THE FUTURE OF THE
NATURAL SYSTEMS SCIENCES

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Abstract

This paper develops an overview of likely developments in the new field of the natural systems sciences. We focus on the specialty areas of the physical, biological, and informational sciences, not on the social sciences, which are the subject of a companion paper by Dr. Jackson in this volume. First, we briefly describe twenty key developments and dramatic growth areas in the natural systems sciences. These are used to demonstrate their current robust health and enable a contrast with the comparatively slow development of the preceding three decades. We next describe seven major challenges or unmet needs that could inhibit development of the systems sciences followed by five unique resource opportunities that could help systems science practitioners overcome these obstacles. We present three major case studies of work at our Institute for Advanced Systems Studies that illustrate how modern systems research might answer problems facing the field. We end the paper with a summary vision of the long-term practical utility, even the ultimate necessity of success in the natural systems sciences.

Introduction

This paper is the latest in a series that taken together provide an historical and taxonomic panorama of the new sciences of "systemness" or complexity. It does not try to discriminate between the three or four major domains of the systems sciences. It does not try to define the uses and abuses of, and confusion between, the terms "system," "systems analysis," "sciences of complexity," "science of chaos," "general systems theory," "system science," or "the systems sciences." Instead, it regards all of these activities and the holistic intellectual movements that feed into them, as one, as yet unsynthesized and unintegrated superspecialty. This paper assumes that there is sufficient similarity in all "mature" systems that transference of descriptive models, diagnosis of

problems, prescription of remedies, and cross-application or cross-fertilization of tools and methods is not only desirable, but is in fact urgently needed. It also assumes that a significant increase of knowledge of natural systems will enable a much more mature social application of that knowledge. So, while the focus of the paper is on natural systems, it should be of use to both natural and social scientists. One special caveat is necessary. The organizers of the World Congress requested the specific title of this paper. They and the author realize that no one person can adequately capture the potential of a new field. We apologize in advance for any omissions or errors you discover.

Part I: Twenty Key Developments & Growth Areas

The abundant number, size, potential for extensive influence, and sophistication of the areas cited below that border on, use, or contribute to the systems sciences indicates that it has a robust future. Some of the most recent developments cited are causing a revolution in the way science is carried out, perhaps even changing its methods forever. That revolution transcends reductionist science, while remaining dependent on healthy reductionist science. It is emergent from reductionist science, and, as in any true emergence, exhibits characteristics unanticipated in the original praxis.

The Next Generation Internet2 (N.G.I.): The New Organizations It Generates, and Its Demonstration Projects will Promote Systems Science

The recent appearance of a set of linked computer hardware networks complementary to the NSF-vBNS (very fast backbone network system) might be compared to the emergence of extensive new neural networks in animal evolution. As in that evolutionary case, they provide the opportunity and likelihood of the emergence of new phenomena. The basic configuration is a super network of regionally networked gigaPOP aggregation points capable of transfering data at very high speeds (OC48 or 2.4GB to OC192 or 9.6GB). This next generation Internet (NGI or Internet2) already consists of 178 connected U.S. universities, industry units, and governmental units. Nicknamed Abilene, for the town that was the site of the final connection between the Eastern and Western parts of our nation's first cross-country railroad (get it – connection across great distances), this net will achieve teraflop scale computing. It will be able to use petabyte archives of reductionist data for the first time. And it will allow emergence of large collaboratories of many researchers working together on a single project characterized by unprecedented speeds of data sharing, data generation, data storage, and data evolution. This is both a large-scale system, and a new system that will allow unprecedented research into large-scale systems.

The physicality of this network has caused the emergence of new organizations of science users. One is called UCAID (the University Corporation for Advanced Internet Development). Designed to promote software advances that make full use of the new network capability, UCAID simultaneously will be promoting the natural systems sciences. Many UCAID projects will develop and deliver new levels of "middleware." So called because they are midway up the software hierarchy between machine language and applications software, middleware will yield significantly advanced protocols for parallel programming & vector supercomputing. A related organization spawned by the NGI is the National Partnership for Advanced Computational Infrastructure (NPACI). It consists of heavy funding by the NSF + 42 partner institutions + 4 international affiliates. NPACI

promotes usage of the NGI in science research based on models and simulations that require vast amounts of data. These organizations run workshops and conferences to help practitioners transfer tools and techniques more quickly and to help the hardware developers, software developers, and science users communicate across their many differences and specialty limitations.

But as a popular phrase in this group states, "Why should you care?" Simply because the future of assembly and use of very large-scale databases and the cause of natural systems simulation will be changed forever by this watershed event. The understanding of very large-scale natural systems is central to systems science. Just as computers allowed us to "see" chaos and fractals for the first time, the NGI and its practitioner organizations will enable us to DO systems science for the first time in history. Just as microcomputers allowed the rapid perception, spread, development, and use of chaos and fractals, the NGI will promote more rapid exploration of new frontiers of systems research as yet unimagined. It will give many prototypical systems scientists new tools to explore what has been unexplorable. It will allow unprecedented levels of collaboration & modeling in the systems sciences, and between the systems sciences and the conventional natural sciences. Many of the most fundamental obstacles to evolving a true science of systems may now be overcome, and its key questions (dimidium scientiae quaestio prudens), may now become tractable (the sign of a maturing science).

Mutual Impacts: Appearance Of "Systems" Biology

Biology is a relatively old and traditional science. It began as an observational science, as all of the natural sciences did. While it will continue as a rigorously reductionist, empirically-based enterprise, it has recently added several entirely new and robust components. Now it is a science of vast databases. Now it is a science that is increasingly integrative, as the multitude of specific facts and measurements are now ripe for synthesis into larger wholes of meaning. The results of bioresearch are also ripe for practical application. Entire industries (pharmaceuticals, biotechnology, bioengineering) now arise from applying its results. It day-to-day function now requires very large research teams of cooperative laboratories. Now it is increasingly a science that uses modeling and simulation. The timing of this last development nicely complements the aforementioned recent surge in development of computer infrastructure. Further, the synergy of these developments enhance each other. The net result of these trends is the appearance of what might be called "systems" biology. Systems science can contribute to the development of "systems" biology, and vice versa.

Developments in the Human Genome Project: Genomics Needs Systems Science and Builds Systems Science

The millions of dollars spent by various national governments and private enterprise has resulted in a map of 99% of the human genome. Consider the size of this single data base; 3.2 billion base pairs of data for the human species alone; possibly 150,000 genes; most likely >2.5 products per gene given the ubiquity of post-translational processing. This last cited characteristic alone yields half a million gene products, most of which are as yet unknown. Beyond this, genes differ between humans in the species. Many of us possess variation beyond the general species genome. Recent research indicates there are widespread SNP's (single nucleotide polymorphisms).

Researchers are right now assembly databases of 2.5 millions human SNP's. It is important when dealing with such numbers that we recognize that the single human mind is simply incapable of dealing with such massive amounts of data. If you consciously counted a number for every second of your life from conception to 80 years old, you would encompass a number only in the low millions. Dealing with billions multiplied by millions is simply not within our abilities. The simplifying processes, tools, and methods of systems science as rendered and delivered by computer networks, algorithms, and modeling will be needed to deal with this part of "systems" biology.

The above only invoked the numbers emerging from work on the human genome. Bioscience has already detailed 30 other complete genomes! All those millions upon millions of base pairs in databased must also be dealt with. The evolutionary and develement consistencies and differences must be catalogued as we share many genes with organisms as humble as fruit flies and nematodes. Knowledge of these already complex organisms has already blessed us with insights into human diseases and aging. And this is just the beginning. Sequencers are approaching capability of yielding 10^6 base pairs in just 5 hours work. What took decades for large teams of workers can now be accomplished in an afternoon. The massive data now characteristic of "systems" biology is clearly just the beginning. It further proves the need for a rigorous future for systems science. It is needed now more than ever before or the potential of many such massive data sciences to serve humanity will be inhibited.

Developments in Proteomics & BioInformatics Will Stimulate Systems Science and Use Its Tools

The bountiful results of research into gene sequences is being matched by continued productivity in elucidating the products of genes. We now know the tertiary structures (three dimensional shapes) of more than 3000 proteins down to a few angstroms resolution (this means down to the positions of their atoms and most important chemical groups). At this unprecedented level of protein resolution, we can begin to understand how vital human proteins work, and why they don't work in cases of some human diseases. We can model how they work to an extent that allows us to modify proteins to cure diseases or make useful products. With computer science and systems science as allies, fractal analysis of protein boundaries can be used to trace protein evolution as well as function.

Dealing with this vast amount of information, has transformed biology to an information science. It has taken a new specialty, bioinformatics, from obscurity to what is predicted to be a $1 Billion industry by 2003 with the incredible annual growth rate of 30%. Yet America is currently training only a handful of bioinformatics specialists today, when we already need many thousands. We cannot even agree on whether tomorrow's bioinformatician should be trained as a biologist adding the computer skills, or trained as a computer scientist adding the knowledge of biology. This paper would argue that they should initially be trained as systems scientists adding computer and biology knowledge along the way.

Developments in Physionomics will need Systems Science Tools

The vast gene databases create the field called genomics. The knowledge of gene products (mostly proteins, but which also include end-function RNA molecules) creates

the field called proteomics. Dealing with the vastness of the databases for both creates the field called bioinformatics. Some now begin to talk about how all of these products interact to create the fundamental living system of the cell. Since this is primarily the old field of physiology, this new, vastly more detailed version of it is called physionomics by some. We cited above circa 100,000 to 150,000 for the human cell alone. But it is now well known that many of these proteins exist as mixed (heterologous) multimers. This means that each entity we name as a protein actually has many different states, each with different mixes of subunit proteins. And these different mixed multimers might be only used by the cell in certain instances, or at certain times in the cell cycle. In doing their work, they enable the cell to exhibit the properties of "life." They do this by the vastly increased number of possible cross interactions. It is becoming common to see complex drawings at cell and medical meetings of networks of numerous proteins interacting and influencing each other to accomplish important cell functions. For example a recently reported simple signal transduction control pathway. As the proteins involved increase barely at all, because of the many possible interactions, the number of components increase eight and the number of rate constants (used to partly explain the group of interactions as a whole) increases thirty-five times. A virtual leap in complexity simply from recognizing network type interactions. While bioloy may be discovering new particular examples, there are several pre-existing lineages of work in the fields now clustered under systems science on how best to represent complex regulatory schema and how to manipulate networks.

Developments in Structural Cell Biology

Do not think that complexity is only found in physiology. Although cell structure is often perceived as static and stable, it is anything but that. The microtubule is increasingly seen as a very complex, very dynamic organelle whose mix and matching of a dozen components changes it function dramatically effecting such vital cell functions as cell division, cell motility, cell shape, and normal health of brain cells. The nuclear pore has evolved from earlier being conceived of as an empty hole in the nuclear envelope to a dynamic"structural complex" of >34 interlocked proteins called nucleoporins. Cell structure will someday be seen as dynamic and complex and free entity interactions in physiology. Again, biology will enhance systems science by its elucidation of particular systems, while systems science can help biology deal with the complexity.

Developments in Cellular Modeling & Simulation

I was convinced more than 35 years ago that the most complex system (per unit mass) known to humans would prove to be the cell. Since I was already passionately interested in both systems and biology, it was that prediction that led me to become a cell biologist. The cell is older and packs much more complexity in a much smaller space than even the brain (the often cited "most complex" system) partly because it was optimized by evolutionary natural selections for more time, at least 3.5 billion years. There were very few serious attempts to model this incredibly complex system until recently. The increasingly detailed knowledge of cellular molecular physiology and its interaction and control networks of recent times, combined with the above mentioned advances in hardware and software power have resulted in the feasibility of modern serious and rewarding cellular simulation efforts. Several attempts to model cell "in silico," such as

E-CELL described recently in Science, are driven by the need to bring the vast detail now emerging under control for human use. The need to understand not just the isolated, reductionist aspect of cell structure and function, but also its irreducible network aspects is dependent on the success of such simulation efforts. The inevitable continued surge in molecular and network detail on cell structure and function demands increasingly complex cell models if science is to continue its work in understanding the basis for life. And this inevitability extends to the attendant need for a better systems science to act as a co-discovering agent. Advances in each specialty will enhance advances in the other.

Developments in the Neurosciences and in Anatomy

The rapid developments that are creating "systems" biology are not just on the cell and molecular levels; they are occurring at all levels of biology. For example on the organ level, the rapid advances in collection and analysis of data on the brain requires supercomputer infrastructure. At UCLA, one collaboratory is creating a terabyte data base on brain activity derived from the vast amounts of data using NMI imagery. To get the most out of such large databases, created by very large expenditures of research funds, the data must be shared across vast distances by large numbers of researchers. Again, we argue that the design and delivery of such infrastructure is inherently a systems problem and these developments will stimulate and require a robust future for systems science. Similar databases are being created for the entire human body, and the development of the human embryo as compared to organ and organism development of other model organisms.

Much more robust models of neural unit function and simulations of neural networks are also emerging. The earliest systems consisted of step-by-step calculations on a tiny number of neurons. Now vast numbers of neurons can be used simultaneously, with several unique new algorithms for directing their summation, selection, and evolution. It is fascinating to see the commonalties between complex networks of interacting entities, whether they be molecules in a cell, neurons in a ganglion or brain, or species in an ecosystem. The output of these very different reductionist specialties feed into systems science when we focus on the similarities that transcend the particulars. Similarity and difference are simultaneously true, but at unique scales of study. Each specialty manifests the structure and function of "networkness" in different particulars.

Developments in Ecological Modeling & Simulation

Ecology/environmental biology is another area under study by an army of researchers and receiving considerable funding. Public concern for our environment has increased dramatically in recent years. Current results from this science now rival those of medicine for relevance to human survival and practical utility. Current estimates of the existence of as many as 30 million species, each composed of a billion individuals, all interacting together, clearly indicates that ecology is another science that intrinsically studies networks. Surely these numbers, and this complexity, rivals the interacting molecular components of a cell, or the interacting neurons of a brain. A specialty that yields results that inform us about networks, hierarchies, and cycling processes is informing us about systems science. The characteristics of an ecology; its open systems configuration, its far-from-equilibrium processes, its non-linear dynamic behavior, all further inform systems science, while the results of systems science should inform ecological studies.

Developments in Evolution Theory as Systems Theory

The mechanism of evolution is itself an intrinsically systems-based theory. Its emphasis on variation, diversity, feedback, environment, and emergence are coincident with systems processes. One dramatic alteration of evolution science has been its recent emphasis on molecular evolution and experimental evolution. The vast amount of data emerging from comparing gene sequences and the direct observation of molecular evolution, in action, in the test tube have added important new dimensions to the study of evolution. More direct observation of origins of life phenomena by manipulation of micro-environments have made an historical-descriptive field more accessible to falsification. The use of chaos simulations to understand the phenomenon of emergence enables quasi-tests of proposed models and mechanisms. Mature systems become mature by survival (dynamic stability) for comparatively long periods of time. These systems are evolved systems such that advances in either field contribute to understanding of the other.

New Multidisciplinary Centers at Major Universities Focus on

Several major universities are making unprecedented investments to build personnel and infrastructure that promotes exactly the comparisons across the conventional disciplines that yield systems science. They see the importance of the nexus between the above biological specialties to human advances and the potential of these fields for attracting external funding. Here is just a partial list of the size of investments initiated this last year for cross-disciplinary institutes at well-known institutions: Harvard ($ 50M); UC Berkeley ($ 100M); Caltech ($ 100M); Princeton ($ 70M); Johns Hopkins ($ 34M); Claremont Colleges-Keck ($50M). Our own, relatively small, non-R1 university has just invested $30M to build a biotechnology building that will focus on cross-disciplinary research and collaboratory partnerships.

Systems Engineering and Systems Production

Systems engineering was one of the first systems specialties to appear and remains one of the most developed. It has the largest number of recognized educational programs on a systems focus at recognized universities. Recent developments in microrobotics and nanotechnology are producing ever tinier microsystems that exhibit ever more complex engineered behaviors. This tendancy, and the promise of benefits it offers for society, puts pressure on design teams to understand the and implement the common principles of systems design in ever greater detail. There is an, as yet unmet, need for a prescriptive general system template version of successful systems behaviors. Parallel developments in pharmocogenetics and combinatorial chemistry contribute to this need for a better understanding of the principles of systems design. In this latter case, a multi-billion dollar, international industry provides a flood of investment resources to stimulate practical results. This entire set of fields highlight the need for historical systems theory to meet and cross-fertilize modern systems analysis.

Sciences of Complexity: New Avenues of Research in the Natural Sciences

Due to the widespread availability of high computation personal computer workstations with gigabyte processors and gigabyte memories, because of more frequent use of massive parallel processing, science can now see relationships it could not see before.

Chaos theory and chaotic processes can be explored at modest expense and in much shorter periods of times. The number of publications and regular conference series on scientific approaches to chaos, and chaos-based approaches to natural phenomena are multiplying in number, and the success of each is expanding []. Software breakthroughs in Genetic Algorithms and Artificial Life Research have obliterated the conventional barriers between isolated disciplines such as biology, computer science, and mathematics creating a super-transdiscipline of complexity theory. Complexity research itself is virtually identical to systems science. Large numbers of graduate students in each of the conventional disciplines have been infected with great enthusiasm and curiosity to enter this new integrated specialty. The stated intention of the new specialty Artificial Systems Research is to apply the tools and techniques of all of the above to investigating the stability and fecundity of alternatively structured systems, in silico []. This could lead to some of the first direct testing of systems structure and function in itself and apart from the particular manifestations of systems in nature.

Development of Earth Systems Science

Like biology, geology has evolved from a primarily descriptive and reductionist oriented discipline to include a much wider synthesis. Large-scale, biome or ecosystem-wide projects are now as respected as investigations on severely reduced isolated sub-sub-systems. Many departments are renaming themselves as "earth systems science" departments. These units are attempting to research the earth as a whole complex system. Their research is relies on computerized networks of instruments that collect vast amounts of data. The data is so vast, that like medicine, astronomy, and biology, the data itself becomes a large system and the tools and techniques to analyze the data approach the level of systems modeling, simulation, and systems analysis. So the prediction here is the same for the other named natural sciences. Earth systems science will contribute information, demonstration, and understanding to an invigorated systems science, and vice versa.

Development of Ecological Economics

The network of international interactions in finance has many similarities to the network of species interactions in ecology, or the networks in the physiology of cells. Many aspects of chaotic systems are found in both. Similar tools and techniques can be used by both fields. Similar patterns are found in both and cross-inform or cross-fertilize each other. This recognition by growing numbers of workers has led to joint meetings of the ecology and economic communities characterized by great enthusiasm and excitement. The excitement comes from the discovery of tools and patterns in one science that are relevant to the other and the promised new developments that result from such insights. It is interesting that these two communities have not yet discovered the bounty that is available to both from the rapidly developing genomics/physionomics results in modern molecular biology. For example, a computer tool first developed to map physiological interactions in bacterial genetics is now being used by social scientists to model social interactions in Silicon Valley for the purpose of understanding the rapid economic growth of that area. Again, it is clear that systems science is about networks, in part, and any natural sciences that involve networks can learn from systems science, will promote systems science, while promoting themselves.

Selected Developments in Physics, Astronomy, & Cosmology

The most reductionist of the natural sciences are these three fields. One might then imagine that they would have the least to contribute to or learn from systems science. I challenge that assumptions. A cursory reading of Greene's best selling popular science treatise on the development of the String/Membrane Theory of particle physics indicates that the 3rd revolution in that theory was based on recognition of the duality of the fundamental equations. Before that recognition the workers were blocked from progress. But the equations unsolvable before the dual opposite or coupled equations were illucidated became solvable through knowledge of the matched pair relations. Now a reductionist scientist would be unlikely to have a concept of paired opposites in mind while working on a reduction-based phenomena. But a systems science sensitive preparation would be suffused with many real examples of complementarity or duality as an inherent property of most mature systems, whatever their scale. That might have led to a more quick recognition of the logjam-breaking duality of the equations in this highly reduced case.

Do not think this is an isolated case of the utility of a systems sensitivity to advances in physics. Fritz Zwicky (the irascible, international figure in astronomy, formerly of Caltech) was the author, user, and advocate of General Morphology. He used the technique to predict dark matter and neutron stars. He also used it to predict a wide range of propulsion processes which became part of the birth of the Jet Propulsion Labs. At our Institute, we have an entire course on this technique and its potential uses in the natural sciences, engineering, and social systems design. Basically General Morphology is a guided, phenomenon-based exploration of potential process space completely predicated on systems science.

Overall, from observing all of these examples, we would claim that many of the most exciting, fastest growing science investigations underway today are systems-based and informed by a healthy systems science, while demanding future development of systems science.

Computer-Based Systems Conferences on the Internet

One of first computer conferences was on general systems theory. It occurred because NSF sponsored a cluster of systems investigators nation-wide in the late 70's and early 80's to try the then new technique to see if it would lead to advances. Stuart Umpleby at George Washington University was the principle investigator, and many lessons were learned about how difficult debate on systems science is, and about the strengths and weaknesses of computer conferencing. Since then, the wisely-named Principia Cybernetica project led by Cliff Joslyn, Francis Heileiden has engaged an international cliental of both natural and social scientists interested in a wide range of systems topics and issues. The New England Center for Complex Systems has a series of active, computer discussion groups under the guidance of Yaneer bar Yam. There are many conventionally employed physicists, mathematicians, and biologists active at this site. The International Society for the Systems Sciences (ISSS) sponsors discussions on a wide range of systems topics involving evolution and emergence, duality, and social systems design. The rather sudden appearance of many independent and large website discussion groups on a diverse range of systems topics indicates both the interest in the need for synthesis in the natural sciences, and the strong potential future for systems science.

Developments in K-12 Systems Education

Historical Perspective. In the early days of work on a general theory of systems, most thought that training in systems science would only work at the doctoral and postdoctoral levels. It was thought that systems understanding required that level of detailed knowledge about some real systems before they could be fruitfully compared to discover and understand inherent similarities. Then in the 80's, ambitious educators began to offer M.S. degrees in various aspects of the systems sciences. Of course, the systems engineering B.S. already was fairly well recognized during this time. But B.S. degree offerings in systems science were not given the okay to proceed. Today, systems science is being taught for the first time at all levels. Sophisticated and demonstrably successful programs exist at the K-6 level, at middle and high school levels, at community college levels, 4-year universities, and even community activism levels, in addition to the formerly established, and multiplying graduate studies and graduate research levels. The purpose of this section is to list some examples to characterize this diversity. It is evident that a recent explosion is occurring that will contribute mightily to the future of systems science. Students using active systems modeling in K-12 mostly love the activity. Their enthusiasm will create a demand for this type of study in greater depth and higher educational levels. This firestorm of awareness and interest will occur just in time. We will need a very healthy pipeline of trainees sophisticated in systems science to solve modern complex systems problems. Here are some examples of the new developments in systems education.

STELLA Systems Modelling K-12. Jay Forrester of MIT long ago developed Systems Dynamics modeling on computers for use in studying complex systems problems. It made a sensation both positive and negative in the Limits of Growth studies of the seventies. The tools and techniques in this body of work continue to develop in the Systems Dynamics professional society and publications. But few know that a very well funded and organized set of projects exist to bring systems modeling to K-12 teachers and school districts. Teams of students create simple feedback models using STELLA on topics in all of the sciences, social science, and especially environmental problems. For example, the Waters Foundation sponsors a STELLA systems dynamics project that involves 10 states, 15 school districts, and is guided by 5 paid professional coordinators. The national effort in K-12 runs a biannual meeting attended by 250 K-12 teachers, principals, and school district administrators.

Systems Biology K-12. Lee Hood, co-inventor of the instrument responsible for the fast sequencing capability that made the Human Genome project possible, is the P.I. for a "systems" biology set of projects sponsored by the NSF. It is a 5-year, million-dollar project that presents biology as an information-based systems science. It uses master teachers paired with practicing systems biologists in the state of Washington. It teaches the systems approach to students as young as 4 years old. The project will result in content and materials for teachers, and contributions to the development of teachers. It is a huge project involving 66 schools, 1,400 teachers, and 23,000 students.

NPACI K-12 Systems Projects. The aforementioned National Partnership for Advanced Computational Infrastructure sponsors a series of projects that makes large-scale (read "systems") modeling possible on the K-12 levels. One of its subsystems is the Education, Outreach, & Training (EOT-NPACI) unit. The EOT sponsors the GirlTECH projects for young women and MDVirtual on the high school level at the Ohio Supercomputing

Center. There are at present at least 17 projects evolving from the efforts of two teams. All involve secondary education learning and technique development in areas fundamental to systems science.

The Creative Learning Exchange. The CLE is a web-based clearinghouse for systems STELLA models for K-12. It is a great resource for teachers with hundreds of simple to relatively sophisticated models involving all of the sciences and math, and even cross-disciplinary phenomena. One can obtain models in both paper and electronic form with their explanations and pedagogical suggestions. These models are not refereed. Those models from the aforementioned Waters Foundation project are refereed.

New Approaches to Systems Education at the College and Post-Doc Levels

Integrated Science (Systems Science) General Education Program. This NSF-funded super project has attracted 14 grants, and >$1M for development of extensive distanced learning courseware development. The year-long course will ultimately deliver 250 rigorous cases studies of phenomena from all 7 natural sciences. It fulfills all the general education science requirements for any non-science student at any university. It uses advanced, highly interactive multimedia that has a whopping 27 built-in learning features designed into every module. These learning features have resulted in 75% of science-phobic students earning an A or B grade based on 900 challenge points per quarter. The ISGE program is billed as a "stealth" systems science program because it uses dozens of fundamental systems processes as the integrating themes that tie the 250 case studies together. So it teaches all seven natural sciences at the same time it teaches a great deal of systems science. The ISGE is targeted for rapid dissemination to the entire CSU system of 425,000 students and to many other colleges and universities nationwide. It has immense potential for reaching a vast number of students.

NECSI (New England Complex Systems Institute) Collaborative Project. This is another NSF sponsored, multi-institutional, multi-regional that plans to coordinate diverse systems education projects on the K-16 levels. The project involves many investigators who are associated with or familiar with recent developments in the sciences of complexity (systems sciences).

Sante Fe Institute Summer Workshop Series. This new series serves fewer workers but is noted for its rigor. It consists of both well-connected and highly visible conventional natural scientists and new graduate students who want to add systems understanding and tools to their conventional training.

ISGE K-12 and S.I.S. Alliance and SYSML Project. This new project would raise the level of individual projects to a self-sustaining social institution connected by the "nerve" complex of computer networking using NGInternet2. SIS stands for Systems Integrated Science. It would link all ISGE distanced learning groups across the CSU, SUNY, CUNY and other national universities. One of its main foci would be teacher training to get the multiplier effect that comes form such efforts. The need for teacher training is in the news. LA County alone needs 200,000 credentialed teachers next year. Who will supply this need. The CSU system has great potential for serving this need, and spreading systems science understanding at the same time through multiple adoption of the aforementioned ISGE. Each CSU campus has >1,000 teacher trainees in any one year. The CSU alone produced 20,000 new teachers in '96-'97. Plans for ISGE include linkage

of all on-site programs to a master service unit using two innovative new computerized assessment tools that enable "Seamless" and "Evolutionary" assessment simultaneously. Lee Hood will also design social institutional self-sufficiency into his Institute for Systems Biology NSF project. The result of several such projects could be an impressive increase in flow of students hungry for systems science throughout the educational system, and emerging into the economy. A healthy systems education will create a healthier systems science.

Part II. Significant Needs and Unmet Challenges

It would be irresponsible to only cite examples that enhance the future of the systems sciences without an honest citation of the forces that might inhibit that idealistic view of its future.

The individual depth and yet wide range of the 20 recent developments just cited are intended to prove that there is a significant explosion of mutually supporting events that will enhance the future development of systems science. But they are not the whole story. There are a number of obstacles that must be overcome to secure that rosy future. Some of these obstacles have persisted over the last four decades. They are anything but trivial. Without a clear understanding and appreciation of these obstacles, effective responses may not be forthcoming, and the otherwise healthy future potential of the systems sciences will not be realized.

Systems Education is BOTH A Promising Development and An Unmet Challenge

The last two key developments are both driving force that will enhance the future of systems science AND potential obstacles. How can this be? This author has worked for thirty years in systems education, both on national and international levels. The history of systems education can be best characterized by initiation of new programs by enthusiastic and dedicated personnel followed by the unexpected and often unjustified dissolution of the new program in a rather short period of time. Here are some examples: the Systems Institute at University of Louisville, the Masters degree program in systems at San Jose State University, the College of Systems Science at University of Denver, the education program of the Dept. of Systems Science, part of a larger Institute at USC, and many others. Only two pure systems-based Ph.D. programs have survived (at SUNY, Binghamton and Portland State University) to the authors knowledge. And only one of these have survived the retirement of the original "star" founder.

However, the most recent new programs described below have some features that past attempts did not have. They start earlier in the educational system. They are organized and sanctioned by a wider range of experienced systems scientists, not be a sole founder. And perhaps the most important new feature, they are also supported by a range of otherwise conventional, and widely respected natural scientists. New funding sources have appeared. New applications for graduates have appeared. More recognition for the need for such training is evident in industry and government. There is also more recognition on the part of students entering the educational system that this is a good career tract to select. These new features have significantly increased the chances of success of systems education programs of the future and so constitute another recent development that bodes well for the future of systems science.

Systems education is one of these formidable obstacles. Any new development in science or engineering depends upon an adequate flow of highly trained, motivated, as well as highly-rewarded population of practitioners. If the systems sciences can contribute to and learn from the many key scientific developments just cited, and if it is so important to designing better complex human systems in the immediate future, doesn't our nation need a healthy pipeline of graduates in this field? Do we have in place a "pipeline supply" infrastructure to produce sufficient numbers of adequately trained systems scientists? Do we agree on the standards and curriculum for this new field? Do we have exemplars of model educational programs in place? Do we have academic infrastructures tested and proven to produce systems scientists? The honest answer to all of these questions must be "no" despite 30 years of attempts at answering all of these needs.

The Need for Key Distinctions & Discriminations

Why we should care about key discriminations? For systems education to be successful, we will need a more robust Systems Knowledge Base. But there is still much confusion and lack of consensus in the new field. Much of the misguided research, lack of communication, and lack of consensus results from a few key distinctions that are not widely recognized. Some of these include a confusion between the following differences: Systems Theory v. Methodology v. Application; Physical v. Biological/Natural v. Social Systems; confusion between Level of abstraction /deabstraction rules ; Inter- v. Multi- v. Cross- v. Transdisciplinary approaches; differences between distinct Classes of Emergence. For example, on the last item, workers often confuse emergence of new scale of entities with emergence of a new level of specialisation within a scale. Both the original general systems theory and the new sciences of complexity groups are prolific & promiscuous in use of these terms. Often the field is guilty of mistaking the tool in hand for essentials of problem. "To a man with a hammer, every problem looks like a nail." It is not the purpose of this paper to try to explain how these key distinctions might be resolved, only to point them out and note that they will inhibit an effective systems education and future for systems science.

In past papers I have suggested the term "Discinyms" for "Disciplinary synonyms" (even though I believe forming neologisms is a disease of systems science). Discinyms are a source of immense confusion at the heart of systems science. There are Synonymic "Discinyms" such as cases where biology says "homeostasis"; and we say dynamic equilibrium, or biology says "autocatalysis; and we say self-organisation or autopoiesis. Or consider for example the truly different uses of a conventional term like "sequence" in systems situations in molecular biology, organism biology, and geology. There are also Antonymic "Discinyms" such as the different uses and abuses of the words entropy and information across the disciplines. Whatever the case, these differences arise from different levels of abstraction and historical precedent in recognizing the self-same systems processes in different particular systems manifestations. Lack of recognition of the problem of discinyms has a deep impact on students trying to learn systems science, and creates immense confusion between different conventionally trained scientists when they try to talk with each other. The simple recognition of their existence could help overcome this obstacles and that is why I advocate naming the problem.

The Need for More Emphasis & Focus on Integration/Synthesis

Comparison of real systems at very deep process-levels is fundamental to systems science. That is an act of integration and synthesis. Many Nobel Prizes and the greatest revolutions in natural science are the result of deep, systems-level integrations and syntheses. It is a most highly valued human product !! But here is a critical question? Who teaches Integration and Synthesis in our schools? At what level is it taught? K-6? Middle or High School? College? Graduate? Where in society? Which Institution(s)? The embarrassing answer is that it is the most secret, misunderstood and undertaught procedure in our school systems. We desperately need a Toolbox for Integration. How could we have gone 40 years without identifying and accomplishing this fundamental task? And who will accomplish it now to enable the future of systems science, and as a result enhance human futures.

The Need for Parameterization of Systems Research

In a recent conversation with Cal-Tech's President David Baltimore, he was asked what is the main problem that causes natural scientists to avoid systems science. He suggested that it was the absence of adequate parameterization in systems research. It is parameterization that enables the experiments that become the "selection" agent that enables gradual improvement of theories. Some systems scientists have recognized this need in systems science. Historically the work of Miller, Odum, and Cowan have identified this critical need. For example, Miller suggested many "cross-level hypotheses" for investigation to build systems science. Forrester claims systems dynamics modeling is experimental. Workers in the new field of the sciences of complexity seem to assume that their simulation attempts are true systems experimentation. But the question is really open. Is simulation really parameterized? Craford prize-winning Odum's emergy modeling certainly has many parameters involved and tests for validity. But is it testing systemness per se or only the model of a particular system. Clearly such central phenomena as emergence, endlessly discussed by systems types, needs a more empirical approach to resolve the infinite disputes words engender. The new, suggested field of artifical systems research would directly approach this question. Until then, systems science may generally not find acceptance by natural scientists.

The Need for Alliances or Confederations of Systems Institutions

Integration of institutions is as critical as the synthesis of ideas. The last forty years of systems science is characterized by Quasi-isolated systems knowledge communities. Worse than that, many of the communities exhibit considerable competitive behavior that inhibits the necessary transfer and cross-fertilization of knowledge. Consider the opinions that the following groups have concerning each other: Forresters Systems Dynamics Soc.; NECSI-Sante Fe Institute axis; ISSS & Spin-Offs; Systems Societies by Continent; or by Systems Domain. So there are many obstacles to Alliance and Confederation much less social integration. Too often this is due to the very thing that enabled some of the knowledge communities; the presence of a super-guru or organizer ego who attracted many to the field, but then becomes overly territorial and competitive. Consider how different this is from the natural sciences. We have tried to establish confederations before, for example, the International Federation for Systems Research, or this recent

World Congress. Perhaps this is a sine qua non for the future of systems science to be a healthy future.

The Need for New Methods of Empirical Refinement

Lack of Shared Internal Methodology
Sine qua non; Without selection, no progress
Notice "refine" not "prove" or "eliminate"
How far can theoretical comparisons go;
Need for Explicit, Consensual "Criteria"
To image & rigorously guide research
1974, Gen. Sys. Bulletin; poll of 33 "diagnostic questions;" judged using 8 "perform. obj" for GST's
Need for Strong Formulation of Systems Res
Need Additions to Analogy Homology
Sat Workshop; forge new NatSys Research protocols

The Need for Systems Exemplars of Research and Application

Tough Question: Where is the Value Added??
Must demonstrate to outsiders, not assume; list of
Robust Transfers
E.g. Using computer network tools developed to model bacterial physionomics to development of collaborative business networks in Silicon Valley
Need for a new Mathematics for SysSci
Reformulation of field theory; calculus unnatural
Integration of probability, number, topology
Concept of "augmented hypothesis formation"
Strong Inference (Platt); sys KB yields strong hints

The Need for A Complete System of Systems Processes: The LPTM Case Study

It is ironic that the field that investigates "systemness" has not systematized its results. Many systems workers concentrate on only a small number of the processes that are true across particular systems. By leaving out many others because of preference or lack of study, they take the systemness out of the system they study. Some may research only the Zipf/Pareto pattern, or mechanisms of feedback, or hierarchical clustering to the exclusion of each other, or of other systems processes. There is a deep need for systems workers to become aware of the blinders they use, and of the widest possible set of mechanisms that need incorporation and investigation. It is quite understandable to delimit and make feasible by reduction the number of things you investigate, but it is not useful to do so in a way that eliminates important processes that impinge on the process you focus on in order to understand a system or systemness.

The L.P.T.M. is an acronym for a multi-year project at our Institute for Advanced Systems Studies. It is a system of 82 Systems Processes (or Patterns) (or Isomorphies) that define what is known from a wide range of literature on how systems work. It is an overall picture of the "mechanism" of "systemness." The 80+ isomorphies are the same for a wide range of natural, mature, systems when observed at a sufficient level of abstraction. They are what is true of very different particular manifestations of systems.

The isomorphies form a self-organizing, mutually reinforcing set. They are highly specific, traceable, referenced, and testable. Only actual demonstrated processes allowed. They are a highly integrated set because they are connected by >100 "Linkage Propositions" with the anticipated set of demonstrated linkages to be a much larger set. Each linkage proposition (LP) denotes a well-studies or hypothesized specific influence of one isomorphy on another. The LP's are also highly traceable, referenced, and testable. The set of LP's enable a new formal logic, >debate, and seeking of consensus. Their specificity enables seeing pathologies/prescriptions when a system isn't working. The net result of the LPTM is a "system of systems processes" that is much more easily communicated, traced, and tested because it exists as a tool on computers and can be shared by many workers.

Part III. Important New Resource Opportunities

NEW   FUNDING   PROGRAMS
at NSF, NIH, ONR
- New Director; New emphasis on Biocomplexity
    - Not just genomic & molecular; also env. diversity
    - Several cooperating "sections"; literally $$millions
- For "biocomplexity" can read systems science
    - Very conscious decision & promotion; attend conf.'s
- NIH: Many fertile syssci branches = biomedical
    - Complexity of diseases = cost to human & economy
    - Many dementia's & auto-immune diseases due to genetic polymorphisms; diseases of aging pop's
- ONR: new multi$M nanotechnology initiative

NEW   FUNDING   PROGRAMS:
PRIVATE FOUNDATIONS
- Already happening.....
    - Waters Foundation already funds Systems Ed
    - Gates Foundation; $100 M request from Hood's Institute for Systems Biology
- Not always clearly defined programs; our job
- Future of SysSci: for 1st Time = well funded
- BUT must be rigorous and refinable
    - Parameterized; demonstrate value-added
    - Collaboratory-based; many co-authors
    - Give detailed prescriptives;
    - Three case studies of future of syssci as glimpse...

Part IV: Case Studies that Capture the Future

CASE STUDY: NEW FIELD OF
SYSTEMS ALLOMETRY

- Like bio/eng allometry, based on empirical data
  - Same data reported in refereed nat sci specialty J's
  - Uses established statistical tools
- Find highly significant relationships on log-log
  - All bio-hierarchical levels follow similar design rules
  - Even physical and life sci levels follow design rules
- Indicate internal self-organization constraints to stable, mature systems wherever in nature
- Startling conclusions; Guide Emergence Res
  - We see individual entities; SA shows scalar classes
  - Same system; diff't era's; diff't manifestations

NEW FIELD OF
ARTIFICIAL "SYSTEMS" RESEARCH

- Inspired by artificial life, complex sys research
  - But agents not based on characteristics of genetics & life processes; resources and selection not the same
- Based on IAS Linkage Propositions
  - Use LP's as agent characteristics; remove one at t
  - Uses similar strategy of very large #'s, trials, time
  - Alter feedback delays; uncouple single feedbacks
  - Add or remove clustering; LP's offer many variants
- Look for effects on systems stability & evol & the General System Lifecycle stages
- Several difficult, non-trivial problems remain...
- Also Sat Workshop on NatSci and Systems Res

CASE STUDY:
XML-SYSML on the INTERNET

- Purpose: to encourage/enable sys integration
- Open-source suite of syntools available to all
- Highly interconnected Hier/Web of carefully selected and organized sys sci data
  - The ISGE "Connection" Beehive on Internet
  - Extensive graphics front-end; ISGE & ESRI project
- An Evolutionary InfoCommunity: Functions
  - Provide for better introduction to field for newcomer
  - Resource for K-18 sys ed; user explores
  - A funneling and screening format for CONSENSUS
  - Based on Sun Workshop; but with very strong selection force
- Who will manage & maintain; IAS; expect several alternatives

Part V: Ultimate Utility of the Systems Sciences

INTEGRATION OF WAYS OF KNOWING: SCI TO ETHICS
- Need for a Mature Systems Pathology
    - In a complex system, easier to study what goes bad
    - Teases out otherwise obscure inter-relationships
    - Moves sys sci from descriptive to prescriptive
- Parallels - History of Medicine & SysSci
    - Our current status; bleeding for bad
    - Medical School: "watch one, do one" (sys ed K-12)
    - Systems Hippocratic Oath: "DO NO HARM"
- A New Science-Based Philosophy (Anduranormism)
    - "toward lasting patterns"; no dogma's; adaptive
    - A prescription on how to build better complex sys

Systems   Science   a   necessity   for   a
SPACE-FARING SPECIES
- SysSci will be a Hallmark of the 21st Century
- SysSci is critical to success of other hallmark: Homo sapiens as a space-faring species
- Discovery of planet systems; 2 dozen cases
- We will colonize the local galaxy
    - Exponential spread; probably this millenium
    - Encounter totally unforseen ecologies & threats
- New way of >rapid knowing & understanding
    - Reductionism will always be needed, but slow
    - "Augmented" hypotheses from syssci will speed discovery if closely coupled with reductionism; survival