# *A New 'Idea of Nature' for Chemical Education*


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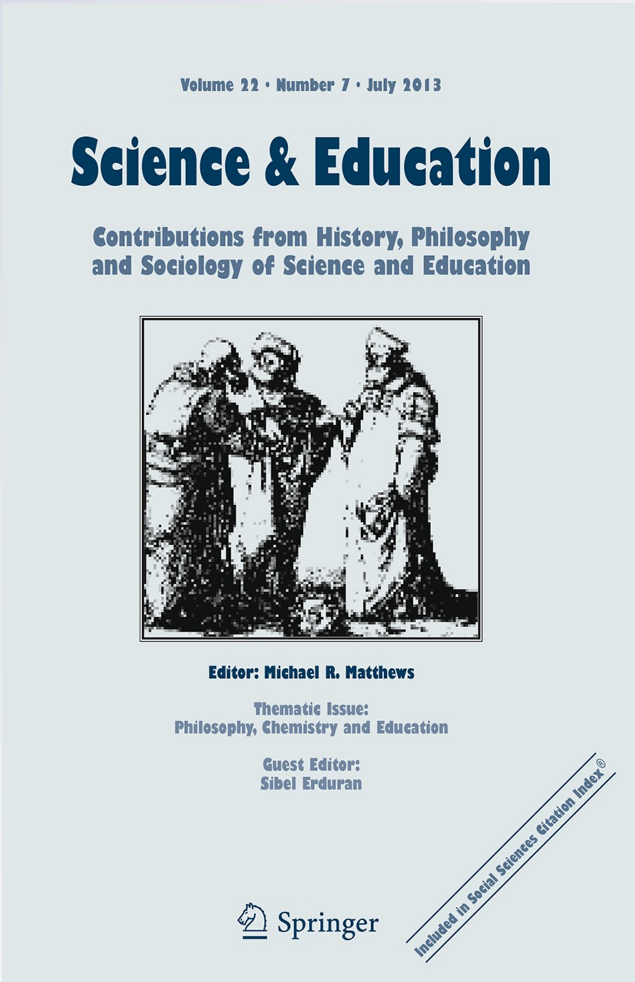



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# A New 'Idea of Nature' for Chemical Education

**Joseph E. Earley Sr.**

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**Abstract** "The idea of nature" (general model of how things work) that is accepted in a society strongly influences that group's social and technological progress. Currently, science education concentrates on *analysis* of stable pre-existing items to minimum constituents. This emphasis is consistent with an outlook that has been widely accepted since the late Renaissance—that characteristics of individuals depend exclusively on the properties of their microscopic components. Much of 19th and 20th century science seems compatible with that now-traditional outlook. But major parts of contemporary science (and fundamental technological problems) deal with *open-system dynamic coherences* that display novel and important characteristics. These important entities are not adequately treated by the presently-dominant idea of nature. In contrast, the notion of how the world works that contemporary science and current technological practice generate emphasizes *synthesis and self-organization* of far-from-equilibrium "dissipative structures." Arguably, eventual success in meeting the severe technological and social challenges occasioned by increasing world population will require general diffusion and appreciation of that newer overall outlook. Chemistry educators have been important in developing and disseminating the earlier worldview—they can and should provide leadership for widespread adoption of the alternative idea of nature.

## 1 Introduction

Human populations remained quite low from the origin of *Homo sapiens* more than one hundred thousand years ago until the invention and spread of agriculture less than ten thousand years ago. About five centuries BC, world-population growth became somewhat faster, and it accelerated again about one thousand years ago. Clearly the present rate of population-increase cannot long continue: several alternative future scenarios can be envisioned. Some thoughtful people fear bloody internecine conflict (such as controlled

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pre-historic populations), others recommend colonization of extraterrestrial habitats or advocate other and less-complex technological measures in order to deal with future population-pressure.

Each prior major change in world-population growth-rate has been *preceded* by significant change in a generally-accepted *"idea of nature"*—the concept of how the world works that is dominant in a society. This paper suggests that, in order for needed technological development to be effectively achieved, the currently-accepted idea of nature (an atomistic outlook adopted in the Renaissance) needs to be replaced (or supplemented) by a different worldview—one that emphasizes spontaneous self-organization of dynamic open-system coherences. Chemical educators have been centrally important in the general adoption of the current worldview: chemical education needs to develop so as to facilitate the *conceptual* shift that our situation requires.

## 2 Outlook Influences Results

Recent archaeological investigations—both in Turkey (Cauvin 2000) and in Mexico (Marcus and Flannery 2004)—have studied the remains of ancient communities that *spanned* the transition from hunter-gatherer to agricultural technologies. In both of these cases, the investigators concluded that specific developments in conceptual systems *preceded*—and made possible—technological transitions on which subsequent population-increase depended. Similar situations occurred thousands of years later in "The Axial Age" (Arnason et al. 2005) when several widely-separated civilizations independently developed novel, rather self-consistent, conceptual systems which *facilitated* higher rates of population-growth. Yet another such conceptual transition occurred in Western Europe before, during, and after the Renaissance. In that well-documented cultural shift, an earlier generally-accepted idea of nature (a complex combination of concepts that had originated in the Axial Age) was *largely but not completely* replaced by the notion that *nature is a mechanism* that runs by the remorseless working of law-determined motions of simple components. As Fig. 1 shows, this conceptual change was followed by a major increase in the rate of world-population growth.

Science educators often mention that the recent increase of world population depended on the rapid development of large-scale industry—which in turn was caused by origin of modern science. Perhaps surprisingly, recent efforts by historians to *demonstrate* direct connections between the 17th century origin of modern science and the subsequent increase in industrial activity have *not* been successful. It has turned out that the innovations that accounted for the rise and spread of industry in the 18th and early 19th centuries were largely made by cut-and-try methods that had pre-scientific origins and did not depend on scientific understanding (McCloskey 2010). Gradual technical developments during the late Middle Ages, sometimes called "The Second Agricultural Revolution" (Thompson 1968), had greatly increased the availability of food before the often-discussed rise of modern science and the Industrial Revolution. On this basis, some have argued that the great flowering of human productive activity during the past three hundred years should be credited, in large part, to changes in general outlook, worldview, or *weltanschauung* rather than directly to science itself. "What really had changed was that innovation gave people the outlook and the intellectual and material tools to search for their own new ways of working" (Goldstone 2009). That is to say, the necessary preconditions for the Industrial Revolution and the development of science were provided by a *shift in ideas*—a major change in the general opinion of the dignity of the motives, behaviors, and habits that

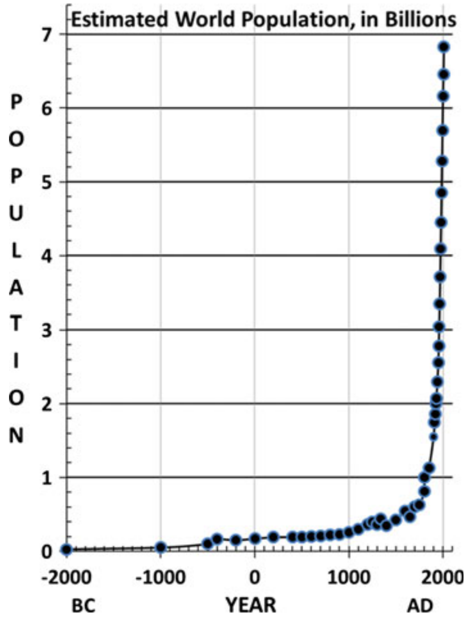


**Fig. 1** The growth of world population. Redrawn after Fogel (2010). Data from http://www.census.gov/ipc/www/worldhis.html

characterize life in progressive cities—as contrasted to the values prized by aristocratic, theocentric, or militaristic cultures. In the late Medieval and early Renaissance periods, social controls shifted so as to allow (or even to favor) innovations aimed at changes in the ordinary patterns of life. This "sociological" shift fostered creativity in both administrative and technical matters.[1] Rather than being related as a chain of causes, the Second Agricultural Revolution, the rise of modern science, and the Industrial Revolution may well have initially been more or less independent developments—and only subsequently merged to produce jointly-influenced outcomes.

## 3 Renaissance Cosmology

A book (Greenblatt 2012) that won the highly-prestigious Pulitzer Prize for general non-fiction describes how widespread study of an ancient epic-length poem, *De Rerum Natura (On the Nature of Things)* by Titus Lucretius Carus (95–51 BC), played a major role in facilitating the transition of worldviews that occurred during the late Renaissance. That Latin work, which was based on ideas of an Axial-Age Greek philosopher (Epicurus, c. 341–270 BCE) had been lost for many centuries until a single copy was located in 1417 in a monastery library. The main point of that work was that nothing exists *apart from* "bodies" and "the void" and therefore many widely-accepted beliefs (especially religious ones) are delusions. Even though *De Rerum Natura* challenged highly-valued traditional beliefs, that work was widely (if cautiously) discussed among educated people from its

[1] "And a century before Defoe [ca. 1660–1731], the English were beginning to learn from the Dutch the improving spirit of active, striving, laborious men such as will put their hand to the plow, try experiments, and give all their attention to what they are about." This transition was also accompanied by a change in rhetoric: "It is a methodical and accounting rhetoric, tied to practical hope and courage, and foreign to the bold gestures in court and battlefield of an aristocratic society" (McCloskey 2010, pp. 367–368).

re-discovery until the recent decline of classical education. Widespread circulation of this work during the 15th and 16th centuries raised issues that Richard Dawkins and other "New Atheists" have brought up again recently.

Long before the "Chemical Revolution" of the 18th and 19th centuries—in which chemists discovered firm evidence supporting chemical atomism—European natural philosophers and scientists (prominently including Isaac Newton and Robert Boyle) generally accepted the Epicurean doctrine (advocated by Lucretius) that all things were made up of minute and rapidly-moving "corpuscles." Although Boyle, Newton, and others *rejected* Lucretius's conclusions with respect to religion, his epic poem deeply influenced their way of thinking. Isaac Newton's famously successful late 17th century treatment of the motions of bodies—even including the long-debated movements of the moon and planets—considered "matter" as self-sustaining stuff, resistant to change in motion to an extent proportional to its mass but otherwise inert—so that all motion was *impressed on* bodies by *external* sources of agency.

As a presumed corollary of the Renaissance understanding of how nature works, many philosophers now hold that properties of composite objects depend only ("supervene") on properties of components—that is the properties of the items at the most-microscopic structural level *determine* all properties (e.g., Armstrong 2010, p. 29 ff.). The doctrine that adequate knowledge of the microscopic components of things (and how they relate to each other) provides a sure basis for understanding nature had strong support from much of the science of the 20th century.

- During the first half of the century, quantum–mechanical interpretation of the electronic structure of atoms—and the description of isotopes in terms of nuclear protons and neutrons—supported the belief that *everything* was composed of *only a few* types of particles.
- At about the same time, "the synthetic theory" rather successfully integrated Mendelian genetics and population biology with Darwin's model of biological evolution.
- In the second half of the 20th century, "the central dogma of molecular biology" rationalized Mendelian genetics in molecular terms.

Correspondingly, one of the main "take-home lessons" of introductory chemistry instruction came to be that nothing exists *apart from* atoms of the chemical elements. Chemical educators (at many levels) have served as an effective sales-force convincing contemporary people that "actuality is incurably atomic" (Whitehead 1978, p. 61).

Whitehead also pointed out that, for more than three centuries: "… the cosmology derived from science has been asserting itself at the expense of older points of view with their origins elsewhere." But he continued: "Men can be provincial in time, as well as in place. We may ask ourselves whether the scientific mentality of the modern world in the immediate past is not a successful example of such provincial limitation" (Whitehead 1967, p. vii). Historian and philosopher R. G. Collingwood predicted (1945) a still-further shift in worldview would soon occur: Whitehead and this paper endorse that prediction. Arguably, dealing with technological and social problems that twenty-first century societies face *will require* that an alternative outlook be widely adopted (Gare 2010).

## 4 Contemporary Science

The main thrust of *current* science differs in important ways from what was envisioned by previous models of science. A few varied examples may suggest some areas of contemporary investigation that lie outside the range of applicability of the Lucretian model.

- Entities believed to be "elementary" in specific earlier periods repeatedly have been found to be composite by subsequent research.
- Recently-discovered self-organized dynamic astronomical structures have immense spatial and temporal extension.
- Macro-molecular and supra-molecular materials are now of central importance in both science and technology (Newth and Finnigan 2006).
- There is good evidence that life originated in evolutionary transitions in (proto-metabolic) cyclical *networks* of chemical reactions operating in open systems (Smith and Morowitz 2004).
- Patterns of persistent biological behavior turn out to be "multiply realizable"—several *diverse* underlying arrangements generate *the same* higher-level structure.
- Studies of evolutionary development ("Evo-Devo") show that complex multi-level interactions *control and regulate* the actions of genes (Carroll 2006).
- The ways in which organisms live and reproduce influence their genetic structure as much as genetic structure influences individual organisms.
- Psychology and neuroscience now go well beyond "reductive" models (e.g., Bennett and Hacker 2003; Bolender 2010; Donald 2001).
- In economics, recognition is spreading that more-inclusive entities must function well in order for action of self-interested economic individuals to be effective (Bowles and Gintis 2011).
- Sociologists now recognize that religions (broadly understood) are main mechanisms that motivate and organize *cooperative pro-social human action*. Counterintuitive (i.e., incredible) features may be transmission-enhancing advantages, rather than fatal flaws, in religious systems (Atran and Heinrich 2010).
- The social function of religious practices is only loosely connected to formal doctrines: religions have played indispensable parts in human evolution and will quite probably continue, albeit with evolutionary changes (Atran 2010).

## 5 Beyond the Renaissance Worldview

The usual philosophic assumption that properties of composite objects depend only ("supervene") on the properties of their components is often *not correct* (Mellor 2006). Generally, principles that apply to the components are *necessary but not sufficient* to deal with the behavior of complicated systems (Kauffman 1993, 1995; Mitchell 2009). Obtaining adequate scientific understanding of important problems requires attention to several "levels" of organization—characteristics of the most-miniscule components *only partially determine* behaviors of macroscopic systems. Regularities considered by "fundamental" microphysics are *necessary* to account for macroscopic coherences, but they are *not sufficient* (Bishop and Atmanspacher 2006). A myriad of detailed configurations would be consistent with any given composition of an isolated mechanical system. The *history of the relevant context* (Earley 2012) determines which of the many possible configurations of each specific real system is the one that *actually exists*. There is no single "fundamental" level of description that is adequate for all scientific discourse.

In the late nineteenth century French physicist Henri Poincaré (1854–1912) studied the details of the motion of the several planets that make up our solar system. He encountered situations for which the methods of Newtonian physical mechanics were ineffective due to the occurrence of "resonances"—more or less long-lived associations of otherwise independently-moving bodies. When such correlations developed, previously well-tested equations gave incorrect results: computed quantities increased without limit at specific parameter-values ("singularities"). Poincaré was able to deal with this difficulty by approximating some variables by divergent series (using "asymptotic expansions"). This technique (Berry 1994; Batterman 2002, 2009) generally led to discontinuous changes of the equations that described the systems. Familiar equations in terms of easily recognized system-components applied on one side of the singularity, but equations with quite different structures (and often involving variables not obviously directly related to the components from which the system had been assembled) were valid on the other side of the singularity. Those alternative expressions were relatively simple, emphasized important features, and *suppressed details* that were not relevant. Beyond a singularity, information about the detailed properties of the components of the original problem was *no longer important* in the description of the system. This approximation achieved success in describing a composite system—but at the cost of *wiping out* the significance of the detailed natures of the components.

Sciences other than "fundamental physics" can and do discover significant natural regularities. Usually, cooperative action of lower-level entities renders lower-level details inconsequential for the purposes of each "special science." This result is the basis on which every developed science treats some entities as quasi-elementary ("honorary simples") for the purposes of that science—even though another science may treat the same items as composites. This situation is well described by Hans Primas (1998): "The task of higher level theory is not to approximate the fundamental theory but to represent new patterns of reality." Robert Laughlin (1998 Nobel Laureate in Physics) writes:

> Over time, careful quantitative study of microscopic parts has revealed that at the primitive level at least, collective principles of organization are not just a quaint side-show but everything—the true source of physical law, including perhaps the most fundamental laws we know. ….[N]ature is now revealed to an enormous tower of truths, each descending from its parent, and then transcending that parent as the scale of measurement increases. Like Columbus or Marco Polo, we set out to explore a new country but instead discovered a new world. (Laughlin 2005, p. 208).

Approaches that are based on the assumption of independently-acting components may well be useful in dealing with relatively simple systems studied in elementary courses, but quite different outlooks are required for more complex cases—especially for self-organizing open-system dynamic coherences.

## 6 Open-System Dynamic Coherences

One of the main growth-areas of twenty-first century science is investigation of how *processes* combine to yield more-or-less stable persistent integrations—self-organizing dynamic coherences that return to prior patterns of organization after disturbance. In such systems, networks of processes (collections of chemical reactions, sets of interactions of quarks and gluons, combinations of actions of biological organisms, assemblies of economic transactions …) fit together to produce more or less persistent dynamic non-equilibrium steady states, sometimes (if rather inelegantly) called "quasi-equilibriums." Such systems sometimes change rapidly and drastically without obvious cause. This and other aspects of the behavior of systems built up from inter-connected processes are *highly counter-intuitive*—that is, they fall outside the range of ordinary experience. Recent progress on the ways that processes of change combine has brought major parts of the behavior of such "non-linear dynamic systems" within the range of possible scientific understanding. Major aspects of the world—such as biological and cultural evolution—can now be at least partially understood on the basis of recently-achieved insights into how self-organized far-from-equilibrium coherences behave. However, rather different modes of reasoning are needed for these systems than for less-complex problems (e.g., Bechtel and Richardson 2010).

Ordinary chemical substances are characterized by equilibrium arrangements of elemental centers ("atoms"): vibrations and rotations around those reference arrangements continually occur. Each system returns to its equilibrium arrangement after a disturbance. Self-restoring capability is the defining characteristic of "structure:" such arrangements are called "equilibrium structures." We now recognize that many entities formerly thought to be substantial and enduring are actually resultants of *networks of processes*. When nature involves what seems to be a persistently-constant concentration of some chemical species, close examination usually leads to recognition that the concentration is maintained near its average value by some sort of *network of interconnected reactions*, generally an *oscillatory* one. Rather than actually persisting without change, concentrations usually alternately increase and decrease in such a way that the average concentration-value is more-or-less constant over time—and the system tends to return to that pattern of oscillation after any modest disturbance (Shinar and Feinberg 2010). Such dynamic structures differ in important ways from equilibrium structures. Ordinary solids, liquids, and gases (all of them are equilibrium structures) can persist indefinitely in *closed* systems, fully isolated from their environment. In contrast, all persistent, dynamic, oscillatory, coherences continually consume higher-energy, lower-entropy materials and generate lower-energy, higher-entropy products. These coherences are designated as "dissipative structures." (Kondepudi and Prigogine 1998). Such dynamic entities *require* interaction with their environment in order to persist—they must exist in "*open* systems." If reactants continuously enter and products leave, then a system may function (oscillate) for an indefinitely long time: otherwise, oscillations will eventually cease. Spontaneous formation of such far-from-equilibrium objects occurs because of the reactive propensities of the components. Although the environment continually supplies high-energy reactants and receives low-energy products, in an important sense these coherences are *self-organized.*

What sort of relationships might give rise to a collection of several dynamic components *behaving coherently*—the collection *functioning as a unit*? *Closures of relationships*—effectively "unit-determining properties" (Armstrong 2004)—can occur in dynamic systems at many levels, from that studied by quantum mechanics to that of interest to international economics or astronomical cosmology. Intense study of such coherences dominates much of contemporary physics, biology, and social science. Networks of *chemical* processes provide typical and accessible examples of such behavior. Chemists—particularly Belgian physical chemist, Ilya Prigogine (1917–2003, Nobel Prize in Chemistry 1997)—made major contributions to our understanding of this type of coherent organization (Prigogine and Stengers 1997; Epstein and Pojman 1998; Kondepudi and Prigogine 1998).

Each chemical dissipative structure involves a reaction (or set of reactions) that gets faster as it goes on—an "autocatalytic" process (The simplest example would be: $A + B \rightarrow 2\,B$, where B is "an autocatalyst."). Systems that involve such reactions tend to be *unstable*—they readily disperse, explode, or settle into a single state. However, if such a system also involves one or more processes that *suitably reduce* the concentration of the autocatalyst (such as $B + C \rightarrow D$) then the system may return to its original condition, and even do so repeatedly, thereby generating continuing oscillations—a kind of long-term persistence (Earley 2003).

In each dynamic coherence, *closure* of the network of reactions that define the structure causes the effects of the coherence on other items to be *quite different* from effects of the same components but without that closure. The structure *as a whole* makes a difference: therefore, that coherence must be counted as one of the items that comprise the world (Ney 2009; Earley 2006)—the structure as a whole has *ontological* significance. The effects of the structure are the sums of the effects of the components, but *which components persist* in the system depends on the details of the closure of the network of reactions. The *network* of relationships regulates the *composition* of the system. For example, the existence of biological dissipative structures accounts for the production (and therefore the existence) of high-energy molecular forms such as sugars, proteins, and DNAs: but those molecules are themselves components of the dissipative structures that produce them. Components are influenced by the characteristics of the coherences which those same components constitute. Lucretius deviated from his master Epicurus in postulating that bodies *sometimes swerve* (in what he called a *clinamen*) away from their normal straight-line motions and thereby (in some way or other) produce macroscopic objects—but he did not consider how this might work out in practice. It has turned out that fluctuations that generate *closure of networks of relationship* are essential for all persistent coherences.

Dissipative structures exemplify the situation described in 1932 by Otto Neurath (1882–1945): "We are like sailors who must rebuild their ship on the open sea, never able to dismantle it in dry-dock and to reconstruct it there out of the best materials" (Neurath 1959, p. 201; see also Cartwright et al. 1996). Reactant molecules and ions that comprise a dissipative structure at a given time are not the same individuals that make up the coherence at a later time—but the coherence maintains itself during the change of components (as Neurath's boat must stay afloat while it is being reconstructed). The particular propane and dioxygen molecules that fuel a steady gas-jet flame at one instant are not the same molecules that fuel the same flame later: when a tsunami moves across an ocean (at several hundred miles per hour) specific samples of sea water move up and down as the wave (which they comprise) moves over them—but those samples do not travel far in the direction in which the wave so rapidly moves.

Although Lucretius and modern chemical educators have been correct in asserting nothing exists *apart from* microscopic components, it is *not* correct to claim that nothing exists *other than* those components. Whenever coherences display non-redundant causality—when they have effects over and above those of their uncoordinated components—significant *ontological* emergence has occurred (Earley 2006).

## 7 The New Idea of Nature

The view of science that dominated the twentieth century emphasized *analysis*: it suggested that the *ultimate sub-microscopic constituents* of nature are what is finally important, when all is said and done. The science of the 21st century embodies a quite a different view—one that emphasizes *creative synthesis*—combining and modifying pre-existing items to produce new and useful coherences (Earley 2008). The new approach does not deny the effectiveness and usefulness of analytic methods—rather it builds on those techniques and then moves beyond them. *Creativity* is now more important than composition: "The problem of evolution is the development of enduring harmonies of enduring shapes of value, which merge into higher attainments of things beyond themselves" (Whitehead 1967, p. 94). Integration and coherence can occur at many levels, and existing coherences can fail to function at each of them. Disintegration at a lower level can bring about rupture of high-level coherence—but failure of higher-level integrations can destroy conditions that are necessary for persistence of lower-level integration. Persistence and adequacy of function at any level depend on maintenance of integrations at several levels.

Rapid development of chemistry in the eighteenth and nineteenth centuries depended on prior description of the behavior of ores, minerals, and other materials—clarification of "natural history." During the nineteenth and twentieth centuries human knowledge of natural history expanded greatly. We now understand that the lighter chemical elements came into being in stars such as our Sun—after protons that had been produced by the initial singularity and subsequent expansion ("the big bang") joined together ("fused") to produce helium, carbon, and other light elements. In such stars gravitational compression is balanced by expansive tendencies due to energy released in the fusion processes—so that long-lived dynamic coherences are produced. Heavier elements result from cataclysmic changes which dynamic stellar systems undergo as they deplete their fuel supplies. Such natural synthetic processes should receive as much (or more) emphasis in elementary chemical instruction as the analytical achievements on which our understanding happens to be historically based (Earley 2004).

The basis of our current scientific worldview—"the evolutionary epic"—is a story of repeated functioning of nested and interconnected dissipative structures including many chemical reaction-networks (Mason 1991; Chaisson 2006). The basic principle that self-organization of dissipative structures *increases the rate of entropy-generation* (compared to otherwise similar situations without dynamic coherence) underlies any understanding of the general characteristics of evolution (Schneider and Sagan 2005). Explicit focus on closure of networks of processes in far-from-equilibrium systems is important—and will be even more significant in the future. Chemical educators should explicitly cover the evolutionary origins of the chemical coherences they deal with—and consider nonlinear dynamic systems (and models) in their courses. Even though most undergraduate students rather easily learn to use appropriate software packages, they encounter real *conceptual* problems with dynamic-system modeling (Earley 1996). The "idea of nature" needed to deal with nonlinear dynamic systems is not the same as the worldview that largely dominated the twentieth century.

Achievements of science under the former banner provide a necessary basis of the newer approach—and the precision of language emphasized by positivistic philosophers (Matthews 2004) must be maintained. The prior approach—now deeply built into 'common sense' (Kincheloe and Tobin 2009)—should not be disparaged, but rather treated 'a special case' for which simplifying assumptions apply. But that now-traditional approach must be extended and reinterpreted by effective educational innovation (e.g., Bryce 2010).

## 8 Shifting the Focus

The pattern shown in Fig. 1 is quite characteristic of autocatalytic processes. In order for human population to long survive, processes balancing that rapid population-increase must increase in effectiveness. Hopefully, this will occur quite soon and by mechanisms other than the violent conflict among human groups that mainly accounted for low growth-rates for pre-historic human populations.

For the past two centuries humans have exploited fossil fuels to obtain cheap energy—taking first coal and then petroleum from below Earth's surface and turning those materials into water and carbon dioxide in the atmosphere. That easy situation cannot long continue—both because of limitations on resources and due to deleterious effects of emissions. Ongoing rapid growth of human population (and also rapid increase of per-capita disposable income) makes it clear that presently-known technologies providing for human subsistence are unsustainable. Since much low-hanging technological fruit has already been harvested, innovations that are explicitly science-related must become even more important in the future than they have been in the past. Previously, many ordinary industrial workers did well with little understanding either of science or of the intricacies of human culture. In the future, people will need stronger and wider educational backgrounds—both as workers and as civic decision-makers. Before petroleum reserves are depleted—sometime during the present century—efficient catalytic systems based on robust and cheap inorganic materials must be developed for artificial photosynthesis and for chemical feed-stock generation.[2] Research on artificial photosynthesis spanning several decades suggests that such developments may be possible, but that achieving such progress will require long-term, high-level scientific and engineering work on a large scale (Gray 2009).

Paradoxically, the notion that composites can be understood solely in terms of the their minimum components has inspired large-scale highly-cooperative state-sponsored projects such as the ten-billion-dollar *Large Hadron Collider*, operated by the European Organization for Nuclear Research (CERN) with long-term funding by 20 European nations.[3] In July, 2012 CERN announced "strong indications for the presence of a new particle, which could be the Higgs boson"—the particle thought to be responsible for the mass of other particles. Technologies necessary for future long-term human flourishing will also require massive technical efforts and large-scale government funding. Populations will need to reduce consumption to support research on complex interrelationships of multilevel open-system coherences. On what basis could effective arguments to support such long-term sacrifice of individual benefit be made? Surely, general understanding of the multi-level structure of things is a prerequisite—but widespread appreciation of how the creative dynamism of nature functions through nonlinear dynamic coherences will also be essential. New concepts of how the world works must be built into the common-sense of future generations in order to justify needed science-related expenditures. Chemistry educators can and should make major contributions to this highly-important shift in the popular idea of nature. Perhaps some future general-chemistry students will move on to emulate Lucretius—and to spread the new idea of nature through outstandingly-creative artistic work.[4]

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[2] Chemsystems.com reports that: "The world consumed over 600 million tons of feedstocks in 2009 in the production of … basic petrochemicals.… Total global feedstock consumption is projected to reach 1 billion tons [per year] by 2025."

[3] Since the end of the Cold War had reduced the apparent military importance of high-energy physics, the US Congress cancelled its annual funding of the corresponding American experiment (The Superconducting Super Collider) in 1993—after more than two billion dollars had been spent on that project.

[4] Tom Stoppard's prize-winning 1993 play *Arcadia* now leads in this regard.

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