more been, we've got bigger telescopes, we've got better image processing and better data handling and so on, so we can learn more about, sort of, how things work out there in the 100 billion galaxies that exist in our universe, and so on.

But I think, kind of, Conceptually, not, you know, the advances in physics.

You know, the big advances happened at the beginning of the century.

And in biology, again, sort of the big advances were, in the last century, had to do with sort of the development of molecular biology, and the notion that there were kind of digital things going on, and that there were kind of pathways and networks you could draw, and all those kinds of things. That's something which kind of had emerged by the 1960s and continued to develop.

You know, lots and lots of detail being discovered.

I would say that a field like chemistry, for example, again, you know, this is a continuing story of science, is there are periods of rapid growth, usually the result of new methodologies, and then the long periods of incremental growth. Chemistry, for example, is a field which

For much of the 20th cent… well, much of the latter half of the 20th century was in kind of incremental growth.

I mean, things like material science, which…

which particularly concerned properties of solids, which chemistry hadn't been very big on. I mean, chemistry is like, you put the things in a test tube, usually in liquid form, and you see what they do. Material science much more concentrating, and material science sort of emerging in the 1970s to 80s to 90s.

much more concentrating on solids and the properties of solids and so on, and that's, that's a thing that, sort of, has continued to advance there. But I think the,

these different fields, you know, they… they get to a point, then they kind of plateau for a while.

I mean, the same thing happens in computer science, for example. I mean, computer science, a funny kind of science, because it's not really the same kind of natural science-y type science as a lot of these other kinds of things.

But it, it kind of emerged

Kind of in the 1960s to 1970s.

And there was a certain amount that could be said about, kind of, the general things you can say about algorithms and so on, the general kinds of data structures you can consider. There was a certain amount that was rapidly said, and then there's just a huge amount of engineering detail that becomes technology that gets built on that.

And… but in any case, this… the question had to do with the last decade, and I would say that… that, the, and I was talking about my own efforts

I think the thing that we've been able to do in the last… well, it's been…

I don't know, and… well, the sort of…

starting in the 1980s, for me, one thing was

Use programs as models of the natural world.

This is an important idea. It's an idea that kind of silently has sort of taken over a lot of areas of science.

It's an idea that, yes, the mathematical equations idea from the 1600s got a long way, but just saying, write down rules and see what their consequences are, that's a thing from the 1980s, basically, and a lot, sort of,
a lot associated with my efforts, and that's something which has become kind of a general way to make models of things. It's kind of a general way of talking about the natural world. It's not in terms of, this is the equation that this thing follows, but this is the rule this thing follows.
And the thing that is sort of the thing one might have said, you know, back in a lot of biology, even from a long time ago, is like, well, this increases, that decreases, it's kind of very structural statements about what goes on.
The point of studying, of defining rules and then working out their consequences, their long consequences, that's a rather different kind of thing. That's something where the underlying description is this kind of very structural description, but then there's a sort of a big lever that is, and, okay, you've got the rule now, now let's work out what happens from that rule.
Much like in mathematics, one might start off from some equation or something like this, and then there's a lot to work out about what the implications of that equation are and how it gets solved in particular cases. But I think the main thing that we're seeing
In recent times, Is, kind of, the… the arrival of, kind of.
rules and computation as a foundation for models of things. And then the question is, well, what is the bigger science that you can build around
kind of rules on what they do. Just like the biggest science you can build around equations and what they do is basically pure mathematics. So what is the science you can build around, sort of, rules and what they do?
I've been referring to that in recent years as ruliology, the study of abstract rules and what they do.
And there's kind of a sort of a big picture of kind of what you can say when you take a computational view of the world. There's both how you actually connect that computational view of the world to natural science, and there's the kind of underlying stuff of what do these rules in and of themselves, the pure mathematics, so to speak, what do they do? I mean, in the mathematical approach to science, there's kind of the pure mathematics, which is thinking about math for its own sake, and then there's the kind of applications of that, of actually setting up the equations of mathematical physics, or whatever else.
I think the thing that is, to me, rather exciting in recent times has been that we understand a lot more about, kind of, rules for their own sake and what they do, phenomena like computational irreducibility and so on, and we can now take that, just as we could take pure mathematics.
And feed its consequences into science, as happened from the beginning of the, from the 1400s and 1500s and the development of algebra.
to the sort of, and then later the development of calculus, but feeding that into the connections to natural science in the late 1600s, going into the 1700s, we're now able to do that with these ideas about computation.
And I guess the other… and that, I think, unlocks kind of the next level of progress in a lot of these fields of science. In physics, in biology, in mathematics itself.
kind of understanding, kind of, this lower-level structure of this kind of ruralogical structure that exists in all these fields, and kind of lets one make further progress in those fields. And I think it's sort of been exciting the last 5 years or so. We seem to have unlocked that sort of direction of progress.

The other thing that's emerged in that period of time is the increasing importance of the observer in defining, kind of, what happens, what we actually see. There is this kind of… this ocean of formalization, but the question is, in that ocean of formalization, where are the islands that we actually live on?
And you can say some things about that ocean of formalization, but they don't relate that well to the things that we actually perceive as observers of the world.
And I think the realization that that's a thing you have to kind of bring in is an important realization, and it's something that it's become, in the last few years, the realization that you can kind of derive the laws of physics.
from observers like us, and their relationship to the Rulliad, and computational irreducibility, and so on. So I think
And to me, I mean, maybe it's just, you know, it's a… it's a self-centered statement at some level, because I've been in the middle of doing this, but I think it's really pretty exciting.
What we've been able to do with both the sort of using the computational paradigm in science, and now with the specifics of thinking in terms of ruliology, in terms of observers, and so on.
to actually make progress in having a different conceptual framework for thinking about these areas of science. You know, when it comes to science versus technology and so on, the thing I would say that, from a technological point of view.
Of course, the, well, the two big things, I would say, that are sort of the great things of the last half century or so are computers and precision manufacturing. I mean, I think that, in,
I suppose in another important direction in, for us.
is things like pharmaceuticals and so on, and, sort of molecular scale manufacturing things that are… do things at a molecular scale, so to speak. I mean, it's kind of always…
When you see a piece of technology, and you're looking at, some piece of electronics, well, you usually can't see what's going on because it's inside a microprocessor these days, but some kinds of technology, you know, you look at a rocket engine, there's lots of complicated things obviously happening there. You look at something in a biology or chemistry lab that's just, you know, a vial of transparent liquid.
But all the technology is the details of the molecules that exist in that liquid.
So, but I think the things that, you know, computers
are sort of the core of so much technology. Precision manufacturing is a key thing as well, allowing us to make all kinds of devices and sensors and actuators and so on
That, that make use of physics, basically, but we can actually successfully make use of that physics, because we have the ability to manufacture things precisely enough
That it's just physics that governs it, rather than, oh, it's because the thing didn't fit together properly.
And I think that,
from a technological point of view, kind of the existence of computers as, you know, the making computers ubiquitous has obviously been crucial. I think in recent times, kind of the… kind of the methodology of
Of making, of making… well, okay, so the other big thing that's happened that people didn't expect…
was the building of layers and layers of technology in computing. I mean, a lot of kinds of technology, you build the thing, and it… what you make, you make a wheel, and you made the wheel, and then the wheel, you know, does its thing.

But in… in the computer area, you make one level of technology down there at the machine code.
You make the next level of technology, the low-level operating system, the next level, the graphical user interface, the next level, you know, the applications, and so on. It builds in many layers, so the thing is, in the end, very complicated. It's different from biology.
In the sense that while biology does have that kind of hierarchical structure, the kind of interfaces between those structures, I think, are…
Well, in computation, I would say that there's a… you can kind of tell the difference between something that was engineered incrementally by humans and something that evolved through natural selection in biology. The thing
that was engineered by humans has many more modular pieces, typically. It's something where the sort of construction pieces that fit together in a… in a kind of… you can… you can take all the pieces apart.
Whereas in biology, it's… if you start taking the pieces apart, the system won't work anymore. It came as a big lump. It came as a big sort of lump of computational irreducibility. Maybe that lump just made one organ, and you've got many organs to make, or whatever, but it's still… it didn't… wasn't factorable in the kind of way that traditional engineering tends to be factorable.
And so, sort of, one of the big things in computation has been the building of more and more layers of, sort of, computational ability there. I mean, my own efforts of building computational language, Wolfram language, and so on.
Have to do with putting in the right primitives to make those computational layers relate to the kinds of things we think about, so that we have, kind of, just as we have, sort of, the technology of human natural language as a way to communicate, we have the technology of computational language as a way to, sort of, take our ideas and make them computational, and also communicate
With actual computers to execute those things.
But I think the… just as there's sort of this difference between the engineered program and the natural biological, natural selection created,
kind of structure, so too, in modern AI and machine learning and so on. Those are programs that were just evolved, basically, like… very much like the ones in biology. In fact, I think there are very close analogies between what happens in machine learning and what happens in biology. It's, I think.
in… and it's the same kind of thing. It's these sort of lumps of irreducible computation that get stuck together, not very explainably.
but nevertheless, can achieve certain kinds of tasks, which turn out to be useful tasks. And I think that's a, that's kind of, as I mentioned, that's sort of a new thing, having that really work.
we don't understand it scientifically very well. We don't understand biology at a theoretical level very well, something I've been working on quite a bit recently, trying to understand how all those components that were sort of found by natural selection and stuffed together in these kind of lumps of irreducible computation
What can you say about all those components, and what can you say in the big picture about, kind of, the nature of living matter and so on? What can you say about, sort of, the bulk orchestration of these molecular processes?
To lead to the thing we call life.

And I think we are able to say some things about that. It's something I've been working on very recently, that we're able to make conclusions just from kind of the overall story of there's an organism, and it's subject to natural selection that determines, you know, that selects out fitness.
all the way down to the rules that are being picked out of the set of all possible rules are certain particular rules. It's an interesting question that I literally started thinking about a couple of days ago.
about the extent to which that same set of ideas can be used in machine learning, the extent to which things like the notion of rural ensembles that we introduced a few months ago, a couple months ago, can be used to think about things in machine learning. But those are kind of future directions for things. I think that's,
the, so, you know, the epochs of development of science, I think if we look at the formalization of science, we had kind of the structural period, where it's just like, this is the structure of how things are made, and some areas of science, that's all you can do even today.
Then there's the kind of mathematical period of the development of science from the 1600s.
Then I would say the computational period, starting in the 1980s, and then most recently, kind of with all of this understanding of the relationship of observers
And the whole story of multi-computation, of different threads of history, and so on, and how those are aggregated by observers.
that's kind of… that's the most recent story, starting, I would say, in the last 5 years or so, of sort of a paradigm for thinking about science. And it's got… there's a lot that can be done with that. That's got a long way to go.
And I think that's the… to me, that's the exciting thing that's happening today. It's kind of a new framework for thinking about science, and that new framework for thinking about science will no doubt lead to new developments in technology. We can already see that's happened to some extent as we go forward.
Anyway, long answer to that.
Let's see…
Junior comments.
But there's a video from 1966 of Edward Teller discussing John von Neumann and what might be termed computational thinking. Do I know of earlier examples?
Well, I don't know of that video. I'd actually like to know what it is. I'd be interested to see it. I never met Edward Teller. I could easily have met him, but I never did.
Unfortunately.
And John von Neumann died before I was born.
There were… Well… There were examples of, kind of, using computers
to think fairly conceptually about science. For example, in the 1950s, Enrico Fermi did a bunch of experiments on thinking about, kind of, how… how solids might work when they're heated up.
and thinking about, kind of, an array of weights and springs, and doing computer experiments on what happens to arrays of weights and springs. That became called the Fermi-Pasteur-Ulaim experiment.
And, the,
that was kind of a computational, kind of almost meta-model of the natural world. It wasn't intended to be a sort of an actual model of what happened in the world, it was kind of a meta model of sort of the kind of thing that happens in the world, so to speak.
I think, let me think about that. The, I mean…

The idea that you would use computers
to make models of things, the vast majority of that modeling was, we've got an equation, we want the computer to solve the equation. A lot of early computers were used for ballistics computations, where the idea is you've got Newton's laws, and you're trying to solve those… the equations from the equations of motion from that.
to work out what happens, not really thinking about things in purely computational terms. I would say that,
the idea of kind of thinking about the world in computational terms, I would say a pretty good piece of that goes back to Ada Lovelace in the 1830s, 1840s,
Because… you know, Ada… Had understood this idea that once you had, kind of, this
this universal machine, this analytical engine, as they called it in those days, that it could be used to sort of weave algebraical patterns, as she put it, of all kinds of things. It could be used to, sort of.
think about music computationally, or what we would now say computationally. It could be used to study the motion of planets computationally.
to, to do all sorts of things computationally. So I would say probably the… the kind of the clearest sort of early,
introduction of that… that idea, probably, is… is Ada Lovelace. I think there were precursors to that. I mean, there were, sort of, in some sense, logic
is a little bit like computation, and the idea of kind of using logic as a way to systematize things, and maybe to make deductions from things. Leibniz thought about that, Buhl thought about that. I would say that,
that… sort of a junior version of this, but I don't think that got all the way. I think… I think the… sort of the big… the big point is
that you can take things in the world, and how do you represent them? You can talk about them with words, some of them you can describe mathematically.
kind of the idea is, what can you describe computationally? And Ada had very clearly, and not very much text even, had very clearly enunciated the idea you can reduce lots of things to something you could run on the analytical engine. And that's kind of, I think, the key idea there.
Let's see…
Let's see, a question from Sand here. Would you say theory summarizes experimental results? How useful compared to theory would it be instead of teaching theory in schools, focus on understanding experimental results and applying them, what is the history of this approach, and how useful might it be?
Well… You know, the relationship between theory and experiment in science is complicated. There are fields of science that are mostly experiment and not much theory. There are fields of science that are mostly theory and not much experiment.
So, for example, the life sciences, it's mostly experiment. I mean, oodles and oodles of data, and not much in the way of overarching theory. We're trying to change that, but that has been the status quo in biology.
In an area like…
Computer science, let's say, it's mostly theory, insofar as it's got science there. It's not experiment, it's not what happens when you run these programs, it's, let's work out some feature of these programs. Are they polynomial time or not, or things like this.
I think the,

And, of course, mathematics, which is arguably not quite aligned with science, but mathematics is all theory, not much experiment. You can do experimental mathematics, I've done lots of it in my time, just sort of find out what's true in the mathematical world.

In fact, many mathematicians, often sort of behind the scenes, have done experimental mathematics, but the methodology of mathematics is very theoretically oriented.

I would say that in mathematics, it's kind of a theory-first thing, and you can certainly do experiments in mathematics and then say, well, why is it true that, you know, gaps between primes occur in this configuration, or whatever else?

I would say that in physics, it's sort of the crossover case where there's both a fair amount of theory and a fair amount of experiment.

The, Relationship between theory and experiment.

Well…

Sometimes, the history is experiments get done, lots of experiments get done, and somebody aggregates all those experiments and says, now I understand them in terms of the theory. That happened quite a bit in chemistry, for example.

In physics.

That's happened a bit. I would not say that's happened, that's not necessarily been the dominant story. It's not been, here are a boatload of experiments, now explain them with a theory. That happened, for example, in the Origin of the quark model, for example, in 1964. That was an example of that.

It, I suppose, happened in a more minor way in celestial mechanics in the 1600s. But, you know, I would say that in physics, it tends to be one phenomenon that you then try to drill down and say, well, how does this work underneath?

And then you get to a theory, and then you build up a lot from that theory, and then you start comparing the theory of the experiment, kind of the well-developed theory with the well-developed experiment, so to speak. That tends to be more the pattern.

And I would say that the… while it is the case that, in principle, you can reproduce lots of experimental results from theory, I would say that the actual practice of the science has not been that the theory is the summary of many experimental results.

It's tended to be that theory is developed for the sake of some particular theoretical results, and then implies… experimental results, rather, and then implies lots of experimental results.

I, I think that, Let's see, I mean, this question of

what's theory, what's experiment, what do you teach about science? I mean, if you take biology. you know, there's almost no theory that's taught. Maybe there's Mendel's laws that gets taught. But beyond that, it's like, there's no theory of how, you know, the Golgi apparatus works in a cell. It's just, this is how it works. It's fact, fact, fact.

And that's the story of big, thick biology textbooks. It's the story of what people

But what people study there, I would say in physics, a lot of the teaching that goes on is, this is this formula, this is how to work things out from that formula. In fact, it's been disappointing to me that when it comes to physics.

that things like… the particles that exist. Have you heard of a muon? Have you heard of a pion? These are all things that make up our world in an important way, but in physics, there doesn't tend to be as much of this kind of fact-based teaching of this is the way the world is made up. Like, there are this set of particles, these kinds of quarks, whatever else. Physics has tended to be more on the, this is something you can calculate from.

Whereas biology, there's not a lot you can calculate.

Chemistry, it's, it's, again, a little bit of a mixture. I would say chemistry is probably more weighted on the experimental side than the theoretical side. There's a certain amount you can calculate about, sort of, sort of the numbers of molecules you need for this or that reaction, or the rates of reactions, and so on.

But if you say, why is this chemical structure the way it is? Well, you can't, like, there's no back-of-the-envelope calculation for that. It's a thing… the far reaches of computer calculations in some cases, or some of it is just, well, it just experimentally turns out that way.

It's a… it's a story where the theory is hard. There's a lot of computational irreducibility in chemistry that limits, kind of, what you can work out easily, what you can make a narrative for easily. So the theoretical side of chemistry tends to be on the simpler end of what one is describing in chemistry.

In physics, there's been kind of the conceit, at least, that a lot of what's relevant in physics can be worked out using mathematical or other methods. I think we're increasingly seeing that there's more computational irreducibility in physics than we thought.

And physics had basically sculpted itself to avoid the places where that happens. But physics, again, has, well, it's a,

It's a place where it… there is theory to be taught.

Now…

You know, it's interesting, to what extent do you kind of memorize what's there versus can you recompute it?

In some cases, there's low enough hanging fruit in the computation that, you know, in that end-of-term quiz, you can actually compute that piece of stoichiometry and chemistry or whatever else. But if somebody says, work out what the structure of the helium atom will be. hopeless.

can be done with the upper reaches of what you can do with mathematics and computers and so on. But it's not something that is a kind of a easy-to-workout human-level narrative. So in terms of what one teaches.

That has to be just… the structure is this, just believe me, that's how it works, because you can't work it out for yourself again.

Now, the boundary between those things is changing, thanks to, kind of, perhaps some of my efforts over the years, that more and more is becoming readily accessible computationally, sort of, in real time, immediately, so you will be able to start talking about

this is how this molecule is set up. You can't, with your own fingers, with your own, you know, pencil and paper, you can't work out what the structure of that molecule is, but you certainly can with Wolfram language.

You know, using… using lots of underlying chemistry and machine learning and things like this to work that out.

And so I think the, kind of, what becomes possible to talk about, theoretically, moves as a result of our computational language efforts and so on. I mean, in the past, if you were going to teach theory, that meant you were teaching something where somebody could work things out with pencil and paper. Now, you can teach

this kind of computational theory where you teach, kind of, what goes into what the elements, the computational elements, the computational primitives of the theory, you're not expected to work out the consequences of those primitives.

I think that's a, that's probably the… an important kind of coming attraction. It should have come in the last 40 years, it should have come more than it has, but certainly a lot of that has been done with Wolfram Language and Mathematica and so on.
But, more could be done that is really, sort of teaching modern… the modern form of theory, which is this computer-assisted theory.
That's something that can be part of the, sort of, main loop of understanding these sciences at a theoretical level.
So, a few thoughts about that.
Gosh, Juna is asking, what are some lesser-known, popular panics in the history of technology along the lines of, deep fakes will destroy the concept of reality, or AI will take everyone's job by the early 2020s?
Well… They've been,
you know, there have been panics in the world, there's, you know, there's gonna be a World War III with nuclear weapons, and it's going to destroy everything.
That's a… that's been a panic that is more not a matter of… of… of sort of the… the science didn't work out, the science is there, that's a matter of the geopolitics of how that's worked out, and the fortunate feature of long supply chains for… for making those kinds of devices.
I would say that other things that have been, if you look in the early 1960s, there were panics about AI at that time.
there was, sort of, the AIs are going to take over. Actually, people were… some people were like, hey, it's all good, you know, we are a chain, we are part of the chain of evolution of things on Earth.
And we are just the species that's going to create the next thing, which is going to be AI, and that's… that's okay.
Now, maybe part of the reason it was the that's okay is because a lot of the people talking about it at that time were technologists who were thinking about the creation of those AIs. I think also maybe, it was a time
not that far away from the end of the Second World War, a time when, sort of, the idea of the infinite future being stable didn't look as obvious as it feels to people to a greater extent today.
I mean, I think that… so that was,
another… so there were panics about AI from the 1960s. There were,
There was the grey Goo Panic, that's a good one. That was nanotechnology,
when was that? That was the beginning of the 1990s. The, the concept was nanotechnology was going to let one make a universal replicator. It was going to make one make something like life, with the same self-reproduction qualities of life.
But made out of things that would make it vastly more efficient.
And the concern was that everything in the world would be turned into gray goo, because this little microscopic molecular-scale machine would kind of eat everything in the world and turn it into, pieces of, you know, versions of that machine. It would be kind of like, the, kind of like in biology, you know, something infects something that takes all of the
All of the good nutrients and so on, and puts it into those bacteria, rather than having it be in the host that's being eaten away, so to speak.
So that was another one. Another panic was, the, let's say the Large Hadron Collider is going to create a black hole that will destroy the Earth.

That was, kind of the origin of that panic, I suppose, is that particle accelerators, this was from the 2000s, particle accelerators are going to be able to create conditions which haven't existed since the early universe, at least not so far as we know, although maybe they do exist.
in some high-energy astrophysical phenomena, but that they're creating conditions that haven't existed since the early universe, and maybe those conditions would cause the creation of a black hole that would swallow the Earth, and that'd be the end of everything.
For many reasons, that just doesn't hold water scientifically, and it didn't happen.
The, other kinds of things, well, there are things that…
people have wondered, I'm not sure they've really caused panics that are very widespread. One of them is, can there be compressed forms of matter?
So, when you try and stuff protons together, they repel electrically, but they have the strong nuclear force that binds them together through pion exchange, or however you like to think about it with QCD or whatever. But in any case, there's a force with a range of about 10 to the minus 15 meters.
that binds together things like protons. It could have been the case that if you squash those things even further, there's suddenly another kind of force that takes over, maybe to do with the exchange of F-mesons or something, that pulls, that makes a sort of compressed form of matter. And that could have led to… forget nuclear weapons, there could have been the equivalent of sort of quark bombs.
That are vastly more powerful, and could do terrible things in the world.
That's another kind of thing. Okay, another panic, I suppose, is various kinds of mind control, and various ideas of things like subliminal messaging.
And so on.
the notion of, kind of, mind hacks. I mean, this was very big in the 1950s, of people saying… I mean, it was a time when psychiatry, psychology were very much, sort of top fields, and sort of there was a concern of, well, what if on television, you know, one frame out of every, I don't know how the frequency was in those days, 30 frames or whatever per second, what if every so often there was a frame that said.
you know, you're thirsty for Coke or something. You know, you wouldn't consciously notice that, but maybe that's a mind hack.
That would let you, that would make you, suddenly go and get your, your can of Coke or whatever.
Again, a lot of concern about, sort of, mind control associated with,
With, sort of, hacks like that.
I would say that, sort of a lot of… you know, back in those days.
In the 1940s, 50s, 60s.
you know, the government, particularly the US government, was seen as being the primary source of, sort of, advances in science and technology. That had been true in the Second World War, with radar, nuclear weapons.
and so on. It had been true in the space program, things like this. It seemed like, you know, the government was the entity that was making for, you know, the leading edge of science and technology.
And there was lots in the government that was secret.
And so that led to the idea, well, maybe there's things going on, maybe, you know, telepathy has been discovered to be real, UFOs have been discovered to be real, whatever, and the government

knows and other people don't. And that was the thing, I think, you know, the sort of conspiracy theories of the 1950s, 1960s.
were rather rampant, and that led, I think, to a number of, kind of, potential panics. I mean, I'm thinking of another panic, which was the War of the Worlds radio program.
Where, you know, I think this was a, what, Orson Welles production or something of, of, is that right? His, is, where…
It was kind of like, you know.
from H.G. Wells' book from the beginning of the 20th century, maybe late 19th century, the, you know, the Martians landing on Earth, and that was a radio program, and they… people thought they really landed in New Jersey. The fact that that was possible, that people really thought the Martians had landed in New Jersey.
is a, Is interesting.
The fact that that was a thing that was plausible at that time.
was, you know, that, that's a kind of a, you know, the extraterrestrials are going to come and, are going to come and, and take over type thing. That's been something, again, that…
I think is in the end a sort of scientifically and philosophically doomed kind of idea, because I think that, sort of, the notion of intelligence is much broader than we imagine, and it's that
There's intelligence all over the universe, it's just not intelligence that's aligned with, and they're gonna show up in their spacecraft and come and beat us up, type thing.
So, let's see, I mean, I guess I'm trying to think of other fun examples of,
I mean, there have been…
so many things in, in scientific history where people have kind of gotten… gotten it wrong, and that's led to different beliefs about what should be done. I mean, in economics.
that's an area where there have been many theories, most of them quite unsuccessful, and… but some of those theories have been acted on, and I suppose
people, mostly in that case, the theories have been acted on by governments, and it hasn't been that people have said, oh my gosh, I know the theory, I can see that the whole thing is going to melt down. It's been rather that the theories have been ahead, and people have been using the theories and doing things which sometimes did melt down, so to speak.
Yeah, anyway, a few thoughts on, science-induced panics in the world. I'm trying to think about others. I mean, I suppose,
While others which… which weren't, you know, sort of…
You know, artificially made viruses and so on are another whole story.
And… but that's been so, kind of, smothered in… in, sort of political machination and so on, that that's a, that's a hard-to-disentangle thing.
And that's not something where people were saying from the beginning. I mean, people, you know, if you manufacture a virus, if you, you know, do gain-of-function, sort of artificial evolution, you can make very potent viruses.
Do those viruses end the world, end our species? We don't know for sure, probably not.
I, you know, it's… it's kind of a little bit, a little bit scary to be saying, yeah, probably not. Oh yeah, I'm gonna think of some… I thought of some other interesting panics from the history of science, but… but in any case, that…
That idea of kind of… yeah, okay, so another big one is the biohackers are going to cook up a killer virus in their garage, and…
that's going to sort of end the species. I would say that that particular story is definitely not

it's not a, there's nothing to worry about, type thing. There's actually quite a bit to worry about there, particularly with very much more targeted viruses that link to particular genetic traits and things like this. But I think that that turned out to be… I mean, people sort of thought
You know, there was that terrible sect in Japan that tried to make, I guess that was not, replicating things, that was just chemical… I think that was, chemical agents. But in any case, the, you know, in,
It turns out, releasing, you know, virus into the wild, seems like it isn't as easy as you think. And, sort of, there has to be sort of a chain of circumstances to get it deployed into the world. Maybe that isn't the case. I mean, maybe it's actually easier than we think, and that's bad, and maybe this is one of these cases where the panic is justified.
I'll give you another panic. It's kind of a weird one. This is from the 1960s, early 1970s. People have been trying to observe neutrinos coming from the sun.
And, the,
There was a certain rate of neutrino production that was predicted on the basis of astrophysical calculations, a certain rate of detection that was predicted on the basis of ideas about these detectors that were in deep minds, so that they wouldn't… so that only neutrinos would make it through to actually be detected there.
But anyway, those experiments saw no neutrinos, and as is often the case with experiments that don't see anything, you have to wonder, is the experiment really right? But if the experiment was right, what it would suggest is the sun has gone out.
Now, it takes a photon 10 million years to get from the center of the sun to the surface of the Sun. The sun is not transparent at all. The photon is being continually emitted and reabsorbed and so on, and it takes… it takes 10 million years to get to the surface. Its effective, sort of refractive index is very, very huge.
So…
It could be the case that in the 1960s, 1970s, the sun had gone out in the middle, and we were just waiting for the whole thing to, to freeze out, and then we're… well, I would say we're toast, except we'd be the opposite of toast. We'd be icicles.
And so that was a… that was a panic for a few people, at least, that, might have, led to things.
Actually, talking of neutrinos, there was a little bit of a panic that I was personally
well, that I had, I suppose, which was back in the early 1980s, neutrinos, by the way, are things that get emitted in certain kinds of nuclear reactions, including the ones that happen in nuclear reactors and nuclear submarines. And so, I briefly thought that there might be a method for detecting,
Neutrinos remotely from a great distance, for example, from satellites in orbit.
And then that would lead to the panic of one day, all the nuclear submarines just suddenly are detectable. Suddenly, you can see where all of them are. Perhaps, fortunately, that idea that I had for how you might make that kind of coherent neutrino detector didn't work.
I'll give you another panic. It's a good question, this question about panics. I'll give you another panic.
That's the quantum computing panic. And…
The panic there is, well, we have all these encryption methods, public key cryptosystems, that are all based on the difficulty of doing certain computational problems, like factoring numbers and things like this. Well, specifically, there are a bunch based on factoring numbers.

Well, back in the 1990s, Peter Shaw showed that with this particular model of quantum computers that originated with people like David Deutsch in the 1980s, with this particular sort of idealization of how quantum things work.

Then, in principle.

One example, it should be possible to factor numbers much more quickly than any ordinary computer can factor them. Well, since that time, people have been trying to actually do that in practice with quantum computers. It's turned out to be a lot harder than one thinks. The idealizations of quantum computers don't really work as well as one might think.

It's very unclear what's really going on, whether it's really ever going to work. I don't think it will, personally, but that's a whole other discussion. But the panic there is, well, what if it suddenly worked?

What if, suddenly, one day, somebody, maybe some government.

Built a quantum computer, and suddenly all of those encryptions, all of those codes that had protected the financial systems of the world.

and all the secrets of the world, or whatever, all the identities of people, digital identities of people, and so on, what if in one day, it all just went away? What if in one day, you just feed these things into a quantum computer, and it unravels it all, and tells you, and breaks all those secrets, so to speak?

That's been something that people have sort of worried about with increasing energy since the 1990s, and that's had a huge amount of investment put into trying to invent quantum computers, because if you're the first person, you know, to get that quantum computer and unravel all those codes.

Well, you could irresponsibly break the whole world, or you could use it in a targeted way for your own benefit, or whatever else.

But, so that's been sort of a panic in the making. There's all sorts of discussion of so-called post-quantum cryptography.

Which is really just particular algorithms that evade the particular things that are known to be doable, theoretically, in these models of quantum computing. But that's…

that's another kind of, potential panic in the making. I think I'm out of panics here.

And, the,

I see sources saying, I'll take a side of grey goo coated with paperclips with AI hype. Yeah, I mean, that's in… in the AI world, the,

the doom scenario tends to be, sort of, AIs

We'll figure out how to do everything in the world much more efficiently than we can do it, but then they'll want to do stuff that doesn't have anything to do with humans. Like, some AI will get the idea, it should produce as many paperclips as possible, and then it will start turning all humans into paperclips.

I think those scenarios, among their many, many problems.

Deny the difficulty of actually making things happen in the world.

There's lots of computational irreducibility in the world, in the physics of the world, and it's like, yeah, I want to make everything into paperclips. Well, actually, it might be quite hard to do that, just in terms of the physics of what goes on, independent of kind of… and then people will say, well, but AI will figure out everything.

And that is a… that's just not true.

I mean, that's just something you can theoretically see isn't true. Now, often when people say, it's an impossibility that this or that thing will happen, it's… it's a, you know, it's a… it's a… it's a formula for being wrong.
I think in this case, it's something which, sort of, the arguments for why it has to be that way are arguments that are very much theoretical, logical, structured arguments. They're not just, oh, I couldn't think of how to do it. They're arguments that it couldn't be that way. It just, from the structure of how things work, it couldn't be that way.
So I feel like it's a much more secure form of impossibility than the ones where one just says, you know, it's impossible to send a rocket to the moon or something, or it's impossible… humans couldn't survive going up more than
20 miles an hour. Of course, that particular one, if humans couldn't survive going more than 20 miles an hour, probably for the roads of that time, and the suspension systems of that time, that might have been absolutely true.
But it turned out there was more technology, to,
To, to, to, to overcome that.
All right, I think I have to go to,
my day job, actually another live stream of a design review of features of our computational language. But thanks for some interesting questions today, and comments, and I look forward to chatting with you another time.
Bye for now.