

# A Survey of Environments and Mechanisms for Human-Human Stigmergy\*

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**Abstract.** Stigmergy (the coordination of agents through signs they make and sense in a shared environment) was originally articulated in the study of social insects. Its basic processes are much simpler than those usually used to model human-level cognition. Thus it is an attractive way to coordinate agents in engineered environments such as robotics or information processing. Stigmergic coordination is not limited to insects. Humans regularly use environmentally-mediated signals to coordinate their activities. This paper develops a schema for analyzing stigmergy among humans, discusses examples (some using a computational environment and others antedating digital computation), and suggests how the use of such mechanisms may be extended.

## 1 Executive Summary

Human-Human Stigmergy is pervasive. A wide range of pre-computer social systems fit the pattern of stigmergic coordination, and have provided a rich set of metaphors on which a diverse set of computer-enabled systems for enabling human stigmergy have been constructed. It would be more difficult to show a functioning human institution that is not stigmergic, than it is to find examples of human stigmergy.

The reason that human-human stigmergy is so common can be understood from the growing body of experience in constructing large-scale distributed computing systems with resource-constrained elements. Central control of such systems is not feasible, since resource-constrained components cannot cope with the large-scale, distributed aspects of such systems. The central insight of stigmergy is that coordination can be achieved by resource-constrained agents interacting locally in an environment. Two fundamental principles govern the success of this strategy.

1. No matter how large the environment grows, because agents interact only locally, their limited processing capabilities are not overwhelmed.
2. Through the dynamics of self-organization, local interactions can yield a coherent system-level outcome that provides the required control.

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The essence of stigmergy is the coordination of bounded agents embedded in a (potentially unbounded) environment, whose state they both sense (to guide their actions) and modify (as a result of their actions). Section 2 introduces the concept of stigmergy and describes its varieties and characteristics. Section 3 classifies a range of human stigmergic mechanisms, both pre-computational and computational. Section 4 describes ongoing areas of research that will foster applications of human-human stigmergy. Reflecting the interests of the client for whom this report was originally prepared, we focus on military applications.

## 2 An Introduction to Stigmergy

The French entomologist Grassé coined the term “stigmergy” in the 1950’s [32] to describe a broad class of multi-agent coordination mechanisms that rely on information exchange through a shared environment. The term is formed from the Greek words *stigma* “sign” and *ergon* “action,” and captures the notion that an agent’s actions leave signs in the environment, signs that it and other agents sense and that determine their subsequent actions.

In spite of Grassé’s preoccupation with insects, stigmergy is ubiquitous in the human interactions. Our experience with a wide range of distributed systems suggests that it is the only way for members of a large distributed population, whatever their individual cognitive capabilities, to coordinate themselves with bounded computational resources. To set the context for our survey of stigmergy among humans, we outline the basic architecture of stigmergy, then develop a taxonomy of stigmergic interactions that can be used to classify specific instances. We discuss further details on how stigmergic systems can be engineered in [71].

### 2.1 Architecture of Stigmergy

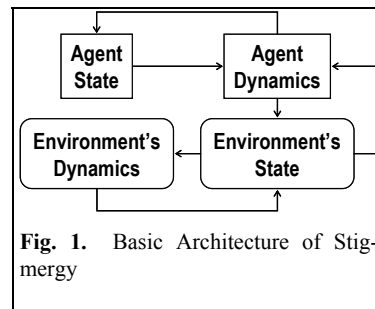
Fig. 1 summarizes the basic components of a stigmergic system: a population of agents and an environment in which they are immersed.

Each agent has

- an internal state, which generally *is not* directly visible to other agents;
- sensors that give it access to some of the environment’s state variables;
- actuators that enable it to change some of the environment’s state variables;
- a program (its “dynamics”) that maps from its current internal state and its sensor readings to changes in its state and commands given to its sensors and actuators.

The environment has

- a state, certain aspects of which generally *are* visible to the agents;
- a program (its “dynamics”) that governs the evolution of its state over time.



The most important distinction between agents and the environment is that the internal state of agents is hidden, while the state of the environment is accessible to an agent with appropriate sensors. In most cases, a second distinction can be observed. Each agent is monolithic, a self-contained computational object with a well-defined boundary. Typically, the environment is not monolithic, but is structured according to some topology. Some examples of environmental topologies include

- a Cartesian space (e.g., the surface of the earth);
- a graph structure (e.g., a telecommunications network or social organization);
- a list of disjoint categories (e.g., a list of topics, though these are usually organized into a graph by imposing an ontology).

When the environment is structured in this way, each agent is localized in the environment. That is, its sensors and actuators are confined to one region of the environment. If the agent is mobile, it can change location in the environment, but at any moment it is at one location. This localization of agents within the environment restricts the computational load imposed on the agents, and enables stigmergic systems to scale without exceeding the load on each agent.

While localization in a distributed environment keeps the computational load on each agent manageable, it does not ensure that a reasonable system-level behavior will emerge from the interactions of the agents. Critical support for this objective lies in the interaction of the dynamics of the agents with those of the environment. The dynamics of individual agents are typically nonlinear, and their interactions are often nonlinear as well, resulting in a system that is susceptible to formal chaos. Far from being a disadvantage, such dynamics actually enable self-organization, since they permit the system to explore its state space efficiently. This exploration is a key ingredient of self-organization, other components of which are discussed in [71].

## 2.2 Varieties of Stigmergic Interaction

We distinguish four varieties of stigmergy, generated by two binary distinctions. One distinction is whether the signs consist of special markers that agents deposit in the environment (“marker-based stigmergy”) or whether agents base their actions on the current state of the solution (“sematectonic stigmergy”) [9]. The other distinction is whether the signals are a single scalar analogous to a potential field (“quantitative stigmergy”) or whether they form a set of discrete options (“qualitative stigmergy”) [12]. The two distinctions are orthogonal (Table 1).

The paradigm for marker based stigmergy is the use of pheromones by certain social insects. Some species use multiple pheromone “flavors” [25] and thus use qualitative as well as quantitative decision-making. In engineered systems, stigmergic markers can consist of actual physical chemicals deposited in a physical

**Table 1.** Varieties of Stigmergy

	<b>Marker-Based</b>	<b>Sematectonic</b>
<b>Quantitative</b>	Gradient following in a single pheromone field	Ant cemetery clustering
<b>Qualitative</b>	Decisions based on combinations of pheromones	Wasp nest construction

landscape, labeled scalar variables stored in a data structure whose topology reflects that of the problem (as in much of our UAV control work), or price signals in a marketplace [17]. The latter metaphor is particularly important in coordinating human interactions, as in our RAPPID system for collaborative design [74-76].

The structure of the domain itself provides sufficient signals for coordinating some insect behaviors, without the need for special markers. Ants cluster corpses in their cemeteries, guided only the density of corpse distribution [7]. This is a quantitative decision, depending only on the distribution of a single type of object. Wasps decide where to add the next cell to their nests based on which of several templates best characterizes the current local shape of the nest, thus making a qualitative distinction. Sematectonic stigmergy is also illustrated by an algorithm that explains how wolves surround their prey [44], by being attracted to the prey while repelled by neighboring wolves. We have applied sematectonic stigmergy to coordination of multiple sensors [68, 72] and the assembly of intelligence information [93].

A subset of stigmergic mechanisms, “coordination fields” or “co-fields” [47, 52, 53, 94], consists of quantitative stigmergy. The scalar field is generated by a combination of attracting and repelling components, and the agents follow gradients in this field, thus tending to avoid repellers and approach attractors. Such techniques have an extended history in controlling individual robots [80].

Whatever the details of the interaction, examples from natural systems show that stigmergic systems can generate robust, complex, intelligent behavior at the system level even when the individual agents are simple and individually non-intelligent. In these systems, intelligence resides not in a single distinguished agent (as in the centralized model) nor in each individual agent (the intelligent agent model), but in the interactions among the agents and the shared dynamical environment.

### 3 Present Status of Technology

We summarize instances of stigmergic human coordination in two broad categories: those that do not rely on digital computers (though they may be enhanced by them), and those that are distinctively creatures of the computer age. For each category, we document an example, and analyze it in terms of the theoretical categories developed in the previous section, using the template shown in Fig. 2. We first identify the environment, describe its topology, the state variables that it supports, and any internal dynamics. Then we identify the agents, discuss how they sense and modify the environment (with attention to the main distinction between sema(tectonic) and marker(-based) stigmergic interaction), and summarize their internal dynamics. Finally, we describe the overall emer-

**Environment:**

- Topology:
- State:
- Dynamics:

**Agents:**

- Sensor:
- Actuator:
- Dynamics:

**Emergent system behavior:**

**Fig. 2.** Template for Analysis of Examples

gent system behavior that the stigmergy achieves.

### 3.1 Pre-Computational

Humans have long coordinated their activities through non-computational environments, though these mechanisms can often be enhanced with computers.

#### 3.1.1 Movement Coordination

Humans have always needed to move in their environment, and have drawn on stigmergic mechanisms both to form the trails along which they travel and to choose among alternate existing trails.

##### 3.1.1.1 Trail Formation

The simplest and most primitive trail formation mechanisms rely on sematectonic stigmergy. Humans wear down the vegetation on frequently-traveled routes, and grass regrows if an old path is not used (Fig. 3). There is an extensive literature on mathematical models for such path formation by “active walkers” [37].

While trails can form entirely with sematectonic stigmergy, humans tend to enhance them with markers. My college campus was notorious for laying pavement along bare tracks through the grass, turning emergent trails into permanent ones. A common modern example is traffic signs, often maintained locally by a variety of jurisdictions, but Native Americans also used artificial markers, including unnaturally bent trees [23] and petroglyphs [54], to mark trails. While such mechanisms can make trails easier to follow, they also render them less dynamic. It takes longer for a concrete path to crumble than for grass to regrow over an unused dirt path.

##### 3.1.1.2 Traffic Flow

Humans not only generate trails stigmergically, but also allocate their movement across alternative routes, both sematectonically and using markers (tolls) (Fig. 4). Note that this behavior builds on the product of a previous stigmergic activity (the formation of the trails themselves).

**Environment:** Vegetated terrain

- Topology: 2D manifold
- State:
  - Degree of ground cover
  - Obstacles
- Dynamics:
  - Trodden vegetation dies
  - Vegetation regrows on untrodden areas

**Agents:** People (pedestrians or in vehicles)

- Sensor:
  - Sema: smoothness to path
  - Sema: direction to destination
  - Marker: road signs
- Actuator:
  - Sema: direction of next step
  - Marker: pave the path
  - Marker: set road signs
- Dynamics: optimize smoothness and direction

**Emergent system behavior:** globally marked paths

**Fig. 3.** Trail Formation

### 3.1.2 Market Systems

Adam Smith's "invisible hand" is an example of the self-organizing potential of a stigmergic system, and have the benefit of an immense body of formal study [90].

There are two varieties of open markets. Both are stigmergic, though at different levels.

In an auction-based market (such as a stock market or commodities exchange), the marketplace provides an environment that integrates the bids of individual buyers and sellers interact, using currency as markers (Fig. 5). The markets for individual products are distinct, so the topology of the environment is strictly speaking a set of disjoint categories. However, different products are linked by other processes in the economy (for example, the markets for steel and automobiles), leading to an implicit graph structure.

A less studied alternative to auction systems is the pattern of Edgeworth barter, in which buyers and sellers interact directly with each other in repeated pairwise transactions, without the benefit of an auctioneer [3] (Fig. 6). In this system, the environment consists entirely of the graph of dependencies among different products induced by patterns of joint use, since it is through these dependencies that individual transactions have an effect on one another.

### 3.1.3 Elections

An election can be viewed as a market in which candidates and issues are the commodities and votes correspond to currency. In a single-issue or single-office election, the dynamics are quite simple. However, many elections involve a series of issues or offices, often linked to one another through political platforms. The ultimate outcome in terms of governance depends on the policies advocated by a candidate. A voter may favor some of those policies and oppose others, but rarely

**Environment:** Trail network

- Topology: Graph
- State:
  - Congestion
  - Toll fees
- Dynamics: Convey traffic across edges of the graph

**Agents:** People (pedestrians or in vehicles)

- Sensor:
  - Sema: current congestion on edge
  - Sema: direction to destination
  - Marker: requested toll
- Actuator:
  - Sema: choice of edges at each node
  - Marker: pay toll
- Dynamics: optimize speed and economy

**Emergent system behavior:** more balanced load on different paths

**Fig. 4.** Traffic Flow

**Environment:** Product-specific exchanges

- Topology: Categories (though often linked by product dependencies, e.g., steel in autos)
- State: Current bid and ask prices
- Dynamics: integrate offers to compute prices that clear the market

**Agents:** Buyers and sellers

- Sensor (Marker): Current prices
- Actuator (Marker): State own bid or ask price
- Dynamics: Maximize time integral of revenue over expense

**Emergent system behavior:** globally optimum allocation of resources

**Fig. 5.** Auction Market Systems

has the opportunity of voting for or against individual policies. Voting for a candidate can be compared to buying a complex product with multiple attributes. For example, in an automobile, one may want high fuel economy, good off-road performance, and low maintenance, but usually must make compromises.

If an election is like a market, representative government is like an economy. Elected officials themselves participate in numerous legislative actions, including both explicit votes and implicit agreements, to pursue their platforms. Voters often choose a set of representatives in anticipation of the subsequent legislative give-and-take, providing for a balance of power in the overall structure.

Viewed in this way, the topography within which elections take place is a graph with different colors of nodes and edges. Some nodes represent candidates, others represent policies, and still others represent representative divisions (such as geographical regions). Edges link candidates to their regions and the issues they support or oppose. Votes for candidates propagate to the issues associated with them (Fig. 7).

### 3.1.4 Document Editing

Joint authorship has always been a stigmergic activity, mediated by the emerging document itself. Each author is stimulated by what previous authors have written to add main-line content or marginal comments. The dynamics of this process have been greatly enhanced by sophisticated word processing software that includes specific facilities for review, comment, and tracking multiple authors.

While a document may seem to be a static entity, internal semantic relations can change as a result of individual modifications. As a trivial example, consider a document on a sensitive issue. A later reviser adds a tendentious definition to the first page of the document. The structural integrity of the document has the effect of propagating the semantics of this definition to later sections, potentially changing their meaning (Fig. 8).

**Environment:** Pairwise encounters

- Topology: Spatial distribution of traders
- State: Current locations of traders
- Dynamics: Support mixing of traders

**Agents:** Traders

- Sensor (Marker): Bid and ask price for single entity
- Actuator (Marker): State own ask or bid price
- Dynamics: Integrate information over successive exchanges

**Emergent system behavior:** In repeated trades, balances supply and demand

**Fig. 6.** Edgeworth Barter Markets

**Environment:** Network of districts, candidates, and issues

- Topology: Graph
- State: Connectivity of links
- Dynamics: Population of districts; support for candidates and issues

**Agents:** Voters

- Sensor (Sema): Affiliation of candidates with issues
- Actuator (Marker): Vote
- Dynamics: Choose policies indirectly through candidates

**Emergent system behavior:** Set of policies aligned with voter interests

**Fig. 7.** Elections

An extension of document editing is the development of knowledge in a scientific community. Each paper that is published contributes knowledge that other researchers can use in stimulating their ideas, modifying their research directions, and deriving their results (not to mention the more mundane results of achieving tenure for the authors and thus prolonging their ability to contribute to the field) [57].

### 3.1.5 Status Boards

Many social settings use a publicly visible display to coordinate activity (Fig. 9). Examples include “in-out” boards indicating which staff are currently in the office, situation boards used in military battle management, and a wide range of bulletin boards advertising items for sale, employment opportunities, services offered, etc. The emergent behavior mediated by the board depends on its theme. “For sale” boards generate market encounters, usually of the Edgeworth variety. Situation boards enable tactical coordination of military forces. “In-out” boards enable more effective direction of inquiries and assignments to staff who are immediately available.

### 3.1.6 Viral Marketing

Viral marketing describes “any strategy that encourages individuals to pass on a marketing message to others” [100]. Before the advent of computers, this form of communication was known as “word-of-mouth,” and in non-commercial venues was known as “rumors.” The speed of digital communication has made it particularly powerful. One classic example is free email such as Hotmail: every message sent by a user includes a system-generated tagline that encourages recipients to get their own Hotmail account, thus opening themselves to follow-on advertisements. Another, less blatant example is the use of planted participants in chat rooms to generate “buzz” in favor of a new

**Environment:** A document

- Topology: Linear or (if structured) hierarchical
- State: Current content, both mainline and marginal comments
- Dynamics: Internal semantic propagation

**Agents:** Writers and editors

- Sensor (Sema): Current state of the document
- Actuator:
  - Sema: New content
  - Marker: Strike-outs, highlighting

- Dynamics: Adjust content to modulate ambiguity, tune an argument, or advocate a particular position

**Emergent system behavior:** Expression of jointly held consciousness

**Fig. 8.** Document Editing

**Environment:** Modifiable public display

- Topology: 2-dimensional surface
- State: Current contents
- Dynamics: Most current material obscures or replaces older material

**Agents:** People visiting the board

- Sensor (Sema): Contents of the board
- Actuator (Sema): New postings
- Dynamics: Add new postings, remove or regroup old ones

**Emergent system behavior:** Depends on theme of the board (see text)

**Fig. 9.** Status Board



music album, film, or book.

The heart of these strategies is the propagation of a message along the social network of participants (Fig. 10), analogous to the propagation of a disease (thus the name). Like disease propagation, viral marketing depends on several critical factors [77], including

- the susceptibility of the members of the network to the message (if the message is intrinsically uninteresting, it will die out);
- the connectivity of the infected individuals (if the product of connectivity times susceptibility falls below 1, the infection will die out);
- the structure of the social network (an infection will die out in a lattice if the percentage of infected individuals falls below a certain threshold, but can persist in a power-law network no matter how small the percentage of infected individuals).

**Environment:** Social network

- Topology: Graph
- State: Connectivity of participants
- Dynamics: Communication

**Agents:** Members of network

- Sensor (Sema): Content heard from others
- Actuator (Sema): Repeating content
- Dynamics: Spread of message

**Emergent system behavior:** Number of individuals who have heard the message increases rapidly.

**Fig. 10.** Viral Marketing

## 3.2 Computational

The advent of information technology has extended the applicability of stigmergic mechanisms for human coordination, by augmenting human abilities for sensing, communication, and information processing. Each of the examples in this section can be viewed as a descendant of one or more of the pre-computational examples discussed in the previous section.

### 3.2.1 Intelligent Transportation Systems

The application of computer technology to human movement coordination (Section 3.1.1) has produced the burgeoning field of “Intelligent Transportation Systems” (ITS, also known as “Intelligent Highway Systems,” IHS), with extensive government attention [22, 86], independent business groups [42, 43], and dedicated research societies and journals [40].

While the field as a whole includes all modes of transportation, our analysis (Fig. 11) focuses on highway systems.

**Environment:** Highway network

- Topology: Graph
- State:
  - Locations and velocities of vehicles
  - Timing of control signals
- Dynamics: Enable movement of vehicles from one place to another

**Agents:** Vehicles

- Sensor:
  - Marker: Signals
  - Sema: Local congestion
- Actuator (Sema): Route choices
- Dynamics: Obey signals; minimize local congestion; make progress toward destination

**Emergent system behavior:** Increased throughput, reduced collisions

**Fig. 11.** Intelligent Highway System

Computational mechanisms in this domain rely on the existence of road networks that in most cases were established using pre-digital stigmergy. Computational enhancements include

- roadbed sensors for real-time estimates of traffic density and velocity;
- improved signal systems (including not only traffic lights but also digital signs) for providing feedback to motorists;
- advanced algorithms [45, 101] for controlling signals on the basis of sensed traffic.

### 3.2.2 Collaboration Environments

Recognition of the potential of stigmergy for promoting coordination in human organizations [19] has led to a proliferation of systems that support human collaboration in one way or another. It is helpful to discuss these under two broad headings: content (technologies that enable a community to assemble knowledge structures that exceed their individual expertise) and process (technologies that enable members of a community to act in coordination with one another). In many ways, these systems can be viewed as a digital extension of the “Status Boards” discussed in Section 3.1.5 above.

Content-oriented collaboration environments can be viewed as digital libraries (a domain with an extensive research literature [21], organizational infrastructure [20, 41], and public-sector support [15, 60]). Their function is to store, index, and provide access to shared materials. Because of the ease with which digital materials can be authored and distributed, these environments can be modified by the same communities to which they provide information, thus closing the stigmergic feedback loop. The computer adds three successive layers of functionality to the traditional library, discussed in the following three sections:

1. Enhanced storage and interlinking of materials, increasingly by the user community
2. Automatic ranking of materials, based on utilization by others
3. Dynamic distribution and sharing of content.

#### 3.2.2.1 Content Storage and Linking

Most computer users today are frequent users of the World-Wide Web (WWW), a worldwide network of interlinked documents to which anyone can add. The notion of such a web of information was initially proposed by Vannevar Bush in 1945 [11]. There were numerous attempts at implementation, but the approach that finally took hold was that developed by Berners-Lee [5], based on a common linking protocol (http) embedded in simple text files.

#### **Environment:** Networked Computers

- Topology: Categories (but linked through cross references)
- State: Current collection of articles
- Dynamics:
  - Web link: Addressing
  - Search engine: Indexing, Ranking, Summarizing

#### **Agents:** People

- Sensor:
  - Sema: Entries
  - Marker: Linking Scores (Google)
- Actuator (Sema): Post a document
- Dynamics: Find desired information

**Emergent** system behavior: Maintain rationalized system of interrelated information

**Fig. 12.** World-Wide Web

The strength of the WWW is its open character, enabling it to grow rapidly. As sites link to one another, the web becomes a framework for self-organizing communities [92] (Fig. 12). In fact, one of the first references to appear in response to a Google search on “stigmergy” (as of the date of writing) is a discussion of the collaborate effect of web logs, or blogs [33]. In the military domain, the US Army has made effective use of the emergent character of the WWW to share knowledge and experience among soldiers [87].

For some commercial purposes private file storage and sharing mechanisms are preferred (and often built on top of the WWW). One widely marketed example is Groove [34], which provides a common file repository and a variety of tools for project management to support distributed project teams.

Originally, the only way to modify the WWW was to add a new document that contained links to documents already there. A given document could only be changed by its author. Recent technical developments (most prominently, Wiki [49]) enable the maintenance of web pages that can be edited by anyone with the appropriate access. A prominent example of the potential of this approach is the Wikipedia [98], an encyclopedia of over half a million articles (many of very high quality), maintained entirely by the users. (By way of comparison, the Encyclopaedia Britannica contains about 120,000 articles.) The Wiki technology is an example of tools for social bookmarking [36], by which people can share not only their documents but also their annotations on the documents of others. This dynamic extends to entire libraries the dynamics of shared document editing discussed in Section 3.1.4.

### 3.2.2.2 Site Ranking

In a shared information system such as the WWW or a Wiki, computers store the content, make it available to users, and facilitate changes and additions, but in the original form of such systems the interpretation of the resulting network is based on the human user’s perception. Computers can augment this perception, to provide the user with a richer view of the network than would otherwise be possible. For example, the same openness to growth that makes the WWW so powerful can also make it overwhelming. A keyword search can return thousands of documents (“stigmergy,” in spite of its rarity, returns 16,500 under Google at the time of writing), far more than a human user can effectively use. A common example of this enhancement is the ranking of web sites.

For example, much of the benefit of the Google indexing system lies in its PageRank™ algorithm [8, 31, 61] (Fig. 13), which assigns each web

**Environment:** Network of hyperlinked documents

- Topology: Graph
- State: Connectivity of the graph
- Dynamics: Maintenance of indices (via web spiders)

**Agents:** Creators of links in pages

- Sensor (Sema): Content of other relevant pages
- Actuator (Marker): Insert links to relevant pages
- Dynamics: Seeks to maximize connectivity of own pages to relevant pages

**Emergent system behavior:** Pages are assigned ranks that guide agents in finding useful material.

**Fig. 13.** Google Page Rank

page a rank based on how many pages point to it, weighted by the ranks of those pages and the number of pages to which they point. This recursive computation is far beyond the ability of a human to calculate, but can readily be performed by computers, and enables users to find valuable material far more easily than would otherwise be the case. A page's rank under this algorithm is a clear example of an emergent phenomenon generated stigmergically. It guides web page authors seeking material to reference in their own pages, and in turn is modulated by the links that those authors insert to the material they find. Authors who wish to promote their own pages often seek to subvert the stigmergic nature of the system and control their page ranking. Much of Google's effort is devoted to blocking such subversion.

Another system for helping users find useful material is the PackHunter [78]. Users deposit digital pheromones on a map of their web browsing activity, leading other users with similar pheromone patterns to sites likely to be of interest to them. Where PageRank™ focuses on the structure of the network as constructed by its authors, PackHunter takes into account the actions of users. It can be viewed as a form of collaborative filtering (Section 3.2.3) applied to web pages.

### 3.2.2.3 Peer-to-Peer Computing

In the WWW, every document lives on some computer, which must be active to make the content available. If a document is very popular, the computer's individual bandwidth may be overwhelmed, making access slow or impossible. The computer hosting the document is the "server," and computers that access it are "clients."

An alternative strategy, peer-to-peer (P2P) computing, seeks to do away with the client-server distinction. In this strategy, content moves dynamically from one computer to another, and may exist in several places at the same time. When a user seeks a document, the network dynamically retrieves it from the nearest available machine. No single server has a monopoly on any document, and if one source for a document is heavily loaded, others can supply the demand.

Current implementations of P2P, such as Gnutella [30], serve mainly as ways to share content without the need for a central file server, and are popular mechanisms for private users interested in sharing media. LOCKSS [50] applies the P2P approach to preserving digital media by distributing them over multiple machines, and is oriented to the library community. BitTorrent [6] provides a general-purpose peer-to-

**Environment:** Computer network

- Topology: Graph
- State: Semantic signature of users at each computer
- Dynamics: Maintain semantic signatures based on documents generated and accessed

**Agents:** Users at nodes of the network

- Sensor (Sema): Review of accessed documents
- Actuator:
  - Sema: Documents and queries generated
  - Marker: Rewards sent to relevant documents
- Dynamics: User interactively generates and reviews documents

**Emergent system behavior:** Documents find their way to nodes where they are likely to be of most value

**Fig. 14.** PARTNER (Smart P2P Document Distribution)

peer distribution system. In principle, such a framework would be an excellent environment for “smart” information that finds its way to users based on an emergent model of their interests, as in Altarum’s PARTNER technology [64] (Fig. 14) and in a research project currently underway at the Université de Tours in France [57].

The collaboration systems described so far concentrate on making digital content readily accessible to users. A further level of collaborative support is represented by systems that help users manage the processes of their work. We briefly describe several examples, beginning with the most mature.

#### 3.2.2.4 BPM: ActionWorks

There is an established market in the commercial world for workflow or business process management (BPM) systems. These systems help organizations define and follow standard processes to ensure uniformity of performance. A premier example is the ActionWorks system [2] from Action Technologies [1] (Fig. 15). This system analyzes all workflows as built on a basic four-step cycle involving a Customer for whom work is being done and a Performer who does the work.

1. The Customer *prepares* a plan of the work to be done and issues a request.
2. The Customer and Performer *negotiate* the terms of the work.
3. The Performer *performs* the work and reports completion.
4. The Customer evaluates the work and either *accepts* it or identifies what remains to be done.

Each of these steps can in turn be broken down into further cycles until the company’s entire business process has been analyzed. The resulting network forms an environment that supports stigmergic interactions among workers, who receive and give local signals concerning the state of their own responsibilities.

#### 3.2.2.5 On-Line Auctions

On-line auctions such as eBay [24] provide a standardized process that guides sellers and buyers in finding one another, engaging in bidding, and concluding deals. The process being automated is essentially a Walrasian auction (Section 3.1.2). The overall system includes WWW structures for organizing products offered for sale and bids offered, a reputation system for enforcing honesty in transactions, and time-based mechanisms for managing the flow of an actual auction (Fig. 16). Similar mecha-

**Environment:** Model of interlocking Prepare-Negotiate-Perform-Accept cycles

- Topology: Graph
- State: Identify of Customer and Performer for each cycle, and current state of the cycle
- Dynamics: Propagate information about the state of each cycle to its sub- and super-cycles

**Agents:** Workers

- Sensor (Marker): State of current cycle and component subcycles
- Actuator (Marker): Report state of current work package
- Dynamics: Seek to move along cycles in which one is either a Customer or a Performer

**Emergent system behavior:** Coordinated execution of an overall workflow without missing or duplicative action.

**Fig. 15.** ActionWorks BPM Framework

nisms are provided by Amazon in support of the network of used book sellers that advertise through its website, or the Yahoo merchants network.

### 3.2.2.6 Market-Based Design: RAPPID

Altarum's RAPPID technology for distributed electromechanical design [74-76] (Fig. 17) helps designers reach agreement on design specifications at the intersections. RAPPID is based on a generalization of Walrasian market model for coordination (Section 3.1.2). A market exists for each interface parameter (for example, the torque or RPM of a shaft connecting a motor and a transmission), and the goods being traded are the assignments to those parameters. The prices manipulated in the markets are either catalog costs for actual components or "play money" that designers are allocated by the customer and must spend to get the functionality they require from other designers.

### 3.2.2.7 Battle Plan Adjustment: Coordinators

A current DARPA program, Coordinators [91], focuses on the task of helping fielded military units adapt their mission plans as the situation around them changes. Each unit has a networked computer or personal digital assistant (PDA). Agents representing each unit and running on their computer negotiate with one another to determine the interactions among tasks, the impact of the unfolding battle, and possible adaptive changes such as task timings, task assignments, or adoption of pre-planned contingencies.

One analyst has briefly described guerilla operations from a stigmergic perspective [81].

### 3.2.3 Recommender Systems

A "recommender system" or "recommendation system" attempts to

**Environment:** Web site

- Topology: Graph
- State: Information about products offered, seller identity, reputation, and conditions, buyer identity, reputation, and bid, state of the overall auction process
- Dynamics: Maintains and publishes current state of the auction; determines the winner; notifies participants.

**Agents:** Buyers and sellers

- Sensor (Marker): Current prices
- Actuator (Marker): State own bid or ask price
- Dynamics: Maximize time integral of revenue over expense

**Emergent system behavior:** globally optimum allocation of resources

Fig. 16. On-Line Auctions

**Environment:** Set of markets on interfaces

- Topology: Graph reflecting product structure
- State: Current bid and ask prices
- Dynamics: Compute prices that clear the markets

**Agents:** Designers

- Sensor (marker): Current prices
- Actuator (marker): State bid or ask
- Dynamics: Maximize time integral of revenue over expense

**Emergent system behavior:** Balanced assignments to interacting design variables

Fig. 17. RAPPID

predict items (such as books, movies, or music) that a user may find interesting, based on the user's profile. Such systems are usually implemented using collaborative filtering [38]. The system (the stigmergic environment) collects a large number of profiles on different users. Each profile is a vector over the universe of items for which recommendations are being made, and the magnitude of each element in a user's profile indicates the attractiveness of that item for that user. To make a recommendation, the system first finds other users whose profiles are similar to that of the user for whom the recommendation is intended (the recommendee). Then it identifies elements in their profiles with high scores, elements for which the recommendee has registered no score.

The big challenge for recommender systems is collecting and maintaining a collection of user profiles. Users typically find it onerous to rank their preferences explicitly. However, their preferences can often be deduced from other actions they take. Perhaps the best known recommender system is that used by Amazon to recommend books to its buyers (Fig. 19). This system functions stigmergically. Every purchase of an item is taken as evidence that the purchaser has a high level of interest in that item, and is registered in that user's profile. Thus individual actions (purchases) leave signs in the environment (the collection of profiles) that are integrated to provide feedback to the individual (what book might be a reasonable next acquisition).

### 3.2.4 Scheduling and Planning

Many problems of operational importance can be cast as scheduling and planning problems. Abstractly, these problems concern the allocation of scarce resources to a set of tasks over

**Environment:** Communication network

- Topology: Graph
- State: Current state of the plan; representation of extraneous events
- Dynamics: Negotiation of plan adjustments among agents

**Agents:** Warfighters

- Sensor (Sema): Learn of constraints from other warfighters, and recommendations from the agents
- Actuator (Sema): Represent state of the battle and current constraints in to the system
- Dynamics: Report constraints and preferences

**Emergent system behavior:** Adjusted battle plan that balances requirements of the entire team

**Fig. 18.** DARPA Coordinators

**Environment:** Collection of user profiles

- Topology: Colored graph (user and item nodes with links indicating preferences between users and items, and similarities between users)
- State: Degree of preference of each user for each item; degree of similarity among users
- Dynamics: Maintain preference and similarity scores

**Agents:** Purchasers

- Sensor (Sema): Description of recommended purchase
- Actuator (Sema): Purchase an item
- Dynamics: Spend money on items most likely to be of interest

**Emergent system behavior:** Identify items most likely to be of interest to the user

**Fig. 19.** Recommender System (Amazon)

time. Much of the research in Operations Research is devoted to formal algorithms for solving such problems, with special emphasis on guaranteeing the optimality of the solution.

A large body of centralized algorithms has been developed for solving these problems. However, many versions of the problem are NP-complete [27], meaning that for an instance of reasonable size, the time required to compute the solution is too long to complete by the time the plan is needed. To address these problems, a number of agent-oriented solutions have been proposed. While these methods vary considerably in their details, they tend to share two features. First, they do not guarantee optimal solutions, but use heuristics to obtain “good-enough” solutions in reasonable time. Second, a common heuristic is for the agents to restrict their interactions to other agents that are near them

in some problem-specific topology. Thus these systems often qualify as stigmergic (Fig. 20), and frequently draw on recognized stigmergic mechanisms, such as market or pheromone systems. We can illustrate these systems with two examples from the domain of manufacturing planning and scheduling.

AARIA [65, 66] is based on the model of the factory as a marketplace [4, 62]. The participants in the market are the workstations in the factory that can change the state of material, and agents representing each job that moves through the factory. A job agent negotiates with workstations to perform the operations that it requires in the appropriate sequence, using market mechanisms as already discussed in Section 3.1.2.

An important innovation in AARIA is the use of a loading profile or “dance card” on each workstation agent [16]. This profile aggregates the expected load on the workstation over time. Job agents search this profile to find relatively unoccupied times when they can be executed, and augment it when they book a reservation on a workstation. Thus the profile behaves like a pheromone over time, leveling the load that each workstation experiences.

The pheromone approach is taken even further in the system described in [9]. Each job sends out a swarm of ghost agents that explore alternative possible routings and record their findings in the form of digital pheromones in a graph representing the factory’s conveyance system. The actual job then follows the emergent pheromone trace. Another set of dynamics from insects, based on task allocation in wasps, has also been exploited in support of manufacturing planning and scheduling [14].

**Environment:** Factory conveyance structure

- Topology: Graph
- State: Connectivity between workstations; capabilities and load profile of each workstation
- Dynamics: Maintain load profiles on workstations

**Agents:** Workstations, Jobs

- Sensor (Marker): Market bids, pheromone levels
- Actuator (Market): Make bids; deposit pheromones; (jobs) select next operation
- Dynamics: Maximize local performance (utilization for a workstation; delivery time for a job)

**Emergent system behavior:** Reduced overall production time and increased throughput

**Fig. 20.** Manufacturing Scheduling and Planning



Yet another leading effort in stigmergic scheduling and planning applied to manufacturing is the work of the PROSA group at the Katholieke Universiteit Leuven in Belgium [89]. The acronym PROSA stands for “Product, Resource, Order, Staff Architecture,” and identifies the main software agents (products, resources, and orders) that interact stigmergically to guide the factory.

David Scheidt of Johns Hopkins University’s Advanced Physics Lab reports work on using markets for shipboard power and fluids distribution at JHU/APL, Rockwell Automation, Nutech, and Icosystems [84], but these systems are not documented in the open literature. Work on market mechanisms for power distribution in residential and industrial settings has been published [103, 104]

## 4 Future Developments

Further technical enablement of human-human stigmergy depends on developments in several enabling technologies, including ubiquitous computing, theoretical foundations, simulation, and privacy and security.

### 4.1 Computing Hardware

The environment is intrinsic to stigmergy. As computing technology becomes smaller, less costly, and lower in power requirements, it can be distributed more widely throughout the environment, increasing the potential for stigmergic interactions.

Embedded sensors in the environment will enable passive tracking of the locations of mobile entities. Roadway sensors that can detect vehicles by their ferrous signature are already a critical component of intelligent transportation systems (Section 3.2.1). RFID [97] provides a way to make less readily sensed objects (including humans) visible, and can provide support for digital pheromones [51]. A new generation of microsensors include limited computational and communications capability. The University of Berkeley is a leading center in the development of this hardware [79].

Today, we think of human interactions with computers as deliberate and explicit, relying on keyboards, display screens, and pointing devices. As sensors, processing, and communications become more tightly integrated with the environment, computers will become invisible [85], yielding “ubiquitous” or “pervasive” computing. Humans will interact with computers via ordinary objects. (A current example is the modern automobile. Most drivers are unaware of the half-dozen or so computers they are manipulating as they drive down the road.) To enhance the transparency of this interaction, human interface devices will be critical. These include

- Heads-up displays to merge computer-generated information unobtrusively with the user’s normal field of vision,
- RFID technologies to track a person’s location and physiological state without explicit action on the part of the subject,
- Haptic technologies to guide the user through touch and feel.

An important area of research will be the development of power sources for pervasive computers. The smaller and more numerous computing elements become, the less power each will require, but the more impractical conventional power sources (such as batteries) become. In some cases (such as passive RFID), many passive sensors can receive the power they need from a few active readers. More generally, mechanisms such as parasitic power extraction from ambient RF or thermal noise will be come critical to the operation of such systems.

## 4.2 Foundations

Engineering requirements for ubiquitous computing are radically different from those that support the development, deployment, and maintenance of traditional computer systems [107], and will rely on a new body of theory and software engineering practices that can cope with the large numbers of processing elements, their physical distribution, the nonlinearity of their dynamics, and the nature of emergent behavior. Leading centers for the development of such software engineering methods include the Altarum Institute [63, 71] and the Università di Modena e Reggio Emilia in Italy with its vision of spraying computers onto the physical environment [106].

An important basis for this new theory is likely to be statistical physics, a mature quantitative science that is concerned with the emergence of macro-level system characteristics (such as pressure and temperature) from the behaviors of micro-level elements (atoms and molecules). Some research has been done on transferring insights from statistical physics to self-organizing systems [10, 48, 67, 70, 73, 83], but the field merits much more systematic exploration.

Applying formal methods will require simplified models of the phenomena in question. One important such model in the case of resource allocation is the minority game [69, 82, 83]. Altarum has been a leader in developing this analogy. Another class of models is derived from the new science of network structure [59], where Mark Newman of the University of Michigan is a recognized leader [58]. Understanding better the dynamics of processes constrained to such networks is vital in understanding the spread of stigmergic information, such as the effectiveness of viral marketing.

The recent institution of the Workshop on Environments for Multi-Agent Systems (E4MAS [18, 96]) enables a necessary focus on the agent environment as a first-class engineering object in constructing and maintaining such systems. Recognizing the environment in this way not only facilitates system engineering, but is in fact essential to avoid inconsistencies that otherwise hamper the design [55]. Researchers from Leuven, Montpellier, and Ann Arbor are the organizers of this series of workshops.

## 4.3 Integrated System-Social Simulation

Because of their emergent character, stigmergic systems require extensive use of simulation for their design and analysis.

Most simulation platforms used historically to study stigmergy in animals or robotic systems focus on support for large populations of fairly simple agents and the

presence of an active environment. The leading simulation platforms in this area are Swarm [46] from the Santa Fe Institute, RePast [88] from the University of Chicago, and NetLogo [99] from Northwestern University.

There is a growing discipline of social simulation that takes account of the richness of human behavior. The University of Surrey in the UK is one leading center [28, 29]. These systems typically do not support large populations or environmentally-mediated interactions. Advances in human-human stigmergy will require simulation tools that combine the features of these two classes of existing systems.

#### **4.4 Security and Privacy**

One of the strengths of stigmergy is that information deposited by one agent can be retrieved and acted upon by other agents that visit the same location in the environment where the deposit was made. This openness of information poses a challenge to security and privacy. Adversarial applications (such as commerce or warfare) require guarantees that adversaries will not be able to learn a system's intentions by eavesdropping, or to disrupt its operation by inserting malicious information. More generally, western society rightly places a premium on the rights of the individual human to protect personal information from broad dissemination.

In some respects, stigmergy is more secure than alternatives. Conventional systems for command and control involve messages whose contents provide considerable semantic detail about plans and objectives. Stigmergic messages, by way of contrast, are often numeric (e.g., a digital pheromone deposit). Such messages make sense only in the context of the entire system, making it much more difficult for an adversary either to interpret an intercepted message or to craft a spurious one to achieve a desired disruption. In addition, the stochasticity implicit in many stigmergic designs means that the detailed behavior of the system is unpredictable even to the user, making it even more obscure to an adversary without knowledge of its context.

Nevertheless, because stigmergic systems post information in the environment, responsible deployment will require new advances in security technology. Leading research in security for highly distributed systems is being pursued at many institutions, including IBM [13] and the University of New Mexico [26], and is published in the IEEE Distributed Systems Online e-journal [39] and workshops such as the International Workshop on Security in Distributed Computing Systems [35] and the International Workshop on Security in Systems and Networks [102].

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