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Power law behavior and world system evolution: A millennial learning process

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Abstract

Is social change on the scale of the human species a millennial learning process? The authors answer in the affirmative, demonstrating that world system evolution, viewed as a cascade of multilevel, nested, and self-similar, Darwinian-like processes ranging in "size" from one to over 250 generations, exhibits power law behavior, which is also known as self-organized criticality. World social organization, poised as it is on the boundary between order and chaos, is neither subcritical nor supercritical, and that allows for flexibility, which is a necessary condition of evolution and learning, and these in turn account for the major transitions marking world history and serving as the general framework for long-range forecasting. A literature review confirms the close affinity between evolution and learning, mathematical analysis reveals the crucial role of the learning rate as pacemaker of evolutionary change, and empirical evidence supports the concept of a cascade of evolutionary processes. The general equation describing world system emergence shows it to be a project whose current period is now 80% complete, suggesting that its major features might now be in place.

Keywords: Power law behavior; World system evolution; Millennial learning process

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1. Prediction and explanation about nature and society

Students of the natural and the social sciences aim to achieve in equal measure both explanation and prediction, but their success at either (such as it may be) does not automatically translate into strength in the other direction. Thus, as all the physics books tell us, Newton's theory predicts and explains. Biologists agree that Darwin's theory explains but only weakly predicts. Quantum mechanics is a powerful tool for prediction, but is poor for explanation. Economics has severe restrictions regarding both explanation and prediction. What can we say about large-scale social change such as that we observe in history? Many great domains of the natural sciences, such as cosmology, geology, and evolutionary biology, are studied with the tools of the science of history, but history itself lacks general laws that allow explanation or prediction. Historians have eschewed any hope of finding general laws, and prediction for them lies in the realm of divination. Recent social scientists have not been active in this field either.

Starting from the perspective that doing science is searching for lawful descriptions of natural and social phenomena and trying to capture in a picture some of the statements above, Casti [1] published a decade ago an interesting and meaningful graph. In it (see Fig. 1), he graded the different fields of knowledge, using the scale (from A to F) employed in the US school system, so as to produce (in his own words) "an ordinal representation of the degree to which science is able to serve up computable functions capturing the empirical evidence available for the phenomenon at hand." In his text, he did not analyze each of the pictured fields (indeed, he discussed to any extent only the weather, developmental biology, the stock market, war, and mathematics), but we can easily infer from his analysis the reasons why our

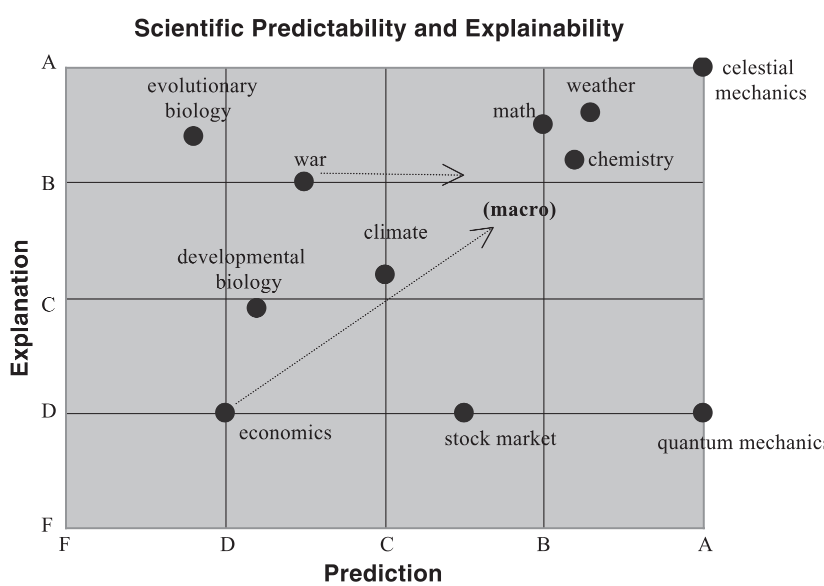

Fig. 1. Grades representing the degree to which different sciences are able to serve up computable functions capturing the empirical evidence for the phenomenon at hand according to Casti (Ref. [1], p. 407).

capacity to explain and to predict weakens markedly as we move from the hard sciences at the upper right corner of the graph toward the soft sciences at the lower left corner. The diagram makes it evident that it is in those areas least susceptible to "human" influence that we have the best computable algorithms, empowering us to say what is next and why.

Casti features in his graph neither history or sociology, nor does he analyze in his text the characteristics of economics, but in a chapter dedicated to warfare and its relationship with political tensions and economic troubles, he claims to recognize many sound theoretical arguments and positive notions about war causation. He singles out for particular attention Lewis F. Richardson's work on arms races and models of power transition. Yet he also points out that the grades he assigns are tentative, hence subject to revision of possibly a dramatic kind. As we gain deeper insight into the common patterns in biological and social evolution, we could experience a pronounced shift from entry-level positions near the lower left corner toward the scientific rigor at the upper right. That perhaps inevitable movement is represented by the two arrows in Fig. 1. The approach presented in this paper hopefully offers a contribution to such a positional shift.

2. Is social change computable?

Every social process involves a long chain of events, each of crucial importance for the actual outcome. Historians explain events in a narrative language where event A leads to B and C leads to D. Because of event C, event D leads to E. If event C had not happened, then events D and E could not have happened either. Alternatively, the course of human events would have evolved in another way, into another chain of events, which could be equally well explained in hindsight with a different narrative. This might be interpreted to mean that history is *unpredictable but not unexplainable*, and in this way, a grade for history could be placed in Fig. 1 not far from the grade for war. The reductionist methodology of physics, through which one obtains detailed prediction followed by experimental verification, is impossible in the social sciences. But we also know that many great domains of the natural sciences are successfully studied with the tools of the science of history. Modern biology sees itself as a deeply historical science. Storytelling is a useful scientific tool where a chain of events is mathematically noncomputable and experiments are irrelevant, since nothing is reproducible. There is nothing wrong with this way of doing science, in which the goal is an accurate description and explanation of specific events.

The reason for the unpredictability in the so-called soft sciences has been attributed to the pervasiveness of contingency, usually defined as those unpredictable but always possible occurrences. Contingency, the reason for the ifs in all spoken languages, gives the social realm that lacework of historical filigree—those wonderful or tragic details that could easily have been otherwise, but were not. Without contingency, life would be extremely boring. The question arising then in this context is: What are the underlying properties of history and biology that make them sensitive to minor accidental events? The emerging theory of complexity is shedding some light on the underlying nature of the dynamics that leads to the overwhelming interdependence of events in life and evolution.

Some critics maintain that the theory of complexity, mostly pervaded by the physicists' search for reductionist explanations, is insufficient, since it does not account for this potential for variability. At most, the theory can explain why there is variability, and why some typical patterns emerge, but not the particular outcomes of a given complex system. That is a biased view of science, common to economists and ecologists, and even to many biologists: that of looking excessively at the details and overlooking possibly beautiful and deep natural laws. Failure in predicting details does not preclude the existence of laws of emergent order, which certainly will someday be reconciled with random mutations and causative selections, and even ultimately with the contingency of life itself. Alternatively, we can say that the processes we propose to analyze might be unpredictable in the short run but tractable in the long term.

It is clear that contingency and variability preclude the possibility that all detailed observations can be condensed in a small number of mathematical equations, but on the other hand, physics has shown how we can build theories of complex systems that are insensitive to details, as is the case of statistical mechanics, that give us the clearest example of the use of statistically averaged properties as compact descriptors of complex systems. Why not look in the same way at large-scale and long-term transformations in social systems such as those found in human history? Exploring patterns and discovering the existence of general laws underlying collective human behavior could lie at the center of a hope to build a deep theory of social order. Science is presently on the way to demonstrating that core phenomena of the deepest importance do not depend on the all details and can be caught through lawful descriptions. Let us try to be reductionist and statistical in looking at history and social evolution and avoid the methodology used in much of evolutionary biology, excessively based on anecdotal evidence for the various mechanisms at work. We tend to agree with Bak (Ref. [3], p. 10) when he argues that "anecdotal evidence carries weight only if enough of it can be gathered to form a statistical statement, for by concentrating on an accurate description of details, we risk losing perspective."

The social system of the human species (for short, the *world system*, comprising the sum of its economic, political, social, and cultural elements) is a complex adaptive system, hence a nonequilibrium system, and there are good grounds for thinking that much of the pattern and order observed in its evolutionary unfolding is a consequence of simple laws underlying complexity (we might use, for this phenomenon of complexity ruled by simple rules, the term "simplexity," defined by Cohen and Stewart (Ref. [4], p. 411ff) as the "emergence of large-scale simplicities as direct consequence of rules"). That order is robust and emergent and must be seen as a collective crystallization of spontaneous structure, arising without regard for the details of the operation of the networks of interacting individuals. If such order and robustness do exist, then deep and general laws must underlie the emergence of life and the coevolutionary unfolding of social arrangements of the human species.

Modern science has reshaped our view of nature. Now we know that order may reflect two types of structures: low-energy equilibrium forms (fixed structures) and nonequilibrium, dissipative structures, which maintain order by discharging entropy to the surroundings. Two very important difficulties arise in respect of nonequilibrium systems: chaos theory demonstrates that very small changes in initial conditions can lead to unpredictable future behavior of such systems, and the theory of computation (Gödel's theorem) seems to imply that nonequilibrium systems can be thought of as computers carrying out algorithms (i.e., as devices that behave in a way that is their own shortest description). For a vast class of such phenomena, no compact, law-like descriptions of their behavior can be obtained—the shortest way to predict what these systems will do, or will be, is just to watch them. Biological and social systems are real nonequilibrium systems and it is conceivable that they behave in ways that are their own shortest description.

But our concern here is that both these limitations, be it the unpredictability of chaotic systems or Gödel's theorem constraining our ability to axiomatize the world, are limitations only on the degree to which we can construct a descriptive law to every phenomenon, and do not preclude the possibility of finding general laws governing the unpredictable flow of social events. And yet, even if it is true that coevolutionary social processes are subject to such unpredictability, it does not follow that we may not find a general description of the processes themselves.

An algorithm, seen as a set of instructions (a set of—mostly mathematical—procedures to generate the answer to a given problem in any circumstances), is itself its own shortest description. In the jargon of mathematics, it is said to be *incompressible*, for it is the shortest (compressed) description of a phenomenon. The very purpose of a theory is to provide such a compressed account of a phenomenon—a law or equation instead of a table of data, or a narrative description of an unfolding. As argued above, social phenomena are the output of real nonequilibrium systems and it is conceivable that they behave in ways that are their own shortest description. There is no way of expressing contingency mathematically; all that we can say is that we are dealing with uncomputable or incompressible processes. That is also the case with social processes, both of the past (history) and of the future (prediction).

The present paper builds upon the expectation that by looking at the human species as a whole, we can uncover some general features and common patterns that are insensitive to details and indicative of a robust order. Self-organized structures—including the world system, leading industrial sectors, and world powers—emerge, wear out, and vanish, suggesting also the presence of recurrent behavior. We think of world history as a social process marked by a series of transitions that embody important innovations and exhibit significant patterns both of regularity and chaos, as if poised at the critical boundary on the edge of order and chaos. That process is *world system evolution*, and it is capable of being projected into the future.

3. Analyzing social evolution

We proceed, then, from the premise that the human species, viewed as the world population, constitutes not just a biological ensemble but is also sustaining a complex social system. It is a complex social system because it is composed of a myriad of interdependent behavioral units, which interact in such a way as to give rise to collective behaviors on various scales up to that of the entire system. Such emergent behaviors cannot be inferred from the behavior of individuals alone and cannot be simply averaged, for a subjacent nonlinear dynamics is in action. Its formative process, exhibiting continuity over a lengthy time span, is *social evolution*, and that is why, at this point, we need to distinguish between *biological* and *social* evolution.

Evolutionary processes are often thought of as purely biological (i.e., concerning "descent with modifications" of organisms via genetic mechanisms). That is the problem that biologists have studied at least since Charles Darwin, so that today all of biology is pervaded by evolutionary theory and its implications. Biological evolution can now be mapped as extending over at least 3 1/2 billion years of the existence of life on Earth. Smith and Szathmary [5] depict evolution as a process depending on changes in the *information* that is passed between generations, and describe the seven 'major transitions' in the way that information is stored and transmitted, starting with the first replicating molecules and ending with the origin of language. They stress, in particular, the emergence of new levels of biological organization at each of these transitions.

We could go still further in this discussion, clarifying what could be a fuzzy difference between social and cultural evolution. Here we have the contrast between *society* and *culture*: *society* that is made up of social organizations and institutions, and *culture* that is made up of the human patrimony of knowledge and experience, some of it embodied in memory, some in artifacts, and accumulated over many generations. This patrimony is the ensemble of values, customs, and technologies that played and continue to play an essential role in the *evolution of our behavior* and, in this sense, culture serves as a *mechanism of adaptation* (and then of *learning*; we will turn to this point later). The transmission of culture between generations involves symbolic communication and the use of stored information. We leave open the question of *cultural evolution*, for this demands separate and sustained attention. Gould [6], for one, has argued in the last chapter of his 1996 book, *Full House*, that culture does not properly evolve, but only changes and accumulates. Alternately, cultural evolution might be seen as the process that increases and/or revises and reformulates the total information stored in the social organization of the human species, possibly in a manner that is self-similar to social evolution.

All this is to say that evolution can also be thought of as the formative process of social organization, and culture as an instrument of social adaptation. Social organization evolves growing in complexity through the mechanisms of mutation (innovation), cooperation, selection pressures, and inheritance through *social and cultural transmission* (learning involves both social organization, e.g., schools, and also the cultural elements that are being transmitted). As a thought experiment, consider the state of the social organization of the human species some six millennia ago. By all accounts, it had no cities, no states, no armies, and no school systems: it was less complex then what we find today. The population of the entire earth might not have exceeded 5–10 million. That time also saw just the tentative beginnings of writing, another classical hallmark of universal civilization. By contrast, world population in the year 2000 was some two to three orders of magnitude greater, and over one half of it now live in cities where many may experience information overload. World history (as distinct from prehistory) might therefore be thought of as the evolutionary trajectory, that, since the fourth millennium BC, has taken mankind through *three major transitions*, toward what we now sense to be an increasingly complex organization of society. These major transitions are those to *urban civilization*, the *ancient-to-classical* transition, and the *classical-to-modern transition*. A finer-grained account of that trajectory would, of course, also discern other, less portentous but equally salient transitions.

Returning then to our starting point, what does, indeed, distinguish biological from social evolution? Some clarification is needed because humans, and the human species, are subject to both types of evolution. The human genome and the nature of human societies are both products of evolutionary processes. As organisms, hominids have been changing for the past maybe 4–6 million years, having evolved from mammals with a lineage extending for several dozen million years. But those changes have affected not just their genetic make-up and physical characteristics, such as the size of the brain, but also behavioral characteristics, such as bipedalism, or the use of fire, which in turn led to new social forms such as family organization. By focusing on what we know as *world history*, we single out for attention those more recent processes of social evolution that might be thought of as initiating the possibility of a common organization for the whole human species, and maintaining that project over the extended period of several millennia. We use the term *social evolution* in an inclusive sense, to comprise also economic, political, and culture-building processes.

Before going to the specifics of the distinction between biological and social evolution, it is worth making some observations:

- The social system of humanity undergoes change according to general principles of evolution [‘Universal Darwinism,’ cf. Plotkin (Ref. [47], Chap. 3)], but the “units of selection” are not genes but social structures at several levels of species organization (see also Section 5);
- There are changes that are equivalent to mutations, like inventions and innovations, but they are not as random as biological mutations because they may exhibit directionality. On the other hand, this directionality might not be as well defined as one might suppose;
- There is also a strong random component at the beginning of an innovative process. That is, given a fundamental innovation (easiest to see in the case of new technology: think of cars, airplanes, or computers), it appears to be common to find a wide range of dramatic early experimentation with radically different forms, which branch further and then settle down to a few dominant lineages. Kauffman (Ref. [2], p. 201ff) holds that qualitative features of technological evolution resemble rather strikingly the Cambrian explosion: branching radiation that created diverse forms, bushy at the base; followed by a dwindling rate of branching, and extinction, with only a few final, major alternative forms remaining.

With these considerations at hand, let us sum up the principal differences between biological and social evolution, whose main aspects are resumed in Table 1.

Social evolution operates then by mechanisms that can validate a general and driven trend toward increasingly complex social structures, very different from the minor and mainly passive trend that Darwinian processes permit in the biological realm in a comparable time frame. Biological evolution is too slow to keep up with changes in society. This is the most striking aspect resulting from the comparison between social and biological evolution, a characteristic that is a direct consequence of the *learning-related* mechanisms found in cultural transmission. Yet it is worth mentioning that among the different routes (vertical and horizontal) observed above, it is the slower one (vertical) that times the social evolutionary process. That is to say that the generational turnover is the pacemaker of change in the social realm.

Granted these differences and given the magnitude of such changes in world history over this (in cosmic terms) comparatively brief period, it is no wonder that the question of a *social evolutionary explanation* did suggest itself as soon as human consciousness emerged, in the 19th century, from the intellectual confinement of traditional time horizons, and when natural scientists paved the way for an understanding of biological evolution. That is, the question before us—Does world history describe a social evolutionary process?—is not really new, but in fact an "old, 19th century question."

Important thinkers launched into such explanations, and propounded schemes of *stages of human history*. Auguste Comte and Herbert Spencer both argued for social evolution even before Charles Darwin launched his own conceptions. Karl Marx and Friedrich Engels produced a schema of world historical transitions, whereby mankind moved from primitive communism, slave system, and feudalism, through capitalism, to socialism in a way that resounded strongly through large stretches of the 20th century. Yet such overly grand intellectual constructions also gradually fell out of fashion. By the mid-20th century, the term *social evolution* came to denote the evolution of particular societies (as in "specific" evolution), and attempts to model "general" evolution all but disappeared. Yet the problem of evolutionary explanation remains a live one because the question of "how the human species came to self-organize" has legs (as journalists say of a story), will not go away, and merits continued attention. We believe that with the aid of appropriate conceptual and technical equipment, it can be decoded and represented.

Is world history no more than the record of "what actually happened" to humans in the past five millennia? Of course not. As the human species constitutes a complex system, with a propensity to evolve toward self-organization and higher complexity (i.e., toward a *world system*), think of it over time as a series of transitions embodying significant innovations. Here are some examples of *major transitions*. One, mentioned earlier, is the transition to what

Table 1
Biological and social evolution compared

Characteristics	Biological evolution	Social evolution
(1) Time horizon	Longer (billions of years)	Shorter (millions of years; few thousands in the present analysis)
(2) Focus of inquiry	Interspecies	Intraspecies (principally human)
(3) Topology	No amalgamation	Amalgamation, anastomosis
(4) Principal questions	Origin of species, tree of life	(Human) social change
(5) Information transfer		
Mode	Genetic (Mendelian)	Cultural (learning—Lamarckian)
Rapidity	Slow	Very fast
Route	Vertical (parental only)	Vertical (parental and non parental), horizontal
(6) Trend (toward complexity)	Random (passive trend)	Directed + random (active trend)

Notes to Table 1:

(1) The time horizon of biological evolution is unimaginably long, extending over billions of years. In that time, innumerable numbers of species have had the time and opportunity to have come and be gone. The social evolution that we propose to analyze concerns, by contrast, no more than some 5000 years, an obviously shorter time span but also one allowing for sharper definition. We call it shorter because it is dwarfed by the sweep of biological processes, even though it is still impressive by the standards of the social sciences that tend to concentrate on the immediate and the contemporary.

(2) Biological evolution refers to developmental patterns in what is probably some millions of surviving species, thought to be only a small fraction of all species that have ever existed. In other words, its empirical domain is immensely large. Social evolution could refer, in principle, to the social organization of a variety of social species (such as ants), but the knowledge of that domain is quite limited, and its principal focus is the trajectory of social change in the course of human history. One important consequence of it is that biological evolution primarily concerns interspecies interactions (as in the "struggle for survival"), while social evolution deals first and foremost with intraspecies interactions, that is, with relations among members of the same species, hence also with greater opportunities for cooperation. That why it privileges forms of social cooperation such as cities, nations, trading systems, information networks, alliances, and international institutions, just as much as it pays attention to competitive arrangements involved in selection mechanisms such as wars, markets, or elections.

(3) Closely related to this last point is the aspect of topology (relations among objects under transformation). As stressed by Gould (Ref. [6], p. 221), once a species becomes separate from an ancestral line, it remains distinct. Species do not amalgamate or join with others. Natural evolution is a process of constant separation and differentiation. On the other hand, learning, as already mentioned, is the mode of information transmission in social evolution, and therefore the mechanism of social adaptation can show amalgamation (and anastomosis or lineage crossing)—an unknown mechanism in Darwinian evolution but that might more readily be expected of members of a species.

(4) The master questions of biological evolution, as formulated by Charles Darwin and not really changed since, concern the origin of the species and the morphology of the tree of life. The mechanisms are genetic and environmental variability, and natural selection as manifested in pressures of the environment and interspecies competition. As already noted, social evolution concerns social organization and, in our project, changes in the institutions, programs, and strategies that have composed the interrelationships of the human species in the past five millennia.

(5) All evolutions involve the transfer of information between generations. In biological evolution, the principal form of such transfer is genetic (Mendelian). DNA is the code of life for all organisms. In social evolution, the main mechanisms of transmission are social and cultural, as in child training (involving the family), imitation (involving social interaction), or education and science (involving schools and the professions), and necessitates symbolic communication. Learning is the principal motor of social evolution. But while in genetic inheritance the information transfer is largely vertical, that is, from one generation to the next (and basically parental, that is, between genetically related individuals), in cultural transmission, the transfer of information is not only from parents to children, but can take place between unrelated individuals (nonparental) and across communities. As noted by Cavalli-Sforza (Ref. [7], p. 179ff), added to the vertical route of information transfer, we find a horizontal route that is among individuals of the same generation and not influenced by any kind of relationship or age difference between transmitter and transmittee. Both routes, vertical and horizontal, and the demotion of the parental restriction of information transfer between generations give to cultural transmission the diffusion characteristic of collective learning, responsible for the explosive rapidity and cumulative directionality characteristic of social evolution. The way information is transmitted makes social evolution more Lamarckian than Darwinian, such that the inheritance of acquired behavioral traits becomes a reality.

(6) Biological evolution has sometimes been equated with the increase of complexity of evolving organisms, seen as a consequence of Darwinian natural selection (blind selection). This constitutes, accordingly to Gould [6], a passive trend towards greater complexity. Social evolution may also be equated with similar Darwinian-like mechanisms leading to increasing complexity, but the addition of Lamarckian-type characteristics just noted gives to it a more active trend for directionality and speed.

we classically call civilization: over five millennia ago, to urban living (civilization stems from the same root as city), and to writing, hence more reliably storing and transmitting culture. If the ancient era of world system evolution was marked by such laying of the foundations of cultural reproduction, then the classical era saw a population surge based on agricultural expansion throughout Eurasia, and the rise of the historical religions as bases of social cooperation over wide areas. The modern era has produced the system of nation-states, and is creating the beginnings of global organization. In world politics, we have the evolution of the role of global leadership, including that in the 20th century, the transition from British to United States global leadership. In the global economy, we have recently observed the onset of the information age.

World history, viewed as *world system evolution*, covers only a minute portion of the timeline occupied by biological evolution, and does it in a similar vein, but at a higher resolution, much higher speed, and can be described with more accurate data, and major transitions can be identified with greater confidence. As it seems unlikely that major social transitions can be purely random and innovations just manna from heaven, we postulate that they are attributable to a cascade of social evolutionary processes at several levels of organization. The ultimate role played by learning in the unfolding of this cascade will be analyzed in Section 4, followed then by the description and discussion of the cascade itself in the following sections.

4. Learning processes and the turnover of generations

We have now established how social evolution differs from biological evolution. We go on discussing what makes social evolution the distinctive process it is, namely *learning*, and, secondly, the *learning rate*, which is the rate at which collective learning occurs in the context of generational turnover.

4.1. Learning-driven evolution

Learning processes are central to social evolution, and we shall review a number of studies bearing on that topic, in three parts: (1) how learning affects biological evolution; (2) how learning affects populations; and (3) how the concept of learning organizes the analysis of world social evolutionary processes.

A fundamental question challenging evolutionary theorists for more than a century has been how the blind mechanism of selection acting on random mutations can give rise to the immense variety of fascinating and complex structures of living organisms. The long and fierce battle opposing geneticists and naturalists has gone strongly in favor of the former, and the attractive (Lamarckian) idea that adaptations acquired during an organism's lifetime, by learning or in other ways, are passed to its offspring has been relegated to the attic of failed scientific theories.

However, over the last 25 years, and to the delight of minds never satisfied with the idea that in biological evolution nothing more is involved than the sorting out of random mutations by the natural selective filter, new insights into this discussion have been achieved both by evolutionary biologists working at the molecular level and by others working in computational simulations with genetic and adaptive algorithms. Something more is involved and is closely related to the nongenetic mechanism of adaptation via information transfer, and that is *learning*.

The idea is not new among biologists, and goes back to the end of the 19th century with Baldwin [8] and clarifies the *indirect* effects that the acquired experiences of an adaptive organism can have on its species' genetic endowment. These are not the modifications of the phenotype acquired over the course of a lifetime becoming incorporated into the genotype, which would get stuck on the impossible mechanism of reverse transcription. We are speaking about the hypothesis that individuals who vary genetically in their capacity to learn (or to adapt developmentally; Ref. [9]) will leave most descendants because they will have the greater capacity to adapt. That is why the genes responsible for the variability will increase in frequency. In a fixed environment, when the most important things to learn remain fixed, this *plasticity of learning* leads, via natural selection, to the genetic fixation of a character. Waddington [10], writing in the 1940s, referred to this as the canalization of development via genetic assimilation.

In a short and insightful paper that appeared in 1987, Hinton and Nowlan [11] developed a simple computational model based on an extended version of genetic algorithm to demonstrate the magnitude of what was now being called the 'Baldwin effect.' Their simulation, suggesting 'how learning can guide evolution,' shows straightforwardly that creatures that are genetically predisposed to learn (in their oversimplified mode) by guessing the solution to a given environmental obstacle, by virtue of having correct settings on all the hardwired alleles, are on average more fit than those who cannot guess the solution. Moreover, their model demonstrated that, without 'learnable alleles,' pure evolutionary search is completely blind and exceedingly slow.

In years that followed, their paper ignited a series of other studies seeking to add more details and improvements in the evolutionary algorithm in order to get a better understanding of the interactions between *learning and evolution*. Biologists and computer scientists [12–15] began to investigate how *culture* (viewed as a process that permits the learning of prior generations to have more direct effects on the learning of subsequent generations) further promotes and speeds evolution.

The Berkeley biochemist, Wilson [12], who in the 1960s introduced the concept of a 'molecular clock' (based on genetic mutations that accumulate since they parted from a common ancestor) in evolutionary biology, predicted in 1985 that the presence of cultural factors may create a selective pressure for the ability to learn itself. Based on his early results on quantitative molecular evolution, he developed the concept of a 'cultural drive,' through which the time required for a population to fix a mutation that complements a new behavior is shorter if the new behavior spreads quickly not only to offspring (vertically) but also to other members of the population (horizontally). His example of this cultural drive was the rise of agriculture that imposed new selection pressures, leading to swift genetic changes in human populations. He then considered the well-known example [13] of the introduction of milk sugar (lactose) into the diet of adults as the result of the invention and social propagation of dairy farming (pastoralism). In the relatively short period of ~5000 years, genes conferring the ability to absorb lactose reached a level of 90% in populations dependent heavily on dairy farming, while, in contrast, the level of these genes is virtually zero in human populations that do not drink milk and in all other mammalian species tested. Analyzing the same phenomenon, the correlation of a genetic variation and a cultural trait, Feldman, Cavalli-Sforza, and Zhivotovsky [13] described it as 'gene–culture coevolution.'

Yet other studies explored the impact of learning on social evolution. Belew [14] agrees with Hinton and Nowlan that 'how learning can guide evolution' is critically important because it is concerned with how the results of one system of adaptive search (individuals' learning) can be capitalized by another system (the evolution of a population) and states that, in the case of the human species, it does seem as if the learning accomplished over a lifetime has become coupled with the process of evolution. To demonstrate this, Belew added to the Hinton and Nowlan algorithm a third adaptive system—*culture*—between the learning of individuals and the evolution of populations, and argued that the addition of 'cultural artifacts' helps mediate between the regularities found by evolution (over many generations) and individual learning (within a single lifetime). His simulations show clearly that *culture*, as an interposed adaptive system, allows the hard-won knowledge learned by individuals to improve the evolutionary fitness of other conspecifics (members of the same species) via nongenetic informational pathways. Important to our purposes is the *fractal (self-similar) structure* arising from his simulations with the three adaptive systems (individual learning, culture, and evolution) when tracking a constantly changing environment—lower-frequency components being tracked by evolution, intermediate frequencies by culture, and the highest frequencies being tracked by learning. This resembles quite closely what, in Section 5, we call the *cybernetic hierarchy* (systems higher in the order are high in information and low in energy—the case here for evolution of a population—and systems lower in the order are low in information and high in energy—the case here for individual learning).

Ackley and Littman [15] present a more highly elaborated algorithm: *evolutionary reinforced learning* (ERL). They explored the interactions between learning and evolution using environments with no explicit evolutionary fitness functions and asynchronous agents (that reproduce only under preimposed conditions), and found that learning and evolution together were more successful than either alone in producing adaptive populations that survive to the end of the simulations. Hutchins and Hazlehurst [16] proceeded in a similar way as Feldman et al. [13], embedding their agent-based simulation in a framework positing culture as a process that permits the learning of previous generations to affect the learning of subsequent generations, but their modeling was more fundamentally semiotic, considering the agents of a cultural world as having their internal structure shaped by two kinds of structures in the environment—natural and artifactual (physically implemented in the environment). Again their results converged to the view that learning guides evolution wherein culture further enhances the ability to learn.

It is worth pointing out that some of the abovementioned studies and simulation models [12–14,16] use the concept of a 'dual inheritance' transmission mechanism, encompassing both paths, genetic and nongenetic, through which conspecifics pass adaptively useful information. Feldman et al. [13] outline a formal theory of gene–culture coevolution and show how a *purely cultural transmission system* (that is involved in the world system processes we propose to analyze) may arise from an initial state of purely genetic cotransmission going through a gene–cultural cotransmission process.

Paramount in importance for the discussion following in Section 4.2 is the finding, both in molecular biology [17] and agent-based modeling [18], of a bias for adaptation (and then *learning*) at the boundary between order and disorder, most commonly referred to as the edge of chaos. RNA molecules and viruses are the simplest known entities showing adaptation mechanisms of their structures to changes in the environment. Schuster [17], studying mutation rates in RNA molecules, reports that these entities 'tune' the error rate in the replication mechanism in order to meet environmental changes, maintaining an existence at a threshold value above which heredity breaks down and the species disappear. The key to their survival is through maintaining the error rate close to that threshold value. He concludes then that such an adaptation, in a rapidly changing environment, drives populations toward the error thresholds that are tantamount to the border between order and disorder, and recalls the catch phrase, 'life is evolution at the edge of disorder.'

In a similar vein, Hübler and Pines [18], describing computer simulations of adaptive predictive agents who respond to evolving chaotic environments, report a correlation among optimal learning rate (defined by them as 'the minimum time required to extract a completely new model from the environmental dynamics'), optimal complexity, and emergent behavior. Their work, too, lends support for the concept of optimal coadaptation near the edge of chaos because the boundary between order and disorder is 'particularly conducive to learning and innovation.'

Lastly, and in the context of the social sciences, the concept of learning has acquired an important role in the study of worldwide evolutionary processes. In 1987, Modelski (Ref. [19], Chap. 5) proposed that the rise and decline of world powers (known also as the long cycle, the constitutive process of world politics) are best understood as a *learning process*, and in 1991 [20] described it as "evolutionary learning." In 1996, he presented the evolution of global politics as a complex system situated at the border between order and chaos (Ref. [21], pp. 331–332), countering conventional thinking that regards it as destined either toward a balance-of-power (ordered) or an anarchical (chaotic) state. Modelski and Thompson [22] showed, too, how, over the last millennium, global politics has coevolved with the global economy and the long waves (K-waves) of industrial, commercial, and technical innovation that animated it. Modelski and Perry [23] argued that, in the perspective of centuries, democratization is the process by which the human species is learning how to cooperate, and demonstrated that the rise in the proportion of the world's population living in democracies (now exceeding 50%) is best described as a logistic process of the diffusion of a strategic social innovation.

On an even broader canvas, Modelski sees "world system evolution"—how the social organization of the human species has changed over the past five millennia—as "the story of humans learning to be human: learning to live with each other, and doing so... in a global setting" (Ref. [24], pp. 24–30). World system evolution is made up of an array, or cascade, of more specialized processes: *economic*, *political*, *social*, and *culture-creating*.

All the processes that constitute world system are self-similar, and exhibit a fractal structure; they are self-similar in that each in its own scale embodies a social learning algorithm. The empirical data supporting this argument will be reported later in this paper.

4.2. The pacemaker of evolutionary change

Learning is a key concept and often used in many different meanings and contexts. In the realm of evolutionary biology, for instance, it is usually defined in accordance with its *purpose*, as a process of changing the behavioral mechanism of an organism in order to promote its survival. Yet, in the same context, it may be defined in keeping with the involved *mechanism*, as a process of information storage and retrieval to meet environmental requirements. Behavioral biologists and psychologists prefer to speak of *taxonomy of learning* [25], referring to the hierarchy of accretion, tuning, and restructuring (*accretion* involving the collection of new information by means of new schemata, *tuning* being the modification of such schemata, and *restructuring* calling for radical change in the structure of internal representation).

In the language of algorithms for computer simulations, we can find *workable* definitions of learning, starting with the simplest trial-and-error or guessing of the solution, as used for instance in the simple models of Hinton and Nowlan [11] and Belew [14]. More elaborated modeling [18] defines learning as a combination of exploration of the environment and improvement of performance through *adaptive change*. Here we face then a definition of learning as a mechanism of adaptation (itself a hard to define concept), the latter defined as the capacity for modification of goal-oriented individual or collective behavior in response to changes in the environment [18], through the mechanisms of *learning* and *innovation*.

Such working definitions of learning may appear simple to psychologists and social scientists but have the advantage of being quite general, and they allow us to discern simple forms of learning in more complex systems, where learning is a fuzzy contextual concept. For the purposes of the present paper, we have to move in this ‘contextuality’ of the concept of learning, for we are analyzing a very broad (in time, space, and mind) human social process with the looking glasses of methods from evolutionary biology, computer sciences, and physics, as well as the social sciences.

Keeping then in mind this conceptual contextuality and its methodological generality, we can infer from the analysis so far the following three main aspects of learning, which will be useful later in this analysis, in a broader context:

1. the role of learning (even if modeled as its simplest form) as an important complement to Darwinian models of natural selection;
2. the function of learning as a powerful mechanism for the transmission of information responsible for the explosive rapidity and directionality observed in social evolution; and
3. the bias for learning/adaptation at the edge of order/disorder.

Regarding this third point, Devezas and Corredine [26] proposed recently a Generational Learning Model that may help to shed some light on it, looking at the collective behavior of human beings. In this model, they relate quantitatively two parameters (apparently unrelated) of cultural transmission: the *rate of collective learning* and the *generational turnover.*

Different authors [27–29] have shown how the cumulative learning following the pattern of *logistic curves* can be found in individual learning or in a group of people following a common goal, be that of manufacturing and selling products, discovering natural elements, or pursuing exploration. The concept of learning curves appears in the technical literature in at least two apparently different utilizations [26]. One, regarding individual learning, is the classical example of an infant's vocabulary (explored by Marchetti [27] and Modis [28]), and a second one concerns the idea of economies of scale, by which the performance and productivity of technologies typically increase as individuals and organizations gain experience with them ('learning by doing'). In the first case, the process is adequately described by the well-known Verhulst differential equation, whose integral is the logistic or S-shaped curve, and in the second by a power law function where unit costs depend on cumulative experience (cost reductions for each doubling of cumulative output). But as Modis [28] has pointed out, both cases are mathematically equivalent: industrial learning curves (power law) are S-shaped learning curves 'in disguise'—the fundamental process involved is *learning*—and the universality of the learning curve pattern is striking; being not restricted to individuals, it is also encountered with a group of people, be they a company, a country, or humanity as a whole.

The model advanced by Devezas and Corredine [26] aimed basically to explain the general aspects and timing (duration) of socioeconomic long waves (K-waves). In this model, the technoeconomic system is conceived as an *evolving learning dissipative structure* consisting of two successive logistic structural cycles, an innovation cycle and a consolidation cycle, and applying considerations from population dynamics, chaos theory, and logistic growth dynamics, it is proposed that two kinds of biological constraints impose the rhythm of collective human behavior—generational and cognitive. The generational rhythm consists of biologically based rhythms; the cognitive rhythm consists of a limiting learning growth rate, manifested in the alternating sequence of two succeeding generational learning phases, a new knowledge phase and a consolidation phase. Then the syncopated beats of succeeding effective generational waves and the dynamics of learning processes determine the long wave behavior of socioeconomic growth and development.

One of the fundamentals of the Generational Learning Model consists of the important role played by the *learning rate* as a codeterminant of the timing of a K-wave. Analyzing the mathematical relationship between the differential (continuous) and discrete logistic equations, the authors demonstrated that the rate parameter δ of the logistic equation and the gain-determining constant k of the recursive discrete logistic equation are closely related through the expression $k=\delta t_G$ (for details of the mathematical demonstration, see Ref. [26]). In this equation, δ (the *diffusion learning rate*) expresses the cognitive biological determinant, the rate at which humankind learns to deal with radical innovations, and t_G, mathematically known as the characteristic time of the logistic function, expresses the effective generational determinant, corresponding to the time span of the generational turnover.

The relationship $k=\delta t_G$ represents the link between the differential and the discrete logistic equations, and is an *intrinsic property* of the logistic growth dynamics. Considering then that the diffusion of basic technological innovations, characterizing each new technoeconomic structure (that of a K-wave), is a *collective learning process* following the path of simple logistic curves, we must look at the possible values of k to find a possible explanation for the dynamics of the phenomenon. In the light of deterministic chaos theory, we know that for $k<1$, there is no growth; for $1<k<3$, a nonzero equilibrium value is achieved; and when $3<k<4$, we have the onset of bifurcations, the logistic function oscillates randomly, but in a bounded limit-cycle regime. As k becomes larger and approaches 4, we get true chaos, and the solutions of the logistic equation lose their reality. Then, the range $1<k<3$ means endurance and stable equilibrium, and $k>4$ means breakdown, uncontrolled behavior. The range $3<k<4$ means *chaotic behavior*, that is, the behavior appears to be random, but is, despite its bizarre appearance, *deterministic*, which means that its past and future courses are constrained by its dynamic nonlinear properties. That is why sustainable growth and evolution requires $3<\delta t_G<4$, granting the necessary oscillations or chaotic behavior. The system is said to be chaotic within predicable boundaries. Social systems are complex adaptive systems exhibiting manifold stability, and $[\delta, t_G]$ are the *biological* control parameters of the K-wave behavior, determining the basic rate of change of the whole process acting, in other words as the *pacemaker of social change*.

Using data on the growth of the Internet [30] and from the literature, mainly stemming from the studies of Cesare Marchetti, Arnulf Grübler, and other coworkers at the International Institute of Applied System Analysis, Devezas and Corredine point out that the typical values for the diffusion learning rate of basic innovations are 16–17%, corresponding to typical time spans of about 25–30 years for the spread of these radical innovations. This seems to imply that the social process of aggregate learning within a generation operates near the threshold limit between order and chaos. Specifically, they declare that, considering the typical duration of generational turnover (and that of the diffusion of leading technologies) of 25 years, the diffusion learning rate δ must be bigger than 12% ($\delta t_G>3$) to avoid paralyzing equilibrium, and must not exceed a typical threshold value of about 16% per year to avoid the breakdown of the system ($\delta t_G>4$), matching the "maximum sustainable growth rate" of about the same value as proposed by Danielmeyer [31].

Further insight on this issue and why things must unfold in this way was delivered in the other recent paper of Devezas and Corredine [32]. In it, the time evolution of a technoeconomic system is described discretely as a logistically growing number of "interactors" adopting an emerging set of basic social and technological innovations. By using the logistic function as the probabilistic distribution of individuals exchanging and processing information in a finite niche of available information, they demonstrate that the *rate of information entropy change* (Kolmogorov entropy) exhibits a "wavy" aspect evidenced by a four-phased behavior denoting the unfolding of a complete K-wave. Following the approach developed in their first paper, the entire process is divided into two cycles, an innovation cycle and a consolidation cycle, and it is shown that the technoeconomic system exhibits a *limit-cycle behavior*, whose basic mechanism is the periodical deployment and filling of information in a "leeway" field of active information. The pace of the process, and hence the duration of the K-wave, is determined by the two biological control parameters already discussed: the cognitive (the collective learning rate), driving the rate of exchanging and processing information at the microlevel, and the generational, constraining the rate of transfer of knowledge (information integrated into a context) between successive generations at the macrolevel.

These authors deduced a time-dependent equation for the rate of information entropy production K in such logistic growing systems (for mathematical details, see Ref. [32]), whose behavior for different values of δ is depicted in Fig. 2.

As we can see in this graph, the parameter δ influences the amplitude of the rate of entropy change, amplifying or reducing it, in such a way that it shortens or stretches the length of the curve and displaces the point where the information entropy production changes signal. The region for $K>0$ corresponds to the innovation cycle of the technoeconomic long wave and may be divided into two phases, the first one with increasing entropy production (chaotic attractor) and a second one with decreasing entropy production (limit-cycle attractor), after which a threshold point is reached (corresponding to 32% of complete growth, where $K<0$ starts). This region with negative entropy production, corresponding to the consolidation cycle, may be also divided into two phases, a first one with continuing decrease in entropy production (limit-cycle attractor) and a second one that starts about 72% of complete growth, after which entropy production ceases to diminish and reverses direction toward a point attractor corresponding to the depletion of the growth process. The resultant of the whole process is a limit-cycle behavior with the important characteristic that the value of $\delta=0.16$ matches well the length of the generational turnover of about 25–30 years. This important property will be paramount for the interpretation of the cascade of social processes that will follow in Section 5.

As Cavalli-Sforza (Ref. [7], p. 176) once stated, evolution also results from the *accumulation of information*. From the findings and conceptions presented in this section,

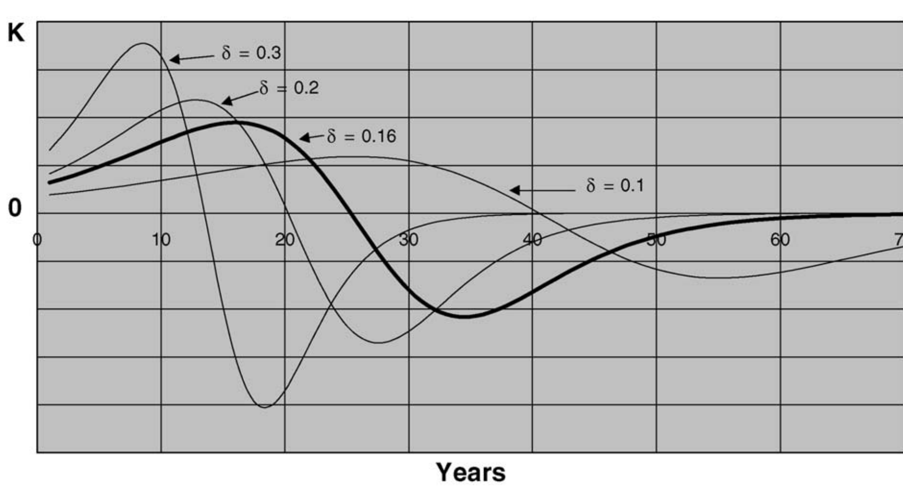

Fig. 2. Temporal unfolding of the rate of information entropy change (information entropy production) for different values of δ (the aggregate or diffusion learning rate) considering a technoeconomic system discretely as a logistically growing number of "interactors" adopting an emerging set of basic social and technological innovations (see Ref. [32] for details).

we see how learning, playing a fundamental role in evolutionary processes, is the key mechanism of the *dynamics of information* that promotes evolution itself. Langton [43], simulating living systems with Cellular Automata, has shown how the dynamics of information gains control over the dynamics of energy (that, as we know, determines the behavior of nonliving systems), demonstrating that information processing emerges spontaneously and comes to dominate the dynamics of a physical system in the vicinity of a second-order ('critical') phase transition. This 'critical' transition, which underlies the origin and evolution of life and intelligence on earth, corresponds to a phase transition between periodic and chaotic behavior, where a complex regime (without explicit rules) dominates. Explaining his findings, Langton suggests that living systems have learned to maintain themselves near the critical transition (the edge of chaos), developing the natural information-processing capacity inherent in this near-critical dynamics and taking advantage of it to further enhance their fitness.

The results of Devezas and Corredine [26,32] imply that such underlying near-critical dynamics endures in social evolution. In social systems, collective learning and adaptation to a new (innovative) environment are processes exhibiting a limit-cycle behavior that takes place in the complex transition regime between order and chaos, following the basic beat of the generational turnover.

5. Cascade of world evolutionary processes

Nineteenth-century conceptions saw social evolution as a singular, simple, and linear process moving through a number of stages. Better historical evidence and progress in the social sciences have made it clear that what we need is a more complex picture. Our own conception is that of a cascade of multilevel, differentiated, and nonlinear processes transporting the world system through a series of transitions. An outline of this conception may be

Table 2
Cascade of modern evolutionary processes

(1) Number of generations (g)	(2) Process period (years)	(3) Carrier	Processes		
			(4) Global–agent-based	(5) Global–institutional	(6) World–species-wide
1	30	Generational turnover			
2	60		K-wave		
4	120		Long cycle		
8	250		Democratization	Global economy	
16	500		Opinion making	Global politics	
32	1000			Global community	World economy
64	2000			Global system	Active zone
128	4000				World socialization
256	8000				World system

found in the study, "World System Evolution" [24]. Table 2 below presents it for the modern period, that is, the last millennium: it displays the processes that operate in today's world, and that have been at work in the past millennium. It includes both the fairly familiar, shorter-range ones, such as K-waves and long cycles, and also the less familiar, longer-range millennial sequences that, too, even while of millennial scope, steadily shape our social experience.

It is a model of the modern era because these are the processes that jointly shape the modern world. Even though the species-wide world processes (of column 6) are, of course, common to both the premodern and the modern eras, this is not a model of the ancient or classical eras that were smaller, simpler in scale, and whose structures were less differentiated. The modern world system is marked by the emergence of a *global* level of interactions—a level that might be best described as oceanic in character, and planetary in range, in distinction to the mostly regional scope of premodern systems (although we keep in mind, of course, the silk roads across Eurasia). That global level of interactions—whose agent-based processes are accounted for in column 4—is gradually devolving a set of institutions (e.g., free trade, international organizations, democratic movements, global media) whose evolution is recorded in processes named in column 5 (the underlying distinction here is among four differentiated levels of organization: global, regional, national, and local). The world system processes of column 6 are, by contrast, species-wide and, in that manner, envelop and summarize the social evolution of the world population. In the paragraphs that follow, we shall, in turn, review and comment upon the processes listed in these several columns.

The first three columns of Table 2 concern *generations*, and the process of generational turnover (which we have just reviewed in Section 4.2; see also Ref. [33]). Generational turnover may be measured by the time it takes for one generation to replace itself biologically. This generational process links biology with social evolution, and it is important, too, for sizing up the status of social evolutionary developments. This basic pulse or beat of generations lies at the basis of the entire array of evolutionary processes shown in Table 2. Generations (g) are the basic metric of all evolutionary processes and that is why the period of these processes is reckoned (in column 1) in terms of generations. Column 2 expresses the extension in years of the different processes considering a mean duration of 30 years for the generational turnover; these numbers for lines 4–9 were rounded for the sake of simplicity (see Ref. [26] and comments about this point in Section 7). The generational process therefore appears in column 3 as the carrier wave of the entire cascade. We know that it is, in itself, a basic learning process, and it carries the information for all the other evolutionary learning processes. We observe that the periods of all the other processes shown in that cascade are multiples of that unit of "generation."

In column 4 of Table 2, we encounter an array of four *global agent-based* evolutionary processes. These are the event sequences that we find at the grass roots level of great social movements. We might call them the microprocesses of the world picture and the micro-foundations of macroprocesses at the population level. They help us understand how seemingly abstract evolutionary developments actually happen: because they reflect and embody the ideas and interests of innovative agents in places "where the action is," and that is why we call these processes *agent-based*. What are the actions, programs, and strategies of which agents that account for large-scale and long-term phenomena described as technological breakthroughs, city- or nation-building, historical eras, or rise of world religions?

For the modern era, they concern agents that execute *innovative* programs, or policies that come to be increasingly global in scope. In *alliance* with other agents, their activities lead to the *selection* of some of these agents and activities and increase in their market share and/or dominance, and their *diffusion* in the relevant segment of the world system. Starting with the best known, we take note of Kondratieff waves, or *K-waves* (period of 60 years), that account for the rise of leading sectors in the global economy, such as automobiles and electricity in the onset of the 20th century, electronics in the middle of the 20th century, and the information industries later in that same century. For K-waves, the agents are innovators and entrepreneurs (such as Henry Ford or Bill Gates, together with their competitors) who lead usually newly founded firms and help diffuse their products often first in one national market, and then throughout the global economy. These are evolutionary processes because they involve mutation (innovation), cooperation (alliances), selection (by the market), and inheritance (the birth of new firms and changes in the global economy) (for a detailed analysis of K-waves and their causal relationship with the generational turnover, see Ref. [26]).

Moving along to global political system, we observe the *long cycle* as the learning process of the rise of world powers to a position of global leadership (a period of 120 years). This is a constitutive process of world politics (tracking what is known as "power transitions") that, via the institution of global leadership, shaped modern world politics from the 15th century onward by helping to resolve impending global problems. Portugal and the Dutch Republic were, successively, the early trial runs of this new form of political organization. After 1688, it was Britain that stepped onto the world stage under the leadership of William of Orange, the Dutch Stadholder who seized the British throne in a bold naval operation, but put in place an enduring constitutional system of parliamentary government. In the wars that ensued, and in alliance with the Dutch, Britain prevailed over the ambitions of Louis XIV of France, the Sun King, and in peace treaties of Utrecht (1713–1714) and, as the holder of the European power balance and "ruler of the waves", consolidated its assumption of the now rapidly maturing position of global leadership. Britain's world position was reconfirmed in 1815, at the end of the Napoleonic wars. At about 1940, within the framework of close cooperation led by Winston Churchill and Franklin D. Roosevelt, United States stepped into Britain's role, and clinched it by its success in leading the victorious coalition of World War II and by playing a key role in the organization of the peace that followed. Here again, we have an evolutionary process at work: *innovation* by certain nation-states and their leaders (creating a new role of global leadership, to defeat designs of continental domination), *cooperation* (in fashioning coalitions), *selection* (in past global wars), and *inheritance* (new political orders).

For the process of *democratization* at the global level (a period of 250 years), viewed as the worldwide spread of democracy, the agents are charismatic and popular leaders, social and political activists, parties, social movements, and their programs and broader ideologies, together with their opponents, nondemocratic regimes, and vested interests. The contemporary growth of democracy, forming as world process around an Anglo-American nucleus, might be dated from the second half of the 19th century, and it still has a way to go. The set of social practices and decision rules that goes by that name goes, of course, back at least to classical Greece, but it is only in the modern era that its rules and practices are revived (i.e., in the Renaissance), sustained by the practice of parliaments, contested by absolutist regimes, but gaining close association with the world powers. It is an evolutionary process because it carries forward a strategic social innovation (democratic society of equals under law) as a substitute for autocratic or totalitarian regimes, involves associative and cooperative activities (such as parties), competes for selection on national and global levels (e.g., in electoral campaigns), and diffuses worldwide by virtue of superior performance.

We have yet to explore more thoroughly the role of *opinion making* but can hardly deny the systemic influence of the media, the educational systems, and the world of knowledge more generally, the stories they carry, and the audiences they address, and the cultural climate that they form. *Opinion making* on a global scale is a product of the modern world, and it shapes our common conceptions of global problems. It is an essential component of evolutionary processes because it supplies the variety and innovative ideas that activate these processes; we conjecture that the formation of such opinion is itself an evolutionary process, subject to the competition of images and ideas, in a number of fields, including popular culture, and science and learning.

We note though that the agents just described (i.e., innovators of several kinds, including entrepreneurs, charismatic leaders, and political reformers, and/or seminal thinkers) may be observed principally in the modern system, that over the last millennium. Their identity and the processes they might have activated in the ancient and classical eras of the world system remain to be investigated.

Global institutional processes (shown in column 5 of Table 2) might be thought of as intermediary between agent-based and species-wide processes. They last longer than those of agents, but shorter than population-based movements. It is as though they represent the institutions that monitor the progress of agents, and program their developments. One period of global institutional change in the *global economy* (some 250 years) might also be expressed as comprising four K-waves that nest within it. The current period of that process might be called that of the "information economy" that took off with the telephone and electric power (after 1850), moved to radio and electronics (after 1914), and, since 1975, has attained the decisive stage of the computer and the Internet, already poised for worldwide diffusion (in turn, four phases of the *global economy* process might be thought of as nesting in one period of the *world economy* process; see discussion on this point, as well as on the analysis of the sequence of 19 K-waves, in Ref. [22]).

Let us now turn (next in the array of global institutional processes in Table 2, column 5) to *global politics*. We have just noted that, between about 1430 and 1850, the modern system experienced four *long cycles*: Portuguese, Dutch, British I, and British II. We propose that this four-cycle sequence makes up one four-phased period of the global political system. Analytically speaking, each of these long cycles constitutes one phase of a learning process whose product (an evolutionary adaptation) is a set of global institutions of which the central one is global leadership—as manifested in its mature form in the 19th and 20th centuries—that came to compose the core of world political organization, but should also be regarded (in a long perspective) as transitional forms of international management. From this perspective, the two British cycles were the third and fourth phases of the *global institutional* learning process (for a theoretical account of phases of these processes, see discussion ahead at the end of this section).

That is, we postulate, for the modern world system only—because in the ancient and classical systems, we find no global-level, worldwide arrangements—the operation of an array of global–institutional processes (in an ordered hierarchy) that is operating for the *global economy*, the *global political system*, the *global community* (on a democratic foundation), and the *global system*.

We now come to the sixth and last column of Table 2, where once again we find an array of four processes, the *processes of the world system* (species-wide). These are, in order of increasing temporal reach, the *world economy* process (a period of 1000 years), which builds structures of planetary production and exchange; the *active zone* process (a period of 2000 years), which tracks the movement of the world system's active zone (the locus of systemic innovation); *world socialization* (a period of 4000 years), which builds the humans' capacity for cooperation; and the *world system*, a process that envelops all them all (or within which the other three nest). Quite broadly speaking, these four processes might be described, respectively, as economic, political, social, and cultural. We observe, too, that the order in which they are listed is a determined one (in one direction, that of control): the cultural precedes the social, and the social precedes the political and the economic.

The *world system* process (postulated period of some 8000 years) might be thought of as the envelope of a cascade of species-shaping (or world population-shaping) processes. In the first place, it expresses the fact that the human species is programmed to proceed on a four-phased evolutionary journey, passing sequentially through the stages of a macrolearning process. The four phases of world system development constitute, in fact, the major eras of world history: generally known as *ancient*, *classical*, and *modern* (and presumptively, shall we say, *postmodern*). In the second place, it 'sits' atop an array of three other differentiated and specialized, social processes through which social evolution is in fact implemented. But is it evolutionary?

The *world system* is evolutionary because it exhibits *variety* in social organization, and in opportunities for, and expectations of, social change; various portions of its population even experience conditions conducive to *speciation*; second, the world's populations encounter abundant opportunities for cooperation and exchange, especially trade from its earliest times, and these opportunities for joint enterprise are the most important feature of intraspecies evolution (Section 3). It also experiences selective pressures, on the part of nature and of biology, and also from within the species. Finally, it has identity and continuity, and involves the nature and care of its human offspring. We postulate that the human species possesses a propensity for self-organization, and that the propensity leads toward improved coordination. In conditions of evolutionary potential, we would expect such propensity to work itself out, over time, in an orderly process. Such a project would be time-consuming and likely to be phased. We propose that the major eras of world history—*ancient*, *classical*, and *modern*—be interpreted as phases of the world system process, the first laying down the learning infrastructure, the second the social foundations, and the current (*modern*) the organizational basis [24,42].

The cascade of evolutionary processes is, in other words, a tabular depiction of the spectrum of processes that propel social evolution on a world scale. We shall now take note in greater detail of three important characteristics of that picture: *multilevel*, *cybernetic hierarchy*, and *self-similarity*. Table 2 presents a multilevel aspect, as a set of processes operating at several levels of social organization; it shows at each of the three levels a differentiated array arranged in a *cybernetic hierarchy*, and the entire cascade consists of *self-similar processes* because they are all structurally oriented to collective learning.

We note, first, the *multilevel* (or hierarchical) character of this evolutionary analysis. It posits that social evolution is not a singular process with one simple trajectory but an entire cascade across a number of levels—agent, institutional, species-wide—and those evolutionary processes occur or proceed at each of these levels. That accords broadly with the position of Gould, described by him as the ‘‘hierarchical theory of selection’’ (Ref. [34], Chap. 8). Contrary to the conventional Darwinian argument, that selection operates solely at the organismic level, and which has recently been expanded to the level of the genes (in Richard Dawkins’ ‘gene selection’), Gould argues that ‘‘Darwinian individuals’’ (those with a reproductive potentiality, hence evolution-capable) may be found across an entire biological hierarchy, beginning with genes and cells, to organism, deme, and species, and it is the last level that is of interest for the present analysis. Without accepting Gould’s argument in every detail, we, too, place the (human) species into the cascade of evolutionary processes.

We note, in the second place, that in each of the three arrays in Table 2, the set of four social evolutionary processes exhibits a distinct order—known as the *cybernetic hierarchy* (Ref. [35], pp. 29, 113–114), a concept already noted in Section 4.1. In that ‘‘hierarchy of control’’ (a concept influenced by studies of communication and control of Wiener [36]) over the four dimensions of social systems, the systems higher in the order are relatively high in information while those lower down are relatively high in energy. That is, in effect, information controls energy (via communication). Listed in the order of their information content, the primary world system processes are, from higher to lower information content, the *world system* process, *world socialization*, the *active zone* process, and the *world economy* process. Accordingly, processes affecting structures higher in information content have the longer characteristic period, the longest being that of the enveloping, the world system process. On the other hand, the economic evolutionary processes are highest in energy, followed by the political, the social, and the cultural. Correspondingly, the most ‘‘energetic’’ economic (the K-wave) process shows the shortest period of all.

Each successive process has a period longer than the preceding one, in systematic fashion, in that it is double the preceding one. In other words, the lower the process ranks in the ‘‘hierarchy of control,’’ the more frequent it is; those high in information have a longer temporal range, hence also lower frequency. In an important sense, too, the shorter-range processes such as the economic (K-waves) *nest* within the longer ones (as in politics) and *coevolve* with them.

In as much as ‘‘information controls energy,’’ the cybernetic hierarchy might be seen as the expression of the requirements of learning. This is why, thirdly, each of the four world system processes can be described as an algorithmic (Dennett [37], Chap. 2) *learning process*, because each might be seen as four-phased, and the phases are ways in which information is transformed into energetic solutions. The phases of a social learning process are generally seen to be (1) developing a variety of information; (2) mobilizing support; (3) choosing and/or deciding; and (4) implementing. Most notably, this concept of learning also comprises the essential elements of Darwinian evolution, namely (1) variation, (2) cooperation, (3) selection, and (4) amplification (differential survival) [9]. This evolutionary concept can also be rephrased as specifying a set of simple rules whose application brings about complex systems. These rules are (1) generate variation; (2) mobilize (and generalize); (3) select; and (4) amplify/reinforce. It is our postulate that the world (social) system, when critical, has the propensity for such learning in conditions of evolutionary potential, that is, one of noise or chaotic behavior generating new information, and mobilizing agents for innovation.

Amplifying this argument is Fig. 2, presented in Section 4.2, which shows how the entropy production unfolds over time for an evolutionary process such as the socioeconomic long wave (K-wave). Let us focus our attention on the curve for $\delta = 0.16$ over a period of 60 years (shown in heavy line), and let us translate K-entropy as the "ignorance" about the system. At first, we see "ignorance" rising to a peak at about year 15 (completing phase 1); it then turns into a low just after year 30 (phase 2) and remains in the low position until year 45 (phase 3, showing knowledge saturation, in readiness for selection), and a final leveling off by year 60 (phase 4). This is the picture of a four-phased learning process moving from awareness of "ignorance," through collection, and then selection and completion. We conjecture that all evolutionary processes in the cascade exhibit such a time structure, albeit with periods that are multiples of that of the K-wave. Further conjectures about why things are so will be handled in Section 7.

Innovation drives social evolution of all kinds, not just technological but also social and cultural. The concept of social evolutionary innovation is used here generally for all those innovations embedded in the evolutionary processes we are discussing. New technologies account for many innovations, in the economy as in politics (e.g., new weapons) or in the media, but we cannot ignore either the innovations that consist mainly in social reorganization (as in state building, new trading methods, or new political or military strategies). In turn, social evolution must be distinguished from the cultural variety. The latter might be seen as the process by which the total information stored in the social organization of the human species is increased and/or revised and reformulated.

The next question is: What is the empirical evidence that might support the claims embodied in this figure?

6. Evidence for world system evolution

The *cascade of evolutionary processes* is a theoretical model that requires empirical support. In this section, we marshal the systematic data now available and that can be drawn upon to show the predicted patterns.

The relevant data bearing on the characteristic times of world processes are summarized in Table 3 (Evidence for World System Periodicities). We shall now proceed with a review of

Table 3
Evidence for world system periodicities

(1) Predicted period length (g)[a]	(2) Predicted number of periods (N), 1000–2000 AD	(3) Measured number of periods (N),[b] 1000–2000AD	(4) Process	(5) Predicted period length ($g \times 30$ years)	(6) Measured[c] mean period length (years)
2	16.7	17.9	K-wave	60	58 (1); 54 (2)
4	8.3	8.9	Long cycle	120	108 (3); 117 (4); 105.5 (5)
8	4.2	4.4	Democratization	240	228 (6)
16	2.1		Opinion making	480	
32	1	1	World economy	960	1000 (7)
64	0.5	0.5	Active zone	1920	2000 (7)
128	0.26	0.25	World socialization	3840	4000 (7)
256	0.13	0.125	World system	7680	8000 (7)

[a] From Table 2.
[b] Based on data in column 6.
[c] These data are derived from data in Refs. [19–24,38,39]:

(1) Observed length over 18 periods, 930–1973;
(2) Measured length over 10 periods, 1430–1973;
(3) Mean interval among five peaks of sea power concentration, 1514–1946;
(4) Mean interval among five global war onsets;
(5) Measured mean interval among four peaks of army concentration in Europe, 1560–1914;
(6) Characteristic period, democratization, data for 1840–2000; and
(7) Periods inferred from world population and world urbanization data, 3400 BC–2000 AD.

those data, beginning with agent-based processes (for an earlier discussion, see Ref. [33], pp. 42–44; Table 1).

The agent-based process most familiar to us is, of course, the *K-wave* of industrial and technological change in the global economy, although, to begin with, centered usually upon a single national economic system. This phenomenon has now been studied for close to a century, commonly and until recently over a population of five cases beginning late in the 18th century. The consensus view of the length of one of these has been between 50 and 60 years (for a review of the literature, see Ref. [26]).

The Modelski–Thompson study [22] extends the range of K-wave analysis over the entire second millennium to a postulated beginning in Song China, then the active zone (mainspring of innovations) of the world system, soon moving on to Renaissance Italy, and focused, after 1500, upon the Atlantic. It proposes a population of 19 K-waves (including the current one) and, for the 18 waves from 930 to 1973, determines the average duration of one to be 58 years. The empirical support for the first eight K-waves is suggestive but nonsystematic; firmer evidence based on data series showing S-shaped growth spurts in 10 sets of leading industrial and commercial sectors for the interval 1430 and 1973 shows an average measured length of just over 54 years.

The *long-cycle* animates the evolution of global politics and has tracked, in the contemporary world, the rise of successive nation-states to global leadership. In the 'learning' mode, such a long cycle indicates the process of 'running for office' (phases of agenda setting and coalition building), followed by those of selection (macrodecision, involving, in past cycles, global war) and execution. The documented length of nine completed long cycles in the entire modern era so far (930–1973) is, on average of these cases, 116 years, but the last completed long cycle (1850–1973) lasted, however, 123 years [21,22].

A systematic study of sea power concentration for the period 1494–1993 and involving a year-by-year inventory of the capital ships of the world's oceanic navies shows five peaks of maritime supremacy at intervals of 108 years [38]; these peaks have the shape of logistic growth curves and coincide with the ascension to global leadership—one of its necessary conditions being a decisive superiority in respect of forces of global reach. Two other indicators of long cycle periods might be mentioned. An analysis of the process or army concentration in the European theater over the period 1560–1914 reveals four analogous peaks attributable to the challengers for global leadership—Spain, France (twice), and Germany—as it were in counterpoint to the maritime powers of Portugal, the Dutch Republic, Britain (twice), and the United States. Not the least relevant in the context of global politics is the role of global wars, the generation-long spells of major hostilities embroiling the entire system, and so far the principal selection mechanism for global leadership. For a total of five such major events, the mean time elapsed between their onsets was 105.5 years, and between their endings was 107 years.

The third in the hierarchy of agent-based processes is *democratization*. We understand this process as one building the foundations for a global community as the basis for sustainable long-term cooperation. An index of the growth of democracy is the proportion of the world's living population, in their several countries, under a democratic regime; let us call it "the fraction democratic." A rise (or fall) in that fraction can be used to chart the rate of spread of democracy in the world system. This collective learning process, whereby humans learn better to cooperate within and across national societies, is forwarded by democratic social and political movements competing against absolutist, authoritarian, and otherwise undemocratic institutions and ideologies. A systematic retest of this process [23] shows it to vindicate the predictions of an innovation–diffusion model whose characteristic time (raising the fraction democratic in the world from 10% to 90%) might be expected to last from the 1880s to 2110s. This is illustrated in Fig. 3: World Democratization that, using the data in Ref. [23], strikingly depicts the learning curve shape of that major historical development. We might take this to be another phase in the trajectory of a process whose antecedents in the democratic lineage may be traced to the beginnings of the modern era.

We are less well grounded in the process by which *opinion making*, that is the prevailing conceptions of priority global problems, form at the global level and then diffuse throughout the system. We would expect it to be centered on the active zones of the world system, and formulated in the interplay of major intellectual currents propagated by the media of their time, and focused preferentially on the world powers and their challengers. It might be fruitful to

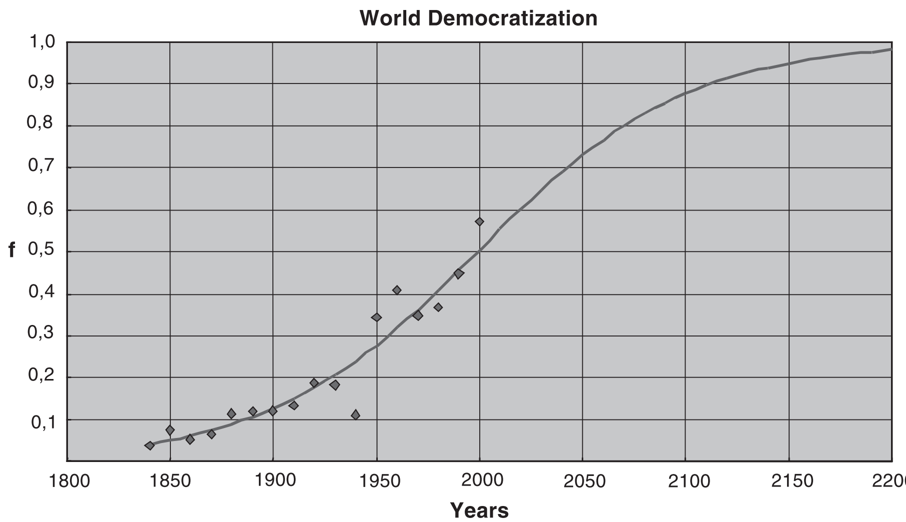

Fig. 3. The spread of democracy in the 19th and 20th centuries displays the classical shape of a learning curve, with a fine fit (R^2 fit of 0.95).

follow up the suggestion of Wierzbicki [40], pointing to what he saw as 'great cultural waves' and recognizing the Renaissance, both in its early Chinese and later Italian modes, as one such wave, the Enlightenment as possibly the second, and the contemporary age, from mid-19th century onward, as the third. This would make those 500-year-long movements as the master programs for the global system.

The second part of our empirical inquiry concerns the evidence for the duration, or periodicity, of the longer-term *world system processes* (species-wide, sixth column in Table 2; lines 5–8 in Table 3). Our model proposes that, in its macroorganization, the world system has already passed through two major phases (the ancient and the classical), and is now well into the third, the modern era. This designation is fairly conventional in studies of world history, even though authors vary in assigning precise dating schemes to these designations. If the first two phases have been, as we have proposed, each of about 2000 years in length, and they are part of a four-phase learning process, then the third phase should also last some 2000 years. That does not mean that the phases must necessarily be identical in duration, because in fact a learning process is one of transformation, and we would expect each phase to be somewhat different. But what is the evidence? What does the overall pattern reveal?

Our first set of data concerns the social base of the world system that is its *population*. That is perhaps the most important single source of systematic data in the form of statistical series stretching across the entire length of world history. The data are spotty for the earliest periods and somewhat uncertain, but they do improve, and a number of alternative series are now available (as may be seen in Ref. [41]).

Contrary to a widespread impression, the story of world population of the last 5000 years is not one of continuous exponential growth. Rather, it can best be described as a series of three major surges, each more substantial than its predecessor, but both of the first two surges also

Table 4
World population history

4000–3000 BC	2000 BC	1000 BC	1 AD	1000 AD	2000 AD
$7-14 \times 10^6$	27×10^6	50×10^6	255×10^6	254×10^6	6000×10^6

Source: United States Bureau of the Census [41].

followed by a long period of population stability. A brief summary of the most pertinent data points appears in Table 4.

The earliest data (4000–1000 BC) must be regarded as most tentative but do suggest a surge up to 2000 BC, followed by lesser, if any, growth to 1000 BC (that is the only available figure, a product of curve fitting, and may be too high). The classical period presents the most striking picture: a dramatic surge between 1000 BC and year 1 AD, followed by a total lack of overall growth (but considerable movement of populations), and overall stability at the level of about 250 million. The modern period to-date (1000–2000 AD) is, of course, a case of the most pronounced and best-known expansion. Current forecasts envisage a leveling-off of this great explosion within the present century, possibly after 2050. In all, therefore, the world population series supports the notion of a phased world system process, and the phases are not inconsistent with a learning interpretation. Each phase is, of course, higher and more complex than the preceding one, and builds upon it.

A related but distinct set of data concerns world urbanization, that is, cities that in a historical era (be it ancient, classical, or modern) exceeded a certain base size, and might therefore be said to fall into a 'world' class. For the ancient period, this might be taken to be a population of 10,000, for the classical period one of 100,000, and for the modern period 1 million. The results are summarized in Table 5.

Here the trend and the shape of the growth spurts are yet clearer. In the ancient world, a surge from about a handful of major cities, say four in 3300 BC, and nine in 3000 BC, to some 20 in 2000 BC, was followed by what was in effect a dark age extending for about a millennium. The same pattern is evident in the classical era. A handful of large cities from the earlier period rise to 20 substantial urban sites by the year 1 AD are then followed by another dark age that, with the same number of large cities, do no more than preserve the memory of urbanity but not always in the same time and place. Rome, which was the world's largest city, with maybe 1 million people at about 1 AD, dropped off the list altogether by the year 500. The great modern expansion is also clearly evident, from just one

Table 5
Number of world cities in ancient, classical, and modern eras

Era (number of cities) Number of inhabitants	3000 BC	2000 BC	1000 BC	1 AD	1000 AD	2000 AD
Ancient: over 10,000	9	20	17			
Classical: over 100,000			4	20	20	
Modern: over 1 million					1	291

Source: Modelski, "Ancient World Cities" [42]; author's estimates.

metropolis in 1000 AD (possibly Constantinople) to close to 300 "millionaire" cities in 2000 AD—an amazing spurt.

Both sets of data shed light on two other world system processes, *world socialization* and *world economy.* In both the ancient and the classical eras (i.e., in each of the two 2000-year-long periods), we observe, at first, a growth period that brings about a flowering of innovation, and a concentration of wealth, as evidenced in the rise of world cities; followed by a period of population movements from the hinterlands, involving attacks on the centers of economic and political power, and bringing about a leveling in the distribution of opportunities and resources. In that way, the first period of world socialization (4000 years) is seen as composed of four 1000-year-long phases of community formation through alternating movements between concentration and dispersal. In the world economy, we have similar 1000-year-long periods of formation of new industries and the concentration of production (metal working, irrigation, agricultural settlement) followed by a 1000-year-long period of expanding trade links and technological dispersion (in the Fertile Crescent, via Silk Roads, etc.). We project that the same type of process is at work in the modern world system.

One question concerns the precise dating of the ancient and classical eras, here rounded off to 3000–1000 BC and 1000 BC–1000 AD. For the ancient world, the rise of a system of cities and of writing (hence onset of urban civilization, and of world system processes) is usually dated to before 3000 BC, and a system of cities does appear to link Sumer and Elam by 3300 BC. But the archaeological evidence on writing suggests the period of 3400–3200 BC as the earliest possible, and the more substantial writing (also from Egypt) really begins only in the period 3200–3000 BC. In other words, there is some latitude possible in demarcating the precise starting date of these processes (and therefore determining the length of their periods), as there is in deciding on its closing, sometimes put at the end of the Bronze age, about 1200 BC, but that may be somewhat early, and a date of 1000 BC could be equally appropriate. The same goes for the start of the modern period; that for China works well at about 930 or 960 AD (start of the Song dynasty), but may be a little early elsewhere. In other words, there is something to be said for round figures, and a roughly millennial phase length (some 2000 years for each phase of the world system process).

7. World system processes: power law behavior

As already discussed in Section 5, the cascade of world system processes depicted in Table 2 follows a cybernetic hierarchy and may be seen as a ranking of processes with increasing informational content and longer time spans. The longer time spans required to run each of the processes are translated in the first columns of Tables 2 and 3 by the doubling number of generations necessary to carry each of them. It is worth pointing out again that the view of a ranking of processes with increasing informational content matches well the results of the simulations of Belew [14] and Langton [43] using genetic algorithms and cellular automata, respectively. At the basis of this array of processes lies the basic beat of the generational turnover responsible for the vertical mechanism of information transfer among generations that might be seen as the carrier process of the entire cascade.

As shown in Section 6, good empirical evidence supports the existence of the processes in the modern era described as agent-based processes and world system processes (fourth and sixth columns in Table 2), noting that most of the processes discussed in Section 5 are better observed in the modern system (since about 1000 AD), mainly regarding the processes characterized as agent-based. Using then a time frame corresponding to the period 1000–2000 AD, we can represent graphically the cascade of processes as the number of occurrences (*N*) observed in this time frame for each of the processes in function of the number of generations needed to run each of them. The resulting graph for the predicted values (column 2 of Table 3) of the set of agent-based processes is depicted in Fig. 4.

As we can observe in Fig. 4, the depicted graph is a hyperbolic function, which translates the fact that a power law behavior is at work for the phenomenon of world evolutionary processes in the modern era. Such behavior is best evidenced in Fig. 5 in which a log–log scale plot for the points appearing in Fig. 4 is perfectly fitted by a straight line. The linear regression of this plot allows us to calculate a general equation for the set of agent-based processes as being:

$$N = 33.2g^{-0.9991} \tag{1}$$

The constant 33.2 appearing in Eq. (1) (log 1 = 0 in Fig. 4) corresponds roughly to the total number of generations living and carrying on all the pictured processes in the time

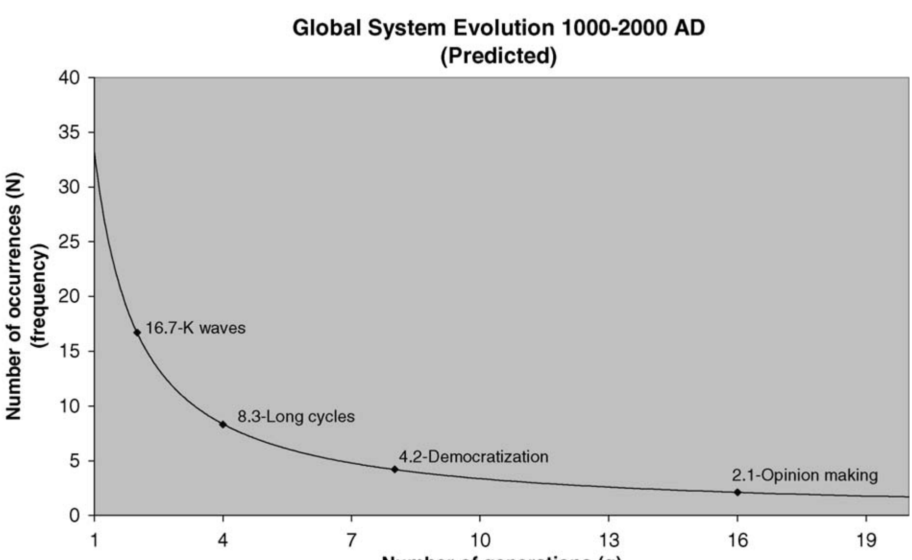

Fig. 4. Predicted number of occurrences or frequency *N* of the agent-based processes, as a function of the number *g* of generations necessary to run each of it, for the time frame 1000–2000 AD. This is evidently the pattern of a hyperbolic or power law function.

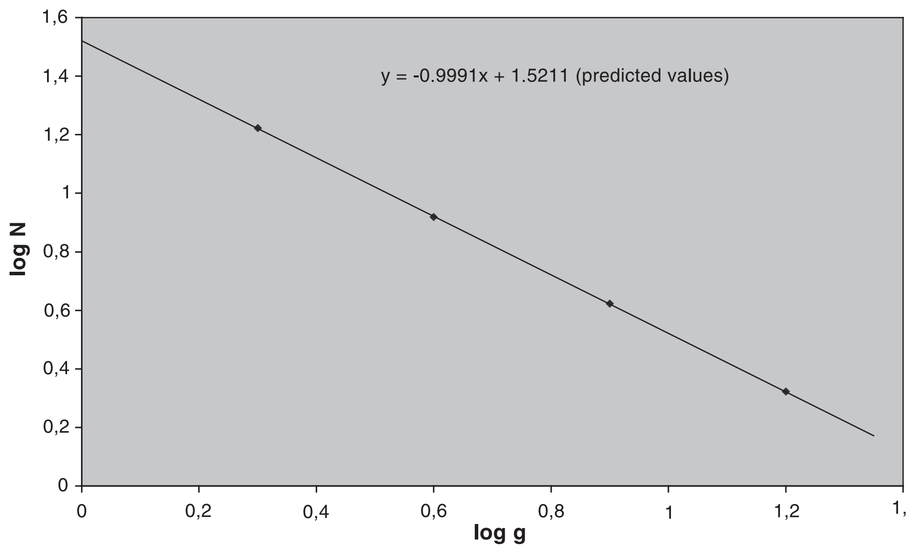

Fig. 5. Log–log scale plot for the set of points represented in Fig. 4, allowing determination of the general equation $N = 33.2g^{-0.9991}$ for the set of agent-based processes (predicted).

of 1000 years considered here, and that implies a mean length of 30.12 years for each generation.

It is worth pointing out that, as is discussed in depth by Devezas and Corredine [26], that there is an inherent difficulty with the concept of generation and with establishing a measure of its length, which in turn is the result of the sum of different biologically based rhythms. Values in the range 25–30 years seem to be quite acceptable [26] and in this work we are considering the round number 30 years as the typical length of the generational turnover interval, and that, in turn, leads us to the numbers multiples of 30 appearing in the fifth column of Table 3.

Considering the predicted values for the world systems processes (for which we also have some numerical values inferred from world population and world urbanization data; see Table 3), altogether with the predicted values for the agent-based processes, we can complete the picture of world evolutionary processes for the modern time frame. This approach gives us the general power law curve depicted in Fig. 6 and its corresponding log–log plot of Fig. 7.

These pictures are only slightly different from the previous two ones and it is manifest that an overwhelming pattern of a power law function underlies the cascade of world evolutionary processes. The linear regression of the points shown in Fig. 7 allows us to determine the equation:

$$N = 33.4g^{-1.007} \tag{2}$$

that expresses the power law behavior for the entire cascade of world evolutionary processes. As we can see, by considering all processes of the cascade together, we obtain a

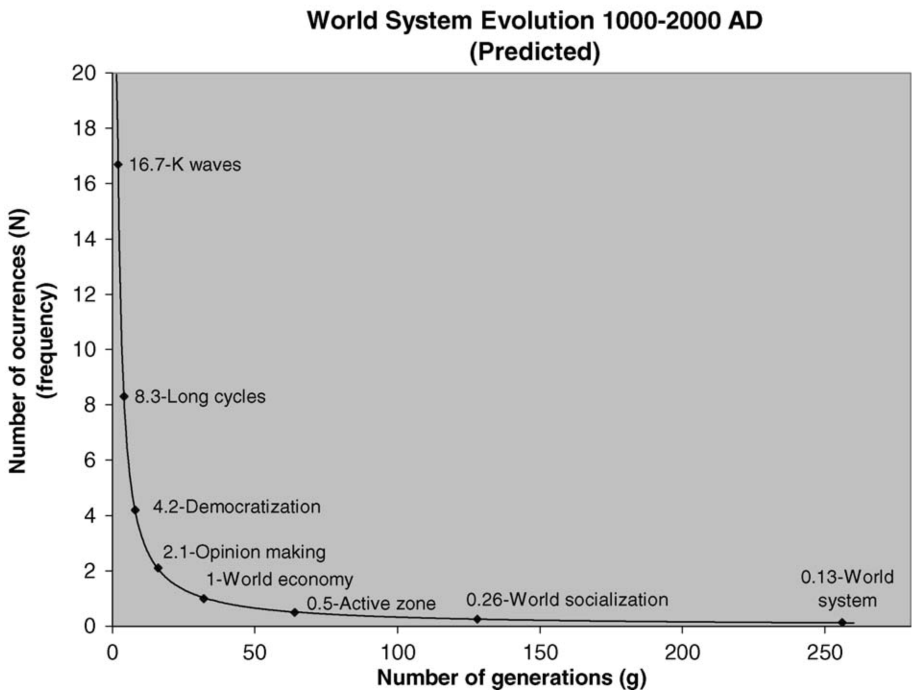

Fig. 6. Predicted number of occurrences or frequency N of the world evolutionary processes, as a function of the number g of generations necessary to run each of it, for the time frame 1000–2000 AD. It evidences the overwhelming pattern of a power law function for the whole cascade of world evolutionary processes.

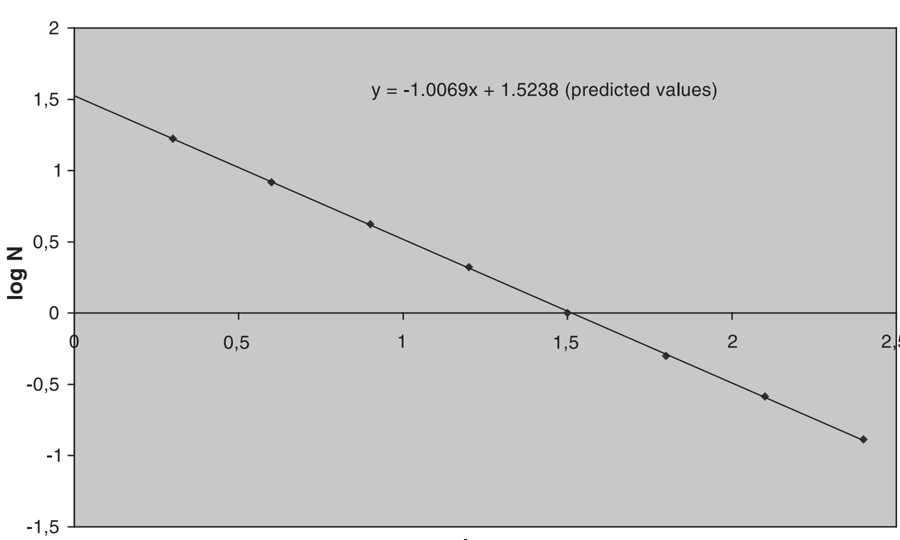

Fig. 7. Log–log scale plot for the set of points represented in Fig. 6, allowing determination of the general equation $N = 33.4g^{-1.007}$ for the whole cascade of world evolutionary processes (predicted).

slightly different (and most general) equation. The constant expressing the total number of generations enrolled in our 1000 years time frame is now 33.4, and that implies a mean length of 29.94 years for each generation. Considering that this power law function embodies an array of processes whose duration is a multiple of two, which can be expressed as $g = 2^n$ (with n equal to any natural number), Eq. (2) may be rewritten as:

$$N = 33.4 \times 2^{-1.007n} \quad (3)$$

which may be regarded as the general equation for the entire cascade of nested, species-shaping, world social processes (i.e., the most compact description of the world evolutionary processes). The increasing positive values of n correspond, respectively, to the successive processes in the cascade presented in Table 2: $n=1$ for the K-wave of technological change, $n=2$ for the long cycle of global politics, and so on; $n=0$ does not correspond to a generation-carried process, but to the carrier process (or carrier wave) itself.

At this point, two steps must be taken to validate our postulated modeling of the world system: first, comparing the predicted curve with the measured values presented in Table 3, and finally, giving a rational explanation for the phenomenon at hand. Regarding the first step, a comparison of the straight line obtained in Fig. 7 with the measured values (third column in Table 3) was undertaken and the mean deviation of the points with relation to straight line is about 1.7%, evidence of the fact that the historical data match well the postulated model.

With regard to the second step, the necessary explanation, we must consider three main questions arising from the results presented here:

1. What is the meaning of a power law function describing the main lines of human social change over the past five millennia?
2. What is the constraint imposing a doubling number of generations carrying out the cascade of processes?
3. What are the implications of the general equation (Eq. (3)) for futures studies and research?

Beginning with the first question, we observe that the behavior evidenced in the graphs presented in Figs. 4 and 6 constitutes a ranking of significant occurrences in the world system. Such power law curves expressing the frequency of events as a function of the inverse order of their “size” (i.e., as a function of their ranking) are quite common in science and known as Zipf’s law, so named after linguist Zipf [44], who published a seminal work on this subject in 1949 (see also Ref. [3], Chap. 1 and Ref. [45]). Zipf’s law gives a compact description of phenomena where large events are rare, but small ones are quite common, stating very generally that the frequency N of the rth largest occurrence of the event is inversely proportional to its rank: $N = r^{-c}$, with c close to unity. In our graphs, the ranking r of the occurrence is expressed as the number of generations’ g necessary to run a given world social process, or, in other words, the “size” of the process. One early application of the inverse power law was due to Richardson (Ref. [46], pp. 149–156), who noticed that the size of wars in the period he studied (ca. 1820–1950) varied inversely with their frequency.

The log–log graphs presented in Figs. 5 and 7 express what is known as scaling functions, a hallmark of phenomena with no characteristic time or size scale (i.e., phenomena with scale-free behavior or fractal structure; self-similarity across scales).

Question 1 should then be completed by asking which are the events underlying this ranking of world evolutionary processes and exhibiting such scale-free behavior, in a manner very similar to the scale-free size-of-avalanches model advanced by Bak (Ref. [3], Chap. 5) some years ago. The answer is quite simple: *innovation*. The broad spectrum of evolutionary processes analyzed in the present work is the result of *major innovations* in their respective spheres, namely in the layers of movement that may be ordered as economic, political, social, and cultural, following the previously noted cybernetic hierarchy (with increasing informational content). The *innovative process* in the world system is a continuum across generations, it being evident that very big and revolutionary innovations are much less common than smaller ones. At the lowest extreme of our cascade of processes lie the quite energetic *technological innovations* responsible for the formation of the socioeconomic long waves or K-waves. With decreasing energy content and increasing informational content follow the innovations responsible for radical changes in political structures and beliefs, ideologies, social organization, etc. The implied law underlying the whole is that the frequency of evolutionary innovations (assuming one major innovation, or cluster of innovations, per characteristic period) is inversely related to their importance, as indicated by its respective temporal reach (or length).

Bak (Ref. [3], p. 27ff) argues that the power law is a characteristic feature of systems exhibiting "self-organized criticality," and he places biological and social systems among them. In one of his chapters, he raises the issue of evolution, but chiefly in the context of mass extinction. He presents earthquakes as the cleanest and most direct example of a self-organized critical phenomenon in nature. As we know, earthquakes occur in all sizes and scales, and the Gutenberg–Richter law (a power law) classically expresses the relationship between their size and frequency. Following this view, it is important to see that earthquakes might not really be "catastrophes," but one among the ways of rearranging the earth's physical structure. They might be seen as steps in the continuing reshaping of the natural world to meet changing conditions. These then are not statistical outliers but rather massive occurrences probably of long periodicity whose impact on the globe's stability is, for all we know, positive. *Innovations* that account for social and technological evolution are analogous to earthquakes as they disrupt the social structure and are subject to the power law that says that the number of evolutionary innovations is inversely related to their importance, the latter being indicated by their temporal length (in our case by the number of generations needed to introduce and consolidate them). As for big earthquakes not being statistical outliers, major innovations are neither, but rather might be seen as periodic rearrangements of the world system in order to accommodate its changing size and complexity.

The phenomenon at hand (the cascade of world evolutionary processes) is then a cascade of scale-invariant, interdependent, and structure-transforming processes at several levels of organization of the self-organizing complex world system. In other words, such structure-transforming processes come to existence through the innovation process occurring at the several levels of the cybernetic hierarchy and at the several scales of world organization (local, national, regional, and global). But innovations must diffuse in and be learned by society, and the adaptive mechanism of learning is paramount in giving the pace of change at each level.

The power law footprint of this cascade of processes can be detected through two distinct but related signatures: from the previously mentioned fractal–temporal arrangement of their length (short processes nest within longer ones), and from the "edge-of-chaos" regime, typical of systems poised in the vicinity of a critical phase transition. The edge-of-chaos regime is the optimal condition to be in a constantly changing environment, because from there one can always explore the patterns of order that are available and try them out for their appropriateness to the current condition. What is not necessary at all is to get stuck in a state of order, which is bound sooner or later to become obsolete. In that way, complex social systems that can evolve will always be near the transition region, poised for that creative leap into novelty and innovation, which is the essence of the evolutionary process. At the base of the cascade, this is translated by the learning algorithm $3<\delta t_G<4$ discussed previously, which expresses the fact that the social process of aggregate learning within a generation operates near the threshold limit between order and chaos.

Kauffman (Ref. [2], Chap. 1) argues that this ("edge-of-chaos" regime) concept provides a powerful new framework for understanding evolutionary biology, as well as coevolution in the technoeconomic realm. He claims that the entire ecosystem may coevolve to a state poised at the edge of chaos, linking the idea with Bak's concept of self-organized criticality. Kauffman (Ref. [2], p. 223) then discusses the idea that in the ordered regime near the phase transition, a complex but nonchaotic cascade of activities can propagate across a network, allowing coordination of complex sequences of events.

Here lies the pivotal point of our postulated cascade of world system processes: social systems may self-tune their structure to a poised regime between order and chaos (as if by an invisible hand, in Adam Smith's felicitous phrase, and as Kauffman has pointed out), with a power law distribution of breakthrough events, or in other words, of innovations. In Fig. 8, the curve given by the general power law function (Eq. (2)) represents the critical boundary between a *supracritical* and a *subcritical* regime. At any hierarchical level of organization, the social system is driven to this second-order phase transition region and remains poised there ever after, held up by the balance between opportunity (if subcritical) and lethality (if supracritical).

A close look at Fig. 2 (in Section 4.2) may help to shed light on this view of a subcritical–supracritical boundary. As we have seen, the rate of learning δ cannot be very different from 0.16. If greater (see the curves for 0.2 and 0.3), this would imply an overshoot in entropy production and reach the threshold point ($f=32\%$) in a time shorter than a typical generation interval. If smaller (curve for 0.1), the intensity of entropy production is quite low and the time for reaching the threshold point would be much greater than a generation interval. Using the learning algorithm δt_G, if $\delta>0.16$, we have an overshoot of the chaos upper limit $\delta t_G>4$, implying breakdown of the system; if δ is very small; allowing values $\delta t_G<3$, we have convergence to a fixed point and then collapse of the system due to a paralyzing equilibrium. The value of δ of about 0.16 fixes the time for reaching the threshold point as approximately coincident with the length of a generational interval. This is the biologically controlled rate of

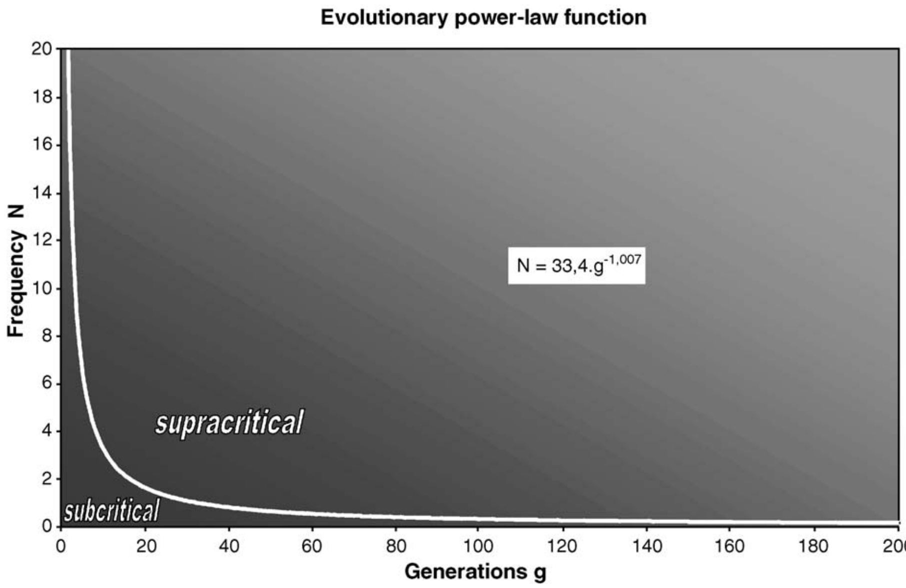

Fig. 8. The curve given by the general power law function (Eq. (2)) represents the critical boundary between a supracritical and subcritical regions, a second-order transition region along which world system processes are poised and unfold.

transfer of information among humans at the aggregate level, which well matches the empirical data for the diffusion rate of basic innovations in the body of society as shown by Devezas and Corredine [26]. In the light of Fig. 8, values of $\delta > 0.16$ imply in shorter processes, and in this way the corresponding number N of occurrences of the cycles would be greater, falling then in the supracritical region. Shorter values of δ imply longer processes, resulting in a smaller number of occurrences N falling then in the subcritical region. Humanity would not tolerate any of these extremes and fall back, being constrained to move along the critical line.

With regard to the second question, about the doubling of the number of generations in the evolutionary cascade, the answer seems to be related to the approach described in answer to the first question. The learning algorithm $3 < \delta t_G < 4$ tell us that there is an optimum rate under which things happen and unfold within a generation. As shown through the Generational Learning Model, at the base of the cascade (in K-waves) major technological innovations cluster within the time span of a generation and need another generation to consolidate, resulting in the basic $g = 2$ rhythm that will nest in all other processes and upon which all other processes will unfold. Since there is an optimum learning rate (considering our daily life that doesn't violate anybody's intuition) and given the pace of vertical information transfer across generations this explanation seems to be a reasonable one, even though, we recognize that this theme remains to be fully explored, and with more empirical data.

Now, for the third question, on the research, future studies, and implications of the general equation for world system processes, Eq. (3) constitutes a compact description of the processes unfolding in the world system and serves to determine the number of occurrences to a given value of n ($g=2$), that is, to a given group of generations that carries out one of the species shaping evolutionary processes. As discussed in Sections 5 and 6, the longest process now firmly identified is that corresponding to $g=256$ generations ($n=8$). The present approach, however, leaves room for the existence of even longer-range processes, the next one ($n=9$) carried by 512 generations and lasting about 16,000 years. For the 1000-years time frame considered this would correspond to solely a very small fraction (0.0625–1000/16,000) of occurrence, then very difficult to observe, but perhaps significant if we consider the whole of human civilization since the invention of agriculture. Moreover, we can speculate too about the existence of a very long process, covering the entire existence of humankind. For instance, $n=12$ could mean a process carried out by 4096 generations and lasting a little more than 120,000 years, corresponding more or less to the time span of modern humans living on planet earth.

Regarding prediction, it is worth pointing out that the present approach (the postulated cascade of world system processes) might make it possible to predict major trends and turning points, including their flavor (the formal–logical aspect) but not the substance or the nature of the events involved, shaped by the fortuitousness, contingency, and uncertainties underlying the innovative process. Eq. (3) allows us to draw a general equation for the logistic curves underlying the different evolutionary processes that can be written:

$$f = \frac{1}{1 + e^{-\frac{\delta}{n}(t - t_0)}} \tag{4}$$

where f expresses the normalized fraction of the process corresponding to a given n (carried out then by a given group of g generations), δ represents the basic diffusion learning rate (that is, as discussed earlier, roughly 0.16 per generation), t is the time in years, and t_0 is a constant to adjust the time axis corresponding to the year when $f=0.5$.

For the *world system process*, we would have $n=8$ ($g=256$) and $t_0 \sim 1000$ AD (33.4×30 years), and the resulting logistic curve is shown in Fig. 9. This logistic curve portrays the fact that, as stressed in Section 6, in its macroorganization, the world system has already passed through two major phases (the ancient and the classical), and is now well into the third, the modern era. This process, started some 5000 years ago and coextensive with what is conventionally understood as 'world history,' is currently reaching its 80% level of completion. The overall picture is that of a *four-phased millennial learning process*: the first phase (ancient era) might be thought of as the phase of putting in place its learning infrastructure (writing, calendars, cities); the second phase (classical) as one of community building by world religions; and the third (modern) as that of selecting the collective organization of the world system, to be consolidated in the fourth phase (presumptively a 'postmodern' phase) (Ref. [24], pp. 186–190; Ref. [42], pp. 37–43). Following this picture, we may say that (time-wide) humanity is now more than midway (62.5 pc) through a decisive stretch of the human experience, one that will or will not consolidate the modalities of its socio-political arrangements on a worldwide scale. On the other hand, our analysis suggests (as shown in the steep rise in Fig. 9) that the process of emergence may already be 80 pc complete, and could "soon" be moving into a phase

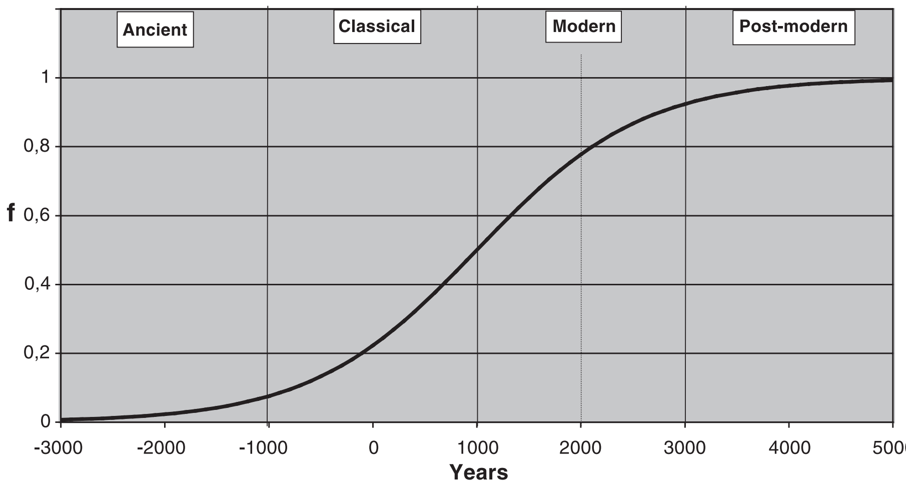

Fig. 9. Logistic curve for the *World System Process* given by Eq. (4), for $n = 8$ ($g = 256$) as evidence of the major phases of world history: ancient, classical, and modern. We are now well into the third phase, the modern era, reaching 80% of completion of the whole process. The fourth phase, postmodern, is yet to actualize.

of consolidation. That would imply the "good news" that the fundamentals of world system construction are now in place, and that a drastic or revolutionary reconstruction of the broad outlines of the contemporary world order is not really to be expected.

In the mathematics of logistic curves, the second and third phases together consist in the 'takeover' time of the entire growing process (corresponding roughly to 50% of the entire growth time span), and the part containing all their essential and significant points (turning points). Following the modeling presented in Fig. 2 (Section 4.2), the fourth phase is one of growing entropy production and depletion of the available information [32], with the system looking for new information, ready for a new beginning. The succeeding growth process usually overlaps and we get a time of instability and chaotic oscillations (due to the growing entropy production of the new process—a chaotic attractor [32]). But if the timetable that underlies the present analysis is correct, such developments are not to be expected for at least another millennium.

8. Final discussion

In our introductory section Prediction and Explanation about Nature and Society, we expressed the hope that this paper might advance the study of world system evolutionary processes toward great rigor, such that it might enhance our capacity for description, explanation, and possibly even prediction in this important field. To what degree have we met this challenge?

As for description, we have found that the cascade of world evolutionary processes exhibits power law behavior. That is, we have established a regular relationship among a number of seemingly disparate processes, such that we can now say that the frequency of such movements (innovation based) is inversely related to their size. We have also reaffirmed the correctness of the conception of the world system as poised on the boundary between order and chaos. Power law behavior, which characterizes a number of other phenomena, has attracted some considerable attention from a number of disciplines, and it is gratifying to know that ours is the first finding that firmly establishes a connection between world evolutionary phenomena at several levels of social organization.

Our inquiry takes us, however, beyond enhanced description, into taking some steps into the realm of explanation, for power law behavior, still largely untheorized, is also the process that represents learning. That opens the door to a wider conception, and the suggestion that world system evolution exhibits it and gives us reason to confirm that what is seen as self-organization might more precisely also be *systemic learning*. In more general terms, ours might be recognized as a "learning civilization." It is good to know, too, that world history might be the unfolding of a *millennial learning process*. If, as Gould (Ref. [34], p. 1055) maintained, "most evolutionists... are historians at heart," then maybe the reverse could also come to be true. Our findings should prove of at least some interest to students who labor to make sense of our past.

There is also the matter of prediction. We know that human behavior is notoriously difficult to predict in the short run. But we may claim to have added to our power to project, into the future, some critical tendencies of social evolution, contributing to the enhancement of our ability to think constructively about the future of society on a global scale.

What remains to be done? If, as some have recently argued, the universe is a computer, then evolution might be the program that makes it work. Social evolution is the program that makes our world go round, and an *evolutionary learning algorithm*, possibly a set of simple rules, would be a statement of such a program. In turn, such a program would also make it possible to simulate world system evolution. If we can simulate some aspects of the earth's weather, maybe we could simulate the world's social evolution over the hundreds of generations that it has taken us to get to where we are now.

Our study has taken us some distance toward such a goal. We have a compact description of the cascade of evolutionary processes. We now recognize that the Darwinian evolutionary algorithm is quite close to the learning model. We understand better the time structure of entropy production within a group of learning agents as a phased process, and its recursiveness. So maybe all it needs is just persistence, and more work. As we are wont to say, this problem calls for more study.

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References

[1] J.L. Casti, Searching for Certainty, William Morrow and Company, New York, 1990.
[2] S. Kauffman, At Home in the Universe, Oxford Univ. Press, New York, 1995.
[3] P. Bak, How Nature Works: The Science of Self-Organized Criticality, Copernicus, New York, 1996.
[4] J. Cohen, I. Stuart, The Collapse of Chaos, Viking, London, 1994.
[5] J.M. Smith, E. Szathmary, Major Transitions in Evolution, Freeman, New York, 1995.
[6] S.J. Gould, Full House, Three Rivers Press, New York, 1996.
[7] L.L. Cavalli-Sforza, Genes, Peoples, and Languages, University of California Press, Berkeley, 2000.
[8] J.M. Baldwin, A new factor in evolution, American Naturalist 30 (1896) 441–451.
[9] J.M. Smith, When learning guides evolution, Nature 329 (1987) 761–762.
[10] C.H. Waddington, Canalization of development and the inheritance of acquired characters, Nature 150 (1942) 563–565.
[11] G.E. Hinton, S.J. Nowlan, How learning can guide evolution, Complex Systems 1 (1987) 495–502.
[12] A.C. Wilson, The molecular basis of evolution, Scientific American 253 (4) (1985) 164–173.
[13] M.W. Feldman, L.L. Cavalli-Sforza, L.A. Zhivotovsky, On the complexity of cultural transmission and evolution, in: G. Cowan, D. Pines, D. Meltzer (Eds.), Complexity: Metaphors, Models, and Reality, SFI Studies in the Science of Complexity, Proceedings, vol. XIX, Addison-Wesley, Reading, MA, 1994, pp. 47–62.
[14] R.K. Belew, Evolution, learning, and culture: computational metaphors for adaptive algorithms, Complex Systems 4 (1990) 11–49.
[15] D. Ackley, M. Littman, Interactions between learning and evolution, in: C.G. Langton, C. Taylor, S. Rasmussen (Eds.), Artificial Life II, SFI Studies in the Sciences of Complexity, Proceedings, vol. X, Addison-Wesley, Reading, MA, 1991, pp. 487–509.
[16] E. Hutchins, B. Hazlehurst, Learning in the cultural process, in: C.G. Langton, C. Taylor, S. Rasmussen (Eds.), Artificial Life II, SFI Studies in the Sciences of Complexity, Proceedings, vol. X, Addison-Wesley, Reading, MA, 1991, pp. 689–706.
[17] P. Schuster, How do RNA molecules and viruses explore their worlds? in: G. Cowan, D. Pines, D. Meltzer (Eds.), Complexity: Metaphors, Models, and Reality, SFI Studies in the Science of Complexity, Proceedings, vol. XIX, Addison-Wesley, Reading, MA, 1994, pp. 383–414.
[18] A. Hübler, D. Pines, Prediction and adaptation in an evolving chaotic environment, in: G. Cowan, D. Pines, D. Meltzer (Eds.), Complexity: Metaphors, Models, and Reality, SFI Studies in the Science of Complexity, Proceedings, vol. XIX, Addison-Wesley, Reading, MA, 1994, pp. 343–379.
[19] G. Modelski, Long Cycles in World Politics, Macmillan, London, 1987.
[20] G. Modelski, Is world politics evolutionary learning? International Organization 44 (1991) 1–24.
[21] G. Modelski, Evolutionary paradigm for global politics, International Studies Quarterly 40 (1996) 321–342.
[22] G. Modelski, W.R. Thompson, Leading Sectors and World Powers, University of South Carolina Univ. Press, Columbia, SC, 1996.
[23] G. Modelski, G. Perry, Democratization in long perspective revisited, Technological Forecasting and Social Change 69 (2002) 359–376.
[24] G. Modelski, World system evolution, in: R. Denemark, J. Friedman, B. Gills, G. Modelski (Eds.), World System History: The Social Science of Long-Term Change, Routledge, New York, 2000, pp. 24–53.
[25] B. Martin, The schema, in: G. Cowan, D. Pines, D. Meltzer (Eds.), Complexity: Metaphors, Models, and Reality, SFI Studies in the Science of Complexity, Proceedings, vol. XIX, Addison-Wesley, Reading, MA, 1994, pp. 263–279.

[26] T.C. Devezas, J. Corredine, The biological determinants of long-wave behavior in socio-economic growth and development, Technological Forecasting and Social Change 68 (2001) 1–57.
[27] C. Marchetti, Society as a learning system: discovery, invention, and innovation cycles revisited, Technological Forecasting and Social Change 18 (1980) 257–282.
[28] T. Modis, Predictions, Simon and Schuster, New York, 1992.
[29] A. Grübler, Technology and Global Change, Cambridge Univ. Press, Cambridge, 1998.
[30] H. Santos, Analysis and interpretation of the growth dynamics of the Internet, MSc Thesis, University of Beira Interior, Covilhã, Portugal, 2001 (in Portuguese).
[31] H.G. Danielmeyer, Development of the industrial society, EuroReview 5 (1997) 371–381.
[32] T.C. Devezas, J. Corredine, The nonlinear dynamics of technoeconomic systems: an informational interpretation, Technological Forecasting and Social Change 69 (2002) 317–357.
[33] G. Modelski, Generations and global change, Technological Forecasting and Social Change 59 (1998) 39–45.
[34] J.S. Gould, The Structure of Evolutionary Theory, Harvard Univ. Press, Cambridge, MA, 2002.
[35] T. Parsons, Societies: Evolutionary and Comparative Perspectives, Prentice-Hall, Englewood Cliffs, 1966.
[36] N. Wiener, The Human Use of Human Beings: Cybernetics and Society, Doubleday, New York, 1950.
[37] D.C. Dennett, Darwin's Dangerous Idea: Evolution and the Meanings of Life, Simon and Schuster, New York, 1995.
[38] G. Modelski, W.R. Thompson, Sea Power in Global Politics 1494–1993, Macmillan, London, 1988.
[39] K. Rasler, W.R. Thompson, The Great Powers and Global Struggle, Kentucky Univ. Press, Lexington, 1994.
[40] A. Wierzbicki, Evolving cultural paradigms, Options, IIASA, Luxembourg, 1987, pp. 10–13.
[41] United States Bureau of the Census, "Historical estimates of the world population", at http://www.census.gov.
[42] G. Modelski, Ancient world cities, Global Society 13 (1999) 383–392.
[43] C. Langton, Life at the edge of chaos, in: C.G. Langton, C. Taylor, S. Rasmussen (Eds.), Artificial Life II, SFI Studies in the Sciences of Complexity, Proceedings, vol. X, Addison-Wesley, Reading, MA, 1991, pp. 41–91.
[44] G.K. Zipf, Human Behavior and the Principle of Least Effort, Addison-Wesley, Cambridge, MA, 1949.
[45] B. Kaye, Chaos and Complexity, VCH Verlagsgesellschaft, Weinheim, Germany, 1993.
[46] L.F. Richardson, Statistics of Deadly Quarrels, Boxwood Press, Pittsburgh, PA, 1960.
[47] H. Plotkin, Darwin Machines and the Nature of Knowledge, Harvard Univ. Press, Cambridge, MA, 1994.