EVOLUTION FOR CHEMICAL ENGINEERS

E. N. LIGHTFOOT
University of Wisconsin • Madison, WI 53706-1691

This essay is written to suggest that a type of thinking described below under the term *evolutionary dynamics* is a key component of chemical engineering that should be given formal recognition in a variety of our professional activities. These include education of our students, recruiting of faculty, and even the direction of research. Moreover, there is available a large and rapidly growing reservoir of literature upon which we can draw for incorporating evolutionary concepts into our profession, and it is important to note that some academic researchers have already begun to implement these ideas.[1-4] We may in fact be lagging behind some sister disciplines in this regard, and the utility of evolutionary dynamics may be particularly important for industry and government.[5]

The basic premise behind the above suggestion is that the primary activities of chemical engineers are either to invent new concepts, processes, and equipment, or to improve existing ones. Since true *de novo* developments are rare, both types of activities may be viewed as evolutionary, and the term evolutionary dynamics seems appropriate to describe the rates at which they proceed. So defined evolution may be seen as related to but distinct from design, and in many ways deserving of a higher conceptual priority; evolutionary considerations provide the primary impetus for design efforts even as the needs of the designer provide the primary justification for engineering science and other descriptive disciplines.

The recognition of evolutionary dynamics is both timely and important for at least two reasons. The first is that we live in an era of rapid and unpredictable changes, most of which are beyond our control, and the ability for both individuals and social groups to evolve rapidly in some effective sense is therefore of critical importance. The second is that the dynamics of evolution are surprisingly complex in detail, and it is only recently that tools and concepts needed for their effective understanding have become available. Selected examples of these tools and concepts are introduced immediately below, and applications specific to chemical engineering education are introduced in the last section.

◀ BACKGROUND ▶

▶ *Biological Evolution*

Often lost in a fog of bewildering chemical and physiological detail is the central fact that modern biotechnology is built squarely and consciously on information theory and that the great complexity of the biological world is in turn the result of evolutionary dynamics, most probably driven by a simple objective function: preservation of information represented by chains of simple organic compounds, the nucleotides generally known as DNA. In fact, elaboration of genetic information theory predated the discovery of its chemical basis, and a successor development, evolutionary theory, is now ahead of experiment in its turn.

Moreover, as biologists are forced increasingly to deal with enormous complexity, there is growing pressure to develop sophisticated hierarchical models that will increasingly make the systems analysis used by engineers look rather primitive. Individual organisms, even microorganisms and mammalian cells, are already more complex than large chemical plants in terms of mass flows and control strategy. One can already see sketched out a spectrum of

Ed Lightfoot *was born and raised in suburban Milwaukee and obtained both his BChE and PhD degrees from Cornell University. After three years of process development at Chas. Pfizer, he joined the University of Wisconsin chemical engineering department, and except for leaves he has remained there since that time. He is still teaching, though he formally retired in October of 1995. His interests have centered around mass transport with an emphasis of biological applications.*

complexity from relatively short nucleotide chains or genes and the proteins produced by them to gene equivalents, such as the "memes" of Dawkins,[6] and on to large social groups and organized bodies of knowledge.

These aspects of biology are steadily becoming more quantitative and systematic, and they are much more easily understood by chemical engineers than such classic sciences as biochemistry and molecular biology where the non-expert quickly becomes drowned in masses of detail and specialized notation. Moreover, I believe that they are also far more important for most of us.

► *Basic Questions*

At first sight, the very existence of evolution is counterintuitive. How can successively more complex life forms arise in a dissipative universe, and is such a tendency to increasing order inevitable? These basic questions have been addressed by a great many eminent scientists, of which the best known is perhaps Jacques Monod.[7] But for many engineers the clearest and most satisfactory answers are provided by Manfred Eigen[8] and his co-workers, on the basis of information theory combined with Darwinian selection. Eigen shows that biological evolution depends upon errors in replication of DNA and that there is an optimum error rate. No evolutionary change can occur in the absence of error, but too high an error rate can overwhelm the process of natural selection and lead to degeneration.

For such simple structures as small viruses, error rates are small enough to permit development of well-adapted organisms, but the scales are tipped toward degradation as the number of nucleotides in the organism DNA increases. Eigen and Schuster[9] have been remarkably successful in estimating the maximum gene size permitting effective simple natural selection, and they have proposed a more complex mechanism, "hypercycles," for organisms with larger genes.

The energy source for evolution is environmental degradation of free energy, and it is found that the entropy generation needed to produce even so complex a structure as a large mammal is not excessive.

Almost as puzzling as existence is the remarkable speed of evolution, shown for example in our current difficulties with the AIDS virus and the development of bacterial resistance to antibiotics. Contrary to general perception, evolution is fast—and ubiquitous. Eigen shows, again for very simple organisms, that this speed results partly from heterogeneity within apparently homogeneous species. He points out that there is always a multidimensional distribution of genetic content about the dominant or "wild" form, and that environmental changes result in a rapid redistribution of frequency. Such adaptation is particularly rapid for sexually reproducing organisms where combinations totally unsuited to a pre-existing set of conditions are continually arising through very large numbers of random binary combinations of parental genes. This is a particularly important point for non-biological evolution, as we shall see below. In one sense important to us as parts of vulnerable ecosystems, nature is very wasteful; individuals and whole species are continually sacrificed in the development of better adapted forms.

► *Non-Biological Models*

No well-substantiated models for natural selection in complex organisms yet exist, and direct experimentation is at best difficult. But analysis of non-biological model systems has provided some provocative and stimulating insights. Among these are the suggestions of Kauffman[10-11] that Darwinian theory must be extended. He suggests a three-tiered approach:

- Recognize and delineate the *spontaneous sources of order, the self-organizing properties* of complex systems, as an essential complement to the disorder postulated by Darwin as the sole source of evolution.
- Understand how such self-ordering properties *permit, enable, and limit* the efficacy of natural selection.
- Understand which properties of complex systems confer on them their ability to adapt and evolve.

Kauffman's texts are characterized by the posing of a great many seminal questions and by attractive but as yet unproved possible answers. Among the most important is his suggestion that living organisms, or their genes, are *parallel distributed regulatory networks* operating on the edge of chaos. His first text[10] is the more complete, but the second[11] is by far more accessible for newcomers to this field.

Prominent in Kauffman's developments is the concept of *fitness landscapes,* which describes the evolutionary fitness of organisms as functions of determining factors such as amino acid content of enzymes. These in turn are used to describe the counterbalancing of evolutionary driving forces with the degrading effects of DNA replication errors and can in principle be used to determine both the limits of achievable fitness and the most attractive search routines across the fitness landscapes. They can also be used, again in principle, to describe co-evolution in ecosystems, a major problem in evolutionary dynamics. Moreover, his ideas are readily applicable to non-biological systems.

The work of Holland[12-13] and others and the concept of *self-ordering* supplement and extend Kauffman's arguments, and a variety of auxiliary ideas appear to be important. Chaos theory and nonlinear dynamics are obviously among them, but the current arguments over the relative merits of holistic versus reductionist thinking (see for example Reference 14) may contribute significantly as well.

Already these non-biological models provide highly useful insight and show for example that evolution does not always produce very high degrees of "fitness." Fitness is itself a difficult term to pin down, as are "adaptability" and the even more vaguely defined "evolvability."

► *Empirical Approaches and Hierarchical Modeling*

At the moment, the suggestions of Kauffman and others must be viewed as interesting but unproved hypotheses, and we must usually settle for empiricisms based on study of a variety of systems, from small biological structures through whole organisms to ecosystems of varying complexity. Moreover, as the complexity of the system under study increases, both the precision and reliability of available models decreases. The more complex situations are often the most important, however, in chemical engineering as well as in biology, and here the biologists may be ahead of us. As a group, they have learned to work at a great many different hierarchical levels, even as individual researchers tend to be highly specialized. Global syntheses are still rare and highly incomplete, but a great variety of useful disciplines (*e.g.,* various aspects of ecology and sociobiology) has emerged.

Fortunately, many useful generalizations are available, and those dealing with very small ecosystems are of particular interest to academics; most of us operate within small and relatively isolated groups. Examples include academia itself relative to the larger world of chemical engineering, groups of researchers in highly specialized fields, and academic departments.

It is thus important to note that diversity within any given ecosystem is a stabilizing factor that also increases ecosystem productivity—and that small systems such as isolated islands tend to be very poor in numbers of species; they simply cannot hold a highly diverse system. Moreover, natural selection within a small system tends to produce highly specialized species that cannot survive contact with a larger and more competitive world. The flightless birds of New Zealand and other island systems have fared poorly on contact with rats and other invading organisms, but supreme opportunists such as coyotes have thrived in fast-changing circumstances. Moreover, the highly specialized species of isolated systems may cease to evolve at an appreciable rate in their protected and stable environments once the accessible "niches" have been filled.

Another very important aspect is that of co-evolution. This field is of considerable potential importance to engineers; all of our work is done within the context of dynamic interactive environments.

► *Useful Similarities*

All of the above discussion would be of relatively little utility to chemical engineers were it not for the fact that non-biological evolutionary processes, from the development of social systems and industries to the refinement of such "species" as chromatographic columns or oil refineries, share many of the key features of biological evolution. This point of view was discussed in philosophical terms by Dawkins[6] is repeatedly expressed by Kauffman, and is analyzed with great enthusiasm and exhaustive detail by Dennet.[15] This last text is not as scholarly as that of Kauffman, but it is more down to earth and accessible. In many ways it is the starting point for the remaining discussion here. But there are now very large numbers of books and shorter analyses dealing with generalizing evolution theory in a wide variety of environments (*e.g.,* References 12 and 13) and even to the philosophy of evolution.[16]

◄ APPLICATIONS AND CASE STUDIES ►

The first priority is to recognize evolutionary dynamics as a key aspect of engineering and then to review our activities in the light of this new concept. The primary goal of such a review should be improving our synthetic, as opposed to analytic, abilities.

At a more detailed level we should take a new look at departmental structures and hiring policies. Here, review of current efforts of this type in other fields should prove helpful. A representative example is the application of Darwinian models for corporate change.[5]

Introduction of evolutionary ideas into our curricula is important, but it must follow faculty development. The tried and true method of exploring new ideas at the research level is the classic means of such development, and it must be given major emphasis.

► *Research*

Much is already being done in biology, and the Proceedings of the National Academy of Science has a section devoted to evolution in nearly every issue. Evolutionary dynamics has proven an important aspect of the AIDS problem.[17]

More recently, engineers have been using either biological evolution or mimicking it is useful ways. John Yin has been studying phage evolution for some years and is now seeking such mundane but important applications as remediation of metal contaminated soil.[1,2] Alex Zehnder has found that evolutionary processes in wild environments can produce hardy organisms capable of detoxifying previously resistant substances.[4] Here, success is achieved by transfer of enzyme producing genes between unrelated bacteria to provide new and complex detoxification complexes. This evolutionary approach has a major advantage over conventional genetic engineering in producing organisms capable of surviving in sewage streams. Ioannis Androulakis[1] has developed what are called genetic algorithms to speed process design.

Combinatorial chemistry[14] is a natural subject for such analysis, and the evolutionary improvement of enzymes[18] may prove of general engineering interest.

At a more philosophical level, evolutionary researchers such as Kauffman may be close to answering basic philosophical questions as to why research and development are even feasible—and perhaps help solve the vexing problems as the economic establishment of research directions. We should join with them.

► *Faculty Hiring and Departmental Organization*

It appears clear that hiring, career development, and interactions with outside influences all need a harder look.

Recruitment of new members is of primary and immediate importance. Faculty hiring policy has great long-range impact, is very hard to rectify once hiring decisions have been made, and is now made rather casually. We seem to be quite faddish as a profession, both as to specific technical fields and to the approach candidates take to them. Moreover, it is abundantly clear that we cannot hire enough individuals into any department to adequately cover all important aspects of chemical engineering.

Each of our departments is a tiny ecosystem, isolated to a significant degree and trying to survive and prosper in a tough world. Most of us are opting for narrow experts in "hot" fields who can bring in substantial sums of research money in competition with literally hundreds of like-minded competitors. Few are thinking very far ahead or very deeply about long-range problems. Finally, a large-scale wastage of individuals and whole ecosystems, characteristic of biological evolution, is highly undesirable for social "organisms" even though it is presently quite common in the United States. A major goal of social evolution should be to mitigate the iron laws of biological evolution.

I would suggest that highly specialized individuals with narrow interests are unlikely to be good bets for making the changes that will prove necessary for survival, and that a "fine-grained" personnel structure characterized by such specialists can make cross-disciplinary interactions in a small group inadequate for development of a strong department. It will also result in inadequate coverage of our wide-ranging profession. This is already being recognized at leading business schools interested in restructuring industrial concerns, and ongoing work in the area may be pertinent to our discussion.[5] In fact, engineering science may not be a good primary focus today, and certainly not for all departments. It appears more likely that we need a mix: experts in important core areas to deal with the increasing complexity of modern science and technology; careful organizers to maximize efficiency of our operations; and carefully selected generalists to supply the "glue" and inspiration for change.

Generalists with wide-ranging interests and good educational backgrounds in the engineering sciences may be an especially good bet right now. They can provide bridges between specialists, extramural as well as intradepartmental, and between academics and industrial engineers. They can also provide the "noise" that may be needed to keep evolutionary trends vigorous. More important, they tend to be the optimistic opportunists who typically respond most quickly and effectively to new circumstances. Time and again specialists have proven excessively conservative and resistant to change.

We must also rethink departmental structures and priorities. The present intense concentration on immediate survival will produce few deep or long-range thinkers, and it will reduce the possibilities for informal "multi-brain" interactions that could be so valuable for rapid evolution of ideas and concepts. Such interactions are the equivalent of multisexual reproduction and can lead to extremely rapid generation of new ideas. Excessive survival stresses also severely limit the kind of unstructured reflection known to stimulate creativity. Our present modus operandi is unlikely to produce the major evolutionary changes needed to meet long-term environmental stresses effectively.

The development of close external contacts must again receive the high priority of past years. Modern means of communication can certainly be used more extensively, but there seems to be no adequate substitute for face-to-face contacts.

Current pressures for submitting faculty to highly structured schedules is a formula for evolutionary disaster. The chief administrative goals of our university are to increase faculty productivity in narrowly focused ways: increased contact hours of formal instruction, more service to society, and more research funding. These are highly unrealistic unless accompanied by as yet unidentified ways to increase efficiency.

Immediate priority must, however, go to increasing the efficiency of funding and of conducting our fundamental activities; money is clearly one analog of the free energy that drives evolution, and all successful organisms are highly efficient energy transducers. Success in these activities may in fact help to achieve the above administrative goals, but we must go one step at a time.

These last are not newly discovered problems, and they need no special elaboration here. But they do need continued restatement, and they are an important part of evolutionary dynamics. Departments of chemical engineering will undoubtedly survive in the face of present administratively imposed pressures, but they may end up like the lycopodium and horse tails of Wisconsin forests: insignificant remainders from a glorious carboniferous past.

► *Curricula and Training of Engineers*

Curriculum modification is clearly near the top of the priority list, and it is important to begin with what we have. Increased emphasis on process invention in our introductory courses is promising, and it appears likely that much of evolution dynamics will be found to parallel design of engineering systems. A careful comparison of biological evolution with design strategy may well prove beneficial to both fields.

It does seem time to give a trial course on evolution, probably as an elective at the graduate level, and this should begin with the relatively advanced area of biological evolution. If possible, the first should be a highly interactive course, preferably given jointly with biologists. Much remains to be done before a realistic organization is achieved, but it is possible to sketch out a rough outline:

Introduction to Evolutionary Dynamics for Chemical Engineers

A. Biological Evolution

1. Basic definitions[19]
    - Information theory and evolution[8]
    - Mechanistic bases of evolution dynamics
        - Origins of variability
        - Driving force and objective function
        - Selection
    - Quasi-species
    - Organizational levels
    - Complexity [8,10,11]
    - Fitness and fitness landscapes [10,11,19]
2. Evolution and adaptation in simple organisms: theory and experiment
    - Simple replicators; small viruses
    - More complex replicators; hypercycles
    - Bacterial adaptation
3. Evolution of more complex systems
    - Overview of the origins of species
    - Comparison of the Cambrian and Permian evolutionary explosions
    - Stasis and radiation
    - Evolution of ecosystems and effects of isolation

B. Evolution in Engineering

1. Introductory remarks
    - Definitions and scope of discussion
    - Foundations: are there coherent theories for non-biological evolution?
    - Bases of non-biological evolution
        - Parallels to mutation
        - Driving forces for change
        - Selection
    - Organization: types and levels
2. Historical perspective
    - Major evolutionary spurts (tentative listing)
        - The western world
            - · antiquity
            - · renaissance
            - · industrial revolution
            - · China, Japan, others
        - The modern world
    - Chemical Engineering: selected examples
3. Search for a new synthesis: interaction of science, technology, politics, and business

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