Chapter 1
Introduction

Abstract. Complexity and emergence are introduced here in relation with the self-organization of systems in levels of reality.

Evolvability defined as the ability to evolve is the projected way to confront and surpass the successive levels of complexity. Polystochastic models allow refocusing from adaptable to evolvable, from a low dimensional to a higher dimensional insight.

Significant concepts for evolvability as level of reality, circularity, semantic closure, functional circle, circular schema and integrative closure are presented.

The correlation with organic computing or autonomic computing research areas is highlighted.

1.1 Complexity

What is a complex system, and what does it means for a system to be complex and emergent?

The study of complex systems or more generally the science of complexity has been a hot research topic for the last decades.

Usually a complex system is described as a structure or process involving non-linear interactions among many parts and levels, which displays emergent properties. In other words this means that the aggregate system activity is not derivable from the linear summations of the activity of individual components and that novel structures, patterns or properties arise, from simple interactions among parts.

Complex systems are ones in which patterns can be seen and understood, but interplay of individual parts cannot be reduced to the study of individual parts considered in isolation from one another. A survey of the literature indicates that there is no standard agreed upon definition of a complex or emergent system. Some of the definitions may even seem contradictory but they may make sense when applied to particular types of systems and from which perspective one choices to observe (Adami 2002, Boschetti et al. 2005, Cariani 1992, Goldstein 1999, Kauffman 1995). This suggests considering several domains of complexity and a hierarchy of levels for complexity. The complexity for an inorganic system should be different from the complexity of a biological, cognitive or intelligent system.

An example of physical complex system is the global climate, including all components of the atmosphere and oceans and taking into account the effects of extraterrestrial processes as solar radiation, tides, and meteorites. An illustration of complex biological system is the human brain composed of millions of nerve cells. Their collective interaction allows recognizing visual, acoustic or olfactory patterns, speaking and performing different mental activities. An example of complex social system is the human society with its participants, natural resources and capital goods, financial and political systems. For the logical and mathematical realm, examples of high complex calculus systems may consists of large scale distributed software systems or hierarchies of layered computing subsystems organized and running together to achieve particular objectives.

What is remarkable is that systems that have apparently little in common-material systems as an array of polymers in a test tube, biological systems as a group of receptors on a cell's surface, knowledge or cognitive systems as a group of ants in a swarm or human agents in a company -often share remarkably similar structures and means of organization. This explains and justifies the need for a science of complexity.

Features such as non-linearity, hierarchy of levels, time-scales, connectivity, non-equilibrium, unpredictability, interconnectivity, collective behavior, self-organization, self-production, self-reference, and multi-agency are associated with complexity studies. Complexity is correlated to non-linearity, which is a necessary but not sufficient condition of complexity, as well as to interconnectivity, self-organization, self-similarity and collective behavior (Mainzer 1996).

The understanding of complexity changes with the domains of application. Some surveys consider that complexity has not an absolute meaning, and it is only a relative notion depending on the level of observation or abstraction. However, it is commonly stated and accepted that some objects and processes are more complex than others.

We must to take into account this facet of complexity as a relative concept which depends both on the task at hand and on the tools available to achieve this task.

For industrial systems, despite the fact that numerous physical or chemical processes are identified as complex, more of the conventional ones may be operated in regimes were complexity properties are neglected. For several centuries, physical and chemical sciences made great steps by experimenting and constructing simplified models of complex phenomena, deriving properties from the models, and verifying those properties by new experiments. This approach worked because the complexities ignored in that models were not the essential properties of the phenomena. It does not work when the complexity becomes the essential characteristic. In an increasing number of cases the complexity is not transient or atypical, but it is an intrinsic property of that systems.

Given this situation the challenge for engineers and scientists is not only to identify complexity domains but also to show how to overtake the successive complexity barriers. The next defy in science and technology is to surmount the complexity, finding the ways from complexity to a new simplicity. The 21^{st} century concerns as energy, nutrition, health, ecology, finance and security pertain without doubt to high complexity sphere and need new methodologies.

1.2 Emergence

As for complexity there is not a consensus on a standard definition of emergence (Bonabeau and Desalles 1997, Boschetti et al. 2005, De Wolf and Holvoet 2004).

However emergence is the property that distinguishes and makes complex systems interesting to study. Emergence is the phenomenon that differentiates complex systems from complicated or multi-component ones. A complicated device is a simple addition of separable preexistent components, whereas a complex system is made out of a large number of components interconnected by a network of relations in such a way that a modification somewhere in the system modifies the whole system.

Emergence is what parts of a system do together that they would not do by themselves. An example is the collective behavior, that a system does by virtue of its relationship to its environment but it would not do by itself. Important facets of emergence concept are: novelty, micro-macro effects, coherence, nonlinearity, interacting parts, local control, robustness, and flexibility.

There are some general trends in the definition and study of emergence.

We will focus mainly towards the emergence of levels. The notion of emergence involves the existence of levels of organization, of description, of behavior and so on.

A direction of studies tries to relate the emergence to semantics and meaning (Pattee 1995, 1997). The emergence is considered as linked to the concept of evolution and its bioinspired models as the genetic algorithm. In addition, the Darwinian-type of evolution was considered the engine for emergence in biology.

According to this route of research, a higher-level of investigation is completely defined by considering not only how the entities involved interact but also what meaning is associated to the interactions by an external observer or by the entities themselves. Correlated to the above studies is the definition of emergence relative to a model (Cariani 1989, 1992). This definition does not consider emergence to be an intrinsic absolute property of a phenomenon, but that it can only be defined by considering the phenomenon with respect to an observer which could be a formal model, for instance. This represents the source of a functional theory of emergence giving an account of how new necessary functions of the observer-measurements, computations and controls, can come into being.

Another class of definitions for emergence emphasizes the role of multiple levels of organization and their interaction. The starting point is that the majority of complex systems exhibit hierarchical self-organization in levels under selective constraints. Self-organization will occur when individual independent parts in a complex system interact in a jointly cooperative manner that is also individually appropriate, such as to generate a higher level organization. Complex systems can be observed at different levels of investigation. For example we can observe an industrial installation at the level of molecules or at the level of devices interactions.

The number of reality and observation levels is inherently finite.

Among the significant versions of the modern theory of levels are that developed by Hartmann (Hartmman 1940, 1952), Piaget (Piaget 1977), Poli (Poli 2001, 2007), and Nicolescu (Nicolescu 2002).

Hartmann considers four levels of reality and associated objects: material or inanimate, biological or animate, mind-related or psychological, and intelligent or spiritual and emphasizes the finite number of sublevels to be taken into account at any basic level.

Poli distinguishes at least three ontological strata of the real world: the material, the psychological and the social stratum.

Fig. 1.1 shows the Hartmann's four-levels of the real world. Hartmann ranked these four levels in the hierarchy: material $<$ biological $<$ cognitive or psychological $<$ intelligent or spiritual. Intelligence may be assimilated to higher cognitive potentiality.

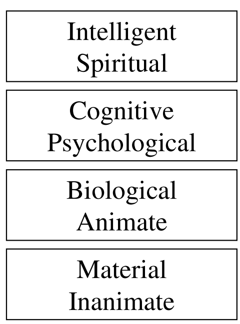

Fig. 1.1 Four levels world-hierarchical framework

The complexity levels follow the hierarchy of reality levels.

Hartmann elaborated several laws for his hierarchy of levels.

- Law of recurrence: Lower categories recur in the higher levels as subaspects of higher categories, but never reversely.

- Law of modification: The categorial elements modify during their recurrence in the higher levels: they are shaped by the characteristics of the higher levels.
- Law of the *novum*: The higher category is composed of a diversity of lower elements. It contains a specific *novum* which is not included in the lower levels.
- Law of distance between levels: The different levels do not develop continuously, but in jumps. The levels can be clearly differentiated. This supposes that there exists a kind of autonomy of a level implying existence of properties, relations, behavioural laws concerning entities at a given level independently from other levels.

The law of the *novum* ascertains Hartmann as one of the modern discoverers of emergence—originally called by him "categorial *novum*" that is a new category.

A property is considered as emergent if it cannot be explained from the properties and interactions of the lower level entities. However, it is mandatory to explain from were novelty comes.

Following the hierarchy of levels shown in Fig.1.1, the hierarchy of emergence types is resulting. There are four levels of emergence, each level corresponding to a reality level. On the basic level there are atoms and organic molecules. On the next level there is the emergence of life, on the next level the emergence of conscious states and then, the emergence of product of human mind, such as the scientific theories (Hartmann 1940, Popper 1987). The existence of material systems allowed the 1^{st} order emergence of biosystems, followed by the 2^{nd} order emergence of cognitive systems, and this in turn by the 3^{rd} order emergence of intelligent systems.

Cariani (1992) differentiates physical emergence, from biological emergence, psychological emergence and social emergence. Physical emergence is related to the appearance of new physical structures, as for instance the Bénard cells in natural convection. Biological emergence is related to the increase in morphological complexity and to the appearance of new functions in biological evolution. The immune system is an example. The psychological that is cognitive emergence is correlated to the appearance of new ideas, of explanations for instance. Another type of emergence is the one encountered in social evolution, which corresponds to the appearance of new social structures and cultural or scientific innovations. Stigmergy example refers to social insects and the stock markets organization is an example for human society.

This kind of approach requires clarifying the relation between higher levels and lower levels in hierarchy. This study refers to the micro-macro, local to global or the two-ways mechanism of emergences and also to the concept of downward causation called also immergence (Pattee 2000). An emergent feature is supposed to have some kind of causal power on lower level entities. Downward form of causality, operates from upper to lower level, and complements the upward causation. Lower entities exercise an upward causation on the emergent features.

Obviously this approach implies a two-levels and two-way causal relation. As an illustrative example we may consider several component transport processes organizing in a compliant installation. The component transport processes affect how the installation develops, upward, and the development of the installation affect the behavior and the interaction of the component processes, downward.

As a working approach, the emergence is considered as a dynamic, nonlinear process that leads to novel properties, structures, patterns at the macro-level or global level of a system from the interaction of the part at the micro-level or local level. Such novelty cannot be understood by reductionism but may be studied by looking at each of the parts in the context of the system as a whole. Detecting and breaking complexity frontier allows in fact exploiting properties of emergence, as non-linearity of interactions and coherence. This may be accomplished by distributed systems constructed as a group of interacting autonomous entities that are designed to cooperate, to have an emergent globally coherent behavior. Due to non-linear reinforcement, local interactions may result in a larger effect in the form of a novelty at the macro-level.

Several studies associate the emergence to predictability and to complexity decrease. A feature use to be considered emergent if it can provide better predictability on the system behavior, compared to the lower level entities. The predictability needs an information theoretic approach and this naturally involves an agent or observer. The measure of emergence the system provides should be an intrinsic property of the whole system including the agents. Entropy and algorithmic complexity represents the appropriate candidates for such quantifiable aspects of complexity and emergence.

1.3 Evolvability

The ability to evolve that is the evolvability means that the system has life-like capabilities and it is viable. Evolvability is the way to confront and surpass the successive boundaries of complexity.

Despite the lack of general designation of life there are some features that necessarily characterize all living systems.

To clarify the implications of evolvability we start from the fact that there are essential differences between adaptability and evolvability. Adaptability refers to optimization or adjustment on the time scale of the existence of a system as for instance some industrial product or organisms. In a hierarchy like that shown in Fig.1.1 adaptability may refer to just two levels as for example animate and its inanimate environment. It is a low dimensional perspective. Evolvability is not the same as adaptability or evolutionary versatility although it might be argued that it subsumes such candidates.

Evolvability requires capacity for change to march into new life cycles, for instance new type of products, new niches, new organisms and new levels. In a hierarchy as shown in Fig.1.1, the evolvability refers to the four levels, to a transformation from inanimate towards animate then cognitive and then intelligent systems. This is a higher dimensional perspective for evolvability. If the functioning of cognitive and intelligent systems is based or not on mechanisms similar to that shown by ordinary Darwinian selection for the biological realm is an open problem (Edelman 1987, Piaget and Garcia 1989).

Although survival is still to the fittest, as in Darwinian scenario, the fittest are those that evolve most ably with the dynamic environment. An example, is to consider that if some individuals are equally fit at a given level but the successors of one at the next level are likely to be more fit that the successors of others, than this individual is considered as the more evolvable (Turney 1999). This is a kind of higher-level equivalence of Darwinian selection.

Several characteristics of the evolvable systems have been outlined in the study of living systems and in the study of real and artificial life, AL (Farmer and Belin 1992, Bedau et al. 2000).

Farmer and Belin (1992) selected eight criteria to define the AL:

- Life is a pattern in space time
- Self-reproduction
- Information storage of a self-representation
- Metabolism
- Functional interaction with the environment
- Interdependence of parts
- Stability under perturbations
- Capacity to evolve that is evolvability

Several other lists of properties have been suggested in the literature to discern the inert material systems from the living systems. These refer to features as: self-organization, growth, development, functionality, adaptability, agency, reproduction, or inheritance.

Usually a system is considered alive or showing viability behavior if it meets criteria as for instance: has a high level of organization and complexity, survive in a dynamic environment, responds to stimuli, is capable of reversing entropy and is capable of open-ended evolution.

This means:

- To have a separate symbolic description, genotype, that makes use of a code
- That genotypes describe the structure of the entity, with phenotype as the low part level
- That parts are self-organizing such that, when put together in different orders, they link up and interact with each other in ways that cannot be easily predicted
- That reproduction makes provision of random mutations of the genotype code

Obviously there is an assembly of acknowledged features that necessarily characterize living systems.

In the next section we focus on the circularity and closure as have been outlined by the study of all evolvable systems, both natural as artificial.

1.4 Closure and Circularity

1.4.1 General Concepts

The notion of closure plays a prominent role in systems theory where it is used to identify or define the system in distinction from its environment and to explain the autonomy of the systems. Closure and circularity are critical for emergence and evolvability (Emmeche 2000).

Significant is the relation between self-adaptivity, cognitivity, intelligence and different notions of closure as encountered in systems theory: organizational closure (Maturana and Varela 1980, Varela 1989), closure to efficient cause (Rosen 1991), semantic closure (Pattee 1995), and operational closure (Luhmann 1995).

Closure does not mean that the system is not in contact with its environment. Rather the term closure refers to the closed loop which connects the structures and the functions of individual life-like entities.

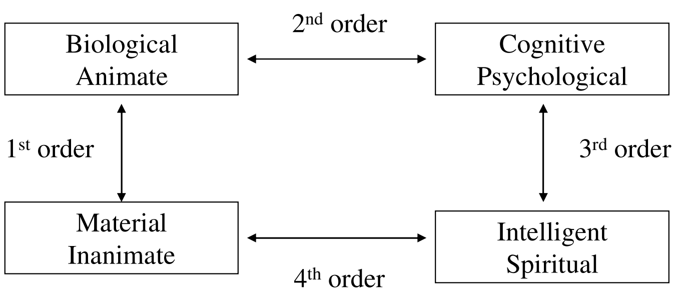

Fig. 1.2 Four realms world-network frame

Hartmann's foresight of four-level hierarchy may be developed toward a network or an integrative closure of the four realms (Fig. 1.2).

The Hartmann's hierarchy shown in Fig.1.1 is retrieved if the network is pursued clockwise but the network perspective is richer. The hypothetical circularity starts with the material realm and follows with biological, cognitive and intelligence realms.

There are four evolvability levels, each level corresponding to the attainment of a new reality level. Fig.1.2 outlines the different orders of emergence. The 1^{st} order emergence refers to biosystems, the 2^{nd} order emergence refers to cognitive systems, and the 3^{rd} order emergence refers to intelligent systems.

The living systems are not limited to the grounding material or biological level but would include also cognitive, intelligent and social systems, that is, the higher levels in Hartmann's hierarchy and higher order emergence.

The fully accomplished evolvability for technologies corresponds to the embedding in the basic material level that is, to the 4^{th} order emergence and integrative closure as shown in Fig.1.2. After one cycle in the network, the material repeated embodiment of cognitive, mathematical and computing capacities may support the emergence of another type of material realm and material science.

For Fig.1.2 it was assumed that different realms in the cycle interact with the neighboring others. The network should take into account the direction of interconnecting arrows. There exist prevailing interactions and directions as well as interdicted ones. In some cases diagonal interactions of the four realms shown in Fig. 1.2 may be considered too. It is possible to suppress or to neglect one level, to connect level n-1 directly to the level n+1.

At the level of biological systems, the closure outlines the qualitative difference between the material non-living systems and the living systems in the framework of autopoiesis. For the cognitive systems, in a constructivist perspective, the closure refers to the ability to employ new distinctions and generate meaning in the system. In the context of psychological or social system the concept of closure directs to organizational and intentional aspects. Finally the intelligent systems realm may have an interaction with the material realm, a kind of embodiment closing in this way the cycle.

Further ontological analysis of the systems requires construction of several sub-realms for each realm of the main structure. Material realm includes

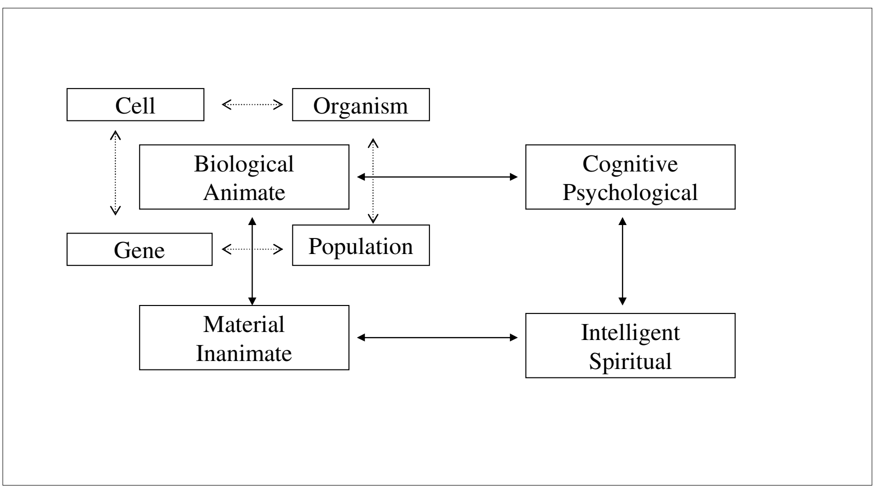

Fig. 1.3 Four realms and sub-realms for biosystems

physical or chemical sub-realms; cognitive realm may include representations, goals, beliefs, desires and so on.

For the example shown in Fig. 1.3 the biosystems realm is represented by four sub-realms: molecules as genes, cells, organisms and population that is, the ecosystem (Poli 2002). The splitting in four sub-realms appears as a natural one and it parallels and in some sense recapitulates the basic splitting of reality in four realms.

The gaining of an integrated understanding of the different scales is a difficult task for disciplinary research. For the biosystems realm the sub-realms includes cellular and sub-cellular spatial and temporal organizations and multi-cellular systems integrating gene regulation networks with cell-cell signaling and bio-mechanical interactions. The biosystems underlies larger scale physiological functions which emerge from sets of cells, tissues and organs in complex interaction within a given environment. At the highest level, the understanding and control of ecosystems involves deeply integrated interactions among organisms in a given biotope.

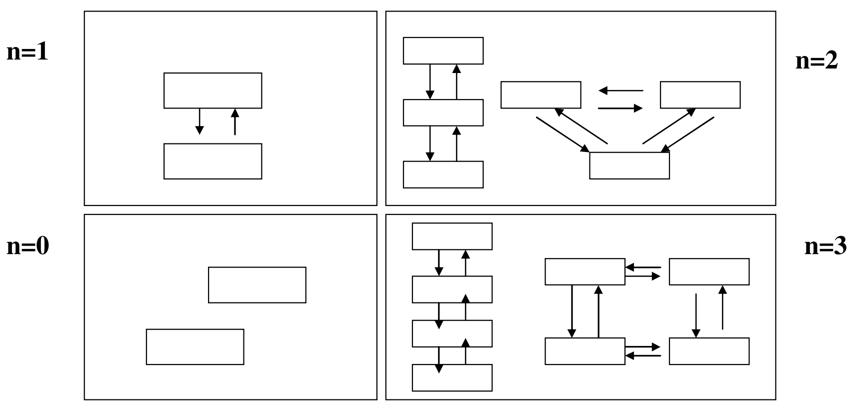

Fig. 1.4 Multiple-realms frameworks

Fig.1.4 summarizes regular types of ontological frameworks.

The number of interacting modules, levels or realms varies from 1 to 4. The n=0 structures are those of the realms studied separately.

The n=1 structures outline interactions between two realms. For n=2 and n=3 the hierarchical frameworks and network frames as the cyclic ones should be taken into account.

The connection between the theory of levels and causality allows inferring that every levels or realm may trigger its own causal chain. Taking into account both upward and downward causation, that is emergence and immergence, we need to distinguish between material, biological, cognitive and intelligent causality chains.

1.4.2 Closure Paradigms

1.4.2.1 Semantic Closure

Some particular concepts of closure or circularity, specifically the semantic closure, the functional circle, the circular schema and the integrative closure will be considered more in detail.

In a significant investigation applicable to both real life and artificial devices, Pattee pointed out that the evolution requires complementary description of the material and symbolic aspects of biological events (Pattee 1995, 2000, Rocha 2001). Life and evolvability involve a semantically closed self-referencing organization between symbolic records and dynamics. Symbols, as discrete functional switching-states, are seen in all evolvable systems in the form of genetic codes, and at the core of all neural systems in the form of informational mechanisms that switch behavior. Symbolic information such as that contained in genotype has no intrinsic meaning outside the context of an entire symbol system in addition to a material organization that interprets the symbol leading to specific function such as construction, classification, control and communication. Self-reference that has evolvability potential is an autonomous closure between the dynamics, that is, physical laws of the material aspects and the constraints, that is, syntactic rules of the symbolic aspects of a physical organization. Pattee refers to this condition as semantic or semiotic closure and concludes that it requires separating and complementing the symbolic description (genotype, design, software, and logical systems) from the material embodiment (phenotype, machine, computer, and physical systems). Semantic closure concept allows a synthetic perspective for the logical and physical aspects. The symbolic description must be capable to generate the material embodiment. Symbolic descriptions that generate local dynamics that promotes their own stability will survive and therefore serve as seeds of evolvable autonomous systems. Finally, the material embodiment must be capable of re-generating cyclically the symbolic description with the possibility of mutation. Cariani (1989, 2001) evaluated the semantic closure principle relation with the design of adaptive and evolutionary devices with emergent semantic functions. Self-modification and self-construction were recognized as important to the symbol-matter problem and as requirements for semantically adaptive devices or for evolutionary ones.

1.4.2.2 Functional Circle

The circularity and closure are correlated also to the "*Umwelt*" concept that was introduced by von Uexküll in theoretical biology to describe how cognitive organisms perceive and interpret their environments. The *Umwelt* concept is basic for biosemiotics and the theory of levels (Hoffmeyer 1997). The *Umwelt* was defined as the part of the environment that an organism selects with its specific sense organs according to its needs (von Uexküll 1973).

Umwelt theory asserts that a complex system doesn't responds to its environment but rather to its perception of the environment. A complex system actively creates its *Umwelt*, through repeated interactions with the environment. It simultaneously observes the world and changes it, the phenomenon which von Uexküll called a functional circle (Fig. 1.5).

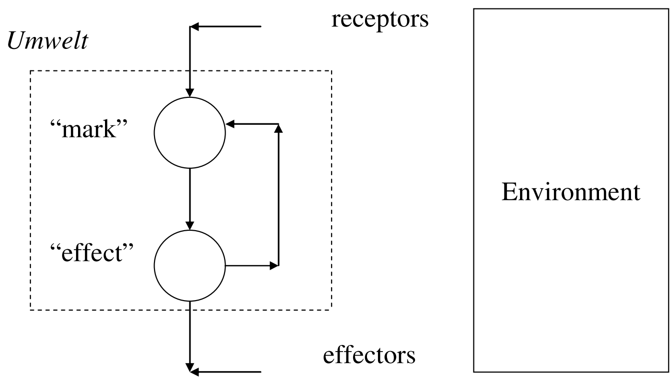

Fig. 1.5 Functional circle

The functional circle includes receptors and effectors. The sensory experience is based on interactions and these have specific purposes. The elementary unit of evolvable systems includes the functional circle of the following four parts: the environmental object, the receptors, the command generator and the effectors. The command generator includes a "mark" organ and an "effect" organ.

The *Umwelt* concept offers suggestions for the study of animats and of artificially evolvable circuits (Iordache 2009). It should be emphasized that *Umwelt* theory takes into account three of the levels of the Hartman hierarchy namely the material, biologic and cognitive level (Cariani 2001). This is illustrated in Fig. 1.5. The material realm corresponds to the environment. The biological level includes the sensors and the effectors while the cognitive level corresponds to the cycle including "mark" and "effect" organs.

1.4.2.3 Circular Schema

Circular reactions have been emphasized in the study of action schema done by Piaget (Piaget 1970, 1971). Piaget called his general theoretical framework "genetic epistemology" because he was primarily interested in how knowledge develops in living organisms. Cognitive structures are patterns of physical or mental actions that underlie specific acts of intelligence and correspond to the stages of development. According to Piaget, there are four primary cognitive development stages: sensory-motor, pre-operations, concrete operations, and formal operations.

The Piaget's action schema, which constitutes the foundation of his learning theory, is a cycle including three elements: a recognized situation, an activity that has been associated with this situation, and an expected result. The recognition of a situation involves assimilation, that is to say, the situation must manifest certain characteristics which the organism has abstracted in the course of prior experience. The recognition then triggers the associated activity. If the expected result does not occur, the organism's equilibrium is disturbed and an accommodation may occur, which may eventually lead to the formation of a new action scheme. Accommodation does not take place unless something unexpected happens.

Assimilation integrates new information in pre-existing structures while accommodation change and build new structure to understand information. The equilibration through assimilation and accommodation, takes into account three of the levels of the Hartman hierarchy, the material, the biologic level, more close to assimilation, and the cognitive level, more close to accommodation concept.

Piaget general equilibration theory offers a standpoint to consider the three level chains of interactions, namely biologic, cognitive and intelligent.

Piaget theory of emergence in the context of social sciences emphasizes on the concepts of feedback and circularity (Piaget 1980). For Piaget there are three types of processes describing the behaviour of populations:

- Composition process, which defines the properties of the population as a whole, that is, the global behaviour
- Emergence, the process through which the whole generates new properties with respect to individuals
- Relation processes, the system of interaction modifying the individuals, and therefore explaining the properties of the whole

It can be observed that semantic closure, functional circle and circular reaction concepts have basic similarity despite the fact that they may refer to different levels of reality. They describe cycles or in other words loops of interaction between two or three successive levels or realms. Pattee focuses on two levels frameworks, the material versus biologic, or biologic versus cognitive, while von Uexküll and in part Piaget focuses on three level frameworks, material, biologic and cognitive level. It should be emphasized that some of the Piaget schemas embraces a four-level perspective including intelligence level (Piaget and Garcia 1989).

1.4.2.4 Integrative Closure

What is less understood and under active investigation for a real word perspective as that shown in Fig.1.2 is the link between intelligence or logical levels and the material level involving the four realms as a whole and allowing the integrative closure, the full evolvability and autonomy. Integrative closure imposes a re-examination of the link between physics and information and implies the 4^{th} order emergence based on the material embodiment of the logical or calculus capabilities.

The autonomic computing (Horn 2001, Kephart and Chess 2003), cyber-physical systems (Lee 2007), organic computing (Müller-Schloer et al. 2004), and other paradigms were identified among the fundamental concepts and paradigms that may be beneficial for integrative closure understanding and achievement.

Autonomic computing addresses complexity and evolution problems in software systems. Autonomic computing refers to computing elements disseminated throughout the system which beyond the material, biologic or cognitive units, embeds computational power. The autonomic computing systems are supposed to share certain feature with living systems.

Actually, the large-scale deployment of computational systems will not be possible without making those systems autonomous and thereby endowing them with properties of living systems as natural robustness, reliability, resilience and homeostasis.

A cyber-physical system is a system featuring the combination and coordination between, the system's computational and physical elements. An antecedent generation of cyber-physical systems is often referred to as embedded systems. In embedded systems the emphasis tends to be more on the computational elements, and less on an intense link between the computational and physical elements, as in cyber-physical systems studies.

Organic computing is the research field developing around the principle that problems of organization in different domains as complex materials, molecular biology, neurology, computer science, manufacturing, ecology and sociology can be studied scientifically in a unified way (Würtz 2008). Instead of looking to ensure statically and a priori the correct execution of programs or designs, organic computing intends to modify these incrementally so that they achieve the prescribed tasks. This approach is tightly coupled with concepts and theories like self-organization, emergence, evolvability and constructivism.

Inspired by the organisms observed in nature, organic computing research extends the autonomic computing objectives and focus on emergence and technological embodiment aspects. Organic computing is broad in scope, in that it touches upon the full range of bioinspired computing, without reference to any particular type of environment, and addresses not only the problems underlying cognitive and intelligent control and cognitive robotics but also the cognitive middleware, sensor networking, artificial immune systems and models of computing derived from chemistry, biology, cognition and mathematics.

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