The Palgrave Handbook of Methodological Individualism

Volume I

Edited by
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Complex Methodological Individualism

Jean Petitot

1 Introduction

This chapter contextualizes the question of Methodological Individualism (MI) in the social sciences into a broader and more general scientific context including physical, biological, and ethological sciences. This approach closely links MI with the sciences of complexity, hence the denomination of *complex* methodological individualism (CMI).

Many other chapters of the *Handbook* deal with the strictly social, political, economic, cultural, and institutional aspects of MI, as well as with the difficult epistemological problems they raise in the humanities. The focus here is on the contrary on the intrinsically *transdisciplinary* and transversal character of CMI. CMI concerns here the emergence of global collective properties (structures, organizations, processes) at the macroscopic level in populations composed at the microscopic level of a very large number of elementary individuals interacting with each other.

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2 Levels of Reality

In many domains, we come across several levels of description, and at least a *micro*-level and a *macro*-level (and often also an intermediary *meso*-level). At the micro-level, there are individual entities endowed with elementary individual states and rules of behavior and interacting through short range very local interactions. In contrast, at the macro-level we observe global structures which can be adequately described using concepts whose content has nothing to do with micro entities. One of the main challenges is to understand conceptually, causally, and moreover *mathematically*, the relations between the two levels. It is a true challenge because any sort of *semantic reductionism* is inapplicable since the concepts used for describing the two levels don't share any content. There is therefore an *antinomy* between the thesis of independence and the antithesis of the non-independence between levels.

The problem is age-old.[1] It is extremely difficult and transversal to the classical disciplinary fields and in particular to the traditional division between the natural and human sciences. Let us begin with two examples from physics where it has been solved.

The first, and most celebrated, example is provided by *thermodynamics*. To describe macroscopically a substance like *water*, one uses concepts such as temperature T, pressure P, and volume V, which do not refer directly to any atomic or molecular concept (no semantic reductionism).[2] It took a long time to find the equations correlating these thermodynamical variables and to describe accurately such striking phenomena, called *critical* phenomena, as *phase transitions* (water boils at the critical value of 100° Celsius under a pressure of 1 atmosphere).[3] But after the molecular structure of water (H_2O) was discovered in the late eighteenth century,[4] it was natural to ask for a micro-level interpretation of thermodynamical variables in terms of local behavior (vibrations) and interactions (impacts, collisions) between molecules. Already Lavoisier had introduced the hypothesis that heat was due to some molecular agitation. But it required the genius of Ludwig Boltzmann (1872) and Willard Gibbs (1902) to achieve this revolutionary reinterpretation of thermodynamics in terms of statistical physics. The interpretation of T as the mean kinetic energy of molecules is one of the major achievements in the

[1] It dates back to Antiquity.

[2] T and P are intensive magnitudes, while V is an extensive magnitude.

[3] At the molecular level, a liquid to gas phase transition is an incredibly dramatic revolution: all the links giving to the liquid its cohesiveness are suddenly broken and the collective state becomes a dispersed state of "atomic" independent units.

[4] Remember the chemical revolution resulting from the celebrated controversy on Oxygen and the atomic composition of water between Joseph Priestley and Antoine Laurent de Lavoisier (1779).

history of science. The micro-dynamics is incredibly complex, but some simple macro "mean field" "order parameters" *emerge*.

Another example, more recent, is provided by the geometry and the morphological dynamics of sand dunes and sandpiles. Here, the micro elementary entities are grains of sand locally interacting by rolling against each other. The micro-dynamics is very complicated and the physics of dry cohesionless granular materials is a very active discipline. The macro geometric shape *emerges* from a *fractal* entanglement of myriads of micro *avalanches* of different scales, and geometric macro parameters such as the slope of the dune or pile (called the "angle of repose") can be explicitly computed using non-linear equations. It is an example of a *complex spontaneous order*. The remarkable fact is that this geometric slope is a *critical* value and the complex multiscale system of sand grains has the extraordinary property of *stabilizing* on its critical state, while criticality seems to be the opposite of stability. This phenomenon, called "self-organized criticality," was discovered in 1987 by Per Bak, Kurt Wiesenfeld, and Chao Tang. Once again, there is no semantic reductionism: the geometrical concepts used to adequately describe the morphology of dunes have nothing to do with fractal micro-avalanches of rolling sand grains.

These two purely physical examples share some epistemological features:

1. The two micro/macro levels are phenomenologically heterogeneous and conceptually autonomous. Their relation is a relation of emergence.
2. But they are not completely *causally* autonomous. The macro-level "supervenes" on the micro-level. Moreover, causality operates bottom-up from the micro to the macro level. There is no *direct* top-down physical causality of the slope on the grains but when the wind is added as an "external field," as is the case for dunes in the desert, then the morphology of the dune produces on the air flow all the well-known phenomena of overpressure-front and rear depression and turbulence. It therefore acts *top-down* on the granular micro-dynamics and generates complicated morphologies. In life sciences or social sciences top-down causalities become omnipresent and essential.
3. The heterogeneity of the two levels results from the immense number of elementary micro units. The local interactions between these units must be *iterated* (in a sequential or parallel mode) and the iteration of elementary rules can reach any possible complexity (it is a theorem on networks of automata).
4. The *mathematical* modeling of the relation of emergence between the two levels overcomes their conceptual incommensurability.

5. An emerging macro structure can be rather simple (a temperature, a slope). But its emerging simplicity encompasses an immeasurable micro complexity.
6. In physical situations, the system is frequently modeled by a large system of differential equations and the emerging properties are represented by *order parameters* which have often a statistical content (as in "mean field" theories).
7. The conceptual independence of the emerging structures is *mathematically justified* by proving that the order parameters are *essentially independent of the fine-grained underlying microphysics*. For instance, in statistical physics, Kenneth Wilson won the Nobel Prize in 1982 for proving that critical behaviors in magnetic materials can be classified, via what is called the renormalization group, in universal classes largely independent of the atomic-molecular structures of the substrates. Without such a proof of invariance, emergence would have no scientific content.

Thus, CMI is justified as a computational synthesis which posits that high-level phenomena, structures, and processes can be deduced, as far as their scientific explanation is concerned, from underlying lower-level phenomena, structures, and processes. We have just seen that it is by no means an "eliminativist" reductionism and is perfectly compatible with emergence, "supervenience" or "functionalism."

Functionalism means that macro structures having a functional role can exist only if they are materially implemented in an underlying material substrate, but are at the same time, as functionally meaningful structures, largely independent of the fine grained material structure they are implemented in.[5] Beside physical examples, another paradigmatic example is the opposition software/hardware in computer sciences (see philosophers like Hilary Putnam, Jerry Fodor, Zenon Pylyshyn, etc.).

Complex systems having different levels of reality whose emergence at different scales can be proved are countless in nature: critical phenomena, percolation, self-organized criticality, reaction–diffusion systems, far from equilibrium dissipative structures, turbulence, cellular automata, neural networks, ant colonies, swarms, stock markets, etc. The proven emerging levels are not epiphenomenal. But they are not interpretable according to a *holist realism* positing their irreducible reality. They are causally reducible but not semantically reducible.

[5] See e.g. Petitot, 2010.

This key point has been also emphasized by Viktor Vanberg in the social sciences concerning the "invisible-hand" explanations we will comment on later[6]: conceptual descriptive adequacy is by no means sufficient to justify any emergence thesis. Emergence must be proved using mathematical models, that is a computational synthesis. Vanberg criticized for instance Hayek, because the latter recognized correctly the "synthetic" and "compositive" character of emergence, but did not insist on the obligation that synthesis must be carried out. It is the most difficult challenge.

Remark. In this chapter we will make many references to Hayek because we consider him an exemplary representative of the CMI. Indeed, Hayek has since his first reflections on the *Sensory Order* constantly developed MI within the general framework of the theory of complex systems.

3 "From Physics to Politics"

The scientific study of multiscale self-organized complex systems is a well-established interdisciplinary field which goes far beyond physics. In 1981, Paul Dumouchel and Jean-Pierre Dupuy organized an important Conference entitled "Self-organization: from Physics to Politics." So, let us progress toward politics through biology, psychology, and ethology.

Neural Functional Architectures

A fascinating micro/macro example in life sciences is the relation between neurology and psychology. Activities of billions of elementary micro-neurons locally connected through *specific* systems of connections called "functional architectures," implement a macro-level of emerging psychological states and processes.

Results depend today upon revolutionary new techniques of in vivo optical imaging. Emergence is proved looking at huge systems of non-linear differential equations expressing how neurons fire and emit spikes when they are (i) activated by external stimuli and (ii) connected through inhibitory and excitatory connections having specific weights and functional architectures. This specificity results from experience and learning. It encodes in a radically distributed and non-conceptual way the knowledge and the cognitive resources of the system. Such equations, due to Jack Cowan, Hugh Wilson, and David Hopfield, are very similar to those found in statistical physics in

6 See Vanberg, 1986.

spin glasses theories. Their numerical study is necessary to prove emergence by a computational synthesis. It is today the issue of some of major international research programs.[7]

Emerging properties are in particular properties of *synchronization* of pools of neurons. They explain many macro-psychological facts because the *common phase* of a synchronized population can act as a *label* for further processing (what is called "binding" and "labeling hypothesis").

The idea of interpreting mathematically psychological structures in terms of complex neural networks goes back to 1940–1950 with John von Neumann, Norbert Wiener, Warren McCulloch, Walter Pitts, and the famous Macy Conferences (1942–1953) at the origin of cybernetics, cognitive sciences, and information sciences.[8] Since then, incredible progress has been made, e.g. concerning the explanation of *categorization* or *learning*.

In fact, as acknowledged by such great neuroscientists as Gerald Edelman (Nobel 1972) and Joaquin Fuster, the great precursor was Friedrich von Hayek in *The Sensory Order*, a unique masterpiece analyzed by Bruce Caldwell, Barry Smith, and Francesco Di Iorio.[9] It goes back to the 1920s and was taken up in the 1952 book. This critique of behaviorism is essential in Hayek's intellectual journey because it is a key example of a *complex spontaneous order*: neural cells are connected into complex, organized, and specific networks which act as communicational infrastructures for complex fluxes of neural spikes ("impulses" said Hayek) and encode learning and memory. We have to take this micro neural organization as the basis for explaining our macro psychological sensory experiences. The specificity of what are now called "neural functional architectures" introduces a gap between, on the one hand, the sensorial micro transduction of the stimuli by peripheral receptor organs such as the retina; and, on the other hand, the perceived scenes endowed with their Gestalt patterns processed by the central cortical brain areas.

In *The Sensory Order After 25 Years*, Hayek's summary is very similar to the contemporary concept of functional architecture: "Mind thus becomes to me a continuous stream of impulses, the significance of each and every contribution of which is determined by the place in the pattern of channels through which they flow within the pattern of all available channels." (p. 291)

[7] For example, the billion euros *Human Brain Project*, which aims to simulate cortical modules of the visual cortex. It uses a computational power up to a million teraflops (a teraflop is 1000 billions operations per second).

[8] See Jean-Pierre Dupuy's book *The Mechanization of Mind*.

[9] They all emphasize the importance of this early contribution of Hayek to the neurophysiology of psychology.

These initial reflections were a model for the further works of Hayek in economics and, after he had come into contact in the 1950s with the transdisciplinary and polymathematical sciences of complex self-organized systems (Norbert Wiener, Ludwig von Bertalanffy, John von Neumann, Warren Weaver, see above), he wrote his 1952 book.

In the Hayek archives managed by Bruce Caldwell at the Hoover Institution of Stanford, there is interesting correspondence with James Gibson, the future author of *The Ecological Approach to Visual Perception* (1979), who was "much impressed" by *The Sensory Order* (24 February 1954) and wanted to invite Hayek to Cornell for a Conference on the "Fundamental Problems of Perception." In the letters there are interesting remarks concerning Heinrich Klüver (1897–1979), the great neuropsychologist at Chicago and a privileged interlocutor of Hayek in psychology and neurology. Klüver was a student of Max Wertheimer and introduced Gestalt theory to the US. He arrived in Chicago in 1928 and joined the "Neurology Club" (Karl Lashley, Percival Bailey, A. Earl Walker, Ralph Gerard, Stephen Polyak, Charles Judson Herrick, and Roy Grinker). His works on vision are now well modeled using Wilson-Cowan equations and tools of Neurogeometry.[10]

Ethology

Other fundamental examples in life sciences are found in *ethology*. In the last decades, a great deal of research and modeling has been dedicated to the collective behavior of large communities of animals: hordes, flocks of birds, fish banks, insect swarms, etc. The case of starling flocks is spectacular and well known. Very complex global geometric patterns can result from very simple local rules, as simple as (i) move in the direction of the neighbors, (ii) move to the center of the group, and (iii) if another animal is coming too close, move away from it.

What is particularly interesting in these collective movements is that individuals possess *internal* states controlling their *external* motions. They are *agents* endowed with sensory-motor faculties and cognitive resources (even if limited). Since they are active and dissipate energy to act, they constitute thermodynamically far from equilibrium systems and can therefore structure themselves by violating the second law of thermodynamics.

The *emergent global geometry* of their collective motions is totally *unplanned* and *unpredictable*. Transcending the cognitive resources of individuals, it is an *unintentional global macro* consequence of intentional, local,

[10] See Petitot, 2008.

and micro actions. It therefore already represents a social phenomenon which is a *spontaneous order* completely transcending individual capacities.

The three rules of (i) local alignment, (ii) group attraction, and (iii) short distance repulsion were implemented in particular by Tamás Wicsek and colleagues in 1995 in a simplified statistical model which shares many features with the *spin glasses* models sketched above.

But the models went far beyond the modeling of mere collective motions. They progressively led to the key idea of multi-agent collective, distributed, and decentralized intelligence as a new paradigm for complex problem solving, more precisely for solving problems that individual agents are unable to solve—what is now called "swarm intelligence," "distributed artificial intelligence," and "ant colony optimization algorithms". The idea is that an algorithm solving a complex problem can be implemented in a distributed way into the collective intelligence of a network of micro-elementary agents sharing very *limited* cognitive resources and interacting through very elementary rules. The collective intelligence is *incommensurable* with individual intelligence and *emerges* from *global cooperation*.

In nature, the most striking examples of collective intelligence are provided by social insects: bee hives, wasp nests, ant nests, and termite mounds. This leads us toward politics because social insects have been considered, since Aristotle, as "political animals" (zoôn politikon) because *they cooperate to produce public goods*. This is the key point. In his *Politics*, Aristotle considers that there are essentially two kinds of political species: humans and social insects. A lot of empirical observations and comparisons led him to a behavioral taxonomy. Animals are either solitary (felines, spiders) or social. Social species can live in small groups (primates, wolf packs) or in large groups. In the latter case, they can have gregarious (herds, flocks) or "political" behavior. Aristotle claimed "man is by nature a political animal," but he is not the only political species. What is true is that man is the only *rational* political species.

What is especially interesting in social insects is that:

1. The collective intelligence is incommensurable with the individual intelligence of the agents.
2. The "political" performances (i.e. collective production of public goods) result from simple but extremely efficient ethological rules selected by evolution.
3. The collectivity constructs global architectures, called "architectures without architects" as honeycombs with miraculous hexagonal tesselations, or immense mounds (they would extend up to ten kms at human

scale) with pillars, external walls, galleries, cellars, channels, ridges, spiral conducts for ventilation and cooling, valves, brood chambers, etc.

Stigmergy

Highly sophisticated buildings such as termite mounds are essential for the species to survive. They result from elementary spatial moves marked by pheromones. The process was called *stigmergy* in 1959 by Pierre-Paul Grassé. Stigmergy is the key concept of the theories of swarm intelligence. In constructing a mound, initially, each individual termite rolls a mudball, invests it with pheromones, and deposits it randomly in some place. But the pheromones are *attractive* and act as *signs* (hence the term of "stigmergy": stigma = sign, ergon = action). So, many mudballs become deposited in the same place. This positive feedback produces high pillars that collapse beyond a certain height, a catastrophe which triggers the *iterated* building of new pillars, etc. This spontaneous emergence of coherent activity builds gradually, without any centralized planning and control, seemingly intelligent structures.

Their mathematical models are highly non-trivial.[11] It must be emphasized that, in contrast with the physical examples, the emerging macro architectures apply here a strong *top-down* "imerging" causality upon the micro individuals.

Eusociality

This very particular paradigm of sociality "invented" by evolution is called *eusociality* in ethology, a neologism coined in 1966 by Suzanne Batra. Eusociality (from Greek "eu" = "good" and "social"), is defined (see e.g. Wikipedia) as the highest level of organization of animal sociality and characterized by cooperative brood care, overlapping generations within a colony of adults, and a division of labor into reproductive and non-reproductive groups. The "queen" and reproductive males monopolize reproduction. Division of labor creates specialized behavioral groups (castes) within the society. Soldiers and workers are sterile and specialize in brood, foraging, defense, or maintaining food and resources.

At the evolutionary level, in a strict neo-Darwinian gene-centered view based on the *selfish gene* principle (individuals maximize the fitness of their

[11] See, e.g., works by Jean-Louis Denebourg, Guy Theraulaz, Eric Bonabeau, or Bernard Manderick.

genes), eusociality seems rather paradoxical. How can organisms increase the transmission of their genes if they become sterile and work for their close relatives? How can we imagine *genetic* bases for cooperation and altruistic behavior? The sociobiologist William Hamilton explained (1964) that it might be possible for a non-reproductive (sterile) individual to share more genes with a close relative than with his or her offspring ("inclusive fitness" principle). It is precisely the case with many species of social insects which are *haplodiploid*: males are haploid (i.e. have a single set of chromosomes from the mother) while females are diploid (i.e. have two sets of chromosomes from the mother and the father). As a result sisters can share up to 75% of their genomes: more than the 50% they can share with their offspring.[12]

Cognitive VS Eusocial Complexification

The eusocial paradigm is the opposite of the dominant paradigm found in superior species of mammals, that of small "communities" which are like extended family groups. In that later case, the communal links are *accessible* to the experience of the agents. Social organization is "cognitively commensurable" and we can speak of a sort of social reflexivity. For the eusocial paradigm it is not the case. Social organization is not community-based and is cognitively inaccessible.

The key point is that there exist (at least) two evolutionary ways for complexifying intelligence. On the one hand a *"vertical" cognitive complexification* of the individual intelligence, and, on the other hand, a *"horizontal" eusocial complexification* leading to a "swarm intelligence" with two levels micro–macro. Either individual intelligence increases but the social groups remain small communities, and it is the case for evolution leading toward primates and *Homo Sapiens*; or individual intelligence remains very limited but the groups increase drastically and become eusocial, which enables a distributed collective intelligence to emerge.

Mandeville's Fable of the Bees

The "political" character of social insects and its analogy of structure with modern human open societies has a long history in Occidental thought and recurred in the modern period. Its best-known occurrence is *The Fable of the Bees* of Bernard Mandeville (1670–1733) which, according to Hayek, "asked

[12] For a critique of Hamilton's inclusive fitness, see Nowak, Tarnita, Wilson 2010.

the right question."[13] His apologue *The Grumbling Hive: or, Knaves Turn'd Honest* (1705), later extended and called *The Fable of the Bees; or, Private Vices, Publick Benefits* (1714, 1723, 1729) had a major impact. The expression "private vices" meant at that time the prevalence of self-interest; what we now call choice rationality and maximization of utility.

The thesis is that a hive functions properly only when each individual bee, each with its very limited representational resources, does what it has to do in the framework of division of labor and follows strict innate rules without bothering about collective advantages or disadvantages. They are the *interactions* of the bees according to efficient selected rules, and not "moral" virtues, which produce the collective wealth, benefits, and public goods of the hive. Individual bees don't have the cognitive resources to enable them to have and share any representation of the hive. In other words, Mandeville's fable on bees as Aristotelian "political animals" concerns the social value of selfish behavior in complex societies where myriad individuals cooperate through labor division.

Mandeville made explicit in a provocative way the conflict arising at his time between the new-born economic liberalism and traditional Christian ethics. Since the beginning of the seventeenth century, some philosophers had already tried to explain that "enlightened" self-interest could be socially positive. This political, and in fact *theological*, thesis can be found in Blaise Pascal and Pierre Nicole (1625–1695, a Jansenist of Port-Royal[14]): society should be based upon "enlightened" self-interest rather than upon charity.[15]

Mandeville inspired Adam Smith and his concept of the "invisible hand" as a mechanism ensuring the "Wealth of Nations." This first formulation of self-organized spontaneous order operates at the metaphysical, theological, and political levels as a "*ruse of reason*." As Pierre Nicole claimed, to make selfish interests cooperate in an unintended way to the benefit of public welfare is "the secret plan of God," "the hidden order of God." "There is no need of virtuous individuals to get a virtuous society." Selfish individuals are able, without knowing it and willing it, to do "an admirable thing": the more the persons aim at their own interests, the more they become interdependent, and the more they compose "a superior reality *able to transcend each bet.*"[16] Thus, God's "ruse of reason" is a "ruse of passion" for men.

13 Mandeville was from a family of liberal-progressive physicians of Rotterdam who emigrated to England following conflicts with the Orange Party and Calvinists.

14 See his *Essais de morale*, 1671.

15 See, e.g., Faccarello, 2006.

16 Here, "transcendence" means incommensurability and emergence.

Later, we find the same kind of "ruse of reason" in Kant (1784, *Idea for a Universal History with a Cosmopolitan Purpose*) to solve the political antinomy of the "asocial sociality" (*ungesellige Geselligkeit*), which is the key concept of Kant's anthropology and philosophy of history. The question is no longer to speculate on the original pre-political nature of humans as hostile wolves (Hobbes) or kind lambs (Rousseau). The problem is that the human is a social species while his individual nature (ambition, domination, cupidity) is anti-social. But, by a "ruse of reason," Nature uses this Hobbesian pathology to compel humans to accept collective *rules of law*.

The *Fable of the bees* triggered a tremendous controversy (in particular with Bishop Berkeley) and was condemned in 1724 for its "diabolic attempts against religion." Even today many people judge it outrageous to introduce a principle of *moral inversion* between micro-social individual intentions and global emerging macro-social properties, to posit that intentionally selfish individuals ("rational" in the sense of the theories of rational choice) governed by their private and local self-interest can, by means of their interactions, generate, in an *unintended* way, a global social order propitious to public interest.

Hayek on Mandeville

The *moral* evaluation of Mandeville's thesis is irrelevant. Mandeville was concerned by the economy of large cities and societies, by wealth rather than by virtue. He explained that a "sympathy fusion" between individuals is not necessary to reach a spontaneous "harmony" of interests. This said, it is not yet clear if, in Mandeville, the "invisible-hand" paradox was solved by a "hidden Providence" as it was previously the case in Pierre Nicole, or already by a *natural* self-organizing mechanism as it will be in Adam Smith, or by an *artificial* legislation as it will be in a physiocrat such as Helvétius or a utilitarian like Bentham.

In his *Lecture on a master mind: Dr Bernard Mandeville*, given at the British Academy on March 23, 1966,[17] Hayek explains that Mandeville was not a moralist but an excellent physician and psychologist-psychiatrist, and that the question is not to know if the "harmony" is natural (phusis and cosmos) or artificial (nomos and taxis), but to understand that it is an emerging *unintended* spontaneous order. Mandeville had already raised the issue of the incommensurability of social structures with respect to reason, and of the selection of "good" social rules by cultural evolution.

[17] In *News Studies in Philosophy, Politics, Economics and the History of Ideas*.

4 Eusociality in Humans

The evaluation of Mandeville's thought must be contextualized with respect to the different conceptions of social order trying to solve the "asocial sociality" of humans in modern open societies.

The Paradigms of Social Order

Three conceptions of social order have long dominated political philosophy.[18] They are analyzed in other articles of the Handbook. But none of them set out to explain the emerging phenomena of self-organization and spontaneous orders in modern societies.

1. The paradigm of hierarchical order and absolute power theorized from the Renaissance by Machiavelli (1469–1527), then Bodin (1529–1596) and Hobbes (1588–1679). In Hobbes' *Leviathan*, the coordination problem is solved by a centralized hierarchical "vertical" power (king's scepter and bishop's crook) which *imposes* a top-down coordination by coercion. This is possible because the wealth surplus produced by global cooperation is monopolized by narrow elites enjoying exclusive privileges and able to pay for the police and the army protecting their power.

   It is in reaction to this form of absolutism that many demands arose for tolerance and human rights, from Grotius (1583–1645), Bayle (1647–1706) and Locke (1632–1704) to Kant (1724–1804), Humboldt (1767–1835) and Constant (1767–1830). The "vertical" orders were challenged by more "horizontal" and "democratic" conceptions advocating, like Mandeville, a sort of eusociality.
2. The rational "constructivist" (in Hayek's sense) paradigm posits that an efficient order can be computed, planned, and applied.
3. The conservative paradigm of natural order, which champions a form of organicist holism and accuses individualism for "atomizing" society and destroying "natural communities" (family, corporations, churches, etc.). For example, for Saint-Simon (1760–1825, *De la physiologie appliquée à l'amélioration des institutions sociales*, 1813) and Auguste Comte (1798–1857, *Système de politique positive*, 1851) holism was a sort of "organicism," a "physiological" conception of the social reality opposing "mechanistic atomism."

[18] See e.g. Nemo, 2002.

An Eusocial Primate

But none of these three paradigms takes into account a major evolutionary characteristic of societies specific to urban civilizations. *Homo Sapiens* is a broadminded primate situated on the "vertical" axis of cognitive evolution. Our ancestors began to live in families, small groups, clans, hordes, and tribes where there existed a cognitive commensurability between individuals and collectivity. A kind of social reflexivity was then possible and there was no *eusocial* organization. A decentralized non-coercive coordination was possible because each member could control the behavior of the others.

But after the prehistoric sedentarization of "hunter-gatherers," the advent of agriculture and farming, with the apparition of great urban civilizations in Mesopotamia, Egypt, Carthage, Rome, China, large cities, new techniques (writing, accounting arithmetic, surveying geometry), currency, land and sea lines of communication, trade exchanges, etc., a fundamental break occurred and a *"horizontal" eusocial-like complexity* emerged, complexity which was completely alien to the evolutive line of *Homo Sapiens*.

This dimension is well explained by many authors, e.g., Daniel Andler in his *La silhouette de l'humain* (2016). The challenge is to articulate cognitive science and social theories from an evolutionary perspective; to understand the very fast *hyper*sociality of *Homo Sapien*s with its division of labor, its cooperation between agents allowing group performance, its "altruism" and its other behaviors closer to those of social insects than those of primates. All the classic debates between MI and MH reappear when we try to understand the evolutionary dialectic between the cognitive and the social. From a phylogenetic perspective, the problem is very difficult. Some hypotheses proposed the concept of a "social brain" resulting from a mind/sociality *co-evolution* having led to a *double complexity*: a cognitive complexity improving that of primates coupled with a social complexity of the social insect type. *Homo Sapiens* would have become "pro-social" and "eusocial." We can cite in particular the works of Richard Byrne, Andrew Whiten, Nicholas Humphrey, and Robin Dunbar, all of whom have been studied in depth by Daniel Andler.

The expression "eusocial-like" uses the term "eusocial" in a cultural sense and not in a biological one. When Edward Wilson, the sociobiologist of Harvard, ant specialist (see *The Ants* 1990, written with Bert Hölldobler) and founding father of *Sociobiology* (1975) wrote *The Social Conquest of Earth: humans are eusocial apes* (2012), after having published with Martin Nowak and Corina Tarnita *The evolution of eusociality* (2010), he triggered a live debate with sociobiologists specialist in eusocial altruism such as Herbert Gintis and Bill Hamilton, or biologists and ethologists like Richard Dawkins (the author of *The Selfish Gene*, 1976), and also cognitivist psychologists such as Steven Pinker. But, in much the same way as Hayek explained that the moral debate about Mandeville was irrelevant, the biological debate about Wilson is irrelevant. Of course, *Homo Sapiens* is not a eusocial species. Human eusociality results from a cultural (and not biological) evolution.

The key problem is the *mismatch* of this eusocial cultural evolution with our primate brain. Our biological inheritance is not adapted to *global* social coordination. The later, requires the introduction and the acceptation of eusocial impersonal, "objective," and external rules. But what type of rules?

Spontaneous Orders and Complex Methodological Individualism

Through all his life, Hayek defended the concept of *spontaneous self-organized orders*, which posits that pluralism and individual freedom are not sources of disorder, anarchy, and social struggle but, on the contrary, a factor conducive to higher forms of organization. His CMI stands in sharp contrast with the other paradigms of social order and conceives social order as neither natural (permanent and universal) nor artificial (rationally construed), but pluralist and self-organized, non-hierarchical and polycentric.[19] As the masters of the Scottish Enlightenment David Hume (1711–1776) and Adam Ferguson (1723–1816) emphasized,[20] they are the results of human actions but not of human intentions.

This conception—that individuals are the basic social entities but interact in a contractual society protected by the rule of law—is in general attributed to the tradition stemming from John Locke (1632–1704) and Adam Smith (1723–1790) and the "*invisible hand*" (*Theory of Moral Sentiments*, 1759, *The Wealth of Nations*, 1776). The essential feature of the invisible hand is that it drives subjects to collective ends that do not proceed from their intentions. But as we have seen, it was already present in Pierre Nicole. And in the volume I edited with Philippe Nemo on *The History of Liberalism in Europe*, we find a chapter by Gilbert Faccarello on one of the main precursors of Adam Smith with Mandeville, namely Pierre de Boisguilbert (works between 1695: *Le Détail de la France*, and 1705: *Factum de la France*).[21]

19 Evident examples of such orders are language, law and morals: they are not natural in the strict sense of the term, but neither are they artificial since nobody has ever made them.

20 Ferguson. *An Essay on the History of Civil Society*.

21 Faccarello, 2006.

For CMI, global macro rules must be rules of a law-abiding state. The function of the state is neither to uphold an "innate" order nor to impose a "rational" one, but only to secure the *institutions* enabling the emergence of an open and evolutive spontaneous order. CMI concerns mechanisms of self-organization, in which the agents do not have in general the cognitive resources for rationally computing all the consequences of their actions. So many collective effects of these actions are *un*intented. It is evident in the case of the evolution of language. Social cohesion, cooperation, and prosperity are *non*-intentional effects emerging from an aggregation of selfish interests.

But, of course, there is a major problem. It is not sufficient to refer to *empirical* examples, remarkable as they may be, as language, religion, law, money, market, etc., and to claim that they are unintended results of human actions and not the intentional outcome of a general collective will.

As we have already emphasized with Viktor Vanberg, the possibility of emergence *must* be proved using mathematical modeling and computational synthesis. This is particularly non-trivial because, as we have seen, the *rationality* (in the sense of the rational choice theories since William Stanley Jevons and Léon Walras) of selfish agents able to compute the maximization of their utility seems to be incompatible with global coordination. The rational economical calculus for maximizing pleasure and minimizing pain seems to be anti-social.

Evolutionary Game Theory

Let us now give an idea of how we can mathematically model phenomena of social coordination. We will take the example of the emergence of *cooperation* in evolutionary game theory. See, e.g., the celebrated works of Robert Axelrod.

The best-known example is the so-called "prisoner's dilemma." It is a game intended to model the dynamics of cooperation. In the simplest case we consider two players, A and B, each having two possible behaviors, namely d = defection (betraying) and c = cooperation. The game is defined by a matrix giving the payoffs of the players for each of the four possibilities (b_A, b_B): A plays b_A and B plays b_B:

$T = (d, c)$ = Temptation (A betrays B who cooperates),

$S = (c, d)$ = Sucker (A cooperates and is betrayed by B),

$R = (c, c)$ = Reward (A and B cooperate and are rewarded),

$P = (d, d)$ = Punishment (A and B betray and are penalized for it).

For the game to be relevant, betrayal T must be more profitable than cooperation R (which explains the "temptation" of betrayal), cooperation R more profitable than generalized defection P and generalized defection P more profitable than unconditional cooperation S. In other words, we must assume that the payoffs satisfy the conditions: $T > R > P > S$.

This very simple game represents a situation where *individual* rationality comes into conflict with *collective* rationality. Indeed, in the case of a *one shot* game between rational players.

i. If player A plays c, then player B wins R if he plays c and T if he plays d. As $T > R$, player B has an interest in playing d.
ii. If player A plays d, then player B wins S if he plays c and P if he plays d. As $P > S$, player B has an interest in playing d.
iii. If player B is *rational*, he will therefore play d whatever the behavior of A. We say that the betrayal strategy *d strictly dominates* the cooperation strategy c: for the player B, d does better than c whatever the behavior of the other player.
iv. The same is true for A by symmetry.
v. The result of the game is therefore (d, d) = (loose, loose), generalized defection which leads to the bad collective gain (P, P).
vi. But clearly, the cooperation (c, c) = (win, win) leading to the collective gain (R, R) would have been a much superior strategy since $R > P$.

With such a payoff matrix, the general defection strategy (d, d) is the only *Nash equilibrium* of the game, i.e., the strategy such that each player does worse if he changes strategy unilaterally. Countless examples of (loose, loose) failures of cooperation are observable in all the domains of action, from personal relationships to international geopolitics.

We therefore have an elementary micro behavior of pairs of agents with its very precise rules leading systematically to a very precise result, generalized defection. *We can then consider societies of such agents, introduce interactions, and wonder if new macro collective behaviors, in particular cooperation, which is the very opposite of defection, can emerge*. This is typically a CMI issue.

And that is indeed the case. The situation changes drastically when the game becomes more complex. First, one can *iterate* the game, which implies that defection can then be punished and cooperation rewarded. In this case, one can introduce more elaborate individual strategies such as unconditional cooperation, unconditional defection, "tit for tat" (*TFT*: start with cooperation, then play what the other player played at the previous move), "vindictive" (start with cooperation and defect forever as soon as the other player defects, defection being punished as an irreversible betrayal), etc. Moreover, games can be *evolutionary* games, where polymorphic populations of individuals use different strategies and generate new generations using the scores in a generalized competition: strategies with good scores increase their number of representatives while those with bad scores progressively vanish. In these models, agents are considered as "phenotypes" expressing "genotypes" identified with strategies, and simple "micro" strategies influence complex "macro" population dynamics.

Evolutionary game theory is more realistic than the classical one based on individual choice rationality. It substitutes a collective selective scheme to an *untractable* variational calculus. Moreover, it enables us to understand the dynamics that drive agents toward global equilibria.

Simulations and computational synthesis prove then that anti-cooperative strategies can be eliminated, and that cooperation can win and become stable. The best strategies are nicely cooperative, rapidly reacting to defections ("retaliatory"), rapidly forgiving, and simple ("clear," without wiles). The best known is the "tit for tat" (*TFT*) strategy.

But such cooperative strategies are *fragile* with respect to *mutations*. Indeed, as far as unconditionally cooperative mutants exhibit exactly the same cooperative behavior as *TFT* agents in a *TFT* environment, they can therefore substitute themselves progressively and "silently" for *TFT*, without any observable effect. But then "bad" (unconditionally defective) mutants can destabilize, invade and destroy the system. So, to be retaliatory is a condition for being *collectively stable*.

Moreover, one can, as did Karl Sigmund, Martin Nowak and Robert May, *spatialize* this evolutionary game by introducing local neighborhood relations between the agents. Simulations show that the transition between non-cooperative global states toward emerging cooperative global states has the status of a *critical phenomenon*, exactly as phase transitions in physics.[22]

Hayek and the Complexity Problem

Hayek was at the same time anti-holist and anti-rationalist. For him, man is not a rational chooser. His cognitive resources are very limited and drastically imperfect, he is unable to perform the economical calculus and has always a dramatically *incomplete* knowledge of economical situations. Hypotheses of perfect information are wrong. He has to choose and to act according to

[22] See the (Modèles formels de la 'main invisible': de Hayek à la théorie des jeux évolutionniste) "Formal models of the 'invisible hand'. From Hayek to evolutionary game theory", (Histoire du libéralisme en Europe) *The History of Liberalism in Europe*. See also Petitot, 2016, where fractal structures characteristic of phase transitions are computed for models of an iterated spatialized prisoner dilemma.

fallible expectations and very local and limited knowledge. It is for that reason that he needs social institutions, as prices in a market, which, as emphasized by Jack Birner in *Cosmos and Taxis*, provide a "communication structure that transmits price information efficiently and rapidly."[23]

The source of complexity has to be found in the fact that, in an open society, knowledge, competencies, and information are distributed, scattered over a great number of cognitively limited and interacting agents. The systemic properties of such systems cannot be conceptually controlled. The political control of social and economic orders rests on a methodological error.

Many consequences derive from this fundamental fact.

1. First, complexity prohibits at the same time a centralized hierarchical organization and a communal link of reciprocity characteristic of small, closed communities. In modern open societies the interaction between agents is no longer ensured by consensus on shared values but by exchange of signals such as prices in a market. The market is a way of circulating information in a multi-agent system whose very complexity makes it opaque to its own agents. In a Hayekian "catallaxy," everyone cooperates with everyone else but without any shared ends. The individual aims are incommensurable with each other but mechanisms such as free trade and markets guarantee, nevertheless, a viable cooperation.
2. Complexity is an evolutionary process resulting from a selection of historico-cultural rules of behavior, practices, and institutions that are impossible to master conceptually.
3. A third consequence of complexity is that rules that govern social exchanges and communication are abstract and formal. Social self-organized complex systems are governed by civil rights guaranteed by public laws.

Cultural Evolution and Emerging Ethical Maxims

At the cognitive level, be it individual or social, according to Hayek, the rules governing perception and action, as well as of conventions and norms, are products of an *evolutionary* process. They result from a cultural selection—a collective learning—which is a competitive/cooperative process having favored the individuals and groups that applied them. They are like cultural

[23] Birner, 2016.

shortcuts enabling people to behave rapidly and adaptively without having to recapitulate every time all the experiences and beliefs necessary to action. For Hayek, *common-sense* is a library of tacit knowledge routines and practical schemes patterning our experience according to generic default schemes. It is necessary to act without being overwhelmed by the overflow of irrelevant information coming from the environment. For Hayek (as for Mandeville, Hume, or Ferguson), common sense norms are not repressive constraints but, on the contrary, cognitive achievements deeply adapted to the contingencies of life. Traditions express an "embodied knowledge" which is "phylogenetic" in the sense of cultural evolution, and it is therefore rational to comply with them "ontogenetically."

In much the same way as in evolutionary biology, phylogenetic a posteriori operates as ontogenetic a priori, common sense rules operate for the subjects as a priori frames. In this sense, we find in Hayek an evolutionary theory of the *self-transcendence* of behavioral rules. Like linguistic rules, they proceed from symbolic institutions whose origin is neither a rational omniscient intelligence nor a deliberative social contract. We see how Hayek articulates cognitive psychology (the "sensory order") with the sociology of complex spontaneous orders (the "catallaxy").

Of course, the very concept of cultural evolution is quite problematic. Defended by a zoologist such as Vero Copner Wynne-Edwards and many sociobiologists, but also strongly criticized and rejected by other biologists such as John Maynard Smith or George Williams, it was philosophically analyzed (and defended) by Elliott Sober and David Sloan Wilson as a case of *multi-level selection*. The latter posits that evolution can operate at many levels, the three main levels being gene selection, individual selection, and group selection. There can exist complex cooperative/competitive relations between the levels.

Group selection is quite well accepted by specialists of the eusociality in social insects—including Nowak, Tamita, and Wilson—beyond Hamilton's inclusive fitness (see above) and also by anthropologists who consider that social norms are the result of some group selection.

For Hayek, as for Popper, cultural evolution selects *groups* and not individuals, subjects having to comply with rules that maximize the collective performances of their group. Among others, Robert Nadeau and Paul Dumouchel have deeply investigated this point. We can emphasize again the fact that, in the case of social insects, biological Darwinian evolution has selected "good" *eusocial* rules of collective organization; that is, efficient group rules.

However, regardless of the answer to this question, what is sure is that the subjects themselves cannot understand in what *operational* sense norms of just conduct can be socially fruitful because they encode a "phylogenetic" historical evolution. These norms are not "moral" in the traditional sense. That's why subjects interpret them as *duties*. We must emphasize the originality of this conception:

1. As individuals cannot understand the pragmatic efficacy of norms, they accept them for *deontic* reasons. We recognize here a thesis we find also in Kantian ethics in the *Critique of Practical Reason.*
2. However, norms being socially useful, we recognize also a *utilitarian* conception of ethics (Jeremy Bentham, John Stuart Mill). The main difference is that the "computation" of moral maxims and actions is cognitively inaccessible to individuals.

Therefore, according to Hayek, cultural evolution implies that maxims of action can act for individuals as transcendent "categorical" imperatives[24] while they are at the same time immanent "hypothetical" (pragmatic) imperatives for cultures.[25] For cultures, maxims are caused by the viability of a social order from which individuals gain much. As was emphasized by John Gray, Hayekian utilitarianism is *indirect* and exemplifies the general evolutionary principle (Haeckel's law) according to which phylogenetic a posteriori operates ontogenetically as a priori. Hayek was able to reconcile, from within a sort of CMI loop (i) individual actions, axiological rationality, values, and (ii) social norms resulting from group selection and cultural evolution and prescribing rules and maxims to individuals.

It is interesting to highlight how Hayek succeeded in renewing the notion of the categorical imperative as a *deontological* (non-consequentialist) conception of actions. According to deontological theses, actions must be evaluated in a principled way, independently of their consequences, while according to consequentialist theses they must be evaluated on the basis of a computation of the costs and benefits of their consequences. But as that kind of computation is intractable for a finite and limited rational mind, it is performed by cultural evolution. As was emphasized by Jean-Pierre Dupuy, cultural evolution is "utilitarian" but bears on "deontological" maxims that can be interpreted in accordance with a test of "categoricity."

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[24] For Kant, a normative judgement is "categorical" when it is independent of any end. Categorical prescriptions are purely "procedural".

[25] For Kant, a normative judgement is "hypothetical" when it is conditioned by an end and prescribes means to achieve the end (consequentialism).

References

Amit, D. (1989). *Modeling Brain Function: The World of Attractor Neural Networks.* Cambridge: Cambridge University Press.

Andler, D. (2016). *La silhouette de l'humain. Quelle place pour le naturalisme dans le monde d'aujourd'hui ?* Paris: Essai NRF-Gallimard.

Axelrod, R., Cohen, M., Riolo, R. (1998). The Emergence of Social Organization in the Prisoner's Dilemma: How Context Preservation and Other Factors Promote Cooperation. *Santa Fe Institute Working Paper*, 99-01-002.

Bak, P., Tang, C., Wiesenfeld, K. (1987). Self-Organized Criticality: An Explanation of the $1/f$ Noise. *Physical Review Letters,* 59, pp. 381–384.

Barabási, A.L., Albert, R. (1999). Emergence of Scaling in Random Networks. *Science*, 286/5439, pp. 509–512. arXiv:cond-mat/9910332

Binmore, K. (1994). *Playing Fair*. Cambridge: MIT Press.

Birner, J. (2016). Metaphysical Models of Man in Economics. *Cosmos and Taxis*, 3/2–3, pp. 78–93.

Boltzmann, L. (1872). Weitere Studien über das Wärmegleichgewicht unter Gasmolekülen. *Wiener Berichte*, 66, pp. 275–370.

Bonabeau, E., Theraulaz, G., Deneubourg, J.-L., et al. (1998). A Model for the Emergence of Pillars, Walls and Royal Chambers in Termite Nests. *Philosophical Transactions of the Royal Society of London, B*, 353, pp. 1561–1576.

Boudon R. (1986). *Theories of Social Change: A Critical Appraisal*. Cambridge: Polity Press.

Bressloff, P., Cowan, J., Golubitsky, M., Thomas, P., Wiener, M. (2001). Geometric Visual Hallucinations, Euclidean Symmetry and the Functional Architecture of Striate Cortex. *Philosophical Transactions of the Royal Society of London B*, 356, pp. 299–330.

Bulle, N., Phan, D. (2017). Can Analytical Sociology Do Without Methodological Individualism. *Philosophy of the Social Sciences*, 47/6, pp. 379–409.

Chaté, H., Ginelli, F., Grégoire, G., Raynaud, F. (2008). Collective Motion of Self-Propelled Particles Interacting Without Cohesion. *Physical Review*, E 77, p. 046113.

Chavalarias, D. (2020). From Inert Matter to the Global Society—Life as Multi-Level Networks of Processes. *Philosophical Transactions of the Royal Society* B, 375/1796.

Coleman, J.S. (1987). Microfoundations and Macrosocial Behavior. In J. Alexander, B. Giesen, R. Münch, and N. Smelser (Eds.), *The Micro-Macro Link* (pp. 153–177). Berkeley/Los Angeles: University of California Press.

Di Iorio, F. (2015). *Cognitive Autonomy and Methodological Individualism: The Interpretative Foundations of Social Life*. Cham: Springer.

Di Iorio, F. (2016). Introduction: Methodological Individualism, Structural Constraints, and Social Complexity. *Studies in Emergent Order and Organization, Cosmos and Taxis*, 3/2–3, pp. 1–8.

Di Iorio F., Chen S.-H. (2019). On the Connection Between Agent-Based Simulation and Methodological Individualism. *Social Science Information*, 58/2, pp. 354–376.

Douady, S., Hersen, P. (2011). Dunes, the Collective Behavior of Wind and Sand. In P. Bourgine and A. Lesne (Eds.), *Morphogenesis*. Berlin-Heidelberg: Springer.

Dupuy, C., Torre, A. (1999). The Morphogenesis of Spatialized Cooperation Relations. *European Journal of Economic and Social Systems*, 13/1, pp. 59–70.

Dupuy, J.-P. (2000). *The Mechanization of Mind: On the Origins of Cognitive Science*. Princeton: Princeton University Press.

Dupuy, J.-P. (2004). Vers l'unité des sciences sociales autour de l'individualisme méthodologique complexe. *Revue du MAUSS*, 24/2, pp. 310–328.

Dupuy, J.-P., Dumouchel, P. (Eds.). (1983). *L'auto-organisation: de la physique au politique*. Colloque du Centre Culturel International de Cerisy-la-Salle 1981. Paris: Éditions du Seuil (reprinted by Hermann, Paris, 2022).

Faccarello, G. (2006). La liberté du commerce et la naissance de l'idée de marché comme lien social. In P. Nemo and J. Petitot (Eds.). *Histoire du libéralisme en Europe* (pp. 205–253). Paris: Presses Universitaires de France.

Ferguson, A. (1767/1996). *An Essay on the History of Civil Society*. Cambridge: Cambridge University Press.

Gibbs, J.W. (1902). *Elementary Principles in Statistical Mechanics*. New York: Charles Scribner's Sons/London: Edward Arnold.

Gordon, D.M. (2010). *Ant Encounters. Interaction Networks and Colony Behavior*. Princeton: Princeton University Press.

Grassé, P.P. (1959). La Reconstruction du nid et les coordinations interindividuelles chez Bellicositermes natalensis et Cubitermes Sp.; la théorie de la stigmergie. *Insectes Sociaux*, VI/1. Paris: Masson.

Hamilton, W. (1964). The Genetical Evolution of Social Behaviour. I&II. *Journal of Theoretical Biology*, 7/1, pp. 1–16 and 17–52.

Hayek, F. (1952). *The Sensory Order*. London: Routledge & Kegan Paul.

Hayek, F. (1974). The Sensory Order After 25 Years. In W.B. Weimer and D.S. Palermo (Eds.), *Cognition and the Symbolic Processes*, Vol. 2, pp. 287–293. Hillsdale, NJ: Erlbaum.

Hayek, F. (1978) *New Studies in Philosophy, Politics, Economics and the History of Ideas*. Chicago: University of Chicago Press.

Heider, F., Simmel, M. (1944). An Experimental Study of Apparent Behavior. *American Journal of Psychology*, 57, pp. 243–259.

Hodgson, G. (1986). Behind Methodological Individualism. *Cambridge Journal of Economics*, 10, pp. 211–224.

Hölldobler, B., Wilson, E. (1990). *The Ants*. Cambridge, MA: Harvard University Press.

Jaynes, E.T. (1957). Information Theory and Statistical Mechanics. *Physical Review*, 106/4, pp. 620–630.

Kant, E. (1784). *Idee zu einer allgemeinen Geschichte in weltbürgerlicher Absicht*. Engl. Transl. (1991) *Idea for a Universal History with a Cosmopolitan Purpose*. Cambridge: Cambridge University Press.

Landau, L., Lifshitz, E. (1967). *Physique statistique*. Moscow: Mir. Engloish Edition: (1958) Pergamon Press.

Laurent, A. (2006). *L'individualisme méthodologique*. Paris: Presses Universitaires de France.

Leroux, A., Nadeau, R. (Eds.). (2000). Friedrich Hayek et la philosophie économique (special issue). *Revue de Philosophie économique*, 2.

Mandeville, B. (1705/1714 [1957]). *The Fable of the Bees: Or, Private Vices, Public Benefits*. F. B. Kaye, ed. Oxford: Clarendon.

Manzo, G. (2020). Agent-Based Models and Methodological Individualism: Are They Fundamentally Linked? *L'Année sociologique*, 70/1, pp. 197–229.

Nadeau, R. (1998). L'évolutionnisme économique de Friedrich Hayek. *Philosophiques*, XXV/2, pp. 257–279.

Nemo P. (1998). *La société de droit selon F.A. Hayek*. Paris: Presses Universitaires de France.

Nemo, P., Petitot, J. (Eds.). (2000). *Histoire du libéralisme en Europe*. Paris: Presses Universitaires de France, 2006. Italian translation by F. Di Iorio, Rubbettino, Soveria Mannelli, 2012.

Nicole, P. (1671/1999/2016). *Essais de Morale, contenus en divers traités sur plusieurs devoirs importans*, 1671. Paris: Presses Universitaires de France (1999). Paris: Les Belles Lettres (2016).

Nowak, M., Tarnita, C., Wilson, E. (2010). The Evolution of Eusociality. *Nature*, 466, pp. 1057–1062.

Petitot, J. (1982). *Introduction aux phénomènes critiques*. http://jeanpetitot.com/ArticlesPDF/Petitot_CritPh.pdf.

Petitot, J. (2006). Modèles formels de la 'main invisible': de Hayek à la théorie des jeux évolutionniste. In P. Nemo and J. Petitot (Eds.), *Histoire du libéralisme en Europe* (pp. 1095–1114). Paris: Presses Universitaires de France.

Petitot, J. (2008). *Neurogéométrie de la vision. Modèles mathématiques et physiques des architectures fonctionnelles*. Paris: Les Editions de l'Ecole Polytechnique.

Petitot, J. (2010). Reduction and Emergence in Complex Systems. In R.E. Lee (Ed.), *Questioning Nineteenth-Century Assumptions about Knowledge, II Reductionism.* NY: SUNY Series.

Petitot, J. (2014). Landmarks for Neurogeometry. In G. Citti and A. Sarti (Eds.), *Neuromathematics of Vision* (pp. 1–85). Berlin, Heidelberg: Springer.

Petitot, J. (2016). Complex Methodological Individualism. *Cosmos and Taxis*, 3/2–3, pp. 27–37.

Poundstone, W. (1993). *Prisoner's Dilemma*. Oxford: Oxford University Press.

Rumelhart, D.E., McClelland, J.L. (1986). *Parallel Distributed Processing: Exploration in the MicroStructure of Cognition*. Cambridge: MIT Press.

Saint-Raymond, L. (2009). *Hydrodynamic Limits of the Boltzmann Equation*. Lecture Notes in Mathematics. Berlin: Springer-Verlag.

Samuelson, L. (1997). *Evolutionnary Games and Equilibrium Selection.* Cambridge: MIT Press.

Sawyer, R. K. (2002). Nonreductive Individualism, I. *Philosophy of the Social Sciences*, 32/4, pp. 537–559.

Sawyer, R. K. (2002/2003). Nonreductive individualism, II. *Philosophy of the Social Sciences*, 33/2, pp. 203–224.

Searle, J.R. (1995). *The Construction of Social Reality*. London: Penguin.

Toulouse, G., Pfeuty, P. (1975). *Introduction au groupe de renormalisation et à ses applications*. Grenoble: Presses Universitaires de Grenoble.

Udehn, L. (2001). *Methodological Individualism: Background, History and Meaning*. London: Routledge.

Uffink, J., Valente, G. (2010). Time's Arrow and Lanford's Theorem. *Séminaire Poincaré (Institut Henri Poincaré, Paris)*, XV, 141–173.

Van der Waals, J.D. (1873). *Over de continuiteit van den gas en vloeistoftoestand*. Leinden: Sijthoff.

Vanberg, V. (1986). Spontaneous Market Order and Social Rules: A Critical Examination of F. A. Hayek's Theory of Cultural Evolution. *Economics and Philosophy*, 2, pp. 75–100.

Vicsek, T., Czirók, A., Ben-Jacob, E., Cohen, I., Shochet, O. (1995). Novel Type of Phase Transition in a System of Self-Driven Particles. *Physical Review Letters*, 75, p. 1226.

Watkins, J.W.N. (1952). The Principle of Methodological Individualism. *The British Journal for the Philosophy of Science*, 3/10, pp. 186–189.

Weibull, J. (1996). *Evolutionary Game Theory*. Cambridge: MIT Press.

Wilson, E. (2012). *The Social Conquest of Earth: Humans Are Eusocial Apes*. New York: Liveright.

Wilson, K., Kogut, I. (1974). The Renormalization Group and the ε Expansion. *Physics Reports*, 12/2, pp. 75–199.