Cliodynamics: the Journal of Theoretical and Mathematical History

Can there be a Quantitative Theory for the History of Life and Society?

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Might there be universal laws of society analogous to those of physics and of life? This question can be addressed by identifying coarse-grained, quantitative variables for human phenomena, and placing these within a proven mathematical framework. It is assumed frequently that human intention, coupled to the purposeful human modification of the environment, renders humanity immune to this kind of atemporal, scientific analysis. On the other hand, human collectives struggle with the same basic energetic and informational needs and constraints that we observe at multiple scales of physical and biological organization. These general requirement for life, give us the confidence to attempt to include elements of human history within the framework of a quantitative, natural scientific theory.

To what extent, if any, can History be viewed as a Science? Needless to say, this begs the two fundamental questions: what is History and what is Science? I have neither the qualifications nor expertise to address the first, and, although I have been a practicing "scientist" for more than 40 years, do not feel entirely secure in addressing the second! Nevertheless, having spent much of my career in the field of high energy physics at several distinguished institutions, and now having spent a couple of extraordinary years at the Santa Fe Institute, I have learnt that such inhibitions should not stop one from expressing an opinion. I recognize that I am on dangerous territory here but would like to make some potentially provocative remarks related to these questions.

History is surely more than "just" a record or accounting of a sequence of events deemed of importance to the human experience. Time and sequential relationships play a special role, and presumably the search for a framework for revealing mechanisms and understanding is an integral part of the historical process. To this extent, history can be loosely conceived of as a science. Science implies a search for patterns and regularities that can be assembled into a rational, analytic framework based on a few "fundamental" principles that will ultimately lead to predictions that can be tested against existing data, and more importantly, against new situations typically in the form of proposed experiments. Parsimony of explanation and its relationship

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Citation: West, Geoffrey B. 2011. Can there be a Quantitative Theory for the History of Life and Society? *Cliodynamics* 2: 208–214.

to elegance also play a role in what we accept as constituting a deep understanding of a problem. This is hardly the view most of us have of history, although we continually hear the phrase “history teaches us that………”, as if history were, in some sense, a “science.” Although there are presumably patterns in history, almost everything of importance is often viewed as special and dependent upon “accidental” events. History appears to be extraordinarily complex, diverse, contingent and devoid of universals and invariance – or is it? The greatest successes in science have been in areas that are relatively simple, show regularities and patterns, “universal” behavior and amenable to logical analyses. Is it at all conceivable that there are significant aspects of history that can be put into such a “scientific” framework?

There is yet another aspect of science that I would like to discuss before launching into how some of my own work can be viewed from this perspective, and that is the central role of mathematics. Such a discussion will expose the cracks in the scientific edifice as we gaze across the spectrum from physics and chemistry to biology and the social “sciences.”

Almost 100 years ago the eminent biologist D’Arcy Thompson began his wonderful book On Growth and Form by quoting Kant’s observation that “chemistry……was a science but not Science……for that the criterion of true Science lay in its relation to mathematics.” Thompson discussed how there now existed a “mathematical chemistry” (thereby elevating chemistry to Science), but that biology had remained qualitative without mathematical foundations or principles, implying that it was not yet “Science”! The basic question implicit in his challenge remains unanswered: are there “universal laws of life” underlying biological phenomena that can be mathematized so that biology can be formulated as a predictive quantitative Science? Most would argue that it is very unlikely that there are yet-to-be-discovered “Newton’s laws of biology” that would lead to detailed calculations of arbitrary biological phenomena to any degree of accuracy, much in the way we are able to calculate the details of planetary or satellite motion to arbitrary accuracy. Indeed, it could be convincingly argued that the very nature of most biological systems precludes such a possibility. Life very likely represents the most complex and diverse phenomenon in the universe and, even though, and maybe because, it is constrained by natural selection, is contingent on “historical accidents”. Each organism, each subsystem, evolved in its own unique environmental niche in interaction with every other system or organism. Furthermore, even the tiniest organism contains an incredible number of variables, constituents and degrees of freedom. Viewed from a “simple” Newtonian viewpoint, it all seems totally mind-boggling.

For the sake of this meeting, I want to ask what might seem to be an even more ambitious question, "might there be universal laws of society analogous to those of physics and of life?" The study of society typically involves the identification of critical events unraveling over the course of time, these events constituting a cumulative, historical account for a pattern we deem interesting. In some fundamental way, history provides a complementary explanation to regular, or law-like processes, as history typically explains patterns in terms of chance events rather than necessary dynamics. Of course, reality represents a complex interweaving of both chance and necessity, and the role of complexity science can be seen to be engaged in the difficult task of isolating each of these factors and weighing their respective contributions to the present.

A critical conjecture in this undertaking is that the generic coarse-grained, or average, behavior of such systems, such as their dynamical structure or organization, obeys quantifiable universal laws that capture their essential features. This view presumes that at every organizational level average idealized systems can be constructed whose properties are "calculable". These provide a "zeroth order" point of departure for quantitatively understanding real systems which can be viewed as variations around idealized norms due to local environmental conditions or historical divergence during evolution as a result of essential contingencies.

This approach is familiar in physics. For example, classic kinetic theory developed in the 19th century is based on the idea that generic features of gases, such as the ideal gas law, can be understood by assuming atoms to be structureless "billiard balls" undergoing elastic collisions. Despite such gross simplifications, the theory captures many essential features of gases and spectacularly predicts many of their coarse-grained properties. Furthermore, this highly simplified theory acted as a starting point for modern sophisticated treatments incorporating structure, inelasticity, quantum mechanics, etc, which allow greater detail to be calculated. Other examples include the quark model of elementary particles and theories describing the evolution of the universe from the big bang. Although the shortcomings of such theories are well-recognized, they quantitatively predict and explain an extraordinary body of data because they do indeed capture much of the essential physics.

When it comes to social phenomena, we would never be so naive as to approximate individuals as billiard balls, but it might be possible as a first working hypothesis in attempting to construct an initial "zeroth order, coarse-grained" theory, to assume that all people are essentially the same. This, of course, is in immediate violation of "traditional" history where the role of special individuals appears paramount. In this context we could imagine asking "coarse-grained" questions like did it actually matter that a specific man named George Washington existed at the end of the 18th century in determining how America has evolved into the early 21st century, or was there an inevitable dynamic at play and America would actually be pretty much the same. In any case, within this paradigm we can choose levels above the individual – groups, villages, and cities for example, and ask whether at these more inclusive levels, we might not hope to observe some average property that does not depend in crucial ways on the complexities of individual psychology and the accumulation of unpredictable, historical events.

Let me briefly review some ideas in biology that are possibly relevant to this discussion and then extend them to social organizations and the role of growth, decay and innovation. Living organisms span a mass range of over 21 orders of magnitude from the smallest microbe (10^{-13} g) to the largest mammals and plants (> 10^8 g). Overall, the life process covers over 30 orders of magnitude from the molecules of the genetic code and metabolic process up to whales and sequoias. This vast range exceeds that of the Earth's mass relative to the galaxy's (which is "only" 18 orders of magnitude) and is comparable to an electron relative to a cat. Similarly, the metabolic power required to support life over this range spans over 21 orders of magnitude, greater than the Planck (or string) unification scale (10^{19} GeV) relative to the mass-energy of a proton (1GeV). Over this immense spectrum, life uses basically the same chemical constituents and reactions to create an amazing variety of forms, functions, and dynamical behaviors. All life functions by transforming energy from physical or chemical sources into organic molecules that are metabolized to do the work of building, maintaining, and reproducing complex, highly organized systems. Understanding the origins, structures, and dynamics of living systems from molecules to ecosystems is one of the grand challenges of modern science.

Despite its extraordinary complexity and diversity, many of life's most fundamental and complex phenomena scale with size in a surprisingly simple fashion. Typically some trait or physiological variable, Y, scales with mass, M, as a simple power law, $Y = Y_0 M^b$; e.g., metabolic rate scales as $\sim M^{3/4}$ over an astonishing 27 orders of magnitude from complex molecules up to blue whales. Of even greater significance, the exponents, b, invariably approximate simple multiples of ¼ for almost any quantity including metabolic rate, lifespan, growth rate, heart rate, DNA nucleotide substitution rates, lengths of aortas and genomes, heights of trees, cerebral grey matter, mitochondrial densities, RNA concentrations and many others. Thus, in a very real way, a whale is a blown up elephant, which is a scaled up gorilla which is a scaled up human which is a scaled up rat, despite their obvious superficial differences!

It is compelling to view the ubiquity of these empirical "laws" as reflecting underlying general principles, independent of the specific evolved design, that constrain the function, structure and organization of much of life across all scales and all systems. Working with the biologists James Brown and Brian Enquist, I suggested that these scaling laws are a manifestation of the "universal" geometric, mathematical, physical properties of fractal-like hierarchical branching networks that have evolved by natural selection for solving the problem of efficient distribution of energy, resources and information in multi-level, multi-component complex systems. Some of us have suggested that at all levels of biological organization from the intracellular to the multi-cellular life is sustained by optimized, space-filling, hierarchical networks, whose terminal units are invariant. By expressing these general principles in a mathematical language we constructed a general quantitative, predictive theory that captures the essential, coarse-grained, features of many diverse biological systems. The theory was able to address questions like: how many RNA molecules or mitochondria are there, on average, in a cell? Why do we stop growing and what weight do we reach? Why do we live ~100 years, and not a million or a few months, and how is this derived from molecular scales? What are the flow rate, pulse rate, pressure, and dimensions in any vessel of any circulatory system? Why do we sleep 8 hours a day and not 2, whereas a mouse sleeps 16 and an elephant 3? What are the limits on organismal size?

It is natural to attempt to extend these ideas and techniques to analogous situations in other fields where there are obvious similar hierarchical branching network systems. In some areas empirical scaling laws already exist but, in others, data have not been organized in this way. Obvious examples are river systems, where good power law scaling data exist, and urban systems, where they do not. An interesting twist in these systems is that they are two-dimensional rather than three. The main aim here is to determine whether the existence of power law behavior reflects fundamental principles controlling the underlying dynamics and, if so, determine in detail their structure and behavior. An important question is: what are the appropriate quantities to be measured and what are the effective degrees of freedom to be used to construct models? In rivers this may be obvious but in the social context, such as urban systems or corporate structures, this is not so clear so a significant part of the investigation is data analysis to determine the appropriate degrees of freedom.

In urban systems there has been some investigation of fractal structure and attempts to measure fractal dimensions. In addition, the scaling of the frequency of towns of a given population size as a function of its population ranking, which reveals an approximate Zipf-type power law with an exponent of ~ −1, is well known. We have extended such studies and performed an extensive analysis of urban data to obtain a taxonomy of urban scaling laws. These include transport and communication networks, distributions of various resources and properties among urban residents, demographic growth rates, patent production, and so on, with the view to revealing a common universal behavior and underlying principles of urban evolution. Of particular interest are data on measures of fundamentally social quantities that have no simple analog in biology, such as number of patents and inventors, crime rates, number of hospitals and laundries, etc. Remarkably, we find that, to a large extent, New York is a scaled up Detroit, which is a scaled up Boise, which is a scaled up Santa Fe, and so on; that is, “all” cities are in almost all respects scaled versions of some average idealized city. Thus, despite all the urban planning and the vagaries of history and specific environmental and geographic factors, the time evolution, the "history" of a city or settlement is to a large extent "determined" and "predictable"!

This suggests that generic properties of cities are derivable from underlying principles common to all urban systems. The theory predicts that, in contrast to biology, the pace of social life increases with size and therefore with "historical" time, in quantitative agreement with data (including the speed of walking!), and leads to a growth equation showing how major innovation cycles must be generated at a continually accelerating rate to sustain growth and avoid stagnation or collapse.

The hierarchical networks that distribute resources in settlement systems are of three different kinds, transporting matter, energy, and organizational information. Our idea is that the differences between the spatial configurations and the structures of these three networks determine the precise forms of scaling observed, as well as the aberrations and the dynamics of settlement systems. By crafting the problem in these terms, we anticipate formulating a theory of metropolization, which is threatening to change the geography of the entire world. Can we find other, perhaps more efficient, ways of distributing resources to everyone? It is remarkable that, despite the central role of cities in human development and the rich evidence at our disposal we do not presently understand, in quantitative and predictive terms, the social dynamics that make cities simultaneously the hubs of innovation, the engines of wealth creation, and the sources of much crime, pollution and disease.

The principal theme unifying the study of cities across the social sciences has been their central role in creating social change and organization, ranging from political structures, new artifacts, dynamics in the detailed fabric of human interactions, and how these affect human behavior. From the perspective of social change it is therefore natural, and even compelling, to attempt to integrate these common threads involving human interactions across multiple scales from communities and cities up to urban hierarchies.

This approach aims to build upon a rich empirical tradition of studies of innovation in cities from economics and the social sciences, by integrating it with a novel quantitative perspective inspired by strategies successfully used in physics and biology on how to bridge different levels of organization. The methods, based on scaling analyses, can potentially generate new insights into how social organization is coupled to change in, for example, urban settings. More importantly this reasoning strongly suggests that the evolution of social organizations, their growth and decay, the essential dynamics of innovation, the very pace of life, obey in a coarse-grained fashion definite laws determined by the underlying dynamics inherent in the networks of human interactions. As such the panoply of history plays itself out on a stage subject to very general laws operating over the spatial scale of the planet and the time scales of socialization.

In summary, our objectives are to identify coarse-grained, quantitative variables for human phenomena, and place these within a proven mathematical framework. We do this in order to generate non-trivial insights and predictions. It is assumed frequently that human intention, coupled to the purposeful human modification of the environment, renders humanity immune to this kind of atemporal, scientific analysis. On the other hand, human collectives struggle with the same basic energetic and informational needs and constraints that we observe at multiple scales of physical and biological organization. These general requirement for life, give us the confidence to attempt to include elements of human history, within the framework of a quantitative, natural scientific theory.