General Introduction:

The Worlds of Science

This book is a selection of my research and popular essays, with particular emphasis on works which review or discuss in a general way some scientific or technical question. The papers are all about the world of science, or rather about the different worlds in which a scientist works. In my own work I can see at least four different kinds of things which might be meant when one talks about the worlds of a scientist.

First, I might point to a little society or social grouping composed of scientists and a few associates. This social world defines the group in which we work and exchange ideas. This is the audience for our papers, the source of our applause, and our critics and competition. A scientist can go to different places all over the world and see mostly just the usual group of associates. A scientist can be thrown into a new little group, formed in an allied field of scientific endeavor, and immediately recognize the society and the social norms. This little world is close and closed. It defines our successes and failures.

But there is in addition a more intimate social group which defines our work. Much scientific work is done in direct collaboration with other scientists. Many of the papers in this volume have several authors. Typically each author brings a slightly different experience and point of view to the joint effort, so that the eventual product is much better than what would have been produced by any single person.

This fact came home to me at the very beginning of my career as an 'independent' scientist. Gordon Baym and I had both been trained at Harvard, he under Schwinger and myself under Paul Martin and Roy Glauber. He had learned how to apply variational methods to the derivation of Green's function approximations. I was working on the development of approximations which built in some thermodynamic and conservation laws. With huge effort over a period of months, I had derived one or two approximations which fit my criteria. A day after I had described to him what I had done, he showed me how to construct an infinite number of new approximations which fit into the general scheme. The results appeared in part in our book *Quantum Statistical Mechanics* and in part in our paper, which appears as # 5 in my publication list.[1] Two heads had done a lot more than one.

My scientific life has contained many other very fruitful collaborations. I describe some of these in the introductory essays which head the various sections of this book.

[1]The publication list can be found at the end of this book. In general, items in this list will be given by a number prefixed by the sign '#'.

But, we scientists also work in a very different kind of tight little world, the artificial little world constructed by our ideas. Some of my recent work has been related to the development of models for the behavior of avalanches or sand slides. To construct this *model world*, we considered a simplified example in which square or cubic grains of sand were stacked in neat piles. If a given pile overtopped its neighbors by more than a specified amount, then several grains would fall onto the neighboring stacks. Clearly, this model represented a totally artificial oversimplification of any picture of the behavior of real sand. Nonetheless, a whole group of us threw ourselves quite wholeheartedly into the study of this little model. For several years at a time, we took this artificial example and pretended it was the whole universe.[2] We examined this tiny world with the same seriousness that one might examine the history of the British Empire, or a science of the human mind. Our goal was to develop and understand the laws which governed behavior in this tiny closed-off cosmos.

Why should serious people study such inadequate toys? Clearly these toys cannot accurately represent the third type of scientific world, the real world in which we work and live. Nonetheless it might be profitable to study such hermetic little model worlds because perhaps the experience developed in the little world can be extended and applied to our real world. Maybe there is something in our model avalanche which can be carried over and give some deep insight into how avalanches work. Perhaps these ideas might even have some practical use in the protection of Swiss mountain villages or in the design of particle detectors. Maybe not. Probably not. But one cannot tell what might be carried to the real world until the model world is examined and understood.

Science also sees another version of the real world, the world of people. People and the society support science. Naturally some return is demanded. One demand is that science generate ideas and concepts which can be meaningful to the public at large and can catch its imagination or satisfy its curiosity. To realize this goal, we scientists must be teachers in the broadest sense. Another demand is that we, from time to time, satisfy the aspirations of society for better technology or for a better understanding of the applications or limits of technology. We can only occasionally help the society in this direction, but our help can be quite crucial. We have served in the development of weapons, of communications, and of health care. We cannot be sure where we will be needed in the future, but we are required to be alert to ways in which we can serve.

The fourth version of the world of the scientist is the most important and the one which we scientists most vividly experience. What is it that one really transfers

[2] In this case, the collaborative team included Ashvin B. Chhabra, Mitchell Feigenbaum, Amy Kolan, Sidney Nagel, Itamar Procaccia, Lei Wu and Su-Min Zhou.

from the oversimplified model world to the complex world of reality? Clearly the medium of exchange is ideas. One carries some concept of how an avalanche must work. Some idea. And then one takes the idea and asks how well that idea agrees with mundane reality. (But reality is in most cases richer, more beautiful, and more fertile than our imaginations. So in most cases, this comparison enriches rather than just checks our ideas.) The results of all the model building, all the comparison with reality, and all the back and forth of scientific exchange is a set of concepts which can then be applied to other situations. Our final outcome then is something which can be added to the world of ideas.

The series of essays in this volume relates in some degree to all the four worlds. I cannot imagine anyone who would wish to go through all this material from beginning to end. So let me take the reader for a walking tour through this material so that he or she might plan a particular path which might prove pleasing or useful.

This book is divided into four parts, which I shall describe in inverse order. The last part, *Turbulence and Chaos*, is connected with my most recent work aimed at describing and explaining how chaos and complexity arise in physical systems. This subject is in the process of development. However, some of the important ideas in it have already become apparent. In one view, this subject starts from a question: Given that the laws of physics are simple and predictive, how can we have a world which is so complex and apparently unpredictable. The question is clearly in the world of ideas. To answer it, one turns to the development of mathematical models and of real physical systems, in both cases looking for simultaneous simplicity and complexity.

This volume's third section describes my introduction to complexity. During the late 1960s, it became fashionable for scientists to look away from the traditional applications of their research to military systems, and to focus instead upon problems which might be relevant to the broader needs of society. In the U.S. National Science Foundation, this relevance boom even gave rise to a new program RANN, Research Applied to National Needs.[3] In any case, the same social forces which pushed the NSF toward RANN pushed me toward studying the complexity of forces which shape the physical and social environments of our urban areas. This part of the book, *Simulations, Urban Studies, and Social Systems*, includes the outcome of this effort. It also includes some editorial pieces written for *Physics Today* which report upon the health and decay in another kind of social system, the one of physics itself.

[3]This program was in a large measure designed and put into place by Joel Snow. Our recent Presidents have had many unkind words for civil servants. In my experience, I have found governmental science administrators to be thoughtful hard-working people. As a group, they have contributed a lot to science without getting much thanks.

The second section in this book comes from my best and most important contribution to science, my work on the understanding of *Scaling and Phase Transitions.* Here I played a part in the invention of a tiny world, the critical system, and then devoted considerable effort to studying the detailed properties of that world. In this period, many different and very intelligent people focused an amazing amount of effort upon a very closed and partial model of reality. Despite the limited focus of the work, it has had its consequences. For more details about what happened, I ask you to look at the introduction to that section.

The book's first section, *Fundamental Issues in Hydrodynamics, Condensed Matter and Field Theory*, is devoted to describing the relationship among different models, either in general or in particular examples. Physics contains many different models, which might describe different aspects of the very same physical system. Clearly, one should ask how the different realities caught by the different models fit together. Some of the essays in this section directly confront this general issue, others ask how it is resolved in a particular physical example. A major theme of this section is that physics is really about how models, which give different levels of physical description, may fit together.

Each section in the book is headed by a specific introduction which goes into more details on the questions mentioned here, and outlines some of the contents of the papers.

There is an overall theme to the whole book. Each of the first three sections is devoted to 'old' scientific questions, questions which have been asked and mostly answered. One can expect that each field of science starts from questions built upon small piece of the world, and that in time these questions will become answered as well as the time and means available permit. Then, the subfield gets mined out. Naturally, the scientist must then direct his or her work away from these particular aspects of reality. Naturally, also, when that happens there is some temptation to see and bemoan 'the end of science'. Perhaps this is particularly tempting right now for a physicist since some of our most exciting problems have been either solved or have run into major technical barriers.

However, in the introduction to the last section, I shall argue that we have in front of us a mostly uncharted territory, concerning the development of complexity in the world. The ideas in this part of science is connected with understanding the relationship and linkage among the worlds we have explored. Right now, I see not an end for physics but a beginning. Now is an exciting time to be working in physics.