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Information networks and systemic properties. An epistemological perspective

Redes de información y propiedades sistémicas. Una perspectiva epistemológica

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En este artículo se acuña una propuesta para un nuevo paradigma epistémico para la interpretación de fenómenos complejos reticulares: la *red de informaciones*.
Partiendo de un análisis del concepto de *red* en contextos distintos, como es el caso de la red neuronal artificial, de la red de señales en una inteligencia de enjambre o de la red sináptica en el cerebro, el presente escrito tiene la ambición de detectar las características comunes a estos retículos y empezar a delinear un paradigma epistémico general.
La idea fuerte del ensayo es que lo que cuenta en una red no es su arquitectura física, sino el *contenido de información* que ésta vehicula: se presenta aquí toda información como un conjunto de *signos*, por ende, toda red de información constituye un *sistema semiótico* (lo cual es particularmente evidente en una inteligencia de enjambre).
Los nodos de una red pueden ser vistos como *agentes de un sistema*: todo agente manipula signos localmente, alterando así su *entorno* (el propio sistema semiótico del que forma parte, la red de informaciones). Se defiende, entonces, que es la propria información la que afecta las respuestas locales de los agentes individuales, retroalimenta el sistema y se auto–organiza.

Red · Auto–organización · Complejidad · Retroalimentación · Estigmergia.

In this article I present a proposal for a new epistemic paradigm for the interpretation of complex reticular phenomena: the *information network*.
Starting from an analysis of the concept of *network* in different contexts, such as in the case of an artificial neuronal network, the signal network of a swarm intelligence or the synaptic network in the brain, the present work has the ambition to identify the common features of all this kinds of net and to start delineating a general epistemic paradigm.
The strongest idea of this essay is that the most important thing in a net in not its architecture, but the information content it conveys: any information is here presented as a set of *signs*, hence, any information network constitutes a *semiotic system* (which is particularly evident in a swarm intelligence).
The nodes of a net can be seen as the *agents of a system*: each agent locally manipulates signs, modifying in this way its *environment* (the very semiotic system it belongs to, the information network). Therefore, I argue that the very information structure influences local responses of the individual agents, feedbacks the system and self–organize.

Network · Self–organization · Complexity · Feed–back Loops · Stigmergy.

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ARTÍCULO

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§1. Introduction

THE MAIN HYPOTHESIS OF THE SCIENTIFIC REDUCTIONISM, for what reality is explainable in all its aspects through a number of fundamental laws as limited as possible, finds an insurmountable problem describing those macro–dynamics characterizing complex systems. Actually, it is not enough to know elementary details about the nature of the components of a system to understand how it works as a whole. Instead, I believe it is crucial the comprehension of the relationship among all those elemental parts; dynamics whose meanings emerge only at a higher analytical level. For this reason not only particle physics turns out to be epistemically productive: both chemistry or biology, for instance, reveal us descriptive levels of natural phenomena which appear hardly explainable only by the theoretical means of the physician, and also anthropology and sociology give us useful cognitive approaches likewise autonomous. In a speculative perspective, it turns out to be very useful the prospect offered by the *epistemic emergentism*. There are two main versions of it: the predictive one, for which emergent properties are systemic characteristics of complex systems, unpredictable with a pre–emergentist point of view; the other one, schematically irreducible, which argues for the existence of autonomous laws regulating the dynamics of those high level characteristics different from the physic laws describing the elemental components of the system. It is exactly in the theoretical frame of the latter version of epistemic emergentism I localize this work. Specifically, I shall analyse the emergent characteristics of an information network and the high level dynamics connoting the development of its macrostructures. Saying *information*, I mean it in a wide sense as a coherent set of signals clearly observable in a background, in a generic context; that is, for instance, chemical or tactile signals in social insects, or electric signals in a neuronal network.

Now, while in the literature about emergent dynamics in complex systems a few key concepts like *module*, *computation* or *information* have already been extensively debated, the concept of *network* (although it has been abundantly used and almost abused) has been described only in the light of both decentralization and distributed information. Then, what I intend to do in this short article is trying to give a hint of a first nucleus of definitions, useful to demarcate the specific epistemic properties of the network concept. I shall do it analysing the characteristics of some reticular systems, both artificial or biological, trying to find those particular evidences which I think research on intelligent reticular systems should head towards.

§1. Distribution of information and the concept of superorganism.

Independently of the kind of support implementing information networks, I am convinced it is possible to identify in different concrete examples some general properties of theirs. Among them, the first one and certainly the most known, is the *distribution of information*, which constitutes, perhaps, the most peculiar character of a neural network, used as the main model by the connectionist tendency in the last two decades (at least). Now, a neural network is basically a cognitive system able to elaborate and share information in a reticular way; it is made up of an intricate set of connections linking among them some *nodes*, elemental elaborators of information just as we think neurons are.[1] These nodes show a certain grade of activation, through which schemes more or less persistent emerge into the net. Some thinkers (P. M. Churchland, 1995), have supposed our brain to be a kind of very elaborate biological neural network. The metaphor is suggested by the same hypothesis of a distributed information which, actually, seems to solve (or better, *dissolve*) the thorny problem of a unique computing centre managing information contained within the network (the brain of the brain!). An essential characteristic of the network is the *parallel distributed computation*, which lets the system to develop two fundamental qualities, *quickness* and *functional persistence*, making its performances radically superior in relation to those of any serial computing system. It is quick because it is able to carry out many tasks at the same time, exploring different ways to

[1] «As the name implies, a connectionist model is characterized by connections and differential strengths of connections between processing units. Processing units are meant to be rather like neurons, and communicate with one another by signals (such as firing rate) that are numerical rather than symbolic» P. S. Churchland – T. J. Sejnowski, «Neural Representation and Neural Computation», in *Philosophy of psychology*, ed. J. L. Bermúdez (Routledge: New York – London, 2006), p. 162.

solve a problem and selecting the best answer. It is functionally persistent, besides, because the loss of an element of the network (a neuron) or of a little number of them does not imply a dysfunction of the system: information can use other ways to reach its destination.

The neural network model certainly presents a few lacks, but I shall deal with them only later. What is more important, at the moment, is reasoning about these main characteristics, common to other examples of cognitive systems organized in a net structure and useful to define better their emergent properties. Especially, I intend to make here a functional analogy with the cognitive dynamics characterizing a complex information network like an ant colony. As a matter of fact, it is important to understand that from the cooperation of many simple elements, a huge series of complex and coordinated behaviours can emerge; so it is possible to talk about swarms as real collective «minds». For that, a particularly weighty concept in this context is just that of *superorganism*.[2] Some of the essential behaviours for the survival of the colony are, for instance, foraging, reproduction, migration (in relation to the suitability of a particular location), but also rearing and plantation of symbiotic insects and plants. These tasks can be successfully achieved only through both a strict and specific *division of work* and an efficient system of *communication* among the elemental agents, which permit a widespread distribution of information throughout the superorganism. So, «The fundamental elements of the superorganism are not cells and tissues, but animals acting in a close collaboration».[3] I believe we can look at these animals as analogous to the nodes of a network because they share, by means of an intense communicative exchange, all the information they have, heading it in a unique pool.

Although, what is most surprising is that the complex actions of an ant colony are the outcome of a small number of compositional rules, of algorithms offering a very wide range of combinatory possibilities. Every member of the colony contributes to this set applying itself to the solution of a simple problem, responding with a differentiated behaviour in relation to a specific context. It is important to notice, then, that an ant does not plan its actions, *does not apply a long sequence of rules, but it gives a simple response to an immediate situation*, it responds to a unique contextualized stimulus. For this reason it feeds the starving larva only inside the nursery, but if the ant finds it out of that context

[2] *Cfr.* Bert Hölldobler – Edward O. Wilson, *The Superorganism. The Beauty, Elegance, and Strangeness of Insect Societies* (New York: Norton & Company, 2009).

[3] Id., p. 29.

simply gets it back there; only then another ant will take care of the larva which, at this point, will just be a starving larva inside the nursery, so the first one of the two exemplar situations will repeat.

Then, we can think of an ant colony as a superorganism, «a superior unit whose integrated actions form ordered schemes which let it to survive and reproduce as a whole».[4] But how these «ordered schemes» can emerge from the simple chaotic intersection of algorithms? The most likely answer is that the natural selection acts in a way which permit only the development of those algorithms which work efficiently as a whole, only of those producing an *efficient order*. Such algorithms (or behavioural modules) determine, in their entirety, the fate of both colonies and their peculiar genes. So, «Conditioned by the simultaneous decisions of the other members, the colony as a whole creates emergent schemes of adaptive responses hard, and perhaps impossible, to forecast only in relation to the behaviour of the single agents».[5]

Substantially a colony, considered as a whole, has to solve a long series of problems which continuously press it. Such problems get an appropriate solution through those algorithms in which the individual behaviour of each single insect materializes; it is *guided by the information* communicated by means of particular signals divided into two main typologies: excitatory and inhibitory. For instance, when a scout worker ant, roaming randomly in seek of food, bumps into an important food source for the colony, it starts dropping off chemical traces, pheromonal markers which will head to that site other workers responsible for foraging. Each one will drop off more chemical traces strengthening that same path which, in a very little time, will be filled up by foragers.

Symmetrically, as soon as the quantity of food will start diminishing, the same foragers will drop off new signals along the path linking the foraging site with the nest, this time marking more and more a minor relevance for that site, inducing in this way each time a minor workers stream. It is clear, so, that «It is the same information which control the number of agents flocking to the foraging site».[6]

Another important aspect characterizing the activity of this particular cognitive network, is the high behavioural plasticity of the agents, which makes

[4] Id., p. 72.

[5] Ibid.

[6] Id., p. 76.

them able to carry out many tasks changing quickly their role. It is a main character in the optimisation of work in the colony: while a non–social insect is forced to follow a *continuous sequence* of steps to reach its objective, a colony can activate many *parallel sequences* carrying out, in this way, different tasks at the same time. Anyway, social insects present not only a simple parallel distribution of work, but they optimise it in a serial/parallel process which combines both mechanisms. That is just due to quickness and plasticity of agents moving from a task to another, to fill every hole that could emerge in the activity of the colony. It is in this way that a worker can move from the reparation of the nest to the rescue of a larva outside the nursery: superimposing sequences of work, limiting waste of both time and energy.

So, the constitution of a unique pool of information and the division of the work in both a parallel and a serial way, based on very elemental decision processes, are characteristic factors of a self–organized superorganism. Moreover, it is regulated by various dynamics such as those of *positive feedback* or *negative feedback*: we are respectively dealing here with signals exhorting to an action (for instance reaching a foraging site) and abandonment signals, that is signals exhorting to abandon the execution of an underway action, just like in the case of a foraging site where food is decreasing. A typical case regulated by this mechanism, is just choosing between two food sources: they will be marked through chemical traces by each ant that will find them interesting. The one where the highest number of ants will flock to, will get a sort of greater «gravity»: actually, it will be able to attract more and more insects because of a simple factor of *accumulation of information*. It is more or less what happens when some objects have to be deposited in a specific point which will become their official depository and, in some sense, the «right place» of those things. Each agent deposits the object he finds roaming in the place he consider the better one; a few heaps of objects will slowly start emerging until one of them will become bigger than the others. So, being smaller, these ones will be considered as «incorrect» places for depositing objects and the stuff deposited there will become, *ipso facto*, «out of place». The right place, the bigger heap, will become more and more evident and it will attract, because of a simple accumulation factor, the objects constituting the other ones up to absorb them. That is more or less what happens in the case of electing a particular food source among others: more ants entail even more ants, in a sort of avalanche effect.

But such rationality is mitigated by the necessary influence of *aleatory events* in the development of an emergent structure. Actually, both a random morphological change of the foraging field (for instance, due to climate factors), or simple procedural errors executing algorithms, or even paths randomly taken by scout workers seeking food, reveal themselves being sometimes crucial for the discovery of new solutions for a problem. For this reason the randomness factor has a remarkable influence on the emergence of superindividual structures and it is an essential property of self–organization.

All these characteristics give us the image of a system which, adapted to constant changes, evolves in the continuous search of a stable balance, trying to regulate each time weights and counterweights of a structure at the mercy of many conflicting forces which, clashing among them, arouse the emergent order. Moreover, I would like to underline that every movement inside a social insects colony is due to reaching a *critical point*: «For example, pillars built by termites can emerge only if there is a critical density of termites. The system undergoes a bifurcation at this critical number: no pillar emerges below it, but pillars can emerge above it».[7]

Finally, the concept of *stigmergy* perfectly summarizes what I have said so far about how self–organization works in social insects colonies. It is used to express environmental influence on behavior, when the same environment has been modified by a previous behavior; also, it can be applied to signals, both chemicals or of another kind, dropped off in that environment. It had been originally proposed by the French biologist Pierre–Paul Grassé just to explain the productive behaviour of termites building their pillars: a particular configuration of a construction would arouse the addition of more material in specific zones of the same construction. The addition of this material modifies even more the environment and the related environmental input, implying a change in the election of the site to add more material. Actually, for Grassé «the coordination of tasks, the regulation of constructions does not directly depend on workers, but on the same constructions. The worker does not head its work, rather it is headed by that one».[8] So, stigmergy is essentially a mechanism which permits the environment to self–organize through the sum of actions executed by many agents, both contemporarily or at different moments. Notice that it is the same environment (and the disposition of involved agents in it) which will

[7] E. Bonabeau et alii, «Self–organization in social insects», *Trends in Ecology & Evolution* 12, nº 5 (1997): p. 190.

[8] Translated by me, from «La coordination des tâches, la régulation des constructions ne dépendent pas directement des ouvriers, mais des constructions elles–mêmes. *L'ouvrier ne dirige pas son travail, il est guidé par lui*». In Owen Holland – Chris Melhuish, *Stigmergy,* «Self–Organization, and Sorting in Collective Robotics», *Artificial Life* 5 (1999): pp. 173.

determine the future structure.

I also would like to evidence that, in the process of building architectures, stigmergy does not do anything more than modifying the *affordances* of the environment, the very structures; in this way it entails different structural meanings and, by consequence, it modifies the suitability of certain responses. Obviously there is not any theoretical awareness of these actions, there is no self–consciousness in the human sense of introspection, even though at a global level the system exhibits a sort of intelligence; a *swarm intelligence* to be more precise or, as I previously defined it, a collective mind.[9]

We have already got, in our theoretical framework, something more than the simple notion of reticular distribution of information: we have already identified the concepts of *serial/parallel computation*, *self–organization*, then *stigmergy*, which heads the emergent movements through the continuous modification of environmental stimuli caused by each agent. Likely, all this is not so different from what another reticular cognitive system does: our brain. Actually, I am convinced that we can consider neurons as little informed minimal elements, which anyway combine those few data in huge heaps through that principle of *accumulation of information* I introduced to describe goal–oriented movements in hymenoptera colonies.

The information reaching first a critical point fires and starts a synapse, which modifies brain informative structure; in this way it activates a sort of *brain stigmergy*, arousing emergent responses which will further modify brain configuration.

§2.1. Brain stigmergy

Now, inside the brain the information network is constituted by synaptic layouts, which are not formed following a unique predetermined scheme, but through an epigenetic process headed by the same neuronal activity. That means that neurons which fire together wire together, and the same set of neurons to which each single neuron will connect with is stochastic. The structuration procedure of this information network, that is the synaptic layout, appears being formed then in a way similar to the self–organization

[9] Similar dynamics have been noted in plant roots development: each root apex works as the node of a web, acting locally and conditioning the responses of the other nodes in an indirect way, through a stigmergic process. See Stefano Mancuso & Alessandra Viola, *Verde brillante. Sensibilità e intelligenza del mondo vegetale* (Firenze: Giunti, 2013). See also Ciszak, Marzena et alii, «Swarming Behavior in Plant Roots», *Plos One* 7, nº 1 (2012): pp. 1–7.

characterizing social insect colonies: two neurons start firing together and wiring together, that is, they stabilise their connection; in this way they modify the *synaptic environment*, influencing step by step the formation of new synapses inside the network. So, I think I can legitimately argue for a brain stigmergy. The synaptic network is also selective: stronger synapses tend to stabilise. A few scholars introduced in this framework the concept of *neural Darwinism* (Gerald Edelman, 2004), but, Darwinian or not, it is the same selection I want to consider here; the fact that some synapses are more enduring than others. In my opinion we likely are in front of a mechanism quite similar to the selection of the most efficient algorithms in a social insect colony, crucial in the same stigmergy. As the construction of a pillar in a termite nest starts when a critical point is reached (and its height is regulated in function of that critical factor), so a synapse starts when the terminal part of an axon reaches a critical point where the difference of electric potential increases up to produce an electric shock trigging the release of neurotransmitter molecules. Synaptic connections form reticular structures which develop, at this point, following an epigenetic process. It is here where we find brain stigmergy, which arouses the emergence of certain structures instead of others: if in a path synaptic strength increases, at the same time chances of conduction through that path grow too; vice versa, if that strength diminishes that probability of conduction decreases too. More or less what happens with foraging paths in the social insects context, whose layout is reinforced in relation to the usefulness and the importance of the message they transmit. I guess this is a situation analogous to the former one: that is, like in ant colony dynamics, also a synaptic network is regulated by a principle of accumulation of information: *more information attracts even more information*, which strengthens the connection. In details, synapses firing together wire together, so they increase the level of «gravity», the level of criticality of that particular area of the brain where they activate, arousing an avalanche effect of synaptic activation as a reaction to «environment modification». So, considering that there is no control centre, no architect supervising synaptic architectures or organizing neurons collective work, it is likely the same information exchange which works as a general organizational principle for brain activity.

§3. Conclusion

I shall synthetize here my thesis: the concept of network we find in classic connectionism does not entail anything more than the simple distribution of information, while the comparison with some swarm intelligence models and their cognitive dynamics lets me guess a synaptic architecture which, just like paths in ant colonies or termite pillars, gradually develops through accumulation of information; although it, once emerged, tends to reach a balance point where it stabilises, until it reaches a new critical point.[10] At the same time, a continuous experience implies an uninterrupted flow of data from both the external world and the body. These data arouse the formation of new synapses, which will develop according to both stigmergy and the previous synaptic context (the *environment*), but, anyway in accordance with an epigenetic process.[11] Moreover, new data modify the previous stigmergic structure (that very information environment), also influencing the previous synaptic architecture: new elements modify the earlier balance implying, for that, a certain variation in that architecture, which is still conditioned by its bases (built on previous information) and nevertheless it remains open to a certain structural variability, because of the continuous flow of new information. Exactly what happens in the emergence process of an ant nest.

More generally, I consider possible that accumulation mechanisms and avalanche effects, which with stigmergy characterize self–organization, are still valid for a wider epistemic interpretation of information networks and their dynamics, independently of the support implementing them, whether biological or artificial.

After this analysis, I am now able to resume the features characterizing any information network I focused on in the previous pages: *communication* among the nodes of the web, which permits a widespread distribution of information; the development of *a unique pool* where all the grains of information collected by each one of the nodes converge; the development of *self–organized macrostructures*, emerging through *stigmergy dynamics*, thanks to the factor of information accumulation which combines the local competences of each node; the *critical point* that information heaps reach, stimulating the development of those new structures in which network data organize themselves. Also, *random events* are crucial; complementarity between competition/collaboration in flexible functional groups of nodes;[12] alternation

[10] About accumulation processes in brain dynamics, see also Cisek & Kalaska, «Neural Mechanisms for Interacting with a World Full of Action Choices», *Annu. Rev. Neurosci.* 33 (2010): pp. 269–98. ; and Cisek, «Cortical mechanisms of action selection: the affordance competition hypothesis» *Phil. Trans. R. Soc. B* 362 (2007): pp. 1585–1599.

[11] See Edelman, op. cit.

[12] See Marvin Minsky, *The Society of Mind* (New York: Simon and Schuster, 1986).

of serial/parallel processes optimizing information distribution dynamics in the network; selection of information paths in relation to the *relevance* of that very information, through those accumulation processes I mentioned above, likewise in a *gravitational attraction*.

Considering all what I said, I would propose this work as a first step to a new paradigm to focus information networks as *per se* self–organizing entities: the very structure of data emerging through stigmergy, heads the local responses of individual nodes, organizing the network self–structuration.[*]

[*] This article originates from my MA dissertation *A fine net. How intelligence develops from a web*, an original research work in Philosophy of Science, developed under the supervision of Prof. Giséle Fischer, at the University of Parma (Italy), publicly defended on March, 28th 2014.

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