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Stigmergic epistemology, stigmergic cognition

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Abstract

To know is to cognize, to cognize is to be a culturally bounded, rationality-bounded and environmentally located agent. Knowledge and cognition are thus dual aspects of human sociality. If social epistemology has the *formation, acquisition, mediation, transmission* and *dissemination* of knowledge in complex communities of knowers as its subject matter, then its third party character is essentially stigmergic. In its most generic formulation, stigmergy is the phenomenon of *indirect communication mediated by modifications of the environment*. Extending this notion one might conceive of social stigmergy as the extra-cranial analog of an artificial neural network providing *epistemic* structure. This paper recommends a stigmergic framework for social epistemology to account for the supposed tension between individual action, wants and beliefs and the social corpora. We also propose that the so-called ''extended mind'' thesis offers the requisite stigmergic cognitive analog to stigmergic knowledge. Stigmergy as a theory of interaction within complex systems theory is illustrated through an example that runs on a particle swarm optimization algorithm.

Keywords: Stigmergy; Social epistemology; Extended mind; Social cognition; Particle swarm optimization

1. Introduction

To know is to cognize, to cognize is to be a culturally bounded, rationality-bounded and environmentally located agent.[1] Knowledge and cognition are thus dual aspects of human sociality. If social epistemology has the formation, acquisition, mediation, transmission and dissemination of knowledge in complex communities of knowers as its subject matter, then its third party character is essentially stigmergic. In its most generic formulation, stigmergy is the phenomenon of indirect communication mediated by modifications of the environment. Extending this notion one might conceive of stigmergy as the extra-cranial analog of artificial neural networks or the extended mind. With its emphasis on *coordination*, it acts as the binding agent for the epistemic and the cognitive. Coordination is, as David Kirsh (2006, p. 250) puts it, ''the glue of distributed cognition''. This paper, therefore, recommends a stigmergic framework for social epistemology to account for the supposed tension between individual action, wants and beliefs and the social corpora: paradoxes associated with complexity and unintended consequences. A corollary to stigmergic epistemology is stigmergic cognition, again running on the idea that *modifiable* environmental considerations need to be factored into cognitive abilities. In this sense, we take the extended mind thesis to be essentially stigmergic in character.

This paper proceeds as follows. In Section 2, we set out the formal specifications of stigmergy. In Section 3, we illustrate the essentially stigmergic characteristics of social

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[1] The first ''is'' denotes a necessary property of knowledge, namely that knowledge acquisition involves the deployment of some cognitive apparatus. The second ''is'' refers on the other hand to a contingent fact: to cognize is to be culturally-bounded (Thanks to Geoff Thomas for pressing us on this issue).

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epistemology. In Section 4, we examine extended mind externalism as the preeminent species of stigmergic cognition. In Section 5 we illustrate how the particle swarm optimization (PSO) algorithm for the optimization of a function could be understood as a useful tool for different processes of social cognition, ranging from the learning of publicly available knowledge by an individual knower, to the evolution of scientific knowledge. In Section 6, we offer some concluding remarks.

2. Characterizing stigmergy

The term stigmergy was coined by zoologist Grassé (1959) whose research concerned cellular structure, protistology and animal sociology, the latter of particular fascination. Grassé sought to understand the mechanisms underlying the emergence, regulation, and control of collective activities in social insects. Specifically, Grassé's research sought to address the so-called ''coordination paradox'': that is, how does one reconcile behavior at the individual level (given that individuals are constrained by knowledge and material resources) with the global/societal level of the termite colony. At first sight, behavior at the individual level appeared to be chaotic, which of course is at odds with the visibly impressive structures that only a highly organized colony of termites could achieve. What Grassé discovered in the coordination and regulation of termite colonies, is the phenomenon of *indirect communication mediated by modifications of the environment* – stigmergy.

Until Grassé, the two competing theories on offer mirrored the individualism–holism debate in social philosophy, discussion of which is deferred to the next section. One theorized that novel properties appeared at the level of the society with its own nomological and causal system: the ''whole'' explains the behavior of the parts. The competing theory treats each individual insect as if it were operating completely alone. Any ascription of collective behavior or division of labor was deemed illusory. Biologist Etienne Rabaud laid the conceptual ground for Grassé by introducing two concepts:

1. Interaction.
2. Interattraction.

The former is the claim that individual behavior is essential to collective action. Creatures in close proximity to one another must have a reciprocal modifying behavior. The latter denotes the idea that creatures of the same species have a mutual attraction (for a detailed history of stigmergy in an entomological context, see Theraulaz & Bonabeau, 1999). Expanding upon Rabaud, Grassé took the view that sociality cannot merely be the result of interaction or interattraction as the individualist would have it. Collective behavior must also play a *reciprocal role in modifying* behavior, an insight he gleaned from his study of termite building behavior. Grassé observed that the coordination and regulation of building activities did not depend on the individual ''agents'' themselves but is informed by the structure of the nest. Pheromone traces left by others and modifications made by others have a cybernetic feedback. In other words, the environment acts a kind of distributed memory system.

Different theorists have proffered different varieties of stigmergy. Wilson (1975/2000, pp. 186–188) identifies two main variants:

- Sematectonic stigmergy.
- Sign-, cue-, or marker-based stigmergy.

Sematectonic stigmergy denotes communication via modification of a *physical* environment, an elementary example being the carving out of trails. One needs only to cast an eye around any public space, a park or a college quadrangle for instance, to see the grass being worn away, revealing a dirt pathway that is a well-traveled, unplanned and thus indicates an ''unofficial'' intimation of a shortcut to some salient destination.

Marker-based stigmergy denotes communication via a signaling mechanism (Engelbrecht, 2005; Kennedy, Eberhart, & Shi, 2001, p. 104). A standard example is the phenomenon of pheromones laid by social insects. Pheromone imbued trails increase the likelihood of other ants following the aforementioned trails. Unlike sematectonic stigmergy which is a response to an environmental *modification*, marker-based stigmergy *does not* make any direct contribution to a given task. This classification seems to be more or less coextensive with Holland and Melhuish's (1999) passive and active variant in that the former is informed by previous environmental modification (e.g. a vehicle obliged to follow the extant ruts in a muddied road); the latter, a positive intentional response to a given state of affairs. As Parunak (2005, p. 11) puts it sematectonic stigmergy is ''the current state to the solution'': by that we take him to mean that what confronts the agent at a given point is the accumulation of prior agent activity.

Theraulaz and Bonabeau (1999, pp. 104–105) talk of two classes of stigmergic mechanisms: *quantitative* and *qualitative*. With quantitative stigmergy, the stimulus-response comprises stimuli that do not differ qualitatively and only modify the *probability* of a response. So the stronger the pheromone trail, the larger the probability of a response. Qualitative stigmergy denotes the idea that individuals interact through, and respond to, qualitative stimuli, which in turn affects the behavior of those who follow – an ongoing iteration. To bring out this contrast better quantitative stigmergy would be the construction of pillars in termites' nests, the initial conditions being soil being infused with pheromone. In a qualitative stigmergic process, for example the construction of wasps' nests, a new cell is constructed to correspond with an existing cell (Camazine et al., 2003, p. 418).

In anticipation of extending the metaphor of stigmergy let's summarize the general features of a stigmergic system.

Following Parunak (2005), a stigmergic system displays characteristics, informally adduced as follows:

1. A global context or environment (that can be virtual)
   - Comprised by an indefinite number of local environments.
   - Only partially perceivable through an internal dynamics (e.g. in the case of viral marketing *communication*; in a network of hyperlinked documents, *the maintenance of indices*) that govern its temporal evolution.
2. Agents
   - There are a multiplicity of agents populating 1 with no one individual or clustering of individuals having global knowledge.
     - Rationality is bounded.
     - Behavior is self-organized.
       - Behavior is stochastic.
       - Behavior is adaptive/dynamical.

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3. *Novel* features arise from interactions of 1 and 2, features that are neither predictable nor reducible to simpler constituents.[2]

Though the concept of stigmergy has been associated with ant- or swarm-like "agents" with minimal cognitive ability or with creatures of a higher cognitive capacity such as fish (schooling patterns) or birds (flocking patterns) or sheep (herding behavior), stigmergy offers a powerful metaphor to be deployed in the human domain. Some might object to the extension of Grassé's insight to the human–human world (Shell & Mataric, 2003; Tummolini & Castelfranchi, 2007). We reject this contention on the grounds that Grassé's concept of stigmergy is a classic case of an essentially contested notion. By this we simply mean that different theorists stress different stands or elements in different contexts inspired by a paradigmatic application – in this case Grassé's concept filling this role. Even if one considers human activity as quasi-stigmergic, the kernel of the idea remains intact: that is, in Clark's words "the use of environmental conditions as instigators of action and the overall ability of the group to perform problem-solving activity that exceeds the knowledge and the computational scope of each individual member" (Clark, 1997, p. 234, note 9; see also Gureckis & Goldstone, 2006) or in Holland & Melhuish's words "All that is necessary for stigmergy to occur is for the *outcome* of the behavior of the relevant agent to be appropriately affected by previous environmental changes" (Holland & Melhuish, 1999, p. 174). Though this characterization is not dissimilar to distributed cognition broadly conceived, stigmergy distinctively relies on the cybernetic relationship of agent → environment → agent → environment through ongoing and mutual modification or conditioning: and it is this aspect that ensures that the concept of stigmergy has extensional adequacy (the set of features that identify the sort of things the concept applies to).

3. A *stigmergic* social epistemology

Social theory in its attempt to make sense of the individual-group equation has often taken inspiration from natural history. Though biological inspired political theory has long since been discredited, evolutionary biology and entomology has inspired a lively multidisciplinary field of research termed *biomimetics* (Grosan & Abraham, 2006, p. 16). Biomimetic inspired computational modeling has epistemology and adaptive intelligence as a central interest. To be sure, some social epistemologists are aware of the suggestiveness of foraging/optimization theory (Goldman, 1999, pp. 172–173).

Given the rather amorphous and diffuse nature of social epistemology its domain, approach, structure and value are highly contested. This is reflected in the two approaches that inform social epistemology: the *sociology of knowledge* tradition and the *classical analytical epistemology* tradition with its new-found interest in the social dimensions to knowledge. Implicit in the former is that all knowledge is social in character and hence this tradition has a non-normative flavor to it: the tripartite concepts of truth, justification, and rationality, the *sine qua non* of orthodox epistemology going back to Plato, appear to be committed to normative nihilism.[3] Indeed because of the downplaying or even dispensing of these concepts, some quarters within orthodox epistemology tend not even to recognize this project as epistemology. By the same token, many within the sociology of knowledge tradition consider the orthodox project as redundant and outmoded, unable to address the all pervasive role sociality has on human experience, its manifold practices and ultimately on knowledge and truth.

We have chosen to employ the distinction of *philosophical* social epistemology (PSE) to stand for the tradition variously known as "orthodox," "analytical," "classical" or "veritistic" social epistemology, and *sociological* social epistemology (SSE) to denote the sociological tradition. This is not to say that the latter is not or cannot be philosophical – it merely marks a difference in structural emphasis. While there is certainly a distinction to be drawn between PSE and SSE, the distinction is not as neat as many would like to believe: there are a bewildering number of cross-currents that feed into both variants of current social epistemology. Indeed, as we will

[2] Many (if not most) in the context of stigmergy use the term *emergent* features to denote *novel* features. We desist from using emergence as it is a highly slippery notion. Novel features might well be a function of theoretical impoverishment.

[3] Thanks to Michael Bishop for pointing out the difference between relativism and normative nihilism.

illustrate, both PSE and SSE have strong stigmergic concerns.

SSE, for instance Marxist-inspired explanations of human behavior, tends to be primarily immergent: to be under the influence of "false consciousness" is in essence to be subject to a distortive *mis*cognition. It should be noted that while individualism is typically associated with an anti-collectivist critique, some Marxist theorists such John Elster accept methodological individualism to counter a Marxist functionalism that posits a purpose without a purposive actor (Elster, 1982). Conversely, forms of holism are to be found in conservative social theory.

PSE, on the other hand, seeks to redress classical epistemology's myopia in giving some credence to the view that individual belief is *mediated* by a social context. In the complex term "social epistemology" does the element "social" denote a social aspect (the corollary being that there is a *non*-social aspect) *or* is all epistemology intrinsically social? How does one apportion the extent to which individuals' cognitive states are causally dependent upon their social milieu? These are the central questions that animate meta-discussion of social epistemology and indeed in the philosophy of mind, manifest in the discussion between narrow and broad content in cognitive science and the philosophy of mind (in social epistemology see Gilbert, 2004 and Tuomela, 2004; in cognitive science/mind see Clark, 1996, 1997, 2001, 2003; Clark & Chalmers, 1998; Wilson, 2004).

Given the vast vocabulary denoting the multiplicity of intermediary institutions that comprises a social system the question is whether all statements about social institutions can be reduced without remainder to statements referring purely to individuals and their interactions. Methodological Individualism (MI) is the label for the view that such replacement is possible. Social Holism (SH) denies this possibility. It posits the idea that novel features are neither predictable nor reducible to simpler constituents. A more interesting distinction is between groups that have mental properties which their individual members do not share and the corollary of whether individuals manifest certain properties *only* as a part of a group (Wilson, 2004, p. 281).

It is important to note that *emergence* (novel behavior emerging from a lower level specification of a system) and its corollary *immergence* (individual interaction informed by a global state of affairs)[4] are concepts that go hand-in-hand: stigmergically speaking, there is a perpetual iterative looping (Kennedy et al., 2001, pp. 323–324; Gureckis & Goldstone, 2006). This iterative looping attenuates the PSE and SSE fault-line.

[4] To confuse the issue, immergence has been used to denote emergence (Castelfranchi, 2006, p. 373).

If PSE has the formation, acquisition, mediation, transmission and dissemination of (for the most part third party) knowledge in complex communities of knowers as its subject matter, then to say that its concern is essentially stigmergic, verges on being tautologous. Our argument, informally adduced, is that:

1. social systems are complex systems;
2. most knowledge is mediated though third parties;
3. social epistemology is concerned with complex social systems;
4. complex social systems are stigmergic;

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5. social epistemology is stigmergic.[5]

It is hardly contentious to make the claim that most of the knowledge we as individuals possess, is second-hand or emanates from some third party. This fact alone is not of concern – what is a critical concern is assessing the *veritistic* inducing merit of the formation, acquisition, mediation, transmission and dissemination of knowledge as mediated through the social network and its constituent nodal gatekeepers. This is implicit in three prominent areas of overlapping interest to PSE – testimony-based belief; the market place of commodities; and the technology and economics of communication (Goldman, 1999). We consider each in turn.

3.1. Testimony

By testimony we denote a broad notion of expertise, trust and authority. Specifically, stigmergy addresses the *epidemiological* character of knowledge that informs the *degree* of expertise, the *degree* of trust and the *degree* of authority that animates social nodes and social networks.

First a little network theory. Newman (in press) outlines some standard *centrality* measures to assess networks. *Closeness* centrality and *betweenness* centrality run on the concept of network paths. A geodesic path is the shortest path between a pair of vertices, and the geodesic distance, the number of edges traversed along such a path. The closeness centrality of vertex i is the mean geodesic distance from vertex i to every other vertex. Closeness centrality is lower for vertices that are more central, i.e. have a shorter network distance on average to other vertices. The *between*-

[5] Strictly speaking, 5 does not follow from 3 and 4 together. In principle, the stigmergic character of complex systems that social epistemology aims to explain could not be reflected in the proposed explanations. This would amount to a reductive account of a stigmergic system. Although this possibility cannot be excluded, a cursory look at typical complex physical systems suggests that reductive accounts in terms of fundamental laws (e.g. at fine scales), although possible, cannot be said to provide an enlightening explanation of the observed behavior (e.g. at the large scale) (see Baas & Emmeche, 1997). The focus, when providing explanations, on the contrary is upon the identification of the patterns which characterize the observations. Our thanks to Roger Koppl for drawing our attention to this issue.

ness centrality of vertex *i* is the fraction of geodesic paths between other vertices that *i* falls on. Stigmergically speaking, it measures the extent to which a node is directly connected only to those other nodes that are *not directly* connected to each other. *Centrality measures* examine which agent or node has central influence within a given network. The simplest centrality measure is *degree centrality:* the degree of a vertex in a network is the number of edges attached to it – nodes with more connections tend to be more powerful. Degree centrality is illustrated by an example from drawn from Malcolm Gladwell's *The Tipping Point* (cited in Solomon, 2006a). Gladwell analyses why Paul Revere's ride and not William Dawes' ride in the Americal War of Independence (both carrying news of British troop movements), became associated with the state of events. On Gladwell's analysis Revere was a "connector" (a social node), and as such he knew who the "salesmen" were (who would be susceptible to propagate and in turn re-infect), but he also knew who the "Mavens" were (the first adopters). This phenomenon, epidemiological in character, has informed the recent notion of viral marketing. Like Sperber (1996) and Goldman (2001) we are skeptical about the *strict* replication of ideas as claimed by memetics: there do not appear to be any promising candidates to populate an ontology of cultural replication in an analogous way that there is in biology. The stigmergic interest lies in the stochastic spread of a marker through a population of strangers. The marketer's hope is that a strong pheromone trail will translate into heightened awareness of a given product, which in turn will convert into sales. Such strategies, if successful, are both financially and logistically highly efficient. Amazon's "recommendation" algorithm is probably the most well-known example of an epidemiological transmission – more on this in the next section.

Traditional information brokers like universities and scholarly journals can no longer keep themselves apprised of developments by the sheer volume of new knowledge and information. The question as to what constitutes qualitative content is a very live issue and has come into sharp focus in the controversy surrounding the accuracy of Wikipedia versus traditional sources such as *Encyclopaedia Britannica*[6] (see Goldman, 2002 on the novice/expert problem). As users of the internet will know, Wikipedia features prominently on a significantly large range of search queries. Wikipedia content is generated by volunteers who may or may not have any formal bona fides or expertise in a particular field or topic. It is not so much the distributed nature of knowledge that is cause for concern, but the *stigmergic aspect of enabling technologies* that has corroded traditional notions of intellectual authority. On the Web, expert opinion typically faces a barrage of skepticism with "alternative" or anecdotal evidence. Perhaps the most sinister development is that the stigmergic nature of the Web can promulgate a *distributed* culture of hate. Hate mongers of old stood some chance of being identified. Now sources of hate can exploit the epidemiological character of the Web – and in all probability, be immune from censure.

3.2. Market place of commodities

Market systems imply a "thick" sense of sociality. The notion of a market is not coextensive with a market as understood by a capitalistic system: though this variant does display the most powerful of stigmergical virtues, private ownership of the means of production is not a necessary feature of a market economy (a market can be a barter market, an illegal market, a free-market, or a command economy). There is, however, very good reason why economic liberalism, or the so-called free-market, is considered stigmergically superior to all other markets. The reasons are to be found in a complex tapestry of (metaphysical, moral, and political) freedoms or autonomy; a large topic that is beyond the immediate scope of this paper. Adam Smith's "invisible hand" metaphor (Smith, 1776/1904) used to denote the unintended emergent consequences of a multiplicity of individuals' actions, is stigmergic in all but name – *it's a theory of collaboration via self-interest*. Leaving aside Smith's theological speculations, the invisible hand metaphor runs on the twofold idea that (a) there need not be any intentional cooperation; and (b) actors need not even know of each others' existence. The stigmergic interest of markets can easily be read off:

- a market is a mechanism for the cooperation among strangers in a given environment;
- a market enables activity that has consequences for all its agents, despite the fact that few transactions ever directly take place *in*-person to *in*-person;
- the pheromone analog in a market system is common currency;[7]
- a market has epistemic (and computational) efficiencies in that knowledge is distributed and dynamic;
- a market displays emergent behavior, behavior that couldn't have been predicted.

Friedrich Hayek's "spontaneous order" (Hayek, 1948/1980) or "complexity" thesis (a direct descendent of Smith's metaphor) and a leitmotif across his work, argues that a socio-economic order in its complexity is not amenable to being centrally managed – knowledge is distributed across a multitude of agents and condenses in dynamic traditions, customs and practices. The complexity thesis is a skeptical position and argues that large-scale social planning can often be a leap of faith and thus a spurious claim to knowledge. Society is too complex, has too many

[6] http://www.nature.com/nature/britannica/index.html.

[7] A pheromone, in a manner of speaking, whereby one can "follow the money . . ."

variables, local and ephemeral, to offer a predictive science of politics and economics. It should be noted that this is not a blanket admonition against social change or social amelioration. The complexity thesis takes to task a global, often rationalistic style of thinking, that abstracts its recommendations from the minutiae of lived, contextualized experience.[8] Extant and spontaneous arising customs, practices and traditions are the sources of practical reasoning: to disregard them is to be irrational.

3.3. Technology and economics of communication

Enabled by the rise of computing technologies (and the democratization of technology), the possibilities and the scope of a stigmergic environment have exponentially increased – collaboration mediated and afforded by an environment – being the mark of stigmergy. To be sure, social cognition has always run on a symbiotic relationship between technology and communication. There seems to be some ambiguity as to whether a stigmergic mode of communication necessitates being *asynchronous*, or whether a *synchronous* mode could equally be stigmergic. *Synchronous* communication, being too ephemeral, has obvious limitations (Goldman, 1999, p. 162). Though asynchronous communication is the bedrock for the extended mind thesis (more on this in Section 4), Clark seems to allow that in certain contexts synchronous communication (or a hybrid of synchronous and asynchronous) can display stigmergic characteristics (Clark, 2001, p. 76). Let's consider a simple and pervasive example of an asynchronous mode of communication – a word processing document. Consider the *modus operandi* for joint authorship – an example being this article. It involves something like one author committing an idea to a document and having the co-author read, amend and add to a previous version and so on and so forth. The authors can track the changes either through conventional markup or using the "track changes" function in a Word document. Following Parunak (2005) let's tick off the stigmergic features that this simple example illustrates:

- There is an **environment** (the document)
  - That has a linear or hierarchical *topology*.
  - That has a *state* comprising both the body of the text and the marginalia.
  - That is *dynamic* – meaning is conveyed and mutually responded to
- There are **agents** (authors and editors)
  - *Sematectonic* and *marker-based actuators*
    - Sema: new content.
    - Marker: strike-outs, highlighting, etc.
  - *Dynamics* – the process of developing an idea.

By way of rounding off this section, we would be remiss if we did not mention the import of stigmergy to collective intentionality[9] – a topic that is of central interest to PSE. Collective intentionality or aggregation connects with the topic of stigmergy in that they are concerned with the question of whether intentional states can plausibly be attributed to an ontology populated by groups over and above an ontology of individual minds. Stigmergically speaking, it is Grassé's emphasis on the modifying effect of global behavior of the social corpora upon the individual agent, that gives rise to novel behavior that *might* be characterized "as an expression of jointly held consciousness" (Parunak, 2005, p. 8). Digital technology has profoundly enabled traditional stigmergic systems and expanded social networking to the point that new social ontologies are being forged. The traditional ontologies posited by political ideologies – liberalism's ontology of individuals and socialism's ontology of class – are being dissipated. But as most people are aware, there are websites devoted to a vast array of social permutations with incredibly narrow collecting features. So a supposed minority interest (a support group for a rare disease on the one hand, to the sexually perverse on the other hand) can, through the stigmergical opportunity afforded by the internet, coagulate into a significantly supported group. With these developments in mind, a stigmergic approach to collective intentionality could offer a powerful addition to the philosophical tool box.

4. Stigmergic cognition

The classic stigmergic themes of decentralization, situatedness, self-organization and environmental appropriation come together to inform a particular brand of externalism – extended mind or active externalism – a thesis that is as suggestive as it is controversial. Our interest here is not to offer a critical assessment of this brand of externalism but merely to suggest that as a theory of cognition, it has clear synergy with the concept of stigmergy: stigmergy on the extended mind account is a *dynamic* form of *scaffolded reason* intrinsic to an adaptive intelligence, an adaptive intelligence essential to negotiating and increasing long term prospects for survival within a given environment.

For the extended mind theorist the mark of advanced cognition depends upon our ability to diffuse propositional and practical knowledge or wisdom through external epistemic and cognitive structures (Chandrasekharan, Esfandiari, & Arthorne, 2004; Clark, 1997). Human intelligence has always been in a reciprocal coalition with the artifactual: *a causal integration that can take ontogenetic, phyloge-*

[8] Oakeshott (1962/1991, p. 26) famously took Hayek to task by pointing out that a doctrinal *laissez-faire* attitude is also a species of rationalism. This is uncritically taken as a knock-down argument by Oakeshott commentators. Hayek explicity and repeatedly distanced himself radical libertarianism as early as 1944 (Hayek, 1944/1976, pp. 17, 35, 36, 39, 42, 81).

[9] This has already been marked by Susi and Ziemke (2001) and more recently by Ricci, Omicini, Viroli, Gardelli, and Oliva (2007).

netic, individual, collective, cultural, or biological forms (Clark, 2003; Clark & Chalmers, 1998; Wilson, in press, p. 14; Sun, 2006, p. 13; Sterelny, 2004, p. 241). Indeed, the perpetual and intense cybernetic impact of the artifactual world upon the brain has outstripped any adaptive alteration of the genetic code (Wexler, 2006, p. 4).

Our representative extended mind externalist is Andy Clark for it is in Clark's work that stigmergy plays a leading role in his case for externalism (Clark, 1996, 1997, 2001, 2003). The notion of stigmergy particularly appeals to Clark's non-Cartesian sensibilities in that stigmergy emphasizes the distributed nature of knowledge and cognition; and the environmental appropriation whereby cognitive processes extend into the world utilizing a range of objects to offload the epistemic burden with a reciprocal and cybernetic relation between our conceptual creativity and the environment, to intimate, regulate and inform concepts and action. Clark takes inspiration from Edwin Hutchins's *Cognition in the Wild* where he explicates the distributed cognition of maritime navigation and which Clark takes to be "a kind of stigmergic procedure" (Clark, 1997, p. 76). It is stigmergic on the grounds that no one crew member has global knowledge – there is no rationalistic master plan or blue-print; much of the navigational calculation is reliant on artifacts; and the iterated looping of behaviors within and through the environment. More specifically, Clark invokes Amazon.com's Collaborative Filtering (CF) technique and Google's PageRank (PR) algorithm to make the point that just like stigmergy of slugs and ants, humans also lay tails, albeit digital trails, trails that can be tracked, analyzed and agglomerated.

Recommendation algorithms generally come in two varieties – collaborative filtering (CF) and cluster models (CM). CF attempts to mimic the process of "word-of-mouth" by which people recommend products or services to one another. CF runs on the notion that people who agreed in the past will agree in the future. CF aggregates ratings of items to recognize similarities between users, and generates a new recommendation of an item by weighting the ratings of similar users for the same item. But this technique is computationally expensive because "the average customer vector is extremely sparse" (Linden, Smith, & York, 2003, p. 77). By contrast CM divides the agent base into segments, treating the task as a *classificatory* problem. An agent is assigned a category comprised of similar agent profiles. Only then are recommendations generated. CM is computationally efficient since it only searches segments, rather than the complete database.

Amazon.com's recommendation algorithm is a derivative form of CF and CM. Consider an example. A search on Amazon for "stigmergy" returns 176 items, the default sort being by relevance (as opposed to price, reviews, publication date). Also given some prominence is a category "Customers who bought items in your Recent History also bought *x*, *y*, *z* ...." supplemented by Listmania, lists of salient material compiled by agents (all-comers as in Wikipedia) who ostensibly have some intimacy with the topic. There are also so-called "reviews" of a given title. All this over and above a record of my recent purchases which included stigmergy related material, assuming one hasn't expunged Amazon's cookies from one's browser. Even on offer is the opportunity, for many titles, to peruse the contents page, read an excerpt and even be enticed by the dust-jacket hyperbole. Furthermore, one can be alerted by email when a new title or new edition of a book matching one's previous trails of interest, will become available: a preorder entitling the buyer to a discount. This all adds up to a highly bespoke experience that is better tailored than being in a bookstore, because it is unlikely the bookstore even stocks a title *you have yet to discover* as one scans the shelves – there is no "pheromone" trail. The Amazon algorithm rather than matching user-to-user finds items that customers tend to purchase together. It is computationally efficient (and easily scalable) because much of the computation has already been done off-line. The stigmergic interest of Amazon's algorithm is patently clear: an *item-to-item* search generates a trail that gives rise to novel patterns of behavior. CF's great virtue is that suppliers can be finely attuned to consumer behavior. The downside is that there runs the risk of "a kind of dysfunctional communal narrowing of attention" that can be self-fulfilling (Clark, 2003, p. 158; Gureckis & Goldstone, 2006, p. 296).

The second prominent swarm-like example discussed by Clark is that of Google. Google's search algorithm is a refinement of degree centrality, namely *eigenvector* centrality, where degree centrality is something we touched upon in the last section when discussing testimony, trust and authority. Eigenvector centrality gives credence to the idea that not all connections should be equally weighted. Google's PageRank (PR) is a star example of eigenvector centrality, and is a direct descendant of the citation system used in traditional librarian science, the most familiar being journal rankings. The more citations *other* documents make to a particular document, the more "important" a given document is and the more status accorded to a journal through aggregation techniques. In much the same way, Google's PR algorithm assesses the importance or relevance of a Web page. Search engines are, as Christophe Heintz puts it, "reputation systems" (Eigen*Trust* algorithms) in that they ostensibly promote epistemic and cognitive worth (Heintz, 2006). PR's power lies in its ability to solve an equation with over 500 million variables and 2 billion terms. Its simplicity lies in its assessing a page's importance by counting back-links as a traditional technique of library science objectivity. Brin and Page (1997) explicate Google's PR as follows:

> We assume page A has pages $T1, \ldots, Tn$ which point to it (i.e., are citations). The parameter d is a damping factor which can be set between 0 and 1. We usually set d to 0.85, ..., $C(A)$ is defined as the number of links going out of page A. The PageRank of a page A is given as follows:

$$\mathrm{PR}(A) = (1-d) + d(\mathrm{PR}(T1)/C(T1) + \cdots + \mathrm{PR}(Tn)/C(Tn))$$

PR(A) is a probability indicating the importance of page A, as measured by the likelihood of a user opening this page. A user may open this page without having been led there directly by another web-page, i.e. on grounds which are for our purposes random, insofar as they are external to the web: a probability $1 - d$ is assigned to this possibility. If, on the other hand, we are dealing with someone who is surfing the web, it is through links from other pages that he will arrive at page A. For any page T_i which has a link to page A, if there are $C(T_i)$ links on that page, it is reasonable to assume on average that the surfer will have a probability $1/C(T_i)$ of choosing any one link, and therefore in particular, of choosing the link to page A. The probability of getting to A via T_i is the probability of the composite event of first, getting to T_i, and then moving from T_i to A. On the reasonable assumption of independence of these two moves, this probability is therefore the product of the probability of first moving to T_i, i.e. PR(T_i), and of later moving from T_i to A, i.e. $1/C(T_i)$. Assuming there are n pages with links to A, we must therefore sum these probabilities. Finally this sum is weighted by $1 - d$, the probability of it being through links from another page that the user arrives at page A, i.e. by surfing the web. PR thus defines a simple random walk which is modeled by a Markov chain (Ding et al., 2005). Popularity (the pheromone) is the mark of significance but of course does not guarantee quality or relevance: but "perhaps *others* know something I don't."

One might conceive of the complex social web of human sociality as the extra-cranial analog of neural networks (Clark, 2001, p. 141; Heylighen, 2007) or as Overwalle (forthcoming) and Overwalle and Heylighen (2006) have termed it, *social connectionism* [10] and is fully consonant with Clark and Chalmers' (1998) canonical formulation of the extended mind thesis.

The idea is this. In much the same way that synapses are strengthened while unused connections weaken and wither away ("neural Darwinism" – Edelman 1987), so too are the social connections between social nodes – the hypertext links in Google's PR being an example. For us, the idea of an extra-cranial analog to neural networks takes inspiration from Hayek's philosophical psychology (who along with Donald Hebb's *The Organization of Behavior: A Neuropsychological Theory* a few years earlier) anticipated the connectionist paradigm (Hayek, 1952/1976). Hebbian theory is of course well-known within cognitive science. Hayek's much neglected work should be of particular interest because, as Barry Smith points out (Smith, 1997), Hayek distinctively made the dynamicism of complex systems the touchstone for his philosophical psychology as well as within his social philosophy in general and his philosophy of economics in particular.[11] Butos and Koppl (2007, p. 42) offer the best explication of the epistemological concerns that motivated Hayek across the two domains of the catallactic and the cognitive:

> [T]he implicit story contained in *The Sensory Order* is that individuals are not mere processors of information, passively responding to stimuli. Instead, Hayek teaches us that cognitive activity, despite being constrained by rules and its own physiology, should be understood as an active, input-transforming, knowledge-generating adaptive system. The cognitive problem Hayek deals with is not about how knowledge is harvested or discovered, but with the process of its generation. While Hayek's treatment of the knowledge problem in the catallactic domain clearly emphasized the discovery and use of decentralized knowledge, his treatment of knowledge in his cognitive work should be seen as an account of its generation. The intriguing question that *The Sensory Order* raises is whether its insights can be applied to the social domain.

From our perspective, the answer to this question is a resounding "yes": this is precisely the case we are making in this paper. Butos and Koppl (2007, p. 43) go on to say:

> Within the social realm, complex routines and feedback mechanisms require us to see such orders as not simply aggregations of agents and their capacities, but as involving a transformation of individual knowledge into a unique kind of social knowledge that could not have been otherwise produced. One way to state this is to observe that only the market order can generate market prices. This points to a different approach in understanding the role and implications of different institutional arrangements, but it is an approach very much in keeping with insights gleaned from Hayek's cognitive theory.

The sentiments expressed in these two excerpts jointly and severally articulate a stigmergic conception of social cognition. For social theorists such as Stephen Turner, connectionism is the only plausible model currently on offer that can accommodate the dynamic tacit dimension to the acquisition and perpetuation of social knowledge – perhaps comprising the greater part of knowledge that includes *habitus*, skills, *mores*, traditions, "forms of life," practices and so on. Turner makes the *stigmergical* (and extended mind) point that that whatever a tradition is, by definition, it cannot reside solely within an individual – there is no direct brain-to-brain/mind-to-mind memetic transmission – continuity can only be *mediated* albeit *imperfectly* through a web of social artifacts (Turner, 2003, p. 3, 11).

[10] Notions of the extended mind enjoy currency both in academic and popular literature: the "global brain," "smart mobs," "wisdom of crowds," "common wisdom," and so on – metaphors that seem to trade either upon an utopian hell (Heylighen, 2002) or a *laissez-faire* world underwritten by an uncritical techno-ebullience (Solomon, 2006a).

[11] Credit to Hayek has been apportioned by two prominent neuroscientists, Edelman (1987, p. 25) and Fuster (1995, p. 87).

5. Modeling stigmergy

Particle Swarm Optimization (PSO) is a social algorithm proposed by Kennedy et al., 2001, and runs on a socio-cognitive model of social influence and learning embodying the three standard social principles; the ability to evaluate, compare, and imitate. Kennedy and Eberhart's work is attractive in that they reject the cognitivist view of mind and its emphasis on symbolic representation, rule manipulation and modification – a view fully in tune with what we have termed the **DEEDS** literature (a loose and internally fluid philosophical and empirical coalition comprising the ***D***ynamical-, ***E***mbodied-, ***E***xtended-, ***D***istributed-, and ***S***ituated- approaches to knowledge and cognition.) Kennedy and Eberhart are of the view that human intelligence results from social interaction and therefore culture and cognition are inseparable manifestations of human sociality. Note: the "particle" component in PSO denotes an individual and the "swarm" in PSO denotes a process or grouping.

In the following we shall examine how the PSO algorithm for the optimization of a function can be understood, at least schematically, as a useful tool for different processes of social cognition, ranging from the learning of publicly available knowledge by an individual knower, to the evolution of scientific knowledge. This will provide the outline of an approach that will be implemented in further work.

5.1. Explaining the SWARM algorithm

Consider a group of n blind individuals randomly parachuted in a landscape at time 0. The group has the task of finding the lowest point in the landscape. Every minute (i.e. at time t), each individual i moves $k_i(t)$ steps in a given direction (e.g. specified by the angle $\alpha_i(t)$ to the East-West direction). In other words, at time t, each individual moves along a certain vector $\mathbf{v_i(t)}$ (see Fig. 1). All individuals communicate with one another, and have instruments indicating their height above sea-level at the end of each minute. The PSO algorithm is a model for the way in which each individual in the landscape develops a strategy to achieve the goal of identifying the lowest point. At the heart of the algorithm lies the idea that the individual will move so as to account for both the lowest point he has reached so far, and the lowest point achieved by the group (including himself) so far. So-called *acceleration constants* $c_{\text{ind}}(t)$ and $c_{\text{group}}(t)$ determine the weights to be put on a move towards one's own best position and the group best position respectively. When $c_{\text{ind}}(t)> 0$ and $c_{\text{group}}(t) = 0$, the individuals progress completely independently, drawing no benefit from the findings of the rest of the group. This would amount to a situation in which the relevant knowledge has no social component. On the contrary, when $c_{\text{ind}}(t) = 0$ and $c_{\text{group}}(t) > 0$, each individual only takes into account the group best, so that the information acquired by the individual along the way is discarded as long as it does not define the group best position. This amounts to equating the relevant knowledge with its social dimension.

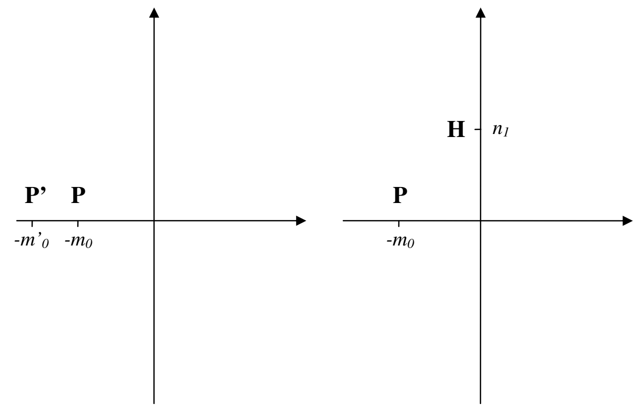

Fig. 1. Mapping scientific theories onto parameter space.

As Engelbrecht (2005, p.120) points out, the ideal weighting is obtained for when $c_{\text{ind}}(t) \approx c_{\text{group}}(t)$. Note that in the optimization process, some randomization is added to the iterative procedure described above, to enable a certain flexibility in the actual weightings which are ascribed to the individual and group components of the information acquired so far. This also has the advantage of more realistically mimicking the way in which actual strategies manage the relative weights of individual and group knowledge, i.e. generally in a non-totally deterministic way, but rather with some random variability. Thus, if $y_{ij}(t)$ represents the component in the jth dimension (in our example there are only two dimensions, i.e. the Northing and Easting) of the best position achieved so far by individual i, and $\hat{y}_j(t)$ the component in the jth dimension of the group best position so far, and if $x_{ij}(t)$ is the actual position in the jth dimension of individual i, the move to the next position $x_{ij}(t+1)$ is defined by:

- an "individual component" which is proportional to the discrepancy between the individual best and the current position, with a coefficient of proportionality $c_{\text{ind}}(t)r_{\text{ind},j}(t)$, i.e. the weight $c_{\text{ind}}(t)$ but randomly perturbed by $r_{\text{ind},j}(t)$ (which is uniformly distributed between 0 and 1);
- a "group component" which is similarly proportion to the discrepancy between the group best and the current position, with a coefficient of proportionality $c_{\text{group}}(t)r_{\text{group},j}(t)$, i.e. the weight $c_{\text{group}}(t)$ but randomly perturbed by $r_{\text{group},j}(t)$ (which is uniformly distributed between 0 and 1).

This approach to optimization is inherently stygmergic in that each individual contributes to the evolution of collective knowledge, which in turn impacts upon the individual.[12] Insofar as it relies upon the transmission of

[12] This approach resembles that of evolutionary algorithms (Fogel, Bäck, & Michalewicz, 2000) in that it involves looking at a population of individuals. However, the Particle Swarm Optimisation (PSO) algorithm comprises a representation of the way cognition is transmitted and aggregated in groups. Evolutionary algorithms rely rather upon the survival of fit individuals, so that the information is transmitted genetically.

information and its constitution into knowledge, the PSO would therefore seem particularly well suited to the representation of the way in which a body of knowledge is constituted. We shall now show how the process of knowledge acquisition can be represented by such an optimization algorithm.

5.2. Applying PSO to cognition

To show how the PSO can be applied to this process, we first need to give an example of how competing theories could define a parameter space. Take the current form of the heliocentric versus geocentric models of planetary motion. Assign one dimension to each planet (starting with the Sun and the Earth, respectively), and the value of the function in each dimension is a number defined in the following way:

– its integral part is the number of circular or elliptical orbits required to describe the motion of the planet in that dimension: this number is 0 if the planet does not move, 1 if it is described by a single orbit, and more if epicycles are required;
– its decimal part is 5 if elliptical orbits are used (i.e. if not all orbits are perfect circles), 0 otherwise;
– it is a positive number if the rotation is around the Sun, and negative if it is around the Earth.

Note that this coding differentiates between types of theories, but obviously does not encapsulate all the parameters describing the model, e.g. the orbit sizes. Our contemporary heliocentric system is thus represented by (0, 1.5, 1.5, ...). Copernicus's heliocentric system made use of circles and required epicycles, so it would have been of the form $(0, n_1, n_2, \ldots)$. The Ptolemaic system involved epicycles (in fact fewer than Copernicus) but a rotation around the Earth, i.e. $(-m_0, 0, -m_2, -m_3, \ldots)$. Tycho Brahe's system had the Earth at the centre, and the Sun orbiting around it while all other planets orbited around the Sun, i.e. $(-p_0, 0, p_2, p_3, \ldots)$. The function f to be minimized must represent the *goodness-of-fit of the theory to the observations*, and this maybe taken to be the biggest deviation (in absolute value) between observations and the theoretical predictions (or some weighted sum of squares thereof). With this in place, finding a theory that is most appropriate given a set of observational data amounts to moving around this parameter space to the point which yields the lowest value of f.

It is important to note here that when more observations become available, f changes, so that the process of finding the optimum is never ending, just like that of providing positive evidence for a theory. In the case of the competing systems just mentioned, we note that Copernicus and Ptolemy's system both correspond to optima of f given the observational data available when Copernicus developed his model. This was however to change later with Tycho Brahe's observations, and his model looked the most promising one before circular orbits were finally abandoned for elliptical ones.

This is just is a sketch of how rival theories can be mapped onto a parameter space. With this in place, the development of scientific knowledge can be represented by having individuals (actual scientists or theories) pursuing their own research while being aware of the existing science of the day. Typically, one of two situations will arise as to the weightings that are put by each individual on his own minimal value for f (recall that the minimum for f represents the theory that best fits the data) and the scientific community's best. In the first case, new data are analyzed with the existing theory and, either the optimum remains the same, i.e. the theory is unchanged, or some small revision of it is required, i.e. some fine tuning. Thus, with new observational data, about further planets, the Ptolemaic system could be revised with additional epicycles for the planets already accounted for by the original system.[13] That is, the optimum would change from $(-m_0, 0, -m_2, -m_3, \ldots)$ to $(-m'_0, 0, -m'_2, -m'_3, \ldots)$.

In the second case, a move to a different region of parameter space would occur if a new theory were considered. Thus, the heliocentric system may be seen as such a departure, taking us from $(-m_0, 0, -m_2, -m_3, \ldots)$ to $(0, n_1, n_2, \ldots)$. The difference between these two cases can be illustrated by looking at them in the first two dimensions (Sun and Earth). Fig. 1 illustrates the move from the original to a more elaborate Ptolemaic system on the left (P–P') and from the original Ptolemaic to a heliocentric system (P–H) on the right.[14]

These two cases capture what Kuhn understood as the normal as opposed to the revolutionary progress of science (Kuhn, 1962/1996).

5.3. What specific adjustments of PSO will achieve this?

Some changes in the original PSO algorithm are required to allow for the historical progress of science to be represented in the way suggested above. First, and most importantly, all individuals (scientists or theories) are not present at the start. As history progresses, new such individuals appear on the scene and will explore new regions of parameter space.[15] Second, as already noted, the function to be minimized will change over time, as new observational data become available. Third, the issue arises

[13] Such a revision would also involve the inclusion of extra dimensions to the existing parameter space, i.e. dimensions corresponding to the new planets.

[14] A suitable norm can be chosen in this metric space to ensure that P and P' (and P'' and P') are much closer to one another than H is to P. The Euclidean norm will do here. Nevertheless, several revisions of the Ptolemaic system would lead to one which is much further from P than P' is. The decision view the change to this system as nevertheless different from that to the heliocentric one is therefore not one that can be translated in quantitative terms, but is ultimately qualitative.

[15] Note that the proper representation of the parameter space for a given area of investigation can only be defined *a posteriori*.

as to whether the proposed weighted combination of moves towards the individual best and towards the group best actually affords enough variability in theoretical development to represent the actual evolution of science. The worry is that the only radical innovation in any simulation with this model is produced by the appearance, in a new location of parameter space, of a new individual. To address this issue, we must distinguish between two subcases. In the first, the individual is a theory, and the model's task is the simulation of the evolution of theories but not the emergence of new theories. As it stands, the model would appear adequate for this task, with the possible modification that the relative weightings between individual and group best are pre-specified functions of time: as time goes on, one would expect the weight to be put upon the group best to increase, thus allowing for the disillusionment with an unorthodox theory which has not born fruit.[16] If, on the other hand, we take the individual to represent a scientist, the model will have to account for the evolution from one theory to the next. Here, the PSO as it stands does not seem to allow for sufficient theoretical creativity. Without going into the detail here, it would seem useful to borrow from evolutionary algorithms the notion of random mutation. That is, with a small probability, the move from one time-step to the next should be along a direction which does not lie in the plane formed by the vectors connecting the current position to the individual best and the group best. This direction could be chosen completely randomly.[17] Fourth, the PSO algorithm actually takes on one of two forms: the *gbest* and the *lbest* algorithm (Engelbrecht, 2005, pp. 94–98). In the first, the group whose optimal performance has an impact upon the individual's progress is the whole population of existing individuals. In the second, it is only a neighborhood of such individuals. In the case of scientific progress, it is probably fair to say that, in practice, only a handful of competing theories are considered at any one time, which would seem to indicate that the *lbest* algorithm is at stake. However, these theories are viewed as having superseded any previous ones, so that in effect, this amounts to a *gbest* algorithm implementation.

Finally, one may wish to discuss whether the function f itself is defined independently of the evolution of the development of theoretical knowledge which is modeled by the algorithm. So far, we have assumed that verifying whether a theory matches the observational data is a theoretically neutral matter. One may dispute this on either of the following grounds. The first objection would amount to pointing out that theoretical developments underpin the very gathering of observational data, so that the latter are already theory-laden (think of what theoretical assumptions are involved in the use of the electronic microscope for instance). This may lead to an alteration of the algorithm which has f dependent upon some well-established mainstream theoretical results which are not in dispute in the further development of science. The second objection would take the first objection further by stressing that if what counts as observational data is thereby theory-laden, so that there is no unbiased evaluation of whether a theory provides a good fit to observations. In a sense, the way on sets up one's experiments, interrogates Nature, is already theory-laden.

The second objection is incompatible with the existence of any normativity which is universally binding and prior to the contingent process of the progress of scientific knowledge. Importantly for our purposes here, the PSO algorithm can in principle be altered to reflect these changes, by making f a function of t, i.e. by replacing it by an indexed function f_t. Thus, in the original example of the blind individuals walking around the landscape, this would amount to having the moves made by the individuals (either each individual's trajectory, or perhaps only the evolution of the group's best position) have an impact upon the actual shape of the landscape – one could imagine these individuals' movements causing earthquakes or landslides for instance. Within the context of the representation of the evolution of scientific knowledge, this algorithm is thus able to fulfill the goal set out at the start of the paper, namely that of providing a framework that can be accepted by proponents of PSE and SSE.[18]

5.4. Further applications of PSO

The application examined above is fairly narrowly defined as the process of development of scientific knowledge. We will conclude this section by making explicit two other potential applications of the PSO to social epistemology. In line with the example of the individuals scanning a landscape, we can see how the process by which a group acquires knowledge can be modeled in this way. The stigmergic aspect of this process is encapsulated in the impact the group's knowledge has upon the individual's investigative strategy, and vice-versa, the contribution the individual's discoveries make to the knowledge possessed by the group. To make the algorithm more suitable for this application, one might wish to dispense with the oversimplified assumption of perfect knowledge by each individual of the knowledge acquired by the group (e.g. by introducing some additional randomness).

[16] If the theory has, on the other hand, proved successful and is supplanting the established scientific dogmas, the group best and individual best will coincide, so the weighting becomes irrelevant.

[17] This could, for instance be achieved by randomly choosing the direction through the choice of a vector defined by independent identically distributed $U(0, 1)$ coordinates in each dimension, and then defining the length as normally distributed with a mean and standard deviation which are the average and standard deviation of all the velocity vectors constructed so far in the simulation.

[18] We acknowledge there are other approaches to modeling computationally the evolution of science (see Thagard, 2004). However, our interest is rather in the possibility of a representation of this evolution which brings out the individual versus social components of knowledge.

Another use of the algorithm would be the modeling of the process of acquisition of knowledge by individuals. Here the population or group best are more or less fixed and uninfluenced by the individual's knowledge acquisition. The algorithm is thus chiefly designed to represent the learning curve characterizing knowledge acquisition. That is, the individual's understanding of a body of knowledge is not a matter of just assimilating it *in one go*, but rather of progressively integrating aspects of this body of knowledge *from the perspective the individual is coming from*.

Note that in these further applications, the *lbest* algorithm may be the most appropriate one insofar as we are now beyond the narrow confines of scientific theories. There are in fact typically different types of neighborhoods to be considered in the process of acquisition of knowledge by an individual or a group: for purely scientific matters, there is probably only the scientific community, but for most other matters, pertaining to what one takes to be correct, there are three types of neighborhoods: the specialists in the relevant field; the cultural milieu; and the family/geographical neighborhood. The first neighborhood is defined by its being necessarily associated with the acquisition of knowledge; the second is associated with the necessary belonging to a cultural milieu, but the fact it is this one rather than another is a contingent matter; the third is entirely contingent: it is an entirely contingent matter whether one has geographical/genetic neighbors which have an influence upon my acquisition of knowledge. The existence of a number q of neighborhoods is best taken into account by altering the PSO algorithm to have several $c_{\text{group}}(t)$ weightings: $\{c_{\text{group }1}(t), c_{\text{group }2}(t), \ldots, c_{\text{group }q}(t)\}$.

In the PSO algorithm, the role played by the group's best position, which represents the group's knowledge is crucial to each individual's evolution. It is important to note that in the algorithm, this group knowledge corresponds to some individual's knowledge at any given time, but there is no single individual whose knowledge it is over time.

In the case where several groups are considered, as we have proposed in our modification of the *lbest* algorithm to reflect the multiplicity of bodies of expert knowledge, there is therefore a distribution of knowledge both among the groups and among the individuals of any given group. This exemplifies the extent to which this stygmergic representation entails a key role for an externalist conception of knowledge, while operating with individual cognizers. Stigmergy just is this interaction of these two forms of knowledge through which both evolve over time.[19]

The PSO model has some resonance to Sperber's (1996) probabilistic model of the epidemiology of belief. His model's space of possibilities comprises two primary attractors – universal human psychology and a local cultural/ecological context – two attractors that have a mutually transformative cybernetic relationship. Though Sperber doesn't invoke the term stigmergy, his description of his model's *transformative* dynamic matches, at least in spirit, what we have been saying about stigmergy (Sperber, 1996, p. 115).

6. Concluding remarks

A great deal of ground has been covered in the course of which we have made a case for two central claims:

1. Social epistemology has the formation, acquisition, mediation, transmission and dissemination of knowledge in complex communities of knowers as its subject matter. Such knowledge is, for the most part, third party and as such it is knowledge that is conditioned and modified. Understood thus, social epistemology is essentially stigmergic.
2. One might conceive of social connectionism as the extracranial analog of an artificial neural network providing epistemic structure. The extended mind thesis (at least the Clarkean variant) runs on the idea that modifiable environmental considerations need to be factored into cognitive abilities. This notion of cognition is thus essentially stigmergic.

With 1 and 2 in mind, two disclaimers are in order. First, a stigmergical socio-cognitive view of knowledge and mind should not be construed as (a) the claim that mental states are somewhere other than in the head or, (b) the corollary, that as individualists, we do not think that what is outside the head has nothing to do with what ends up in the head. A stigmergic approach, necessarily dual aspect, does not require one to dispense with one or the other. There is no methodological profit whatsoever to throwing out the Cartesian baby along with the bath water. Second, a socio-cognitive view of mind and knowledge be not be mistaken as a thesis for strong social constructivism, the idea *all* facts are socially constructed (a denial that reality in some way *impinges* upon mind) – again, it would be inconsistent with the environmental emphasis entailed by stigmergy.

For Clark, "[M]uch of what goes on in the complex world of humans, may thus, somewhat surprisingly, be understood in terms of so-called *stigmergic* algorithms." (Clark, 1996, p. 279). Traditional cases of stigmergic systems include stock markets, economies, traffic patterns, supply logistics and resource allocation (Hadeli, Valckenaers, Kollingbaum, & Van Brussel, 2004), urban sprawl, and cultural memes. New forms of stigmergy have been exponentially expanded through the affordances of digital technology: we've expounded upon Google's RP and Amazon's CF but of course include wiki, open source software, weblogs, and a whole range of "social media" that comprise the World Wide Web. These particular examples serve to make the wider stigmergical point that the Janus-like

[19] The implementation of these algorithms is a matter of ongoing research which will be reported later.

aspect of knowledge and cognition must be set against a background fabric of cultural possibility: individuals draw their self-understanding from what is conceptually to hand in historically specific societies or civilizations, a preexisting complex web of linguistic, technological, social, political and institutional constraints.

It is no surprise then that it has been claimed that stigmergic systems are so ubiquitous a feature of human sociality, it would be more difficult to find institutions that are *not* stigmergic (Parunak, 2005; Tummolini & Castelfranchi, 2007). If stigmergy were merely coextensive with "the use of external structures to control, prompt, and coordinate individual actions" (Clark, 1997, p. 186), then the concept would amount to a claim about situated cognition in all its dimensionality Solomon, 2006b. While stigmergy includes these aspects, it distinctively emphasizes the cybernetic loop of agent → environment → agent → environment through an ongoing and *mutual process of modification and conditioning*, appearing to dissolve the supposed tension between the self-serving individual and the social corpora at large through *indirect interaction*. Though this process of behavior modification has long since been identified by both PSE and SSE theorists, only recently has there begun a concerted effort (Turner, 2001; Turner, 2003) to, as Ron Sun puts it (Sun, 2006) "cognitivize" human sociality. Social theory and cognitive science must now recognize the virtues of a "cognitivized" approach to all things social.

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