Towards a theory of structural change

Carlos Domingo a,b,*; Giorgio Tonella a,c

a Centro de Simulación y Modelos (CESIMO), Universidad de los Andes, Av. T. Febres C., Mérida 5101, Venezuela
b Instituto de Estadística Aplicada y Computación (IEAC), Universidad de los Andes, Mérida, Venezuela
c Università della Svizzera Italiana, Lugano, Switzerland

Abstract

The objective of this paper is to summarise essential aspects and types of structural change that may contribute to the development of a general theory. First a brief ontological introduction presents the underlying worldview and clarifies the meaning of key terms. Second the basic general mechanisms of structural change are explored and relations among them are pointed out. Finally some considerations are made about the use of the developed concepts in the prediction, analysis, and management of structural change situations. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Since the late 1970s, huge changes in the socio-political world system and the consideration of complex problems in science have rekindled the interest in the issues of complexity and structural changes (SC), in other words, of changes that affect the identity of the entities. The world has entered an era of structural change, that started in the economic subsystem and that it is propagating to other aspects, affecting enterprises, nations, economic and political blocks and the global ecosystem. Is this a revolutionary transition between two rather stable periods, or a new

* Corresponding author.
E-mail address: cessimo@ing.ula.ve (C. Domingo).
modality that has come to remain permanent? It is difficult to say. But it seems that
the last possibility is very likely. This belief is supported by the possibility to
understand and manage SC (see Section 6) and by different patterns of generating
SC (see Sections 3–5) such as: integration and diversification, the importance of
diversity in quantitative-qualitative processes, the balance of continuous stimuli and
responses, and the evolution at the edge of chaos. Perhaps people are not looking
for a new stabilisation but to adaptation to the situation of change. There is a
feeling (not without empirical basis) that revolutions are costly, destructive and
their outcome is unpredictable. The stable periods that follow them are only the
preface to new revolutions. So the idea of creating a new flexible system and
maintaining a convenient degree of continuous structural change does not seem too
absurd. Mathematicians have accepted chaos and fractals, biologists emerging
variety, entrepreneurs flexibility, politicians alternation, and centralists have to
tolerate many ‘isocentric’ systems (in which each individual considers himself as the
centre) as it is seen in the displacement of TV by WEB. Of course this new tendency
is far from being consolidated, but these may be the early symptoms of an era in
which revolutionary structural changes would be rarer each time. In any case, there
is a need of new instruments to navigate in the SC of the turbulent times ahead.

The present paper is a step in this direction. It is a descriptive presentation of a
preliminary exploration for a general theory of SC. After a brief introduction on
past attempts and on some basic definitions, such as the differences between SC and
other changes (Section 2), the paper discusses the most elementary processes of
generating SC: assembling and disassembling (Section 2); bottom-up and top-down
(Section 4); and their related mechanisms such as evolution and self-reproduction
(Section 5). Furthermore, it presents some suggestions on the prediction, analysis
and management of SC (Section 6) that can be obtained from the study of the
different patterns of SC.

2. A general theory of structural changes?

During the last decades, there were many attempts to cope with complex
problems and some aspects of SC. These attempts have resulted in formalisations,
such as in the general theory of systems (see, for example, Klir, 1969), and in the
development and unification of many principles and methods that are useful to deal
with SC. For example:

1. Concepts to deal with changing systems: state space, stability, chaos, feedback,
   resonance, catastrophes, irreversibility and entropy, which were developed in
   system dynamics, control theory, catastrophe theory and thermodynamics.
2. General methodologies to approach the analysis of complex problems: input/
   output analysis, system identification and system decomposition.
3. Techniques to cope with complexity: graphs, matrices, computing methods,
   optimisation methods, databases, simulation techniques, econometrics, and the
   new techniques of emerging computing.
However, with some exceptions, such as the valuable contributions to the system theory and even some formalisation of certain aspects of SC (Löfgren, 1972), one feels the lack of a general coherent theory. All the above methods and formulations have not been very useful to understand processes such as the emergence of new systems, their structural transformations and their destruction. The feeling is that theories, such as the systems theory, must be enlarged and transformed. Probably the required development is worth to be considered a new paradigm.

There are at least two important approaches to a systematic study of complex structurally changing systems: (1) to build simple basic models (artificial systems), which show structural change behaviour similar to real systems. This is linked to artificial life, sociology and economy and it uses simulation techniques with models built of a set of rather simple elements. On-going researches at Santa Fe Institute are examples of this approach. (2) To discover analogies between observed processes of SC in different fields and infer some general laws. This uses large complex simulation models, such as structural and agent based simulation (Ören, 1975; Zeigler et al., 1991; Domingo et al., 1996) and modelling based on empirical data.

Of course both approaches are justified and in the present study results from both are used as sources of ideas and concepts for the general theory of SC. In addition, both are useful to find formalisations, which will allow rigorous scientific analysis of SC, and for developing a pragmatic approach for the prediction, analysis and management of situations of SC. Nevertheless, as in the development of the general system theory, the second approach is used here as a starting point towards a general theory. There are many other sources of ideas and reflections about SC, for example, in primitive thinking, religion, philosophy of history and many branches of the natural and social scientific knowledge. An examination of these ideas has been very useful to focus the attention in patterns of SC. They have helped to point out many processes, which are normally omitted in the literature of SC, such as the destructive processes that are of great importance in social, ecological and biological systems.

Without entering into detailed ontological considerations that would be necessary for the future development of the general formal theory of SC, some brief comments (not thoroughly developed definitions) about the used terms are necessary. The world is considered a multiplicity of distinguishable entities called objects (a basic concept in the new approach to computing and system design) with relations among them. A system is a part of the world; its objects are called parts or components of the system. It is considered an entity (another object) for some reasons such as: proportion between the number of external and internal relations, perception of its relative autonomy, functional behaviour, or relation with a problem to be solved. The set of objects related to the system and not belonging to it is called its environment. Objects and relations have properties. These may have different modalities and degrees (called values) in intensities. A specification of the parts, their properties, and the description of the relationship describe the structure of the system. According to the point of view of the specification, a system can have various structures. For example, a house has a static structure (columns, beams, plates and walls), a spatial structure (different rooms and spaces and their intercon-
nections), a functional structure (the uses of the different parts), which interest respectively to the engineer, the architect and the user. The philosophical problems posed by the above deceptively simple view of the world are not discussed here. The view corresponds roughly to the idea of the world implicit in scientific research. For a detailed account of ontology and a theory of knowledge compatible with science see Bunge (1974).

For the purpose of this paper, it is important to point out that objects, properties and relations change. So, systems change. It is possible to distinguish between two kinds of changes: structural changes and variations. Structural changes appear when some part or properties are lost or added to the object, some relations appear, disappear or change their form. In other words, SC imply changes in the object identity. Of course, this may happen in such small degree that the change is unnoticeable, or in such a degree that the system becomes practically a new one. Variations, on the contrary, appear when the values of one or more properties change, but the object maintains its identity. In other words, the parts, their properties and their relations remain the same. A chameleon may change its colour and an aeroplane its velocity and they remain the same objects. The above characterisation of SC is more general than those that consider only changes in the parameters (as in catastrophe theory or evolutionary dynamics) and even of those that take into account emergent properties and relations. It considers the addition and elimination of parts and subsystems, disintegration, collapses and changes in the main behaviour.

In many cases, both types of changes, variations and SC, are present. For example, the evolution may follow a general pattern in which processes of variation or minor structural modifications alternate with drastic structural changes. Perhaps the best known example is the one described by Kuhn (1962) about the change in scientific paradigms. During the periods of normal science, the paradigm (theories, worldview, methods, and focusing in certain problems) does not change or it undergoes only slight, sometimes ad-hoc, modifications, while scientists solve new enigmas using the paradigm. When some observed facts defy the paradigm, a period of crisis takes place. Some ad-hoc changes in the paradigm are tried, and entirely new paradigms are proposed. Extra-scientific elements enter into the conflict: generation gaps, philosophical positions, personal influences, nationalistic considerations, perceptions of research opportunities, etc. These disagreements are produced by the lack of a consensus about the paradigm. Finally the scientific community accepts the new paradigm, and a new normal period is open. This general schema has been applied to social, political, psychological and economic systems. The key points are: the accumulation of ad-hoc modifications during the period of normal development; the impossibility to solve some anomalies; the questioning of the paradigm during the crisis; the multiplicity of alternative outcomes; the influence of many factors not present during normal periods; and the difficulty to predict the new normal state. In general, a more particular and concrete analysis is required. It is important to remarks that the cause of crises or revolutions, with all the uncertainty in their outcomes, is the tendency to cling to a fixed structure. The transit between paradigms could be easier and more rational, if
the scientists (in the examples of Kuhn) would be more prone to manage a multiplicity of models and to remark, instead of avoiding, the anomalies that challenge the paradigm.

3. Relations between parts to form a whole: assembling and disassembling

Although there are many types of structural change, the most evident and simple examples are those in which some objects unite to form a whole (assembling) or a whole disintegrates into parts (disassembling). In the assembling process, new properties appear in the whole, which are not present in the components (emergent properties). The components, if they can be distinguished in the whole, may lose some properties and relations that existed when they were free. Furthermore, new properties and relations may be gained. Reciprocal processes may happen in disassembling, in which an object is decomposed into two or more objects. The properties of the whole may disappear (not remaining in the now isolated parts) and the parts may gain and lose properties and relations. These are observed facts. The bricks, assembled in a wall, lose mobility and gain reactive forces that they apply to other bricks: the wall displays a size and shape not present in the individual bricks. If the wall is dismantled, by separating its bricks, the reverse process of disappearing and appearing properties will happen. Another example: the numbers 5 and 7 are both odd, \( > 3 \), and not divisible by 3. When they are combined by addition, some of these properties remain as properties of the whole (12) while others are no longer in it and new ones (as divisibility by 3) may appear. Many (and more interesting) examples can be given of these well-known processes that are at the heart of structural change. Partial assembling and disassembling take place when some components are added or taken away from an object. The changes in properties and relations for the objects involved are similar to those described for the complete assembling or disassembling. Note that the addition of elements to a system may produce variations and SC in the whole system.

Two important questions arise in relation to assembling and disassembling: (1) Are the changes in properties explainable? (2) What are the causes of assembling and disassembling? In many cases, the new properties of the whole may be deduced from the knowledge of the properties of the components and from the general properties of the assembling process or, in more general terms, from the definition of the whole. In the simple case of \( 5 + 7 = 12 \), the emerging property of parity (or divisibility by 3) can be deduced from elementary properties of congruencies (and these from an axiomatic theory of the integers and the operations among them) and could be predicted before performing the actual test on the result. In the example of the bricks, the loss of mobility is caused by the force-transmitting properties of the unions (by friction or sticking) and the elastic and gravitational interactions between the entity that apply the force, the brick, the wall and the earth. The explanation is based in laws of elementary mechanics, but when details are analysed it is by no means trivial. With these laws and properties the immobility and its limits could be explained and even predicted before any observation of them. In
general, the explanation of the emergent properties is very complicated as compared with the simple test of the presence of these properties in the whole. In the artificial approach to the study of SC, as in the use of cellular automata, it is possible to show, using simulation, that many simple properties of a set of similar items originate, by interactions, assemblies with new interesting emergent properties (Hegselmann, 1996).

There are two positions in the problem of explaining emergent properties: reductionism and emergentism. The hypothesis of reductionism is that, from a better knowledge of the properties of the components and the assembling processes, it will always be possible to deduce the properties of the whole. Aside from the fact that, almost always, the method of deduction is developed after the observation of the emergent properties, it is also a fact that in many cases the properties of the whole remain without reductive explanation. On the contrary, the emergentists, from Morgan (1922) to Blitz (1992), assert that, in many cases, the properties of the whole cannot be deduced at all. True new unexpected and unpredictable properties emerge in the assembling process. Both cases, reductionism and emergentism, are non-falsifiable meta-theories. In fact, reductionists do not anticipate when they may give up their position in cases in which the explanation is not found, and emergentists do not declare on which conditions, after a successful reduction, they will abandon their position. So the polemic may go on forever. However, the practical attitudes derived from both philosophical positions have been useful. The efforts associated with reduction and the works, which consider the emergent properties simple starting points of further developments without reducing them, have been very fruitful for the development of knowledge. Physiology, for example, has advanced both, by studying the relations between physiological processes as such and by reducing some of these phenomena to chemical processes. It is a tactic of scientific research which kind of approach is more fruitful in the next step of an investigation.

The causes of assembling and disassembling are usually called forces or actions. These words are used in many fields, for example, in the mechanical, social or economic field. Actions are produced endogenously, by interactions between the parts of the system such as in self-assembling processes, or exogenously, by the interactions of the objects with the environment, or by both processes that may interact. It is not difficult to imagine simple artificial systems that can self-assemble when put in an environment of parts and submitted to random agitation. For example, in Penrose's experiments (Penrose, 1959) a set of plane equal pieces of plastic are moved randomly on a smooth horizontal surface. The pieces have notches and points that hold some of them together. According to their form, the pieces may assemble in chains of a well-defined length. More complex pieces united by a short axe may produce sets of fairly complex individuals of different structures. The process of change may be activated or slowed down by self-reinforcing or self-extinguishing closed chains of interactions produced by the assembling processes. These chains are called in the system dynamics terminology positive or negative feedback loops. In particular, a closed chain of self-reinforcing interactions may produce strong (positive or negative) variations in the values of the variables,
which, as it is discussed latter, may trigger SC. Self-extinguishing interactions may produce the stability of the original or of a new structure. For example, in the formation of a star from a molecular cloud, the attractive force produces a contraction, which reduces the distances among the molecules, which increases the attractions in a self-reinforcing process. Contraction continues, forming a high-density nucleus that accelerates the contraction. In the central part of the cloud, the velocity and intensity of collisions between the atomic nuclei are enough to start a new process: a thermonuclear reaction with great heat production that stops the contraction (self-stabilising process) and leads to the formation of a stable star. In economic systems, there are also many examples of self-reinforcing (Arthur, 1990) and of self-extinguishing processes. For example: (1) the regulation of prices by the market through self-extinguishing interactions of demand and supply or through self-reinforcing interactions among production, employment and consumption, which cause economic booms or slumps. (2) A self-reinforcing process in a subsystem (such as technological innovation) that may induce structural changes and instability through the whole economy and may affect the institutional, social and political environment (Pasinetti, 1993).

In the process of assembling, the closed chains of interaction may form integrative mechanisms that affect all the parts. These may be as simple as the gravitational field in a cosmic molecular cloud or as complex as the neurological or the hormonal integrative systems in living beings, or the institutions in social systems.

4. Relations between whole and parts: bottom-up and top-down processes

Once a whole is assembled, important cases of endogenous interaction are those in which global mechanisms affect each part or, reciprocally, the parts affect those global mechanisms. In other words, some news properties or subsystems of the whole may affect parts by restricting or freeing the manifestation of certain properties or relations between the parts (top-down processes). The parts, in turn, may affect the whole (bottom-up processes). Each process, or the combination of both, is a basic mechanism in structural change. There are a lot of examples of this pattern of SC. Some nations may unite (bottom-up) to form an economic block. The whole is implemented as a set of rules (tariffs, exchange types and production quotas). Changes in the rules, such as decrease of intra-blocks or increase of inter-blocks tariffs to increase trade and specialisation, may affect the economy of each country (top-down process) and this in turn affects the economic characteristics of the whole block. The interaction between the whole society that educates and socialises the individuals and the free activity of these, which change the society, is another example. The evolution and adaptation of the society depend on a balanced interplay between socialisation (top-down process) and the activities of individuals (bottom-up process). Too strong top-down processes (as in repression or enforced unification) may paralyse the society; if the bottom-up processes predominate, disintegration may result.
The followings are special types or aspects of these top-down and bottom-up processes:

1. **Qualitative changes induced by variations beyond a threshold.** In many processes a general top-down action, induced by endogenous or exogenous processes, varies steadily in a system built up of uniform parts and produces similar variations in them. In these cases, it may happen that, if the value of the action crosses a threshold, all the parts undergo changes in their relations, almost at the same time, producing a spectacular qualitative change in the whole. The classical example is physical phase transition, like the heating of a solid in which the parts (atoms, or ions, or molecules) vibrate around rather fixed positions determined by their mutual electromagnetic interactions. If the solid is heated, the amplitude of the oscillation increases and, beyond a temperature threshold, the parts go out of their limits and wander through the whole space of the body that has became, rather suddenly, a liquid. This type of change, pointed out by Hegel (1830), is usually referred to as **quantitative-qualitative** change. There are a lot of examples of it in natural and artificial systems and they are even mentioned in proverbs and folklore. It is worthwhile noting that, if the system is heterogeneous, the sudden change is less likely. An example is the heating of a piece of wax, which is a mixture of different substances; in this case, there is a plastic intermediate state. The influence of diversity is also seen in some social changes. In a more homogeneous society, revolutionary changes are more likely than in a society with a high degree of social and institutional diversity, which allows evolving SC.

2. **Responses to balanced stimuli.** There are systems that are complex enough to react constructively to general top-down stimuli. In these cases, a pattern of structural evolution is frequent when the stimuli are in the adequate range to induce such constructive answer: not too feeble to be coped without change in the system or too strong to destroy or paralyse it. Toynbee (1934–41) (vol. II) has observed this process in the development of many civilisations. The education of a child or a student, or living systems competition in co-evolution are familiar examples of this type of change. The system evolves solving problems that pose new problems.

3. **Integration** and **diversification** of the parts of a compound object are respectively top-down and bottom-up processes that occur as structural progressive change. The parts become more united and similar or more independent and diverse, and the system may reach an optimum balance of these two aspects.

4. **Unification** and **disintegration** are the extreme results of the preponderance of top-down or bottom-up processes respectively. The unification may result in a paralysed system, disintegration in the destruction of the system. There are many examples, in which forced political unification produces a tense state of unity that explodes in disintegration when the top-down unifying forces fail.

5. **Structure adaptation and evolution at the edge of chaos.** In general, evolutionary and adaptive structural changes depend on a subtle balance of top-down and bottom-up processes. Only those systems, which are loose enough to be creative and controlled enough to avoid complete disintegration, can evolve. The new
ideas about chaos allow seeing other aspects of this balance. Studies on dynamic systems show that in non-linear systems described by three or more differential equations a chaotic behaviour may occur. In other words, for certain values of the parameters, although the system is strictly deterministic, the behaviour of the variables appears to be completely unpredictable and to follow only statistical regularities. Very small changes in the parameters or in the initial conditions or a little variation in the values of an exogenous variable quickly produce great differences in the subsequent values of the variables (Schuster, 1987). The parameter space has three regions: one in which the values of the parameters are such that the system tends to stability (point attractors), another in which the system is oscillatory (orbital attractors), and a third in which the system is chaotic (strange attractors). Many examples of chaotic behaviour may be found in mechanical devices (as a pendulum under periodic perturbations), in turbulent movements of fluids, in meteorological phenomena, in economic and social systems, to mention only a few. There is an interesting model of artificial system that shows clearly the relationship between the stable (frozen), evolutionary and chaotic behaviour of a system. The system is a set of components each one with only one property with the possible values 0 or 1. Each component receives as inputs the values of some other components; a Boolean function of the inputs determines what will be the next value (0 or 1) assigned to the component. A set of values 0 or 1 for the components is called a state of the system. These systems show cycles in which the whole system or one part of it repeats cyclically the same states. The key parameter for this behaviour is the mean number of inputs for the entities. For a very large number of inputs the behaviour of the system is generally chaotic. Some cycles are possible, but an exogenous change in only one value may lead the system to a chaotic wandering or to another cycle. The system is structurally unstable. If the mean number of inputs is two, the system becomes frozen into separate regions of behaviour. For values a little greater than two, the system has a relatively stable but not fixed behavioural structure. It is a region of formation and decay of behavioural structures reminiscent of those of living and social systems. The suggestion is that selection drives the system to this region of loose connectedness, which allows the appropriate balance of stability and change that may result in adaptation and evolution. This was called adaptation and production of new structures at the edge of chaos (Kauffman, 1993 pp. 189–208). These experiments suggest that in sufficiently complex almost chaotic systems order may emerge spontaneously in the form of structures at variable degrees of stability and flexibility, which make those structures apt to adaptation and evolution. An interesting example of emerging order is the formation of Benard cells (Prigogine and Stengers, 1984). If a pan full of liquid is gently and uniformly heated from below, the molecules at the bottom are accelerated and transmit the increased speed to higher molecules in a totally random stationary process. When the heating increases and the thermal gradient exceeds a certain threshold, ascending convection currents start and the whole mass of liquid is organised in a pattern of cells each with ascending currents in the centre and descending currents at the edges. The sudden local fall
in the entropy, i.e. the increase in organisation, occurs by the supply of heat from below. Process of this type may occur in situations far from thermodynamic equilibrium in systems maintained by a flux of matter and energy from outside (open systems). There are many situations of evolution and adaptation; for example, the inheritance governed by the genetic code shows a balance between chaotic behaviour, produced by the lability of the complex mechanisms of copying, and the stability maintained by the genetic regulation and error correcting processes. In a similar way, the evolution of societies is based on balance between the diversity of individual behaviour (produced by genetic changes, variable environments and roles), and the unifying forces of education and socialisation. In many of the above examples (e.g. abstract networks, living beings, societies, Benard cells), a multiplicity of elements is organised in an emergent order.

6. **The production of similar objects.** Some top-down and bottom-up processes result in the production of a multiplicity of objects that are starting point of new structural changes. These processes are discussed in the following section.

5. **Multiple production of objects**

   The simplest process of object production may be disintegration by global top-down actions or by bottom-up self-sustained processes (like combustion, chain reactions, and chemical decomposition). Assimilation is decomposition followed by a new assemble as it happen in living beings. Top-down actions in a system with non-homogenous regions may also produce a multiplicity of objects. Non-homogeneity in the original multiplicity brings out a new type of multiplicity. For example, the production of many crystals from a solution, or many stars from a giant molecular cloud in space, or many population centres during the occupation of a new territory create a higher level of objects (crystals, stars, towns). There are a lot of artificial processes for objects production (moulding, printing, copying) in which one or more structured objects act on other objects to produce a multiplicity of new objects. All these productions are not self-sustaining because resources (original objects) or activators (moulds, enzymes) or both are exogenously controlled and their supply may be stopped or exhausted.

   The multiplicity of new produced objects may sometimes be referred as a higher organisational level of the original objects. Quarks, elementary particles, atoms, molecules, inanimate objects, living beings, individuals, societies, are examples of organisation levels (Miller, 1978). The theory of levels tries to establish a hierarchy based on the origination and complexity of organisation levels. Reductionists try to explain the properties of a level by the laws and properties of the lower level while emergentists deny this possibility. These positions were discussed in Section 3.

   The importance of level theory in structural change lies in the fact that, in many cases, structural changes are unexpected, because the usual observation is made at one level and the change is triggered off by processes at a different level. A socio-political revolution may surprise the authorities that observed the apparently
regular global social and political facts, but, at local and individual levels, changes are taking place in opinions, expectations, and perceptions of many individuals. These create a hidden structure that abruptly emerges in the whole. A similar case occurs during crises in which the structure of the upper level is perturbed and there are many possible outcomes of the situation. The laws of the evolution of the upper level have collapsed and cannot be used to predict the outcome (see Section 2 on alternation of variations and SC). The system has become very sensitive to microprocesses at lower level.

Some objects have the properties of producing copies of themselves. This property of self-reproduction requires some special characteristics and has far-reaching consequences. Living beings have this property but other systems as human communities and organisations also have it, as it is seen in colonisation of virgin lands and creations of enterprises. Self-reproduction is important for SC theory because (1) it may originate an exponential growth in the population of individuals, which bring about conflicts within the population, with other populations, or instabilities in the environment, which can trigger SC processes. (2) When it is combined with variability in the reproduction, the generated entities may evolve by the Neodarwinian process: Mendelian inheritance and natural selection. This structure-adapting and optimising system is observed in other fields. In biology it is important the destructive and self-destructive processes of individuals (death) that allow the evolution in a limited environment. Some biologists doubt that such a simple process may produce the marvellous adaptations of living beings, especially the emergence of new functions that requires the simultaneous appearance of many traits, which individually do not afford selective advantages. Some scholars have appealed to self-organising processes to explain the emergence of new functions and adaptations (Kauffman, 1993 pp. 287–341).

The necessary mechanisms for self-reproduction of a general automaton of any complexity were established by Von Neumann in his famous lectures about automata (Von Neumann, 1948, pp. 288–328). Besides the practical importance that this result may have in robotics, it shows the capacity of a mechanical device to produce another device of the same complexity and, as will be pointed out, able to adapt and evolve. The importance of Von Neumann proof is that self-reproduction is shown to be a structural characteristic of a system and that it is a computable process, without any reference to life.

Von Neumann bases his abstract machine on the definition of a general and simple imaginary computer device designed by Turing. The device consists of a long tape on which symbols (usually 1, 0 and stop) can be written. The tape can move so that the symbols can pass, one by one, in front of a reading-writing head. This head is a device that can sense the symbol in the tape, change it and move the tape one place to the right or left. These operations are controlled by the instructions of a program (written using the same kind of symbol). It can be shown that this simple device, when the adequate program and data are put on its tape, can perform complex calculations and can record the results on it. The importance of this machine is not its practical use as a computer, but its simplicity, which allows demonstrating some fundamental characteristics of the computing processes. The
self-reproducing system may have the following describable automata that may have any degree of complexity:

(i) An automaton A, capable of building, when activated, any other automaton, when a description I of the parts and rules of assembling are given to it. This description I is a ‘program’ written in a certain code of 0s and 1s. Of course, the parts to be assembled must be provided. A can build any automaton, but not by itself: it needs an external action for its activation and for the order to execute the adequate description.

The idea is to add the following additional automata so that the whole system is self-reproductive:

(ii) An automaton B that can make a copy of any description.

(iii) A computer C (a Turing machine) that can execute any program with the data that is written in its tape. C is also an automaton. It contains in its tape the reproduction program described below.

(iv) An automaton D formed by assembling A, B and C, and let I be the program to build this automaton D.

(v) An automaton E formed by D and I.

Then the automaton E = D + I is self-reproductive. This is shown by noting that component C (the computer) is started and executes the reproduction program that is written on its tape.

In this program: (1) E activates the automaton A, telling it to use the description I, so that it constructs D = A + B + C. (2) C tells B to be active and to make a copy of I. (3) C tells this copy I to aggregate to D to obtain E.

The key point is the aggregation of I that makes new automaton (‘the son’) reproductive. In a more concrete consideration, the device must operate in a sea of parts that contain all possible components of A, B, C and I; and A is a complex machine that can detect parts, transport them, and arrange them according to a codified description. C is a computer that can also act as a copier B and I is a ‘girder’ made of a sequence of parts that can encode the description (parts and rules to assemble) of the automaton. Von Neumann observed that, in this reproductive mechanisms, variants and errors may be introduced in the girder I, which may produce non viable individuals, but also someone endowed with new functions or better adapted to changes in the environment, producing adaptation and evolution.

No physical example of such a machine has been built, but an elegant simulation is described in Langton (1984). The difficult problem is how this reproductive mechanism comes about. The Von Neumann self-reproducing system is artificial and includes very complex elements as a computer and the information system in the girder.

Living systems and the socio-economic institutions are examples of self-reproducing systems that are also a complex assemble. Their origins have been studied, but there are no widely accepted theories of their formation based on empirical evidence. Nevertheless, a brief mention of some problems and suggested solutions may throw light on the problem of structural change. The problem of the origin of life with self-reproducing properties has been approached in two ways. The first one looks for the origin of proteins (the basic components and catalysers of living
systems) as chains of amino-acids, which, according to some experiments (Miller, 1953), may have been originated from inorganic simple compounds present in the atmosphere of primitive earth. Some of these chains have been obtained in laboratory conditions, in some cases on moulds of certain clays (Cairns-Smith and Harman, 1986), but the problem is how the reproductive mechanism was formed. The basic elements of reproductive mechanism are the DNA and RNA, which are not proteins but chains of nucleic acids. The prebiotic synthesis of these nucleotides is harder to achieve, although some progresses have been made. The problem is that, to produce proteins, the actions of these nucleic acids require enzymes that are catalytic proteins. One interesting suggestion is that, as simulation experiments in artificial system show, in complex systems, autocatalytic processes may develop. In other words, some combinations of elements, produced by simple rules of affinity, may generate a chain of compounds, in which a previous component of the chain is produced. Thus close chains are formed. This is a self-reinforcing process that grows by taking elements from the environment. This view makes self-reproduction a very probable result of complexity rather than very improbable. The proliferation of these autocatalytic processes, especially if they are produced at the edge of chaos, may produce competition for the components in the environment. They may evolve and integrate previous developed elements as proteins and nucleotide chains (Kauffman, 1993 pp. 287–341). This suggestion is a hint for future research rather than a well-developed theory, but may have interesting analogies in other fields. In the economic theory business cycles or long waves (Kondratieff, 1935) are associated with the spontaneous assembling of a set of new technologies that reinforce one another (Freeman and Perez, 1988). This is like an autocatalytic process, forming a system that may generated in a country and then may be reproduced in others using the information and implementation subsystems associated with it.

6. The pragmatics of structural change

The application of the discussed general ideas of SC has three aspects: prediction, analysis and management of situations of structural change.

The prediction of SC is difficult, because stable states of the system are usually taken for granted and they appear as natural laws, ‘business as usual’, straightforward projections and well-known problems. This is a veil that hides the perception of the emerging structure, before the change is triggered, and even it hides the detection when the emergent structure is in its early phases. It is therefore important:

- To discover the hidden tensions that maintain the status-quo: opposed equilibrium forces, reverse compensating processes, silent repressed efforts, suppressed manifestations of tendencies, hidden relations and affinities. All these can produce drastic changes when equilibrium conditions are altered.

- To notice apparently fortuitous events: casual encounters, abnormal behaviours, odd coincidences, may appear insignificant facts, but may produce by powerful not yet emerging forces. The accidental may be the first warning of a new behaviour.
To take into account some intuitive information, before it is destroyed by common sense, and experienced reasoning based on habitual evidence: first impressions, early appearances, subtle feelings, arising of bizarre analogies, even dreams (dear to old folklore) may detect unusual aspects of the situations.

To use unconventional deductions based on random devices, as cards and apparently magic procedures. Without giving credit to superstitious practices, it is a common experience that they may be useful to promote mental block-busting by directing the mind to possibilities not likely to be considered by more rational thinking. Those that fear loss of respectability because of these practices, or for the kind of advisers they imply, may try bold experiments with randomly altered simulation models.

The analysis of SC is hampered by a lack of adequate methodology. Many methods exist in science to deal with quantitative changes or variations. In the case of SC some of the following advice may be useful:

To bear in mind the types of SC that have been discussed above, such as:
1. Assembling and disassembling, with exogenous or endogenous causes and changes of properties. In particular, the addition of a strange element to a system may generate unexpected unbalancing processes. This has been pointed out by Toynbee (1934–41) (vol. III-C-III-b) in many historical examples.
2. Building of self-reinforcing and self-stabilising changes that produce SC processes and stabilisation in a new structure.
3. Top-down and bottom-up processes, such as quantitative changes and thresholds to qualitative ones, integration and diversification, proliferation and unification of objects.
4. Adaptation and evolution at the edge of chaos.
5. Evolution by variability and environmental selection.
6. Many other types, subtypes or combinations of these patterns may help to understand the SC situations.

To study the history of the system. In the past SC of a given system, some deep characteristics of the system’s reactions to the crisis can be discovered, which may throw light on the possible future behaviour. Some social systems, for example, tend to use violence, others to look for consensus.

To study similar systems and their reactions in the face of similar crises. The study of what was similar and what was different may bring examples and counter-examples for the case at hand. The exercises in alternative history are useful to stimulate imagination and to lead to deeper analysis of the system.

To explore the processes at a lower level of organisation where future structural changes may develop. As it was pointed out, during the crisis, concrete analysis is needed.

To take into account the two main forms of knowledge: the intellectual knowledge by models, belonging to science and the sympathetic knowledge, typical of the artists and the mystics (Bergson, 1903). The first method of knowledge consists in building another system (a model) and to understand the original system by analysing the model. The second tries to get some sympathetic,
non-manipulative identification with the system and to express it in a particular holistic way. In structural change, the known model breaks down because it does not grasp the lower levels of organisation in which the structural change originates; additionally, more profound, particular and unexpected aspects of the object become important. In this situation, those non-conventional types of knowledge may be full of new suggestions.

- To make thought experiments, to put oneself in someone else’s mind, and to generate multiple scenarios may be useful exercises to imagine possibilities of the accidents and outcomes of a structural change situation (Wack, 1985a,b).
- To try the new techniques generated in complexity analysis. AI techniques especially those related to simulation of creative processes, agent simulation, studies in artificial life, artificial societies and artificial economy, clustering techniques, neural nets, genetic algorithms, simulation-database combinations, and qualitative simulation may be useful in particular cases.

The management of structural change is the central problem and the main target of the general theory. The only thing presented here is a list of recommended suggestions and warnings to the reader, who may follow up on them through his or her own experiences or reflections.

- To refrain from excessive concentration on the problem. When the problem to be solved requires creative thinking, as it is usual in structural change situations, rational efforts useful when exploring related situations, may lead to dead-ends. As it was pointed out by Poincaré (1908) and Hadamard (1954), by diverting one’s attention from the problem, the solution may spring to the mind spontaneously. Perhaps the conscious rational effort sparks some type of automatic but random unconscious process that may lead to a solution. For a simulation of such process see Domingo et al. (1995). On the other hand, temporary disengagement with the problem may allow seeing apparently unrelated objects that may suggest an original solution.
- To promote unusual encounters. For example, to invite to the discussions of a group a specialist in a field unrelated to the problem. This person may have a new vision or approach.
- To maintain a flexible system with a diversity of view of the situations and open the many possibilities of operations to avoid the need of drastic re-structuring.
- To balance stimuli and new stimuli after the responses. This may bring about controlled structural change processes that are important in education and in planned development.
- To balance competition and collaboration. This is a particular and subtle case of balanced stimuli that can be promoted as a powerful process of change in biological systems and social organisations, if the extremes (conflict and complexity) are avoided.
- To study new use of old elements. Old elements may be easily discarded in a rage of change, instead of considering their usefulness in the new structure. In the biological evolution, there are many examples of this transformation of function. The use of the quadrate bone that allows a wide opening of the mouth in reptiles is one of these. This bone became some of the middle ear bones in the mammals that transmit and multiply the vibrations to the inner ear (De Veer, 1959).
To promote processes of ‘retirement and return’. These processes (Toynbee, 1934–41, vol. III-C-II-b) allow us to distance ourselves from particular absorbing problems and to take notice of the more profound causes and circumstances. After this withdrawal it is possible to come back to the temporarily abandoned situation with a new vision.

To stimulate proliferation and variety. Multiple production of diverse entities that may be afterwards selected to fulfil the needed function may be a useful application of the variation-selection scheme. Brain storming, immunological mechanisms, in which hyper-mutation of antibody receptors is stimulated (Playfair and Lydiart, 1995), and increase of the genetic mutation rate, when the environmental conditions are threatening, are examples of these proliferation of objects that must be followed by a rigorous selection. Besides, as it was pointed out in Section 5, diversity favours evolutionary structural changes instead of sudden ones that are difficult to manage.

To alternate top-down and bottom-up processes. In organisations and institutions the change may be elicited top-down (Crozier and Friedberg, 1985), but the true change comes from bottom-up modifications in people’s attitudes, expectations, projects, self-images and feelings.

7. Conclusions

A general theory, to grasp the essential features of SC and to help in developing guidelines and techniques for its management, is not only possible but also necessary. In an empirical approach to this development, the first step may be to find and classify different patterns of SC from many branches of knowledge and then to look for relationships and hierarchical organisation of these patterns. As this is a theoretical and practical task, it is important, at the same time, to extract from the incipient theory, principles and ideas to be applied in SC situations and to test their efficiency in concrete situations. As happened in general system theory, it is hoped that after these preliminary works, more formal developments might be successful.

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References


