On Finding Meaning in the Language of Physics

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1. The mathematics of physics

Since Galileo's time it's been clear that the language of the physical world is mathematical. Today, giving an accurate explanation of any term in physics – particle, force, mass, even space and time – means invoking quite sophisticated mathematical ideas. But it isn't mathematics in general that works so well as the basis for physics. It's a complicated combination of many particular types of math, very different in general relativity, quantum mechanics, quantum field theory and the Standard Model of particle physics.

While a lot is still mysterious about these theories, the mathematical language is known to a remarkable extent. Physicists have mastered it well enough to give an amazingly detailed picture of our universe and its history. They can explain with great precision nearly all phenomena they've been able to observe, which is saying a lot. Just one example: CERN's Large Hadron Collider generates copious data on the huge variety of events produced in head-on collisions between atomic nuclei, at energies replicating the state of the universe a billionth of a second after the big bang. So far all this data seems to agree with the predictions of the Standard Model, a system of mathematical symmetries discovered four decades ago. So it's fair to say that despite its deep difficulties, the language of the physical world is pretty well understood.

What's not at all understood is why the universe should be built on such strangely diverse mathematical structures. They're so far from making an elegantly unified formal system that the math of general relativity and of quantum theory seem hardly compatible. The language is fairly simple and coherent at the scale of daily experience, in classical physics. But the math involved in atomic structure is far more involved, while the equations that govern interactions among nuclear particles are so complex that exact calculations are impossible. Yet physicists have found ingenious approximation methods that are often not strictly justifiable on mathematical grounds, but do effectively predict the results of experiment. So even where the language becomes too intricate to follow logically, they've been able to confirm that their mathematical models are essentially correct.

The lesson of all this is that math is more than a convenient tool we humans have invented for describing nature. In many different ways, at many levels, specific types of mathematics are built into the physical world itself. But this opens up a new kind of question. Physics has succeeded brilliantly in explaining a vast range of phenomena by uncovering their underlying mathematical structures. The question now becomes, how can we explain the peculiarly various architecture of the mathematical language itself?

2. Unification and meaningful difference

Since ancient times, physicists have hoped to derive the entire universe from one simple mathematical idea. Even now that dream is very much alive, as witnessed by more than a few contributors to the FQXi contests. In mainstream physics too, there's still a hope that once we finally have the long-sought theory of quantum gravity, it will give us that basic nugget of pure logic from which spacetime geometry and the Standard Model emerge. This could happen; at least, we have no shortage of proposals for a unifying theory. There seem to be many ways to extend the language, taking the math to higher levels of abstraction, building in more complex symmetries, that could cover everything. But so far this is all mathematical speculation, having little connection with empirical physics. And whether there's any kind of deep simplicity at the end of this tunnel remains to be seen.

In any case, though, what's most important about the language of physics isn't its formal unity as a mathematical system. Much more consequential is what this language does – how it's able to support such an incredible wealth of diverse phenomena over an immense range of scales. And whether or not this is all built on some deep unifying principle, it's not any simple logic that makes all this possible. Whether or not all physical interactions turn out to be mathematically identical at very high energies, what's more meaningful is how different they are at the energies prevailing throughout cosmic history. Their differences have meaning in that literally everything in the universe depends on them.

If things interacted with each other only through gravity, for example, or only through the electromagnetic field, or if there were no short-range nuclear forces, there would be no higher-level structure in the universe at all. A world where all particles were bosons, or all fermions, would be equally uninteresting. In fact, most of the complications in the language of physics may be needed to support the existence of anything more than a chaotic soup of particles. At least, the language of our universe seems to be finely-tuned in quite a number of ways, to support all these levels of complex structure. Just tweaking the values of a few basic physical constants would be enough to ensure that no galaxies or stars or even stable atoms would ever have come into being.

Now what makes this language work so well as the basis for a richly-endowed world is only partly that it's mathematical – that there are precisely defined rules that operate in just the same way everywhere. For one thing, the world is more than its mathematical patterning – at every level it includes a lot of random or chaotic interaction. But the main thing is that not just any precise regularity, or any combination of order and accident, could do what this language does. So how do we understand what makes this complicated system work? What does it take to articulate a universe like ours?

Since the language is known in great detail, we don't need to speculate about it. We know all about its various components; the problem is in understanding what it's doing, and why. We have a tremendous depth of empirical knowledge to draw on, but we're don't usually think of physics as a functional system. So it's not clear even what questions to ask, to clarify what this means. Just seeing that the language is finely tuned in various ways hasn't helped us much. So far, the only proposed explanation for this is the so-called anthropic principle, which just points out that any universe we can observe has to be able to support our existence. That's rational but useless, since it tells us nothing at all about what it takes to do that.

3. The web of physical semantics

How then can we focus the question about how all these particular mathematical structures work together, building up a highly-developed world out of largely random events? One way may be to take Galileo's metaphor seriously, and consider how physics works as a language.

Again, the language we're thinking of here isn't just the collection of theories we've invented to represent the physical world. Rather, we're talking about the diverse set of mathematical regularities we've found in the physical world itself. But it is quite like a language, in that it has its formal grammar and its fixed vocabulary, that together support a limitless variety of possibilities for interaction.

The formal structure of this language is represented in our equations; its vocabulary consists of all the parameters that appear in the equations. I use "parameter" in a very broad sense, to include all the variables as well as constants. The language of physics has a fairly large and utterly heterogeneous collection of quantitative terms, like space and time, mass and electric charge, energy and momentum, hypercharge and isospin, etc. Some are variables with a continuous range of values, some have discrete units. Then there are constants with specific physical dimensions, like the speed of light and the quantum of action; and there are quite a few pure numbers. Each of these has a unique meaning, a different functional role within the language, that's expressed in the equations by the unique set of relationships it has with certain other parameters.

Now the main way the language of physics differs from any other language is that it gives meaning to all its various elements by defining them in terms of each other. Take mass, for example. This same parameter shows up in many different equations, in relation to others like distance and acceleration, the gravitational constant, frequency of oscillation, particle decay-rate, and so forth – reflecting the various physical situations in which the mass of an object makes a difference. The physical meaning of mass is defined by these relationships with other parameters, each of which also shows up in many other equations, and makes its own contribution to the semantic web of the language as a whole.

To some extent, any language does this, making all its terms depend on each other for their meaning. In human languages, words often have several meanings, depending on context, and each of these meanings can be explained in other words. In a computer language, each instruction has a particular function that can only be carried out in the context of other kinds of instructions. The same is true of instructions encoded in a molecule of DNA. So context is always an important aspect of meaning. But in all these other kinds of language, words and instructions have meaning mainly by referring to things outside the language itself. The word "tree" refers to trees; "wow!" indicates surprise. Symbols in computer code direct a certain action; sequences in a molecule of DNA manage the production of proteins.

So the meaning of any other kind of language depends on the existence of a well-defined world beyond the language itself. That is to say, ultimately they all depend on the complex factual reality defined by the physical world. But because the language of this world is the fundamental one, it has nothing beyond itself to depend on or refer to. It has to be able to define all its facts, parameters and principles in terms of each other – as in fact it does.

Unfortunately, this key feature of our world is easy to overlook. When we think of mass, or space, or any other parameter, we usually imagine it just as given in the nature of things, as a separate element of reality that's well-defined in and of itself. Yet all these parameters are meaningfully definable only because of the extremely reliable and consistent way things happen in the universe. And there's nothing in what happens that corresponds to mass all by itself, or gravity by itself, or even spacetime by itself. None of the parameters of physics have any meaning in isolation from the others.

In practice, of course, physicists give meaning to parameters by measuring them. They have several ways of measuring any parameter, and never need to concern themselves with the semantic structure of the language as a whole. Yet no parameter ever gets measured apart from some context in which other parameters have also been measured. Even just laying out a distance in space requires something else besides space. So measurements aren't really primitive givens, defined outside the language, even though for practical purposes we can treat them that way. Ultimately, though, any observation or measurement is possible only in and through the same web of semantic relationships among parameters that we summarize in our equations.

Now no other system has this sort of completeness, defining itself entirely in terms of itself. Mathematics in general certainly does not. Every branch of mathematics is built on certain primitive notions that are left undefined, such as "point" or "set". Such terms are usually chosen because they have some intuitive meaning for us, based on our experience of the physical world. But mathematics doesn't care about these intuitive meanings; it develops its theorems out of logical relations it defines among these primitive elements. It would defeat the purpose of pure mathematics, which is based on logical proof, to define all its elements in terms of each other; that would only make all its arguments circular.

The language built into the physical world, on the other hand, is not about proving things; it's about giving them contextual meaning. And if there's nothing beyond the physical universe to provide these contexts, then a specific kind of circularity or semantic closure is required.

4. What's more than mathematical in physics

To sum up the argument so far – our universe is built on a finely-tuned combination of very different mathematical structures. Together they function as a unique kind of language, one that provides contexts of meaning for all its own parameters and principles. So the world is in a very deep sense mathematical, yet not in the sense imagined by the long tradition of philosophical speculation that extends from Pythagoras and Plato to Max Tegmark. What's fundamental in this universe is not its mathematical pattern *per se*, but what all these highly diverse kinds of patterning are able to accomplish.

Even the language itself isn't purely mathematical. True, all its parameters are quantities, related to each other through equations. Yet a quantity of mass is not at all the same as a quantity of space, or time, or even energy. What makes each of them different isn't that it represents some absolute, "qualitative" reality that lies beyond the mathematical language. Rather, each term in the language has its special character because it plays a different role within the semantic web. Each depends on others for its meaning; each contributes to the contexts that make other parameters definable and observable.

So the relationships among parameters like space and time, gravity and mass, are all mathematical. But what makes each of these terms unique is its place in the structure of the language as a whole, as a functional system, not a purely logical one. This system uses numerous kinds of logic and mathematics to support contexts in which its elements can be physically meaningful, each in its own way.

To make this idea less abstract, we can illustrate it by any experiment in physics. Consider an arrangement that determines the properties of a particle by tracking its trajectory as it shoots through a magnetic field. Assume the apparatus gives a frame of reference and a means of measuring intervals in space and time; assume we've determined the strength and orientation of the magnetic field. Our equations can then predict the particle's trajectory from its mass and its initial velocity, its electric charge and intrinsic spin. If we know three of these parameters from measurements made in other contexts, then observing the particle's trajectory gives us a measurement of the fourth. Or, if we know all of these parameters, we can use the same set-up to measure the strength of the magnetic field.

It's clear that each of these eight or so parameters plays a different role in the experiment. And while only a small part of the language is illustrated here, it shows how each parameter is defined in terms of the others, and contributes to a context that defines the others.

Now for most purposes it makes sense to treat all these parameters just as given facts, as if they were well-defined in themselves, apart from any context of observation. But we know that fundamentally, at the quantum level, this kind of description breaks down. The math of the quantum realm doesn't say anything about what things are in themselves; it only gives probabilities for the values of certain parameters, in some specified context that defines and measures them. So ultimately, parameters have determinate values only when and where these values are meaningful; there's no well-defined reality outside of the language.

This is why quantum physics has no equation for the "collapse" of the wave function, when a quantum system is observed. Measurement isn't a specific kind of physical event described within the language. To measure something only means to provide a context that defines a specific value for some variable. What makes the quantum realm so strange is only that at the deepest level of interaction, such contexts don't generally exist. This contrasts with the macroscopic domain of classical physics, where the interactive environment provides richly redundant contexts that constantly determine all the parameters of all objects. We can only observe quantum effects when we isolate some system well enough that no such context of interaction exists that can meaningfully define certain values – for example, by setting up an arrangement that makes it impossible to tell which of two slits a photon passed through. In this kind of set-up, any new event that completes the context and makes these parameters definable, then counts as a measurement.

In themselves, such events are just like any other events, and happen according to the usual equations. What makes them measurements is not that they're in any way special; it's that together with other interactions in the environment, they define a value for something that was previously indeterminate. So what it means to observe or measure something has to do with the semantics of the situation, not the formal mathematics of the language. It pertains to the meta-mathematical structure through which different parameters of different systems make each other physically meaningful.

5. The atomic principle

For further exploration of how this language works to measure and communicate physical information, I invite you to look at two previous essays I submitted to the FQXi contests.(1) Those papers focus on how the values of parameters become observable in the web of interaction, and offer thoughts on how this kind of environment may have evolved in the early history of our universe. The theme of the present essay focuses at a higher level, on how the parameters are related through the language of equations. This is a different approach to the same basic question, about how the different kinds of information in the universe are able to define each other.

Here I want to give another illustration, having to do with a particular physical system that incorporates nearly the entire language in a single highly functional package – that is, the atom. Of course, physicists haven't thought of atoms as fundamental entities for over a century. During this time they've developed a profound understanding of the intricacies of atomic structure, but this hasn't seemed relevant to fundamental physics. Instead they've probed deeper, investigating the interactions of subatomic particles. That line of inquiry proved extremely fruitful, at least to the point of uncovering the Standard Model. Since then, researches have continued to pursue the quest for a unifying logic far beyond the scope of observable phenomena, sketching possibilities for mathematical structure at a scale as far beneath the level of atoms as atoms are from the scale of human perception. Here on the other hand we're exploring a functional approach, thinking about how different kinds of math support each other in defining a meaningful world, beyond mathematics. In this picture, atoms clearly play a fundamental role.

Let's start with a simple question, that was already in the air a century ago, when quantum mechanics emerged. Since atoms have a positively charged nucleus surrounded by negative electrons, why don't they just collapse into tiny structureless clumps of neutral matter? The first great success of quantum theory was in explaining the stability of electron orbits, giving atoms a complex structure at a scale many thousands of times larger than their nuclei. But in fact it only explained this for hydrogen atoms, for which Schrödinger's equation gave an exact solution. The full mathematical basis for the stability of other atoms turned out to be very subtle, and wasn't fully worked out until the 1970's.(2) The Pauli exclusion principle plays a major part in the explanation; since this rule applies only to fermions, it was found that atoms would collapse, if electrons were bosons. A variant of Heisenberg's uncertainty principle is also involved, along with the quantization of energy-levels, etc. Together these peculiar quantum rules are able to modify quite drastically the behavior of electrons in the electromagnetic field of the nucleus, letting them maintain stable orbits in a series of well-defined concentric shells.

Meanwhile, all this depends on the vastly more difficult math of quark interaction, which gives us stable protons, and also binds protons and together with neutrons into tiny, dense atomic nuclei. These are massive enough to be highly localized, in spite of the uncertainty principle, and so generate a uniform spherical field for the electrons. To build any atom heavier than hydrogen, though, we also need another interaction – the "weak force", a mathematical extension of electromagnetism that incorporates not only massless photons but also massive bosons and neutrinos. This complex interaction keeps the neutrons from breaking down, so long as they're bound inside a nucleus. In turn, having neutrons in the nucleus allows many protons to be bound together, despite the very strong electrostatic repulsion between their positive charges.

In sum, the existence of atomic matter in our universe depends on all these very different mathematical structures. And in fact, we need gravity too. Gravitational interaction is so weak compared to the others that it contributes nothing to atomic structure, but it's very important at the astrophysical scale, where it pulls cosmic hydrogen and other matter into clumps, that eventually form galaxies and stars. It's gravity that eventually makes stars collapse and explode, when they've fused their hydrogen into helium, and these stellar explosions are needed to create all the heavier atomic nuclei, which were absent from the early universe. The heavy nuclei get blasted out into interstellar space, to be pulled back together by gravity to make new stars, as well as clumps of solid matter like planets.

So quite a lot of the mathematical language of physics seems to be dedicated to supporting the existence of stable, structured matter. But what does this have to do with semantics – with how all these different parameters and principles can define each other? In what way does atomic structure contribute to the meaning of the language?

Well, in a lot of ways. In fact, atoms do most of the work of defining things, in our universe. Without stable atoms, the soup of interacting particles would have no measures of distance or frequency; space and time would be undefinable. But atoms make very accurate clocks, and each atomic isotope defines a precisely uniform size and spacing of energy-levels in its electron-shell structure. This same structure links atoms into stable, quasi-rigid molecules, defining precise spatial angles and shapes; and the great variety of stable molecules, each mathematically identical with others of its kind, makes it possible to build up very diverse forms of highly structured matter, even at to the macroscopic scale, and supports the vast diversity of chemical interactions. Finally, atoms communicate. They're able to distinguish electromagnetic signals of specific frequencies, store this information in the energy levels of their electrons, and transmit signals out again to other atoms. So in short, essentially all the functionality we take for granted in the material world – including giving a physical basis for every sort measurement – depends on the capabilities of atoms.

Now there might conceivably be many other ways to construct a language that defines all its own parameters. The only one we have available to investigate is one that uses atoms to make things definable and measurable. So if we're looking to explain why our universe is built on all these diverse and sometimes finely-tuned mathematical structures, we have at least part of the answer in the "atomic principle". This points out that any universe we can observe has to define all its observable parameters, one way or another – and at least one way to do this involves producing atomic matter.

The anthropic principle, in contrast, tells us practically nothing about our universe, since the existence of human observers depends on so many other things besides physics. However the language of physics may have arisen, in the beginning, this was only the first stage in a long series of adventures that eventually gave birth to humans. There's the long geological history of Earth, the accidental appearance of the first self-replicating systems, the evolution of life over billions of years, the rise of animals with complex nervous systems, and then the development of the human form of language. A so-called "principle" that encompasses all these different kinds of happening won't explain much about any of them. On the other hand, the structure of atoms is at the heart of the language of physics. And given all that's known about this, we should eventually be able to sort out what it takes to make this kind of system work. That could explain a lot about why our universe is built the way it is.

6. Our world and its meaning

I've suggested that the mathematical language of physics supports a kind of meaning that goes beyond mathematics. It defines each parameter through a unique set of relationships with the others, in a very diverse array of mathematical structures. And the language as a whole has meaning, in that it underlies all the intricate complexity of physical phenomena in the universe.

The word "meaning" can of course mean many things. When linguists talk about semantics, they generally have in mind the representational aspect of language – i.e. the relation of a word or symbol to the thing it signifies. In the physical language of equations, it's the contextual aspect of semantics that's important – things have meaning when there are situations in which they make a definable difference. In biology things are meaningful if they affect a species' evolution, i.e. which sequences of DNA get reproduced in the next generation of organisms. The meaning of computer code lies in the particular purposes for which the software was designed. And human relationships provide fruitful ground for all these different kinds of meaning and more.

Is there something all these different kinds of meaning have in common? I think that at bottom what makes anything meaningful is that it makes something possible, beyond itself. Words have meaning, basically, because they make it possible for us to say things, and what I say has meaning if it makes it possible for you to make a meaningful response. So nothing is meaningful in and of itself; meanings always depend on the possibility of other meanings.

In any language, this interdependence has two levels. One is static structure of the language, its grammar and vocabulary. In physics, the meaning of each parameter depends on the meanings of other parameters, and helps make others meaningful. Likewise the mathematical structures of curved spacetime, electromagnetism, quark and weak-force interaction, electron-shell bonding between atoms, etc. each makes a different contribution to the language, which in turn makes all of them physically definable and observable. This whole semantic system was established long ago, in the early stages of the universe's history, and has remained the same ever since.

But even languages have meaning not in themselves, but in the open-ended possibilities they support. The grammar and vocabulary of English make possible an endless stream of thoughts and conversations, unfolding in time. The math of physics too works at both levels, supporting a dynamic universe of interaction where everything that happens depends on things that happened earlier, and contributes to new situations where new things become possible. Just as the English language only exists in the web of actual talking and writing, the language of physics only exists in this web of events that constantly creates new contexts of meaning.

This basic, physical meaning gets taken for granted when we talk about the facts of reality, as if facts were just given and well-defined in themselves. And that's fine; we can afford to take the factuality of things for granted, nearly always, since the language of physics works so well to make things meaningful and observable in terms of each other. On the other hand, if we can appreciate what this system does, we can investigate what's required to support this kind of semantic self-sufficiency – a requirement that doesn't apply to any other kind of meaning. And that could eventually explain the many kinds of complex mathematics it employs.

References

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