Complexity from Microscopic to Macroscopic Scales: Coherence and Large Deviations

Edited by

A.T. Skjeltorp and T. Vicsek

NATO Science Series

II. Mathematics, Physics and Chemistry – Vol. 63

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Series II: Mathematics, Physics and Chemistry – Vol. 63

PREFACE

This volume comprises the proceedings of a NATO Advanced Study Institute held at Geilo, Norway, April 17 - 27 2001. The ASI was the sixteenth in a series held biannually on topics related to cooperative phenomena and phase transitions, in this case applied to complexity from microscopic to macroscopic scales. It addressed the current experimental and theoretical knowledge of the physical organizing principles of a collection of many interacting particles or entities such as mesoscopic spin- and electron systems, complex matter, biological and economic systems that are important for quantum coherence, complex dynamics and large deviations from what we would ordinarily expect. The main purpose of the lectures was thus to have a pedagogical approach to these themes and provide a basic understanding leading to the latest state of knowledge.

The task of forging a link between the microscopic world described by quantum mechanics and the macroscopic world lies at the heart of condensed matter physics. Philip Anderson once coined the phrase "More is different: The behaviour of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles." In most instances, the different regimes are treated differently, and the breakdown of the description in one regime often lacks logical connections to adjacent regimes. There are thus quantum- and classical "protectorates". The notion being that in many areas you can compute forever based on an understanding of microscopics and never predict a particular phenomenon - like perhaps high temperature superconductivity, protein folding, the genetic code etc - because there is some other higher organizing principle that takes over, perhaps at a particular length or time scale.

The main motivation for arranging this ASI was to have a closer examination of a few of these protectorates and most importantly, how they come together and establish whether there are common vocabularies. Many of so-called mesoscopic systems display what some researchers now try to identify as "adaptive" behaviour - that is strong changes in some physical property that results from a small change in an internal or external driving force. Among the adaptive phenomena themselves there is a kind of logical progression, from the behaviour of quantum mesoscopics to complex evolved cooperative systems and large events like turbulence.

The field of mesoscopic and molecular magnetism, in particular quantum coherence and quantum tunnelling in spin systems, and the coupling between mesoscopic magnetism and mesoscopic transport, is at present a very active and interesting area in solid state physics. It is highly probable that the next decade will focus on this type of quantum spin physics ("spintronics") as much as the last decade has focussed on mesoscopic electronics.

"Dephasing" is a very important concept in mesoscopic systems like those referred to above. A basic question is how far is it possible to extend quantum mechanics with quantum coherence before it breaks down and what it can be replaced with. It is thus a need to understand how one goes from those ideas of mesoscopics to modern ideas of "complexity". The ASI therefore aimed at focusing on these interesting questions by also including several different types of computation in connection with the specific physical areas specified above - quantum computing and spintronics. Besides its fundamental interest, it is also obvious that this field is of relevance to novel applications.

Another interesting "crossing" is that between "complexity" and large excursions or events, with turbulence as a prototype example. Again, we have carefully chosen speakers with broad experience in several different related fields to address this problem.

The proceedings also include a small discussion about finance to keep up the Geilo ASI traditions of bringing out the point that "physics is promising to offer insight into phenomena once considered outside the physicist's domain". On a qualitative level, turbulence and financial markets are apparently similar. For example, in turbulence, one injects energy at a macroscopic scale by, e.g. stirring a bucket of water, and then observes the manner in which the energy is transferred to successively smaller scales. In financial systems "information" can be injected into the system on a large scale and the reaction to this information is transferred to smaller scales - down to individual investors. Our understanding of turbulence might thus be relevant to understanding price fluctuations.

The Institute brought together many lecturers, students and active researchers in the field from a wide range of countries, both NATO and NATO Partner Countries. The lectures fulfilled the aim of the Study Institute in creating a learning environment and a forum for discussion on the topics stated above. They were supplemented by a few contributed seminars and a large number of poster presentations.

At the closing of the Study Institute there was a ceremony to mark the 30 year anniversary for the start of the unbroken biannual series of NATO ASIs at Geilo. Financial support was principally from the NATO Scientific Affairs Division, but also from the Institute for Energy Technology and the Research Council of Norway.

The editors are most grateful to M.H. Jensen, A. Hansen, J. McCauley, R. Pynn, D. Sherrington and H. Thomas who helped them plan the programme and G. Helgesen for helping with many practical details. Finally, we would like to express our deep gratitude to Else-Brit Jørgensen of the Institute for Energy Technology, for all her work and care for all the practical organization before, during, and after the school, including the preparation of these proceedings.

June 2001

Arne T. Skjeltorp　　　　　　Tamas Vicsek

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CONTENTS

PHYSICS OF COMPUTATION:
FROM CLASSICAL TO QUANTUM

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1. Introduction

In this lecture, I give an introduction into the physics of computation. The emphasis will be on the development of the field, leading from the thermodynamics of computation to reversible computation and to quantum computing, and on the basic physical aspects. The development of the foundations of quantum computing was essentially completed by 1996. I will not cover the vast multitude of applications published after that date. Also the highly interesting areas of quantum cryptography, quantum communications and teleportation remain outside the scope of the present lecture.

An introduction into the whole field can be found in Feynman Lectures of Computation [1]. On the individual parts of this lecture, there exists a number of good reviews. The physical aspects of computation have been emphasized by R. Landauer [2]. A detailed review of the thermodynamics of computation, as well as a thorough account of the history of reversible computation, have been given by C.H. Bennett [3, 4]. A number of papers ranging from thermodynamics of computation [3, 5] to reversible computation [6, 7] and quantum computing [8, 9] presented at an international conference in 1982 provide a good snapshot of the state of the field at that time. Various aspects of the physics of quantum computation are discussed in a number of useful reviews, in particular [10, 11, 12, 13, 14].

A.T. Skjeltorp and T. Vicsek (eds.),
Complexity from Microscopic to Macroscopic Scales: Coherence and Large Deviations, 1–20.

2. Computation in Classical Physics

2.1. COMPUTATION AS A MATHEMATICAL PROCESS

2.1.1. *The Turing Machine Concept*

The concept of a Turing machine was developed in order to study the *mathematical* limitations of computation

A. M. Turing:
On computable numbers, with an application to the Entscheidungsproblem.
Proceedings London Math. Society (2) 42 (1936) 230-265, 43 (1937) 544-546.

A Turing machine consists of an unlimited tape and a head. The tape, of which only a finite portion is ever used, contains symbols S_x of a finite alphabet at positions x. The head comprises the reading and writing head proper and the processor which has finitely many internal states Q (Fig 1). The present state Q of the processor and the symbol S_x at its present

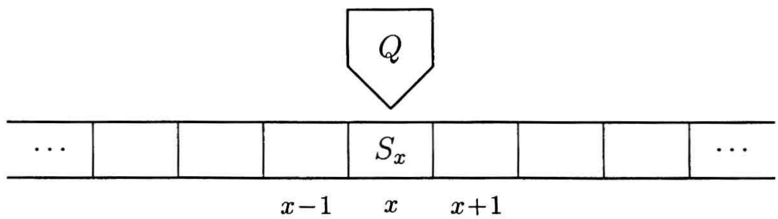

Figure 1. Turing Machine

position x determine the action of the machine during a single computation step:

$$\begin{array}{llcll}
\text{read symbol in cell } x\text{:} & S_x & & & \\
\text{write new symbol:} & S_x & \mapsto & S'_x & = F(Q, S_x) \\
\text{move right or left } (\sigma = \pm 1)\text{:} & x & \mapsto & x' & = x + \sigma(Q, S_x) \\
\text{change processor state :} & Q & \mapsto & Q' & = G(Q, S_x)
\end{array}$$

Thus, a Turing machine is completely described by a finite set of rules, which are represented by the mapping

$$M \; : \; (Q\,S) \mapsto (Q'\,\sigma\,S') \tag{1}$$

defined by the three functions F, σ, G.

At the start of the computation, the processor is in an initial state Q_0, and the tape contains the input in some specified region. The computation is finished, when the processor reaches a special state $Q_{\mathrm{H}} = \texttt{HALT}$; the result is then contained in a specified output region.