Cooperative Behavior in Simple and Complex Systems*

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I will first give an overview of how statistical mechanics works for simple systems and then discuss some successes and failures in the attempts to extend it to cooperative behavior in complex systems. I will also discuss the question of the social responsibility of scientists qua scientists.

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Nature has a layered hierarchical structure, with time, length and energy scales ranging from the submicroscopic to the supergalactic. A central lesson of the very successful advances in the physical sciences during the past three hundred years is that while there are many new phenomena as one proceeds from the consideration of individual entities to that of aggregates, there are no new fundamental laws, and explanations between different levels always go from smaller to larger scales. (It should also be noted, however, that some of the mathematical dualities currently being studied in string theory suggest possible direct connections between the highest and the lowest level, closing the loop.)

On the other hand there are *higher level phenomena*, including some of the most interesting ones to us humans, e.g. life, whose origin in the more fundamental lower level laws is as yet little understood. Even where the connection between the levels is more

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transparent, the specific form of complex higher level phenomena cannot in general be deduced, in any meaningful way, directly from the behavior of its microscopic constituents; think of the weather and the motion of the air molecules. In fact, due to the scale separation between different levels, it is often possible and sometimes essential to discuss different levels independently—quarks are really irrelevant for biological processes and atoms are a distraction when studying ocean currents. Still, deeper understanding always results when the cooperative behavior of an aggregate can be traced back to properties of its constituents. Such understanding is often a prerequisite for innovation, as in the design of new materials or of new drugs. (It may be worth montioning here that there is one phenomenon, consciousness, where even "explanation in principle" in terms of lower level laws is far from established and perhaps impossible.)

Statistical mechanics provides a framework for describing how well-defined higher level patterns of organized behavior may result from the activity of a multitude of interacting lower level individual entities. The subject was developed for, and has had its greatest success so far in, relating macroscopic thermal phenomena to the microscopic dynamics of atoms and molecules. Some of these phenomena can be understood as the additive effects of the actions of individual atoms, while others are paradigms of emergent cooperative behavior, having no direct counterpart in the properties or dynamics of the microscopic constituents considered in isolation.

An example of the former is the pressure exerted by a gas on its container; this is just the sum of impulses due to atoms colliding with the walls. A particularly fascinating example of the latter is the observed irreversible behavior of macroscopic systems, as in the tendency of an isolated macroscopic system to evolve towards equilibrium—a state characterized by the maximization of the entropy function under the relevant constraints. The explanation of why and how such time asymmetric collective behavior arises from completely reversible microscopic dynamics is one of the great achievements of the founders of statistical mechanics, J. C. Maxwell, W. Thomson and L. Boltzmann. Other examples of emergent phenomena, well explained by statistical mechanics, are phase transitions in equilibrium systems, such as occur in the boiling or freezing of a liquid. Here dramatic changes in structure and behavior of the macroscopic system are brought about by small changes in the temperature or pressure without any change in the individual atoms or molecules making up the fluid. (The volume occupied by a kilo of water molecules at atmospheric pressure in the Vatican, while changing only very little when the temperature increase is between 5^oC and 95^oC, increases by a very large factor when its temperature changes from 99.9999^oC to 100.0001^oC. Even more dramatic things happen in the freezing transition around 0^oC where there are essentially "infinite" changes in some properties, like 'fluidity'). I will try to give you a birds-eye view on both of these, as I think they may have general implications for the topics discussed at this meeting.

The methods of statistical mechanics used to understand and predict these phenomena owe their success to the facts that, (1) due to the separation of energy scales alluded to earlier, atoms or molecules (or possibly ions and electrons) can be taken as the basic building blocks of matter at temperatures below about one million ^oC, (above which nuclear structure may become relevant), and (2) that even very crude modeling of these atoms and molecules yields many essential features of their collective behavior.

Statistical mechanics therefore often takes as its lowest level starting point Feynman's description of atoms as "little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another." Why this crude classical picture (a refined version of that held by some ancient Greek philosophers) gives predictions about the properties of many substances which are not only qualitatively correct but in many cases also quantitatively accurate, is not entirely clear. Of course one must not get carried away by these simplifications.

An important question is whether and how we might adapt the methods of statistical mechanics, which may be characterized as *subdivide*, *simplify*, and *average* (all up to a certain point), to higher level collective systems in which the relevant basic constituents are themselves complex entities. Let's call them Collective Complex Systems or CCS. Here the interest is not so much in typical equilibrium behavior, or even in the approach to equilibrium, as it is in the dynamic responses of open systems, like the biosphere, evolving over long times in an environment subjected to a variety of regular and irregular (sometimes best modeled as random) influences. What may be particularly important in some of these systems are rare but powerful events (avalanches, catastrophes) which have long term effects. Our understanding of such far from equilibrium systems is at present unfortunately very poor even for simple atomic systems, such as the turbulent flow of water in a pipe. It still lags far behind that of equilibrium systems, the approach to equilibrium or stable stationary nonequilibrium states.

There have nevertheless been many attempts to apply statistical mechanical principles to complex systems. A well known example is the idea of self organized criticality (SOC).

While some of these are still controversial, others have achieved a certain degree of success; examples include the self sorting of different cells in an organism, the flow of vehicular traffic and the formation of galaxies. This suggests that internal complexity and individuality need not exclude cooperative behavior amenable to statistical mechanical analysis. There is however something special about each of these systems. For example, the reason that statistical mechanical methods work well when we treat stars as point particles is clearly due to the fact that the aspect of their behavior in which we are interested, e.g. their tendency to aggregate into clusters and galaxies, depends on a property, gravitational attraction, with respect to which their internal structure and individual differences play little or no role. Similar considerations apply to the use of statistical mechanical methods for the behavior of vehicular traffic, where transitions between "free flow" and "jam" traffic can, to a certain extent, be treated as phase transitions. Here the special nature of the situation comes from the fact that it deals with structured and highly restricted possibilities of behavior.

Still the above examples show that applications of statistical mechanical methods to certain types of complex systems can indeed yield useful insights. The studies of traffic flow have apparently been successful in predicting patterns and suggesting actions for better traffic management. This leads us to hope that we might be able to apply the methods of statistical mechanics, or at least the more general methods of theoretical physics, also to the analysis of those complex collective systems whose behavior is of direct relevance to our survival and well being. Perhaps the most important such system is human society itself.

The goals of such studies should go beyond the applications of science to the development of useful technologies, however important—even crucial—these are. The type of analysis I have in mind would ideally provide us with insights needed to guide technology towards achieving basic humanistic goals, ranging from improvements of the environment to the elimination of hunger and social injustice. Such guidance of technology and applied science in general is clearly desirable. For while many practical applications of science have greatly advanced the quality of the lives of most people—witness the green revolution and the improvements in health together with increased longevity—science can be, often has been been, and unfortunately continues to be used also for evil purposes. While technology is indeed very important for improving the human condition, by itself it is far from sufficient.

What we scientists therefore need to do within our discipline is to develop a moral vision inspired by science itself. This is the vision of an unimaginably grand universe of which living beings and particularly conscious ones, like us humans, are a very small but unique component—a component able to appreciate and formulate general fundamental laws, unifying the great variety of existing levels. So while I agree with Einstein that, "scientific statements of facts and relations cannot produce ethical statements", it is also my belief—and was Einstein's— that the scientific perspective strongly resonates with humanistic values. This perspective makes differences between peoples based on nationality, race, belief or gender entirely trivial, while making the things humans have in common, e.g. the ability to comprehend many aspects of our universe, very special and significant. Indeed the scientific outlook should make us scientists evangelists for a sustainable and just world.

I very much hope that this meeting will contribute to making scientists aware of their special responsibility towards all humans and indeed to all life—a responsibility which arises from our ability to appreciate the grand and subtle structure of the universe we inhabit.

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