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TIME IN THE EARTH SCIENCES

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The Earth sciences deal with processes which have characteristic times range from microseconds to billions of years. The proper times of biospheric processes used by human being for counting time, are formed with the aid of cyclic phenomena such as rotation of the Earth, its revolution around the Sun, etc., superimposed on the irreversible development of life and the whole biosphere. The extensive number of specific "clocks" operating in the environment are actually independent of each other, being only partially matched by resonance in the hierarchic "queue" of asymptotic processes. Time for us is an indicator of conditions and differences and informs us of causal relations among various phenomena. Thus it can be conjectured that a world model might be constructed where time would be a secondary, definable notion, or be absent at all.

1. Geographic time

Two symmetric viewpoints on what we are measuring when determining the duration of an event, are possible by logic. First, one can believe that we are determining a certain characteristic of an event or process as it is occurring in the independent, Newtonian time. Hence we discover nothing about the time itself. Second, the opposite viewpoint is viable, that the time and the processes occurring in reality are one and the same thing. When measuring some duration, we are determining the properties of a variable depending on the process under study, i.e., those of time related to the process. Essentially the question is: what is primary, what is the original cause of the changes in the world around us, the course of Time or some other cause which could be called Energy, or the General Law of Development, etc. As shown by Vernadsky (1988), the second viewpoint is becoming more and more attractive for the scientists.

For the Earth sciences, dealing with an enormous diversity of processes extended over a large range of temporal characteristics, a solution of the above problem is of great significance. There has been an increase in the number of researchers who support the view that some specific geological time, or even a few geological times, exist. Nevertheless, so far there is no ground for saying that the geological and geographic sciences have presented a decisive foundation of that or other viewpoint.

In practice, however, measurements are carried out with the only purpose: to gain the possibility to compare an interval duration, or process rate, with duration of another interval or rate of another process. The only difference is the interpretations of the results. In the first case the result bears a purely practical loading while in the second it is implied that the result reveals a certain ontological content. In order not to go further in this discussion, we would like to operate in the present chapter the neutral notion of "characteristic time" of a process (Liapunov 1968) or of a corresponding complex of material bodies, while the interpretation in the first or the second manner is postponed to the last part of the chapter.

The humanity's social experience led to the notion of time as a vector. This restricts the possible character of processes suitable for measuring time. First, the process must be directed in an unambiguous way, thus pointing out the direction of the "arrow of time". Second, the changes that happen cannot be continuous and homogeneous. Their qualitative and quantitative characteristics should change, providing "labels" which quantize the process and thus form a unit for comparing process durations. The duration of events which is important for identifying a certain process is the second, scalar feature of a characteristic time. Evidently, time cannot be measured by entirely closed cyclic processes, as well as by highly uniform, "entropy-free" ones.

In inanimate nature such processes are clearly directed as terrain smoothing, magmatic and sedimentary rock formation (in intervals between repeated orogeneses, meltings and erosion cycles), rock weathering and others. At the level of living matter irreversible are such processes as cell, organism or species development, primary and restoring succession of a biocoenosis and its associated soil. The unrepeatedness of life evolution stages on the Earth allowed geochronology to be developed. Likewise, the irreversible historical event sequence created the human society chronology.

The concept of characteristic time is aimed at giving an idea of relative rates at which the events under study are happening (Table). The greater the characteristic time is, the lower is the rate. The choice of a time unit in the Earth sciences depends to a great extent on the character of changes (Armand and Targulian 1974).

Table. The characteristic times of geological and geographic processes.

Char. Time (years)	Lithosphere	Atmosphere	Pedosphere
10^{9}	Mass exchange in crystal rocks		
10^{8}	Geological cycles. Mass exchange in sedimentary rocks	Great climatic cycles	
10^{7}	Mountain system levelling	Oxygen exchange cycle	
10^{6}	Solid rock terrain form levelling	Carbon exchange cycle	Formation of nature soil mineralogical and weathering crust profile
10^{5}	Sediment terrain form levelling	Climate changes within a glacial epoch	
10^{4}	Earth axis precession		Formation of nature soil profile differentiated in morphology and chemistry
10^{3}		Climate changes within a historical period	Mature humus profile formation
10^{2}	Epeirogenic Cycles	90-year climatic cycles	Formation of mature soil carbonate profile
10^{1}		Decade climate changes (solar cycle)	Biological substance rotation in a soil
10^{0}		Seasonal meteorological cycle	Formation of easily soluble substance profile, pH
10^{-1} (month)	Terrain microform levelling in sand, snow, dust. Tides in Earth 's crust		Solid hydrological and thermal profile
10^{-2} (day)		Cyclones, diurnal weather cycle	Humidity and temperature of soil surface horizons
10^{-3}			
10^{-4} (hour)		Hour weather changes	
10^{-5} (minutes)	Microseisms	Minute weather changes	

(Table continued)

<table>
<tr><th>Char. Time years</th><th>Biosphere</th><th>Hydrosphere</th><th>Electromagnetic fields</th></tr>
<tr><td>10^9</td><td></td><td></td><td></td></tr>
<tr><td>10^8</td><td></td><td>Sodium exchange in the ocean*</td><td></td></tr>
<tr><td>10^7</td><td></td><td>Magnesium exchange in the ocean*</td><td></td></tr>
<tr><td>10^6</td><td></td><td>Potassium, calcium and carbon exchange in the ocean*</td><td></td></tr>
<tr><td>10^5</td><td></td><td></td><td>Geomagnetic field inversion</td></tr>
<tr><td>10^4</td><td></td><td>Formation of lake water chemical equilibrium</td><td></td></tr>
<tr><td>10^3</td><td></td><td rowspan="2">Ice sheet self-development. Aluminium* and titanium exchange in the ocean.</td><td>Western drift. Earth dynamo time constant</td></tr>
<tr><td>10^2</td><td>Mature arboreal vegetation formation</td><td>60-years magnetic field variation</td></tr>
<tr><td>10^1</td><td rowspan="2">Formation of grass vegetation, mouse-like rodent population, insect population.</td><td>Antropogenic lake euthrophing</td><td>11-year solar activity cycle</td></tr>
<tr><td>10^0</td><td>Snow cover metamorphization. Seasonal hydrological cycle.</td><td>Seasonal external geomagnetic field cycle.</td></tr>
<tr><td>10^{-1} (month)</td><td rowspan="2">Microbiocoenisis formation.

Circadic biorhythms</td><td>Ground water levelling</td><td>Planetary field sector crossing. 27-day geomagnetic field variation</td></tr>
<tr><td>10^{-2} (day)</td><td>Diurnal hydrological cycles, tides</td><td>Diurnal geomagnetic field variation. Magnetic storms</td></tr>
<tr><td>10^{-3}</td><td></td><td>Rough sea extinction</td><td></td></tr>
<tr><td>10^{-4} (hour)</td><td></td><td>Small reservoir levelling</td><td>Magnetic field "coils"</td></tr>
<tr><td>10^{-5} (minutes)</td><td></td><td></td><td>Short-term magnetic field variations</td></tr>
</table>

Comment. For substances marked by asterisks (*) the average stay time in a relevant medium is taken for characteristic time.

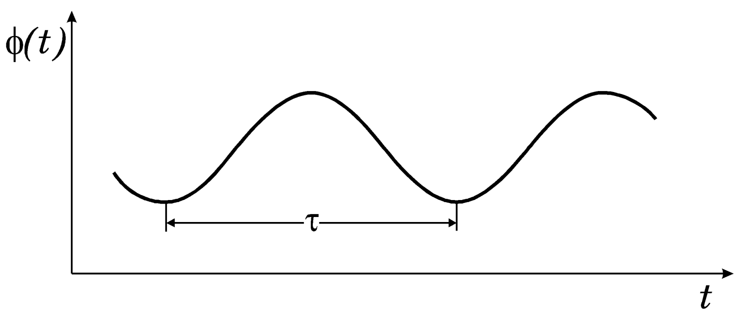

Fig. 1. The characteristic time τ of an oscillatory process. The values of the variable characterizing the process are plotted along the ordinate axis.

A basic time unit is chosen most simply in the cases when an irreversible process is superimposed by harmonic oscillations or some cyclic process. The term "characteristic time" in such a case means the period of a full cycle (Fig.1). The time of biological processes is naturally quantized by the geophysical cycles into days, (lunar) months, years and other periods.

In Fig.1 the values of a variable characterizing the process are plotted along the ordinate axis.

If the process is of an asymptotic nature (Fig.2), then the process decay intensity will be measured by the time required for the parameter to decrease by a factor of 2 or e = 2.72 (the relaxation time).

As for "arrow of time" definition, natural scientists have at their disposal two physically opposed but equally directed classes of processes: those of entropy increase and those of diversity, or, more widely, information increase. Both principles are used when biosphere chronology is created. The time counting by entropy provides the basis for the radio-carbon time measurement methods, for dating by bone remains decay in paleontology and by mineral remains destruction in lithology, for landforms age determination, etc. The negative-entropy processes allow the paleontological history to be ordered in a temporal sequence, they help the researchers to bring in order the events of human history, to identify the stages of vegetation succession, etc.

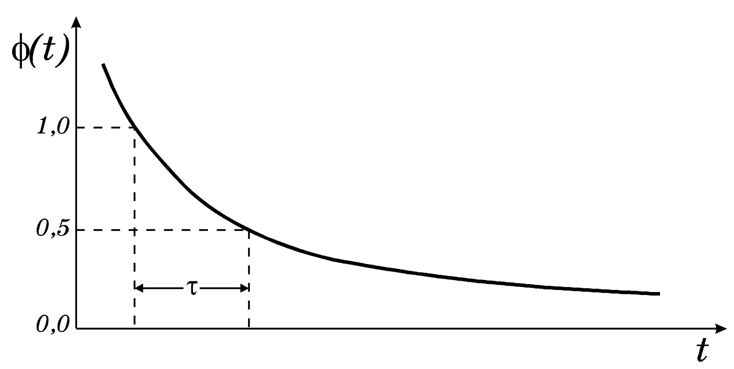

Fig. 2. The characteristic time τ of an asymptotic process

However, to create a chronological event sequence certain reference points, or marks, are needed. The diversity of natural processes yields a rich choice of suitable characteristic phenomena.

In the Earth's history the most significant marks have been: the atmosphere and hydrosphere formation, the appearance of life, the oxygen atmosphere formation, the organisms' going out to dry land, the appearance of mammals and later of man, the beginning of the last glacial epoch, the human history beginning, the great geographic discoveries. For each living being the most important instants of its history are the instants of birth and death.

However, for the involved network of events to be ordered, the most suitable are rhythmically repeated events. The two most stable rhythms have been taken as the basis of the time scales for building chronology of the biosphere and the human society. The role of a pendulum is played by the Earth, by its rotation around its axis determining the diurnal rhythm, and its annual revolution around the Sun.

This time standard has revealed a great number of processes with more or less stable periods in the surrounding nature and in ourselves. Here are some of them: the orogenic cycles; climate variations, from the two- or three-year ones to those compatible with geological epoch duration; the solar factor variations; the epeirogenic Earth's crust variations; river water expenditure variations; ocean tides, seiche and wind waves on water surfaces. Many of the natural rhythms are directly or indirectly related to each other, are multiples of one another. Many social and socio-geographic rhythms depend on them, such as migrations of peoples, golden ages and decadance of cultures, droughts, epidemics, spreads of agricultural vermin insects, etc.

This diversity of cycles must be probably divided into two groups: the variations and rhythms of the objects themselves and those forced by higher-rank systems. For instance, evidently the seasonal and daily landscape variations, agricultural working rhythms or sea tides are dominated by geophysical phenomena, which are external for them. On the other hand, the seiches of the Baikal or the Caspian sea, although stimulated by external factors (atmospheric pressure overfalls), obey the rhythms determined by the masses of water oscillating and the reservoir shapes.

Apart from a small number of rhythms with strictly fixed frequencies, the geographic scale systems (10^1 - 10^7 m) vary in many cases with variable periods. The changes can be directed or more or less accidental. Paleontology has fixed the acceleration of life development as it occurred on the Earth. If the astronomical time unit, the year, is considered to be constant, then the number of taxons appearing in a certain period, increases with time. The historical science also admits the assertion that the intervals between "marks" determining the society development rate, are reducing (the marks are outstanding discoveries, inventions, birth of cardinal religious and philosophic teachings, etc.). It can be thought that we are witnesses of the manifestation of a certain general law of matter self-organization, by which new information in evolutionary processes emerges in an accelerated manner, by the exponential law:

$$dI/dt = kI^n,$$

where I is the diversity achieved in a certain material domain by the present moment and $n > 1$.

However, a directed process rate variation is connected not only with the self-organization processes in the biosphere. Tidal effects cause slowing down of the Earth's rotational motion with respect to its revolution around the Sun. Although very slowly, the course of the main pendulum, determining the biospheric life rhythm, is changing. The day gradually becomes longer. The number of days in a year of the Cambrian epoch was twice as big as that of the present-day.

2. Matching the characteristic times

A float being thrown to a water surface, is rocking on the waves, obeying simultaneously a few rhythms: the small wind ripple, two or three bigger wave systems and tidal variations if all that is happened in a sea. Oscillation theory asserts that if the frequencies step are sufficiently far away from each other, these rhythms do not interact despite the fact that the pulsating object is the same. This law is valid for all the objects of the Earth's geographic cover. The course of the soil, geomorphological, climatic, biological and social processes not only measured by their own proper "clocks" but also each component has a number of them, even each element, an organism, a soil horizon or a reservoir. The world around us seems to be built extremely unreasonably in the chronological respect. It can be imagined as a set, or a mechanical sum, of an infinite number of clocks, each of them working at a rate of its own, independent of all the others. In such a condition a study of one of the natural or social processes can yield no information about the processes occurring to the same object, or some surrounding ones, in another characteristic time. The science destined to study the temporal organization of geographic object, becomes a collection of facts unrelated to each other.

In reality there are connections between processes occurring with different characteristic times. The set of mechanisms implementing that connection, is not so big.

Oscillation processes interact with each other by resonance. The theorem of oscillation independence refers to the frequencies which are sufficiently separated from one another. If the systems whose oscillations are close in period ω, so that $\delta\omega = (\omega_1\text{-}\omega_2) < \sqrt{2}$, are connected physically or through information, then their synchronization takes place. A rhythm less powerful in the sense of energy, is adjusted to the more powerful one. A bundle of oscillatory processes with about the same frequencies passes to a single rhythm, with mutual amplification. In a random frequency spectrum like a flicker noise certain preferred frequencies appear, which are separated by energy "gaps". The smallest spacing at which the mode frequencies can appear in the condition of a resonance, is about triple the frequency (in the increasing or decreasing manner). Thus if there is a preferred rhythm in the spectrum, determined by a certain oscillatory mechanism, then this tuning fork leads to organization of not only other oscillations with similar frequencies, but also in principle the whole spectrum of oscillations involved in the interaction. The information is transferred consecutively, from one frequency bundle to another.

A resonance filter probably creates the more or less exact periodicity of such processes as geyser eruptions, pulsating glacier motions and fluctuations of sea currents such as the Peru one.

The oscillation rhythms are determined by feedbacks in system structures, playing the role of oscillatory circuits. The oscillation period is determined by signal transition rate along the circuit.

Probably such an oscillatory process self-organization is expressed in the spatial structure of the Earth' s landscape sphere. B.V.Vinogradov (1979) has studied the sizes of natural territory complexes (landscapes) decoded from aerial and space photographs by colour variations. The whole sequence (spectrum) of sizes turned out to be decomposed into bundles, i.e., sizes observed most frequently, and gaps between them. The ratio of the progression is close to 3.

Another mechanism of characteristic times interaction is revealed for processes of asymptotic rather than periodic nature. This mechanism may be called adjustment of more rapid processes to slower ones, resulting in a specific sort of system hierarchy, namely, the characteristic time hierarchy.

Such an adjustment can be exemplified by the following chain of events. After some cataclysm (a tectonic raise, a landslide, seashore receding, a sharp climate change, a fire, etc.) a number of compensatory processes begins: denudation, new vegetation formation, changing properties of the surface water and the lowest layer of the atmosphere.

These asymptotic processes have different rates. Naturally the most rapid of these processes is the first to lead the corresponding system to a stationary state, equilibrium or homeostatic equilibrium if living components of the landscape are dealt with. A transition to a stationary state is controlled by self-regulation mechanisms existing in that or other form in practically all the natural systems. As soon as an equilibrium is achieved, self-regulation almost stops working, it just compensates small deflections from the stationary point. However, the environment of the most rapid system continues to change since the slower processes have not been completed. Therefore the "rapid" system has to pass to the regime of following the variable environmental parameters, i.e., the regime of adjusting its average conditions. A forced "movement" is accomplished so that a quasi-equilibrium (nearly equilibrium) or quasi-homeostatic state is preserved. When the second process comes to an end, the role of the main motor passes to a still slower regulator, etc., until a mechanism with the longest characteristic time comes to a stationary state (Fig.3).

This is the approximate way of natural complex (also called a geosystem, an ecosystem, a biogeocoenosis) formation in the course of a primary or restoring succession. A sequence of processes, as ordered by increased characteristic times, includes a transition to radiation balance equilibrium, that of the lowest part of the atmosphere (microclimate), surface and ground waters, invertebrate population, annual grass crops, perennial herbs, mosses and lichens, bushes and trees, big animals, soil and terrain (see the table). Somewhere at the level of grasses agricultural production could be included in this sequence. The economy of a state having suffered from war, can be restored after a longer period of time.

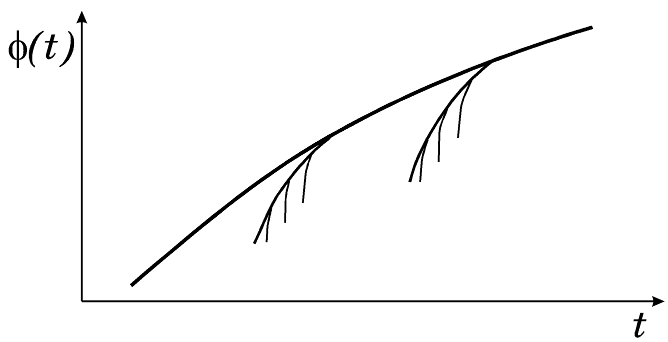

Fig. 3. Graph of a complicated process combining a number of asymptotic processes with different characteristic times.

If one returns to the imaginary picture with a number of independent clocks, then the succession looks like winding-up exhaustion, beginning with the most rapid clock. However, the continued operation of slower clocks supports the "rapid" clocks in the state of a weak winding-up, until that of their own is exhausted. This connection makes it possible to divide all the specific processes taking part in a complex process into two parts: the practically completed ones and the continuing ones. In practice the slowest processes among the known ones have not enough time to lead the system to equilibrium. They are stopped by new cataclysms of tectonic or space origin and these again launch the whole collection of slow and rapid clocks.

There is another permanent cause leading to the natural system equilibrium violation. That is, the self-organization processes always occurring in the biosphere and interlacing to a continuous process of the Earth' s evolution. Four relatively independent series can be selected from the recent past, although actually they just continue each other: lithospheric evolution (it actually includes the hydrosphere and atmosphere), the living substance evolution, that of the human society and the human mind and psyche evolution. Unlike the self-regulation processes, the evolutionary sequences have no apparent theoretically necessary end. All the other biological, social and abiotic clocks operate on the background of environmental changes permanently growing due to the evolution.

Thus for all the asymptotic processes biospheric evolution implies the overall continual equilibrium violation and displacement of self-regulated system attractors. That is the second cause of asymptotic "clock" continue "winding-up" in the course of evolution. Such an adjustment has shown itself in the recent rejuvenation of ecosystems due to enhanced technogenic influences.

An additive superposition of out-of-resonance oscillations can create the "beating" effect, i.e., that of periodic or accidental extreme deviations of system states from their averages. The extremes occur at points where different rhythms are in phase and reinforce each other. The rhythms synthesized in this way as though add one more arm to the natural clock, the one moving slower than the others, but multiply related to them. Maybe the rare climate cataclysms like extremely strong droughts, floods, etc., can be explained by such beats.

The content of evolution is in creating new quality, new systems which never existed before, such as new plant or animal species, biocoenoses, industrial enterprises, collectives or ideas. Each new system means a new characteristic time, a new clock, sometimes more than one. Former systems, including their clocks, are then eliminated or pressed aside, to secondary roles, due to competition. Their places are occupied by systems more adapted to the environment and its variations, for instance, natural ecosystems are replaced by agrocoenoses. One could believe that the mean characteristic time of the geographic sphere, if such a notion makes sense, is decreasing.

We conclude that the processes occurring around man with different characteristic times, are far from being independent of one another. Their interrelations create a hierarchic co-subordination of specific clock systems. However, this dependence is not of absolute nature, it leaves enough space for the autonomy of clocks united to form systems. It looks like that only such a "soft" dependence makes biospheric evolution possible. Both extremes, namely, entire subordination of the lower (within the hierarchy) systems to the higher ones and, on the contrary, entire independence leaves no place to self- organization, the latter being the key link in the process of evolution.

3. The conditional nature of time

A chronological date can be used as a mark that makes it possible to replace a large amount of information.

One more function of the time is to measure the destruction (or preservation) degree of structures created earlier. In other words, one deals with an indirect estimate of a specific object condition reached in the course of entropy increase. For a geochemist the age of a mineral contains information on how much of the heavy radioactive isotopes have been converted to lighter ones. For a petrologist the age of a rock yields information on the metamorphic transformation degree of its initial structure and thus on the possibility to study its origin. In the same sense one can speak of erased "memory" of terrains where the ancient levelling surfaces, ancient river valleys, terraces and glaciation-created forms gradually disappear.

In cases when a process is directed not to an equilibrium (in a thermodynamic sense of the term) but from it, time can be equally applied for coded transfer of information on the achieved system complexity, perfection or orderedness. By naming a stage achieved by vegetation succession on a certain territory, a researcher delivers information on how close is the phytocoenosis under study to its relatively stable, in a certain sense perfect, climax state. By calling a plant community old or young, a biologist defines the mutual adaptedness of the constituent species and the related properties of the community, i.e., its closed character, its stability to disturbances from outside. The terms "young", "mature", or "decrepit" terrain (Davis 1954) inform a geomorphologist on the extent to which the seashore profiles and the longitudinal river profiles have approached the perfect curve close to a hyperbole and the meanders to conjugate arcs of a circle.

Thus in the anti-entropy processes time serves as a generalized indicator of the stored information (order, complexity, "perfection").

It could be easily noticed that all the above functions performed by the time concept in science and everyday life, are connected with interval durations, with the property of time which could be designated by the word "lasting". No less significant is another property, namely, successiveness. Unlike the spatial series whose points can in principle replace each other, one cannot change the order of time instants as he likes. This property is related to one more "face" of time, its ability to separate cause and effect, whatever sense is being put into these concepts. This property is especially significant when the direct causal connection of phenomena is hidden from the researcher. Chronological ordering enables one to temporarily replace an exact knowledge of a certain dependence by a more or less grounded conjecture according to the rule: an effect cannot precede its cause. This principle is used, for instance, in weather predictions resting on folkloric signs of weather and scientific observations, e.g., using a barometer. If in sedimental rock layers of different ages paleontological remains of close forms of organisms have been discovered, it is plausible to assume that the latter form was originated from the earlier one. Sometimes paleogeographers connect the temperature fall in glacial epochs with the cainozoic mountain formation; although only the chronological order of these events is known for sure.

The review of the status of time in the Earth sciences allows the question formulated at the beginning of the article to be pose once more: does time, as it exists objectively, indeed determine the motion of the world, or is it, to a smaller or greater extent, a product of human mind? Without anticipating the result of the controversy, let us present a viewpoint seeming plausible in the light of the above facts.

As we have seen, there is a nearly unrestricted possibility to select specific "times" in the ambient nature and the society, sometimes weakly connected or completely unconnected with each other. Essentially any process having a direction, being quantized using its own or some external oscillations, allows one to speak of its proper time. When we change nature, for instance, by cultured plant or domestic animal selection, or by creating combined nature-technological systems (hydroelectric power stations, etc.), we create new rhythms, for instance, reap three harvests a year instead of one, i.e., form new proper "times". By extending this idea, we can pay our attention to the fact that modern technology, especially electronics, produces an enormous number of oscillatory circuits and each of them, being fed from a power source, counts a new time which had never existed before.

However, if it is so easy to create time, it is quite natural to conclude that in the observed natural processes time is also just created and inserted by human thought. The process is similar to the one concerning space: after Descartes we cannot look at space without three crossed coordinate axes. For convenience we have covered the Globe with a net of meridians and parallels which have never been seen in reality. The relativity theory has been created, it seems quite natural to think that the reality could be better studied using four (space-time) coordinates instead of three. Physicists discuss world models of five, six and more dimensions. More and more time becomes just a model parameter, an artefact.

In order not to be drowned in the diversity of proper times, it is also natural to create a unique standard for comparison, something like a global currency easing the transitions from one national currency to another. Such a unique time was constructed on the ground of astronomical processes which were taken *a priori* for uniform ones and later supplemented by radioactive decay processes. However, a question arises: could one create an equally ramified world picture starting from some other premise than the concept of time course? In such a case time can remain being in use but only as a derivative of other categories.

The answer depends on what are the purposes for which time is needed, what are its functions in the scientific and common world picture. The preceding section was dedicated to considerations on this point. The examples offered show that we use the time concept in order to assess the differences between states of a changing object, in particular, to estimate information storage or destruction. Time can sometimes replace distances, energy, money (a payment for distance) and helps one to specify causes and effects in event chains. Now, if one postulates such concepts as "distance", "distance difference", "energy", "cause and effect", then it would be possible to construct a world picture where time is a derivative concept. It is just hard to say whether or not this picture might be more convenient than the one in use. Maybe it will turn out to be more cumbersome. Is it the reason for the fact that in the competition of models the one resting on the concept "time is passing", wins, that it makes it possible to describe the reality in more economical manner? However, one cannot entirely eliminate from mind the possibility to "turn over" time, so that it would be a derivative, secondary concept rather than a basic, undefinable one; maybe it could even be excluded from the elite of the necessary words. It is possible that the future development of science will lead to the necessity of just this kind of revolution in our world outlook.

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