International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

The Computing Universe

Konrad Zuse

Im Haselgrund 21, 6418 Hünfeld, West Germany

Received May 7, 1981

In theoretical physics the concept of "field" is often applied to various phenomena in the space, normally represented by differential equations. In contrast to that, the theory of automata operates with discrete states. In this, the digitalization of procedures is an important aspect. Cellular automata allow the construction of "moving state structures" representing digital particles, which may be compared with the behavior of physical particles. The theory of automata further presupposes certain attitudes towards determination and causality. In close connection is the problem of the reversibility of time direction.

I got my first stimulations when I began to develop computers in electromechanical technology, about 35 years ago. In relay machines, there are shifting registers. Observing an impulse passing through a relay chain (Figure 1) I had the following idea: In a similar way a photon should travel through space. This induced me to the conception of the universe as a big computer. But at that time, these ideas could not be followed up seriously. Later on, however, I could develop some concepts (Zuse, 19, 1975). During the last years at Professor Vollmar's institute at the Technische Universität Braunschweig, some experiments with a computer could be made, supported by the Gesellschaft für Mathematik und Datenverarbeitung, Bonn (GMD). The following lines represent a summary of the most important points. Theoretical physicists, so far, utilized the computer chiefly as a tool for the performance of large numerical computations. In addition, some basic considerations have already been performed in order to apply the terms of information theory to theoretical physics. Reciprocally, it can be stated that the physical term *entropy* has been adapted by information theoreticians, stimulated by the conformity of certain formulas.

Sometimes, one starts with the idea that information as a new physical quantity or physical phenomenon may be set by the side of the older physical quantities as energy, momentum, mass, etc. This is formulated rather cautiously, corresponding to the way of thinking up to now. Of

0020-7748/82/0600-0589$03.00/0

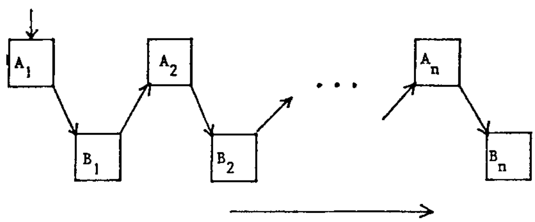

Fig. 1.

course, one could proceed more strictly and state: Perhaps it is even so that only by using the term *information*, laws as that of the conservation of energy, conservation of momentum, etc., can be fully explained.

My own considerations are presently directed more to the theory of automata. What we need here is the cellular automaton. The basic concept of the cellular automaton is the arrangement of single little automata in form of a grid, neighbors being interconnected. We may begin with the assumption that each of the grid points contains a small computer and that an exchange of information takes place between these computers.

Presently, the question arises: Is it justified to apply the term *information* here? Does there exist a transmission channel in the sense of information theory? In any case, there is a data transmission effective between the single elements, and if we content ourselves with the term *data*, we need not use the strict criteria of information theory.

Such automata have already been constructed. As one can imagine, they may be utilized very well to compute partial differential equations. We only may think of weather computation, which is performed as plane computation over a network of grid crosspoints.

Now the decisive problem is the following: So far it was the task of the computer expert to supply a good instrument, capable of computing partial differential equations, as good and as accurate as possible. He has been trying to perfect the accuracy upward to exclude sources of error as far as possible. Nevertheless, it will never be possible to realize exactly, even by means of an extremely well-constructed automaton, perhaps, the model of Maxwell's equations or any other physical equations. There exists a different behavior between the computing model and the mathematical one. The mathematician and the theoretical physicist assume that nature corresponds to their model of differential equations. This is a hypotheses, which so far can neither be proved or disproved. For numerical computation, a first condition is to assimilate as far as possible the model to nature in the sense of a continuum.

But one can assume an inverse standpoint: I do free myself from that condition of possibly greatest accuracy and do not attempt to develop an instrument for the solution of differential equations. But instead, I investigate the behavior of cellular automata. The question is then, how inaccurate I may construct my computer in order to make it work well enough so that it could be compared to the behavior of nature?

One may begin with a very simple model—the propagation of pressure waves in tubes. Not only waves are propagated, but also shocks. So far, it has been attempted to simulate natural processes as accurately as possible.

If one, however, puts the question, "How inaccurately may one operate that all observable effects become apparent?" then one gets the behavior of a relay chain in which simple pulses are propagated. One can establish rules and recognize analogies to the physical laws of the preservation of momentum and energy. This investigation can be extended to plane cellular automata or even to three- (or more) dimensional systems. We are not bound to an orthogonal arrangement, but may choose in a three-dimensional space an arrangement which corresponds to the problem of densest ball packing. The designer of a cellular automaton has a bunch of possibilities which he first can design on paper, then simulate by the computer, and possibly achieve new effects.

One may put the additional question, if it is possible to conceive a cellular circuitry in which pulses may move through the system in a random direction. Therein, the single computer in a grid crosspoint of the cellular automaton only should be composed of few switching elements for basic logic operations. We may then speak of patterns which consist of combinations with "yes, no" values. Such a pattern propagates itself on the base of the circuit laws. There exists a normal state of the system, if all members are set to zero.

Another pattern represents a disturbance of that normal state. Such disturbances and patterns are of special interest which do not dissipate or dissolve themselves, but which are preserved in their configuration even if they are propagating as a whole. Then such pattern propagate through space, similar to elementary particles of physics. Therefore, I would like to introduce the term *digital particles*. Figures 2–6 demonstrate some examples. The patterns are formed by arrow combinations. A simple arrow (Figure 2) moves in its direction through the space. A special law corresponding to Figure 3 is supposed for the arrows crossing at the same grid

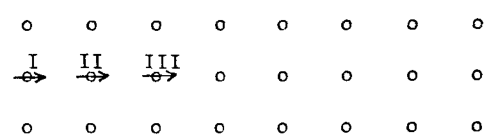

Fig. 2.

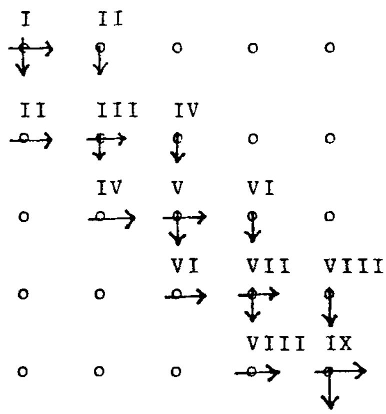

Fig. 3.

point. The patterns undergo several phases I, II,... during the transmission. Now one may play with such effects in many ways. I intentionally say "to play" in order to emphasize that we do not yet deal with a rounded up theory, but with a game with various possibilities. If such digital particles are approaching each other. What happens then? It may happen that theoretically the particles should collide, but actually would pass through each other without an interaction between them (Figure 4). But it may happen as well that they interact so that it would be an information process. As a result, a new particle could be created, which could proceed in another direction (Figure 5).

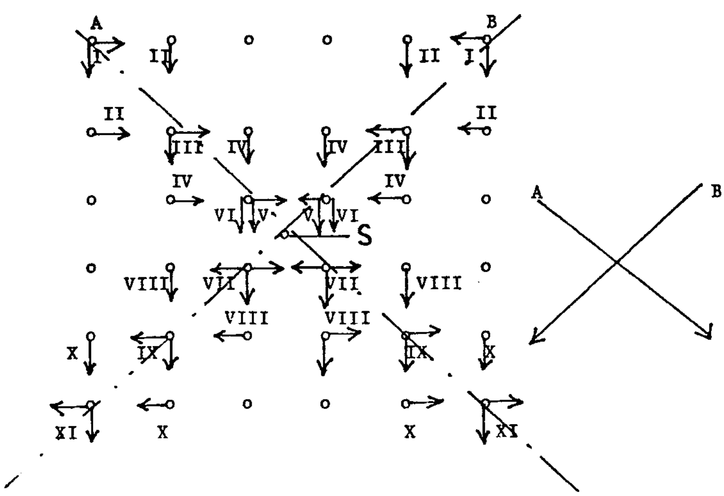

Fig. 4.

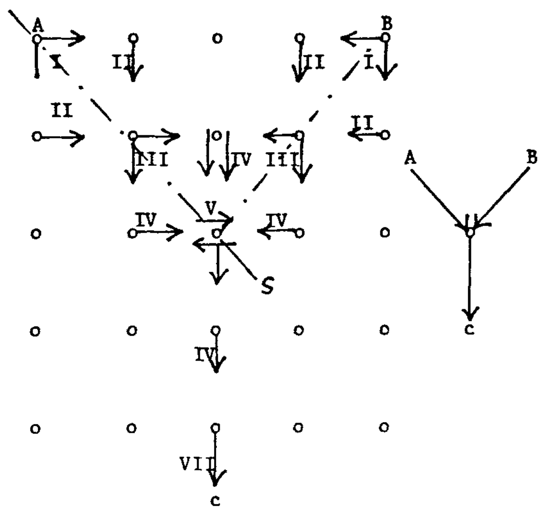

Fig. 5.

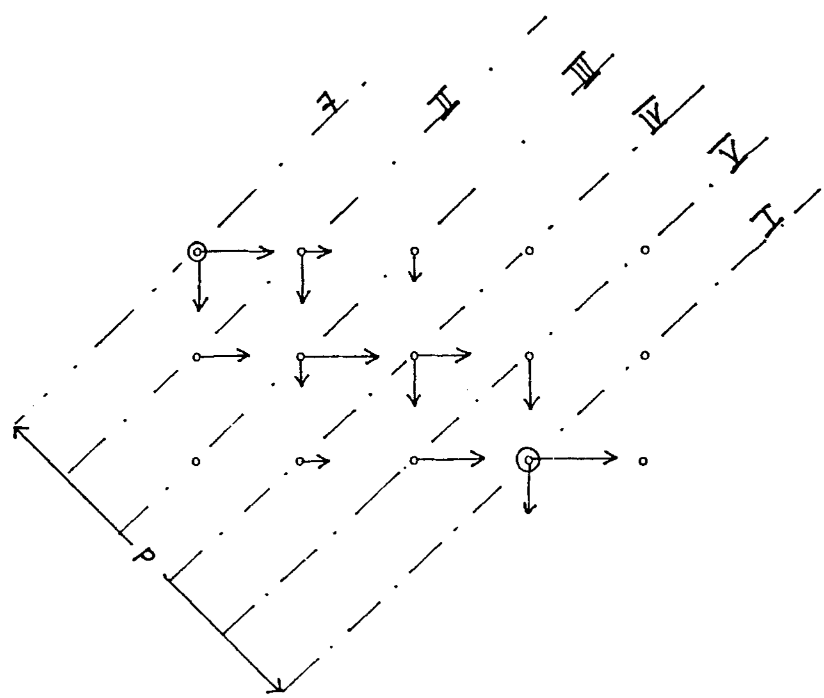

Fig. 6.

If one would demonstrate this effect to a mathematician, for instance at a display screen of a terminal connected to a computer, without telling him that he is watching digital processes, what could he do? He could only perform measurements and observations. He would conclude: The particles interact with the probability of one half, and they do not interact with the probability of another half. We have a similar effect in physics, where the interaction of two particles is determinated by probability laws. Consequently, we operate with interesting models, i.e., with particles being still far from real physical models. Anyway, they stimulate cogitations and make one curious, what would happen further on. It should be worthwhile to perform more intensive investigations and to observe the future development of the theory of cellular automata. Well, this requires a considerable investment, since rather large computers must be utilized.

One of the main reservations toward the cellular automaton has been directed against its anisotropy. Therefore, the concept of a gridlike structure of the space has been disapproved by the physicists because of basic considerations, and, in fact, our models have favored directions. However, there does not exist so far any information that such conditions really exist in space. The interative structure of a grid is in contradiction to the theory of the curvature of space, as defined by the general theory of relativity.

To achieve an approach of standpoints, one had to proceed from regularly constructed to irregularly organized grids. This leads us to the theory of variable and growing automata. Irregularities of the grid structure are a function of moving patterns, which is represented by digital particles. Now, not only certain values are assigned to the single crosspoints of the grid in the concept of the cellular automaton which are interrelated and sequencing each other, but also the irregularities of the grid are itself functions of these values of the just existing interlinking network. One can imagine rather easily that in such a way the interdependence of mass, energy, and curvature of space may logically result from the behavior of the grid structure.

Even if it is not yet possible to establish such theories with satisfying exactness, one may already develop some general ideas.

The theory of information is using the term *information* in the sense of a quantity, a term which is frequently wrongly used. Therefore it should be clearly defined before being applied. We know the meaning of the term in connection with the communication channel. In this case, a certain information is assigned to the message. The information theory contributes the bit as a measuring unit.

Does this concept of information exist also in nature? If one applies the model of the cellular automata, the question can be answered relatively easily. If one approaches the problem differently and insists on using the analog model of differential equation, one is confronted with a difficult situation.

At first one can assign an information quantity to structures of limited variability. Let us take a punch card as an example. If one may punch holes in predefined positions, then a card with 80 columns and 12 positions has a capacity of 960 bits. If this capability for the transmission of information is utilized, the object punch card has a variability in its structure, which corresponds to 960 bits. This means, that one can vary the structure to the amount of 2^{960} variations.

Now we can apply the concept of the variability of structure also to the cellular automaton. To start with, one can take a single cell and consider it as an automaton, which in the concept of the automaton theory can assume a discreet number of states. The logarithm in base 2 of the number of states would be the quantity of information of that single grid crosspoint. We would then have a limited information in the model of the cellular automaton, measured within a certain area. Principally an infinite extension is assumed for a cellular automaton. But realized automata dispose of a limited number of elements. One could give cellular automata with regular grids the shape of a toroid, and finally find solutions. If irregular grids are used, different solutions are possible in analogy to the curved and finite spaces of physics. Surely the irregular grids contain additional information concerning the grid structure.

The following ideas are especially interesting: What is the information being contained in a particle in space? Can one speak of a preservation of information in the same way as of a preservation of energy or a preservation of momentum or a charge? Well, this question cannot be answered easily. If we begin with the concept of a differential equation, with which today's physics is operating, the information would be infinite in each point of the space. So far, I believe, that not sufficient criticism has been applied yet to see the consequences which result from that concept.

Classical mathematics permits to insert an arbitrary number of intermediate values between two given values. This is the concept of mathematical analysis, on which the differential equations are based. Such conditions do not prevail in digitalized computing, because of the technically limited number of digits of the computers. Therefore, a singular automaton has only a limited number of values, i.e., discrete values, as it is not possible to insert between two values an arbitrary number of others, respectively, to intersect field quantities at random. There are certain maximum values, and there are threshold values. These are the limits that an active scientist has to watch, which he tries to eliminate as far as possible, but that are of special interest, seen from a different point of view. How do automata behave, if one chooses to limit the values intentionally narrow upward and downward?

Perhaps just the occurring effects lead us ahead. What does happen if I assign a wave equation to such a system? Perhaps quantized values and events occur which have a resemblance to those of physics.

As mentioned before, no satisfactory answer can be given to these questions. It is certain, however, to speak of digital particles in regard to the concept of the cellular automaton.

One could apply the concept of a preservation of information also to digital particles. But the following question arises: Is the quantity of information of two interacting particles preserved? The answer is not yet possible today. We hardly have models of such particles which are operating well.

In the cellular automaton the single computer located in a grid cross-point has a discrete number of states. But now one can speak of flowing states. One introduces some patterns. The switching and the structure of the patterns reproduce itself. But here the original pattern is cancelled and not preserved. If such a particle is not hindered to propagate itself, it undergoes a number of states, which return periodically, but together with a change of location where these states prevail.

Figure 6 shows a digital particle with different arrow lengths which proceeds in five phases and with a period of five steps. Such a behavior is principally different from a wave with a wavelength λ, as normally seen from the physical point of view (Figure 7).

Now it is possible to conceive classes of particles, which represent a certain type and which are distinguished between each other because of their pulse and velocity vector assigned to them. Then the number of possible patterns produces a measure for the information of the particle. In this way, we really arrive at the possibility to apply the term *information* for such processes.

In a variable automaton with irregular grid structure, the digital particles represent wandering grid patterns which propagate themselves with their distortions within the grid. In this way, the anisotropy of the space can be explained statistically. Terms as distance in space and time and their quotient and velocity become statistical quantities. Transferring such ideas to the cosmos, one has to consider that space is extraordinarily fine

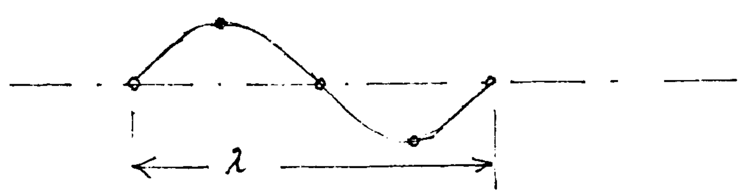

Fig. 7.

structured so that the statistical dispersion of the velocity of light is far beyond detection by the best available instruments.

Now I would like to add something to the problem of determination. Generally one starts from the assumption that ambivalence of time direction holds true for the law of physics. Consequently in classical mechanics Newton's laws are valid in both time directions. There is no reason to give preference to one time direction within a theory based on differential equations. Therefore, it probably was a matter of course for Laplace to assume ambivalence of time direction in his famous theses, as the mathematical laws gave no reason to prefer one time direction. This behavior of nature based on mathematical laws does not correspond to daily observed physical phenomena. Everyone knows that most processes in nature are irreversible, e.g., melting a complicated figure or mixing two gases of different composition and temperature.

Only since the introduction of the term *entropy* physicists of today believe in being able to give preference to positive time direction despite of the ambivalence of time direction usually assumed for physical laws. But one likes to suppose that these processes are actually reversible and consequently defines the entropy as a measure of our lack of knowledge.

The problem looks different from the standpoint of the theory of automata. An automaton usually has a determined structure, i.e., it is operating according to strict rules. A sequence of states follows each other. The following state is always a consequence of the preceding state. This is not the case in reverse. The present state does not allow us to determine the foregoing state, as several states may result in an identical state. Therefore, it is interesting to perceive that the behavior of automata is entirely different from that of the models of physics which have been presented so far.

In contrast to a mathematician of Laplace's time, the automaton theoretician, studying the behavior of automata, should not even consider assuming an ambivalence of time direction. On the contrary, he would probably have to search with considerable effort for complicated solutions to fulfill a request for ambivalence of time direction. Nevertheless, nowadays mathematicians prefer reversible solutions even in cellular automata to simulate physical processes. In this way, even for computers reversible circuits are proposed. But in my opinion, the surmounting of traditional concepts may pave a new way for the formulation of nature laws. The theory of automata may offer useful models.

I should like to mention another consideration here: If one, for instance, submits something to the quantum of action h (Planck's constant), which somehow corresponds to a switching action, the energy would appear as a switching action per time unit, and the preservation of energy would become a preservation of switching action. With a cellular automaton, it would mean that it would currently change its states, beginning from a certain original state, wherein the degree of complexity is being preserved.

In my opinion it is not justified to identify energy and information. Finite automata only have a discrete number of states, and consequently only discrete values of their single parameters. This means that all its quantities being handled must be digitized in some form. The most consequent possibility is to transform all information into combinations of bits. Accordingly, as with circuitry, the basic operations of the propositional calculus play an important role. This allows us to view many effects under new aspects. As generally known, a reciprocal interaction of different events, for instance of waves, can only be produced with difficult equations after the introduction of nonlinear superpositions. With consequent digitalization to the extreme, one arrives at the logical addition of two bits, i.e., at the propositional disjunction. In this way, also interaction has been reduced to an elementary case.

In general, the behavior of circuitry is strictly determined. However, by introduction of "yes, no" decisions obeying probability laws, one may get to elementary cases of stochastically determined events. From the engineer's viewpoint, such lottery elements in the frame of an automaton which is governed by strict laws are not at all simple. Lottery mechanisms have to be constructed very exactly, in order to work sufficiently. Dice and roulette are also subject to strict deterministic laws. Even small inexactness in construction leads to undesirable results.

It is not surprising that today there are not yet available models which satisfy the physicists. We have not at all explored our discipline yet, but only taken a glance behind the scene of a new world. We do not yet have starting points from which we could search in experiments for effects that would comply with automata theoretical concepts. Possibly, this could be the case in procedures involving high energy.

Perhaps this can be illustrated as follows: The task could be, for instance to compute with a cellular automaton the behavior of an antenna by means of Maxwell's equations. In the sense of the Lorentz transformation, inertial systems are assumed which move relative to the grid of the automaton and the model which function well, as long as the velocity is low in relation to the velocity of light. The model of relativity theory, however, sets no limitations. So I may perform this process at random and approach with the velocity of the inertial system the velocity of light at option. The system of Lorentz transformation permits this without any difficulties. The cellular automaton could fail, however, or show effects which would correspond to a miscalculation of the system. If one now doubts the unlimited validity of the differential equations and assumes similar conditions in nature as they prevail in a cellular automaton, then similar effects must be

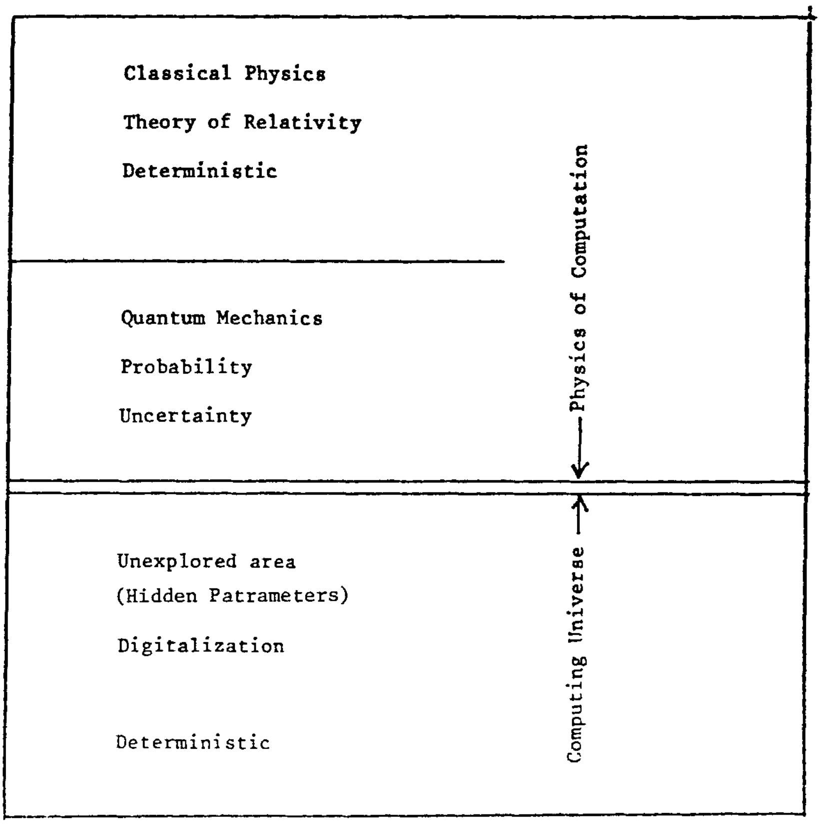

Fig. 8.

observable. This can become realistic, if we manage to generate ever higher energies with our particle accelerators. One day perhaps, an experiment will have the result that a basically different behavior becomes apparent, which no longer follows up present known laws. Then perhaps the meanwhile further developed theory of automata may come in and offer an explanation for such an effect.

It is my firm conviction that the theory of automata in the future will supply important contributions to the exploration of the universe.

The considerations which I have presented did not yet reflect a completely founded and mature theory. My concept has been developed gradually in the last 20–30 years while I was predominantly engaged in the development of the computer and directly related problems. Their source were considerations about algebraic switching in connection with the development of complex logic circuitry. I have to confess that my knowledge of physics is more that of an engineer than that of a professional physicist. Nevertheless, I believe, that my presentation may stimulate further progress in this field.

REFERENCES

Zuse, Konrad (1900). *Rechender Raum*, *Schriften zur Datenverarbeitung*, Vol. 1. Friedrich Vieweg und Sohn, Braunschweig, West Germany.

Zuse, Konrad (1975). "Ansätze einer Theorie des Netzautomaten," *Nova Acta Leopoldina*, **43** (220) (Halle, Saale, West Germany).