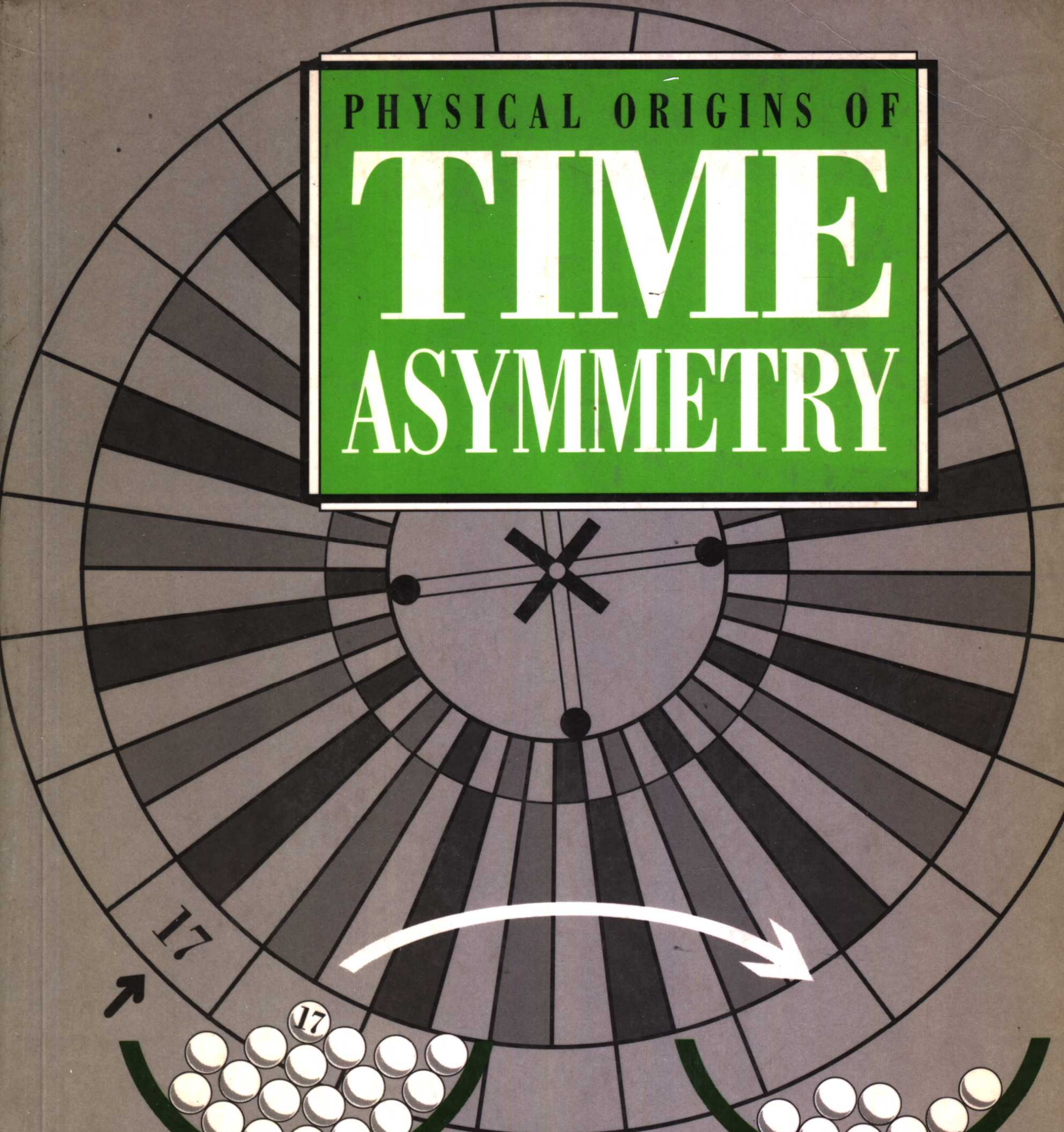
PHYSICAL ORIGINS OF
TIME ASYMMETRY



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Physical Origins of Time Asymmetry

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Foreword

The concept of time is perhaps one of the most integrating in human knowledge. It appears in many fields, including philosophy, psychology, biology and, most prominently, in physics, where it plays a central role. It has interested Man of all Ages, and the finest minds from Saint Augustine to Kant to Einstein have paid attention to its meaning, and the mystique shrouding its most notorious property: that of flowing only forward, its irreversibility.

Today, largely thanks to the efforts in popularization of science by some leading physicists, even laymen show an interest in these problems.

More than 25 years ago a meeting on "The Nature of Time" took place at Cornell University. Since then, there has been no forum for discussing these ideas in the light of important developments being made in several areas of physics. Cosmology, general relativity, computer science and quantum mechanics, to mention a few, have undergone a profound evolution in these 25 years.

Identifying these important problem areas, and then fostering and helping their development by bringing together experts in the field, is one area in which our Fundación sees its duty fulfilled.

Fundación Banco Bilbao Vizcaya, in its interest to create the appropriate framework for creative thinking in Frontier Topics in Science, which at the same time affect society at large, and are capable of integrating knowledge, felt that a meeting devoted to a rigorous, deep and exhaustive study of the Physical Origins of Time Asymmetry, was particularly suitable.

We were happy to contribute with our sponsorship to this meeting, where so many of the world's experts came together to discuss such an important and fundamental question. We also hope that through the publication of these minutes the discussions can be brought to the attention of a much wider audience which can profit from what was presented and discussed at the meeting.

José Angel Sánchez Asiain
Presidente
Fundación Banco Bilbao Vizcaya

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Introduction

The world about us is manifestly asymmetric in time. The fundamental laws of physics that describe it are not. Can these two undeniable facts be reconciled? This question has been the focus of much attention ever since it was first addressed by Boltzmann in the last century. The fact that it does not belong exclusively to a specific area of academic research makes it a particularly suitable focus for an interdisciplinary meeting. This volume is the outcome of such a meeting.

The meeting, a NATO Advanced Research Workshop, took place in Mazagon, in the Province of Huelva, Spain, from 29 September to 4 October 1991. Its aim was to consider the question of time asymmetry in the light of recent developments in quantum cosmology, quantum measurement theory, decoherence, statistical mechanics, complexity theory and computation.

The case for such a meeting is not hard to make. Although many physicists and scientists from other disciplines have been very interested in the arrow of time, there has not been a meeting on this topic for over twenty years. The last one was at Cornell in the 1960s. In the spring of 1989, and again in the spring of 1990, there were workshops at the Santa Fe Institute on Entropy, Complexity and the Physics of Information. These workshops were of an interdisciplinary nature and cut across many of the fields involved in the time asymmetry workshop reported here. They were very successful, and indicated that workers in the different disciplines involved have many mutual interests and are keen to exchange ideas.

It was of course in the context of statistical mechanics that the question of time asymmetry was first investigated, and this area still remains central to any discussion of the topic. The new areas of investigation, at which this workshop was aimed, are as follows.

1. **Quantum Cosmology.** Cosmologists have appreciated for many years that much of the observed time asymmetry in the universe may be traced back to the particular set of initial conditions with which the universe began. Unfortunately, the great difficulty of modeling the very beginning of the universe has for a long time presented a serious obstacle to further investigation. However, recent

developments in the field of quantum cosmology have led to the construction of a framework in which the beginning of the universe may be discussed in a precise and meaningful way. This has led to a revitalization of interest in the question of the cosmological arrow of time.

2. **Quantum Measurement Theory and Decoherence.** The special needs of quantum cosmology, together with a number of recent experimental advances (the generation of squeezed states, macroscopic quantum effects, mesoscopic systems, and the possibility of interference experiments with large systems) has led in recent years to a resurgence of interest in quantum measurement theory and the interpretation of quantum mechanics. More generally, studies in both quantum cosmology and inflationary universe models have underscored the necessity to acquire a deeper understanding of the emergence of classical properties from quantum systems. Central to discussions of this issue is the distinctly time-asymmetric process of *decoherence* – loss of quantum coherence as a result of interaction with an environment. In particular, the direction of decoherence coincides with, and maybe even defines, an arrow of time. Moreover, a number of recent attempts to quantify the degree of classicality of a decohering system use the notion of information and entropy, providing a link with the fields of complexity and computation.
3. **Complexity.** Many attempts have been made to capture, in precise mathematical terms, the notion of the *complexity* of a physical system. A suitable definition of complexity would provide a rigorous distinction between states of randomness and states of self-organization. Many candidates for a formal measure of complexity have been suggested. They include, for example, the *algorithmic information content* (the length of the shortest computer program required to generate the object in question), the *logical depth* (the execution time required to generate the object by a near-incompressible universal computer progam), and the *thermodynamic depth* (the amount of entropy produced during a state's actual evolution). These efforts are of particular interest in relation to discussions of the arrow of time, in that a measure of complexity might permit one to formalize the intuitive notion that the universe generally evolves from order to disorder, but without having to appeal to the probabilistic considerations involved in the statistical (Gibbs–Shannon) definition of entropy. Indeed, it has been argued by Zurek that in the course of measurements the second law of thermodynamics – and its associated arrow of time – will hold only if the usual definition of entropy is modified to take account of the algorithmic information content (*i.e.*, Kolmogorov complexity) of the acquired data.
4. **Computation.** A comparatively new class of systems which may define an arrow of time has emerged in the field of the physics of computation. This field is concerned with the energetic cost, structural requirements and thermodynamic reversibility of physical systems capable of universal computation. Through the work of Landauer, Bennett and others, it is now established that only

logically *irreversible* operations inevitably dissipate energy, whereas logically reversible ones need not, implying that it is in principle possible to compute at no thermodynamic cost. However, the logically reversible operations may be accomplished only at the expense of cluttering up the memory with an otherwise useless step-by-step record of the computation. This leads to the recognition that — as was anticipated by Szilard more than half century ago — it is actually the erasure of information which results in the increase of entropy. Real systems are in fact always dissipative and the irreversibility is important for stability and error correcting. These considerations may shed considerable light on various long-standing questions in the foundations of statistical mechanics, such as Maxwell's demon. They are also closely related to studies of complexity and tie in with information transfer and processing in biological systems.

Approximately half the papers presented here concern time asymmetry specifically, in the variety of contexts discussed above. The rest concern related topics, reflecting the discussions that took place at the meeting and the participants current interests. The papers are loosely grouped according to the predominant subject they address. The six parts of the book do not fall into a particular order. We will not attempt to summarize or review the papers found here, because the range of topics covered is too broad to describe in a concise and coherent way.

An important part of the workshop was the discussions that took place after each talk. In order to give a flavour of these discussions, transcripts are included after most of the papers. They are neither verbatim nor complete. They have been edited for clarity, and generally just a few of the more interesting and relevant questions and answers are included.

J. J. H.
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Literature on Time Asymmetry

The meeting at Cornell in the 1960s is described in,

Gold, T. (ed.) (1967) *The Nature of Time*, Cornell University Press, Ithaca.

The first of the two Santa Fe meetings is reported in,

Zurek, W.H. (ed.) (1990) *Complexity, Entropy and the Physics of Information, Santa Fe Institute Studies in the Sciences of Complexity, vol VIII*, Addison-Wesley, Reading, MA.

The following are some general references on time and time asymmetry.

Davies, P. C. W. (1976) *The Physics of Time Asymmetry*, University of California Press, Berkeley, CA.
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Landsberg, P.T. (ed.) (1982) *The Enigma of Time*, Adam Hilger, Bristol.
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Zeh, H. D. (1989) *The Physical Basis of the Direction of Time*, Springer-Verlag, Berlin.

Contents

1

Time Today

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How come time? It is not enough to joke that "Time is nature's way to keep everything from happening all at once. [1]" A question so deep deserves a deeper look. Let's come back to it, therefore, towards the end of this account, and turn for now to the less intimidating, "How come the asymmetry between past and future?"

In 1939–1945, Richard Feynman and I explored the idea of sweeping out [2], [3] the electromagnetic field from between all the world's charged particles. We knew that Tetrode [4] and Fokker [5] had postulated instead that every charge acts directly on every other charge with a force governed by half the sum of the retarded and advanced potentials. Their considerations and ours led us to the thesis that the force of radiative reaction arises from the direct interaction between the accelerated source charge and the charged particles of the absorber. In this work we encountered so many interesting issues of principle that we went to 112 Mercer Street to consult Einstein about them. He told us of his dialogue with W. Ritz. Ritz [6] had taken the phenomenon of radiative damping to argue that, at bottom, the electrodynamic force between particle and particle must itself be time-asymmetric. Einstein, in contrast, had maintained that electrodynamics is fundamentally time-symmetric, and that any observed asymmetry must, like the flow of heat from hot to cold, follow from the statistics of large numbers of interactions. Einstein's words made us appreciate anew one of our findings, that the half-advanced, plus half-retarded action of the particles of the absorber on the radiating source only then added up to the well-known and observationally tested [7] force of radiative reaction when the absorber contained enough particles completely to absorb the radiation from the source. By this route, Feynman and I learned that the physics of radiation can indeed be regarded as, at bottom, time-symmetric with only the statistics of large numbers giving it the appearance of asymmetry.

The idea that time asymmetry is not the attribute of any individual interaction, but the statistical resultant of large numbers of intrinsically time-symmetric individual couplings is not a new one, of course, but implicit in the great tradition of physics associated with the names of Boltzmann, Kelvin, Maxwell, Smoluchowski, the Ehrenfests, Szilard, Landauer, Bennett and their followers. The essential idea stands

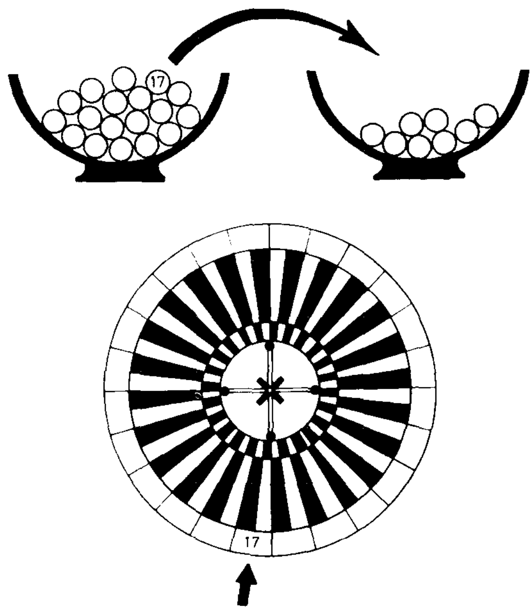

Fig. 1.1. The Ehrenfest double urn in a 1979 rendering. When number seventeen comes up on the roulette wheel, the ball carrying that number is transferred from whichever urn it happens to be in to the other urn. Thus 100 balls, 75 of them initially in the left-hand urn and 25 in the right hand one, gradually approach a 50–50 distribution as "time increases" (more spins of the roulette wheel).

out nowhere more clearly than in the double-urn model of Paul Ehrenfest. (Fig. 1.1). Each spin of the roulette wheel brings up a random number, say seventeen. We look for the ball with that number on it and transfer it from whichever urn it occupies to the other. At the start, there are 75 balls in the left hand urn and only 25 in the right hand urn. Therefore, ball seventeen is three times as likely to lie in the left hand urn as in the right hand one. Thus, the first spin of the roulette wheel is three times as likely to narrow the count discrepancy to 74 and 26 as to raise it to 76 and 24. The numbers of balls in the two urns approach equality with three times the probability that they go the other way. So, too, with further spins of the roulette wheel. Thus the Ehrenfest double-urn models the probabalistic approach of the energy content of two masses to thermal equilibrium: That's how come, we understand, that heat flows from hot to cold. Water and alcohol, once mixed, don't unmix. Past and future don't exchange garments. The one-sided flow of energy from accelerated source charge to multiple far away receptor charges plays out a like scenario.

As Ehrenfest's double-urn model displays a difference in number of balls in the two urns that undergoes smooth exponential decay plus zigzag up-down fluctuations,