Would Introductory Chemistry Courses Work Better with a New Philosophical Basis?

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Abstract:

One of the main functions that introductory chemistry courses have fulfilled during the past century has been to provide evidence for the general validity of 'the atomic hypothesis.' A second function has been to demonstrate that an analytical approach has wide applicability in rationalizing many kinds of phenomena. Following R.G. Collingwood, these two functions can be recognized as related to a philosophical 'cosmology' (worldview, *weltanshauung*) that became dominant in the later Renaissance. Recent developments in many areas of science and in, chemistry have emphasized the central importance of understanding synthetic, developmental, and evolutionary aspects of nature. This paper argues that these scientific developments, and changes in other aspects of culture, amount to a widespread shift to an alternative cosmology, a quite different general worldview. To the extent that this is the case, introductory chemistry courses ought to be changed in fundamental ways. Rather that having a main focus on analysis to microscopic components, introductory chemistry instruction should emphasize current scientific understanding of the (synthetic) evolutionary origins of the present world. This altered approach would make better contact with the perceived concerns of students.

Keywords: ***cosmology***, process, metaphor, dynamic systems, evolution, chemical education.

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The title of this paper suggests several questions. Do introductory chemistry courses *now* have a particular philosophical basis? *Why* should that present basis be changed? *How* might this be done?

The Present Philosophical Basis of Introductory Chemistry Courses

Experienced instructors in introductory chemistry courses generally deny that their professional activity has anything to do with philosophy. But recall what the eminent economist John Maynard Keynes (1883-1946) wrote:

> Practical men, who believe themselves to be quite exempt from any intellectual influences, are usually the slaves of some defunct economist. . . It is ideas, not vested interests, which are dangerous for good or evil. (Keynes, 1936)

Keynes (during the Great Depression) was referring to the 'hard-headed business men' of his acquaintance — but his observation may apply (*mutans mutandis*) to teachers of general chemistry. Perhaps chemical educators are unwittingly influenced by long departed philosophers — as Keynes' 'practical men' were unknowing disciples of dead economic theorists. This paper claims that current introductory chemistry courses generally share certain basic (philosophical) presuppositions — a 'cosmology', a 'worldview.' Furthermore, that set of presuppositions is now obsolescent, at best, and should be replaced by an alternative outlook.

To develop the idea of the philosophical basis of current introductory chemistry instruction, I use the analysis of the English historian and philosopher, R. G. Collingwood (1889-1943).

> In the history of European thought there have been *three* periods of constructive cosmological thinking; three periods, that is to say, when *the idea of nature* has come into the focus of thought, become the subject of intense and protracted reflection, and consequently acquired new characteristics which in their turn have given a new aspect to the detailed science of nature that has been based upon it. (Collingwood, 1945, p. 1, *emphasis* added.)

What does Collingwood mean by 'cosmological thinking'? A dictionary definition of 'cosmology' is 'a theory of the universe'. A part of astronomical science is called cosmology, but in the philosophical sense that Collingwood uses, 'a cosmology' is a general conceptual system (or set of presuppositions) dealing with how the world works — a worldview, a *weltanshauung,* an 'idea of nature.'[1] Collingwood's book claims that only a few 'ideas of nature' (cosmologies, in the philosophic sense) have been dominant in Western civilization over the past several millennia[2]. These cosmologies have been separated by *three* great intellectual (and cultural) transitions. To anticipate what follows, I will claim that chemical pedagogy is now largely dominated by an obsolescent cosmology, and suggest that a shift, already in progress, to a different idea of nature should be completed expeditiously.

A Shift in Cosmology

Collingwood holds that a major change in the idea of nature took place in the late Renaissance — concomitant with the origin of modern science.

> ....The Renaissance view of nature ..(was) ..antithetical to the Greek view. ... The central point of this antithesis was the denial that the world of nature, the world studied by physical science, is an organism, and the assertion that it is devoid of both intelligence and of life. The movements which it exhibits… are imposed on it from without, and their regularity is due to 'laws of nature' likewise imposed from without. Instead of being an organism, the natural world is a machine. (Collingwood, 1945, pp 3, 5.)

In the Renaissance, nature came to be viewed in 'mechanical' terms — as an articulated collection of components, none of which was self-moving.[3] Each part of the cosmic machine was considered to be set into motion by some other part(s). The success of Newtonian science in rationalizing the motions of the bright objects in the night sky — planetary trajectories seemed to become matters calculable *a priori* — gave a powerful endorsement to the 'mechanical' cosmology. About the same time that the mechanical nature of the world was being widely accepted, an opinion formerly held by a few became more general — conviction spread among educated segments of society that indivisible corpuscles ('atoms') were fundamental constituents of all naturally occurring things. Both atomism[4] and mechanism were main features of what Collingwood calls 'Renaissance cosmology.'[5]

Advance in understanding the workings of the physical world was only one of the great achievements of the Renaissance — during the same period that modern science was invented, Latin literary works were located and studied[6] and human individuality was 'discovered.' (Cassierer, 1964.) Painters celebrated the detailed beauties of nature in new ways (Barringer, 1999. Erickson, 2000) and — perhaps aided by advances in the technology of optics (Hockney, 2001. Wheelock, 1997) — depicted human faces with unprecedented realism and individuality. These coupled artistic developments — increased sensitivity to the small scale details of the natural world, and recognition of unique individual characteristics of each human person — might well have been interpreted as two insights into a single complex reality. But historically, quite a different interpretation came to prevail. The dominant opinion came to be that *physical nature* worked in fully deterministic ways, but *human* actions were subject to causes of quite different sorts. As Rom Harré puts it:

> …much philosophizing about human nature in the last 500 years of the second millennium has been based on the assumption that the mental and material attributes of persons are utterly different. (Harré, 2000, p. 268.)

In his highly influential oration "On the Dignity of Man", Giovanni Pico della Mirandola (1470-1533) put these words into the mouth of God:

> We have given to thee, Adam, no fixed seat, no form of thy very own, no gift peculiarly thine, that thou mayest feel as thine own, have as thine own, possess as thine own, the seat, the form, the gifts which thou shalt desire. A limited nature in other creatures is confined within the laws written down by Us. In conformity with thy free judgment, in whose hands I have placed thee, thou art confined by no bounds; and thou wilt fix the limits of nature by thyself. (Pico della Mirandola, 1965; Randall, 1940, p. 123.)

For Pico, each human person is *self-organizing* (each determines their own nature) — but other physical things, and even the non-physical angels, were quite different — they were all *immutably pre-determined* in their natures.

By the end of the Renaissance, the maxim of the Roman poet Lucretius:

All nature, then, as self-sustained, consists
Of twain of things: of bodies and of void.

had been generally accepted (Leclerc, 1972) but in a modified form that probably would not have pleased that antique author. It was widely conceded that *non-human* events dealt with rearrangement of atoms[7] — subject to physical and chemical laws that were then beginning to be discovered — but *human* becoming was held to operate on a different plane, following quite different logic.[8] Such 'dualistic' opinions can be traced back through Scholastic theologians, (Aquinas, ~1264) and Neo-Platonist thinkers (Plotinus, 1952) of late antiquity — but issued in full clarity in the philosophy of Rene Descartes (1596-1650), who explicitly taught that there were two sorts of substantial things, extended stuff (bodies) *res extensa*, and thinking things (spirits) *res cogitans.* Collingwood claims that some version of this bifurcated cosmology was the general (and largely unexamined) presupposition of much of the philosophic thought of the late Renaissance and of subsequent periods. Alfred North Whitehead (1861-1947) agreed with Collingwood's analysis, calling the dualistic outlook that has been prevalent during the 'modern' period 'scientific materialism.'[9] (Whitehead, 1967)

Introductory Chemistry Courses and Renaissance Cosmology

Galilei Galileo (1564-1642), Robert Boyle (1627-1691), and most of the other founders of modern science, were convinced 'corpuscularians' — adherents of the philosophical doctrines developed by Democritus (460-370 BCE), Lucretius (c. 99 - c. 55 BCE), and Pierre Gassendi (1592-1655) that bodies were somehow composed of minute particles — atoms or corpuscles. Certainly Boyle, (Hall, 1965) and quite probably the others, also held firmly to the existence of 'spirits' — beings quite separate from those bodies that were composed of corpuscles. However – even though those earlier savants had accepted 'the corpuscular philosophy' – solid, convincing evidence of the widespread applicability of 'the atomic hypothesis' was not available until after Antoine Lavoisier's (1743-1794) chemical revolution of the late eighteenth century. The great work of nineteenth century chemists (Bensaude-Vincent, 1996) — following ideas outlined by John Dalton (1766-1844) and leading to Dmitri Mendeleev's (1834-1907) periodic system, and on to Jacobus van 't Hoff's (1852- 1911) structural formulae — established secure knowledge of the atomicity of all material objects as a permanent feature of human culture.

The elucidation of the composite nature of the atomic nucleus, and of the relationship of the nucleus to radioactivity (joint achievements of chemists and physicists in the early twentieth century) confirmed and extended this achievement — by showing that the internal constitution of the atoms themselves was also understandable on a corpuscularian basis. The explanation of the nature of chemical bonding – essentially complete by the 1950s (Pauling, 1939. Coulson, 1952.) – further demonstrated the general power of that approach by showing that the mutual attachment of atoms in molecules could be understood (in an approximate way at least) on the basic of the interactions of electrons and atomic nuclei. Much of the success of chemical research up to the middle of the twentieth century can be regarded as elaboration of the details of one part of the cosmology that had been assumed, without proof, by Renaissance scientists and humanists.

Modern physical science recognizes its continuity with the 'natural philosophy' of the late Renaissance. Galileo Galilei, Isaac Newton, and Robert Boyle are counted founders of the style of investigation that we call modern science. Every beginning student of physics repeats a version of Galileo's inclined plane experiment: a scientist not familiar with Newton's second law would be badly educated indeed: each introductory chemistry laboratory course includes manipulations of gases somehow related to experiments done by Boyle. Clearly, concepts developed during the late Renaissance are now learned and used by everyone that has even a passing familiarity with contemporary science.

During the first half of the twentieth century, introductory chemistry courses featured large amounts of descriptive material — what might be called 'natural history' — including accounts of industrial chemical processes. Exposition of the quantitative evidence for Daltonian atomism and illustration of the power of the periodic table in rationalizing vast amounts of descriptive information provided an intellectual structure ('story-line') for the course.

The central importance of atomic doctrines for introductory chemistry instruction is shown in the two prefaces to the influential *Textbook of Chemistry* by William A. Noyes (1857 – 1941) of the University of Illinois. The preface to the first edition, published in 1913, reads, in part:

> The atomic theory has been made the fundamental basis of the work and has been treated throughout as essentially true and not merely a convenient hypothesis likely to be some day displaced by something very different. It is believed that the

> development of our knowledge during the last few years fully justifies this course. (Noyes, 1926, p. iii.)

The preface to the second (revised) edition of the same book, published in 1926, states, in part:

> The past ten years have been years of very rapid advance in some of the most fundamental concepts of chemistry. Atoms are no longer the ultimate, indivisible and unchangeable particles which they once seemed to be. Physicists and chemists are beginning to gain an insight into the fundamental structure of the atoms somewhat as the chemists of the last half of the nineteenth century learned how to decipher the arrangements of the atoms of the of organic compounds. The intimate connection between electrons and chemical combination now seems to be fully established. The Periodic Table has acquired a new meaning and the development of X-ray spectra in close connection with the atomic numbers has set very narrow limits for the possible discovery of new elements. (Noyes, 1926, p. v.)

Clearly, during the early 1900s, establishing the validity of the corpuscular hypothesis was a major aim of chemistry instruction. Around the middle of the twentieth century, simplified treatments of thermodynamics and quantum chemistry partially displaced descriptive chemistry in introductory chemistry courses. Linus Pauling (1901-1994) who had played a key role in understanding chemical bonding (Pauling, 1939.) also led the mid century 'reform' of introductory chemistry instruction (Pauling, 1952.). Emphasis shifted away from a 'natural history' approach towards understanding and applying 'chemical principles'— generally by means of quantitative physico-chemical (mechanical, in a broad sense) explanations of selected phenomena.

> In writing this book, we used a "principles" approach, an approach which encourages students to understand ideas instead of memorizing definitions. We also posed hundreds of problems that call for comprehension in their solution. In the revised edition, we have continued the emphasis on principles and problems. …. (Sienko, 1961, p. v.)

This modification of emphasis might seem to be a shift in basic 'story-line' of the introductory chemistry course — but it is also possible to interpret this change as a consistent development within a single narrative pattern. One major social function (among others) that introductory chemistry courses fulfilled throughout the twentieth century was introducing successive rising generations to the atomistic and mechanical cosmology that was framed during the late Renaissance. The residual descriptive (mainly inorganic) chemistry that survived the mid-twentieth century reformulation of introductory chemistry courses still served to establish the validity of the atomistic approach to nature well enough to convince students that 'actuality is incurably atomic' (Whitehead, 1968, p. 61.). The physico-chemical parts of that course demonstrated that mechanics (in its classical, quantum, and statistical versions) can rationalize all sorts of interesting things — even aspects of biology. The take-home message of such a course (the perceived point of the story being told) seems likely to be that *submicroscopic components of things are what is ultimately important,* when all is said and done — '..the elements of analysis are *more real* than the terms of synthesis.' (Teilhard de Chardin, 1969.)

But do present-day students find that philosophical doctrine attractive, or even credible? Students know that they, their friends, and their concerns, are real and interesting. To the extent that they get the impression that chemists seriously hold that what is 'really real' are the smallest, most miniscule, components of things, students may adopt towards chemistry an attitude similar to one that a Charles Dickens character held towards the law.

> "If the law supposes that," said Mr. Bumble, "the law is a ass, a idiot." (Dickens, 1837)

On such a basis, many students may conclude (logically enough) that they can safely *ignore* chemical science, and turn their attention to matters likely to have more importance for their lives.[10] To the extent that the interpretation of the 'story-line' of introductory chemical instruction given above is correct, it may not be surprising that chemists have an unflattering public image.

General Education and Professional Training

In the nineteenth century, chemistry was widely taught in American colleges as a part 'the general education curriculum'. Science in general and chemistry in particular were valued for their contribution to liberal education — in economic terms, this would be considered a 'consumer good'. A major change occurred in the early years of the twentieth century — greatly fostered by the Flexner Report (Flexner, 1910) that brought on a major reform of medical education in the United States. Collegiate instruction in the rudiments of chemistry came to be required for admission to medical schools and other professional programs. Large numbers of students filled the chemistry lecture rooms and laboratories of American colleges and universities — many, in order to prepare for later professional studies. For many students, chemistry had become 'a producer good'. This change had a definite impact on the content of chemistry instruction. Proficiency in technical computation (e.g., stoichiometry calculations) came to be highly valued — general education concerns receded in importance. Chemistry courses with focus on general education continued to be offered but had much lowered prestige — serious students were expected to take the 'main' General Chemistry course.

There is no doubt that in many respects this system worked well. Large introductory courses formed a secure base on which elaborate systems of more specialized courses for small groups of students, and vigorous chemical research activity, thrived. Chemists were free to concentrate on the principles of their own science — matters of concern to the wider society could safely be confined to 'text boxes' for optional reading, or ignored. But, as often happens in complex dynamical systems, over time, previously functional arrangements may become increasingly unsatisfactory.

In a guest editorial in *Chemical & Engineering News,* Ronald Breslow (President of the American Chemical Society for 1996) outlined widely felt dissatisfaction (of students and others) with present-day introductory chemistry courses. (Breslow, 2001) He urged that introductory chemistry courses should become 'more general' by including more material of the 'natural history' sort and relying less on numerical calculations.[11] Perhaps such minor tinkering can ameliorate some aspects of the problem Breslow cites, but it is also possible that more radical change is needed. Stuart Kaufmann's computational experiments on the evolution of model dynamic systems show that in complicated environments, systems often reach 'local maxima' on a 'fitness landscape.' In such a case, no amount of incremental change will improve the situation — a major shift to a quite different arrangement, though risky, is the only route that will lead to evolutionary advance (Kaufmann, 1998). Perhaps the present philosophical basis of introductory chemistry instruction (the overall 'story line' of the course) has outlived its usefulness, and should be replaced. What alternative is there to the present narrative structure?

The Present Transition

Writing near the middle of the twentieth century, Collingwood discerned that a *new idea of nature* was coming to the fore — he held that Renaissance cosmology was being superceded by something different, that a major transition was under way — a change as momentous as the origin of science in the late Renaissance.

> .... (A new) view of nature, which first begins to find expression toward the end of the eighteenth century and ever since then has been gathering weight and establishing itself more securely down to the present day, is based on the analogy between processes of the natural world as studied by scientists and the vicissitudes of human affairs as studied by historians. (Collingwood, 1945, p. 9.)

Collingwood prophesied the new transition, but did not describe it fully — though he did call attention to philosophical ideas of Berkeley, Hegel, Bergson, and Whitehead that partially exemplified what he had in mind. During the more than sixty years that have elapsed since his prediction, events have further specified his insight — and have validated it. Contemporary thought and practice have moved far beyond the atomistic and mechanistic outlook that was characteristic of Renaissance cosmology. Science has abandoned the idea that there is a *fundamental* level of description (e.g., Dehmelt, 1990) — the doctrine that the submicroscopic world is simple, that there is a small set of elementary (non-composite) particles.[12] The entities that contemporary scientists encounter (and imagine) are not inert — as bits of Newtonian 'matter' were held to be — but rather they are active, dynamic, self-moving, self assembling, and even self-organizing (Prigogine, 1997.).

Mechanistic explanations abound in all areas of contemporary science — but they rarely involve mere collisions of simple units as Renaissance mechanism supposed.[13] Modern industrial chemistry, and biological science deal with complex networks of chemical processes involving high selectivity and subtle controls that depend on intricate details of interactions between complex macromolecules. In many branches of present-day science (including many parts of chemistry (Lehn, 2001.)) questions of evolutionary development (history, in a sense) are of central importance. (Mason, 1991.) There is as much (or more) interest in understanding how existing units come together to constitute complex functional agents (e.g., Wolfram, 2002.) as in resolution of such wholes into component parts. Mathematical and conceptual tools developed in one new scientific area rapidly find application in others. Atomism and mechanism have not been abandoned— but they have been reinterpreted so that the meaning of these terms is now quite different from what it was a scant half-century ago. Investigation of nonlinear evolutionary dynamics – the study of complex self-organizing systems (Epstein, 2000. Rescher, 1998.) – both requires and generates (Hacking, 1983) a *new idea of nature* quite different from notions that have been generally held for several hundred years. Taken together, these shifts in emphasis and interpretation amount to a transition in cosmology — development of a different basic attitude toward how the world works. To oversimplify, the change may be regarded as a shift from substance-based ('rock') metaphors (Brown, 2003), to process-centered ('flame') ways of thought (Rescher, 2000, _________ 1992, 1998a, 1998b, 2000, 2003a, 2003b, 2003c, 2003d)

A conceptual scheme based on simple, material "particles" as fundamental constituents of physical things – on a single ultimate level of explanation to which all other levels of explanation were related as approximations – is no longer adequate. In the new 'idea of nature' priority is not ascribed to any single *type or level* of entity – be it microscopic corpuscle, individual biological organism, or self-determining human agent. What *is* fundamental is the (historical) processes by which individual entities are integrated into functional unitary aggregations. Humans are no longer regarded as somehow *apart from* the natural world, but rather are seen as *parts* of nature (Kauffmann, 2000), comprised of myriads of smaller systems, and also components of large-scale natural aggregations – including, familial, political, economic, linguistic, cultural, and ecological systems. Science is no longer held to be different in kind from other human intellectual pursuits – the myth of 'the scientific method' has been superceded (Harré, 2000). Introductory instruction in science can no longer be carried out as if in relative isolation from other human concerns.

What Should Be Done?

Every human culture has used *'creation stories'* — accounts of how the world came to be as it is — to convey important values (e.g., Urton, 1990). Contemporary Western culture now has *two* *sets* of such stories. One of these sets — let's call it 'the Evolutionary Epic' (Chaisson, 1998) — derives from science. The other, more traditional, set of stories arises from 'older points of view with their origins elsewhere' (Whitehead, 1967, p. vii.) However, both of these collections of accounts have major problems. Traditional creation narratives (if interpreted literally) are convincing only to a minority of educated people. The corresponding scientific accounts have not yet made sufficient contact with the lives of ordinary people to serve the important social functions of creation stories. This suggests that introductory science courses should be designed with the explicit goal (among others) of introducing students to the main points of the story that science now tells about the origin of the world in which we all dwell, while at the same time maintaining the maximum contact with other aspects of human culture — including venerable traditions that have been important parts of the upbringing of many students. (________, 1990, Del Re, 2000.)

Nancy Abrams and Joel Primack suggested that the scientific cosmology being developed by astronomy and astrophysics can provide a cosmology (in the more general sense) that may be useful (as earlier creation stories have previously been) in

> defining a larger context and grounding people's sense of reality, and their codes of behavior in [a] grand scheme. (Abrams, 2001.)

Chemists may wish Abrams and Primack well in their efforts to combine the two sorts of cosmology, but clearly we should also make similar efforts in our own field. Many of the most important and interesting stages in the evolutionary epic are deeply chemical in nature (mason, 1991)— combustion of hydrogen in stars, cooking of heavy elements in supernovae, coalescence of inorganic compounds to produce cosmic dust and eventually planets, segregation of Earth's core and mantle, geochemical cycles, origin of life (________, 1998), initiation of photosynthesis, symbiosis of simple organisms and eventual formation of multicellular life-forms — all of these transitions can profitably be approached from the chemical point of view. And evolutionary change is not restricted to the distant past. Introductory chemistry courses would make excellent venues for serious discussion of evolutionary changes now taking place — and those likely to occur in the foreseeable future. This is especially true since new materials, produced by chemists, will surely play crucial roles in those developments.

Most of the exciting areas of present-day science, including much of chemistry, involve a mainly *synthetic* approach rather than a primarily *analytical* one. The old story-line of introductory chemistry courses — 'whatever exists can be understood through *analysis* into its component parts' — is no longer sufficient. A more appropriate story-line would be — 'everything came to be though *synthetic* processes' — that is, the Evolutionary Epic. Perhaps we should start with some remote situation, and tell a connected, coherent story of how the world came to be as it is — a story that *ends up* where the students live. Logically, perhaps one should start with *the vacuum* — an excitable medium. New classes of entities — quarks, atoms, molecules, stars, organisms, societies — could then be introduced as arising in evolutionary (historical, in Collingwood's sense) transitions from prior entities.[14] However, since the new cosmology builds on prior ones (classical antiquity and the Renaissance) it seems to work better to start at a somewhat later point in the evolutionary story, then backtrack after needed concepts are introduced.

One Approach

Chem. 044, *Evolution & Creation* — a one-semester introductory chemistry course involving nonlinear dynamics (_______, 1993) taught at __________ University for well prepared freshmen, used an evolutionary approach, with significant success.[15] A topical outline of that course is given in the Appendix. That course was divided into three sections.

The first section covered aspects of the evolution of human culture — from the time of separation of hominids from other primates to the first third of the twentieth century — and developed main points of the 'Renaissance cosmology.' Every human culture has had specialists of two main types — one group concerned with working with naturally occurring materials to produce useful items (herders, smiths, farmers, etc.), and the other group that dealt with organizing cooperative action of groups of people (shamans, warlords, priests, lawyers, etc). Practical action, in both material and social spheres, raises questions that call for explanation — interpretive stories offered as responses to such questions, in turn, influence how practical activity is carried out. The supposition that entities are composed of smaller bits, like building stones — 'the rock metaphor' — has proved to be especially effective in understanding phenomena and in guiding action. Prehistoric metallurgy discovered ways to break down (analyze) natural ores to produce useful metal objects. Formal mathematics – developed by ancient Greeks (at least partly on the basis of the experience of earlier land surveyors) – facilitated intellectual analysis of conceptual problems in terms of *archē* ('principles' or, less accurately, 'elements') — and even yielded predictions of motions of bright objects in the night sky (the planets) that were important in organizing religious calendars. The discovery of Pythagoras, that mathematics and physical nature are closely related, was illustrated in that course by use of the model that salts are composed of spherical electrically charged particles (ions), and that demonstration that the ratio of the radii of those (rock-like) entities correctly predicts the several types of structures found for MX salt crystals. In this context, particular attention was paid to *galena* — a lead ore found in the Athenian mines at Laurion that produced byproduct silver which financed the Greek fleet that defeated the Persians at Salamis in 480 BC. The responses of Aristotle and Plato to the corpuscular hypothesis, and the medieval problem of nominalism and realism, were also introduced. Quantitative calculations concerning simple stoichiometry, elementary mechanics, kinetic theory, and heats of reaction were introduced. Students were given the opportunity to 'play Dalton' in inventing an atomic weight scheme to fit data on analyses of ores (containing three previously unknown 'elements') from some other possible world. The interaction between scientific investigation and the concerns of religious specialists with astronomical timekeeping was discussed in terms of the career of Galileo. Nineteenth century developments in atomic spectroscopy and chemical periodicity, early twentieth century progress in understanding internal structures of atoms – and bonding within chemical entities – were briefly considered. Several other examples that showed the wide utility of the corpuscular approach were considered. At the end of this segment, developments in modern physics that suggested limits for 'the rock metaphor' were briefly outlined.

The second third of the course introduced an alternative basic metaphor — 'flame' rather than 'rock' — corresponding to the distinction between 'equilibrium' and 'dissipative' chemical structures (Kondepudi, 1998.). Initial illustrations included chemical oscillating reactions and self-assembling and self-organizing systems. With the background in physics and chemistry established in the first section, the narrative line now doubled back to outline current concepts of the evolution of the universe from the primordial vacuum (considered as an excitable medium), through the Big Bang, generation of particles, concrescence of stars and galaxies, nucleosynthesis of heavy elements, accretion of planets, differentiation of the Earth, origin of life, evolution of photosynthesis, and plate tectonic motions leading to opening of the East African Rift (the event that opened the first segment of the course). This narrative involved introduction of aspects of thermodynamic reasoning (Konepundi, 1998. Prigogine, 1997) applied to systems both close to and far from equilibrium, and reviewed aspects of current astronomy, the 'central dogma' of molecular biology, and the molecular structure of important biomolecules.

The third portion of the course applied the background developed in both prior segments to problems that will directly concern future activities of many of the students. The question of whether events can be predicted (determinism) was considered — both in terms of nonlinear chemical dynamics (chaos theory) and of quantum systems. The question of to what extent animal (and human) behavior is genetically controlled ('selfish' genes) was discussed from the point of view of a plurality of levels of selection, and of evolutionary stable strategies (Simon, 19900. The relationship of these concepts to chemical dissipative structures (previously covered), on the one hand, and to economic systems, on the other hand, was pointed out. These discussions invoked concepts introduced throughout earlier portions of the course. The final week of class mainly concerned a single specific problem — whether it would be advisable to build a titanium mining operation on the littoral forests of Madagascar.[16] The chemistry of titania (TiO_2), and the fact that titania replaces lead oxide (whose poisonous nature had been covered in the first section of the course and featured in the current local news) in white paint pigments was covered, along with arguments given by the World Bank and the Government of Madagascar in favor of that project — and those of the World Wildlife Fund against it. The goal of this discussion was to make clear to students that continued human flourishing depends on widespread understanding of basic concepts of chemical science.

James Watt's steam engine was first used only in especially deep coal mines, where horses could not function — only after much development was that invention used in 'important' industrial applications (Carnegie, 1910). Similarly, any seriously deviant version of introductory chemistry instruction must be developed in 'less critical' sections of the educational effort — as a non-science majors' course. The one semester course described above was taught for non-science majors (although some students who eventually earned the Ph.D. in science have started in that course). If a similar plan were used to design a two semester course for students interested in science (Both Brandeis University and Tufts University have experimented with the use of evolutionary approaches in parts of the chemistry majors' course.), all material necessary for further work in science could be included, as well as a number of important topics that are now not addressed.

Conclusion

Our society requires widespread *general* understanding of evolutionary cosmology — an understanding that is consistent with contemporary scientific practice. This is an important 'general education' mission that differs from the mission of preparing students for further work in science and related disciplines — but is not necessarily inconsistent with that pre-professional mission. Introductory chemistry courses could fill both these important social functions in the future, by shifting to a story-line that emphasizes synthetic processes (including evolutionary ones) rather than analytic techniques. (Many biology departments have already switched from a taxonomic organization of introductory instruction to an evolutionary model.) Alternatively, introductory chemistry instruction could emulate other formerly dominant educational vehicles (e.g. study of classical languages) and retreat towards irrelevance, serving an ever-decreasing population of students who need to learn some technical chemistry for other purposes. In that case, biology, earth science, and astronomy departments may take up the challenge that chemistry chooses to decline.

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Appendix

Chemistry 044

Evolution and Creation: Self-organized Dynamic Coherence as Basis for **Our** *World*

Part I.

1. *Prologue*: creation stories; metaphor and science; evolution by natural selection; scientific arithmetic.
2. *Origins, Analysis, Structure*: Hominid evolution; social archaeology; prehistoric metallurgy and astronomy; elements, compounds, mixtures; structures of MX salts; chemical and conceptual analysis.
3. *Search for "Principles":* ancient and medieval achievements; the ‘rock’ metaphor; atoms and chemical calculations; Galileo and his trial; Newtonian physics; kinetic-molecular theory; heats of reaction.
4. *Particles and Fields*: proton, electron, neutron; electromagnetic spectrum; relativity; isotopes and nuclear stability; fundamental forces and vectors; limits of the ‘rock’ metaphor.
5. *Periods and Bonds*: periodic properties; electrons in atoms (I); ionic and covalent bonds; shapes of molecules; electronegativity; hydrogen bonds; solubility; science and method.

Part II.

6. *The Alternative Metaphor — 'the Flame.'* Oscillating reactions; equilibrium structures and dissipative structures; reaction mechanisms; 'self-assembly' and 'self-organization.'
7. *Origins of Elements*: colors of stars; Big Bang and before, origins of protons, expansion of the Universe; galaxies and stars; the "standard" model, nucleosynthesis, dispersion of atoms.
8. *Thermodynamics and the Earth:* concentration, equilibrium constants; interstellar molecules; solar system and planets; convection; plate tectonics; chemical cycles: Gaia hypothesis; free energy and entropy.

9. *Kinetics, Catalysis, Life*: rates; catalytic cycles; protocells; biological energy storage; photosynthesis; amino acids, enzymes.

10. *Genetics, Symbiosis:* nucleic acids; protein synthesis; genetic code; phage X-174; fermentation, respiration; eucaryotes; sex; *D. Discoidium.*

Part III.

11. *Causality, closure, chaos:* quantum indeterminacy; complementarity; electrons in atoms (II); nonlinear dynamics; deterministic chaos.

12. *On Reported Selfishness of Genes:* replicators; genetic variation; kin selection; human altruism (Simon, 1990).

13. *Games, Strategies, Mind:* units of selection; evolutionarily stable strategies; brain structure; memes and cultural evolution.

14. *Technology, Economics, Ecology, and Ideology:* sulfate and chloride processes for titania production – ecological and economic considerations; exploit Madagascar titanium ore deposits? opportunities and responsibilities in evolutionary development.

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Notes

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[1] Anthropologist Mary Douglas (Douglas, 1970) defends the thesis that the social structure of each human group deeply influences the general outlook on nature — the cosmology — that the members of that group hold. In view of the great changes in society since the origin of science, this view is consistent with the suggestion, made in this paper, that a major shift in cosmology is now under way.

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2 This is not meant to suggest that, at any time, a single outlook was held by every segment and member of any society, but rather that one worldview, or cosmology, was predominant at each period —in the sense that it formed an unexamined background of presuppositions for the elite, educated, parts of that society.

3 Newton's second law can be stated: $a = F / m$ — acceleration equals force divided by mass. Massive objects do not change their motion unless acted on by some external agent — that is, 'matter' (mass) is essentially inert (McMullin, 1963.).

4 A referee pointed out that since Democritus and other early Greek thinkers held atomistic doctrines it might not be useful to consider atomism as specifically a Renaissance notion. The point being made here is that the atomistic outlook, long the opinion of a minority, became quite *generally* held by educated people during the Renaissance. For a detailed discussion of this point, see Leclerc, 1972.

5 Collingwood is not claiming that mechanism was invented during the Renaissance —this outlook, like atomism, had been held by some groups in earlier ages. What is being asserted is that both these concepts became, in the late Renaissance, so widely held in educated circles as to become unexamined general presuppositions.

6 For an insightful discussion of the strengths and weaknesses of the humanistic literary movement of the Renaissance, see Randall, 1940, Chapter VI.

7 Recently, the claim has been made that what was really at issue in the trial of Galileo Galilei for heresy was not the astronomical theory of Copernicus, but rather Galileo's adherence to a corpuscular philosophy that was inconsistent with the Catholic doctrine of transubstantiation defined at the Council of Trent (Redondi, 1988.) — but that claim has been convincingly refuted. (Westfall, 1989.)

8 'Matter' as classically conceived was inert, not self-organizing. But Leibniz maintained: 'If nothing is active by its own nature, there will be nothing active at all'. (Leibniz, 1956.) Renaissance cosmology required a *second* principle, however it might be imagined. The philosophical cosmology that emerged from the Renaissance and the accompanying "scientific revolution" was a *dualistic* one — which admitted *two* distinct ontological realms — matter and spirit — each capable of independent existence. This dualistic

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outlook was what Whitehead called 'scientific materialism' (Whitehead, 1967). See also Leclerc, 1972.

9 Whitehead would include under this designation the ideas of some of our contemporaries who would strongly object to being called 'materialists' — because they hold some modified version of late-Renaissance dualism, with more or less independently existing 'bodies' and 'minds'.

10 Some report that persons who have studied economics are less 'cooperative' than others. (Frank, 1996.) Such a difference, if real, may be partly ascribed to self-selection of students, but also partly to an influence of the study of 'the dismal science' on those that study it. Economics courses may inculcate a 'social atomism' that is related to doctrines featured in chemistry instruction.

11 This might be interpreted as a suggestion to reverse, at least partly, the developments of the mid-twentieth century in introductory chemistry courses mentioned above.

12 Stephen Weinberg's recent catalog (Weinberg, 1994) of the *dramatis personae* of contemporary high energy physics does not give an impression of simplicity, as corresponding lists of fifty years ago did.

13 Even collisions of an argon atom with a diatomic molecule can be seen to be quite complicated. (Lorenz, 2001.)

14 It is important to emphasize the contrast between this recommended approach and the more customary procedure of starting with items familiar to the students and moving to ever smaller (more 'fundamental') units, on which understanding is supposed to be grounded — even though those microscopic units are far from experience of the students.

15 This course was taught for non-science majors, most of whom had three or more years of secondary school science.

16 http://allafrica.com/stories/200201080322.html