Noise and bias for free : PERPLEXUS as a material platform for embodied thought-experiments

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Abstract. There is a growing interest in attempting to study cognitive and social phenomena under the umbrella of "complex theory". We are indeed immersed in so-called "complex systems", but we are still a long way from a clear understanding of the concepts and principles that underlie the "complexity thinking" [1]. The purpose of this paper to provide a simple (and too short) conceptual framework to understand the basic ideas that allow us to think and speak of complexity in the context of PERPLEXUS as a physical *substratum* for the embodiment of questions related to cognition (individual and/or social) and the material realization of philosophical thought-experiments. To do so, we will notice the controversies concerning the very existence of such a thing as a "theory of complexity". We also will capture some features that can be considered as characterizations (or fingerprints) of "complexity thinking" by contrasting them with a classical Cartesian-Newtonian mode of thinking. Then, we will stress the key role of embodiment as a necessary ingredient to be incorporated in the explanatory efforts of different domains dealing with cognition, development and evolution. We will finally explain how the platform PERPLEXUS can represent such an ideal *locus* for reformatting and tackling conceptual and philosophical questions grounded in aspects of complexity and embodiment.

1 COMPLEXITY : A THEORY ?

Does a "theory of complexity" really exist, or is this expression just a label for a collection of disparate methodologies ? The concept of complexity is often linked today with network science, and researchers wonder if a comprehensive theory with a steady ontological, epistemological and methodological foot is genuinely here. For some, despite its early commercial successes, it will take decades to bring to full fruition what network science provides for an understanding of complexity. For example, Barabasi expressed in 2005 his opinion that: "Despite the necessary multidisciplinary approach to tackle the theory of complexity, scientists remain largely compartmentalized in their separate disciplines. Can they find a common voice ?"[4]. It is a patent fact that "complexity science" (as it is sometimes called) uses in its practical applications both an impressive set of very specialized and technical formalisms (non-linear differential equations, difference equations, networks clustering algorithms, computer simulations to name a few) and less operational, more heuristic guiding principles crystallized in expressions such as "edge of chaos", "emergence" and so on. These ideas have intricate acquaintance with a myriad of others notions such as, higgledy-piggledy: levels of explanation, self-organization, non-linearity, bifurcation, phase transition, fractal, determinist chaos, attractor, dissipative structure, catastrophe, etc., that can make one's head spin. Confronted with the plethora of concepts and terminologies from different disciplines and facing the multiplicity of specific tools and techniques for managing "complex systems" (from now on CS), one could legitimately wonder if it is possible to claim for the existence of a unified theory of complexity. De facto, an "emerging science of complexity" lacks integrated theoretical foundations. In everyday parlance, the expression "CS" is often used to describe an entity that is composed of many interacting parts or components whose structure and behaviour are just plain hard to explain, but even in the systems analysis literature where the adjective 'complex' is ubiquitous, one can find very little to indicate what an author really has in mind when using this terminology. To Casti's eyes for example, the fact is that everyone seems to understand complexity until it is necessary to define it: "In short, we can't really define what we mean by a CS even though we know one when we see it"[2].

Since the question of what constitutes the essence of a CS seems difficult to pin down, Casti thinks that there are actually several facets to the complexity issue depending on the problem, the analyst, the questions being investigated, etc. The pursuit of a viable theory of complexity should take into account theses different facets. We can first discern static complexity which includes inter alia the aspects of hierarchical structure, of connective patterns, of variety of components and of strength of interactions, from dynamical complexity which considers the issues that arise in connection with a system's dynamical motion or behaviour. The different mathematical tools for these aspects are not always naturally related (or even compatible with each other). This is even more the case as soon as we turn to computational complexity which has been approached from different angles too, for example in terms of the size in bits of the shortest program for calculating a binary string (or by extension any digitizable object/phenomenon) in the context of algorithmic theory of information by Kolmogorov-Chaitin [3], or in terms of logical depth by Bennett [4]. These two ways of

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4 Barabasi, A.-L. :"Taming complexity" in Nature Physics, Vol.1, Nov. 2005, p.68-70. Besides, The National Research Council, National Academy Press, Washington DC (2005) reports that "95% of the respondents classify their own work as potentially belonging to network science, yet only 70% claim that such a field exists !".

approaching complexity are associated with two different conceptions of emergence. The former is concerned with synchronic emergence which refers to the identification at a given time of a property present at a given level of a system such as the phenomenon of face recognition; this kind of emergence is associated with a sudden drop of descriptive complexity which allows for a much more concise description of the explanandum than its constituent parts, and which is interpreted in terms of compressibility of information. The latter has to do with diachronic emergence and concerns systems which undergo a process of evolution such as cellular automata where a property (or a pattern, or an object) is considered as emergent if the only way to predict it consist in simulating/running the system by unfolding the scenario of its trajectory from the basic atomic rules deterministically governing its constituent parts. No shortcut possible. This diachronic notion of emergence is obviously illustrated by the increasing degree of complexification of natural entities by the incremental, continuous gradual process of evolution by natural selection.
Many measures of complexity have been proposed for different contexts. However, there is no universal measure that would allow us to establish the degree of complexity of an arbitrary system. Again, each aspect of these distinctions (static, dynamic, computational aspects, …) can be served by different formalisms. The moral is, therefore, that complexity is a multipronged concept that must be approached from several direction keeping in mind the objectives of the analysis. A phenomenon or a system is never universally complex (or complex per se, or complex in an absolute sense). It is complex only in some respects, but not in others. This makes complexity a relative concept, and we now are ready to look in more details some of its constitutive facets, and thus, by first setting the classical Cartesian-Newtonian stage from which complexity thinking detaches itself.

2 TWO PARADIGMS

Based on the above considerations, one can think that a good way of getting a general understanding of complexity thinking is to clarify its principles and concepts by contrasting them with the traditional Cartesian-Newtonian way of thinking. Let's start with a coarse-grained and somewhat caricatural list of contrasting features to then select some of them for further discussion. Firstly, a caveat: we have to keep in mind that this prosthetic list is non-exhaustive, b) that the concepts in each column could be grouped differently, and c) that the columns could be "confronted" differently:

Classical thinking	Complexity thinking
Objectivist theory of knowledge - Strong representationalism - "Naïve" realism Top-down analytical approach Reductionism - Isolationism Determinism - Predictability Rationalism - Fondationalism Dualism …	Constructivism – Structural coupling Bottom-up synthetic, generative approach Interactionism – Modularity - Emergentism Unpredictability - Non-linearity – Loopyness Bounded Rationality Decentralisation, distribution, parallelism, locality Self-organization, adaptation, flexibility robustness, …

Our common-sense understanding of the world alongside with an impressive set of successful scientific models since the advent of modern philosophy and science rely on a classical or Cartesian mode of thinking which is expressed in its most vivid form by Newtonian physics. The ontological and epistemological assumptions of this paradigm that have dominated the scientific view of the world for centuries are -inter alia- a strong representationalist, objectivist, rationalist theory of knowledge which basically establishes a one-one correspondence between the world and our representations of it. Descartes famously codified a top-down notion of analysis consisting in a "divid ut regnat" strategy for conducting reason and seeking truth in sciences via his four principles in his Discours de la Méthode: (1) "never to accept anything as true if I did not have evident knowledge of its truth: that is, carefully to avoid precipitate conclusions and preconceptions"; (2) "to divide each of the difficulties I examined into as many parts as possible"; (3) "to direct my thoughts in an orderly manner, by beginning with the simplest and most easily known objects in order to ascend little by little… to knowledge of the most complex"; and (4) "throughout to make enumerations so complete and reviews so comprehensive, that I could be sure of leaving nothing out". According to this methodological canon, in order to provide a discursive and rational explanation of a phenomenon, one embraces the idea that a whole is a linear combination of its parts, an idea which can be formulated in different idioms such as "superposition" or "compositionality principle".
These principles, when applied to physics, led to the Newtonian materialistic ontology comprising only matter, absolute space and time in which matter moves, and the forces or natural laws that govern these movements; apparently different phenomena are merely different arrangements of separate pieces of matter, of elementary particles ruled by the strict law of cause and effect, leaving no place for intentional, purposeful action unless extended, as Descartes did it, by dualistically postulating an independent category of *res cogitans* completely isolated from *res extensa*. Moreover this reductionist and indefeasibilist way of conceiving a top-down analysis deflates drastically (if not completely) the role played by the interactions between components at the same and different levels of the hierarchical structure of the system under study. The traditional scientific method based on analysis, isolation and the gathering of complete information about a phenomenon is in no position to capture interdependencies between the component parts of an assemblage. Here, what has been called "the laws of nature" deterministically explain both the future trajectory of the system and the path it has taken in the past, implying its predictability and explanation via reversibility. This strict causal determinism finds its standard expression with Laplace in his Essai Philosophique sur les Probabilités: "We may regard the present state of the universe as the effect of its past and the cause of its future. An intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed, if this intellect were also vast enough to submit these data to analysis, it would embrace in a single formula the movements of the greatest bodies of the universe and those of the tiniest atom; for such an intellect nothing would be uncertain and the future just like the past would be present before its eyes". Of course, this fondationalist, rationalist view of the universe where an epistemic *Übermench* such as Laplace's

demon can be conceived clashes completely with the "bounded rationality" philosophy of the complexity thinking, where no exhaustive knowledge is at the disposal of faillibilist agents limited in resources and local information, and who have to find good-enough solutions in real-time.

Emancipating itself from this classical paradigm, complexity thinking manifests other "fingerprints" and adopt a set of different and often opposite ontological and epistemological assumptions. The conception of knowledge as passive reflection of the world has not only been questioned in physics by quantum mechanics, relativity theory and by other duality and indeterminacy principles, but also in formal domains such that the foundations of mathematics via formalist or other intuitionist programs and their extensions in verificationist theories of meaning for natural languages. The ontological view of a reality *per se*, as a sort of pure given expecting to be labelled, and the epistemological view of an objective, observer-independent knowledge have been also challenged by numerous developments in cognitive sciences [5] under the general philosophy of constructivism whose motto is best expressed by logician and philosopher Nelson Goodman: "The world is many ways"; cybernetics, biology and embodied cognition have equally shaken the commitment to naïve realism by showing that knowledge is a coevolutionary affair between the knowing subject and the "object", the result of an interactive constructive loop where both pole of the relation co-specify each other. This constitutes a major departure from the reflection-correspondance view of Newtonian epistemology for which the task of science is to refine as much as possible the mapping between the external "reality" and the structures that represent it, be they systems of concepts, images or whatever symbols; in the limit, this mapping should eventually result in a perfect and objective representation of a pre-existing and independent reality, the same for all observers, the understanding of which should be perfect, infallible, reversible and predictable.

As a corollary of this departure from classical reductionism, a recurrent signature of the complexity thinking is, then, the notion of interactionism inducing emergent macroscopic entities -be they properties, objects, processes…a handy general term could be "patterns"- that are non-mystical outcomes resulting from microscopic interactions. The idea is often illustrated by everyday tap water whose properties of being a liquid and non-combustible are emergent properties arising from the interactions of the hydrogen and oxygen "agents" which are both highly flammable gases. We can note at this point that ideas advanced by Conway and Wolfram to avoid a subjective understanding of the concept of emergence consist in showing that there is no shorter path allowing a knowledge of the state of a cellular automata in the future (say after 1000 iterations of the rules) otherwise that the effective applications of their rules; this diachronic characterisation can be formulated more rigorously but, for Wolfram, it suffices to operationalize a subjective notion of emergence rooted in surprise and/or epistemic-cognitive limitations of the observers.

This naturally leads to the fact that the behaviours of CSs are to be understood holistically, i.e. that the global manifested behaviours are the outcome of the multiplicity of its interacting parts whose contributions cannot be detected when taken in isolation. For example, a protein is formed as a chain of amino acids; this one-dimensional sequence of amino acids, strung together like beads on a necklace, specifies how it folds up into a unique three-dimensional configuration that determines its function in the living organism. But it is simply not possible to see how a protein will fold by cutting it at various spots to see how these sub-chains of amino acids fold, and then cementing together somehow the solutions of these individual sub-problems. It must be studied as a single, integrated whole. Relationships between sub-systems turn the whole into a coherent organization with its own identity and autonomy. Actually, the Latin root "complexus", which means something like "entangled, entwined, embraced" analytically contains the idea of components being both distinct and connected, both autonomous and to mutually dependent. Complete dependence would imply order like in a crystal, and complete independence would imply disorder, like in a gas where the state of one molecule gives one no information whatsoever about the state of the other molecules. Etymology indicates us that it is the relations weaving the parts together that turn a system into a complex one, producing emergent properties. Contrary, then, to a complicated TV set whose global functioning can be understood by dissecting it and analyzing its component parts dedicated to one specified function (signal detection, image/sound separation, amplification, etc.), the components of a CS do not implement functions which are totally independent.

That is what Simon [6] has called the property of near decomposability. Near decomposability is a property of a CS, and is two-fold: first, it says that the interactions between sub-systems in a complex system are weaker than the interactions within them (one can think of how interactions between employees in a department are much more frequent than interactions between employees of different departments); second, it says that each sub-system in a decomposed system is almost autonomous, meaning that each is independently functional and useful, but still provides value to the overall system by maintaining a weak connection with it. This kind of near decomposability is reflected in the object-oriented philosophy of programming where loose coupling and encapsulation methods are applied. Thus, CSs can be seen as hierarchical nested structures at different levels of analysis, and what is described as complex at a given level can be understood as a simple component at a higher level. Interactions between such super-systems (that can be seen as agents at the higher level) may recursively produce systems at even higher hierarchical levels, and are a major cause of their unpredictability.

This fingerprint of unpredictability of CSs has been largely popularized under the slogan "butterfly effect" and related concepts such as the sensibility to initial conditions, phase transitions, bifurcations, etc. The common-sense motto "more is different" captures intuitively here the idea that sudden unpredictable new qualitative behaviours can happen once a threshold or a critical mass has been attained. Here, non-linear dynamics and statistical mechanics are the roots of the complexity thinking for dealing with randomness and chaos. The fact that there can be a non-proportional relation between cause and effect can be partly explained by the concept of interaction discussed above: an action induced by a component can cause multiple effects in different parts of the system, and some of these causal chains can close in on themselves. This creation of feedback loops will then either amplify small fluctuations to provoke eventually large global effects by positive feedback, or they can drive and maintain the system in a controlled state assuring a homeostasis in viable limits by negative feedback, as illustrated by the functioning of a thermostat. Feedback-regulation allows for the emergence of goal-oriented or teleological behaviours that are often describe as being intentional from the outside observer.

3 OTHER FINGERPRINTS

This loopyness is at the heart of a property which is often considered as the hallmark of complexity, namely self-organization [7]: CSs spontaneously organize themselves so as to better cope with various internal and external perturbations, assuring by this their robustness. Fault-tolerance and damage-tolerance make them flexible and guaranty a certain autonomy and adaptability in front of changes of the environment in which they are inserted. No external organizer is required for this organization. Biologists such as Varela and Maturana have discussed at length this kind of autonomy, this "autopoiesis" and this functional interdependence in terms of interactive loop or co-determination between a biological system and its environment/ecological niche. "Order for free" is Kaufmann's slogan for explaining the fact that the property of self-organization can dispense with a notion of an intentional designer. Self-organization can be accelerated by exposing the system to random perturbations, making it visit its state space so that it will reach sooner a state that belongs to an attractor, e.g. the shaking of a pot filled with beans will make them explore a variety of configurations tending to settle into the one that is most stable, i.e. where they are packed most densely near the bottom of the pot, normally reducing their volume. Cyberneticist von Foerster and thermodynamicist Prigogine called this process respectively "order though fluctuations" and "order from noise". This innovative, creative process of self-organization by which the system arranges its components and their interactions into a global structure that tries to maximize its overall fitness without the need of a dedicated controller can be seen as a process of adaptation when we focus on the relations the system has with its environment: whatever the pressures imposed by it, the system will adjust to cope with them. So, evolution can be viewed as the self-organization of an ecosystem into a network of mutually adapted species, and natural self-organization can serve as bio-inspiration as it is the case for genetic and ants algorithms.

This naturally drives us to another directly related fingerprint of complexity, namely the idea of decentralization as vividly illustrated by the decentralized activities of pheromones trails constructions, pigment cells differentiation, fireflies synchronization, applause-bis synchronization, swarm intelligence, etc. There is a feeling of an "invisible hand", one could say, when we witness at a high level of description of a phenomenon the emergence of global patterns which are the outcome of the local properties of the constituent parts without any central organizing force orchestrating the whole process. Decentralized systems are numerous in nature, and one of the distinctive traits of complexity thinking is the abandonment of the "centralized mindset", i.e. the natural tendency for observer to postulate the existence of a cause, a leader, an organizing principle (you name it!) as a decisive causal factor. Complexity thinking reverse completely this view (the famous "argument from design") by adopting the order-for-free or blind-watchmaker view. Indeed, in decentralized, self-organized CSs, no central control is needed for managing, piloting and coordinating the activities of the constituent parts, every one of which has only a partial and limited access to the information computed by the global system. Each element or agent being endowed only with local information, no explicit global description is represented in them. This distribution of information and of competences over the entire system, over all parts or agents constituting it, together with the parallel or asynchronous functioning of the computational resources, are of course the rationale of the robustness, flexibility, fault-tolerance, graceful degradation and other virtues of adaptability of self-organized CSs. Local interactions of the type agents-agents, agents-environment, agents-agents via environment (stigmergy), limited accessibility to information, limited capacity for treatment, etc., can be seen as concepts analytically contained in the idea of distribution, and manifestations of the bounded-rationality principle.

Besides, in complexity thinking computation is substrate-neutral, making the ideas of functionalism and of multiple realizability (no Cartesian nor other forms of dualisms here) parts of its characterization. The Cartesian split between two ontologically incommensurable spheres of being, mind and matter, vanishes: both are particular types of relations. This idea according to which the material substance of a system is irrelevant to the way it performs its function is famously expressed in Bertalanffy's general systems theory [8]: living systems are intrinsically open, i.e. integrate and release information and energy; they therefore depend on an environment so that their effects can never be completely controlled nor predicted. This view is completely different from the traditional Cartesian-Newtonian paradigm in the sense that, ontologically speaking, the building blocks of reality are not to be found primarily in the Newtonian material particles; instead, patterns of organization, i.e. abstract relations, are what are common to different phenomena rather than common material components. Information understood as "a difference that makes a difference", realized on whatever substratum, is what counts. By making abstraction of the concrete substance of components, complexity thinking can establish isomorphisms between systems of different types, noting that the network of relations that defines them are the same at some abstract level, even though the systems at first sight belong to completely different domains. In this context, a super-system imposes a certain coherence on its components, meaning that the behaviour of the parts is to some degree constrained by the whole. This concept of "downward causation" points out for example that the behaviour of an individual is not only controlled by internal neurophysiologic criteria, but also by the emergent regularities of its environment, a point which is of crucial importance in contemporary evolutionary theory of culture.

At that point of our reviewing of the fingerprints of complexity thinking, it is illuminating to remind ourselves of the important historical fact that the concept of self-organization first proposed and developed in the 1940s by the cyberneticists Wiener, Ashby and von Foerster was picked up during the 60s-70s by physicists and chemists studying phase transitions and other phenomena of spontaneous ordering of molecules and particles, and then extended and cross-fertilized during the 80s with the emerging mathematics of non-linear dynamics and chaos. Although, the kind of investigations of CSs practiced by physicists became essentially quantitative and mathematical, a tradition closer in philosophy with the cybernetics origins, developed in parallel

under the heading "complex adaptive systems" with the work of associates of the Santa Fe Institute for the sciences of complexity, among which John Holland, Stuart Kauffman, Robert Axelrod, John Casti, etc. This trend is more qualitative, draws inspiration more from biology and from the social sciences than from physics and chemistry. It is also strongly rooted in computer simulation, and promoted by that the new disciplines of "artificial life" and "social simulation".
This underlines the key role played by spatial structures of interacting agents. These notions of locality, neighbourhood, spatial structures and other dynamical topologies are central ingredients of the dissemination of ideas application of PERPLEXUS, to which we now turn with all these fingerprints in mind.

4 EMBODIMENT AND "ORDER FOR FREE" ON PERPLEXUS

It has been extensively stressed by the robotics community that the synthesis of intelligent behaviour has to transcend the artificial-toy world of pure simulation, and to allow thereby the agent under study to confront its situated body with the for-ever unpredictable contingencies of its environment.
A pretty-fancy program can indeed work without problems in the frictionless and always shining crystal-world of simulation; nevertheless it can, at the same time, not function at all once operating in the real world. The rationale for this phenomenon resides in the ineliminable discrepancies (at all levels of analysis) existing between a simulated model and its real instantiation-implementation : a robot may get stuck against a wall in simulation, whereas it can escape its temporary trap in reality, or vice versa. *De facto*, information-processing tasks that are confined in software abstractions are resolved in ways that are different from the ways employed in real wet life; for example, the real-world structures can be exploited on the fly by cognitive agents without them having a complete-exhaustive representation of it, neither a stock of stored artefactual responses to problems such us collision on the same spot : mobile robots will solve this problem without the need for a conflict resolution scheme that would be, in contrast, needed in a software simulation. As Brooks said in many places : "The world is its own best model".
Although some software tools do integrate today libraries that mimic dynamical properties such as friction, collision, mass, injection of noise, gravity and inertia, etc., these discrepancies between simulation and reality will inevitably cumulate over time : it is a matter of principle that this fact (that could be labelled "the reality gap") is a problem that cannot be resolved without adopting an embodied and situated perspective.
Apart from the increasing recognition in the artificial-intelligence and robotics communities that the nature of the body significantly affects the mind, considerations for supporting an embodied perspective on cognition have had a long story in the biological, ethological, psychological, sociological and philosophical literature : indeed, behaviour is a dynamical process resulting from nonlinear interactions between the agent's control system, its body, and the environment; all these features and the complex patterns of their interactions induce a non linear behavioural trajectory of agent, making its behavior unpredictable although fully determined.
Common theoretical points of the sort (despite differences in terminology), characterizing the "embodied cognition paradigm", will catch the eye of who scans the works of authors from different fields ranging from traditional philosophy (Heidegger, Merleau-Ponty, …), psychology (Vigotsky, Piaget, Thelen, …), ethology (von Üxküll, Gibson, …), biology (Maturana, Varela, …), artificial intelligence (Winograd and Flores Dreyfus, …), robotics (Brooks, Brezeal, Mataric, Beer, Hutchins, Agre and Chapman, Cliff, Harvey, Pfeiffer, Floreano, Mondada, …), neurophilosophy/cognitive sciences (Churchland, Dennett, Clark, van Gelder…), etc.
In this quarters, a generic principled formulation could be the following : intelligent action results in this agent-environment structural coupling which implies a "fuzzification" of clear-cut delineations between mind, body and world as well as perception, cognition and action. Internal world representations that would be complete and explicit representations of the external environment, besides being impossible to obtain and impossible to be used in real time (frame-problem), are not at all necessary for agents to act in a competent manner. To escape the frame-problem, the brain, the body and the world are united in a complex dance of circular causation and extended computational activity (and not considered any more as being clearly separated as in a "Sense-Model-Plan-Act" philosophy typical of a symbolic, a-temporal, static approach which is the typical signature of symbolic AI for example). Emphasis on the physical, environmental, sociological, cultural context reflects the fact that different kinds of minds develop in a given "milieu" and that they use the tools, the representational media, the cultural items, etc., provided by it to support, facilitate, extend, and reorganize mental-cognitive functioning. Here, the relation Subject-World (Agent-Environment, Individual-Ecological Niche, Animal- Umwelt, …) is not simply a one-way (passive) street, but a constructive bi-directional interaction where the agent is a full-blooded constructor of its own behavior and knowledge. The world is here, ready to be "picked-up" and full of connotations of activities decoded according to the needs and possibilities of an embodied agent. This action-centered view of perception is therefore also a plea for embodiment and its indispensable role in reducing the computational burden of cognitive agent.
As a fundamental and defining principle, the embodied cognition paradigm argues that the understanding of the different aspects of cognition rely on explaining them in the context within which the real physical agents operate. That is here that the interdisciplinary project PERPLEXUS [9] enters the scene as an unprecedented opportunity to assess questions that are not ideally addressed in classical computer simulation approaches because of the fact that software abstractions do not do justice to the real anchors of perception-action cycles of embodied cognitive social agents. The project PERPLEXUS aims to develop a scalable hardware platform made of custom reconfigurable devices endowed with bio-inspired capabilities. This platform will enable the simulation of large-scale complex systems and the study of emergent complex behaviours in a virtually unbounded wireless network of computing modules. At the heart of these computing modules, we will use a Ubichip, a custom reconfigurable electronic device capable of implementing bio-inspired mechanisms such as growth, learning, and evolution. These bio-inspired mechanisms will be possible thanks to reconfigurability mechanisms like dynamic routing,

distributed self-reconfiguration, and a simplified connectivity. Such an infrastructure will provide several advantages compared to classical software simulations: speed-up, an inherent real-time interaction with the environment, self-organization capabilities, simulation in the presence of uncertainty, and distributed multi-scale simulations.

Therefore, our agents will have "bodies" and will experience the world, have immediate feedback of their actions on their own sensations so that so that they will be part of a constructive dynamics with their physical environment and their changing social networks. Ubidules-marXbots will operate in dynamic environments using real sensors and effectors and will not be deprived of the possibilities offered by the "world" they live in. Embodiment will assure that they won't get caught in the frame-problem according to which it is by essence impossible to specify a complete model of the world and of the up-dating of its modifications after applications of the operators of its dynamics.

Our embodied societies will be constituted of adaptive agents living in constantly changing environments; more precisely, situated Ubidules riding marXbots able to interpret signals coming from their environment and to communicate thanks to their sensors/effectors equipment, will move around in their environment and disseminate ideas in a non predictable way as function of their perceptual and social biases, and of their constantly changing social networks (dynamical interaction and imitation neighbourhoods). We will profit from the marXbots' perceptual capacities to interact with the real environment and with themselves as a source of the injection of "noises" such as misperceptions, inherent conceptual limitations, interfered transmission, idiosyncratic or socially-influenced preferences to choose these or those (the successful, the common type, etc.) as targets to be imitated.

Although our purpose here is to present the platform as an invitation for researchers to use it as an implementation locus for their own models, we propose in the following paragraphs a possible use of it, just to illustrate its potential exploitation. We think for exemple that questions related to the topics of the dissemination of cultural items will thus find some new opportunities of treatment by the use physical Ubidules-marXbots on the real world platform PERPLEXUS. By making agents embodied and situated, it will be possible to explore aspects of the dissemination of cultural items (and to assess socially-philosophically-oriented questions related to it) that are not ideally addressed in classical computer simulation approaches. From a technical perspective, the embodiment of cultural dissemination mechanisms in a group of mobile robots implies a set of challenging requirement for the mobile robotic infrastructure itself: *1) network size:* we need a sufficiently high network size to achieve emergence and run experiments that are representative for social exchanges. Therefore we need to ensure that experiments will involve at least 20 robots. If this number is not exceptional anymore in the field of collective robotics, it appears to be an interesting challenge when combined with the others requirements of our application in term of flexibility, monitoring and embedded features; *2) complex interface with the environment:* the robots need a sufficient number of sensors and actuators to perform basic tasks combined with some social communication and exchange of ideas. The communication of ideas implies extended possibilities of expression and of perception. The marXbot's design is the result of a long experience in collective robotics, where this topic has been already addressed at a lower scale and exploited in the European projects “swarm-bots” and “ECAgents”; *3) flexibility*: the marXbot's design is based on a modular structure allowing a very efficient adaptation of the functionalities of the robot and will provide the necessary flexibility; *4) experimentation tools*: research in collective robotics is extremely demanding in term of infrastructure to efficiently run experiments, monitor and document them. Controlling the operational condition of 20 robots, monitor their activity, movements and provide the pertinent information to the researcher is a heavy task demanding a specific infrastructure. The marXbot's design takes in account this aspect providing each robot with an onboard LINUX and wireless access. This allows an excellent accessibility to the machines both from the development and the experimentation perspective. The robots will be exploited in an arena equipped with a tracking system allowing an optimal monitoring of the displacements. Because of the compact size of the marXbot, the arena will have a reasonable size and allow a wide range of experiments; *4) duration of experiments:* the systematic exploration of complex emergent phenomena will require experimentation on long periods of time. Energy is a well-known limitation in mobile robotic systems and often sets strong limitations in term of duration of experiments. The marXbot's design includes an energy management system allowing swapping battery during operation. This feature will be exploited to provide several days of autonomy to our mobile robotic system.

With this set of technical features we will be able to embed into a robotic system a set of social interaction experiments exploring emergence of culture in an innovative and efficient way. But we insist on the fact that, from a more general point of view, in additional to an ideal setup for evaluation of culture dissemination (which is just one exploitation among many possible), this setup will be an optimal tool to explore ubiquitous computation in a dynamic network of mobile systems.

5 CONCLUSIONS

We have explained that for some mathematicians and thinkers the notion of complexity, as ubiquitous as is, is nevertheless a multipronged concept and that a system is not complex per se, but deserves the predicate "is complex" only in a relative sense. A full-blooded, unified formalized a theory of complexity does not yet exists and still awaits its Pascal and Fermat. This fact implies that the elaboration of a decent theory of complexity must begin by identifying and analyzing the key components of the kind that we have evoked in this paper. Although humility must win over hubris talking about a comprehensive understanding of the notion of complexity, reasons for optimism are fuelled by an interdisciplinary pursuit towards characterizing these key facets of complexity, formulating organizing principles, making distinctions and clarifying their ontological and epistemological foundations in order to augment our awareness of its multidimensional fingerprints [10].

We have then discussed some of these fingerprints of complexity thinking by contrasting it with a classical Cartesian-Newtonian mode of thinking. This allowed us to underline the transition from a mechanist and deterministic ontological and epistemological view to a more global and modest approach. This modesty hides a new ambition: crating an artificial world, with virtual and embodied agents/societies which manifest behaviours analogous with the ones we observe in the real world [11]. However, computer simulations are intrinsically limited for capturing what the real word has to say (so to speak) concerning, cognitive downloading and other co-evolving agent-environment phenomena. PERPLEXUS represents an opportunity to gain insights into dynamic processes that standard mathematical techniques would not reveal and that computer simulations would not capture. As a material computational platform, it does overcome these kinds of limitations and can serve as a physical *substratum* for the embodiment of questions related to cognition (individual and/or social) and the material realization of ***philosophical thought-experiments.***

In this sense, PERPLEXUS will represent a unprecedented aid for intuition, imagination, testing as well as a major adjuvant for explorations of ideas concerning multi-secular conceptual and philosophical questions. It is our hope that the family of models developed so far on the pervasive computing infrastructure PERPLEXUS (and whose generality allows for extensions) can humbly serve as ***tools for thinking*** aspects of the deep and important topics of the "embodied cognition" paradigm.

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