EXCERPTED FROM

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A NEW KIND OF SCIENCE

SECTION 9.14

Elementary Particles

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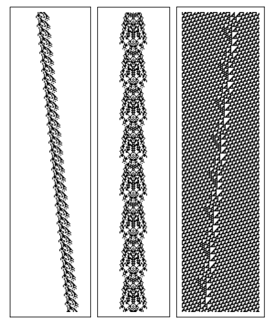
There are some aspects of the universe—notably the structure of space and time—that present-day physics tends to assume are continuous. But over the past century it has at least become universally accepted that all matter is made up of identifiable discrete particles.

Experiments have found a fairly small number of fundamentally different kinds of particles, with electrons, photons, muons and the six basic types of quarks being a few examples. And it is one of the striking observed regularities of the universe that all particles of a given kind—say electrons—seem to be absolutely identical in their properties.

But what actually are particles? As far as present-day experiments can tell, electrons, for example, have zero size and no substructure. But particularly if space is discrete, it seems almost inevitable that electrons and other particles must be made up of more fundamental elements.

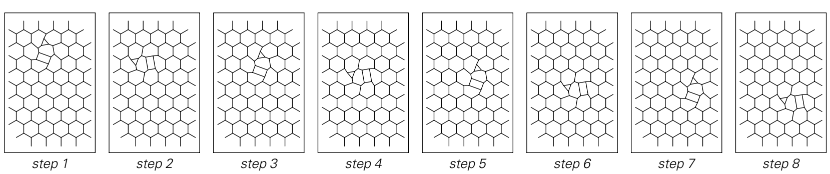


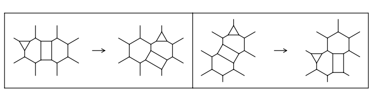
Typical examples of particle-like localized structures in class 4 cellular automata.

So how might this work? An immediate possibility that I suspect is actually not too far from the mark is that such particles are analogs of the localized structures that we saw earlier in this book in systems like the class 4 cellular automata shown on the right. And if this is so, then it means that at the lowest level, the rules for the universe need make no reference to particular particles. Instead, all the particles we see would just emerge as structures formed from more basic elements.

In networks it can be somewhat difficult to visualize localized structures. But the picture below nevertheless shows a simple example of how a localized structure can move across a regular planar network.

Both the examples on this page show structures that exist on very regular backgrounds. But to get any kind of realistic model for actual

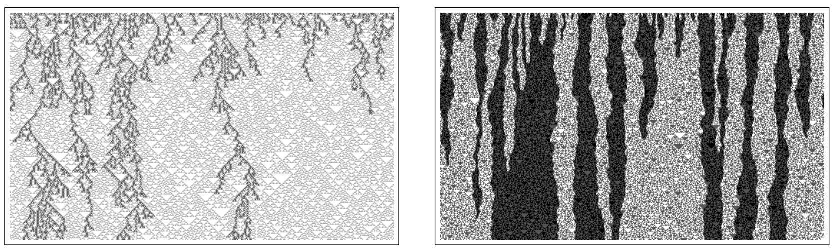




A particle-like localized structure in a network.

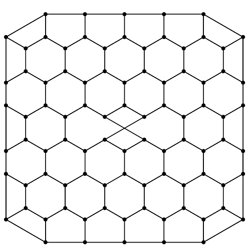
particles in physics one must consider structures on much more complicated and random backgrounds. For any network that has a serious chance of representing actual space—even a supposedly empty part—will no doubt show all sorts of seemingly random activity. So any localized structure that might represent a particle will somehow have to persist even on this kind of random background.

Yet at first one might think that such randomness would inevitably disrupt any kind of definite persistent structure. But the pictures below show two simple examples where it does not. In the first case, there are localized cracks that persist. And in the second case, there are two different types of regions, separated by boundaries that act like localized structures with definite properties, and persist until they annihilate.



Examples of one-dimensional cellular automata that support various forms of persistent structures even on largely random backgrounds. These are 3-color totalistic rules with codes 294 and 1893.

So what about networks? It turns out that here again it is possible to get definite structures that persist even in the presence of randomness. And to see an example of this consider setting up rules like those on page 509 that preserve the planarity of networks.

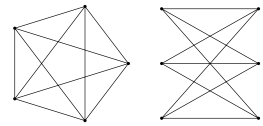


A network with a single irreducible crossing of lines.

Starting off with a network that is planar—so that it can be drawn flat on a page without any lines crossing—such rules can certainly give all sorts of complex and apparently random behavior. But the way the rules are set up, all the networks they produce must still be planar.

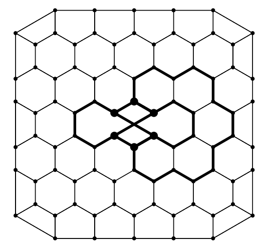
And if one starts off with a network like the one on the left that can only be drawn with lines crossing, then what will happen is that the non-planarity of the network will be preserved. But to what extent does this non-planarity correspond to a definite structure in the network?

There are typically many different ways to draw a non-planar network, each with lines crossing in different places. But there is a fundamental result in graph theory that shows that if a network is not planar, then it must always be possible to identify in it a specific part that can be reduced to one of the two forms shown on the right—or just the second form for a network with three connections at each node.



The K_5 and $K_{3,3}$ forms that lead to non-planarity in networks.

So this implies that one can in fact meaningfully associate a definite structure with non-planarity. And while at some level the structure can be spread out in the network, the point is that it must always in effect have a localized core with the form shown on the right.



How $K_{3,3}$ is embedded in the network from the facing page.

In general one can imagine having several pieces of non-planarity in a network—perhaps each pictured like a carrying handle. But if the underlying rules for the network preserve planarity then each of these pieces of non-planarity must on their own be persistent—and can in a sense only disappear through processes like annihilating with each other.

So might these be like actual particles in physics?

In the realistic case of network rules for the universe, planarity as such is presumably not preserved. But observations in physics suggest that there are several quantities like electric charge that are conserved. And ultimately the values of these quantities must reflect properties of underlying networks that are preserved by network evolution rules.

And if these rules satisfy the constraint of causal invariance that I discussed in previous sections, then I suspect that this means that they will inevitably exhibit various additional features—perhaps notably including for example what is usually known as local gauge invariance.

But what is most relevant here is that it seems likely that—much as for non-planarity—nonzero values of quantities conserved by network evolution rules can be thought of as being associated with some sort of local structures or tangles of connections in the network. And I suspect that it is essentially such structures that define the cores of the various types of elementary particles that are seen in physics.

Before the results of this book it might have seemed completely implausible that anything like this could be correct. For independent of any specific arguments about networks and their evolution, traditional intuition would tend to make one think that the elaborate properties of particles must inevitably be the result of an elaborate underlying setup. But what we have now seen over and over again in this book is that in fact it is perfectly possible to get phenomena of great complexity even with a remarkably simple underlying setup. And I suspect that particles in physics—with all their various properties and interactions—are just yet another example of this very general phenomenon.

One immediate thing that might seem to suggest that elementary particles must somehow be based on simple discrete structures is the fact that their values of quantities like electric charge always seem to be in simple rational ratios. In traditional particle physics this is explained by saying that many if not all particles are somehow just manifestations of the same underlying abstract object, related by a simple fixed group of symmetry operations. But in terms of networks one can imagine a much more explicit explanation: that there are just a simple discrete set of possible structures for the cores of particles—each perhaps related in some quite mechanical way by the group of symmetry operations.

But in addition to quantities like electric charge, another important intrinsic property of all particles is mass. And unlike for example electric charge the observed masses of elementary particles never seem to be in simple ratios—so that for example the muon is about 206.7683 times the mass of the electron, while the tau lepton is about 16.819 times the mass of the muon. But despite such results, it is still conceivable that there could in the end be simple relations between truly fundamental particle masses—since it turns out that the masses that have actually been observed in effect also include varying amounts of interaction energy.

A defining feature of any particle is that it can somehow move in space while maintaining its identity. In traditional physics, such motion has a straightforward mathematical representation, and it has not usually seemed meaningful to ask what might underlie it. But in the approach that I take here, motion is no longer such an intrinsic concept, and the motion of a particle must be thought of as a process that is made up of a whole sequence of explicit lower-level steps.

So at first, it might seem surprising that one can even set up a particular type of particle to move at different speeds. But from the discussion in the previous section it follows that this is actually an almost inevitable consequence of having underlying rules that show causal invariance. For assuming that around the particle there is some kind of uniformity in the causal network—and thus in the apparent structure of space—taking slices through the causal network at an appropriate angle will always make any particle appear to be at rest. And the point is that causal invariance then implies that the same underlying rules can be used to update the network in all such cases.

But what happens if one has two particles that are moving with different velocities? What will the events associated with the second particle look like if one takes slices through the causal network so that the first particle appears to be at rest? The answer is that the more the second particle moves between successive slices, the more updating events must be involved. For in effect any node that was associated with the particle on either one slice or the next must be updated—and the more the particle moves, the less these will overlap. And in addition, there will inevitably appear to be an asymmetry in the pattern of events relative to whatever direction the particle is moving.

There are many subtleties here, and indeed to explain the details of what is going on will no doubt require quite a few new and rather abstract concepts. But the general picture that I believe will emerge is that when particles move faster they will appear to have more nodes associated with them.

Most likely the intrinsic properties of a particle—like its electric charge—will be associated with some sort of core that corresponds to a definite network structure involving a roughly fixed number of nodes. But I suspect that the apparent motion of the particle will be associated with a kind of coat that somehow interpolates from the core to the uniform background of surrounding space. With different slices through the causal network, the apparent size of this coat can change. But I suspect that the size of the coat in a particular case will somehow be related to the apparent energy and momentum of a particle in that case.

An important fact in traditional physics is that interactions between particles seem to conserve total energy and momentum. And conceivably the reason for this is that such interactions somehow tend to preserve the total number of network nodes. Indeed, perhaps in most situations—save those associated with the overall expansion of the universe—the basic rules for the network at least on average just rearrange nodes and never change their number.

In traditional physics energy and momentum are always assumed to have continuous values. But just as in the case of position there is no contradiction with sufficiently small underlying discrete elements.

As I will discuss in the last section of this chapter, quantum mechanics tends to make one think of particles with higher momenta as being somehow progressively less spread out in space. So how can this be consistent with the idea that higher momentum is associated with having more nodes? Part of the answer probably has to do with the fact that outside the piece of the network that corresponds to the particle, the network presumably matches up to yield uniform space in much the same way as without the particle. And within the piece of the network corresponding to the particle, the effective structure of space may be very different—with for example more long-range connections added to reduce the effective overall distance.

The Phenomenon of Gravity

At an opposite extreme from elementary particles one can ask how the universe behaves on the largest possible scales. And the most obvious effect on such scales is the phenomenon of gravity. So how then might this emerge from the kinds of models I have discussed here?

The standard theory of gravity for nearly a century has been general relativity—which is based on the idea of associating gravity with curvature in space, then specifying how this curvature relates to the energy and momentum of whatever matter is present.

Something like a magnetic field in general has different effects on objects made of different materials. But a key observation verified experimentally to considerable accuracy is that gravity has exactly the same effect on the motion of different objects, regardless of what those objects are made of. And it is this that allows one to think of gravity as a general feature of space—rather than for example as some type of force that acts specifically on different objects.