II. Your Present Moment in Spacetime

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Abstract

This essay extends the argument begun in “Why Quantum Mechanics Makes Sense,” exploring the conditions under which a physical world can define and communicate information. I argue that like the structure of quantum physics, the principles of Special and General Relativity can be understood as reflecting the requirements of a universe in which things are observable and measurable. I interpret the peculiar hyperbolic structure of spacetime not as the static, four-dimensional geometry of an unobservable “block universe”, but as the background metric of an evolving web of communicated information that we, along with all our measuring instruments and recording devices, actually experience in our local “here and now.” Our relativistic universe is conceived as a parallel distributed processing system, in which a common objective reality is constantly being woven out of many kinds of facts determined separately in countless local measurement-contexts.

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1 The World from Inside

As compared with Quantum Mechanics, Relativity is a classical theory. It takes for granted that there are always objective facts about things, and that the facts are also observable. It assumes the existence of uniformly accurate clocks and rigid measuring-rods, and doesn't consider what underlying physics might be needed to accomplish this. Like quantum theory, however, it makes the values of many observables depend on the context in which they're measured. And while it deals only with one aspect of these contexts – the observer's local frame of reference in space and time – it defines these strictly on the basis of local measurements, without relying on any objectively given global geometry.

My goal here is to show that like the dual dynamics of quantum theory, the peculiar four-dimensional geometry of relativistic spacetime reflects the functional requirements of an observable universe. As noted in the previous essay,[1] information determined in one local context can only be communicated to other contexts if it can be treated as objective, context-independent fact. And even so, these facts must always be definable in local contexts. Though we're used to conceiving the physical world from a "God's eye" viewpoint, as if we could stand outside of space and time and see things as they are in and of themselves, the structure of an observable world has to be definable from inside, from particular points of view in spacetime, communicating with other local viewpoints.

I'll argue that this requirement is the basic rationale for Relativity. To support a physics that continually creates new measurement-contexts, there needs to be a universal structure of spacetime relationships that's everywhere the same; yet even so, this background geometry must be determinable by local observers in their local reference-frames. A global background is needed, but just as in quantum physics, it can't just be given in reality. It has to be defined empirically, through the real-time communication of locally measured information.

I also noted in the previous essay, in discussing the EPR scenario and delayed-choice experiments, that measurement-contexts can never be strictly local in space and time, because every context depends on facts determined in other contexts, which depend on still other contexts. This nonlocality is basic to the quantum domain, where the wave-function represents the possibilities of a situation prior to an actual measurement. Here, on the other hand, we're dealing with the larger-scale spacetime structure of facts that are actually observed. At this level, measurement-contexts are necessarily local, in that the context in which any fact is determined must always consist of other facts that are also available in that same time and place (referring not to an infinitesimal point in a continuum, however, but to the local area in which a certain situation unfolds). Even in the EPR scenario, where the quantum wave-function correlates the spin-states of entangled particles measured in two spacelike-separate locations, these correlations only become observable when both measurement results are available in the same local context. We'll come back to this scenario later on, in considering how Relativity and Quantum Mechanics are related.

2 Two Versions of Spacetime

We're conceiving the physical world as a process in which new facts are constantly being determined in the context of already given facts, determined in previous contexts. This evolving web of communicated information is just what we, along with all our measuring instruments and recording devices, actually experience in present time.

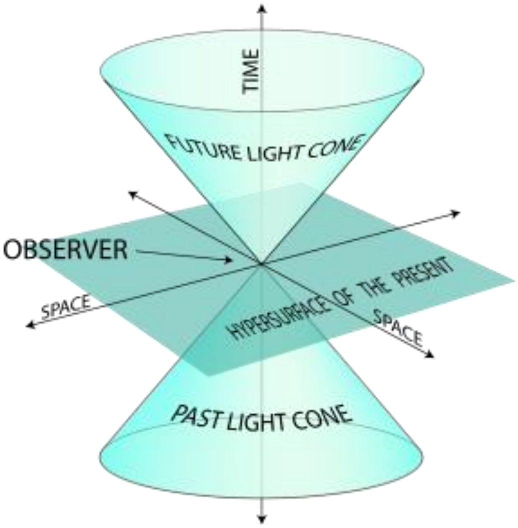
Unfortunately this picture doesn't match the way Relativity is commonly understood today, though it's close to the picture presented in Einstein's initial theory. In essence, Special Relativity is a method for translating between the inertial reference-frames of different observers. Its key innovation was to insist on defining space and time in terms of local measurements, coordinated with each other not by locating them within a global framework, like Newton's absolute space and time, but by means of the light-speed postulate, relating to the dynamics of communication between local contexts.

Early on, however, Minkowski recast the theory as describing the intrinsic geometry of four-dimensional spacetime, once again conceived as a global background-framework. When this opened up the path to General Relativity and the new theory of gravity, the viewpoints of individual observers seemed to be superseded by this deeper conception of objective reality. In fact, because space and time were now conceived as inseparable parts of a single geometry, Relativity came to be seen as proof that our view of the world from inside is profoundly wrong. While from the standpoint of any observer there's a basic and obvious difference between space and time, Relativity seemed to make them fundamentally the same. This gave rise to the idea that our experience of living moment-to-moment in present time must be some kind of illusion: in truth we're actually four-dimensional beings in a static "block universe" where past, present and future events all co-exist, in a body of changelessly given fact.[2]

Now I have no problem with the theory of four-dimensional spacetime, but this way of interpreting it is badly misleading. Relativity certainly does not treat time as another dimension of space, as the "block" image implies. I'm going to argue that the original view of the meaning of Relativity still makes sense, and the peculiar way that space and time are connected, in Minkowski's geometry, perfectly corresponds to our present-time experience of an evolving world. In fact, this particular way of structuring spacetime is just what's needed to support the real-time distributed processing system we're envisioning here. If the world were just a static pattern of events laid out in four (or more) dimensions, there would be no reason why it should have this very special type of spacetime geometry.

To make my argument, I want to contrast two distinct versions of spacetime, both of them conveniently illustrated in the familiar diagram below.

The layout of the diagram itself, with time and space on orthogonal axes, represents an observer's local region in a four-dimensional block universe. It depicts spacetime as if we were standing outside of it, seeing the past, present and future as different regions within a static geometry. Here the observer's present moment is pictured as a 3-dimensional hypersurface containing all events throughout the universe that are happening simultaneously, at this particular point on the time-line.



The basic argument made by proponents of the "block universe" is that according to Relativity, this present moment "now" is frame-dependent – it has no objective physical reality. Different observers can disagree about which set of events are happening "now", since one observer's hypersurface of simultaneity may be tilted with respect to another's. But if there's no physical reality corresponding to our experience of the present moment – no definite boundary distinguishing past events from events in the future – then past and future must be physically the same. Since past events are evidently factual, then future events must be factual as well. Hence the bizarre notion that our experience of living in present time is an illusion somehow generated in our minds, with no basis in physical reality.

The problem with this argument is that it has nothing to do with the present moment that anyone or anything can experience. It's true that there's no physical reality to this universe-wide "hypersurface of the present." But none of the events on this hypersurface – or anywhere else outside the observer's past light-cone – can actually be observed, or have any physical relevance to what's visible from the observer's present-time viewpoint. In the diagram, it's the lower light-cone that represents the three-dimensional space of the observable world – the web of communicated information, as seen from inside. For any observer, this is the boundary that separates the given facts of past history from events that may or may not happen, and will only become knowable sometime in the observer's future.

So what Relativity tells us is not that there's no such thing as the physical present moment. From any observer's viewpoint there certainly is a physical difference between past and future, but this ongoing moment "now" in which each of us lives is essentially local, not universal.[3] The spacetime structure of the observable world is not a global geometry in which everything it situated, but a web of connections between local present moments, connections on or within each other's light-cones. It's the structure of information communicated between real-time local contexts in which new facts are constantly being determined.

These are the two versions of spacetime I want to contrast: on the one hand spacetime as imagined from outside, as a four-dimensional "block"; on the other, spacetime as seen from inside, as a web of local present-time contexts exchanging information. Both conceptions are reasonable and useful, but the view from inside is the more fundamental one. It's also unfamiliar, and much harder to grasp, while the "block" conception illustrated in the diagram is easy and natural to us. That's because it accords very well with classical Newtonian physics, and incorporates very little of what Relativity teaches us.

The difference between these two notions of spacetime can be expressed very simply. In the global block geometry pictured in the diagram time is essentially a fourth dimension of space, so that the spacetime distance between any two events is given by the Pythagorean theorem – it's the square root of $S^2 + T^2$, where S is the spatial distance between two events on the horizontal plane, and T is the distance between them on the time-axis. This means that if two events are distant from each other both in space and in time, then they're even farther apart in spacetime. But Relativity tells us just the opposite. In Minkowski's spacetime the invariant interval between any two events is the square root of $S^2 - T^2$. The minus sign means that space and time are stitched together backwards, so to speak, so that spatial and temporal distances cancel each other. Events that are equally far apart in space and in time – that is, in the diagram, events that lie on each other's light-cones – have zero separation between them in spacetime.

This is well-known to any physics student, but the meaning of these "null intervals" is hardly ever clarified. We often hear, in fact, that the spacetime interval between events lacks any physical significance, being only a convenient aid to calculation. That lets us hang on to our common-sense notion of space and time as an objective universal framework – the view from outside, as shown in the diagram. We're so used to representing space and time this way, on orthogonal axes, that it's hard to realize this is not how space and time are actually connected.

When we think of spacetime from inside, though, the relativistic geometry of null intervals has a clear interpretation in terms of our actual experience. When I look up at night and see the stars, for example, I'm witnessing light emitted from events on the surface of those stars. In the diagram these events lie on my past light-cone, so they're equally distant from me in space and in time, and since spatial and temporal distances cancel each other, these events are immediately present to me here and now. From any point of view, all events on the past light-cone are experienced as happening in local present time.

Of course this doesn't mean the emission of a photon from a star and the absorption of the photon in my retina are simultaneous. Simultaneity is a reciprocal relationship, and light-speed connections across null intervals go only one way, from emission to absorption. There's still a real distance in time as well as in space between these two events, though these distances will be measured differently by observers with different frames of reference. But in every frame of reference these spatial and temporal distances will be equal, offsetting each other.

Now this is not how we usually describe this situation. Usually we take the objective view: if a star is five light-years away from me, then I'm seeing the star as it was five years ago, because that's how long it takes for light to travel across all that intervening space. That way of putting it is reasonable and easy to understand, but it's not fundamentally correct. Relativity tells us that as velocities approach light-speed, clocks run slow and lengths contract. At the limiting velocity of light, time stops and length vanishes – so it actually takes no time at all for a photon to cross any distance in empty space. Events on my past light-cone really are part of my physical present moment "now", in relativistic spacetime; the image of light crawling along through space for many years is just a convenient way of representing this in terms of our commonsense notion of space and time.

At a fundamental level, then, the so-called velocity of light isn't really a speed at which anything moves. It's just a conversion constant between our units of measurement for space and time, reflecting the fact that space and time are cross-connected, so a given distance in space is canceled out by an equivalent distance in time. This explains why light always has the same velocity in any inertial reference-frame. It also explains why nothing can ever move or be communicated faster than light. In Minkowski's geometry there's no such thing as "faster than light," because a spacetime interval can never be less than zero.

This kind of geometry is hard to envision, compared with the "block" geometry that lays out space and time using Cartesian coordinates. Instead we need to conceive spacetime structure built on a web of light-speed connections across null spacetime intervals. For every observer there's a unique, ongoing local "now" – the real-time context in which we witness new facts coming into being. As noted above, these contexts are not "strictly local," in that measurements don't happen at any precise point in space or time. Contexts have no definite boundaries; we share the same physical present time with everyone and everything that's immediately present to us – that is, close enough that we exchange information back and forth with no appreciable time-lag, all participating in the same local situation. And this "now" is directly connected by null intervals with specific moments in time for any distant context, where our past and future light-cones intersect.

Because the speed of light is so fast, on the scale of human perception, my "now" effectively includes everyone on the planet. If we drew the "block" diagram on this scale, both past and future light-cones would flatten out, and essentially coincide with the horizontal axes. This means that in our ordinary experience there's no perceptible difference between the two versions of spacetime: the difference shows up only at astronomical distances or at speeds approaching the velocity of light. That's why we can take it for granted that everything in the universe "moves through time" together, on this "hypersurface of the present," assuming that events can be simultaneous in time no matter how far apart they are in space. If I'm on a videocall with a friend on Mars, on the other hand, it will be obvious that we don't share a common present time. When I make a joke, I have to wait maybe twenty minutes before I see her laugh; her "now" will always be several minutes in my future, and vice-versa. This separation between our local contexts isn't due to the slowness of light, but to the way space and time are cross-connected.

3 Asynchronous Spacetime – EPR and Schrödinger's Clock

But why should a universe be structured in such a peculiar way? What we see here is very similar to what we find in quantum physics: while the clear and simple space and time of classical Newtonian physics operates on the scale of ordinary experience, the fundamental spacetime structure turns out to be far more complex and counter-intuitive. To explain this we need to understand why both the Newtonian and the relativistic versions of spacetime are needed to support a world of definable and measurable facts. The key point is that only facts that are locally observable can contribute to the contexts in which other information becomes locally observable. It would certainly be much simpler to structure a universe in the absolute space and time of Newtonian physics, but that involves assumptions – for example, about the simultaneity of events throughout the universe – that can't be supported by observation. So even though our higher-level reality is effectively Newtonian, the deeper-level structure has to be definable entirely in terms of local measurements.

Now in order to support the ongoing process that creates new facts in the context of prior facts, there needs to be one common framework of spacetime relationships everywhere, along with the changeless structure of the laws of physics and a consistent background of historical facts. Specifically, among other things, there needs to be a universally consistent time-ordering of events, so that everything proceeds from a common past history of given facts into a future that's not yet determined. Yet the structure of events in space and time can't just be given in an underlying, absolute geometry. It can't be built, for example, out of slices or "foliations" of spacetime – like the "hypersurface of the present" – that are unrelated to anything observable. It has to be defined in and through the web of communicated information.

This is precisely what's accomplished by the spacetime of Einstein and Minkowski. It's structured so that the web of light-speed communication effectively separates the factual past from the possible future, for any set of communicating observers. When two observers are in communication, that is, events in the past light-cone of one of them can never be in the future of the other. Whatever's still only a future possibility for one can never be an already decided fact for the other. But this is done asynchronously – it does not assume any simultaneity between events experienced by one observer and those experienced by others who may be very distant. The "now" – the context in which possibilities become facts – consists only of locally observable events, independent of what happens in distant locations. And even so, any set of communicating observers do share a common factual history, where their past light-cones overlap. Anything that's factually determinate for one observer can eventually become a fact for any other. But this shared objective reality has to be accomplished over time, by weaving together the separate strands of fact defined in separate local contexts.

This basic time-ordering of events is achieved by the invariant structure of null intervals, physically instantiated in our universe by the electromagnetic field. It provides a kind of rigid skeleton for an otherwise asynchronous system of parallel distributed processing. Every measurement-context gets set up by facts communicated on or within its past light-cone; all newly defined facts get communicated out to other possible contexts on or within the future light-cone. And though all measurements of spatial and temporal distances are relative to the observer's local reference-frame, these light-speed connections are absolute. Null intervals are null in any frame; the speed of light is always the same, however spatial and temporal intervals are measured. Moreover, the speed of light is so fast that over a very wide range of scales, even down to the quantum level, physics operates in an effectively Newtonian background, where space and time can be treated as they appear in the diagram, as independent variables.

This means that even though the objective view of the world "from outside" is not fundamentally correct, there are very few situations in which it causes any problem. One such situation, however, is well known – the EPR scenario, as realized in experimental tests of the Bell inequality. Here the spin-orientations of two entangled particles are measured by Alice and Bob in spacelike-separate regions, so that observing one of them should not be able to affect a measurement made on the other. Nonetheless, the two results turn out to be correlated per the usual quantum rules. Objectively, it seems that measuring one of the particles must somehow have determined the state of the other, though Relativity rules out any such faster-than-light connection. In fact, it tells us that there's no objective fact as to which of the two measurements happened first.

What this scenario illustrates, though, isn't any "spooky action at a distance." Rather it's just the thesis of this essay – that at bottom the world is not an objectively factual reality, but a web of communicated information. The laws of physics apply to what's actually experienced from some particular point of view in its local context, not to any underlying reality. From Alice's point of view, Bob's measurement hasn't happened until it falls within her past light-cone. Until then it remains in a superposition of possible outcomes. Likewise from Bob's point of view, Alice's measurement doesn't have any definite result, when he makes his measurement. Only later, when both results become available in the same location, does there arise a physical context in which a correlation between the two results can be determined. Only then can the overall situation described by the entangled wave-function "collapse" to select out a definite combination of results, which turn out to be correlated according to quantum rules.

This seems paradoxical, because we think in terms of a global objective reality. We want to locate Bob and Alice within a common framework of space and time, where both measurements had already taken place long before either of them could learn about the other one's result. We assume that since Alice's result was already factually determined in her context, and Bob's in his, then the two results must really have been correlated with each other long before they could be compared. This seems incontrovertible, because it seems self-evident that there's one overall space and time for the universe, just as there is, effectively, for us here on Earth.

However, both Relativity and Quantum Mechanics show us this is not the case. Within the asynchronous spacetime structured by light-speed communication, Alice's time and Bob's are not the same. It's simply true that when Alice makes her measurement, Bob's result remains undetermined, and vice-versa. For either Bob or for Alice the “collapse” has already occurred for one measurement, to give a particular random result, but only much later, when both results can be compared, can these separate threads of existence get woven together into a shared objective reality. Until then there’s no physical situation to which the quantum rules can apply.

This is an extremely unusual situation, though – it takes a lot of careful effort to set up an arrangement in which quantum superpositions are spread out over such distances. But what this scenario demonstrates is no different from what we see in delayed-choice or quantum eraser experiments: the laws of physics only apply to what’s observable – to the structure of measured and communicated information – not to any underlying reality. The spacetime geometry in which things happen is likewise the structure of a communications web, where distant regions evolve independently – where Bob’s measurement is still physically in Alice’s future when she makes her measurement, and vice-versa. This doesn’t mean that Bob or Alice or both exist in a superposition of states for a long period of time, until their results are compared. It’s just that in this peculiar kind of spacetime geometry there’s no definable actuality that encompasses spacelike-separate regions.

Let’s consider another similar scenario – that of Schrödinger’s Clock. To avoid mistreating animals, we replace the cat in the box with a clock, which is set up so that will stop when and if a particle decays. So long as the box remains closed, we represent the situation inside the box as a superposition of possible states, in some of which the clock is still ticking, while in others it’s stopped. When we open the box, the superposition collapses, and we find the clock had in fact stopped just half an hour earlier.

The point is the same as with Bob and Alice: the time going on inside the box is not the same as the time outside. For an observer inside the box, the “collapse” has occurred and the clock has stopped – but for us outside, the collapse occurs only when we open the box. Here we assume the box is able to block any physical connection between the clock and the world outside, which may not be realistic. In the EPR scenario, the separation is definitely real, due to the structure of spacetime itself. But in both scenarios the objective view of the situation makes sense, after the fact. Once the box is open, we can all agree that the clock had in fact stopped half an hour ago; once Bob and Alice compare results, we can all see they’re correlated with each other. But the physical world does not operate after the fact: it exists in real time, in the web of communications between local contexts. And while eventually all observers can agree about past facts, they don’t all share a single present time in which the facts get determined.

Whether or not this seems paradoxical to us, the laws of physics governing an observable world have to operate in and through the web of communicated information. Laws that apply to objective reality are obviously important, at the level of classical physics and our everyday experience, but they can’t be fundamental laws. On the other hand, the fundamental laws need to work together to achieve the objective reality of classical physics, to the greatest extent possible. It therefore takes a lot of care and effort to make quantum effects manifest on a large scale – as in tests of the Bell inequality over spacelike intervals. Likewise relativistic effects appear only when dealing with astronomical distances or velocities near the speed of light. So there's a very broad range of scales over which there are always clear and causally deterministic relationships between factual events, set in a common framework of objective Newtonian space and time.

As to the underlying physics, we've learned that it's strange and complicated in many different ways. My task here is simply to suggest a reason for that.

4   The Equivalence Principal and the Gravitational Metric

So far we've discussed only one aspect of spacetime geometry – the invariant skeleton of null intervals. This structure is independent of the metric defined by local measurements with clocks and rulers, as reflected in the fact that the basic structure of the electromagnetic field – which physically realizes the skeleton of light-speed communication – can be expressed mathematically without reference to the spacetime metric.[4] In the accompanying essay on "The Origins of Determinate Information" we'll take up the suggestion that this invariant structure of intersecting light-cones represents a primitive stage in the pre-history of our self-defining universe, before the emergence of the measurable space and time defined by interacting atoms.

Here I want to focus on what we've learned about the metric from General Relativity. That theory arose from the question, why is there an exact equivalence between gravitational and inertial mass? Einstein pointed out that measurements made inside an elevator – which, like Schrödinger's box, is assumed to block all signals from outside – can't tell us whether we're in a gravitational field or are being accelerated uniformly by a rocket. Objectively, of course, there's a great difference between these two situations. If the elevator had windows, we could see whether there's a massive planet below us or something pulling us upward. But in the local context of the elevator, the two situations are physically the same.

Now if it's true that fundamental physics has to be definable entirely in terms of local measurements, and such measurements can't distinguish between gravity and inertia, then those two must be the same so far as the laws of physics are concerned, even though they're objectively very different. This was the gist of Einstein's theory, though he didn't base it on this kind of argument – he always maintained an objective view of spacetime structure. Yet both Special and General Relativity do define spacetime geometry strictly on the basis of local measurements.

For Einstein the Equivalence Principle was an empirically established fact. His theory doesn't explain why gravity and inertia are physically identical, but it gives a mathematical law that accurately predicts a wide range of observed phenomena on that basis. It says that in the absence of any other forces, everything moves inertially along geodesic paths in a spacetime metric shaped by the distribution of mass-energy, without considering how or why this happens. But we can understand why the universe operates this way if we can show how Einstein's equations contribute to the structure of an observable world.

To begin with, clearly gravity played a key role in the emergence of our world of solid material objects, through which intervals in space and time become measurable. Without gravity, atoms would never have formed stars, and there would be no heavy nuclei from which to build molecular structure. But the law expressed in Einstein's field equations does much more than that. For example, it makes the curvature of spacetime flatten out, locally, and the smallness of the gravitational constant makes its geometry essentially Euclidean on a local scale. The way space, time and gravity are defined by General Relativity very closely approximates a Newtonian framework at the level of local measurements, and the curvature of the metric is entirely negligible at the quantum level. This is why quantum physics can be structured mathematically on a background of flat spacetime.

Even where gravitational curvature is not at all negligible, the relativistic structure of spacetime still provides a basis for defining inertial frames of reference anywhere in the universe: where other forces are absent, the local rest-frame of any object in free fall is always inertial. And where things are not in free fall, as on the surface of the Earth, local measurements can always determine the magnitude and direction of their acceleration, whether due to gravity or other forces, and this acceleration will be found to have the same value in any inertial frame.

Moreover, Einstein's equations include a cosmological constant governing the rate of expansion of the universe. In the early universe this expansion brought about the gradual cooling that allowed for the eventual emergence of atomic structure, through a complex series of stages. To open up enough time for an observable world to evolve, however, the expansion rate had to be extremely finely-tuned to balance the pull of gravity, taking into account the contribution of quantum fluctuations to the energy-density of the vacuum. If the value of the cosmological constant had been slightly different, the universe would either have re-collapsed on itself long before there were any atoms, or else have blown itself apart so quickly that no galaxies and stars could form. So this one basic law of physics given in Einstein's theory accomplishes a remarkable variety of important tasks in creating our observable universe.

The bottom line is that Relativity, like quantum theory, supports the world of classical physics, where stable material structures have precisely determinate properties, and interact according to simple laws in an objective framework of Euclidean space and time. But this framework is not just given in reality, as it is in Newton's conception. All of this gets accomplished strictly on the basis of information defined in local measurement-contexts and communicated between such contexts.

Relativity shows us that this is done through a combination of two distinct systems. The metric of General Relativity – incorporating the skeleton-structure of the light-cone web – defines a system of local inertial reference-frames throughout the universe, where things can be measured in a locally flat Euclidean space and time. Then the rules of Special Relativity allow for the consistent translation between measurements made in different inertial frames. The result is that in principle, any two observers in communication with each other can reconcile their respective local observations to achieve a shared objective knowledge of the facts, no matter how different their local situations may be.

This may seem an exceedingly complex and roundabout way to accomplish something very simple. Why not just begin with an objectively given factual world, organized by Euclidean geometry and the laws of classical physics? But such a world is a fantasy. It tacitly assumes the existence of contexts in which facts are determined and laws are defined, without considering what's needed to support such contexts. In the real world, highly functional atoms are needed to build stable material structure, and the interactive environment needs to convey many kinds of information, including the laws of physics and spacetime geometry. The clear and simple classical physics of the world we experience can only operate because our universe provides all the complex informational technology that makes it work.

5 Cosmological Questions

To conclude, I want to mention several outstanding issues in cosmology that seem problematic only because it's taken for granted that the universe should be described "from outside," as an objectively factual reality, rather than as a functional web of communicated information. For example, there's the question why gravity is so much weaker than all the other basic forces, and why the energy-density of the vacuum is so much smaller than expected, given all the virtual-particle contributions to vacuum energy given in the Standard Model. The approach sketched out above explains these apparent anomalies: if the gravitational and cosmological constants in Einstein's equations were not very small, flattening out our spacetime geometry, none of the technology of measurement could have come to exist.

In general, fine-tuning seems problematic because physics is understood as an essentially mathematical structure. It's bad enough that the deep-level physics is mathematically subtle and complex, without having to include many unexplained parameters whose values seem "unnatural." But if the mathematical structures of our theories are explained by the functional requirements for defining and communicating information, their finely-tuned parameters can be understood the same way.

A different sort of explanation is possible for the "horizon problem" – why the background radiation left over from the early universe is so nearly homogenous in all directions, given that no interaction can ever have occurred between widely-separated regions in our sky. A similar question asks why the interactive environment of the early universe had such extremely low entropy that it's still rather low today, after billions of years in which entropy has steadily increased. Such questions conceive the world as body of well-defined objective fact, and the problem is to understand why the universe began in an extremely special state. For example, the notion of inflation is invoked to account for the uniformity of the early universe by tracing it back to an earlier factual state that seems more general and "natural."

In the context of my argument here, I would turn these questions around. If we'd found that there were major differences in the temperature of background radiation from distant regions of the universe, how could we explain those differences? If those regions were always spacelike separated, in what physical context could differences between them have been defined? Here we're not supposing there were well-defined factual states throughout the universe, to begin with, that were all highly correlated with each other. The assumption is rather that all facts must be defined in some context of local interaction, and no differences could have been meaningfully defined between unconnected parts of the universe. When we look at the sky in different directions, from the Earth today, our local contexts let us measure and compare radiation from widely separated regions of the early universe. But since there were no such contexts to begin with that encompassed these distant regions, there can't have been definite factual differences between them. In order for them to be observable here and now, however, the physics of all these regions needs to be essentially identical, consistent with the requirements of our observable world.

As a matter of fact though, we do see very small deviations in the temperature of the cosmic microwave background from different directions in the sky. These are understood as reflecting quantum fluctuations in the energy-density of the early universe, which happen to be the right order of magnitude to seed the emergence of galaxies. These differences would not have been measurable from any local viewpoint, in the early universe, but they became observable later on, in retrospect, and play a clear and important functional role in the emergence of our world of measurable information.

Finally, what seems today to be the main outstanding issue in fundamental physics is the relationship between quantum physics and gravity. A great deal of effort has gone into the project of unifying these theories, on the assumption that there must be some ultimate reality at the bottom of things, and some unified mathematical structure that describes it. Despite the near-complete lack of empirical evidence for any such physics beyond the scope of current theories, it's certainly possible that a deeper unifying theory may eventually be found. But if what's fundamental in physics is not the mathematical structure of reality but the functionality of the communicative environment, then there may be no need for any deeper unifying theory.

General Relativity and Quantum Field Theory address very different aspects of the interactive system that supports measurement, and there are few if any observed phenomena to which both these theories are relevant. As noted above, the very small constants in Einstein's field equations give an effectively flat spacetime environment in the quantum domain, so that gravity plays no direct role in determining facts at the level of atoms and molecules. And it seems that quantum contributions to the vacuum-energy of spacetime are precisely cancelled out, leaving only the tiny fluctuations needed to support the historical emergence of galaxies and stars. So Relativity and quantum physics work remarkably well together, complementing each other, but it's not obvious, from a functional standpoint, that there has to be any reconciliation between their very dissimilar mathematical foundations. Nor does it seem sensible, from the point of view taken here, to speculate about physics at the Planck scale, so far beyond the range of any conceivable measurement.

There may still be important questions to be resolved, once we've found observable phenomena that involve both quantum physics and gravity. But the answers may not lie in the formal unification of these two types of theory. So at least as a working premise, it may make sense to assume that current theory already gives us what's needed to understand the workings of our self-defining universe. Outstanding issues like the mystery of dark matter may become more approachable once we have a well-developed framework that focuses on the contextuality of information. After all, dark matter also plays a significant role in creating the galaxies, stars and heavy nuclei needed for the emergence of stable material structure.

Notes

1. "Why Quantum Mechanics Makes Sense". To summarize the basic argument of that essay: no information can be measurable or definable apart from a context that involves other kinds of information, defined and measured in other contexts. Since only observable facts can contribute to the contexts in which other facts become observable, the existence of any unobservable reality is irrelevant to the fundamental structure of an observable universe. The web of communicated information has to be able to define itself entirely in terms of itself, not relying on any hypothetically given facts about an underlying reality.

2. The argument about whether Relativity proves this notion has gone on for many decades in hundreds of papers, and there's still no sign that one side might convince the other. In my view the clearest picture is that of the "Evolving Block Universe" developed by George F. R. Ellis – see for example "Physics in the Real Universe: Time and Spacetime," arxiv.org/abs/gr-qc/0605049, and "Time and Spacetime: The Crystallizing Block Universe," arxiv.org/abs/0912.0808. This comes close to the view presented here, though based on different arguments.

3. This is consonant with the Evolving Block Universe picture – see Note 2 above. The notion that the past light-cone represents the space of the local "now" has been developed by Hanoch Ben-Yami (2007), "Apparent Simultaneity," philsci-archive.pitt.edu/3260/1/Apparent_Simultaneity.pdf. A recent paper summarizing the debate over the block universe criticizes both the "Presentist" and "Eternalist" standpoints, proposing the "local present" as a preferable third option: Carlo Rovelli (2020), "Neither Presentism nor Eternalism," arxiv.org/abs/1910.02474.

   The view proposed here rejects the "Eternalist" position that there's no physical distinction between past, present and future events. But the "Presentist" position – that only what exists in the present time is real – makes no sense to me. Its proponents are generally thinking of a universal present moment, which has no basis either in physics or in any possible experience. But it's not clear to me what kind of "reality" can be ascribed to events without reference to anything in the past or future. The determination of any fact always depends on the communication of prior facts and the context-structure of possibilities that these prior facts set up; moreover, facts have meaning only insofar as they make a difference to what can happen in the future.

4. See for example David H. Delphenich (2014) "On the electromagnetic constitutive laws that are equivalent to spacetime metrics," arxiv.org/abs/1409.5107, David Delphenich (2015) "Pre-metric electromagnetism as a path to unification," arxiv.org/abs/1512.05183. Delphenich also has a two-volume exposition available on his website: Pre-Metric Electromagnetism, Neo-classical Press, 2009, neo-classical-physics.info/electromagnetism.html.