

# TIME IN BIOLOGY AND PHYSICS

JONATHAN D.H. SMITH  
*Department of Mathematics*  
*Iowa State University*  
*Ames, Iowa 50011, U.S.A.*

## 1. Introduction

Traditionally, time has been modelled as a basic variable taking its values from an interval on a real axis. Although special relativity introduced Lorentz transformations mixing rectilinear time and space axes, while general relativity introduced curved spacetimes, the concept of a single underlying time dimension parametrised by a real interval remained. The pervasiveness of this concept was certainly due in large measure to the success of the models it supported, in particular to the expression of physical laws by differential equations which ultimately relied on the limiting process inherent in the notion of a (total or partial) derivative. Despite this success at the computational level, it has long been clear that the truly ramified nature of time cannot be captured by what amounts to a mathematical convention. The current paper sets out to recall some of the perspectives on time and space that have been emerging from the study of biology and complex systems. Although these examples are still rather isolated and underdeveloped, they are already leading to some new insights. Summarising briefly, it is becoming apparent that each part of a complex system is equipped with its own intrinsic spacetime. When the system functions, the spacetimes of its constituent parts interact in various ways. As biological systems are able to insulate their component parts from environmental influences to a greater or lesser extent, one may propose an answer to Schrödinger's question "What is life?" [1], characterising biological systems as those systems complex enough to isolate their component spacetimes. By contrast, the success of the single traditional "universal," "clock," or "calendar" time in physics is seen to be due to the way in which the component spacetimes of low-level systems are mutually coupled. This presents a different approach to universal time. Rather than being built in to our models *ab initio*, uni-

versal time should be seen as a phenomenon that emerges from the closely coupled interactions of low-level components.

## 2. Biological Spacetimes

This section presents a sampling of some of the various space and time phenomena that have appeared in studies of biology and complex systems.

### 2.1. PSYCHOLOGICAL SPACES AND TIMES

#### 2.1.1. *Normal Psychological Time*

The distinctions between clock time and perceived, subjective time have been well documented [2]. It is also recognised that human subjects are unable to give a temporal order to events that differ by less than around 20 milliseconds [3] [4]. (Incidentally, this time scale appears to correlate with the 50 bit per second limitation on conscious information processing.) Now intervals of real numbers are *totally ordered*: given two distinct real numbers, one is always strictly less than the other. It is thus apparent that real intervals are not suitable for the fine-scale modelling of psychological time.

#### 2.1.2. *Pathological Spacetimes*

Saniga [5] has collected a range of descriptions of spacetime distortions perceived by mental patients and drug users. One important feature of these experiences is the way in which space and time distortions go together. It is not only in relativity theory that a discussion of time necessarily involves a corresponding discussion of space.

### 2.2. EIGEN'S EQUATION: STATISTICAL SYSTEM TIME

Eigen [6] introduced what he called *phenomenological rate equations* to describe the evolution of a population of individuals of various species competing for limited resources. Suppose that the  $i$ -th species has a known net growth rate (birth rate minus natural death rate) of  $E_i$ . In other words, if a population of  $n_i$  units of the  $i$ -th species is allowed to develop without constraint, its net rate of change is given by  $\dot{n}_i = E_i n_i$ . Now suppose that the  $r$  species are brought together in a joint population maintained at a constant count  $N$  (e.g. by control of a common food supply). Thus the birth of one individual has to be compensated by the death of another, not necessarily of the same species. If  $n_i$  now represents the number of individuals of species  $i$  present in the joint population, its net rate of change is given by

$$\dot{n}_i = [E_i - E(t)]n_i. \quad (1)$$

Here  $E(t)$  or  $E$  is the death rate required to keep the total population constant. This rate is common to all the species, but varies with time. Let  $p_i = n_i/N$  represent the probability that a member of the population belongs to the  $i$ -th species, so that  $\sum p_i = 1$ . Summing (1) over all the species yields

$$E = \sum p_i E_i. \quad (2)$$

Maximising the entropy  $-\sum p_i \log p_i$  with respect to the constraint (2), one obtains the solutions  $p_i = \exp(\tau E_i) / \sum_j \exp(\tau E_j)$  to Eigen's equation in terms of the time  $\tau$ . The catch is that the time  $\tau$  appearing here is the Lagrange multiplier conjugate to the constraint (2). Mathematically, it is analogous to the temperature in Gibbs' canonical ensemble. As such, it is an emergent statistical property of the system.

More elaborate versions of Eigen's equation involve mutation between the species. Eigen had been unable to give exact solutions of such versions in [6], but subsequent papers used conventional techniques to deal with the case of mutation [7] [8]. Solutions using the classical Gibbs ensemble as above were presented in [9] [10], but recent work [11] suggests that a more satisfactory treatment demands the quantum canonical ensemble.

### 2.3. LOGARITHMIC TIMES

Biological and other complex systems often involve the logarithm of a suitably shifted clock time as a fundamental parameter. Here are some examples.

#### 2.3.1. *Organic Time*

Based on the study of a wide range of higher organisms, Backman [12] defined the concept of an *organic time* as a certain linear function of the logarithm of the age of the organism in days. Although he studied organisms with a range of calendar lifetimes from 3 to  $10^5$  days, the lifespans of the various organisms became comparable in terms of the organic time, generally around a value of 1.2, but extending up to 2.6 for man. Backman and others used the organic time in comparative life cycle studies of different species. Later, the term *physiological time* was used [13] [14].

#### 2.3.2. *Thermodynamic Time*

Prigogine [15] defined the *thermodynamic time*  $\tau$  of a system as the time scale with respect to which the rate of entropy production in the system was constant. Given that this rate  $\sigma(t)$  of entropy production generally decreases monotonically with respect to universal time  $t$ , and tends to zero as  $t$  tends to infinity, as at least a first Padé approximation to  $\sigma(t)$  one may take the rational function  $p_0/(q_0 + q_1 t)$ . This yields the thermodynamic

time  $\tau$  as a linear function of the logarithm of the universal time. In a recent paper, Prigogine's thermodynamic time has reappeared under the name *eigen time* [14].

### 2.3.3. Demography

In human demography, the *net maternity function* describes the expected number of (female) babies borne by a woman during her sojourn in a given age period. The net maternity function has normally been described in detail at a microscopic level, essentially specified by a table of values [16]. Recently, in what is known as the *macroscopic* approach to demography, an attempt has been made to specify the net maternity function analytically in terms of just two parameters [17] [18]. For this specification, the fundamental argument is not the age of the mother, but the logarithm of that age. This logarithm yields a net maternity function that is both realistic and analytically tractable. In addition, one is also led to the logarithm of the age, rather than the age itself, by dimensional analysis.

## 2.4. THE LOGISTIC EQUATION AND ROUTE TO CHAOS

Let  $y_t$  denote the number of individuals present in a population at discrete time  $t$ . Malthusian growth at rate  $\rho$  (birth rate minus death rate) is described by the equation  $y_{t+1} = [1 + \rho]y_t$ . On the other hand, if the carrying capacity of the environment is limited to no more than  $Y$  individuals, then the development of the population is more closely described by the *Verhulst equation*  $y_{t+1} = [1 + \rho(1 - y_t/Y)]y_t$ . To handle this equation analytically, it is convenient to make the substitutions  $x_t = (y_t/Y)[\rho/(1+\rho)]$  and  $r = 1 + \rho$ , yielding the *logistic equation*  $x_{t+1} = rx_t(1 - x_t)$ , with  $0 \leq x_t \leq 1$ . As the parameter  $r$  ranges from 2 to 3.5699..., the behaviour of the logistic equation is described as following the *Feigenbaum* or *period-doubling route to chaos* [19]. The "chaotic" behaviour in this range is reflected in the varying degree of precision with which one has to specify the real number  $x_t$  in order to guarantee the determinism inherent in the logistic equation. On the other hand, the logistic equation is sufficiently complex to determine its own intrinsic space. Using this intrinsic space, it is possible to give a completely combinatorial description of the behaviour of the logistic equation in the given range [20]. The intrinsic space is given by the so-called "superstable" periodic points  $p_0 = .5$ ,  $p_1 = .809$ ,  $p_{00} = .384$ ,  $p_{01} = .5$ ,  $p_{10} = .827$ ,  $p_{11} = .875$ ,  $p_{000} = .352$ ,  $p_{001} = .372$ , ..., together with the corresponding unstable periodic points, and all the preimages of both kinds of periodic point. The superstable periodic points are those lying in periodic orbits that include the maximum 0.5 of the logistic function  $rx(1 - x)$ . With respect to its intrinsic space, the logistic equation behaves quite transparently. The

complications arise only in comparison with Euclidean space.

## 2.5. TIME TRAVEL

Animals travel through space in search of food, mates, nesting places, or better conditions. Patients that have lost the ability to move are described as being in a vegetative state. However, it may be argued that certain plants have the ability to travel (forwards) through time. For example, foxtail weeds (*Setaria*) produce seeds that may remain dormant in the soil through several bad seasons, and then germinate once they have determined that conditions have improved [21]. It is important to note that there is an active selection of the final destination of this time travel, as opposed to the passive travel through space exhibited by tumbleweeds, sycamore seeds, or plant seeds ingested by animals.

## 3. Spacetimes in Complex Systems

The various examples presented in the previous section all exhibit spaces and/or times that are intrinsic to a part of a complex system, and that are distinct from universal space and time. One may thus postulate the following properties for spacetimes in complex systems:

1. Each part of a complex system has its own intrinsic spacetime;
2. System interactions may influence these intrinsic spacetimes.

To illustrate a typical interaction, consider a dormant foxtail seed as in Example 2.5. During dormancy, the intrinsic developmental age of the seed is on hold, being decoupled from calendar time. But once the seed receives an appropriate signal from the environment (such as a suitably high oxygen level in the soil), then the seed's developmental clock is restarted, and germination begins. In Example 2.1.2, ingestion of a drug may lead to the distortion of an individual's psychological spacetime.

## 4. Applications and Speculations

This final section discusses some possible applications and implications of the view of time offered by considerations from biology and complex systems.

### 4.1. BIOLOGY VERSUS PHYSICS

The relationship between physics and biology has often been controversial. Vitalists of varying hues have maintained that biology is immune from many of the laws of physics, the Second Law of Thermodynamics being a notorious example, while biologists occasionally resent physicists' attempts

to address their discipline. The physicist Schrödinger posed the question “What is life?” [1], seeking to reconcile the Second Law with biology by claiming that evolving organisms dump entropy onto their environment.

The postulates of Section 3 suggest a different approach to the demarcation between biology and physics. Answering Schrödinger’s question, one may propose a characterisation of biological systems as those systems which are sufficiently complex to be able to isolate the spacetimes of certain of their components. On the other hand, physical systems are those systems in which all the components are coupled to universal time.

Adopting this approach, one is then confronted with the task of explaining how the coupling to universal time takes place in physical systems. In fact, this task subsumes the problem of explaining the emergence of universal time in the early universe. As Stuckey cogently observes [22], circularity precludes the use of quantum physics or relativity to address that problem, since the existence of universal time is already built in to the foundation of those theories.

Of course, one cannot hope for an immediate answer to the extremely deep early universe problem. However, there are certainly known examples of the emergence of a uniform time parameter through the coupling of the components of a complex system. Perhaps the most familiar case is that of an interconnected AC power generation system [23], where the individual generators synchronise to a common frequency.

#### 4.2. CENSORSHIP THEOREMS

Following the discovery of closed timelike curves in solutions of Einstein’s equation of general relativity, there have been a number of theorems and conjectures aimed at restoring causality, avoiding effects such as the famous “Grandfather Paradox” in which one is supposed to return around a closed timelike curve and murder the boy who was to become one’s grandfather. From the present perspective, it may be observed that carriers of causally significant information possess inherent senescence, pre-programmed by the Grouping Principle [24]. To maintain such information, an active process of homeostasis is required. Causality would thus be rescued if the information was unable to survive the passage around the closed timelike curve.

#### 4.3. QUANTUM EFFECTS IN CONSCIOUSNESS

Recently, some arguments have been advanced for the presence of quantum effects in consciousness [25]. These arguments have been regarded as controversial, since mammalian brains do not appear to afford the regimes that might be required for quantum computation. This is true even more of such entities as ant colonies [26]. However, Mayburov [27] has indicated

how to obtain quantisation from fuzzy order relations, while the discussion of Section 2.1.1 suggests that the chain of events in the brain may be viewed as a fuzzy ordered set, the fuzziness appearing at the scale of around 20 milliseconds. Significantly enough, this is the time scale for the orchestrated objective reduction events in the Penrose-Hameroff model. It may well be that the mathematical structure of quantum mechanics appears naturally in other contexts outside the restricted domain of quantum physics. An example is given by the work of [11] in the context of Section 2.2.

#### 4.4. PHENOMENOLOGY OF THE PRESENT

A classical problem of time is the perception of the “present moment.” (In the interests of linguistic clarity, it seems advisable to avoid trying to use the adverb “now” as a noun.) The complex systems perspective suggests that the baffling phenomenology of the present is due to the many levels at which perception is taking place, from the immediate dynamics of the body to the longer-term contemplations of the mind. What appears as a brief instant on the slow time scale of the higher-level processes may well encompass the observation of motion and change in the rapid time scales of the lower-level processes.

#### References

1. Schrödinger, E. (1945) *What is Life?*, Cambridge University Press, Cambridge.
2. Gruber, R.P., Wagner, L.F. and Block, R.A. (2000) Subjective time versus proper (clock) time, in R. Buccheri, V. di Gesù and M. Saniga (eds.), *Studies on the Structure of Time: From Physics to Psycho(patho)logy*, Kluwer Academic / Plenum Publishers, New York, NY, pp. 49–63.
3. Hanke, W. (2000) The perception of time, in R. Buccheri, V. di Gesù and M. Saniga (eds.), *Studies on the Structure of Time: From Physics to Psycho(patho)logy*, Kluwer Academic / Plenum Publishers, New York, NY, pp. 37–48.
4. Pöppel, E. (1988) *Mindworks: Time and Conscious Experience*, Harcourt Brace Jovanovich, Boston, MA.
5. Saniga, M. (2000) Algebraic geometry: a tool for resolving the enigma of time?, in R. Buccheri, V. di Gesù and M. Saniga (eds.), *Studies on the Structure of Time: From Physics to Psycho(patho)logy*, Kluwer Academic / Plenum Publishers, New York, NY, pp. 137–166.
6. Eigen, M. (1971) Self-organization of matter and the evolution of biological macromolecules, *Naturwissenschaften* **58**, 465–523.
7. Jones, B.L., Enns, R.H. and Rangnekar, S.S. (1976) On the theory of selection of coupled macromolecular systems, *Bulletin of Mathematical Biology* **38**, 15–28.
8. Thompson, C.J. and McBride, J.L. (1974) On Eigen’s theory of the self-organization of matter and the evolution of biological macromolecules, *Mathematical Biosciences* **21**, 127–142.
9. Smith, J.D.H. (1996) Competition and the canonical ensemble, *Mathematical Biosciences* **133**, 69–83.
10. Smith, J.D.H. (1998) Canonical ensembles, evolution of competing species, and the arrow of time, in G. van de Vijver, S.N. Salthe and M. Delpos (eds.), *Evolutionary Systems: Biological and Epistemological Perspectives on Selection and Self-*

- organization, Kluwer, Dordrecht, pp. 141–153.
11. Smith, J.D.H. (2000) Competition and the quantum canonical ensemble, ISU Department of Mathematics Report No. 00-05.
  12. Backman, G. (1940) Lebensdauer und Entwicklung, *Archiv für Entwicklungsmechanik* **140**, 90–123.
  13. Schmidt-Nielsen, K. (1984) *Why is Animal Size so Important?*, Cambridge University Press, Cambridge.
  14. Andresen, B., Shiner, J.S., and Uehlinger, D.E. (2002) Allometric scaling and maximum efficiency in physiological eigen time, *Proceedings of the National Academy of Science* **99**, 5822–5824.
  15. Prigogine, I. (1947) *Etude Thermodynamique des Phénomènes Irréversibles*, Dunod, Paris.
  16. Keyfitz, N. and Flieger, W. (1990) *World Population Growth and Aging*, University of Chicago, Chicago, IL.
  17. Smith, J.D.H. (1999) A macroscopic approach to demography, ISU Applied Mathematics Report No. AM99-05.
  18. Smith, J.D.H. (2000) Time in biological systems, in R. Buccheri, V. di Gesù and M. Saniga (eds.), *Studies on the Structure of Time: From Physics to Psycho(patho)logy*, Kluwer Academic / Plenum Publishers, New York, NY, pp. 75–96.
  19. Leven, R.W., Koch, B.-P. and Pompe, B. (1989) *Chaos in Dissipativen Systemen*, Akademie-Verlag, Berlin.
  20. Smith, J.D.H. (1999) Wreath products along the period-doubling route to chaos, *Ergodic Theory and Dynamical Systems* **19**, 1617–1636.
  21. Dekker, J., Dekker, B., Hilhorst, H., and Karssen, C., (1996) Weedy adaptation in *Setaria* spp. IV. Changes in the germinative capacity of *S. Faberii* (Poaceae) embryos with development from anthesis to after abscission, *American Journal of Botany* **83**, 979–991.
  22. Stuckey, M. (2000) Pregeometry and the trans-temporal object, in R. Buccheri, V. di Gesù and M. Saniga (eds.), *Studies on the Structure of Time: From Physics to Psycho(patho)logy*, Kluwer Academic / Plenum Publishers, New York, NY, pp. 121–128.
  23. Stevenson, W.D. (1982) *Elements of Power System Analysis*, McGraw-Hill, New York, NY.
  24. Smith, J.D.H. (1999) On the evolution of semiotic capacity, in E. Taborsky (ed.), *Semiotics, Evolution, Energy*, Shaker Verlag, Aachen, pp. 283–309.
  25. Hameroff, S., this volume.
  26. Reznikova, Zh.I. and Ryabko, B.Ya. (2000) Using information theory approach to study the communication system and numerical competence in ants, in J.-A. Meyer, A. Berthoz, D. Floreano, H.L. Roitblat and S.W. Wilson (eds.), *From Animals to Animals 6. Proceeding of the Sixth International Conference on Simulation of Adaptive Behaviour*, MIT Press, Cambridge, MA, pp. 501–506.
  27. Mayburov, S., this volume.