SIX CASE STUDIES OF EMPIRICALLY-BASED CHAOS/FRACTAL RESEARCH: DOES CHAOS/FRACTAL ANALYSIS YIELD ISOMORPHIES FOR GENERAL SYSTEMS THEORIES

Len Troncale, Chung Lee, Kristie Nelson, and Jaimie Tres
Institute for Advanced Systems Studies
California State Polytechnic University
Pomona, California, 91768

Statement of The Problem

Many of the recent books which survey the research results of chaos/fractal analysis either illustrate how **multi**disciplinary are their potential applications by the range of fields represented in the included papers [2, 7, 9, 13] or directly state that this new "approach" crosses conventional disciplinary lines and so is **inter**disciplinary [8, 5, 13]. This paper has two purposes: to introduce the program of non-linear dynamics research at Cal-Poly and to test whether or not chaos/fractal research can be **trans**disciplinary.

This paper briefly introduces six case studies of non-linear dynamics projects at or associated with our Institute. These projects are investigating particular phenomena from physical, biological, or social systems using computer analysis of empirical data. Each of the projects was initiated to achieve results that are significant to the particular target discipline and also of practical benefit to mankind. For example, one would increase our understanding and predictive power over an important human biological disease, while another focuses on the growth dynamics of an organism critical to fundamental ecological processes. Both practical industrial and deep theoretical types of projects are included. Aside from these pragmatic contributions, the analytical depth of the projects protects us against producing general systems theories without the all-important constraints of testing --- an all-too-often neglected dimension of general systems modeling.

The second purpose of the paper is to ask whether or not chaos and fractal analysis is truly transdisciplinary from the perspectives and experiences of these Institute case studies. Since our projects range from natural to social systems we can address this key question of interest to the ISSS. We maintain that the words **inter**disciplinary, **multi**disciplinary, and **trans**disciplinary are best kept separate and rigorously distinct. Only the word transdisciplinary maps completely on the attempts at formulating a general theory of systems which is the stated objective of ISSS research. This paper will review the above distinctions and suggest criteria for judging whether or not chaos theory and fractal analysis sometimes approaches the level of **trans**disciplinary research.

Introduction to the Institute

The Institute for Advanced Systems Studies is staffed by thirty-two, part-time Fellows and Associate Fellows. Although Fellows are primarily faculty from six Departments in the College of Science and the College of Engineering, we also have appointed Fellows from the College of Arts, College of Business, and the College of Environmental Design. The Institute has ongoing programs in three areas: systems education, basic/theoretical systems research, and practical/applied systems design. Its systems education programs are described in another article [23]. This paper focuses on one of our four long-term, basic/theoretical systems research programs, that of the non-linear dynamics (or Chaos/Fractal research program. Other core research programs are described in the Institute Introductory Pamphlet available from the authors [10].

Position of the Non-Linear Dynamics Research Program

Research programs at the Institute are organized into Task Forces staffed by the Fellows. The Chaos and Fractal Analysis Task Force is composed of the following Fellows (followed by their Departmental affiliation): Dr. Chuck Amelin, Mathematics; Dr. Carlos Ford-Livene, Mathematics; Dr. Bill Larson, Behavioral Sciences; Dr. Chung Lee, Computer Science; Dr. Ed Luloff, Physics; Dr. Steve McCauley, Physics; Dr. Earl Pye, Chemistry; Dr. Ron Quinn, Biological Sciences; Dr. Carl Rathmann, Mechanical Engineering; Pete Siegle, Physics, and Dr. Len Troncale, Biological Sciences. Each Fellow accomplishes their accepted part of the research program by attracting, organizing, and supervising a team of undergraduate Special Problem research students, and/or of graduate Masters students from his or her disciplinary area. Students receive University credit and other benefits for their efforts. Currently, the Chaos and Fractal Analysis Task Force has six projects at various stages of activity. Progress on these projects, sharing of techniques and problem-solving methods, and discussions of the implications of findings are shared at bi-monthly meetings among the participating Fellows. Results from each project are reported to the full Fellowship periodically as part of its bi-monthly Convocation series. The relationship between non-linear dynamics and other systems isomorphic processes are a regular feature of the Convocation presentations and debates. Using this low-frequency, but long-term method of conducting cross-departmental research, especially as it is amplified by participation of students, enables faculty busy at specialist tasks to also engage in generalist research beyond their individual strengths and preparations. As illustrated in this paper, serious attempts to contribute to a better understanding of disciplinary-based phenomena can be cross-compared for transdisciplinary results and advances in information and understanding. Both are accomplished simultaneously.

Case Study I: Fractal Tumor Boundaries and Cancer Prognosis

Introduction and Hypotheses

Cancer is a leading killer of both men and women in countries whose quality of life otherwise guarantees a long lifespan. Two important characteristics of cancer are its loss of normal feedback control mechanisms which limit growth (it grows too much and never stops growing) and its invasive or metastatic potential (it grows where it's not supposed to grow). Much modern research indicates that these macroscopic characteristics of cancer are related to genetically inheritable changes to a cell's DNA that happen in a two-step transformation process. These molecular changes alter cell physiology in numerous ways but among the most important are microscopic changes to the cell membrane. In cancer cells the cell surface glycoproteins are altered, cell growth hormone receptors are changed, cell type surface markers are missing, and the cell loses surface-mediated contact inhibition of division. The cancer cell no longer recognizes what it is or where it is. Thus, the macroscopic characteristics of cancer are related to the microscopic surface changes, and the deadliness of different cancers are sometimes related to the extent of difference from normal of these cell surface changes. Other basic research programs established that the overall form of a normal tissue or organ depends on cell surface signals.

We realized that despite the immense amount of data on various cancers, there were only limited measures (with short turnaround times) of the extent of surface differences of a particular cancer from its normal progenitor. Clinical pathologists use their experience and primarily subjective measures when evaluating biopsies at presentation by patients. They view stained slides for unusual nuclear:cytoplasmic ratio, degree of departure from the appearance of normal differentiated cells, vacuolization, and departure from the normal tissue organization. Staging of cancer is usually related to the number and extent of invasion of surrounding tissues by the cancer-looking cells. True, more sophisticated, less subjective microscopic tests exist, but they are much more costly and time-consuming, and their universality for all cancers is contraindicated. In effect, the molecular and the macroscopic are not yet well linked in clinical diagnosis and prognosis procedures. Yet there is a fundamental relationship between extensive cell surface changes and increased malignancy which is reflected in some cancers by extensively altered cell organization at the tissue/organ level.

We thought that fractals might offer a beneficial and very fast method for characterizing the degree of departure of an aggregate of cancer cells from normal. Fractals are a measurement of "the degree of topological irregularity" that remains constant across different scales of measurement [see 7, 9, 13, 14, 15]. Perhaps a consistent relationship exists between magnitude of fractal dimension (or degree of roughness or irregularity of a tumor) and extent of malignancy. Perhaps there is a way to directly and non-arbitrarily measure macroscopic disorganization in some cancers that would improve diagnostic and prognostic procedures. But are cancer margins fractal? Many irregular things are not fractal.

Methods

Test images of solid tumors were taken directly from cross-sections published in the literature [6]. The boundaries of the tumors at varying magnifications were digitized directly using a 12" by 12" Digitizing Tablet by Scriptel supported by Sigma Scan (V. 3.0, 1987) of the Jandel Corporation. Tables of digitized coordinates were thus directly created, maintained, and analyzed by using Supercalc 5 spreadsheets. Coordinate sets were analyzed for fractal dimension either by using commercially available software, such as Fractal-D (V. 1.0) for estimating fractal dimensions for two-dimensional data sets offered by "d. slice" software from Exeter Publishing Ltd., or by software programs produced by our own Institute Fellows and students. Professor Chung Lee, Institute Fellow, built a set of software which reads the digitally generated data file, reformats the coordinate values for easier processing, and then calculates the fractal dimension. The fractal dimension was calculated by estimating the quantity

$$D \text{ (fractal dimension)} = \frac{\ln (N)}{\ln (1/S)}$$

where S is the scaling factor (therefore 1/S is the segment size) and N is the number of subdivisions at each step (or the number of segments forming a line). For the estimation, an algorithm was devised where the combined total length of edges in the object is compared with the area of convex hull formed by the points from the digitizer. Work is in progress to compare this measurement with other known algorithms used to calculate fractal dimensionality including the R/S method. Further study will establish the consistencies of such measurements by estimating the confidence interval of the fractal dimension.

Status of Results

Figures 1 and 2 show our initial tests to establish whether or not a tumor might possess a fractal dimension. Figure 1A is an organoid solid tumor biopsy and cross-section at 15 power magnification and Figure 2A is the same tumor at 60 power magnification (remember a true fractal object exhibits the same fractal dimension at different scales of resolution). Figures 1B and 2B are the digitized versions of the tumor boundary (surface) at the two magnifications, and Figures 1C and 2C are samples of the lengthy computerized coordinates of the two magnifications of the same tumor. Computer analysis of the coordinates as described above indicated that the tumors show a **consistent fractal dimension of 1.53**. This fractal estimate is preliminary as described above and we must perform estimates on many other types and magnifications of tumors, as well as check for robustness of the parameterization and statistical analyses to become confident that tumors do exhibit significant fractal characteristics.

Future Work

If different types of cancers and different levels of malignancy of the same cancer show non-arbitrary and unique fractal dimensions, then a fast method for diagnosis of cancers at presentation could become available. Verifying this possibility will require extensive comparative fractal analysis of a wide range of cancers. We are negotiating with cancer research institutes at USC and UCLA which possess large data banks of tumor cross-sections along with patient histories including diagnosis at presentation and eventual fate of the patient under differing treatment modalities. Any correlations between fractal dimension and these hindsight parameters would

Fig. 1 (15x)

Fig. 2 (60x)

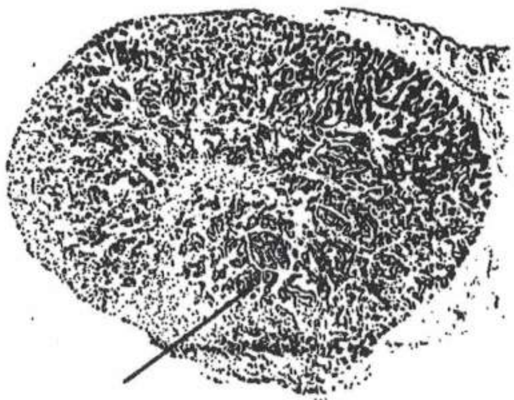

Fig. 1(a) The arrows indicate regions of fissured carcinoma within a simple radiate organoid tumor.

Tumors

Fig. 2(a) Edge of the molluscoid tumor with keratinized tubules and end-bulbs without keratin.

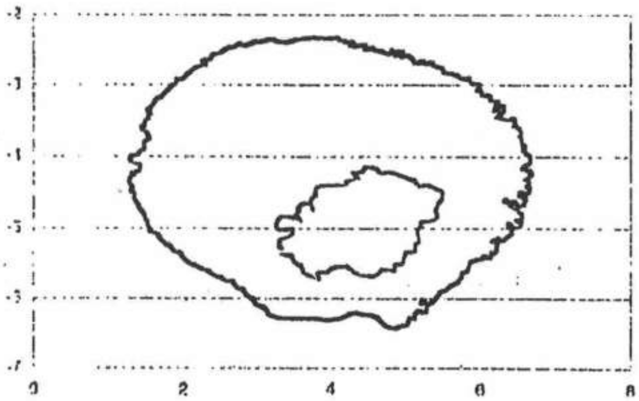

Fig. 1(b)

Digital Version

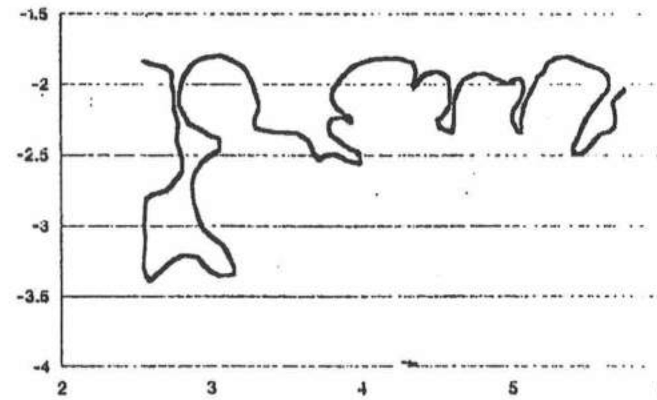

Fig. 2(b)

2.102157	-5.[illegible]
2.066347	-5.47172
2.038062	-5.477[illegible]
2.034542	-5.[illegible]
1.977653	-5.42776
1.938372	-5.[illegible]143
1.953488	-5.[illegible]
1.903215	-5.35276
1.830643	-5.34152
1.844733	-5.27857
1.828239	-5.26210
1.774966	-5.24562

Fig. 1(c)

Data Example

5.001187	-2.18469
4.998071	-2.21633
4.99911	-2.23776
5.004304	-2.26327
5.023004	-2.3
5.030276	-2.32245
5.058326	-2.33878
5.062481	-2.33469
5.065598	-2.31531
5.06352	-2.29796
5.057287	-2.27857
5.057287	-2.24796

Fig. 2(c)

Figures 1 and 2 are 15-power and 60-power magnifications, respectively, of a solid organoid tumor showing (a) the tumor cross-section, (b) the digitized version of the tumor perimeter, and (c) a sample of the digital data.

provide medicine with another tool to fight cancer. The recent improvements in MRI (magnetic resonance imaging)[1, 3, 4], and CAT-SCANS (computer automated tomography) suggests that non-invasive characterizations of the surfaces of cancers may soon be possible. Certain cancers responsible for a large percentage of cancer deaths, for example, breast cancers may be especially amenable to these studies.

Case Study II: Chaos in a Physical Electrodynamic System

Physicist and Fellow Peter Siegle and two undergraduate students have been studying chaos in an experimental mode by examining the transient motion in a simple, non-linear physical system. They have constructed a small bar magnet pivoted over the center of a constant, vertical magnetic field, but driven by a sinusoidal magnetic field of varied angles. They are investigating the decay properties of this non-linear systems as characterized by its Lyapunov exponents. They are attempting to measure the real and imaginary parts of the Lyapunov exponents, and demonstrate how these depend on the parameters of the system. Notice that this is not a series of theoretical calculations on an imaginary chaotic system but a real, measurable system. Their experimental results to date have demonstrated surprizing sophistication in such a simple system with scaling behavior and bifurcations clearly evident. They have examined the Lyapunov exponents as the system goes through the doubling periods; one to two to four to chaos; and one to two and returning to one. The experimental method and recording accessories of this application appear to be generalizable to many different mechanical systems. As theory matures its predictions, systems like this might be used to constrain and otherwise improve theoretical resolution, while unexpected physical clues might suggest to theoretical forays.

Case Study III: The Hierarchical Organization of the Universe As A Fractal Form

Another long-term basic systems research project of the Institute, reported in several recent papers [18, 21], has been the attempt to provide empirical tests of the hierarchical structure of natural systems ranging from the sub-atomic, chemical, geological, biological, to the astronomical scales. A large data base of empirical measurements of 15 parameters for various natural objects provided by the disciplines has been statistically analyzed to answer the question, "Can levels be non-anthropomorphically demonstrated?" Current results indicate that the date does show some statistically significant clustering (hierarchical levels), but that these clusters may not be the one's normally described as the "emergent" levels by the conventional disciplines. Further, the grand mean averages that characterize each "level of structure" when examined as pairs of the parameters have been demonstrated to exhibit regular allometric relationships expressible as formulae that are invariant across all the clusters of objects of the disciplines just cited. This has led to the formation of a new specialty tentatively called systems allometry [20, 21 22]. While continuing these investigations, we are beginning to use the tools mentioned in Methods above to examine the following sets of values to see whether or not they exhibit a fractal dimension: (1) the sequence of grand mean averages for each of the parameters for each empirically-demonstrated natural cluster; (2) the sequence of minima and maxima (extremum) values for each such cluster; (3) the combination of 1 and 2; as well as other statistical variants that characterize the "gaps" between the naturally occurring levels or clusters. As many natural objects that have "strings", "aggregates", "voids", or "holes" exhibit fractal form we would not be surprized if the overall structure of the universe at its largest scales down to its most minute scales also had an empirically demonstrable fractal form. If this proves to be so, we would then like to examine why it is so.

Case Studies IV - VI: The Chemodynamics of Rusting, Coral Growth Patterns, and Fractal Patterns in Social Communication

Three additional teams are studying a chemical, biological, and social system respectively for evidence of either chaotic processes or associated fractal form.

Institute Fellow Earl Pye, Professor of Chemistry, and his colleague Jim Stephenson have for some time been studying the process of corrosion for industry and government. The basic chemistry might seem simple, but as has been shown for so-called simple, non-linear physical systems the apparent process might contain cryptic properties of great value. This project has widespread implications of significant economic importance. Some say that there may be as many as eleven different classes of oxide and hydride corrosion of metals, while potentio-dynamic scans indicate that there are several different "domains" of reaction types for any one corrosion case study when kinetic parameters of the reactions are plotted against the thermodynamic parameters. These potentio-dynamic diagrams look something like a super complex "phase diagram" showing multiple "critical points." One might be tempted to imply that each reaction domain is controlled by an "attractor" and the shifts between would exhibit chaotic behavior. This is a working hypothesis to be investigated. Further, rust build-up as a result of the fundamental reaction kinetics leads to macroscopic aggregates which may well be controlled by the same "diffusion limited aggregation" (DLA) dynamics found in other cases of chaos. Scanning electron micrographs of the rust aggregates would be amenable to surface and string digital analysis as described above for a quick test of fractal form on the chemical level. Again, correlation of the various classes of corrosion, or the domains of reactions with a particular fractal dimension could lead to significant insights into the process.

Professor Peter Castro of the Biological Sciences Dept. has spent part of a lifetime collecting corals from around the world. He is recognized as an international scholar in the specialty. When one looks at a preserved "skeleton" of some species of coral, they appear similar to the bronchiolar branching of the lung, which have been shown to possess fractal form. The growth of coral worldwide is of fundamental importance to balanced ecosystems dynamics. We intend to investigate the growth dynamics of coral colonies using fractals as a new handle or clue to its contributing influences. To do this we are combining forces with the Computer Science Dept. to purchase a three-dimensional digitizer to add to our tablet described above.

Institute Associate Fellow Ed Luloff is completing his Ph.D. Thesis at the University of California at Irvine on applications of chaos to various natural and social systems [11]. One attempt of his that has intrigued us is the extension of the parameterization "length of intervening time" from natural systems such as rainfall and temperature (where they have been shown to have a unique fractal dimension) to human conversation. Using an admittedly small sample, he has claimed to demonstrate multifractals in time given a lengthy enough conversation between two people passing through a number of different topics [12]. We hope to encourage such attempts to bridge the usual chasm between natural and human systems by investigating whether or not both have similar features of non-linear dynamics.

Relevance of Chaos/Fractal Analysis to G.S.T.: Are the Results Truly Transdisciplinary?

The ISSS is a professional society whose expressed purpose is the fostering of advances in understanding of systems, particularly the transfer of systems theories across disciplines, and their unification, where possible, into ever more comprehensive general theories of systems. Clearly, the plethora of research texts already cited [2, 5, 9, 13, 14, 15, 16], and the numerous articles of the primary literature behind them are admissable under the general heading "systems science." They clearly are scientific in their focus on the many natural systems phenomena studied, and they are clearly systems-oriented as they explore by both theoretical and experimental methods the "dynamics" of systems. Non-linear dynamics, long a known mechanic of most systems was ignored due to its formidable complexity, and now the combined approaches of chaos and fractal analysis provide manageable clues to systems understanding and performance. Human-oriented, popular books [8] describe workers in the fields of chaos and fractal analysis as confused as to which discipline they now inhabit since whatever their original training they are now working in the more interdisciplinary area of non-linear dynamics. The answer is simple....they are among the first real systems scientists.

But is their work transdisciplinary enough to contribute to general theories of systems? We define as **inter**disciplinary any research or design which involves non-trivial contributions of knowledge or experience from two disciplines. This definition is derived from the Latin meaning of the word "inter" which is "between." It is the intimate interface between two conventional sciences to the point of creating a new discipline as in biophysics, biochemistry, or sociobiology. The fusion of description and methods between two disciplines in interdisciplinary work is often very deep and detailed on both factual and theoretical levels. Virtually all chaos and fractal research fuses information and approaches from both the discipline of the natural phenomenon under study and the fields of mathematics and computer science. As such it is clearly correctly termed interdisciplinary although the extent of the fusion is not yet as developed as in the interdisciplines mentioned above.

Multidisciplinary work is characterized by work focused on a design or engineering goal or product which involves important contributions from several disciplines. Examples include the engineering of commercial aircraft, weapon systems, or space vehicles by NASA. The several disciplines and their specialists are deeply involved in making their contribution to the whole, but the intent of the work is the product, not the fusion of the knowledge bases or methods of the various participating fields. The Latin word "multi" meaning "many" here describes limits on the meaning of this term. Chaos and fractal applied research is sometimes multidisciplinary.

Transdisciplinary is a rarely used, but much needed term. Derived from the meaning of the Latin term "trans" = "across", it means focusing on knowledge or natural processes or mechanisms which are common "across" many disciplines or scalar levels of organization. As such the meaning of the term transdisciplinary closely resembles the meaning of the term "isomorphy" when used as a noun, not a comparative adverb as it was used by Bertalanffy and followers. For chaos and fractal analysis to be useful to formulation of a general theory of systems, they have to fulfill some of the criteria for a GTS [25, 26], and at very least must be transdisciplinary, or result in the recognition of isomorphies.

Isomorphies have been defined by some as ascalar, invariant, self-organizing, and self-defining sets of mechanisms, structures, or processes found in many systems and crucial to the origin, development, stability, and evolution of those systems [17, 19, 24]. Since many interesting and complex systems do exhibit non-linear dynamics, and therefore, have components of the system which show chaotic behavior, they are isomorphic at this level of comparison. Other systems show fractal form across an impressive range of scalar magnitudes. But in both of these cases, the exact nature of that isomorphy (the phase space topology of stable histories of dynamic values for combined parameters) (or the actual fractal dimension empirically found) turns out to be unique and different. Dust particles, snowflakes, metal fracture surfaces, earthquakes, river branching patterns, coastlines, mountains, lightning, blood vessels, tree branching, protein surfaces, heart rhythms, ecosystem vegetation transcripts, electronic circuitry, etc. etc. may all have been shown to possess fractal dimensions, but the dimension of each is a different and unique fractal number. In fact, different taxons of trees and proteins appear to have different fractal numbers.

Thus the question becomes what underlies the generic possession of fractal form or exhibition of chaotic dynamics. Inherent in deeper studies of the different chaotic motions there are, in fact, some hint of isomorphic components. The universality of the Fiegenbaum constant, for example, or the ability to class apparently different types of chaotic system on the basis of their sharing similar phase space topologies or Poincare slices. This would imply that future work might reveal additional understanding of what is common to all non-linear systems, or a range of isomorphies true of different cohorts of non-linear systems. For example, many of the systems mentioned above as having fractal form really are *growth* systems. The particular mechanics of growth differs in each (mechanical, chemical, or biological), however, whatever the mechanism all have a determined (predictive) mechanism of growth which is surrounded by an environment which is unpredictable, noisy, both in its effects on the mechanism of growing for that entity and on its offering of the components necessary for the growth. The interaction of the deterministic and non-deterministic elements contribute the isomorphic and unique aspects of the phenomena respectively which we witness as the regular and irregular portions of chaotic and fractal dynamics. Our Institute also is studying the various effects that the non-linear dynamics of chaos and fractal form have on the operation of other isomorphic processes like hierarchical form and function, self-organization, positive and negative feedback loops, etc., and codifying these into our "linkage proposition" sets [17, 19, 24]. It is still too early to conclude that non-linear dynamics will contribute directly to formulations of general theories of systems, but the many findings from chaos and fractal analysis, their rigor, and the enthusiasm and hard work of their proponents have already stimulated significant contributions to the foundation for such theories.

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