EXCERPTED FROM

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A NEW KIND OF SCIENCE

SECTION 9.8

The Relationship of Space and Time

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To make an ultimate theory of physics one needs to understand the true nature not only of space but also of time. And I believe that here again the idea of thinking in terms of programs provides some crucial insights.

In our everyday experience space and time seem very different. For example, we can move from one point in space to another in more or less any way we choose. But we seem to be forced to progress through time in a very specific way. Yet despite such obvious apparent differences, almost all models in present-day fundamental physics have been built on the idea that space and time somehow work fundamentally the same.

But for most of the systems based on programs that I have discussed in this book this is certainly not true. And thus for example in a cellular automaton moving from one point in space to another just corresponds to shifting from one cell to another. But moving from one point in time to another involves actually applying the cellular automaton rule.

When we make a picture of the behavior of a cellular automaton, however, we do nevertheless tend to represent space and time in the same visual kind of way—with space going across the page and time going down. And in fact the basic notion of extending the idea of position in space to an idea of position in time has been common in scientific thought for more than five centuries.

But in the past century what has happened is that space and time have come to be thought of as being much more fundamentally similar. As we will discuss later in this chapter, the main origin of this is that in relativity theory certain aspects of space and time seem to become interchangeable. And from this there emerged the idea of thinking in terms of a spacetime continuum in which time appears merely as a fourth dimension just like the three ordinary dimensions of space.

So while in a system like a cellular automaton one typically imagines that a new and separate state of the system is somehow produced at each step in time, present-day physics more tends to think of the complete history of the universe throughout time as being just a single structure laid out in the four dimensions of spacetime.

So what then might determine the form of this structure?

The laws of physics in effect provide a collection of constraints on the structure. And while these laws are traditionally stated in terms of sophisticated mathematical equations, their basic character is similar to the simple constraints on arrays of black and white cells that I discussed at the end of Chapter 5. But now instead of defining constraints just in space, the laws of physics can be thought of as defining constraints on what can happen in both space and time.

Just as for space, it is my strong belief that time is fundamentally discrete. And from the discussion of networks for space in the previous section, one might imagine that perhaps the whole history of the universe in spacetime could be represented by a giant four-dimensional network.

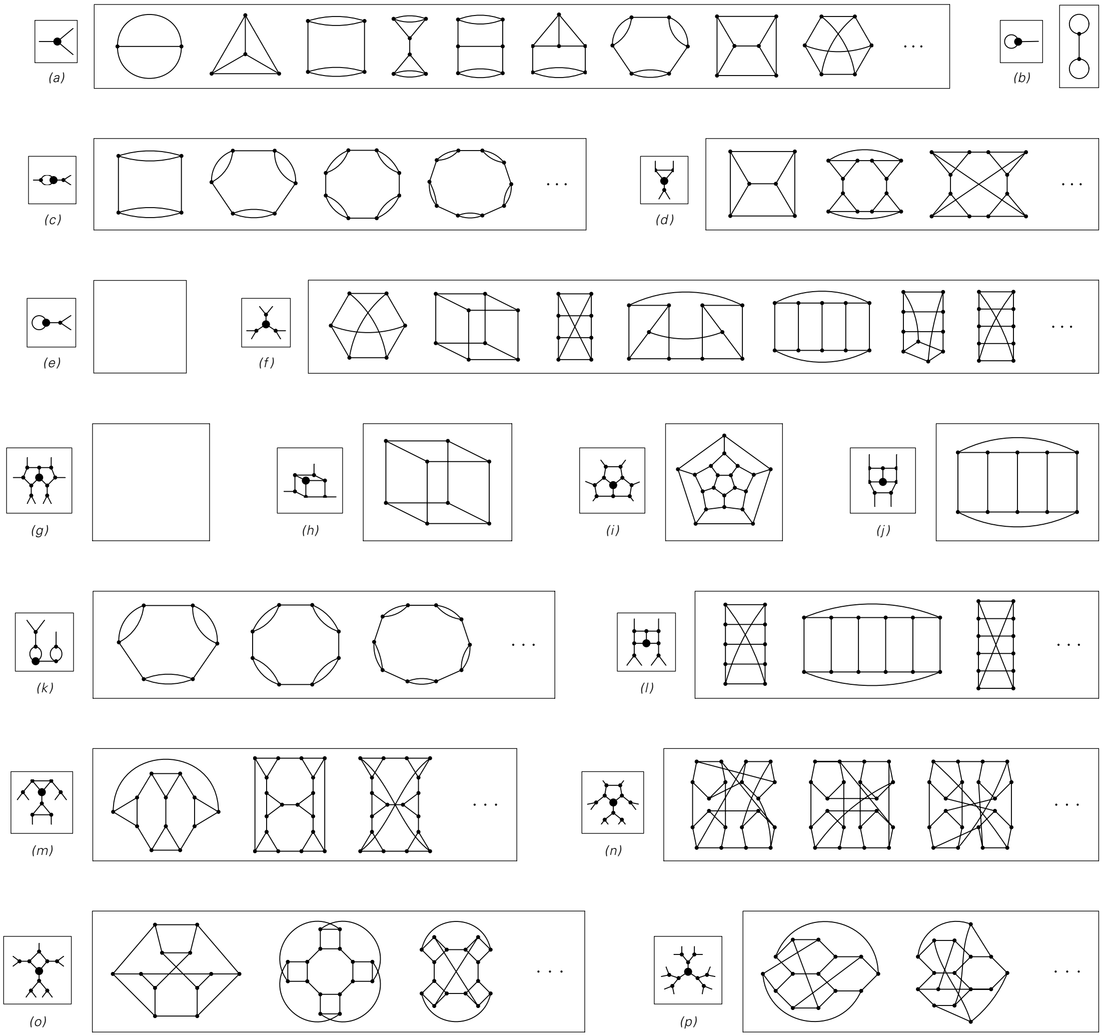
By analogy with the systems at the end of Chapter 5 a simple model would then be that this network is determined by the constraint that around every one of its nodes the overall arrangement of other nodes must match some particular template or set of templates.

Yet much as in Chapter 5 it turns out often not to be especially easy to find out which networks, if any, satisfy specific constraints of this kind. The pictures on the facing page nevertheless show results for quite a few choices of templates—where in each case the dangling connections in a template are taken to go to nodes that are not part of the template itself.

Pictures (a) and (b) show what happens with the two very simplest possible templates—involving just a single node. In case (a), all networks are allowed except for ones in which a node is connected directly to itself. In case (b), only the single network shown is allowed.

With templates that involve nodes out to distance one there are a total of 11 distinct non-trivial cases. And of these, 8 allow no complete networks to be formed, as in picture (e). But there turn out to be three cases—shown as pictures (c), (d) and (f)—in which complete networks can be formed, and in each of these one discovers that a fairly simple infinite set of networks are actually allowed.

In order to have a meaningful model for the universe, however, what must presumably happen is that essentially just one network can satisfy whatever constraints there are, and this one network must then represent all of the complex spacetime history of our universe.



Examples of networks determined by constraints. In each case the networks shown are required to satisfy the constraint that around every node their form must correspond to the template shown, in such a way that no dangling connections in the template are joined to each other. The pictures include all 14 templates that involve nodes out to distance at most two for which complete networks can be formed. In most cases where any such network can be formed, an infinite sequence of networks is allowed. But in cases (b), (h), (i) and (j) just a single network turns out to be allowed. The network constraint systems shown here are analogs of the two-dimensional systems based on constraints discussed at the end of Chapter 5.

So what does one find if one allows templates that include nodes out to distance two? There are a total of 690 distinct non-trivial such templates—and of these, 681 allow no complete networks to be formed, as in case (g). Six of the remaining templates then again allow an infinite sequence of networks. But there are three templates—shown as cases (h), (i) and (j)—that turn out to allow just single networks. These networks are however rather simple, and indeed the most complicated of them—case (i)—has just 20 nodes, and corresponds to a dodecahedron.

So are there in fact reasonably simple sets of constraints that in the end allow just one highly complex network, or perhaps a family of similar networks? I tend to doubt it. For our experience in Chapter 5 was that even in the much more rigid case of arrays of black and white squares, it was rather difficult to find constraints that would succeed in forcing anything but very simple patterns to occur.

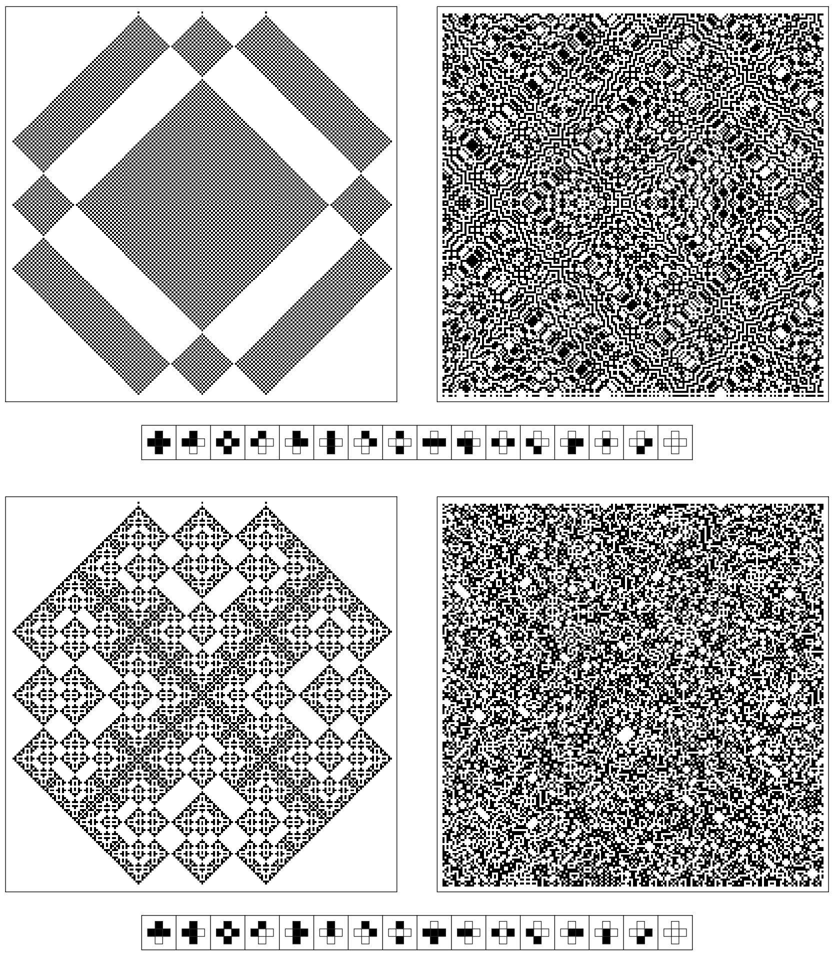
So what does this mean for getting the kind of complexity that we see in our universe? We have not had difficulty in getting remarkable complexity from systems like cellular automata that we have discussed in this book. But such systems work not by being required to satisfy constraints, but instead by just repeatedly applying explicit rules.

So is it in the end sensible to think of the universe as a single structure in spacetime whose form is determined by a set of constraints? Should we really imagine that the complete spacetime history of the universe somehow always exists, and that as time progresses, we are merely exploring different parts of it? Or should we instead think that the universe—more like systems such as cellular automata—explicitly evolves in time, so that at each moment a new state of the universe is in effect created, and the old one is lost?

Models based on traditional mathematical equations—in which space and time appear just as abstract symbolic variables—have never had to make much distinction between these two views. But in trying to understand the ultimate underlying mechanisms of the universe, I believe that one must inevitably distinguish between these views.

And I strongly believe that the second view is the one most likely to provide a meaningful underlying model for our universe. But while this view is closer to our everyday perception of time, it seems to contradict the correspondence between space and time that is built into most of present-day physics. So one might wonder how then it could be consistent with experiments that have been done in physics?

One possibility, illustrated in the pictures below, is to have a system that evolves in time according to explicit rules, but for these rules to have built into them a symmetry between space and time.



Examples of one-dimensional cellular automata which exhibit a symmetry between space and time. Each picture can be generated by starting from initial conditions at the top, and then just evolving down the page repeatedly applying the cellular automaton rule. The particular rules shown are reversible second-order ones with numbers 90R and 150R.

But I very much doubt that any such obvious symmetry between space and time exists in the fundamental rules for our universe. And instead what I expect is much like we have seen many times before in this book: that even though at the lowest level there is no direct correspondence between space and time, such a correspondence nevertheless emerges when one looks in the appropriate way at larger scales of the kind probed by practical experiments.

As I will discuss in the next several sections, I suspect that for many purposes the history of the universe can in fact be represented by a certain kind of spacetime network. But the way this network is formed in effect treats space and time rather differently. And in particular—just as in a system like a cellular automaton—the network can be built up incrementally by starting with certain initial conditions and then applying appropriate underlying rules over and over again.

Any such rules can in principle be thought of as providing a set of constraints for the spacetime network. But the important point is that there is no need to do a separate search to find networks that satisfy such constraints—for the rules themselves instead immediately define a procedure for building up the necessary network.

Time and Causal Networks

I argued in the last section that the progress of time should be viewed at a fundamental level much like the evolution of a system like a cellular automaton. But one of the features of a cellular automaton is that it is set up to update all of its cells together, as if at each tick of some global clock. Yet just as it seems unreasonable to imagine that the universe consists of a rigid grid of cells in space, so also it seems unreasonable to imagine that there is a global clock which defines the updating of every element in the universe synchronized in time.

But what is the alternative? At first it may seem bizarre, but one possibility that I believe is ultimately not too far from correct is that the universe might work not like a cellular automaton in which all cells get updated at once, but instead like a mobile automaton or Turing machine, in which just a single cell gets updated at each step.