Complexity and the Emergent Web

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Index Terms-- **Autocatalytic Individuals, Collective Adaptive Objects, Complexity, Emergence, Stochastic System**

Abstract-- **The main conceptual tool of Complexity is to express, explain and control the complex collective objects arising at a certain space-time scale as emerging from the simpler interactions of their components at a finer scale. This is a sort of extension of the "atomic-molecular" stochastic thinking and computational methods to social, biological, cognitive and information technology problems. The integration it implies is not a juxtaposition of various expertises but rather a much more intimate fusion of knowledge. This involves a coordinated shift in the very objectives, scope and ethos of the affected disciplines. Complexity is not offering just a way of answering a question from one science using concepts from another: it is introducing a new language which allows the formulation of novel questions or rather a new grammar which allows novel interrogative forms. Complexity induces a new relation between theoretical and applied science. In the past, as technology was acting on hardware objects, applied science was mainly experimental science applied to real life situations. Today, when technology is acting on information, applied science consists often of theoretical / abstract operations applied to real life information items. One may have to get used to the expression "Theoretical Applied Science".**

1- The Scope of Complexity

Long after the discovery of atoms and molecules it was still customary in science to think about a collection of many similar objects in terms of some “representative individual” endowed with the sum, or average of their individual properties. It was as if, in spite of the discovery of the discrete structure and its capability to induce dramatic phase transitions [1] , many scientists felt that the potential for research and results within the continuum / linear framework has not been exhausted and insisted to go on with its study. For another hundred of years, the established sciences were able to progress within this conceptual framework.

In fact, one may argue that this “mean field” / continuum / linear way of thinking is what conserved the classical sciences as independent sub-cultures. Indeed, it is exactly when these assumptions do not hold that the great conceptual jumps separating between the various sciences arise.

When "More Is Different" [2] life emerges from chemistry, chemistry from physics, conscience from life, social conscience/ organization from individual conscience etc.

Similarly, the emergence of complexity takes place in human created artifacts: collections of simple instructions turn into a complex distributed software environment, collections of hardware elements turn into a world wide network, collections of switches / traffic lights turn into communication / traffic systems etc.

This study of the emergence of new collective properties qualitatively different from the properties of the “elementary” components of the system breaks the traditional boundaries between sciences [3]: the “elementary” objects belong to one science - say chemistry - while the collective emergent objects to another one - say biology.

For lack of other terms (and in spite of many objections that can be advanced) we will call below the science to which the “elementary” objects belong - the “simpler” science while the science to which the emergent collective objects belong will be called the “more complex” science. As for the methods, they fall “in between”: in the “interdisciplinary space”. The ambitious challange of the Complexity community (its “manifest destiny”) is prospecting, mapping, colonizing and developing this “interdisciplinary” territory.

It is not by chance that the initial reaction to this enterprise was not very enthusiastic: the peers in the “simpler” science recognized the complexity objective (explaining the emergence and properties of the “more complex” science) as strange to its own endeavor. The peers in the “target”, “more complex” field felt that the basic concepts (the elements from the “simpler science”) are strange to the conceptual basis of their discipline (and too far away from its observable phenomenology). And all together felt that the very problematics and methods proposed by Complexity are not faithful to the classical way of making and dividing science.

In the case of the electronic and software artifacts, the “more complex” science is not defined as such to this very day. The naïve (and probably wrong) assumption is that the scientists responsible for it are and should be the people in charge with the elementary artifacts (computer scientists and electronic engineers). In the case in which the elementary objects are humans, the situation can be further complicated / complexified. Indeed, in this case, their behavior can be influenced by their recognition of

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the collective emergent (social) objects as such. This is a final blow to even *neo*-reductionist thinking, as the emergent “more complex” level becomes explicitly and directly an actor in the “simpler” individuals dynamics.

Fortunately an increasing number of scientific leaders and many young students find the challenge of Complexity crucial for further progress not only in pure science but also in understanding and mastering the most of our daily experience. In the last years this claim is being more and more substantiated.

In conclusion:

- The Complexity community has in addition to its intrinsic interdisciplinary character a common problematics and methodology.
- It carries the potential for synthesizing a large portion of reality into a well defined and integrated discipline.
- Supporting Complexity is scientifically and socially justified.
- The support has to be awarded to Complexity as such: there is no hope that funds allocated to the classical fields will end up being used for the advancement of Complexity.

2- Theoretical and Phenomenological Origins of Complexity

Even though the Complexity community had to take its distance from the core of theoretical physics due to the unenthusiastic reception it received there, many of the crucial ingredients of Complexity appeared in the context of Theoretical Physics. In fact Anderson listed [4] as his preferred examples phenomena which take place in physical systems: superconductivity, superfluidity, condensation of nucleons in nuclei, neutron stars, glasses.

He emphasized that in spite of the fact that microscopic interactions in the above phenomena are very different they can be all explained as realizations of a single dynamical concept: Spontaneous Symmetry Breaking. Similarly, the laws of emergence of computing (and thinking?) are independent of whether they are implemented on elementary objects consisting of silicon, vacuum tubes, or neurons. Therefore, the mere fact that various phenomena fall superficially in different empirical domains should not discourage scientists to study them within a unified conceptual framework. This birth gift of an extreme unifying potential haunted in the intervening 30 years the Complexity community as its main blessing and curse.

The role of Complexity ideas and techniques originating in theoretical physics is hopefully going to grow in the future as more and more theorists realize the inexhaustible source of fascinating challenges that real world offers to their thought.

After all, the renormalization group was introduced exactly in order to bridge between elementary microscopic interactions and their macroscopic collective effects.

2.1 Discreteness and Autocataliticity as Complexity Origins

The discrete character of the individuals turned out to be crucial for the macroscopic behavior of complex systems. In fact, in conditions in which the (partial differential) continuum approach would predict a uniform static world, the slightest microscopic granularity insures the emergence of macroscopic space-time localized collective objects with adaptive properties which allow their survival and development [5].

The exact mechanism by which this happens depends crucially of another unifying concept appearing ubiquitously in complex systems: auto-catalyticity. The dynamics of a quantity is said **auto-catalytic** if the time variations of that quantity are proportional (via stochastic factors) to its current value. It turns out that as a rule, the "simple" objects (or groups of simple objects) responsible for the emergence of most of the complex collective objects have auto-catalytic properties. In the simplest example, the size of each "simple" object jumps at every time instant by a (random) quantity proportional to its current size.

Autocatalyticity insures that the behavior of the entire system is dominated by the elements with the highest auto-catalytic growth rate rather than by the typical or average element [6].

This explains the conceptual gap between sciences: in conditions in which only a few exceptional individuals dominate, it is impossible to explain the behavior of the collective by plausible arguments about the typical or "most probable" individual. In fact, in the emergence of nuclei from nucleons, molecules from atoms, DNA from simple molecules, humans from apes, there are always the un-typical cases (with accidentally exceptional advantageous properties) that carry the day. This effect seems to embrace the emergence of complex collective objects in a very wide range of disciplines from bacteria to economic enterprises, from emergence of life and Darwinism to globalization and sustainability. Its research using field theory, microscopic simulation and cluster methods is only at its beginning.

2.2 Autocatalytic stochastic growth and power laws

One of the early hints of complexity was the observation in 1897 by Pareto that the wealth of individuals spreads over many orders of magnitude (as opposed to the size of a person which ranges roughly between 1/2 meter and 2 meters). The dynamics of the social wealth is then not dominated by the typical individual but by a small class of very rich people. Mathematically one realized that instead of the usual fixed scale distributions (Gaussian, exponential), the wealth follows a "power law" distribution. Moreover, in spite of the wide fluctuations in the average wealth during crises, booms, revolutions, the exponent of the power laws remained between narrow bounds for the last 100 years.

Similar effects [7] were observed in a very wide range of measurements: meteorite sizes, earthquakes, word frequences and lately internet links. In all these systems, the presence of power laws constitutes a conceptual bridge between the microscopic elementary interactions and the macroscopic emergent properties. It turns out that the autocatalytic character of the microscopic interactions governing these systems can explain this behavior in a generic unified way.
A quick plausibility argument is based on the observation that a dynamics in which the changes in the elementary variables are proportional to the current values is scale invariant. I.e. the dynamics is invariant under rescaling (= a transformation that multiplies all the variables by an arbitrary common factor). The fact that the auto-catalytic dynamics is invariant under rescaling, suggests that it leads to a distribution of the variables which is invariant under rescaling too [8]. The only functions which are invariant under rescaling are the power laws: $P(K x) \sim (K x)^{-1-a} \sim x^{-1-a} \sim P(x)$.

Note that by taking the logarithm of the variables, random changes proportional to the present value become random additive changes. This brings auto-catalytic dynamics within the realm of statistical mechanics and its powerful methods can be applied efficiently. A promising concept which might dominate this direction for the coming years is stochastic differential systems of generalized Lotka-Volterra type [9].

2.3 The Language of Dynamical Networks

The unifying power of the Complexity view is expressed among other in the emergence of a common language which allows the quick, effective and robust / durable communication and cooperation between people with very different backgrounds [10]. One of these unifying tools is the concept of dynamical network.
Indeed, one can think about the “elementary” objects (belonging to the “simpler” level) as the nodes of the network and about the “elementary” interactions between them as the links of the network [11]. The dynamics of the system is then represented by (transitive) operations on the individual links and nodes ((dis)appearance, substitutions, etc.) [12].

The global features of the network correspond to the collective properties of the system that it represents: (quasi-)disconnected network components correspond to (almost-)independent emergent objects; scaling properties of the network correspond to power laws, long-lived (meta-stable) network topological features correspond to (super-)critical slowing down dynamics. In this way, the mere knowledge of the relevant emerging features of the network might be enough to devise methods to expedite by orders of magnitude desired processes [13] (or to delay or stop un-wanted ones). The mathematical tools implementing it are developed presently and include multi-grid and cluster algorithms.

2.4 Multigrid and Clusters

The mathematical counterpart to the physicist's Renormalization Group is the Multigrid tradition [14]. In the last decade the 2 have interacted profitably and their relative strengths and weaknesses were complemented. A direction with a particular conceptual significance is the **Algebraic Multigrid.**

The Algebraic multigrid basic step is the transformation of a given network into a slightly coarser one by freezing together
a pair of strongly connected nodes into a single representative node. By repeating this operation iteratively, Algebraic Multigrid ends up with nodes which stand for large collections of strongly connected microscopic objects [15]. The algorithmic advantage is that the rigid motions of the collective objects are represented on the coarse network by the motion of just one object. One can separate in this way the various time scales. For instance, the time to separate two stones connected by a weak thread is much shorter than the time that it takes for each of the stones to decay to dust. If these two processes are represented by the same network then one would have to represent time spans of the order of millions of years (typical for stone decay) with a time step of at most 1 second (the typical time for the thread to break). The total number of time steps would become unbearably large. The Multi-grid procedure allows the representation of each sub-process at the appropriate scale. At each scale the collective objects which can be considered as "simple" elementary objects at that scale are represented by just one node. This is a crucial step whose importance transcends the mere speeding up of the computations. By labeling the relevant collective objects at each scale, the algorithm becomes an expression of the understanding of the emergent dynamics of the system [16] rather than a mere tool towards acquiring that understanding. Multigrid (and their cousins - Cluster) algorithms have the potential to organize automatically the vast amounts of correlated information existing in complex systems such as the internet, fNMR data, etc.

3. Particular Examples

Much of the present Complexity work may be thought as an application (with appropriate adjustments) of the table proposed 30 years ago by Anderson [2] where the "simpler" science appears in the second column and the "more complex" one in the first:

Atomic physics - elementary particles
Chemistry - Atomic physics
Molecular Biology - Chemistry

Cell Biology - Molecular Biology
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Psychology - Physiology
Social Sciences - Psychology

Below is an incomplete list of particular complexity directions substantiating this table.

3.1 The emergence of traffic jams from single cars

The traffic simulation [17,18] is an ideal laboratory for the study of complexity: the network of streets is highly documented and the cars motion can be measured and recorded with perfect precision. Yet the formation of jams is not well understood to this very day. In fact in some of the current projects it became necessary to introduce details not only of the car motion but also of the location of the workplace and home of the driver and passengers, their family structure and their life-style habits. Providing all this realistically for a population of 1 M people is an enormous computational and human time load and sometimes it seems that even this level of detail is not sufficient. Simpler, but not less important projects might be the motion of masses of humans in structured places, especially under pressure (in stadiums as match ends, or in theaters during alarms). The social importance of such studies is measured in many human lives.

3.2 From customers to markets

After loosing a fortune in a bubble (triggered by the South Sea Co.) in 1720 at the London Stock, Sir Isaac Newton was quoted to say: "I can calculate the motions of the heavenly bodies, but not the madness of people." It might seem over-ambitious to try where Newton has failed but let us not forget that we are 300 years later, have big computers and had plenty of additional opportunities to contemplate the madness of people. The traditional approach in the product diffusion literature, is based on differential equations and leads to a continuous sales curve. This is contrasted with the results obtained by a discrete model that represents explicitly each customer and selling transaction [19]. Such a model leads to a sharp (percolation) phase transition [20] that explains the polarization of the campaigns in hits and flops for apparently very similar products and the fractal fluctuations of the sales even in steady market conditions.

3.3 The emergence of financial markets from investors

The financial economics has a long history of using precise mathematical models to describe the market behavior. However, in order to be tractable, the classical market models (the Capital Asset Pricing Model, the Arbitrage Pricing Theory, the Option Valuation Black-Scholes formula) made assumptions which are found invalid by the behavioral finance and market behavior experiments. By using the direct computer representation of the individual investors' behavior, one can study the emergence of the (non-equilibrium) market dynamics in the presence of completely realistic conditions. The simulations performed until now [21][22] have already suggested generic universal relationships which were abstracted and then taken up for theoretical study in the framework of stylized models.

3.4 The emergence of the Immune Self from immune cells

The immune system is a cognitive system [23]: its task is to gather antigenic information, make sense out of it and act accordingly. The challenge is to understand how the system integrates the chemical signals and interactions into cognitive moduli and phenomena. Lately, a few groups adopted the method of representing in the computer the cells and enzymes believed to be involved in a immune disease, implement in the computer their experimentally known interactions and reactions and watch the emergence of (auto-)immune features similar with the ones observed in nature [24]. The next step is to suggest experiments to validate/ amend the postulated mechanisms.

3.5 The emergence of Perceptual Systems (the example of the visual system)

The micro-to-macro paradigm can be applied to a wide range of perceptual and functional systems in the body. The main steps are to find the discrete microscopic degrees of freedom, their elementary interactions and to deduce the emergent macroscopic degrees of freedom and their effective dynamics. In the case of the visual system [25] this generic program is quite advanced. By using a combination of mathematical theorems and psychophysical observations one identified the approximate, ad-hoc algorithms that the visual system uses to reconstruct 3 D shapes from 2 D image sequences. As a consequence, one predicted specific visual illusions that were dramatically confirmed by experiment [26]. This kind of work can be extended to other perceptual systems and taken in a few directions: guidance for medical procedures, inspiration for novel technology, etc.

3.6 Microscopic Draws and Macroscopic Drawings

The processes of drawing and handwriting (and most of the thought processes) look superficially continuous and very difficult to characterize in precise terms. Yet lately it was possible to isolate very distinct discrete spatiotemporal drawing elements and to put them in direct relation to discrete mental events underlying the emergence of meaningful representation in children [27]. The clinical implications e.g. for (difficulties in) the emergence of writing are presently studied. This realization that there are intermediate (higher than neuron) scale "atoms" in the cognitive processes is very encouraging for the possibility to apply complexity methods in this field.

3.7 Conceptual Structures with Transitive Dynamics

Dynamical networks were mentioned as a candidate for a "lingua franca" among complexity workers. The nodes are fit to represent system parts / properties while the links can be used to represent their relationships. The evolution of objects, production processes, ideas, can then be represented as operations on these networks.

By a sequence of formal operations on the initial network one is lead to a novel network. The changes enforced in the network structure amount to changes in the nature of the real object. The sequence of operations leading to novel objects is usually quite simple, mechanical, well defined and easy to reproduce.
It turns out that a handful of universal sequences (which have been fully documented) are responsible for most of the novelty emergence in nature. Incidentally, ideas produced by a computer that applied one of these sequences obtained (from double-blind humans) higher inventiveness marks than the ideas produced by (a second group of) humans [28].

The basic dynamical element in this conceptual dynamics seems to be "the diagonal link" or the "transitive connection" (the emergence of a link between A and C if there are already links between A and B and between B and C). This object has been found in recent measurements to be highly correlated with crucial conceptual events as identified by competent humans. Moreover the density of "diagonal links" has been found to be strongly correlated with the salience of the text [29].

4. Directions for the Future

Of course, below are only guesses of which could be the possible
directions in which the subject may evolve. Some of the ideas may looks strange, but they have an illustrative purpose of the potentialities of the approach (see also [30-32]).

4.1 Identifying and Manipulating the "Atoms" of Life

The situation in molecular biology, genetics and proteonics today resembles the situation of Zoology before Darwin and of Chemistry before the periodic table: "everything" is known (at least all the human genes), some regularity rules are recognized, but the field lacks an unifying dynamical principle. In particular the dynamics of "folding" (the process that gives the proteins their shape given a certain base sequence) and the relation between each protein shape and its function are anybody's guess.
In principle it is arguable that these problems can be solved within the borders of the present techniques and concepts (with some addition of data mining and informatics). However, I would bet rather on the emergence of new concepts, in terms of which this "total mess" would become "as simple" as predicting the chemical properties of elements in terms of the occupancy of their electronic orbitals. So the problem is: what are the "true" relevant degrees of freedom in protein/ genes dynamics? Single bases / nucleic acids are "too small"; alpha chains or beta sheets - too big.
Of course answering this problem will transform the design of new medicines into a systematic search rather than the random walk that is today.

4.2 Interactive Markets Forecast and Regulation

Understanding and regulating the dynamics of the (financial) markets is in some ways similar to predicting and monitoring weather or road traffic, and at least as important: One cannot predict individual car accidents but one can predict based on the present data the probable behavior of the system as a whole. Such prediction ability allows the optimization of system design as well as on-line intervention to avert unwanted disturbances etc. Moreover one can estimate the effect of unpredictable events and prepare the reaction to them.
It is certainly a matter of top priority that the public and the authorities in charge of economic stability will have at their disposal standard reliable tools of monitoring, analysis and intervention.
In the past it was assumed that the market dynamics is driven by exogenous factors and/or by uncontrollable psychological factors and/or by purely random fluctuations. This discouraged the study of their endogenous dynamics in a systematic quantitative realistic way. Other difficulties were the lack of knowledge on the numerical stability properties of the problem and on the nature of the relevant data necessary to describe the dynamics realistically. To make the things worse, until a few years ago, much of the trading data was also not available (especially in as far as the identity of the traders performing various successive transactions).
In the last years progress was obtained in all the issues above and the main difficulty that remains is at the cultural human level: the successful study of the stock market dynamics requires the synthesis of knowledge and techniques from different domains: financial economics, psychology, sociology, physics and computer science. These fields have very different "cultures": different objectives, criteria of success, techniques and language. Bringing people from these disciplines

together is not enough - a deep shift in their way of thinking is necessary.
Usually this requires "growing" a new generation of "bilingual" young scientists that produce the synthesis in their own minds. Otherwise, even the most efficient software platform will just be reduced to a very expensive and cumbersome gadget.

4.3 Horizontal Interaction Protocols and Self-Organized Societies

The old world was divided in distinct organizations: some small (a bakery, a shoe store) and some large (a state administration, an army) [33].
The way to keep it working was for the big ones to have a very strict hierarchical chain of command and for the small ones (which couldn't support a hierarchy) to keep everybody in close "horizontal" personal contact. With the emergence of the third sector (public non-profit organizations), with the emergence of fast developing specialized activities, with the very lively ad-hoc merging and splitting of organizations, the need for lateral (non-hierarchical) communication in large organizations has increased. Yet, as opposed to the hierarchical organization, nobody knows how to make and keep under control a non-hierarchical organization. The hope is that some local protocols acting at the "local" level may lead to the emergence of some global "self-organizing" order. The study and simulation of such systems might lead to the identification of modern " Hammurapi codes of laws" which to regulate (and defend) the new "distributed" society.

4.4 Mechanical Soul (re-)Search

The internal structure of psyche came under scientific scrutiny with the work of Freud. Yet to this very day there is no consensus of its nature. Even worse: most of the professionals in this field have resisted any use of the significant new tools that appeared in the intervening 100 years. This is likely to be a great loss as even the simplest computer experiments lead often to very unexpected and clue letting results. The old Turing test measuring the computer against the humans may be now left behind for a more lateral approach: not "who is better", but "how do they differ?", "can human thought learn from mechanical procedures?" This may help humans to transcend the human condition by identifying and shading away self-casted limits to ones selves.
Example of specific projects:

- Invention machines: programs that generate "creative" ideas.
- Predicting / Influencing the emergence of new political/ moral /social / artistic ideas out of the old ones.
- Identifying the structure of meaningful / interesting stories / communication.
- Understanding and influencing sentiment dynamics: Protocols for education towards positive feelings.
- Automatic family counselor: Inventing procedures, "rites" for solving personal / family problems.
- Automatic art counselor: Documenting, analyzing and reproducing ideas dynamics and personal development in drawings (small children, Picasso drawing suites)
- Pedagogical aids: Understanding and exploiting the interplay between ideas expressed in words and their internal (pictorial) representation.

5- Real and Mythical Difficulties

5.1 EXPERIMENTAL DATA

There is a myth that there are no experimental data for complexity. This is related with the fact that the tasks of experiments in complexity are different than in the usual sciences. E.g. in particles one knows the macroscopic behavior and has to look for experiments to probe the micro. In complex systems one usually knows both the macro and the micro but the intermediate scales connecting between them are not understood.

The experimental characterization of the collective objects relevant at various scales including their (conditional and unconditional) probability distributions and time (auto-)correlations is a very well defined objective. As with all Complexity, the only problem is that it does not fall within one of the classical disciplines.

The myth of irreproducibility is not more justified than accusing classical mechanics of irreproducibility just because in real life one cannot reproduce dice throwing experiments.

5.2 The Laws of Complexity

The archetype of finding "the basic laws" of a science is to find a small group of basic dynamical principles from which "all" the phenomenology of the field can be explained. For instance, the chemical properties of the atoms can be (in principle) deduced from the quantum electromagnetic interactions between electrons and nuclei. Pauling earned his Nobel prize for putting forward this program.

In the case of Complexity the rules of the game are completely changed: BOTH the macroscopic phenomenology of the collective objects AND the "elementary" properties of the "simple" objects are known. The challenge is to deduce one from the other WITHOUT introducing new natural laws !

In this sense finding the "laws of complexity" has to be preceded by a better understanding of what are we really looking for.

In the meantime, one can concentrate on producing uniform criteria by which to decide in generic situations which objects are to be considered "elementary" and which collectives are to be considered (and to which degree) as emergent objects.
These criteria should be standardized together with the search for other regularities (power laws, scaling, critical slowing down etc).

5.3 THEORETICAL TREATMENT

Here there are 2 levels at which theorists can function in the context of Complexity:

- the long range level with its hope for a "grand theoretical synthesis" providing the "laws of complexity emergence" (modulo the doubts above).

- the level at which we act now: applying the tools which we have described above: thermodynamics, statistical mechanics, scaling, multiscale, clusters, universality, graph theory, game theory, discrete dynamics, microscopic simulation, informatics etc.

The use of these methods (especially by somebody else) often reminds one of the saying: "when carrying a hammer, a lot of things look like nails". This might caution us to keep looking for simplicity even when carrying complexity.

6. IST and Complexity
When IT gets a mind of IT-self

The physical, biological and social domains are full of complex systems that emerge spontaneously from the interactions between the simpler elements existing in nature or in society. In recent years, though, with the proliferation of man-made artifacts, Information Technology (**IT**) and networking, many artificial systems have acquired a large number of elements and started to emerge collective complex phenomena. For people unaware of the complexity emergence mechanisms, it came as a surprise that a bunch of man-made artifacts would develop a mind of themselves to the level that their behavior couldn't be described, understood and utilized with the usual engineering methods.

Some examples of behavior in such systems are:
growth and information flow dynamics in computer networks,
the multi-agents ecology,
the world-wide-web contents evolution,
commerce arenas filled with negotiation agents and
traffic networks.
All of these phenomena have in common the following facts:
They are all built from or operate on multitudes of similar components which interact intensely with each other.
The technological/research field in which the components were initially designed and developed is not adequate to analyze, study and manipulate the overall system. For example, when a computer network grows so much that it can be looked at as a statistical ensemble, understanding the computer's hardware architecture or its operating system design is just not relevant to the task of identifying emerging collective qualities of the network.
While there is immense difference in the detailed structure of the elementary components composing each of these systems, their complex collective features can be shown to be analogous. In fact it doesn't even matter whether the basic elements are man-made or natural ones.

6.1 Designed to Emerge;
Bottom-up design of self-organized complex systems

In spite of this analogy with previous complex systems, the systems made of man-designed elements offer an unprecedented opportunity. While the complexity emergence in biology and society took place unintentionally, often as a result of chance, in man-made objects the emergence can be planned and influenced through the way in which the elementary objects are designed and displayed. The convergence of complexity and IT paradigms enables for the first time the deliberate development of a new breed of complex applications and systems:
Systems designed so that the simple interactions between their elementary components create collectively a desired global behavior.

Using the methodologies developed to study complexity phenomena, one can design complex behavior in artificial systems. This paradigm has the potential of transforming entire fields of IT applications. It may boost the development of directions that otherwise would reach a dead-lock, or would be increasingly limited by a mere logarithmic growth with the computer power. For certain applications, e.g. network routing, orthodox, global, hierarchical design methodologies can be proved to be inapplicable, even if the hardware capabilities will continue to grow exponentially. Similar examples of such fields and applications are:
Car traffic control optimization
Texts translation
Information retrieval and knowledge extraction
Network routing, content routes optimization
Adaptive collaborative software development
Real time air traffic scheduling adaptation

Autonomous UAV (Unmanned Aerial Vehicle) flocks

Bioinformatic research algorithms and tools optimization

Integrated robot flocks (or "dividuals", see below)

Below, we look further into some of these examples, but first let us discuss the generic advantages and problems of such "bottom-up" designing of complex systems. The most important are their

1. freedom of scale
2. adaptability and robustness
3. ease in design, implementation and maintenance

1. In algorithms theory the O(N) computational complexity measure is the corner stone of the entire science. The functioning of many of the "bottom-up" designed systems is often "simple" in this respect: all of the work is done locally and the issue of the cost at the level of the entire system does not even arise (nobody has yet submitted the next year budget for the world web :-). Similarly, one may add autonomously traffic lights, install new routers, or add additional UAVs to a flock as much as one wants, and the robustness or cost of the rest of the system will not be significantly affected. The local adaptive-agent based control algorithms become unavoidable in applications where in principle there are possible interactions between any arbitrary elements of the system. In such examples, the global hierarchical algorithms have to deal with an exponentiation in the number of alternatives to be considered. The local adaptive agents are usually dealing well with avoiding to even considering the cases that do not actually appear during their current functioning. Usually this is a great relieve as most of the computationally "worst cases" never appear in practice.

2. The high non-linearity of certain systems, like the control of traffic lights in a large city, makes it virtually impossible to find the optimized global algorithm for these systems. However, using methodologies developed in the study of complex phenomena optimality and predictability become possible, and in addition the systems themselves become understandable.

It is extremely hard, and in many cases plain impossible, to built a global logic system with good reflexes. By good reflexes we mean the ability to rapidly adapt to changes in an adequate manner. The need to tell in a top-down manner to each element what to do next makes it extremely difficult to react fast in the correct way. However, when one gets a collective behavior as an emergent character of a multitude of elements, adaptation comes naturally, and only in regions where it is needed.

3. Another important advantage of "designing for emergence" is the fact that it makes the applications easy to design, program and maintain. This is crucial for keeping-up the expansion rate of computer uses in domains with low programming literacy. There are simply not enough programmers around to design, implement and maintain classical software tools for every user.

The big disadvantage, but truly the big challenge, is that there exists no standard theory and practice for designing systems that emerge self-organized complexity bottom-up. It is obvious that this will require not only technological progress but also scientific effort. On the other hand its results might fare much beyond efficiency and impinge upon the very frontiers of human knowledge.

Let us look now on several promising examples of IT applications that may benefit from applying complexity concepts.

6.2 Specific Applications

6.2.1 Agent based and collaborative applications

There are two approaches, about agents cooperating in the management of complex tasks. The more traditional approach is making the agents more and more sophisticated, with AI core etc. The second and more promising approach aims "collaborative applications" i.e. applications that encompass multiple agents in a collaborative manner in order to fulfill a task.

The main conceptual limitation of the current collaborative application approach is that it tries to divide the global task into small independent segments performed by independent agents. This external division and stream-lining of the tasks preserves some of the rigidity and weaknesses of the logical-tree, centralized methods. The challenge is to design the right interaction protocols and feedback mechanisms that to insure the self-organization of the work in an optimal way.

6.2.2 Traffic Lights on the Spot

Centralization was a major paradigm for control theory since its inception. And for good reasons. A centralized control system is deterministic, and can be developed in a straightforward manner. But currently we are in a convergence point of several processes that suggest a coming paradigm shift. First of all, the amount of computer power which can be squeezed into a portable computerized device has grown exponentially. Even more important is the exponential growth in communication abilities, which makes both land based and wireless communication technology a mature, cheap and accessible option. These technological developments are met with new research paradigms described above, aiming to study the complex systems behavior that emerges from the interaction of the system's components. Among control applications, traffic management looks especially promising. It is composed of many identical components, which need to adapt rapidly to changing circumstances. A centralized system, wishing to adapt to a car accident will need to check all of the global ramifications of a change, while in a local-rules-built system such a process may occur naturally.

Ultimately, the very concept of traffic light may come under revision. The same information, instructions, regulations and signals which are currently communicated through road signs might be transmitted and may be even enforced at the level of the individual cars: Your car will slow and stop at "red lights" unless you explicitly choose to override the order it receives from the "traffic lights" system. Reciprocally, the traffic regulator program will take into account your travel plans, constraints, and the condition of your car in issuing its orders to the other cars.

6.2.3. Self-Organized Unmanned Aerial Traffic

The concept introduced above: emergence of self-organized traffic is particularly fit for Unmanned Aerial Vehicles (UAV) navigation:

- in aerial traffic there are less intricate obstacles than in ground transportation,
- the danger for hurting humans is less direct in unmanned vehicles
- humans do not have a head start in 3D navigation skills compared to computers (as opposed to hundreds of thousands of years of 2D navigation).
- The 3D geometry allows for the formation of large flocks that form, join and split according to the individuals initial and final destination points.

Relaxing the demand for a central control center that communicates with all of the UAVs in real time and directs them what to do, will enable creating large flocks of UAVs, that will be able to travel much further from their home. In addition it will enable to enlarge significantly the set of possible tasks such flocks will undertake, due to the fact that their reaction time scale will be reduced dramatically. In the case of Cruise Missiles Flocks the possibility to share their location and visual information, may result in a dramatic improvement of their navigation and target identification skills.

6.2.4. From Integrated Robot Flocks to Dividuals

The idea above that a collection of objects sharing information can be more efficient than a more intelligent single object has tremendous potential far beyond the realm of self-organized navigation.
As opposed to humans, robots can share and integrate directly visual, and other non-linearly structured information. They do not suffer from the humans need to first transform the information in a sequence of words. Moreover, the amount, speed and precision of the data they can share are virtually unlimited.

Like in the story of the blinds feeling an elephant, the communication channels typical to humans are not sufficient to insure fast, precise and efficient integration of their knowledge / information / intelligence. By contrast, robots with their capability to determine exactly their relative position and to transmit in detail the raw data "they see" are perfectly fit for the job perfectly.
So, in such tasks, while

1 human > 1 robot

one may have

100 humans < 100 robots.

This may lead to the concept of Integrated Robot Flocks which is much more powerful than the biologically inspired ants nest metaphor because the bandwidth of information sharing is much more massive. Rather than learning from biology, we may learn here how to avoid its limitations.

For instance, rather than thinking of the communicating robots as an integrated flock, one can break with the biology (and semantics) inspiration and think in terms of the **divided individual (**should one call them **"dividuals"?):**
Unlike biological creatures, the artificial ones do not have to be spatially connected: it may be a great advantage to have a lot of eyes and ears spread over the entire hunting field. Moreover, one does not need to carry-over the reproduction organs when the teeth (mounted on legs) go to kill the pray (the stomach too can be brought-in only later on, in case there is killing).
Of course, a good idea is to steal from time to time the control on somebody's else wings (as a form of Non-Darwinian evolution). Contrast it to the usual way real animals exploit one another: they are constrained by their biological reality to first degrade the wings of the prey to simple molecules at which stage, it is too late to use them for flying.
The anthropomorphic- biological grounding here is a liability that one has to free oneself from, rather than a source of creative inspiration. All said above is true both for robots (acting in the real physical "hardware" world) as well as for "bots" acting as software creatures.

6.2.5. Encounters of the Web kind

The emergence of a "thinking brain" by the extension of a distributed computerized system to an entire planet is a recurring motif in science-fiction stories and as such a bit awkward for scientific consideration. Yet, if we believe that a large enough collection of strongly interacting elements can produce more than their sum, one should consider seriously the capabilities of the web to develop emergent properties much beyond the cognitive capabilities of its components. As in the case of the Integrated Robots Flocks, the relative disadvantage of the individual computer vs. the individual human is largely compensated by the "parapsychological" properties of the computers: any image perceived by one of them at one location of the planet can be immediately shared as such by all. Moreover they can share their internal state with a precision and candor that even married couples of humans can only envy.

A serious obstacle in recognizing the collective features emerging in the web is the psychological one: people have a long history of insensitivity to even slightly different forms of "intelligence". In fact various ethnic / racial groups have repeatedly denied one another such capabilities in the past. Instead of trying to force upon the computers the human version of intelligence (as tried unsuccessfully for 30 years by AI), one should be more receptive to the kind of intelligence the collections of computer artifacts are "trying" to emerge.

An useful attitude is to approach the contact with web in the same way we would approach a contact with a extraterrestrial potentially intelligent being. A complementary attitude is to study the collective activity of the web from a cognitive point of view, even to the level of drawing inspiration from known psychological processes and structures.

6.2.6. Making the Net Work

Network routing is probably the most natural application for the complexity approach. First, routers are junctions of a network (in itself a central concept in complexity). Secondly, there is no conceivable practical way in which the network routing problem can be solved by a hierarchical, global algorithm. Thus routing is solved through the use of local routers that know where to send the information that is flowing through them. However, due to the fact that the development of routing algorithms still resides exclusively in the realm of computer engineering and computer science, the routing algorithms themselves do not pass the line of triviality. Billions of dollars are lost every year in damage due to bottlenecks, congestions, Denial Of Service caused by malicious attacks, negligence or simply by mistake or mis-design. Many other applications and businesses do not get transferred to the Internet due to these problems. Building systematic algorithms, which utilize the fact that the Internet has grown big enough to be thought of as a statistical ensemble, promise to create a more flexible, vibrant, trustworthy Internet.

6.2.7. Customized Information Providers and the Distributed Cognitive Space

On Passover, Jews are supposed to tell their children about the Exodus. The fit way to do it is exemplified in the Passover "Hagada"(=the "telling") by 4 cases:
1- the case of the wise child which asks "what are the rules we were instructed to follow on this occasion ?".
2- the naughty, which asks "why this effort to you?"
3- the naive / simple: "What's this?"
4- the child that doesn’t know how to ask.
For each of them a different answer is prescribed.
This situation is typical for every transfer of information. It is not enough to have in the data-base the correct answer and to deliver it. In order to be meaningful, the answer has to take into account the previous knowledge of the questioner its conceptual structure, its preconceptions and feelings and the situational context in which the question is asked. This background is given away in great measure by the very formulation of the question (or the lack of formulation in the case 4 above).

Consequently, there is a "large" infinity of answers on the same subject, each of them fitting a certain questioner and context. Yet the amount of existing documents written already on the subject is usually very finite. While all the elements for giving the "fit" answer to a current question may be available in the data-base, the answer itself is usually not.
It is a difficult, but increasingly compelling task to design "machines" which can do exactly this it: given a subject and a questioner to give the "fit" formulation of the answer(s). While in principle such a machine might require inputs from psychology, pedagogy, AI, the hope is that a host of adaptive agents might be able to "learn" the profile of the questioners population and the procedures to tailor documents fit to their individual needs.

6.2.8. Bringing the Rosetta Stone into the Chinese Room

The translation capability became one of the stumbling stones of AI. The belief that translation capability is tantamount to artificial understanding leaves one with a very bleak prospect for achieving it soon or easily. Yet the proliferation and globalization of knowledge makes massive online translation and processing of documents, especially on the Internet, an unavoidable and ubiquitous task.
The problem is wider than simple translations from one national language to another. One may equally refer to various technical jargons as technical "languages" and to writing executive abstracts as translations from verbose texts to their terse versions. "Translations" may also be the transformation of plain unstructured text into some structured canonical template (code to be used as input to further processing by specialized programs).
One possible approach is the bootstrap one: using the abundance of already translated documents as a resource for new translations. The bulk of documents written in a given "language" can be used as an operative definition of that language. Documents expressing in different "languages" the same thing can be used as operative models for "translations" between those "languages". This would be the automatic version of the techniques applied at the time for translating the old Egyptian hieroglyphs using the Rosetta stone [On

that stone, the same text appeared written in hieroglyphic script and in parallel, in Greek and Demotic].

Rather than designing heavy AI machines with large databases and sophisticated "intelligent" algorithms, all one has to do is to let a host of adaptive Internet agents to adapt the chunks of text of the already existing "translations" to new texts. If the result is not satisfactory (may be due to the lack of a large previous pool of "translations" between the two "languages"), the human corrections necessary to improve it, will insure that the current document can be used in the future as a basis for better performance (supervised learning). Of course, the agents may be endowed also with the capabilities to use transitivity: given a set of translations from a "language" A to a "language" B and a set of "translations" (in roughly the same subject) from B to C, they will produce automatic "A-to-C translations".

Instead of having to repeat each time the "translation" process, one would use the Internet with all the previously created documents as a global intelligent Chinese Room populated by many cooperating adaptive agents and furnished with a huge Rosetta stone.

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