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The Direction of Time: Seven Arrows for One Stream? A Program

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I review the role of entropy in the Second Law of Thermodynamics in providing time with a direction and explaining irreversibility. I then list seven seemingly different features, each characterizing an additional "arrow." In one case, connected to Black Hole Physics, the arrow has been successfully merged with the thermodynamical and may serve as model; in another case, that of the Evolutionary drive, the adequate function has been identified as *complexity.* We define the aims of the program and also provide information for an alternative, "*geometrical*" (effective) approach.

KEY WORDS: time arrows; black hole physics.

1. INTRODUCTION: THE SECOND LAW AND ITS ARROW

In "The Nature of the Physical World" (1929), Sir Arthur Eddington (1929), dealing explicitly with "time's arrow" first makes the distinction between *geometric* time (which carries no arrow) and *physical* time, with its arrow's direction determined by the Second Law of Thermodynamics. Quoting Eddington's description of the fall of a stone, "looking microscopically . . . we see an enormous multitude of molecules moving downward with equal and parallel velocities—an *organized* motion like the march of a regiment. We have to notice two things, the *energy* and the *organization of the energy.* To return to the original height the stone must preserve both of them. When the stone falls on a sufficiently elastic surface, the motion may be reversed without destroying the organization . . .

> The famous Duke of York
> With twenty thousand men,
> He marched them up to the top of the hill
> And marched them down again

. . . what usually happens . . . is that the molecules suffer more or less random collisions and rebound in all directions . . . they have lost their organization . . . "

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This view of the statistical/probabilistic nature of the Second Law has been prevalent since Boltzmann's time. Let us set it in its precise physical frame. Classical thermodynamics covers a physical region in which the short-ranged (nuclear) interactions (Strong and Weak) have been integrated out, together with the atomic and molecular electromagnetic bindings, leaving us with just *kinetic energy*, perhaps disregarding some weak chemical potentials. In the conventional terminology, this is the *ideal gas* picture. All other parts of the fundamental Hamiltonian are included *indirectly* through the masses, angular momenta, and various structural parameters at the molecular level. It is under such an assumption of *no-interaction* conditions that we present the elementary illustration demonstrating the relationship between entropy and the arrow of time: two pictures of a group of molecules, one [S] showing them *spread out* over a large volume, the other [D] showing them all in one relatively *dense* bunch. [D] is the relatively *more ordered* set up, [S] is the *less ordered* one. With *chance* as the only intervening factor, and as the probability of many molecules accidentally converging toward and arriving at the same point is negligible, we conclude that [D] is the *earlier* take, [S] the *later* one, reached naturally as a result of the molecules' random motion. In the example of the stone falling, [D] would be the ordered state, i.e., the original fall, with the molecules reminding Sir Arthur of a regimental march, [S] the disordered state, namely the disorganized return, after the intervention of randomness, of blind Tyche, goddess of luck, during the collision with the ground.

2. SIX (OR MORE) POINTING ARROWS

The picture became more opaque when new and apparently disconnected time-arrows appeared on the physical scene. Counting (1 $\rightarrow$) for the thermodynamical arrow above, we got (2 $\rightarrow$) for the cosmological, in the twenties, with the discovery of the universal expansion (Gal-Or, 1974); the development of Quantum Electrodynamics brought yet another arrow (3 $\rightarrow$) in its wake, the one connected with radiation and the advanced or retarded potentials, etc. The discovery in 1964 of CP violation in $K_L^0 \rightarrow 2\pi$, was assumed to imply T violation (4 $\rightarrow$), with CPT still invariant, a reading which was recently reconfirmed. This therefore brought in yet another arrow, *microscopical* and *nonstatistical*. The *evolutionary drive* (5 $\rightarrow$), fully generalized to include everything from *cosmogony to epistemology*, also appears to carry its own arrow; and finally, there is (6 $\rightarrow$) the cognitive inner human *sense of duration*. We looked at some of these issues at the time (Aharony and Ne'eman, 1970a,b; Kuper and Peres, 1970; Ne'eman, 1969). The situation appears to call for a *unification* program, aimed at replacing *six* or seven different arrows by one single underpinning mechanism for one same stream.

3. AN ACHIEVEMENT IN UNIFICATION: MERGER OF THE GRAVITATIONAL ARROW (7 →)

Our list was incomplete. There was yet a seventh—interaction-related—irreversibility, namely the attractive action of gravity; more specifically, the action of *gravity* in its *strongest attractive* phase, namely in the formation of *black holes*, and thus in a region of phase space which is far from thermodynamics. At first sight, it would seem that order is generated, with all masses converging as in [D] onto the singularity at the center of the black hole (or accumulating on its surface, as seen by an outside distant frame). Thus, as for [D] in our previous discussion, a black hole would represent the generation of order, i.e. negative entropy. This approach, however, is wrong in that it follows the history of *noninteracting matter* solely (as represented by the *energy–momentum tensor current density*) still uncoupled to the gravitational field in the Hamiltonian and does not consider radiation and the gravitational field itself, with the tensions it exerts in its strong binding.

Black Hole irreversibility was identified as yet another arrow and treated by J. Bekenstein in an intuitive formula (Bekenstein, 1973), namely a *positive* contribution to entropy, proportional to the *area* of the black hole's envelope. This result was tested and confirmed by S. Hawking, using thermodynamical considerations and quantum barrier-penetration (Hawking, 1975). What then is this entropy? Some insight indeed came after Bekenstein's formula was *rederived* by C. Vafa and A. Strominger *within Quantum Gravity*, as described by Superstring Theory and by its (lower energy) Supergravity Quantum Field Theory components (Strominger and Vafa, 1996).

This revealed where the *disorder* was: in the organization of the *quanta of the supergravitational field, due to the inclusion of their interactions*! Note that supergravity is generally treated as a self-source theory, in which both fermions and bosons in nature are components of the same field. The Hamiltonian is quadratic in the supercurvatures and contains both free and interactive pieces. The states counted by Strominger and Vafa are solitons and *topological* realizations of the supergravitational field with all its *self-binding* action between its components, especially gravitons with gravitinos. As a matter of fact, it is through the use of the BPS formalism and the resulting equations for the *bound states* due to the interactive pieces that it becomes possible to evaluate the entropy and compare it to the value predicted by the macroscropic guesses. True, there is this *negative* contribution to the total entropy coming from the "improvement" in the orderliness of the nucleons and electrons now imprisoned within the black hole, or even better, now stuck on its envelope (in view of the *holographic* interpretation of the conservation of quantum information (Susskind, 1995)). As against this negative increment, however, there is a (larger) positive contribution originating either in the tensions created within the black hole's gravitational field quanta themselves or by the mixed quanta making up the bound states.

Summing up, we note that the successful merger of the gravitational traffic into the mainstream of the generalized Boltzmann freeway requires counting at the *quantum level.* This is not surprising, as such an involvement with the quantum level is already present in the quantum *tunneling* required by Hawking's analysis.

Note that in Cosmology, with *arrow*—(2 →) we had indeed assumed that the dense state [D] being the most ordered, with the lowest entropy, a *contracting universe* would produce negative entropy, in violation of the Second Law. The conclusion used to be that *a collapsing universe would invert its time-arrow* and would then *become an expanding* one (Aharony and Ne'eman, 1970b). We now realize that this picture was *incomplete* and *wrong*, as it ignored the contribution of the main actor in cosmology, namely *gravity itself* (Schroedinger, 1967).

4. EVOLUTION AND ENTROPY: MEASURES OF COMPLEXITY

It appears that the next best candidate arrow to be ready for a merger is now (5 →) Generalized Evolution, and we are cearly again in regions in which the Hamiltonian contributes through *binding* components. These range from the role of Quantum Chromodynamics in *nucleosynthesis* to the biophysical contributions (mostly electromagnetic) making up nature's own *genetic engineering.* As with the area of the envelope of a black hole in the Bekenstein formula, we have to *identify* a *time-arrowed quantity* characterizing the action of the *evolutionary drive.* Moreover, as against Schroedinger's view in "What is Life" (Schroedinger, 1967), accordling to which Evolution represents negative entropy, because it produces *order*, we note that this negative entropy, however again relates to *matter*, while the *complexity* function will represent the positive entropy produced by the tension within the binding fields.

Two approaches have been used to date, the more abstract (Bennett, 1988; Chaitin, 1975; Fogelman, 1991; Li and Vitan Yi, 2002), inspired by Kolmogorov's treatment of information, and given by the length of the shortest program describing the system—and a pragmatic one, used in the biological domain, inspired by genetic studies. Here, effective measures of *complexity* have been abstracted from *experimental* requirements, e.g., in cases involving two species deriving from the same ancestry, estimating the time elapsed since that branching. This is done by *counting* the *number of mutations* which are not common to the two species, a linear procedure. Whatever the choice, evolution occurs through the growth of complexity; as to the sign, complexity grows with time, it *thus has to have the same sign as entropy, and has to represent positive entropy originating in the binding fields.*

Once a useful and informative *level of complexity* has been properly defined, it should be appended as additional positive entropy to the *Second Law*, in an extension of thermodynamics (or better to a related formulation in Shannon's *Information Theory*) on top of Schroedinger's order-generated negative entropy and more than canceling it, a price fixed by the Second Law.

5. A GEOMETRICAL SOLUTION?

For the sake of completeness, it is worth noting that there are mathematical ways of putting the arrow in the geometry—in fact in the topology of space–time. At worst, it could be useful as an "effective" representation, here at the coordinate's level. Note that Riemannian geometry with its *metric* does define different "*orbits*" for the Poincare group in the local tangent Minkowski space–time: a *time-like* state cannot move faster than light and *cannot stop the flow of time*, but it can always find a rest frame, in which it *never moves*; whereas a (*space-like*) *tachyon* has to move faster than light, *cannot stop the "flow of space"* but *it can stay at one instant throughout.* However, the metric relation being quadratic, *the time-like orbit allows a backward flow of time.* To represent the arrow of time and irreversibility one is thus forced to go beyond "plain" Riemannian Geometry into a "directed" topology. This method was initiated by F. C. Zeeman in the sixties and was developed in three stages:

(a) Special-relativity and flat space (Zeeman, 1964, 1967);
(b) Curved space (Goebel, 1976)
(c) Feynman paths (Hawking *et al.*, 1976). in a relativistic Quantum Field Theory.

Mainly, one guarantees the sequential ordering along these lines. I refer the reader to my (Ne'eman, 1986) discussion of this approach in a different context—and to a recent revival of the topological approach (Wickramasekara, 2001).

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