

## What does it take to be physically fundamental?

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### Part I – How does a universe define itself?

For forty years we've had an amazingly detailed mathematical account of fundamental particles and forces, in the Standard Model plus General Relativity. It's confirmed by mountains of experimental data, in which hardly a shred of clear evidence has been found for any deeper level of structure. The problem is, it doesn't look anything like what a fundamental theory was supposed to be.

Ironically, the classical physics of the 19<sup>th</sup> century seemed much closer to the traditional goal of a clear and simple mathematical foundation unifying all known phenomena. Of course our current theory explains vastly more about the universe than anyone could have imagined back then. But quantum theory is notoriously obscure, and the math of the Standard Model is impressively subtle and complex. Its three basic forces are “unified” mathematically, but have very different levels of complexity, and play completely different roles in atomic physics. And there's still no connection between the Model and the theory of spacetime curvature that explains gravity.

Moreover, in many ways this physics seems to be very finely tuned. If just one or two basic constants had somewhat different values, our universe would never have produced any galaxies or stars, or even stable atoms. So not only are the deep structures of physics bizarrely complex and counter-intuitive, but it seems they might have to be like this to function as the basis for any higher-level structure.

My goal in this essay is to try to make sense of this picture, as it stands. Instead of speculating about some still deeper level of physics, I want to ask what it means – and what it takes – to be a foundation for a world like ours. My working assumption is that we already know, to a great extent at least, what the base-level structures of our universe are. But we haven't appreciated what these structures do, or what's needed for a system to do that.

Imagine an alternate universe with exactly the same physics as ours, except for a change in the mass of its up- or down-quark, or the value of its cosmological constant, or the strength of its Higgs field, so that no stable atoms could ever form. Without atomic structure there would be no physical basis for determining distances in space or time, or the masses and charges of its particles, or any other kind of information. Never producing anything but a clumpy soup of interacting particles, this universe would be in no way distinguishable from one based on totally different laws of physics, or from one that had no laws at all.

So what does it mean that in a world only slightly different from ours, no information would be physically observable, or even meaningfully definable? Recently it's become common to explain fine-tuning – or rather, to explain it away – by imagining a “multiverse” or “landscape” of universes defined by different equations, different spacetime dimensions, etc. The idea is that even though our universe may seem extremely special, that's only a selection effect. In the big picture all these worlds are

equally real, or equally possible, but of course any world we can observe will be one that can support observers. So the fact that our universe does that is hardly significant.

But this misses the point. What fine-tuning tells us is that a very highly specialized system of physics could well be needed to define anything at all about its own structure. Though we can write down different equations for all these universes in our theoretical landscape, nearly all of them would be physically indistinguishable.[1] None of the symbols in these equations would have any meaning, outside the context of a finely-tuned interactive environment like the one our universe provides.[2] Here, all the various kinds of information represented by our symbols make a measurable difference to something, in the context of other kinds of measurable differences.

Now the fact that things are observable is so obvious that it's always been taken for granted. It's also obvious that atoms are stable, and form molecules that support many kinds of complex structure – and we usually take that for granted too. So when we think about what's fundamental in physics, we're not thinking about atoms, or about how things get measured. We think about the underlying particle-fields, searching for some kind of unifying framework that might give us back at least a little of the clarity and simplicity we used to have in classical physics.

From a functional standpoint, though, atoms clearly play the same foundational role in physics that living cells do in biology. Cells are also remarkably complex and finely-tuned systems, but we don't try to explain them by resolving all their components into a unified pattern. We understand their internal structure as what's needed to support the basic functionality of self-reproduction, something that happens only at the level of cells and organisms. Biological molecules and other sub-cellular systems don't replicate themselves outside the environment of a living cell. Likewise in physics, no information can define or communicate itself apart from an environment of interacting atoms.

For a cell to be able to reproduce, it has to do a lot of other things as well. And atoms also have a lot to do, to make an environment where information is definable and communicable. They function not only as extraordinarily versatile building-blocks for material structure, but also as tiny clocks and rulers, providing universal standards of distance and frequency. They're measuring instruments, selectively absorbing light at certain energies, storing this data over time in the energy-configuration of their electron-shells, and communicating it to other atoms. Their nuclei concentrate and stabilize gigantic amounts of energy, giving atoms enough mass that gravity can pull vast numbers of them together to make galaxies, stars and planets. And by confining the tremendous forces of quark-gluon interaction within themselves, nuclei can serve as simple point-like positive charges around which the delicate structure of electron-shells can organize itself. Yet these shells are also resilient – able to maintain their structural integrity while hooking into the shells of other atoms, forming molecules with precisely defined geometries. Finally, it's the complicated energy-exchange between these shells that powers every kind of chemical interaction.

Nothing remotely like this multi-leveled functionality occurs at the subatomic level. On the other hand, nearly everything we know of in subatomic physics contributes to it in some way – the nuclear forces, electromagnetism, the uncertainty principle, the exclusion principle, etc. Gravity does too, since without it our universe would be just an expanding gas of hydrogen and helium, affording no basis for

any measurement. So it's no stretch to imagine that all of the finely-tuned structure in fundamental physics might be required to support a self-defining, self-measuring and self-communicating system.

Nor is it hard to understand why, in principle, such a complex system might be needed to define its own information. The reason is that no kind of information can ever be measurable, or even definable, except in the context of certain other, related kinds of information. And this contextual information must also be observable and definable, in the context of other kinds of information.

Physicists normally treat information as an abstract quantity – a number of bits or qubits. But any information that can actually be defined or used in any way is always information of a specific kind, related to other kinds. Even in mathematics, for example, to define numbers we also need to define the operations we can perform on them. For a binary data-bit to hold any information, we also have to specify its location in a string or a microchip. So while quantifying information can be useful, it leaves out something fundamental to the nature of information as such.

In physics we have a large and very diverse set of empirical variables and constants, each of which can be determined in various ways, in different contexts. But any context in which one of them can be measured always involves other kinds of information too, that are measurable in other contexts. And in principle, the physics of any universe in which any information is definable must provide a closed system of measurement-contexts, each of which can not only determine specific types of information but also communicate it out to other contexts, where other information gets defined.[3]

This obviously happens in our universe. And apparently nearly all the structure of known physics is needed to make this work. So I think there's a tremendous opportunity here for reverse-engineering.

We have precise specifications for nearly all the components of this system. And we know what it does: somehow, out of the indeterminate chaos of the deep quantum vacuum, it's able to generate the precisely definite and deterministic reality described by classical physics. So it should be possible to figure out how this system works. I'm not saying that's easy. But I think we should expect to be able to explain someday why every part of this system has to operate the way it does.

## **Part II – Towards an Archaeology of Physics**

The problem is that we're not used to thinking of the world as a functional system. The vast body of knowledge contained in our current theory is well organized in the service of reductive explanation, breaking systems down into separate components. There's nothing wrong with that; this approach has been extremely successful, down to the level of the Standard Model. But it doesn't try to explain why the world should be built this way. To approach that question we'll probably need to take the puzzle apart and put it back together again, from a functional standpoint. Not being a physicist, I can only imagine what this challenge entails. But I'll try to show you how I've imagined it.

Our knowledge-base not only gives deep insight into fundamental physics, but offers an empirically well-grounded history of our universe, back to the first nanoseconds. This tells us that the underlying

physics has remained essentially constant all that time, though the interactive environment it supports has gone through great transformations. It also tells us that while hydrogen and helium nuclei were created in the extreme conditions of the big bang, it took some 300,000 years for the universe to expand and cool enough that electrons could form stable bonds with these nuclei, to make atoms.

I'm assuming this is basically correct – yet before there were any atoms in the universe, physics as we know it would not have been definable. There was no way to distinguish this particular history from countless others, including those based on much simpler physics, or those based on no rules at all. So we might think of the early universe as a superposition of all these possible histories,[4] and consider how the one that eventually produced our observable world could have come to distinguish itself from the rest, building up the complex system of rules that would eventually support atomic structure.

Let's suppose that to begin with, anything was possible. There were no rules or constraints at all, since there was no context in which any constraint could be defined. So everything happened – but there was no way to tell what happened, or where or when, or whether it made any difference to anything else. On the other hand, it was perfectly possible for any kind of system to emerge within this chaos, so long as it could provide its own constraints. It would have to be able to define selection rules for the subset of events that happened to “obey” those rules.

Now we know that such self-defining systems can exist, since we live in one. Evidently our laws of physics do set up an environment in which all those same laws are empirically definable and verifiable. So we can think of them as selection rules, picking out random events in an underlying chaos that just happen to fit together, making contexts for each other. Our laws of physics are the conditions under which events can make a determinable difference. So in the big picture everything happens, but only what happens to follow all these rules can make any definite impact on other things. The rest remains “virtual” – a subliminal ocean of indeterminate events.

Could there have been simpler systems that were able to define their own constitutive constraints? In the initial superposition of all possible histories, could there have been some very primitive subset of events that could do this, which then set up a context in which other, more complicated self-defining systems could arise? Might we imagine a series of such systems, each adding new layers of structure to those already established, eventually laying the foundations for our world of interacting atoms?

If that is in fact how our universe came to exist, we might expect all these primitive layers still to be discernible in the basic structures of physics today. And, as it happens, there are quite a few basic features of the physical world that we might identify this way – as “fossil” structures left over from the pre-atomic era, when nothing was quantitatively measurable. To show the feasibility of such an “archaeological” approach, I'm going to try to describe these layers of pre-metric structure, sketching out very roughly what the sequence of self-defining systems might have been.

## I Interaction

Imagine that in the original chaos there was some set of possible events that all connected with each other. These connected events are what we call “interactions”, which are certainly a basic feature of our universe. At the quantum level, in fact, it’s reasonable to think of the universe as a web of momentary connections between things, where the “things” – elementary particles – are interactions too, some of which interact with themselves as well as connecting other particles.

So let’s imagine the interaction-web as the first stage in the emergence of a measurable world. This initial system defines itself by the constraint that every event in the web must connect at least two other such events. This “law” is not enforced by anything. There’s no way to tell which events are connected to which, or to order these events in space or time, or to distinguish different types of interaction. It’s just that any events that don’t happen to “obey” this rule, don’t participate in the web. They can’t make any difference in any higher-level system that might be able to define itself within the web.

This doesn’t give us much, but it’s a start. It seems clear that any system in which anything can ever be observed or measured needs this kind of underlying structure, where every event has a context of other events, which also have contexts. Even if, to begin with, the contexts have no structure, and no information is conveyed by these random moments of connection.

## IIA Reconnection

We don’t yet have a system that unfolds in time, or has any definite topology. But we can think of this web as a superposition of all possible paths, all the chains of connected events within it. And we can imagine a class of paths that define themselves by looping back on themselves. This class will be large, since between any two events in the web there can be many different paths, and any pair of paths from A to B forms a loop. But we can also imagine chains of events that keep on winding on and on through the web, never reconnecting with any of their events.

There’s no way to determine which possible paths “obey” this selection rule – forming loops – and which don’t. The paths that don’t happen to do this, just don’t participate in the class. In this case, though, it’s these participating events that get eliminated – that play no further role in the emergence of any higher-level systems. In our universe today, all observable event-chains go from past to future, all aligned on a single axis of time, never looping back on themselves. So it’s the relatively tiny class of paths that go on and on that make up the structure of our world.

Nonetheless, we can find fossil traces of the looping paths everywhere in the statistical fabric of the quantum realm. For example, in the path-integral formulation of quantum mechanics, when a particle goes from A to B it takes all conceivable paths – including those that violate our current laws of physics. For every such weird path, though, there’s another path that exactly cancels it – effectively looping back in time from B to A. Only the tiny set of paths that happen to stay close to the “lawful” trajectory don’t get cancelled out this way.

So the system of self-reconnecting paths seems to play a basic role in defining all the higher-level laws of physics – in that all such paths eliminate themselves. Only chains of events that never happen to reconnect participate in the further emergence of self-defining systems. Even so, we still have to take all the looping “virtual” paths into account, in computing probability amplitudes for the paths we actually observe. Similarly, internal loops along paths in a Feynman diagram have to be taken into account, though no definite amplitude can be assigned to them – this is the problem of infinities that’s resolved by renormalization.

## **IIB Balancing Opposites**

Though we don’t yet have any spacetime structure in the web, paths that never reconnect with themselves could potentially be oriented along a universal time-axis. But what kind of system could define a sequencing of events along parallel paths in time?

It’s hard to imagine how this could arise, since the previous stages give us little to work with. We have a superposition of all possible non-looping paths, with no way of telling which events connect to which, or in what order. To line these paths up with each other, we need connections between them that don’t create loops. What kind of selection-rules could accomplish this?

Luckily we don’t need to figure this out, since it’s fairly clear how our universe does it – through the laws of electromagnetism. It’s a complicated system, though simple in comparison with the other gauge fields we’ll come to later. Notably, its basic structure is definable without reference to any spacetime metric[5] – so we can see it as another fossil structure from pre-atomic physics.

Roughly sketched, it looks like this. Event-sequences that never loop back are what we call “charged particles”. Those oriented one way along the time-axis we call “positive,” those oriented the other way are “negative” – since positrons are the same as electrons going backward in time.[6] So at this stage we don’t yet have any “arrow” of time, pointing from past to future. Electrodynamics is time-reversible.

Charge is conserved – meaning that this system excludes not only looping paths, but any paths that don’t keep on connecting, adding new events. Paths that terminate don’t participate in its structure. But the system also incorporates interactions we call “photons”, connecting events on different charged-particle paths. And a set of mutually-defining selection-rules associates each event on one charged-particle path with a specific event on another, lining them up in parallel sequence.

Each of these rules defines a different kind of information, in the context of information defined by another rule. All information here consists of variables with two opposite possibilities, like the (+) and (–) charges representing opposite directions on the time-axis. This system of symmetrical opposites also defines three spatial axes, setting up the basic topology of spacetime before there’s any context for determining relative positions, distances, angles or velocities.

Since there’s no global frame of reference, the spatial axes are defined locally, in each interaction between a charged particle and a photon. Electromagnetism has “local gauge-invariance”, meaning

that the axes and field-potentials can be defined arbitrarily at each point, without changing the system's structure. In terms of our current physics, these axes are (1) the direction of motion of each charged particle at any point, (2) the direction of the photon linking two charged particles, and (3) the direction of each particle's spin-orientation. The motion and spin-orientation are defined in relation to the magnetic field, while the photon-axis corresponds to the electrostatic field.

Each axis defines opposite alternatives – for example, a positive charge creates a magnetic flux curling one way around its axis of motion; the flux made by a negative charge curls in the opposite way. Electrostatic interaction between two charges pushes them in opposite directions on the photon-axis between them. A particle's spin-axis is oriented either with or against the local magnetic field. And every change in the electric field makes a difference to the magnetic field, and vice-versa.

But why don't the photon-connections between charged-particle paths create time-loops? After all, many photons connect particles that have opposite charge – opposite orientations on the time-line. But there's another rule: photon-connections between particles with the same charge carry positive momentum – which means, in our current universe, the two particles repel each other. Photons between particles with opposite charge carry negative, time-reversed momentum – so they pull the two particles toward each other.

At this stage we can't yet define positions or distances between particles, so there's no distinction between "toward" and "away". But the photon's momentum-orientation does make a difference to each particle's motion. And together with the systems' other binary selection-rules, it helps define the topology we can envision as a web of intersecting light-cones, interconnecting all charged-particle paths. It's able to ensure that all these paths proceed consistently either in one direction or the other, aligned to one universal axis of time.

Again, nothing "enforces" these rules. In the big picture, everything still happens at random. But only those random connections that happen to participate in this topology can have any definable effect within the system itself – or in any higher-level system that might be able to define itself within this electromagnetic environment.

### **IIIA Higher-Order Symmetries**

The first transition above, from **I** to **IIA**, came easy. A web naturally gives a superposition of paths that form loops. But getting from **IIA** to **IIB** was a leap, since none of the new selection rules would be definable by itself. Electromagnetism is a structure of interdependent relationships, each of which makes a different contribution.

Once this system of symmetries was established, though, it's easy to imagine that further levels of symmetry might define themselves within it. Our current universe incorporates electrodynamics into the higher-order  $SU(2)$  symmetry of electroweak interaction. Then there's the far more complex  $SU(3)$  symmetry of quark-gluon interaction. Both these systems have local gauge-invariant fields, so they again look like fossils from a pre-metric universe. In fact, the new kinds of particle charge they define for nuclear physics operate in their own internal space of relations, distinct from our spacetime.

In these new systems particles interact by changing their identities – this shows up in our universe in statistical patterns of particle creation and decay. A subtle asymmetry appears in the weak-force decay modes, where right-handed particles decay differently from left-handed ones. This points to a time-asymmetry as well, so this may be the stage at which entropy and the “arrow of time” first become definable.

Now if these two particular higher-order symmetries could define themselves in the **IIB** context of electromagnetism, presumably many others could as well. So we can think of the **IIIA** environment as a superposition of all the possible interaction-patterns that could define their own selection-rules within the **IIB** context – much as we treated the initial interaction-web as a superposition of paths. But the situation here is far more complex – there may be nothing corresponding to the simple distinction between looping and non-looping paths. But in any case, it seems that only these two specific versions of  $SU(2)$  and  $SU(3)$  symmetry turned out to be useful in the physics of our current universe.

### **IIIB The Metric Continuum**

In contrast to these emerging higher-order symmetries, the creation of the spacetime metric would have required another leap, far more radical than the one that defined electromagnetism. If atomic structure is what makes spacetime measurable, a remarkable diversity of new selection-rules must have emerged together, making contexts for each other. All the structural elements of the previous stages were redefined within this new environment, translating them all into measurable quantities.

The primitive simplicity of the Stage **I** web, connecting all interactions without distinction, reappears here in the universal spacetime geometry of general relativity. Both gravity and the “cosmological constant” governing the expansion of the universe affect all forms of matter and energy in the same ways. And their measurable values are apparently very finely-tuned – for example, the weakness of gravity as compared with the other forces is needed to open up a long enough history and a quiet enough environment for higher levels of material structure to emerge, providing a physical basis for measuring and communicating many kinds of quantitative information.

The **IIA** structure of looping paths plays a basic role in quantum physics, as already noted. But all particles now have measurable frequencies, and their paths are described by continuous wave-equations. The mutual cancellation of virtual paths is now redefined as destructive interference between paths with same wavelength but opposite phase. Constructive interference becomes the basis for determining the lawful trajectories of particles in space and time.

Electric charge and the field-potentials of **IIB** electrodynamics also now have quantitative values, with relationships defined in terms of angles, distances and accelerations. Every event now involves a balanced exchange of momentum (= mass x velocity). The electromagnetic field acquires several new functions, providing the medium for essentially all long-distance communication as well as structuring atomic electron-shells, forming molecules and driving all the various modes of chemical interaction.

The symmetries taken over from **IIIA** get partially broken, as masses are assigned to each particle and coupling constants to their various interactions. Many such quantitative parameters are apparently

needed to stabilize and localize the intensely energetic interaction of nuclear particles. The peculiarly complicated structure of the nuclear forces also has cosmological implications, since they govern the dynamics of stellar evolution that produces heavy nuclei.

Now all these new quantitative variables ultimately affect how things move – they’re all determinable by measuring the motion of things in a continuous metric of space and time. All the previous stages defined generic relationships between patterns of information. Now we have dynamic relationships between individual entities, each with its own unique place in the continuum. All the complexities of atomic physics result in a high-level geometry that seems remarkably simple, approximating that of Euclid. The original chaos of indeterminate happening has become an empty homogeneous vacuum, a backdrop for the simple deterministic dynamics of Newton and Maxwell.

The emergence of all the complicated selection-rules that define this system may seem miraculous. But it’s just another pattern that happens to be able to keep on defining all its own information, in countless interrelated contexts. Out of the plenum of unconstrained possibilities, it constantly finds some that follow the rules, that can play some measurable role in making other events measurable.

## **Conclusion**

My goal in sketching out these stages is only to show that a scheme like this is possible – that we can reasonably hope someday to explain how all the diverse aspects of physics are functionally related, rather than trying to reduce them to a single fundamental structure.

There might of course be deeper layers of physics beneath the Standard Model. There are certainly many pieces of the puzzle that are still unknown. But I don’t think “unification” and “naturalness” are reliable guides to further exploration. Even if there were one simple equation at the bottom of everything, how much of the marvelous complexity of our universe would that explain? And how would it improve our situation if we could satisfy ourselves that all this fine-tuning is illusory, that nothing here is really out of the ordinary?

Ultimately we investigate the foundations of physics because we want to understand why the world is built the way it is. But that doesn’t mean proving that it couldn’t have been built any other way. Why should we need to exclude accident at a fundamental level, when it plays such a vital and creative role everywhere else?[7] Rather, we need to be more creative in considering what the “why” might be, that could explain how such an astonishing universe came to exist.

## Notes and References

The A/B numbering system for the Stages presented above reflects a general scheme I inherited for describing emergent levels of relationships. Unfortunately it would take a longer essay to explain it, so I don't attempt that here.

[1] For an easy introduction to fine-tuning see Matt Strassler's short essay, "Naturalness and the Standard Model" – <https://profmattstrassler.com/articles-and-posts/particle-physics-basics/the-hierarchy-problem/naturalness/>

[2] See my essay "On Finding Meaning in the Language of Physics" discussing the relation between physics and mathematics – <https://fqxi.org/community/forum/topic/2354>

[3] For discussion of the physics of measurement and quantum theory, see my earlier FQXi essays:

"An Observable World" – <https://fqxi.org/community/forum/topic/1513>

"On the Evolution of Determinate Information" – <https://fqxi.org/community/forum/topic/1851>

[4] See S.W. Hawking and Thomas Hertog, "Populating the Landscape: A Top Down Approach" – <https://arxiv.org/abs/hep-th/0602091>. Though operating within the string theory landscape, this takes a similar approach in regarding the early universe as a superposition of possible histories, only a few of which could have led to our current universe.

[5] See sections 6-7 of the Introduction to D.W. Delphenich, Pre-metric Electromagnetism (2009) – [https://www.researchgate.net/publication/304990103\\_Pre-metric\\_Electromagnetism\\_First\\_part\\_of\\_file](https://www.researchgate.net/publication/304990103_Pre-metric_Electromagnetism_First_part_of_file)

[6] The interpretation of positrons as time-reversed electrons was introduced by R.P. Feynman. See "The Development of the Space-Time View of Quantum Electrodynamics" – [https://www.nobelprize.org/nobel\\_prizes/physics/laureates/1965/feynman-lecture.html](https://www.nobelprize.org/nobel_prizes/physics/laureates/1965/feynman-lecture.html)

[7] On the role of accident, see my last FQXi essay, "Three Technologies: On the Accidental Origins of Meaning" – <https://fqxi.org/community/forum/topic/2791>. This compares the functionality of the physical world with that of the biological environment and human communication.