III. The Origins of Determinate Information

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Abstract

This paper continues an argument begun in “Why Quantum Mechanics Makes Sense”, which explores the conditions under which a physical world can define and communicate any kind of information. Since it appears that nearly all of what’s known in our most fundamental theories may be needed to do this, the question arises as to how such a complex, many-leveled system of rules and principles could have emerged from much simpler initial conditions. Following the earlier treatment of Quantum Mechanics, the initial state of the universe is taken to be a plenum of unconstrained (and therefore structureless) possibility. Any sort of system can emerge, in these conditions, so long as it’s able to define all its constraints in terms of each other – as our observable universe does. I attempt an “archaeological” analysis of currently known physics into component layers of self-defining structure, each of which can be understood as emergent on the basis of previously established constraints. I also consider how this kind of reconstruction might relate to our currently well-established Concordance Model of the early history of our universe.

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1 Toward an Archaeology of Physics

How could a self-determining system as deeply complicated as our universe have come to exist? This system is made of many kinds of interaction that continually set up new situations that let certain kinds of facts be determined, which are then passed on to set up other such situations, in a self-sustaining process. The goal of this chapter is to sketch out a possible approach to understanding how this kind of system could have emerged through a sequence of stages, from more primitive self-defining systems that involved fewer and simpler kinds of information.

The idea is that the structures that emerged in each of these stages should all still be evident in the complex foundations of our current theory. This means that we don't need to guess at the nature of these earlier systems. We should be able to sort out the corresponding layers of organization in our current physics, through a kind of archaeological analysis.

In the Conclusion to the opening essay of this series, though, a key issue was raised that needs to be dealt with before we proceed. The key point of my argument has been that at a fundamental level, there can be no information apart from a physical context that makes that information meaningful – which is to say, definable, measurable and communicable through the interactive environment. Yet we have, in the current concordance model of cosmology, a detailed and well-substantiated sequence of events going nearly all the way back to the beginning of the universe, on the assumption that the basic laws of physics were already established in the first nanoseconds. And since nothing could have been measurable in the high-energy chaos of the early universe, doesn't this prove that our very complex system of physics was for a long time well-defined independently of the contexts that in our current universe make all of its components determinable?

I don't think so. But I want to be clear that what I'm sketching here is not meant to replace our current cosmological history, which explains so much about the composition of the universe we see today. Apart from aspects of this story that are speculative (e.g. inflation) or not yet understood (dark matter), I assume this account is essentially correct, even though it tells us that the physics of our universe pre-dates the first formation of atomic structure – and the possibility of any measurements – by some 300,000 years.

The question is, though, how to interpret this account from a quantum mechanical standpoint. When we look back toward the origin of the universe today, empirical evidence made available by our current environment lets us reconstruct the long, complex sequence of events that eventually resulted in the emergence of atoms, molecules and higher levels of material structure. But before all that happened, no such evidence could exist. Early on, our finely-tuned system of particles and interactions – the system of physics that turned out to support atomic structure – wouldn't have been distinguishable in any way from countless other possible histories.

What quantum mechanics suggests is that all these possibilities need to be taken into account when we consider the state of the pre-atomic universe.[1] Only as there gradually emerged a structure of contexts that could define and communicate facts, did it also become possible to define the specific sequence of historical events that resulted in this particular system. At that point all other possible histories became irrelevant. The only prior events that could leave any definite trace in the newly emerging universe of atomic interaction were those that conformed to the changeless laws and principles of this new world.

This doesn't mean that the entire structure of our current physics suddenly appeared all at once, out of a chaos of indefinite possibilities. It's true that before there were atoms there could have been no way to define a spacetime metric, or to make any kind of quantitative measurement. But there are important features of our current physics that can be defined without reference to any metric – for example, the basic underlying structure of electromagnetism, or the many types of symmetry we find in the structures of spacetime and the Standard Model. Here we'll consider these diverse types of pre-metric structure as evidence for a sequence of "prehistoric" stages through which our self-defining universe emerged. That is, certain basic kinds of information may already have been definable in terms of each other, before there were physical contexts that could determine intervals in space and time, or define trajectories for individual particles, or make other quantitative parameters physically measurable.

So while I have no doubt that something like our current model of the early universe is essential to understanding the world as we see it today, this model doesn't tell us anything about how or why this particular complex, multi-layered system of broken and unbroken symmetries came to exist. It doesn't try to explain why our physical world is based on this particular set of observable parameters, or why it's finely-tuned to support the emergence of many levels of stable higher-level structure. Within the framework of current theory it hardly seems possible to ask such questions. But my aim here is to show that our established theories are telling us much more than we've so far been able to recognize about why our world is built the way it is.

As I've argued in the first two papers in this series, any observable world has to base itself on a changeless system of universal laws that apply throughout all space and time. Beyond that, it needs to define and maintain a historical background of commonly-shared objective fact, to support communication between local contexts. So the origin of our universe involved not only selecting out a specific system of physics from all other possibilities, but also choosing a specific past history based on those laws that could result in the emergence of atoms and molecules, as the basis for stable material structure. So it's not surprising that the empirical evidence available today lets us trace the history of our current physics as far back as spacetime itself can be defined, by this physics.[2] Even so, we should keep in mind that before the emergence of atoms, spacetime structure would not have been definable, nor would the system of the Standard Model have been distinguishable from any other possible physics.

In any case, while our current cosmology explains a great deal about our universe, no history based on changeless laws and principles can address the question of how or why this system of physics came to exist. The question of origins requires a different kind of answer, which is what we're trying to imagine here. Since our current cosmology takes the context-structure of the observable world for granted, it needs to be supplemented by a theoretical account of how that kind of structure could have emerged.

Evidently such a theory can't assume any well-defined factual state of affairs, to begin with. But as proposed in the initial essay in this series, what's fundamental in the physical world are not facts but possibilities. Essentially our world is made of situations in which various things can happen, given the constraints imposed by past history and the laws of physics. And situations become more specific and more complex as their possibilities are more tightly constrained. Definite facts arise only in very complex situations – i.e. measurement-contexts – that can select one specific outcome from all other possibilities, and then use that outcome to constrain new possibilities in other contexts.

To start with, then, we assume a situation with no given facts, nor any other kind of constraint on what was possible – since in the beginning there would be no context in which facts or laws could have any meaning. We imagine the original environment as a more radical version of our quantum vacuum – as a chaos of entirely free possibility, where anything at all can happen.[3] Here there's no way to distinguish what happens from what doesn't, or to define where or when anything happens in relation to anything else. Even so, any more structured system of events could come to exist in this environment, so long as it was able to define all its own constraints in terms of each other – as, for example, our own observable universe does.

I proposed in the initial essay that at a fundamental level, the laws of physics don't force things to happen the way they do. At bottom, all events are random – but the only events that can ever be observed, or have any definable character, are those that satisfy the conditions for maintaining a communicative environment. Unlawful events don't need to be suppressed, since they can't make any determinate difference to what happens in the observable world. So this world we experience is just a tiny subset of all the possible events in an underlying unconstrained and indeterminate chaos. It's an ongoing random selection of events that happen to provide contexts that keep on making things measurable.

Now our current universe operates with so many complex constraints, involving so many different kinds of information, that it's hard to imagine this entire system coming to define itself all at once. So instead we'll assume that this physics emerged in stages, beginning with very primitive self-defining systems of constraints.[4] At each stage the environment was able to delimit a certain subset of possibilities, ruling out those that didn't happen to meet this system's requirements. Then within this self-selected subset, new kinds of contexts could emerge, defined by more complicated systems of constraints. Eventually this gave rise to the many-leveled system of many kinds of mutually-defining constraints that constitutes our observable universe.

At each stage, most of the possibilities allowed in the previous stage were ruled out by new constraints. So as this process went on, the indeterminacy of the original chaos was gradually used up. In the final stage, with the emergence of our current system of physics, situations constantly arise that are so tightly constrained that events seem strictly determined by exact mathematical laws. But even at this stage, at the quantum level, what happens is still essentially random. Yet the complex constraints of quantum physics produce a statistical weighting of probabilities that maintains our higher-level environment of precisely measurable facts.

What's appealing about this idea is that each stage inherits and incorporates all the constraints defined by prior stages. This should make possible an empirically grounded reconstruction of the sequence of stages through which our current physics emerged. Here I attempt a very rough and incomplete outline of such an "archaeological" analysis. The goal is not to develop any actual theory, but only to make it plausible that a functional analysis of our current well-established theories can potentially explain where our universe came from and why it works the way it does.

2 Stage I – Interaction

What kind of constraint could be the starting-point for this process? In quantum theory, everything that happens in the world ultimately consists of one particular kind of event, i.e. quantized interaction – tiny discrete moments of connection between things, involving a minimal quantum of action. In our current universe this is a measurable quantity – Planck's constant – and there are many different ways in which different types of particles interact. But none of this could have been definable in the original chaos of unconstrained happening. To begin with, then, we need a more general concept of interaction.

Usually we think of interactions as distinct from the things that interact. But quantum physics blurs this distinction, since interactions are described as particles, and particles are defined by their interactions. And in our initial environment of free, indefinite possibility, there's no context for defining "things" of any kind. So we start by conceiving interactions just as momentary connections between other interactions, in a web of interlinking events that are otherwise indeterminate. At this stage we'll imagine the physical environment as a superposition of all possible connections between events, in a network with no definite topology. We can't yet distinguish different types of connection, or specify which events are connected to which others. The fact that all interaction is quantized, in our current physics, just means that these connections are the simple basic elements from which all observable phenomena are built. To begin with there's no context in which any deeper structure could appear within these primitive events.

The initial constraint, then, selects out events that connect at least two other such events, within a web of momentary happening. There's no context to determine which possible events satisfy this constraint, but events that don't connect to other events are in any case irrelevant – they can make no difference to anything that happens within this network, and can't contribute to any higher-level order.[5] So this is a self-defining system in the most primitive sense, where the only events that matter are those that connect to events that connect to other events. Neither space nor time have any meaning here – but as we'll see, even this minimal level of structure provides a basis for defining higher-level contexts.

3 Stage IIA – Recurrence

That first constraint is easy to justify, since it's clear that any observable event needs a context of other events it's connected with. And if we imagine the primitive environment as a superposition of all possible one-to-one connections between events, we can also treat it as a superposition of all possible sequences of events, where one interaction leads to the next. We have no context yet for relating these possible chains of events to each other, or for orienting them in space or time. But we can distinguish two different types of possible sequences – those that loop back on themselves and those that don't.

In a web of all possible connections, there are countless different paths between any two events. All such paths are essentially equivalent, since there's no way to differentiate direct from indirect connections, or to count the number of events along any path. Likewise there are countless equivalent paths from any momentary event that loop back again to that same moment, in a recurring sequence. And we can also imagine possible sequences that never loop back on themselves – that always keep on connecting new moments of connection without ever reconnecting to prior ones.

This gives us a second primitive selection rule, where each recurring sequence of events provides its own context, selecting its own events. There's still no broader context that could determine which sequences satisfy this rule. There's no way in which this repeated recycling of events could make any difference to anything else. Nonetheless, the distinction between recurrent and non-recurrent event-sequences does play a fundamental role in the physics of our current universe. In our world, every observable sequence of connected events has a definite order in time, and these sequences never loop back on themselves. All observable happening goes from the past into the future, never the other way. And as we've seen in the last chapter, the four-dimensional spacetime of our universe is specifically structured so as to maintain a consistent distinction between the factual past and the possible future for all communicating observers.

So in our current physics, this second selection rule operates negatively: it eliminates all the recurrent event-sequences, to enable a universally consistent time-ordering for all observable events.[6] On the other hand, at the deeper level of quantum superpositions, these recycling sequences are ubiquitous; they constitute the entire structure of the quantum domain. As described by wave-functions, quantum systems aren't things that just persist through time, maintaining a static identity, as things do in classical physics. These systems exist by continually recycling through sequences of all their possible states and interactions. Probability amplitudes are largely determined by phase-relationships between all these cyclical sequences.

In the path-integral picture, for example, if a photon is emitted by particle A and absorbed by particle B, its wave-function includes amplitudes for all conceivable paths between A and B – including paths that are disallowed by the laws of classical physics. Each of these paths contributes to the total amplitude for the interaction – but almost all paths are cancelled out by nearly identical paths that have opposite phase. The only trajectories whose amplitudes aren't cancelled out are those close to the photon's classically defined trajectory; only these possibilities end up with a significant probability of being observed in an actual measurement.

This is essentially how quantum physics achieves the precise determinism of the classical realm, on the basis of random events. Phase-relationships between cyclical quantum systems shape the statistics of interaction so that classical outcomes become overwhelmingly probable. Of course all these phases and amplitudes are defined by the physics of our current universe, where quantum systems have measurable frequencies, and wave-functions represent a cyclical process that takes place in space and time. But we can see this recycling as reflecting a more primitive stage in the emergence of our current physics, where the only sequences of events that could have any definable character at all were those that defined themselves by continually reselecting a sequence of events.

At that stage there was no external context to define any relationships between these cyclical sequences, while all the other, non-looping sequences were entirely unconstrained. There's so little structure here that it's not clear how any higher-level system could emerge from it. Fortunately, it's not our task here to invent new levels of self-defining structure *a priori*. Rather, within the complex physics of our current universe, we're looking for some simple system of selection rules that provides a context for relationships between different event-sequences. This system needs to be able to define itself without reference to the spacetime metric, and yet serve as a framework on which our world of measurable space and time could be built.

4 Stage IIB – Pre-Metric Spacetime

As noted above, a basic feature of our observable universe is the ordering of all events in time, which means excluding any event-sequences that loop back on themselves (or rather, restricting all these self-recycling sequences to the subliminal domain of quantum superpositions). But there also needs to be some way of relating all the non-looping sequences to each other so they all proceed in parallel, so to speak, lined up along a common time-axis. The events along one sequence need to be connected with events on other sequences in a way that maintains a universally consistent temporal order.

Now as discussed in the accompanying essay on Relativity, our universe does have a way of ensuring the consistent time-ordering of all connected events, based solely on the local frames of communicating observers. Rather than assuming any relations of simultaneity between distant events, as in Newtonian physics, it orders events through the structure of light-speed communications. We noted that this "skeleton" of null intervals is independent of the spacetime metric, since null intervals are null in any reference frame. If we take this skeleton to represent a primitive level of structure underpinning our measurable space and time, this indicates clearly enough where we can look for the next stage in the series of emergent self-defining systems – in the structure of the electromagnetic field.

Usually we describe this field in terms of measurable quantities – potentials with specific values at each point in the spacetime metric. But there are peculiar features of electromagnetism that point to a more primitive underlying structure. The field is gauge invariant: its local potentials are defined in relation to each other, and have no absolute values at particular points in space and time. The magnetic field is determined by variances in the electric field and vice versa, so these two components of the combined field provide contexts for each other. Accordingly, Maxwell's equations can be cast in a form that has no reference to measurable intervals in space or time.[7]

While the two previous stages were each defined by a single selection rule, in this primitive, pre-metric version of electromagnetism we have a system of several rules, each defined in the context of the others. The first of these constraints selects out a specific subset of all possible non-looping event-sequences, as the set of sequences on which all the other rules of the system operate. This initial rule corresponds, in the physics of our current universe, to the conservation law for electric charge. It selects sequences that always keep on adding new events, never terminating or looping back on themselves. It also requires that selected sequences remain distinct from each other, never branching into multiple paths or merging with other paths. That is, it selects event-sequences corresponding to the paths of charged particles in classical electrodynamics.[8]

To begin with, these continuous charge-sequences have no definite relationship with each other. The function of all the other rules is to define such relationships, setting up a structure of cross-connections between charge-sequences corresponding to the field of photon-interactions across null intervals. The resulting system selects out sets of possible charge-sequences that are everywhere consistently aligned with each other, on a common time-axis.

In this primitive pre-metric system, though, charges don't have definite positions or trajectories, and its parameters have no quantitative magnitudes. All parameters of this system represent simple binary choices between symmetrically opposite possibilities. Each of its rules determines whether a charge goes in one direction, relative to some axis, or in the opposite direction.

For example, the initial parameter – the conserved electric charge of each sequence – can either be positive or negative. These represent the two opposite directions along the time-axis defined by the system – that is, positively-charged sequences are those that go one way in time, negatively-charged sequences go the opposite way. The time-axis is symmetrical, having no preferred direction; however, the charge conservation rule requires positive charges to remain positive and negative charges negative; they're never allowed to turn around in time. Of course in the physics of our current universe, there's only one direction of time, defined by the irreversible processes of measurement at the quantum level, and by classical thermodynamics. But even here, electromagnetism has no "arrow of time" – all its rules are time-reversible, and negatively-charged particles act just like their oppositely-charged antiparticles going the other way in time.

The other rules of this system define the two related fields, electric and magnetic, that connect charge-sequences with each other. Each of these rules determines a binary choice between opposite directions in space, so that positive charges go one way, negative charges the other. These can either be opposite directions along a spatial axis, or opposite directions of cyclical rotation around a spatial axis. This is a feature peculiar to electromagnetism – that its rules relate these two types of direction to each other, linear and cyclical. We can think of this as another higher-level version of the difference between looping and non-looping sequences taken over from the previous stage. The electric and magnetic fields are symmetrically connected, with a linear direction in one field corresponding to a rotational direction in the other.

These fields are defined by two other conserved parameters – linear momentum and intrinsic angular momentum (spin). These properties are carried both by the charge-sequences and by the photon-field of cross-connections between them. These momenta have no magnitude, since this system doesn't yet define any distances, angles, velocities or accelerations. Here momentum is just another binary choice between opposite directions, either along some spatial axis (for linear momentum) or around a spatial axis (in the case of spin). Because the system's rules relate linear directions on a spatial axis to rotational directions in a plane orthogonal to that axis, the system as a whole defines a pre-metric space of possible directions that's inherently three-dimensional.

Conservation of momentum serves two functions. This rule maintains the continuity of each charge-sequence, by requiring that the direction of a charge's linear momentum and the direction of its spin get passed on from one interaction to the next along each charge-sequence. But these directions also change as the charges interact, exchanging momentum with each other through the combined fields. So the rule of momentum conservation also ensures that any change in the momentum of one charge is balanced by an opposite change in another charge's momentum, along the same spatial axis.

I won't try to detail all the rules for electric and magnetic interaction between charges, in which both types of momentum are involved. These are familiar, corresponding to Maxwell's equations: for example when two charges interact, the linear momentum of each charge is redirected along the spatial axis between them: if the two charges are different they go toward each other, or the opposite way if the charges are the same. Every change in a charge's linear momentum also generates a change in the local magnetic field, which affects both the linear momentum and the spin of other charges. In the space and time of our current universe, the combined effect of these several interaction rules defines remarkably complex trajectories when charged particles interact. But in the primitive system I'm sketching here, there are no positions or trajectories in space and time, only a simple self-defining system of rules and parameters determining symmetrical changes of direction along arbitrary sets of orthogonal axes.

These rules operate on a web of null-interval connections between charge-sequences, a web that has no definite structure to begin with. Any event on one sequence can be connected with any event on another, giving a superposition of possible cross-connections. But from this superposition, the system of rules selects out sets of connections that maintain a rigidly determinate structure. Every interaction along a charge-sequence inherits its directions of linear momentum and spin from the prior interaction in the sequence, and those directions change, in each interaction, according to a rule that connects it with an opposite change on another sequence. All the rules are temporally symmetrical, applying the same way in either direction on the time-axis. But in each interaction there's a binary choice between opposite directions, and a rule that strictly determines which direction must be chosen. And the system as a whole operates to select out sets of possible sequences that are all consistently aligned with each other on the universal axis of time, in a three-dimensional space of possible directions.

This rigid determinism doesn't carry over to the physics of our current universe, where there are many more degrees of freedom and many more interaction-rules. As noted in the initial essay of this series, the dynamics of our current world is far too complex to be mathematically determined – instead, the trajectories of particles are defined statistically, by a combination of mathematical laws and random selection. At this primitive, pre-metric stage, however, the rules need to be simple and unequivocal, because there's so little pre-established structure to build on. Only interactions that happen strictly according to this set of universal laws can have any definite character at all. The rigidity of this system is what enables it to maintain a consistent set of spatial and temporal orientations among all its selected sequences.

While each of its rules and parameters are quite simple, though, this system as a whole is fairly complex. Couldn't there be a much simpler set of mutually-defining constraints that could organize relations among sequences of events? Yes, very likely – but it's not hard to see why this system in particular became the basis for our observable world. The metric version of electromagnetism is incredibly versatile, playing a key role in every interaction except gravity. It underlies the structure of atomic electron-shells and their ability to make molecules, and it determines the higher-level properties of all forms of matter. Its twin fields sustain oscillations that not only distribute stellar energy over vast distances, but provide a medium of communication that carries essentially all the empirical information we have about our universe. The functionality of this system is unparalleled, and it may well be that no simpler system could have filled all these roles.

So we can imagine that in the superposition of all possible sequences of events, there was some set of interconnected sequences that happened to satisfy this complicated system of constraints. Since several different kinds of rules are involved, such a constellation would be extremely unusual – but if it did arise anywhere, its structure of mutually-defining fields would provide a context in which more and more events could be selected, conforming to the same rules. Just as light propagates out into space, in our current physics, we can imagine such a system spreading out into the space of possibilities, propagating its structured superposition of relationships across null intervals, in both directions along its self-defined axis of time, continually replicating the same pattern in new sets of interactions.

5 Stage IIIA – Local Gauge Symmetries

In the physics of our current universe, electromagnetism is one of three very different systems of rules that reproduce themselves this way – each interaction according one rule setting up a context in which another rule applies. The other two are the systems of weak and strong nuclear interaction, which inherit many of the features of pre-metric electromagnetism. They both define certain subsets of non-looping sequences as particles that carry new conserved parameters – weak and strong versions of hypercharge and isospin – as well as electric charge, linear momentum and spin. Like electromagnetism, they both connect fermions with each other through local gauge-invariant boson fields.

But neither of the nuclear forces is anything like a straightforward extension of electromagnetism. Both are remarkably complex, and in distinctly different ways. So the Standard Model actually gives us three quite disparate theories that are unified only in being described by similar mathematics. That similarity is important, pointing to some kind of common origin for the three Standard Model forces. But the usual way of conceiving this – imagining them as originating from an initially unified force through spontaneous symmetry breaking – doesn't tell us very much. It can't explain why the initial unified force should have such complicated symmetry to begin with, or why random breakage should result in three so peculiarly different systems of interaction.

On the other hand, it's clear that each of these systems plays a significant functional role in creating our observable world of atoms and molecules. The strong force confines huge quantities of energy in tiny atomic nuclei, giving them enough mass that they're precisely localized in space, with enough inertia to serve as stable, point-like central charges for the Coulomb field in which electron-shells are organized. The weak force plays the key role in nucleosynthesis, supporting the emergence of many types of atoms and molecules; it also regulates the distribution of matter and energy out into the universe when stars collapse and explode.

Here we imagine the relationship between these three systems of interaction in the following way. We'll suppose that the pre-metric structure of electromagnetism provided a context in which a great variety of higher-level systems could define themselves, by adding new sets of selection rules to those already established. Just as we imagined Stage IIA as a superposition of all possible event-sequences, here we imagine a superposition of all possible systems that could define themselves on this same pre-metric pattern of conserved charges interacting through local gauge fields. But out of all these possible configurations, only two very complicated ones turned out to be useful in the foundation of our world. Along with electromagnetism, they provided a framework of universal rules that could support atomic structure and measurable spacetime. And in the newly emergent environment of interacting atoms, all the other possible pre-metric structures became irrelevant, leaving no trace in the physics of our current universe, where even virtual interactions in the quantum vacuum follow the Standard Model.

Each of these three systems has its own mutually-defining parameters and fields, its own set of rules operating in its own space of possible directional orientations. The pre-metric space of electromagnetism discussed above is a primitive version of the four-dimensional spacetime in which we live, whereas the spaces of the nuclear forces are unrelated to spacetime, being structured by different symmetry groups. And since these spaces define themselves separately from spacetime, we can interpret them as distinct self-defining systems arising in the pre-metric universe.

Now symmetry in general can be conceived as a relation between different kinds of information, where one parameter has a definite fixed value while other related parameters remain in a superposition of all their possible values. In archeological physics, symmetries can be seen as reflecting the different stages at which certain parameters become definable. For example, if electromagnetism defines a universal time-axis before there's any context that can determine a preferred "arrow" of time, then the rules of that system will be symmetrical with respect to the direction of time. A symmetry arises by default, whenever the values of one parameter are defined before those of other related parameters.

The local gauge symmetries of all three Standard Model systems can be understood this way. If these systems of mutually-defining selection rules emerged before the establishment of the spacetime metric, then their potentials could not be defined in terms of relative locations in space and time; they could be defined only relative to the gauge fields. So, in our current universe, these potentials can be assigned arbitrary values at any spacetime point without changing the underlying field-structure.

I won't attempt to describe the many complex selection rules of the nuclear interactions. I will only point out some of the ways these systems differ from primitive electromagnetism, since these set the stage for the emergence of our measurable space and time.

In the first place, it's clearly important that both the weak and strong forces have limited range, acting mainly on the scale of nuclei. But since these are originally pre-metric systems, the range of these two forces isn't defined directly in terms of distances in space. Instead, quite complicated mechanisms are involved. In the case of the weak force, the three bosons that carry weak hypercharge and isospin also interact with the Higgs field. In the metric spacetime of our current physics, this gives these particles large masses, drastically limiting the range over which they can transfer energy and momentum. As to the strong force, quark confinement is accomplished by an entirely different mechanism that's not yet well understood, although the strength of interaction between quarks is thought to be independent of the distance between them, consistent with the pre-metric character of this system.

Both nuclear forces thus contribute to the extreme localization of nuclear interaction, though at this stage there's no continuous scale of measurable distances. We don't yet have a space and time in which particles with mass move at sub-light speeds. Here there's only the electromagnetic "skeleton" of null intervals, supplemented by new selection rules with larger symmetry-groups, defining interactions in their separate possibility-spaces. Before the actual emergence of atomic structure, these nuclear forces wouldn't yet have been distinguishable from any other conceivable system of pre-metric, locally gauge-invariant interaction.

The nuclear forces depart from the pattern of electromagnetism in another way. Electric charge never varies – any charged particle is permanently either positive or negative. Charge-sequences exchange linear and angular momentum through the photon-field, but photons don't carry electric charge. The situation is different with the two nuclear forces, whose boson-fields do carry charge. The strong force operates with a three-fold color charge, so the charges of quarks constantly change through gluon-interaction with other quarks. Only the total color charge of nuclear particles is conserved – and in fact, selection rules require that any stable combination of quarks has to have a net zero color charge.

I noted above that the basic pre-metric system of electromagnetism is fully deterministic, and needs to be so in order to define itself. That's because in Stage IIB there was no given external context that could define relationships between charge-sequences. So for there to be any definable relationship between charge-sequences, all the rules of the system had to be strictly followed. If a positive charge could at any point become negative, for example, there would no longer be any definable axis of time.

Stage IIIA, on the other hand, already has the established context of electromagnetism as a basis. This means that the gauge-field structure of relations between sequences can be much more permissive. So long as the total color-charge of every nuclear particle is zero, the color of their constituent quarks can be indeterminate, always cycling through a superposition of three possible colors. Likewise in the weak force interaction, the protons and neutrons in a nucleus are constantly exchanging identities with each other, though in stable nuclei the total number of protons and neutrons remains constant.

To take another example, the electromagnetic system is symmetrical not only with respect to time and charge, but also parity. If magnetic interaction follows the left-hand rule for a negative charge, it has to follow an identical right-hand rule for positive charges – again, because there's no external context to define any difference between one direction and the other on the time-axis. But the larger symmetry-groups of the nuclear forces do allow for differences between right-handed and left-handed particles, though it appears that parity symmetry is actually broken only in weak interactions. This also implies that weak interactions break time-symmetry, though this is can only be observed in a few rare types of particle decay. It has no clear connection with the emergence of a radical difference between the past and future in our current world – to be discussed in the following section. But this illustrates the much greater freedom of operation that local gauge-field systems can have, being built on top of the stringent selection rules of primitive electromagnetism.

Since many aspects of the weak-force system are still mysterious, it's not clear whether its breaking of parity-symmetry plays a significant role in supporting our observable world. It's possible that some of the peculiar complications of the Standard Model have no functional role, being merely epiphenomenal – for example, it's not obvious that the three generations of quarks and leptons are required to make our self-defining universe work. So while we should expect to find a functional explanation for all the primary features of our currently-known physics, there's no reason to assume that this should apply to every peripheral detail.

6 Stage IIIB – Locality and Gravitational Spacetime

So far we've been dealing only with superpositions of possibilities, constrained by selection rules. The self-defining systems described above are only possible patterns of connected events, within an ocean of other possibilities. What distinguishes them is only that these particular patterns were incorporated as fundamental supporting structures in the architecture of our observable universe. And this universe is based on an entirely new way of defining constraints on what's possible. In addition to universal laws of physics, we now have "initial conditions" to which those laws apply – that is, specific local situations shaped by specific facts determined in other local contexts. Here the world not only defines patterns of possibilities, but also determines which patterns are actually instantiated in observed phenomena – for example, which of all the possible outcomes of a given situation are actually observed, becoming the objective basis for further determinations.

Our task now is to try to imagine how this factual and observable kind of physical existence could have begun. I've argued that the key event was the formation of stable atoms, connecting and communicating with each other via the electromagnetic field. But this was neither the beginning nor the end of the process. Atoms do have a fundamental role in physics, much as self-replicating cells have in biology. They define basic universal standards for distance and frequency; they operate as primitive measuring instruments by absorbing and emitting photons of specific energies, and they're able to store this energy-data over time by reconfiguring their electron-shells. And of course, they also serve as building-blocks for every kind of stable material structure. Nothing in the subatomic domain even approaches this level of finely-tuned functionality.

Nonetheless, the formation of atoms depended on a long and varied pre-history, as discussed above, that produced the array of subatomic particles early on, and eventually gave rise to an environment in which stable atoms could exist. Moreover, even once the web of interacting atoms began to operate, it could at first define very little higher-level information, since it consisted mainly of hydrogen and helium atoms widely scattered through space. The emergence of our world of observable phenomena happened very gradually over a long period of time, as the cosmic environment underwent great changes. Similarly, the "collapse" that happens in quantum measurement is not a specific event at a specific point in time. Measurement occurs insofar as a context makes it possible to define certain aspects of a factual situation, to a certain degree of precision, and such situations arise only over a certain space and time. Likewise the origin of our observable universe happened just insofar as the evolving interactive environment began creating contexts that made the various aspects of our physical reality empirically determinable.

That's the historical picture, of a world gradually evolving over time. This is the picture we construct retrospectively from presently available evidence, assuming that the basic underlying physics hasn't changed since the beginning. In the other complementary picture, the one we're trying to develop here, time and space and the laws of physics weren't just given from the start. They came into being in a series of distinctly different stages. And in this picture, the emergence of a world of measurable facts was not at all gradual; it required a tremendous leap to a new level of self-determining organization. We saw another leap like this above, in Stage IIB, where the origin of pre-metric electromagnetism involved the co-emergence of a complicated set of rules and parameters. The case with Stage IIIB is more radical: it could only happen because two very different and profoundly complicated systems were somehow able to emerge together, providing contexts for each other.

One of these was the quantum physics we describe in the Standard Model. It inherits many rules and parameters from the previous stages, but redefines them all as a system of quantitative relationships. All its interactions (Stage I), now come to involve specific quantities of action, based on the minimal unit of Planck's constant. The self-recycling sequences of Stage IIA show up in the superpositions described by quantum wave-functions, where these sequences acquire definite frequencies and wavelengths. The parameters of IIB electromagnetism – electric charge, the field-potentials, spin and linear momentum – are all now redefined as the scalar and vector quantities related by Maxwell's equations. Likewise all the parameters of the nuclear forces (Stage IIIA) acquire specific values tuned to support the existence of stable complex nuclei.

Now all these parameters – even those of the nuclear forces – are empirically measurable through their effects on the motion of things in space and time. This depends on the other newly emergent system – the spacetime metric, built upon the IIB skeleton of null-intervals. This metric is structurally complex in a completely different way from quantum physics. Where the latter defines many different interactions and constraints, here we have only gravitation and inertia. But gravity not only pulls distant things together; it also determines the distances between them at each moment. It defines an environment of continuously changing spatial relationships between pairs of local entities, operating over a tremendous range of scales. The formal structure of its rules, expressed in Einstein's equations, is remarkably simple and elegant, in stark contrast to the mathematics of the Standard Model. But the actual patterns of interaction it determines – the trajectories of countless particles and aggregate bodies, all affecting each other's motion – are far too complex to be mathematically computable.

Because every kind of quantitative measurement depends on this geometry of relative distances and velocities, it provides a common ground for translating between different kinds of physical information. This is a key requirement in a world where different systems of observable parameters provide contexts for each other. But spacetime geometry doesn't accomplish this by itself. Space and time themselves are only observable because there are locally situated entities that follow continuous trajectories, which the electromagnetic field makes it possible to track. To define such entities, Stage IIIB introduces a new kind of conserved parameter, one that ties together all the various types of interaction. This is energy – including the energy that's localized in the form of mass.

Like other conservation rules, the conservation of energy has multiple functions. It preserves the constant rest-mass of individual entities along their trajectories, and regulates the sharing of energy between them when they interact, whether through gravity and electromagnetism or through the nuclear forces involved in particle collisions and decays. Unlike all the other conserved parameters, though, energy takes many different forms, including the potential energy of all the various fields, and even vacuum energy. Since every interaction involves a transformation of energy, this parameter plays a key role in making facts defined in different contexts relevant to each other.

Energy conservation also plays a key role in the "collapse" that creates new facts by random selection, in quantum measurement. Only one outcome can be observed, in a measurement, because this selection rule requires that the total energy involved in the situation must remain constant. While many kinds of interaction are needed to set up any measurement-context, the factual input that constitutes a situation has always a specific total energy; that same total energy has to appear in the facts that constitute the outcome. All other possible outcomes included in the situation's wave-function just vanish without consequence, since there's only energy enough to realize one of them. So both the transformations of energy and the conservation of total energy have vital functions in maintaining a determinate reality constituted by different kinds of information.

What essentially distinguishes the physics of our observable world from the previous stages, then, are these two new parameters: distances in space and time, on the one hand, and the energy conveyed by fields and particles, on the other. The relationship between these two parameters is given in Einstein's field equations, which relate the geometry of spacetime to the distribution of local energy-densities.

To unpack this, let's consider first how energy gets localized. This happens in many different ways, but primarily by giving mass to atomic matter. Atoms localize energy mainly in their nuclei, where several complicated mechanisms are involved. First, elementary particles acquire mass through interaction with the Higgs field, which operates differently on quarks and leptons. But particle masses make up only a small part of the total nuclear mass, most of which comes from the huge confined energy of strong-force interaction among quarks and gluons. A much smaller contribution to atomic mass comes from the mass of its electrons, the energy of their self-interaction with the electromagnetic field and the energy binding electrons to the nucleus. Then too, all the higher-level dynamics – from chemical interaction between molecules to gravitational interaction between planets, stars and galaxies – also contribute localized energy to the densities that appear on one side of Einstein's equations.

On the other side is the local curvature of spacetime – gravity – which plays an indispensable part in evolving our observable universe by pulling atoms together into galaxies and stars, eventually producing all the heavy nuclei needed to make stable material structure in dust, rocks and planets. But there are other aspects of this geometry that are equally important. As noted in the essay on Spacetime, locally and at low velocities it very closely approximates a flat Euclidean geometry, with space and time as independent variables. And since gravity is so weak, compared with all the other forces, the curvature of spacetime has no effect on the scale of quantum physics, which can therefore define itself within an essentially classical framework of space and time. Further, Einstein's geometry makes inertial reference-frames definable even where the curvature is very strong. This means that unlike position or velocity, acceleration and related parameters have objectively measurable values that are the same for all observers, so long as they make their measurements in local inertial frames of reference. So together with quantum mechanics, general relativity supports the simple deterministic framework of Newtonian physics over a very broad range of scales.

Finally, besides the small gravitational constant, two other parameters play key roles in this spacetime structure. One is the cosmological constant in Einstein's equation, related to the anomalously small vacuum energy coming from virtual interactions in the quantum domain. The other is the initial rate of the expansion of the universe. All three of these parameters need to be very finely-tuned to each other, to provide enough time for stable material structure to emerge in the universe. If their values had been slightly different, either the expansion of space would have ended very quickly in a gravitational collapse, or it would have accelerated so rapidly that no higher levels of structure could ever have evolved.

The bottom line here is that the origin of our observable world involved the co-emergence of two complementary kinds of information. On the one hand, there came to be determinable facts about localized entities with mass, eventually included everything from particles to clusters of galaxies. On the other, it became possible to determine facts about the interrelated trajectories of all these entities in space and time. At a fundamental level, both the existence of local entities and the coordination of their relative motion depend on exceedingly complicated functional arrangements, as described respectively in quantum physics and general relativity.

To complete this picture, however, we need to consider one more basic feature of our Stage IIIB universe, equally essential to making this system work. In different ways, based on different structural foundations, quantum physics and gravitational spacetime both support the clear and simple objective reality described by classical physics. Over a very wide range of scales, all the underlying complexities of our deeper-level theories can be ignored; within this range, the world operates as a vast body of precisely determinate, context-independent fact, subject to a simple set of mathematical laws. It's hard to imagine how any kind of measurement could be possible without the perfect dependability of this higher-level physics, with simple and exact mathematical relationships among all its parameters, in a transparent framework of Euclidean space and time. Neither relativity nor quantum theory could function without reliable clocks and rulers that define local intervals in time and space exactly the same way everywhere. So there are really three pillars needed to support the functionality of an observable world: quantum physics, spacetime physics and the classical physics they maintain between them.

7 Summary – The Physics of Possibility

We come back to the question posed at the beginning of this essay: how could a self-determining system as deeply complicated as our universe have come to exist? The aim of this archaeological analysis was to break the problem down into a series of stages, in each of which a new dimension of physical structure could plausibly emerge. Yet the transition to this final stage involves so many new kinds of quantitative information, related to each other in so many different ways, that it may hardly seem reasonable to suppose it could all become definable at once.

In the earlier stages we could sort out most of the structural components of our known physics into a more or less plausible sequence, though with increasingly dramatic advances in complexity from each stage to the next. Stage I has only the basic notion of interaction. In Stage II we consider all possible sequences of interactions – IIA involving sequences that define themselves by recycling through a series of events. These sequences are special, but arise naturally in a superposition of all possible sequences. In contrast, Stage IIB requires a leap to a new level of structure, one that defines reciprocal relationships between distinct charge-sequences. To accomplish this a number of different selection-rules have to emerge together, along with the new conserved parameters of charge and momentum.

The same pattern is repeated in Stage III, which considers higher-level systems based on the skeleton-structure of pre-metric electromagnetism. In IIIA, again we imagine a superposition of possible systems of this kind – those that define themselves by adding new selection rules to the IIB structure, with new types of charges and gauge fields. The two Standard Model systems of nuclear interaction can be seen as arising naturally within this superposition, along with many other complex systems as well as simpler ones. When we come to Stage IIIB, however, we see another leap to an entirely new level. This requires two very different kinds of complex systems to emerge together – the quantum structure of atoms, and the gravitational metric of spacetime. Between them they define the self-sustaining process of setting up measurement-contexts, in which all the parameters of the prior stages become determinable quantities.

Now as already noted in the previous section, this last transition – from superpositions of possibilities to a world of objective, measurable facts – didn't take place all at once. It happened over a long period of time, as contexts arose in which new kinds of facts were defined, that could keep on setting up these contexts. This process first began in the environment of communication between stable atoms; the key facts that kept on being redefined were about the atom's locations, their uniform structure and behavior, quantitative facts about the properties of sub-atomic particles and the kinds of interaction that make those properties determinable. But for a long time, the facts that are most familiar to us today wouldn't have been definable – such as the properties of bulk matter or the trajectories of massive bodies. At the very beginning of the atomic universe, the only higher-level facts that could make any difference were the gradually declining energy-density of the environment and the gradually increasing differences in density over vast regions of space.

So what slowly emerged over the first few billion years was our environment of deterministic interaction at intermediate scales of distance, velocity and energy – the world of macroscopic objects, where classical physics and chemistry give rise to the amazingly diverse array of phenomena we can observe today. But the physical foundations of this universe could not have developed gradually over time. The relational geometry of spacetime couldn't define itself apart from the context of communications set up by nuclear and atomic physics, or vice-versa. The basic premise of this essay is that all observable information needs the support of other kinds of observable information, and that most of what we know about the deep-level structure of physics may be needed for there to be any observable phenomena at all. And if that's so, then the transition to a world that's able to define specific facts necessarily involved the co-emergence of many different kinds of measurement-contexts.

That may well seem miraculous.[9] Yet given the wealth of possible systems of interaction that became definable in the previous stages, it must have been possible for one particularly complex set of mutually defining systems to begin a self-sustaining process of determining quantitative facts. Some combination of selection rules must have been able to knit the nuclear forces together with electromagnetism to support the appearance of stable atoms and molecules, in the context of an expanding gravitational spacetime. And though we've so far given little thought to the question of how all these systems work together to define a metric of distances and frequencies, it seems that our current theories must have a great deal to teach us about this. If we can gain some clarity about the functioning of our contemporary universe, that should offer insight into the question of how the creation of measurement-contexts first began.

At any event, the "collapse" that occurs in every measurement-event recapitulates this same sort of miracle. As argued in the initial essay, whenever a context makes it possible for a fact to be determined and communicated, the laws of physics require that a specific fact be selected at random; nothing more is needed to bring this about. Though any such context depends on many kinds of information defined by many other contexts involving other interactions, this tremendous complexity presents no obstacle to a process that operates by random selection. The laws of physics function to ensure that these contexts continually arise, and that there are always possibilities that will satisfy all relevant constraints. But the laws don't need to determine the specific outcomes of measurement situations. Outcomes just happen because they can, and insofar as they happen to satisfy all the constraints, they make further outcomes possible in new situations.

The origin of this self-perpetuating physics of measurement can be conceived in a similar way. In the underlying chaos of indeterminate happening, there were relatively simple sets of events that happened to satisfy combinations of mutually-defining selection rules. These became the basis for a plethora of much more complicated systems of rules and parameters, including those that constitute our current physics. And once the environment could sustain a web of mutually-supporting measurement-contexts, nothing further was needed to realize certain possibilities as facts. Like the process of self-replication in biology, it was in the nature of the process to keep on making itself possible again, in new situations.

This means that our so-called laws of physics are entirely *de facto*. Nothing established them, nothing enforces them; they’re just a set of constraints that reflect the way random events can keep on setting up the same kinds of opportunities, continually redefining the same system. At bottom anything can happen and everything does. But only when things happen according to all these laws, only where they cooperate with other events to sustain a dependable communicative environment, can things be observed or have any definable character, contributing to the contexts in which other kinds of things become definable and observable. It doesn’t matter how complex the laws are or how much fine-tuning in required, so long as they work. It doesn’t matter if several different mathematical frameworks are needed to represent them, or if the math is only computable in very simple situations, or even if it’s only self-consistent within certain limits. Physical laws don’t control the world; they only express its particular ways of defining itself.

Notes

1. A somewhat similar approach is presented in the context of string theory by S. W. Hawking and Thomas Hertog, "Populating the Landscape: A Top Down Approach", https://arxiv.org/abs/hep-th/0602091:

   > "Here we put forward a different approach to cosmology in the string landscape, based not on the classical idea of a single history for the universe but on the quantum sum over histories. We argue that the quantum origin of the universe naturally leads to a framework for cosmology where amplitudes for alternative histories of the universe are computed with boundary conditions at late times only."

2. The fact that our current theories break down and become inconsistent as we approach the "Planck scale" is generally taken as evidence that a deeper theory is required. This assumes there must be some set of facts and principles that were definable even at the very origin of the universe. Here we don't ask what really happened at the beginning, because no aspect of our current physical reality could have been definable then. Our cosmological history of the early universe is a retrospective projection of the emergence of the world of communicating atoms, and this projection only makes sense in terms of atomic physics.

3. In contrast, the quantum vacuum of our current universe is a highly structured combination of many kinds of quantum fields. It consists of "virtual" events that satisfy most of the constraints that apply to actually observable interactions, as described by the first four stages presented in this chapter, but not the constraints of the final stage that defines our observed reality. This quantum vacuum is "empty" in the sense that its events can have no determinate effect on anything observable, but it plays an important role in structuring the statistics of the quantum realm.

4. For an explanation of the schema of five stages developed in this chapter see the forthcoming Appendix on The Concept of Context and the Stages.

5. Clearly events that connect with no other events can't play any role in an observable world. But the same is true of events that connect to only one other event in the network. Such dangling loose ends aren't interactions, in the sense of this section – they can't participate in any higher-level contexts that might give them definable characteristics.

6. Of course spacelike separated events are not connected and do not have a definite order in time. But the light-cone geometry of relativity still disallows any looping back in time – assuming that certain "pathological" solutions to the equations of General Relativity don't apply to our universe.

7. See David H. Delphenich, Pre-Metric Electromagnetism (2009), Neo-classical Press, neo-classical-

physics.info/electromagnetism.html, "On the electromagnetic constitutive laws that are equivalent to spacetime metrics," arxiv.org/abs/1409.5107, "Pre-metric electromagnetism as a path to unification," arxiv.org/abs/1512.05183, "A pre-metric generalization of the Lorentz transformation," arxiv.org/abs/2002.09500,

The following is from the Introduction to "Complex Geometry and Pre-Metric Electromagnetism," arxiv.org/abs/gr-qc/0412048:

> Since the early days of Einstein's theory of gravitation, it had been suspected by some researchers… that the introduction of a metric into the geometrical structure of the spacetime manifold, although fundamental to the theory of the gravitational interaction, was not only mathematically unnecessary in the theory of the electromagnetic interaction, but from a physical standpoint it was also naïve. This is because the metric structure of spacetime is so intimately related to the electromagnetic structure by way of the propagation of electromagnetic waves that one rather suspects that the metric structure might plausibly follow as a consequence of the electromagnetic structure, rather than represent a basic component of that structure… This also has the effect of saying that gravitation is not entirely independent of electromagnetism since gravitational waves are governed by the same light cones that are defined by the demands of electromagnetic wave propagation.

8. This section considers only the pre-metric structure of classical electrodynamics; it ignores not only quantum electrodynamics, but also the unified electroweak theory and the fractional charges of quarks in the Standard Model, all of which are relevant to the complex combination of roles played by electromagnetism in the physics of our current universe. The assumption here is that none of this complexity was definable in the earliest stages of the emergence of self-defining structure, but that the simple electromagnetism of Maxwell's equations does reflect the most primitive skeleton-structure of spacetime, as described in this section.

9. The origin of the earliest forms of life on Earth could also seem miraculous, since it must have required a very unusual combination of conditions on a quite unusual planet. Even once self-replicating systems became established, it certainly took a great deal of luck for them to survive major geological changes during the early stages of their evolution. But the situation is similar to that proposed here in physics: evidently it was possible for a process of self-replication to begin somewhere, and once it happened it kept on making itself possible. No matter how improbable it was that life could begin and continue to survive, that doesn't make the theory of biological evolution any less explanatory.