

Complex Systems as a Basis for Education and Pedagogy in the 21st Century

Luis Fernando Cruz Quiroga MD PhD(c)

cruzluis@unbosque.edu.co

Abstract — Pedagogy as a science of education must be epistemologically grounded on complex systems, being a contemporary scientific paradigm that explains the processes of teaching and learning based on a neural network that integrates electrochemical, biological, genetic, and social elements in a complex reality that is surrounded by uncertainty, indeterminism and emergences resulting from the constant interconnectivity and which can be represented by complex mathematics such as constantly changing nonlinear dynamic behavioral patterns. These patterns cannot be established just by looking at the student's neural circuit, but as a result of the inter-cerebral dynamic between the professor and the student. The professor plays now a new role as detector of emergences and as creator of learning scenarios for unstable and trans-disciplinary contexts, while designing pedagogical processes grounded in non-classical logics that enhance the development of the student within the framework of complexity.

Keywords: Complex systems, education, emergences, neural networks.

INTRODUCTION

The world goes through a complex set of changes at the social, economic, political, cultural, ecological and scientific levels, which are focused on instability, probabilities and indeterminism. At the same time, this scenario implies an education system immersed in the same dynamic by moving in different levels of complexity.

So far the educational and pedagogical processes have been planned and developed for stability and certainty, but the education of the future has been oriented towards probable states (uncertain ones), into the unknown, where the university professors of different disciplines must be prepared to move and manage volatile and uncertain contexts. Therefore, it is necessary to develop an epistemology that responds to the demands of reality and to the current knowledge of society.

Education and pedagogy as a streamline science should start from the understanding of educability processes, grounded in the complexity of the neural network and its nonlinear and uncertain connectivity, in order to design effective didactic and learning scenarios.

TOWARDS A NEW EPISTEMOLOGY OF EDUCATION

To manage unstable contexts, education and pedagogy in the 21st Century must respond to the needs of current society and the logic of postmodern thinking. According to Vattimo, "it is determined by the fruition, and it opposes to the functionalism of modernism, with a radical rejection of the instrumentation of the reason, focused on the vividness of each moment, as a presentist aesthetic that goes beyond fixed principles or criteria, determined, founded once and for all. (...) A thought that focuses on openness, on the dislocation of what had been consistent; it breaks the established methods and allows the search for dissent and instability as the authentic human [1]."

Therefore, it requires an education that responds to the complexity of current society through models, methodologies and pedagogical tools that are epistemologically based on contemporary paradigms. That is, on a dominant paradigm valid for this historical moment, with an explanatory power that satisfies the scientific community according to the current perception of reality [2].

For Zidane, “this current phase of paradigmatic shift, transitional stage in which we live, can be defined on the basis of uncertainty. After the era of continuous progress, of faith in the infallibility of science, the human being rethinks the complexity of reality [3].”

Educational knowledge must move beyond being a pedagogical knowledge based on a historical-philosophical reflection of past centuries. This is because, although the history of teaching and pedagogy is an essential element to understand the educational process that “allows to determine the purposes that should be pursued by education in every moment of your time [4],” the contemporary world requires pedagogy to go further and to work as a science applied to education; that is, to build their own theoretical and epistemological autonomy. It cannot continue denying the scientific nature of education, which is constituted as a science “as it tries to capture or grasp the complex phenomenon of education [5].” This implies, according to Foucault, the understanding of different thresholds of scientificity. This is why the scientific speech must define “the axioms that are necessary, the used items, the propositional structures that are legitimate for it and the changes accepted by it [6].”

Pedagogical knowledge has been developed through pedagogical models, but these have been intended to regulate and standardize the educational process by defining what, who and how to teach in order to shape qualities and virtues. However, their “main purpose is not to describe or penetrate into the essence of teaching. And, it is this normative character which differentiates their

essence between knowledge models and scientific knowledge. Pedagogical models become then, epistemological obstacles because normative speeches cannot account for cognitive speeches (...). A language of level of differentiation and inferior cognitive hierarchy cannot explain or communicate complex messages of qualitatively superior order.” The contemporary scientific models are heuristic models based on the creation of new roads and rely on logic, cybernetics, mathematics and problem solving simulations. Therefore, it considers that traditional pedagogy based on a “naive theory of knowledge, is not in a position to contribute to the translation of cultural scientific thoughts and their creation processes to the contemporary context of the students [7].”

However, pedagogy as a science of education must respond to today's society of knowledge because “the scientific model on which our civilization rests has been changing since the advent of the theory of relativity, quantum physics and the laws of thermodynamics. From all these fields of scientific knowledge, comes a new vision of the world that transforms humankind. If before the human being was looking at himself as the center of the universe, today he finds himself as the consciousness of the biosphere (Lovelock's Gaia hypothesis), as an observer of the world (Einstein) and even as a creator of reality (Schrödinger). Thermodynamics gave the western men back the freedom and the role of evolution (Prigogine) that had been kidnapped by Newton's mechanistic [8],” which means that the reality and the dynamic of today's world require a new science to explain it, a new thought to confront it, a new rationality and therefore, a new educational system to energize it.

Within this framework of contemporary science, a new paradigm must emerge to create normal science, which becomes a new relative truth [3] that explains reality by

allowing the construction of new educational knowledge.

The emerging paradigm of complex systems that is part of a category and that configures complexity as science, tries to explain the world in an eminently scientific work focusing on: dynamic, changeable and mutable systems, together with the study of concepts such as attractors, chaos, and rupture of symmetry and bifurcation, nonlinear logic, simulation, probabilistic behavior, artificial intelligence, artificial life and study of emergent phenomena, among others . These systems must acknowledge the existence of dialogue among biology, physics, mathematics, logic, information theory, psychology, neurophysiology and philosophy and many others, while providing the basis for transdisciplinarity [9].

The educational process is unpredictable and presents changes not previously envisaged. It is non-linear -as some have sought to state-; each class is different, full of new aspects and unforeseen situations derived from elements with highly complex variables such as genetic, social, cultural, biological, cognitive, and psychological ones. Educational theories are superficial and based on order, structure and everything that it is considered to be consistent. Therefore, they differ from what actually exists in a complex reality of educational practice –which is changing, unexpected and different in every individual and in every group of students.

It cannot be otherwise because, unlike traditional science, the epistemology of social and human sciences is currently based on incompleteness, uncertainty, and on the chaotic relationship between order and disorder. And education as part of this context must be conceived that way. Therefore, the epistemological grounds of modernity must be reconsidered and its educational narrative must be rebuilt because "the only reason that can be accounted for in educational phenomena is the complex reason [10]."

In order to achieve this it is necessary to establish the teaching-learning processes that are rooted not only in an epistemological positivist vision, behavioral and linear (empirical-analytic type), and also in social-critical approaches or historical-hermeneutical but it should go even beyond the contextual and relational, conceiving reality as a complex system surrounded by uncertainty, randomness, indeterminism, nonlinearity, chaos, constant change, and the interactions and emergences that are beyond any prediction or traditional scheme.

This approach deserves the support of a new education oriented by non-classical logics, and the development of heuristics and metaheuristic tools in order to understand nonlinear dynamic systems [11] and thus being able to address the new education landscape issues.

Contemporary university dynamics remain linear and rigid, based on determinism without responding to the dynamic that has been shaping the production of knowledge and progress in various disciplines, evolving into a gap between current scientific development and educational processes. This is the case of engineering, where there have been great advances in knowledge production on the basis of complex systems, but educational systems are still developed using parameters of past centuries. Science must be taught, epistemologically speaking, under the same fundamentals by which knowledge is produced when looking for a meaningful learning of the discipline, because the same logic that is applied to the production of knowledge should be used when this knowledge is taught. This gap between production of disciplinary knowledge and pedagogy has been historically shown to society because "pedagogical conceptions are delayed with respect to social changes (political, economic and cultural), implying that there is a disconnection and a gap between social phenomena and educational phenomena [12]." The reason is that university teaching in the different sciences

has been conducted, in most cases, empirically (only with the knowledge of the discipline but without educational training or teaching) and also, the lack of pedagogical training and research in education responds to paradigms used out of context.

Paradigmatic understanding in education is essential when considering that paradigms respond, according to Guba (1990), to basic considerations of different types, such as: ontological on the nature of reality, epistemological about the nature of the relationship between the researcher and the discipline's known object. Also, these paradigms clarify the methodology to produce knowledge [13].

COMPLEX SYSTEMS, EDUCABILITY AND NEURO-LEARNING

Pedagogy as a science of education, systematizes the pedagogical knowledge with its main concept, educability of the student, which studies the human being as a subject of education, by asking not only how they learn, but also by considering how humans develop their skills in different human dimensions such as: cognitions, attitudes and values (the ability to be formed) [14]. This educability has its biological roots in the brain and its neural networks (like a complex system with many interactions in which multiple possibilities emerge, energizing brain plasticity). And, it is in the understanding of the complexity of these systems that neurological teaching, science, and their different educational areas must be based.

When approaching the study of the brain within the framework of educability as a complex system, it must be considered that these systems are, in general, cyclical self-organized structures that streamline genetic, informational, biochemical, energetic and thermodynamic processes. Then, these systems extract energy from the environment in order to grow, maintain and expand their shape while working, processing data, exchanging information, and building

themselves. Finally, they transform energy and release heat and thermodynamic waste (entropy) into the environment (driven by flows of energy), behaving like systems with an organization that depends on the entropy released around, the environmental gradients and their interaction in a non-thermodynamic equilibrium [15].

The brain is a complex system, structured by a large neural network which, on a genetic basis, has an electrical intrinsic activity and permanent chemistry and flexibility, with intermittent oscillatory exchanges among different groups of neurons (that can oscillate or not at some point, depending on multiple variables that emerge from the electro-chemical interaction). Even when facing the same signal, different aspects can be perceived or encoded. These neural networks resonate not only with one another, but also with distant groups, generating a swing phase, in which disparate elements work together as if they were one (in an amplified way which allows them to travel great distances). This resonance, oscillatory neuronal consistency and concurrency, generated by electro-chemical activity, determine the root of cognition and learning [16].

According to Ramon y Cajal, learning processes are set by electric flows through brain cell membranes, strengthening their ability to generate new synaptic connections [16].

Memory also plays a part in that neuronal electrical activity. The ones in the same neural circuitry determine short-term memory (Coldman- Rabice 1996) by generating an activity that produces a synaptic feedback with activation of neuron's intrinsic properties (Camperi and Wang, 1998). Long-term memory can also be determined by associative circuits that determine long-term potentiation (LTP) [16].

The activity of the circuits that determine memory are very fluid and in turn determined by changes that occur in the synapses, which also have the ability to modify the amount of

neurotransmitter released by a potential action, producing receptors that make the cell more sensitive to LTP or less sensitive to long-term depression (LTD) [16].

In short, the brain function has a closed system which is responsible for the subjectivity and semantics, and an open system, responsible for the sensorimotor transformations that relate the private component to the external world (Llinas, 1974.1987) [16]. However, there are situations in which certain properties of the external world define the intrinsic central connectivity as in the case of perceptual learning (Bateson 1996) [16].

These complex neural networks process cognitive, emotional and learning elements, also mediated by the constant interaction of multiple neurotransmitters such as: noradrenalin (located in the brainstem and ending in the amygdale, hippocampus, thalamus and hypothalamus) which acts in the cerebral cortex by modulating the cognitive functions of the brain; dopamine from the brain stem, which acts in the brain stem and cerebral cortex; acetylcholine (in the neocortex, the amygdale and hippocampus); amino butyric acid (from the hypothalamus and reaching the occipital and frontal area) and serotonin, which acts widely in the cerebral cortex, among others [17].

Additionally, the brain system is modulated by hormones secreted by the hypophysis such as oxytocin, vasopressin and ACTH, as well as peripheral hormones such as adrenaline or endogenous opioid peptides such as endorphins [17].

Learning depends on brain plasticity, which is determined by changes in the structure and functioning of synapses. The synaptic efficacy depends on the early ontogeny in the formation of synapses, of the tuning of new synapses (which depends on adequate stimulation), and finally, of the synaptic regulation which lasts over a lifetime and which has a direct relation with experience. This constant and dynamic

interaction of genetic processes of maturation and learning will shape the student's behavior and learning. [17]. For instance, "neural circuits equipped with fast plastic mechanisms from the hippocampus and from other medial temporal lobe components, make this region particularly suitable for associative learning [17]."

Although structural changes are determined by synaptic connectivity, it is the local characteristics of these connections – given by the molecular changes– which determine the effectiveness of these connections and "can drastically modify the operating mode of large neural networks [18]."

The brain system may also be modulated by conditions such as stress, where peripheral endogenous hormones are released or by contextual situations where learning occurs by the discharge of neurotransmitters, hormones and endogenous opioids, facilitating or interfering in the process with motivational or affective elements [17].

The dynamics of electro-chemical connectivity within the brain network is performed under a complex system as follows: "The human brain consists of more than 10^{10} million and perhaps more than 10^{11} neurons (tens of thousands of millions), where each of them receives multiple contacts from other neurons and in turn connects with other many cells; the combination of possible interactions is more than astronomical (...). This activity also produces multiple changes in other parts of the body, such as in the sensory cells of muscles and in areas of contact with the medium through interneurons that interconnect them. Thus, in the human body about 10^{11} (one hundred billion) interneurons connect some 10^6 (one million) motor neurons that activate a few thousand of muscles, with about 10^7 (tens of millions) sensory cells distributed as receptor surfaces along the body. Between the motor and sensory neurons, the brain interposes as a giant tumor filled up with interneurons that interconnect with one other (ratio of

10/100,000/1) in a constantly changing dynamic [18].

This magnitude of interconnections generates an infinite number of possible situations. In fact, "given that there may be an unlimited number of possible states within this network, the possible behaviors of the organism may also be virtually limitless"[18]. Therefore, the emergences that arise will always be dynamic and changing, under uncertainty, randomness and nonlinearity (disabling any linear mathematics and forecasting, and always considering them exclusively within the field of probabilities). Therefore, neuronal connectivity has a chaotic feature or nonlinear dynamic properties that change continuously.

Living systems respond to external influences with structural changes that affect their behavior, adapting structurally to their environment, and resulting in a structure that holds the previous structural changes or past interactions. These systems react to the environment by coupling with structural changes, according to their nature and organizational pattern (non-linear) of unpredictable behavior. This structural coupling determines intelligence, learning and behavior [18].

These structural changes can be triggered by interactions with the environment or as a result of the internal connectivity dynamic, which is constantly changing. But this ongoing transformation of the structure does not entail disorganization.

The environment and the internal network generate reciprocal perturbations. In this interactive dynamic with the environment, the neural network classifies the disturbances or sees them according to its current (in that precise moment) structure [18]. That is, "in these interactions, the structure of the environment only triggers structural changes in autopoietic units (not determined or instructed) and vice versa for the environment. The result will be a history of mutual structural changes, that is consistent

when not disintegrate: there will be *structural coupling* [18]. The nervous system of an organism changes its connectivity with every sensory perception [19]."

The nervous system as an autopoietic system provides continuous structural changes that determine plasticity, but retains its full identity or pattern of network organization (despite the fact that these network components are produced and processed continuously, renewing and regulating themselves) [19]. "The neurons, the body that integrates them, and the environment in which they interact, operate reciprocally as selectors of their respective structural changes, and couple structurally with each other: the body operator, including the nervous system, selects the structural changes that allow it to keep operating, otherwise it will be disintegrated [18]."

Learning is an expression of the structural coupling [18]. Interactions of the neural network "allow the generation of new phenomena by allowing new dimensions of structural coupling [18]."

The nervous system is involved in cognitive phenomena by "opening up new dimensions of structural coupling for the body, by enabling the association of a variety of internal states in the body with the diversity of interactions in which it can enter [18]."

NEURAL NETWORKS AND PATTERNS

This dynamic of neural circuit connectivity originates intricate patterns of interconnected frames that establish nonlinear relationships, determining stimuli or messages that become cyclical feedback loops, with the ability to regulate themselves [19].

The neural network is determined by complex internal patterns that must be represented on an abstract geometrical space in the brain [16]. This type of pattern responds to "a configuration of characteristic relationships within a given system [19]."

The self-organization of complex structures develops a stable state, which however, is distant to the balance (different from one in balance such as a crystal). Those are dissipative structures that evolve in instability, transforming themselves in structures of increased complexity [20]. “A seemingly complex and chaotic behavior can lead to ordered structures, to subtle and beautiful patterns [19].”

Nonlinear interconnectivity of networks and self-organizing systems has been only modeled through the mathematics of complexity or theory of nonlinear dynamic systems [19]. This mathematic is one of relationships and visual patterns, known as topology or elastic geometry in which figures can be converted into other figures [21]. That is, they belong to ordered patterns that correspond to chaotic systems.

This kind of mathematics can map solutions –curved or graphed shaped– by using computer systems [19]. These patterns represent an abstract mathematical space, known as phase space [20]. There, patterns can be represented in the space by open curves that close themselves in spiral towards the center like strange attractors (because of the attraction towards the center), which are specific to chaotic systems. They never repeat themselves, covering new regions of phase space by forming highly organized complex patterns [19].

These paths help transform random and uncertain data into visible forms. The path may contain thousands of points and multiple variables but its movement is represented in a low dimensionality and still, it is impossible to predict the point of phase space where the path will pass by [19].

These attractors lead to an abstract region of space called basin of attraction. These patterns favor the non-linear structural analysis of complex systems by identifying and classifying themselves accordingly to their characteristics in a comprehensive scheme called phase portrait [21], which

allows analyzing features of complex dynamic problems that outweigh any prediction.

Phase portraits can disappear or change and new attractors will appear because either critical points of instability act, or bifurcation (catastrophe) points change the phase portrait by giving a new pattern or order [22]. Then, the new paths that are open by bifurcations, even when determined by the history of structural coupling, are unpredictable [19].

The structures of chaotic attractors can be described with the mathematical language of fractal geometry, language used to describe and analyze the complexity of the natural world (clouds, mountains, lightning) [23].

In fractal language, each piece is a reduced-size copy of the whole (a kind of holographic approach). Strange attractors are examples of fractals –multilevel structures with the same patterns. In fact, “strange attractors are paths in phase space that exhibit fractal geometry [19].”

The stated above is important because, although it is impossible to predict the value of variables, “the qualitative characteristics of the system’s behavior and the degree of blunting can be predicted [19].”

The interaction of the nervous system with the environment –with the constant modulation of its structure through abstract patterns in space– generates a cognitive process that is always accompanied by emotions, feelings and bodily processes that determine intelligence, memory, learning and decision making.

INTERCEREBRAL CONNECTIVITY

The neurological dynamic that has been revised so far with emergent patterns, has been established at individual levels (a brain without any external interaction), but when it comes to interaction with another person, a neurological intercerebral connection is produced –a nervous bridge that allows to impact the other person’s brain and vice

versa–, while generating positive or negative situations of cognitive, biological, emotional, immune or genetic type in both systems. These interactions “affect our brains and our biology [24].”

Interactions with other people reshape brain neuroplasticity (size, number of neurons and synaptic connections) [24].

This has to do with the activation of specific neural cells such as spindle cells and mirror neurons. That is, the brain, through “neural circuits, commands our interactions.” It creates a resonance between mental patterns and mental maps known as shared reality [24].

COGNITIVE DYSFUNCTION AND SIGNIFICANT LEARNING

There are situations in teaching and learning processes that encourage the use of the maximum mental capacity with a bit of pressure, leading optimizing attention, memory and performance .But when this pressure is excessive (depending on the student’s susceptibility, and his or her neurohormonal and electrochemical responsiveness) stress, fear and anxiety are triggered, determining a cognitive dysfunction where hormonal axes are shot and biological changes take place. The amygdala triggers circuits that affect the function of the prefrontal cortex and a negative impact on hippocampal neurons occurs (the key organ of learning and neurogenesis). Soon processes of learning and memory are interfered, because automatic emotional responses have been fired, decreasing attention, concentration, memory, creativity, learning capacity, performance and the ability to make decisions and solve problems in students [25][26]. There are also conditions such as sadness and boredom that generate discouragement and difficulties in cognitive functions and learning. In order to make learning processes enjoyable, states are required to be optimal. Feeling well and calm determines how neural networks that control the mental processes

can be more efficient, faster and operate at its maximum performance [27]. Pleasure and tranquility go hand in hand with cognitive efficiency.

THE NEUROLOGICAL DYNAMICS OF INTERSUBJECTIVITY AND THE ROLE OF PROFESSORS

The ultimate goal of the teaching-learning processes is for the student's brain to reach an efficient connectivity of his or her neuronal networks; integrating in this way cognitive, affective, communicative and social processes. To generate significant learning (not just rote-like, linear and behavioral), while developing creative and innovative processes, critical thinking, the ability to solve problems and with the competence to learn how to learn and learn to live together. That is, to create a better human being for the complexity of current society.

With regard to the above, the following questions arise in the context of complex systems. What role does the professor play to facilitate the learning process in this context? How can the professor possibly activate the student’s brain to reach optimum levels of learning and creativity?

In this respect, this thesis has been established:

The professor's role is to identify structural patterns and emergences that occur in the interaction with the student as a result of intersubjective dynamics of intercerebral circuits. Also, the professor must modulate them and help the student's brain reach a state of optimal cognitive efficiency.

When the professor-student relationship takes place in different educational scenarios (classroom, tutoring, counseling, etc.), a neurological dynamic of intersubjectivity can be established under the structure of a complex system between both brains, as a product of this intercerebral interaction. This generates a number of cognitive and emotional situations in both professor and

student, which are represented in a phase space in the form of attractors or patterns that tend to be repeated and that can be received at the intellectual, emotional or physical level. These figures or models tend to be repeated if the stimuli are similar, but if the incentives are changing, new attractors or more complex figures of fractal type are generated in an abstract level. However, these are manifested in the reality of relationships at different levels.

Bifurcations or catastrophes of the patterns are being constantly generated by stimuli of the professor, the students or the context, creating new and unpredictable situations that can be perceived in the actors of the system by looking at their cognition or affection and which are manifested in its corporeality.

To potentiate the process of creativity, learning and problem solving, a special field is required, given by emergences derived from appropriate emotional states between the student and the professor. These states are the result of neurological dynamics of intersubjectivity among the actors.

The professor, therefore, is an essential part of the system, not as a giver of information, neither as applier of rigid and decontextualized models of education, but as a catalyst for neurological intercerebral networks that are activated between professor and student within a context of uncertainty and permanent change.

The professor's goal should be to enable the student's brain and his own to reach an optimal cognitive, emotional, social and emotional level with impact on the system. This role is completely different from the traditional one: linear, behavioral and authoritarian (attitudes that favor the appearance of patterns –fractals– not conducive to learning).

The emergence can also cause stress, boredom, or anxiety in the professor or in the student, situations that hinder the learning process for the student and, the teaching process for the professor.

The educator's role should be to identify, each time, patterns and signal of disaster or bifurcations when observing the context and the student at a verbal and nonverbal level, together with what is perceived at these levels. And, according to that, the educator should generate changes that affect the whole system, by designing learning scenarios suitable for uncertain and unstable environments and, by adjusting didactics according to the moment, attractors and emergences as they appear. Linear and pre-planned methodologies will not work because they are designed for stable contexts, not real ones. Educability must respond to a complex dynamic that transcends the forecast, the goals and objectives that are not achievable.

CONCLUSIONS

The focus of education in the 21st Century must be transdisciplinary and with new pedagogical models based on uncertainty, randomness, chaos, nonlinearity, emergence and permanent change; that is, based on complexity.

Pedagogy as a science of education must be grounded epistemologically in contemporary paradigms

Educability is grounded in the brain and its complex neural network. On this basis, the learning processes and contemporary didactics should be designed

Although the educational process must focus on student learning, the professor is an essential part of this system and significantly affects the final result

Science should be taught, epistemologically speaking, on the same grounds on which knowledge is produced when looking for a deep understanding of the discipline, because the same logic that is applied when knowledge is produced should be used when this knowledge is taught.

The professor's role is to identify structural patterns and emergences that occur in the interaction with the student as a result of the

intersubjective dynamics of the intercerebral circuits. Also, the professor must modulate them and help the student's brain reach a state of optimal cognitive efficiency.

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