intrigued by this problem too. In a 1931 lecture described in his *Science, Theory, and Man* he publicized Exner's sceptical criticism of the view that conventional perfectly-deterministic, and time-reversible, classical mechanics is the only possible model describing "classical" phenomena. So long as energy and momentum are conserved in collisions, a small stochastic contribution to the dynamics *could* also be present, accounting for irreversibility. Exner's explanation, though technically possible, seems implausible, because it fails Occam's test of simplicity. Apart from integer algorithms, like Levesque and Verlet's, finite precision results in computational roundoff error. It seems to me very unlikely that stochastic low-level noise differs in any *significant* respect from this computational error.

1.6 Simple Explanations of Complex Phenomena

Time itself can be viewed as a puzzle, but I choose not to do so. And I also choose to ignore the couplings between mass, space, and time revealed by relativity. For me, Time is a primitive intuitive notion, like Space and Place. I think of time in purely-classical nonrelativistic terms. Time's passage can then be quantified through any periodic motion. It is the result of experience that the exact nature of that motion is immaterial. The difficulties involved in finding a precise and general definition of "time" are not important to an understanding of time reversibility. Simplicity dictates an understanding based on nonrelativistic classical concepts.

At the end of the nineteenth century, and again, toward the middle of the twentieth, some vocal physicists looked forward to finding a unified view of nature. In addition to linking our sensations to the physical world, through understanding consciousness, such a unified view would also require a consistent mathematical description of complex phenomena. The emergence of chaos and complexity renders such a goal obsolete. Gödel showed that most interesting purely-mathematical theories are intrinsically incomplete, unable to decide the truth or untruth of definite statements.

The premature announcements, around 1900 and again around 1950, that "classical mechanics is dead" evidently stemmed from this same obsolete viewpoint of a "complete" theory. If there were some complete and unified view of nature, then more-specialized and restricted special cases of it could perhaps be thought of as second-rate, even if their structure were simpler. Chaos limits the ability of the various theories to overlap.

Physics, chemistry, and biology are intrinsically *different* subjects, rather than special cases of a unified theory. Quantum mechanics is unable to select a particular evolving path. Simulations of *real-world* chaotic processes must *invariably* do just that. Organized biological activity is too complex for a description at the atomistic level. In view of the unattainability of a unified theory, classical mechanics furnishes the best possible basis for understanding problems on its borders with thermodynamics and irreversible fluid and solid mechanics. The exploration and penetration of this artificial perimeter is the main subject of this book.

By now, it is both necessary and commonplace to subdivide knowledge, separating biology from economics and engineering. Within physics classical, quantum, and relativistic mechanics all have their own idealizations, with none of them describing our experience perfectly. I take the point of view that mechanics is an imperfect, but educational model. It is because mechanics' consequences have apt real-life analogs, that this subject is worth knowing. The classical mechanics of isolated systems can be profitably generalized, to describe the interaction of systems with surroundings, nearing the realm of thermodynamics. But the lack of fluctuations in thermodynamics prevents the agreement from being perfect. The only way to distinguish a better theory from its competitors describing the same phenomena, is to wield Occam's Razor, shaving away irrelevant assumptions, and leaving the *simplest* possible explanation as the best. The simplest theories can and do lead to the discovery of complexities as absorbing and interesting as those created by Bach, Brubeck, Mingus, and Monk.

Engineers deal with the application of physical theories to real problems. Their approach is typically totally different to the time-reversible approach of basic physics. Engineering problems include viscosity, heat conductivity, plasticity, and other patently irreversible phenomena based on observation. How does it happen that engineers' alternative approach has lost the fundamental time symmetry of microscopic physics? For one thing, the macroscopic theories used by engineers incorporate averaging, both in space and in time. Their theories are continuum field theories which ignore short-ranged and high-frequency fluctuations. For another, the dependent variables are different too. They reflect the averaging over microscopic details and the process of measurement. Typical variables are temperature, strain rate, and stress, rather than position and momentum, or the wave function. Finally, the systems considered by engineers are seldom isolated. Ordinarily external sources and sinks for heat and work are included. The microscopic analogs of these sources and sinks require generalizing the purely-Newtonian mechanics familiar to physicists.

The familiar irreversible processes which are all around us are not at all similar to the near-equilibrium fluctuations exploited by linear-response theory. Linear-response theory deals with ensemble-averaged infinitesimals. Macroscopic irreversible processes are individual and strongly driven, far from equilibrium, and inherently complex. These far-from-equilibrium conditions require special computer simulation techniques.

1.7 Reversibility Paradox: Irreversibility from Reversible Dynamics

The conflict between basic time-reversible physics and applied irreversible engineering is the "reversibility paradox". For gases, Boltzmann clarified this paradox by showing that averaging, justified by collisional chaos, was an essential part of its resolution. He showed that a statistical averaging of collisions, which ignores any pre-existing correlations and fluctuations, converts the reversible equations governing low-density gas dynamics to the irreversible equations of continuum mechanics. His approximate Boltzmann equation¶, for the evolution of the single-particle probability density, f_1, makes detailed predictions for the approach to equilibrium, and for the velocity distributions characterizing systems undergoing diffusive, viscous, and conductive dissipation. For dilute gases, the time-development of Boltzmann's approximate single-particle entropy,

$$S_{\rm B}(t) \equiv -Nk\langle \ln f_1 \rangle \equiv -k\int dr \int dv f_1(r,v,t) \ln f_1(r,v,t),$$

agreed with the predictions of irreversible thermodynamics, opening the way for Gibbs' formulation of statistical mechanics for general systems, but restricted to equilibrium.

Green and Kubo showed that Gibbs' averaging links the irreversible transport coefficients of phenomenological continuum theory to the decay of equilibrium fluctuations. For dilute gases, these results are also equivalent to Boltzmann's. After Green and Kubo discovered linear-response theory, theoretical progress was stalled, awaiting the development of fast computers. The need to understand complex chaotic behavior frustrated

¶ $\dot{f}_1 \equiv (\partial f_1/\partial t)_{\rm collisions}$. The approximate collision term, $(\partial f_1/\partial t)_{\rm c}$, is ***quadratic*** in f_1.