

## Homeokinetics: A Physical Science for Complex Systems

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Complex systems do not act chaotically. Instead they exhibit well-defined chains of behavior that have been regarded as purposeful, even historical and evolutionary. Everyday language affords many common descriptive usages which

sion energy. They exhibit considerable diversity in their internal activities. Examples of increasing complexity are plastic-elastic behavior, thixotropic behavior (behavior that depends on past history), behavior in living organisms

*Summary.* A physical basis for reductionism is put forth in the form of five propositions that bridge levels of organization in natural phenomena. The outlook is that complex systems and processes all have to be traced back to physical law, which applies the only general scientific constraint on reality, but that out of physical law a hierarchy of organization emerges. The basic extension of normal physics in this homeokinetic field form is to complex systems. In such systems the repetitive units of concern are internally complex and exhibit elaborate internal time-delayed processes, for example, memory.

mix up teleological purpose with the physical actions that systems must perform in order to survive. The question can therefore be raised whether there is a common science for the behavior of complex systems, a science that includes the internal control of those essential actions. Simple physical field systems can be defined by statistical mechanics (1, 2). They are ensembles of interacting similar atomic-like particles (atomisms) in which the atomisms equipartition their interactional energy among their mobile internal degrees of freedom. Fluid mechanical fields and solid-state physical fields are examples of such "simple" systems. By extension, complex field systems are those ensembles in which the atomisms have many internal degrees of freedom, and they do not equipartition collisional or interactional energy over each collision cycle, but instead internally time delay, process, and transform such colli-

with a more extensive memory system, on up to human societies with an extensive epigenetic heritage as well as an internal (emic) construct for culture.

### A Physical Foundation for Complex Systems

We offer some common hierarchical propositions about complex systems found in nature. Together with our proposed basic doctrine of the operation of complex systems, they provide a unified point of view for the scientific study of nature.

While we are aware of many themes regarding the operation of complex systems as they have recently been discussed (3), we are more inclined toward the comment of Anderson (4), who expresses little doubt that physical scientists are reductionists, but points out that

the problem is to determine the "constructionist" path with some adequate physical detail.

To establish a physical foundation for complex systems, we take our theme from the originators of homeostasis, Bernard (5) and Cannon (6).

*Homeostasis.* This is the regulation of the internal degrees of freedom of a complex autonomous system, independent of variations or fluctuations in the external milieu. The implication is that such regulation persists for a long time, the lifetime of a system.

*Homeokinesis.* This is the achievement of homeostasis by means of a dynamic regulation scheme whereby the mean states of the internal variables are attained by the physical action of thermodynamic engines.

The internal state of the complex system (for example, organism) is characterized by the fluxes and potentials that drive and are driven by the engines in a cyclic manner akin to limit cycle behavior. Included as an essential part of this homeokinetic regulation scheme is an ensemble of active catalytic switches, themselves comprising thermodynamic engine parts, which by inhibition or release from inhibition shift the operating points of the engine cycles. As a result, the internal state space is mapped by a ring of operational modes which control the activity of the complex system (7, 8).

L. J. Henderson's 1926 preface to Claude Bernard's seminal work (5) points out that Bernard's principle of the constancy of the internal environment (that is, homeostatic regulation, which may be both cyclic and adaptive) as the condition of free and independent life, is the first approximation to a theory of the organism. We offer the new physical doctrine of homeokinesis as a second approximation to such a theory of complex autonomous systems. Homeokinesis is a technical doctrine of how homeostatic regulation can, in fact, be achieved by thermodynamic engines within physical laws.

These ideas apply not only to the regu-

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lation of the internal milieu of the biological system, but also to the invisible regulatory hand of the marketplace in society, as well as to the notion that the observed properties of visible bodies apparently at rest are due to the action of invisible molecules in rapid motion, and the sustained minute motion of larger sized particles embedded among such invisible molecules (9).

A "homeokinetic physics" for complex systems is not independent of the standard physics of elementary processes or simple systems. It clearly must subsume this physics. But in addition, it provides an organizing view for describing, analyzing, and applying physics to all complex viable systems.

In standard physics, the collisional interactions of pointlike atomisms can be treated by Maxwell's kinetic theory of gases and its extensions. The averaging techniques of statistical mechanics can be used to derive laws for the motion of ensembles of such atomisms, leading for example to hydrodynamics as a continuum theory for mobile mass particles. Underlying atomicity is identified and used within the dualistic system of atomism and continuum. The atomistic character is first described by kinetics, and the summation of such processes is used to characterize the deviator transport states from equilibrium to establish the continuum description. Independent atomistic particles and idiosyncratic processes are treated by kinetics.

In the case of nonpoint-like atomisms, statistical mechanics describes the internal structure and process within the atomism by a conservative Hamiltonian, resulting in equipartition of energy among the translational and mobile internal degrees of freedom. Such a description is frequently modeled by regarding the atomism as consisting of a set of non-dissipative oscillators and rotators.

But this standard approach is inadequate to deal with complex field systems. As we stated, they are ensembles of interacting like atomisms in which the atomisms have many internal degrees of freedom. Such complex atomisms do not equipartition interaction energy per collisional cycle, but instead internally time delay, process, and transform collisional inputs, generally using many fluidlike dissipative mobile steps. We may regard such atomisms as factories, undergoing their process chains. Each atomism, as a factory system, operates homeokinetically. It rings through its operational modes. The process chains furnish their own intrinsic timing, and this factory clock, the internal "day" of the factory, ultimately must be in time with the colli-

sional cycles so as to balance inputs and outputs and maintain homeostatic persistence.

In contrast to the conservative Hamiltonian approach, the homeokinetic view regards the internally complex atomistic factory itself as a field, requiring for its description of the same dual-analysis process—continuum thermodynamics with bordering kinetics. Thereby a natural hierarchy is established as one goes up or down through the size or order of structures. At every level, the complex atomistic entities are internally mobile factories. The cascade complexity of the eddy structure in the turbulent hydrodynamic field provides a physical example.

Complex atomisms do not change their fundamental physical nature on account of their factory complexity. Regardless of hierarchical level, the variables are still mass species, charge, energy, momentum, or action, and they include population number for atomistic species that live and die (with added conservations at more primitive levels). The fundamental spatial field processes remain diffusion, convection, and wave propagation. The complexions are still associations of the one, the few, and the many. The generalized subject "chemistry" is still concerned with the making, breaking, and exchanging of bonds. The internal modal states of the atomisms do not consist of hard-wired, hard-gear (holonomic), hard-molded subcomponents (10). They are alternative paths of nearly equienergetic states, with the pistons, cylinders, valves, and switches of the engine factory arising from the internal hydrodynamic processes. Their component states are more often gel-like than solid. This is the picture we would like to present. To fix the picture, we offer a set of five propositions that illuminate the underlying physics. More detailed discussion of their content may be found elsewhere (11).

### Five Propositions

The complex systems in nature may be hierarchically linked by five thermodynamic propositions. A scientific scaffold is thus established that provides conceptual linkages across a great variety of levels of organization from elementary particles below to cosmology above. The level bridging propositions that follow (12) thereby provide a "hunting license" to extend the methods of physical science to many kinds of complex systems found in nature.

1) Ensemble mechanics implies thermodynamics. A deterministic continuum

description of homogeneous matter must include dissipation for consistency. In this sense, mechanics implies thermodynamics.

2) Atomistic ensemble below implies continuum above. An ensemble of interacting atomistic entities (atomisms) at any organizational level acts like a continuum at an appropriate space-time scale (for example, a glass of water).

3) Continuum below implies superatomisms above. A fluidlike continuum at any organizational level becomes dynamically unstable locally at some sufficient scale of stress, creating a spectrum of patterned structures of superatomisms that are freely mobile in broadly extended media (for example, small eddies in a turbulent stream).

4) Atomisms below imply superatomisms directly above. The physics of interacting superatomisms, including their internal processes, appears as ad hoc at their level, even though derivable in principle from the physics of the lower atomistic level. However, the Liouville theorem and the existence of a distribution function for the translational degrees of freedom in an ensemble of these superatoms is directly transferred from the lower level (for example, Brownian particles).

5) Continuum above implies fluctuations—generally atomistic—below. The dissipative nature of a continuum, as required by proposition 1, implies fluctuations at a lower level of organization.

These propositions link the hierarchical systems found in nature and imply a statistical mechanics—irreversible thermodynamics—for each level. Earlier presented only as a conjecture (13), the physical framework for natural systems was represented by the notion that these natural systems were organized into successive levels of atomisms (A) and continua (C). An ensemble of atomisms forms a continuum. The continuum becomes dynamically unstable and forms superatoms. The line . . . -A-C-A . . . ends when it becomes singular at either end, for example, one universe above, fundamental particles (quarks?), below.

In the following paragraphs we briefly outline or exemplify the thrust of each proposition.

*Proposition 1.* A Newtonian conservative mechanical description of a continuous homogeneous fluid is necessarily incomplete, except for the case of a Hooke's law medium (14), one in which the pressure  $p$  is a linear function of specific volume  $v$ . The nonlinear dissipation-free wave equation for such a homogeneous continuum leads to singularities that are described by disconti-

nities, or shocks. Further, mass, momentum, and mechanical energy cannot all be conserved across a shock front. Mechanical energy here is the sum of kinetic energy and elastic potential energy  $e(v) = -\int p(v)dv$ . In a "normal shock," mechanical energy is lost. In an "anti-shock," it is gained. Finally, solutions generally become nonunique when initially smooth solutions generate colliding shocks.

The minimal extension of Newtonian mechanics required to save energy conservation introduces a new non-mechanical parameter,  $s$ , on which the energy depends. The "missing energy" is then the change in energy due to the change in  $s$  across a shock, according to  $\int (\partial e / \partial s) ds = \bar{T} \Delta s$  where  $T$  is defined as the derivative  $\partial e(v, s) / \partial s$ . The missing energy is positive in normal shocks and negative in antishocks. To save Newtonian determinism, to avoid non-uniqueness, it is necessary to disallow antishocks.

Thus, energy conservation demands the introduction of entropy  $s$  and temperature  $T$ , and determinism demands the positivity of  $T \Delta s$  and of dissipation.

**Proposition 2.** The continuum description of a collection of like atomisms is a standard reduction in the physics of matter ( $I$ ), in the case that the atomisms easily equipartition energy during collisions. For example, with mobile atomisms, fluids, one obtains the Navier-Stokes formulation valid for space-time scales several times larger than the scales of a molecular collision. An analogous description exists in the solid-state case ( $I5$ ). But as the atomisms increasingly delay collisional energy internally (being out of phase, it is dissipative), the "instantaneous" summation of processes involving translational motion (for example, momentum) and transport (shear viscosity, heat conductivity) are inadequate for the description. Instead, a longer period of integration has to be specified, one long enough for internal degrees of freedom to achieve a total net cycle of balance. That such a cycle must exist, if the system is known to exhibit near stationary dynamic behavior or some weak form of the ergodic hypothesis in finite time ( $I6$ ), is obvious because the materials and energies for the internal degrees of freedom must come through the translational gate. The appropriate measure of the process is  $\lambda/\eta$ , the ratio of bulk to shear viscosity, and the physical process proposed (as a substitute for momentum balance) is action balance by characteristic internal modes (factory modes), and the ensemble physics is denoted as homeokinetic. As

shown by Tisza ( $I7$ ), the ratio  $\lambda/\eta$  basically measures the ratio of the action involved in the cycle of internal processes to the action appearing in the fluctuating translation processes.

**Proposition 3.** But now we may imagine a uniform continuum field stretching indefinitely (for example, to remote boundary conditions). The question is, if that system is stressed sufficiently for a given size (or for a given stress, if the size is sufficiently large), can there be a homogeneous time-independent solution? The proposition indicates that at sufficient scale, the same concept as the critical Reynolds number of a transition to some form of inhomogeneity will apply. The generalized concept of the Reynolds number will be that of the ratio of a flux sweeping convectively (nonlinearly) into a local medium, as compared to what local bonding mechanisms can absorb (within its internal thermostatic energy). If this ratio reaches or exceeds one, new local forms have to emerge.

Beyond its obvious validity and exhaustive testing in second-order transition flow phenomena, we show how it may be applied homeokinetically to first-order transition condensation or phase change phenomena, including its implications for human transition from hunter-gatherer to settled trading agricultural societies.

The basic proviso must be added that for a free and autonomous life, the newly emergent inhomogeneous dynamical element (superatomism) should be small compared to the spatial constraints of the boundaries. Dynamical elements may emerge at first which remain highly confined by the boundaries, but there will exist a sequence of such instabilities, tending toward increasing chaos and smaller size which ultimately will be free.

**Proposition 4.** If we start at the level of some very small-sized atomism (for example, quark, electron) then there exist ensembles which obey well-known statistical mechanical constraints, for example, a Liouville theorem regarding the conservation of density-in-phase. At this point, we can transfer attention to higher ordered atomisms, if they exist, without concerning ourselves with the intermediate continuum-like state from which the higher ordered superatomistic associations arose. We simply note that in the phase space in which we were watching the original particles, we could find some indefinitely long temporal correlations, the higher ordered superatomisms. Thus there exists a phase space in lower order dimensions for which the same Liouville theorem and a similar trans-

lational momentum (or action) description goes through. However, one will have to add, ad hoc, a quantization theory, among hidden variables as it were, by which the atomistic associations occurred. Any new continuum mechanics based on these superatomisms will have to be limited by this higher ordered quantization.

**Proposition 5.** Proposition 1 demonstrates the existence in a fluid continuum of an energy component that is not macroscopically mechanical, that cannot be accounted for as the sum of macroscopic kinetic and elastic energies. Insistence on a mechanical accounting of energy then implies the existence of lower level motions "fluctuations," with zero mean value.

The scale of such fluctuations can be described only by going beyond the minimal extension of Newtonian mechanics described in proposition 1, and including in the equations smoothing terms which prevent the formation of mathematical discontinuities. The simplest smoothing term from the mathematical point of view is that which corresponds to viscous drag. Inclusion of a viscous term with viscosity  $\eta$  automatically introduces a spatial scale  $\eta/(\rho c)$ , where  $\rho$  is density and  $c$  is sonic speed, and an associated temporal scale  $\eta/(\rho c^2)$ . In a gas, these are the mean free path and collision interval.

## Conclusions

A physical reductionist construct has been offered. Its outlook is that complex systems and processes all ultimately have to be traced back to physical law, which applies the only general scientific constraints on reality; but that out of physical law a hierarchy of organization emerges, and that it behooves the generalist or user of general principles to become familiar in a constructive sense, both theoretically and experimentally, with the detailed content of any level that these principles are to be applied to ( $4$ ).

We realize that the notion that physics is capable of dealing with complex systems such as nature, life, society, mind, has been philosophically offensive to most students in these fields; and that to make such a claim has been offensive to physicists as well. But we are trying to establish the point that simple conservative Hamiltonians for the description of the processes within the atomisms of complex systems are inadequate "constructionist" bases for achieving the task. We ask (i) that serious attention

be paid to the internal "hydrodynamic" factory complexity within the atomism (cell, brain, organism, society) (18) and (ii) that the cascade complexity of the turbulent hydrodynamic field, such as the atmosphere, be used as a prototype model exercise.

As an organizing view for the analysis of viable complex systems, we present the new physical doctrine of homeokinesis, a dynamic regulation scheme whereby homeostatic persistence is maintained by the action of chains of thermodynamic engine processes. The homeokinetic view of a complex atomism itself as a factory field establishes a natural hierarchy of organizational levels. The basic physics underlying this description is illuminated by five level-bridging propositions.

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9. We note that the priority of discovery might be considered to be Lucretius, Adam Smith's "invisible hand," Bernard's constancy of the interior, and lastly Maxwell's maintenance of the motion distribution in an ensemble of colliding molecules. However, it was Maxwell, and later, Einstein in the theory of Brownian motion, who provided a reductionist model for such phenomena.
10. The Enlightenment pursued the notion of Newtonian and Cartesian clockworks which proved inadequate for the complexity of historical and evolutionary processes. An extreme current form of Cartesian clockworks is the circadian rhythm, an expectation among some that it will prove to be the timekeeper for biological processes and complex organisms. [See G. Luce, *Biological Rhythms in Human and Animal Physiology* (Dover, New York, 1971)].
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12. While largely described in a classical spirit, these propositions are essentially neutral with regard to quantum effects.
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14. The motion of a Hooke's law medium is the superposition of noninteracting harmonic acoustic waves. The Hamiltonian separates into a sum of oscillator terms, one for each mode. This is the continuum equivalent of the particle picture situation of a set of noninteracting particles. In both cases, there can be much motion, but nothing can be said to happen. Each particle or each acoustic mode performs its own inertial motion independent of all others. Structure and process do not arise without interactions. Nonlinearity is required.
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## Economics of Nuclear Power

Nuclear plants have been good investments and have produced substantial savings to consumers.

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In 1977 nuclear power plants produced about 12 percent of the nation's electric power. This was 20 years after the first almost-commercial-size unit began operating (1), 17 years after the first privately financed nuclear plants went into service (2), and 8 years after the first large units went on line (3). Since 1973 the increase in nuclear energy production has been rapid, averaging 30 percent per year from 1973 to 1977. In 1977 nuclear energy production increased 29.5 percent

over 1976, while total electric energy production in the United States increased only about 5 percent.

This article deals with only one aspect of nuclear power: the economics. The industry states that despite problems, delays, and cost increases, nuclear plants saved U.S. consumers well over \$1 billion each year in 1975, 1976, and 1977. Nuclear critics claim either that the savings are artificial, or that they will not be there in the future, or that they are irrelevant for various reasons. Some argue that the costs have not all been internalized or that vast hidden subsidies exist.

We believe that documented evidence

is publicly available with which to sort out these arguments. In this article we examine the performance of nuclear power in the United States to date by evaluating its economic record relative to that of alternative sources of electricity, with particular reference to nuclear and coal-fired plants in the Commonwealth Edison Company (CECO) generating system. We also evaluate the available electric energy supply options for the late 1980's and discuss what the critics consider hidden costs or subsidies.

#### Energy Supply Options for Utilities

Utilities must choose between supply options that are technologically feasible, meet environmental criteria, are economically competitive, and for which the fuel supply is reasonably ensured over the expected life of the facility. Today the only available options that meet this test for new plants are nuclear and coal.

A few utilities may have particular options that are not generally available. Some hydroelectric sites may still be capable of development, but the estimates of lead time and the licensing uncertainties exceed those for nuclear plants. In addition, water has other uses, so regulatory bodies as well as the whims of

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