Stigmergic Coordination in Wikipedia

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ABSTRACT
We look for evidence of stigmergic coordination (i.e., coordination mediated by changes to a shared work product) in the context of Wikipedia. Using a novel approach to identifying edits to the same part of a Wikipedia article, we show that a majority of edits to two example articles are not associated with discussion on the article Talk page, suggesting the possibility of stigmergic coordination. However, discussion does seem to be related to article quality, suggesting the limits to this approach to coordination.

ACM Classification Keywords
H.3.5 Online Information Services: Web-based services; H.5.3 Group and Organization Interfaces: Computer-supported cooperative work

Author Keywords
coordination, stigmergy, distributed groups, Wikipedia, on-line epistemic community

INTRODUCTION
In this paper, we examine how coordination is achieved in Wikipedia, that is, how editors can manage the dependencies between their activities [22] as they collaboratively but independently contribute to articles. There is significant evidence that writing articles collaboratively in Wikipedia requires a high degree of coordination between users. Each new editor working on an article in Wikipedia has the potential to contribute new knowledge with which to extend an article, insight into how the article should be written and vigilance to discover errors in fact, grammar or judgment. But for these contributions to be productive, the editors need to manage the interdependent aspects of the article, such as its content, structure and style.

THEORY
We start with the definition of coordination as managing dependencies among tasks [22]. This definition is consistent with the large body of literature developed in the field of organization theory (building on classics such as [15, 21, 30]) that emphasizes the importance of interdependence in group work. Given this definition, studying coordination in a group means analyzing the dependencies that emerge among the tasks undertaken by the group members (e.g., by analyzing how tasks use common resources, including the effort of group members [8]), and then how those dependencies are managed.

Theories of group coordination suggest a basic distinction between explicit and implicit coordination. Explicit coordination covers cases where individuals explicitly communicate about their actions or planned actions to identify and manage dependencies. Much of the focus of research on supporting coordination has addressed ways to improve explicit coordination. For example, an early CSCW system, the "Coordinator", sought to improve coordination by making communication more explicit about the coordination required [14, 35].

In contrast, theories of implicit coordination (e.g., [27]) suggest that team members can predict and adjust behaviors without communication. By sharing well-developed mental models, members of a team can determine what needs to be done and how to do it, even in the absence of explicit communication. In other words, people's background knowledge allows them to engage in interdependent activities without explicit communication. They simply know what to do next based on past experience.

However, the reliance on shared mental models poses limits on the viability of implicit coordination. For example, in self-organized groups, there is no formal authority to impose a particular way of working. Distributed teams pose particular problems, as they often lack face-to-face meetings at which to develop shared understandings. As a result, distributed work is characterized by numerous discontinuities [34], that is, a lack of coherence in some aspects of the work setting (e.g., organizational membership, business function, task, language or culture) that hinders members trying to make sense of the task and communication with others [32], or that produces unintended information filtering [12] or misunderstandings [1]. These interpretative difficulties, in turn, make it hard for group members to develop the shared mental models necessary for implicit coordination [10, 13]. More effort is required for interaction when participants are distant and unfamiliar with each others' work [23, 28].

In this paper, we explore a third alternative to the traditional dichotomy of explicit and implicit coordination. Specifically, we draw on research that suggests that the information needed to coordinate work can be communicated through the outcome of the work itself [2,4,7,29], a mode of coordination analogous to the biological process of stigmergy [16]. Heylighen defines stigmergy thusly: "A process is stigmergic if the work... done by one agent provides a stimulus ('stigma') that entices other agents to continue the job" [17]. Accordingly, stigmergic coordination can be defined as coordination (i.e., management of dependencies among tasks and resources) based on signals

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from the shared work rather than on shared understandings or explicit communication. Note that this distinction relates to the mode of communication rather than the dependencies or the coordination mechanisms used.

Stigmergy was first described as a mechanism of coordination used by insects. The principle is that work performed by one insect leaves a trace in the environment that stimulates the performance of subsequent work by the same or others. For example, ants follow scent trails to food found by other ants, thus assigning labour to the most promising sources. This mediation via the environment ensures that tasks are executed in the right order, without any need for planning, control, or direct interaction between the agents. The organized collective action emerges from the interaction of the individuals and the evolving environment, rather than from a shared plan or explicit communication. The notion of stigmergy allowed Grassé to solve the "coordination paradox" i.e., the question of how insects of very limited intelligence, without apparent communication, manage to collaboratively tackle complex projects, such as collecting food or building a nest.

While stigmergy was formulated to explain the behavior of social insects following simple behavioral rules, it has also been invoked to explain classes of human behaviors: the formation of trails in a field as people follow paths laid down by others (similar to ant trails), or markets, as buyers and sellers interact through price signals [24]. For humans and intelligent systems, the signs and processing can be more sophisticated than is found for insects [26]. For example, the shared environment can be a complex workspace including annotations. Signs may convey different kinds of messages, such as having the ability to do something, having done something or having a goal [31]. In the CSCW literature, [4–7] discussed how architects and builders coordinate their tasks through "the material field of work" such as drawings. Stigmergy has also been used to explain coordination in open source software development [2, 17].

As an illustration, we can see how stigmergy might support attempts to achieve alignment, the simplest form of coordination, in which different agents and their actions follow the same direction to the same goal. Taking the example of pushing a heavy object out of the way, if one agent pushes to the right while another pushes the opposite way, their actions will oppose each other because of the lack of coordination. The two agents need to push in the same direction to align their actions. In self-organization, the two agents can't see each other or communicate to settle on a plan. But while they don't know what the other is doing, they will feel if their movement is blocked when they push in opposite directions. In response, they may try to change direction. If they feel the obstacle is moved, they will continue pushing in the same direction, even they don't know whether the others do the same or not. In this way, actions can become aligned and the actors' efforts, more and more productive. This mechanism does not require any planning from the agents. Agents follow a logic of trial-and-error or variation-and-selection and produce some actions until they maximize action productivity.

Alignment can extend to more than two agents. Once two agents are in alignment, for a third one to be coordinated is to move in the same direction. In this case, the more agents there are trying to achieve alignment, the more difficult to oppose the movement, the easier to join the group with the same movement, and the faster others will join it. If the agents are dispersed in space, the agents in one region may start to align on one direction while others align to other directions. As a result, space will subdivide in several aligned region with local homogeneity.

Stigmergy is particularly relevant for technology-supported teams, in which the cost of explicit coordination may be high, making it advantageous to avoid it. When work products are shared via a computer system, team participants can see the artefacts produced by remote colleagues as easily as those from local colleagues [11] and these artefacts can provide information to support team coordination. But coordination through artefacts (the stuff actually worked on, such as software or documents) is different than coordination through prior planning, roles or explicit discussion.

Stigmergy can be readily interpreted in the coordination theory framework developed above. [22] describe coordination mechanisms as relying on other necessary group functions, including decision making, communications, and development of shared understandings and collective sense making [3, 9]. The stigmergic approach suggests that the "shared material" itself can be a communications medium, allowing coordination without recourse to separate coordinative mechanisms [6]. Christensen observed this type of coordination among architects, noting that their work is:

> "partly coordinated directly through the material field of work.... [I]n addition to relying on second order coordinative efforts (at meetings, over the phone, in emails, in schedules, etc.), actors coordinate and integrate their cooperative efforts by acting directly on the physical traces of work previously accomplished by themselves or others" [7].

Coordination in Wikipedia

In this paper, we attempt to disentangle the different ways in which coordination is achieved in Wikipedia, with particular attention to the possibility of stigmergic coordination. We choose Wikipedia as a venue for studying coordination for several reasons. First, Wikipedia is a prominent example of online epistemic community, in which many editors contribute to a collaborative output, meaning that coordination among editors is required for a quality output. However, coordination is expected to be particularly difficult for Wikipedia editors, as they are dispersed all over the world with limited opportunities for interaction and they are diverse with different backgrounds, knowledge and expertise. And yet the desire to create a coherent article means that there are dependencies between the editing tasks that each undertakes: knowing where and what to contribute and connecting individual contributions into a whole.

Second, any user can contribute and edit the content of the articles, allowing us to examine group interactions in an uncon-

trolled setting, where the nature of coordination is emergent rather than dictated. Third, all editing on the articles is done via the Wikimedia platform that records essentially all editing and social interaction for each article. Finally, there are formal guidelines and mechanisms for assessing quality ratings of Wikipedia's articles, allowing researchers to have a somewhat objective measurement of group performance outcomes.

In the Wikipedia setting, the main tasks undertaken by members of the group are edits to articles. These tasks are interdependent because they affect a common output, namely the article, and so must be done in a way that yields a coherent results (e.g., choices about content, organization and style). Our focus in this article is the editors' decisions about which editing tasks to undertake, that is, where to allocate their effort, which manages a dependency between an editing task and an available actor.

In Wikipedia, we see opportunities for all of the kinds of coordination noted above. Editors can explicitly coordinate with each other via the article Talk page, a dedicated page associated with each article that provides a forum for coordinating changes to the article, prioritizing additions, discussing policies and procedures and eliciting assistance from other editors. Empirical studies in Wikipedia coordination have generally explored explicit coordination (e.g., [18–20, 25, 33]). Editor can also coordinate implicitly. For example, editors may share a vision of what an article should cover that guides their decisions about coverage, perhaps based on earlier discussions, earlier collaboration, or a common point of view.

Finally, as the editors share a common work space (the article), there are possibilities for stigmergic coordination, where the edits made by one editor spark edits made by another. We identify as stigmergic coordination cases in which one editor's edit is made in response to another editor's edit rather than in response to explicit discussion. We note that the Wikipedia infrastructure provides direct support for this type of coordination. To facilitate tracking modifications and edits, the Wikimedia systems enables a logged-in user to set a watchlist. A watchlist is a page that generates a list of recent changes made to the pages being watched. In this way, an editor can keep track of what's happening to these pages and so react to these changes.

METHOD

The over-all design of the study presented in this article is comparative case study. We describe the pattern of editing observed in two articles of two different quality levels to determine the extent to which coordination appears to be done stigmergically. Specifically, we chose *Abraham Lincoln*[1] a Good (formerly Featured) article on a controversial topic and *Business*[2], a C-level article (i.e., one still lacking important content). The two articles were selected from the English-language version of Wikipedia, as it has the largest number of articles and the software we used was originally developed to process this version. As well, within each article we compare stigmergic and non-stigmergic edits. Finally, we include a preliminary examination of the relation between stigmergic coordination and article quality in a stratified random sample of 61 articles.

[1]https://en.wikipedia.org/wiki/Abraham_Lincoln

[2]https://en.wikipedia.org/wiki/Business

Evidence of stigmergic coordination in Wikipedia

In this section, we describe how we analyzed Wikipedia edits for evidence of stigmergic coordination. As noted above, the kind of coordination we are examining in this article is the editor's decisions about where to edit.

The work done in Wikipedia is recorded in the revision history of a Wikipedia page. The revision history shows nearly every version of the article (in extremely rare cases, a revision can be deleted, e.g., if an edit added libelous content), with a time stamp (date and time of creation), the most recent editor (or IP address for anonymous edits), an optional flag for minor changes applied by the editor, the size of the changes (in bytes) and an optional comment given by the editor (see Figure 1). We call these items the revision metadata, as opposed to the textual content of each article revision.

The changes between pairs of revisions can be accessed through so-called diff pages. Diff pages display a line-by-line comparison of the wiki markup text of two revisions (see figure 2). The diff page for a pair of chronologically adjacent revisions *rev-1* and *rev-2* thus displays the editing activity of one editor at a certain point in time in the history of a page. We call the changes from one revision to another a diff.

For each Wikipedia page, there is a corresponding Talk page, which provides a forum for editors to discuss possible changes to a file. By examining diffs, we can identify individual contributions to this discussion. These discussions are evidence of the possibility of explicit coordination.

By looking for diffs that changed the same lines of the articles, we can distinguish cases where two editors contributed to the same part of an article versus editors making changes in unrelated sections of an article. (Note that a line in a Wikipedia article is more like a paragraph in a word processing document, as it may span multiple lines when displayed on the screen.) This approach is an advance over simply connecting editors who have edited the same article, without considering if these edits are at all related.

We identify as possible cases of stigmergic collaboration consecutive edits made to the same line of the article by two editors who do not similarly interact in the discussion on the article Talk page. Such a situation suggests that the second editor's actions were prompted by the first editor's edits rather than by explicit discussion.

Stigmergic edit network structure

We represent the way one editor's edits might influence another editor's edits in the form of a social network. A social network is a graph comprising nodes representing individuals or organizations and edges between pairs of nodes representing some kind of relationship between the nodes. In our case, the nodes in the network represent the editors who have contributed to the article. We dropped bots (i.e., programs that automatically make edits) from consideration. We add an edge from editor B to editor A when B edits a line in an article that

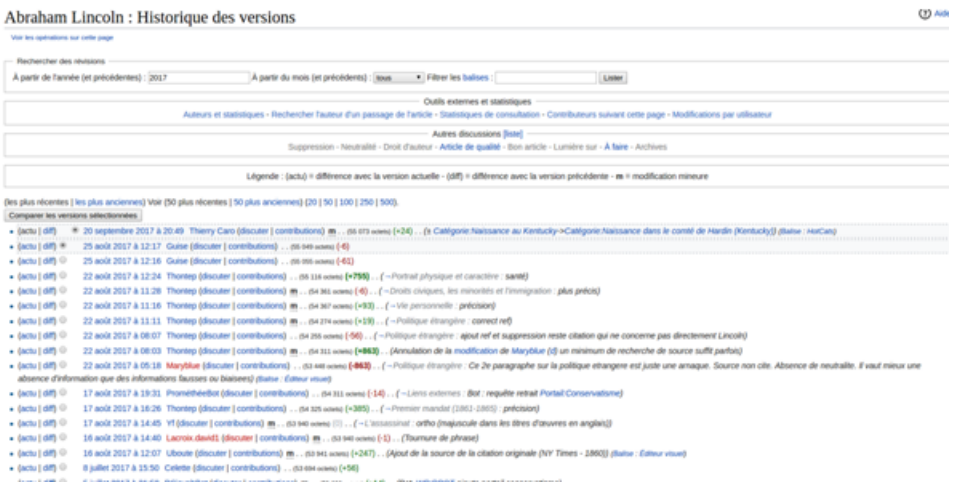


Figure 1: Example of revision page in Wikipedia

Figure 2: Difference between two versions of an article: A diff

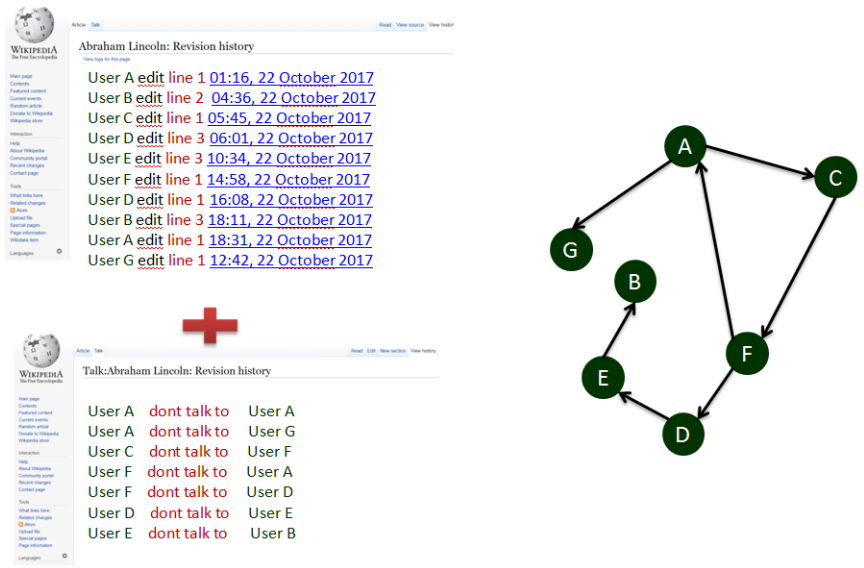


Figure 3: An example of stigmergic Network of a wikipedia article

was last edited by *A* (loops are allowed when an editor edits the same line repeatedly). This creates an oriented graph. We call this network the *Edit* network. The presence of a edge from *B* to *A* means that *A*'s contribution may have influenced *B*'s. The count of the edges added represents how often *B* edited following *A*. A similar network is created for edits on the Talk page (a *Talk* network). In this network, the count of the edges from *B* to *A* represents the number of times editor *B* replied to a contribution to the Talk page by *A*.

Finally, we form a network of stigmergic edits (the Stigmergic network) by considering only edges in the *Edit* network where

Figure 4: Assessing edit quality in Wikipedia using ORES scores

Editor 2		Editor 1		
		Damaging	**Good faith**	
			Minor	**Not minor**
Damaging		Vandalism		
Good faith	**minor**	Minor fixes		
	not minor	Repairing vandalism	Own contribution	Interesting cooperation

Table 1: Cooperation quality

B never replied to editor *A* on article Talk page (i.e., we remove from the *Edit* network the *Talk* network). Contrariwise, the intersection between the *Edit* network and the *Talk* network represents edits made by editors who have also communicated at some point in the creation of the article. An instance of the process of constructing the networks is shown in Figure 3. We note that this is an overly strict operationalization of stigmergy, since the discussion on Talk might not have been related to the edits or even come after them, but it provides a first estimate, which may be refined in future versions.

Contribution quality and stigmergic coordination

We are interested in how an edit by one editor might prompt action by another without the need for explicit discussion, thus showing evidence for stigmeric coordination. We note though that there can be several kinds of prompts. It could be that the second editor is reacting to evidence of vandalism by the first or simply fixing small errors (e.g., typos or grammar). In both these cases, it would not be surprising to see a second editor make an edit without feeling the need to explicitly coordinate with other. And of course, it might be that the second edit is itself vandalism, rather than a response to the first edit. While the first two cases can be considered stigmergic coordination, we are most interested in situations where both editors are making substantive additions to the article, showing that the editors are able to use the changes to article itself as guides to their own contributions.

To identify vandalism, we assess the quality of each edit using the web service ORES (Objective Revision Evaluation Service[3]), which generates a score of edit quality as shown in Figure 4. According to this score, it is possible to classify edits into damaging or good-faith edits. We also consider the scale of the edit as declared by the editor's use of the "minor edit" flag (applied when "only superficial differences exist between the current and previous versions"[4]). Based on these classifications, we identify five type of contributions, as shown in Table 1 (referring to the type of the second edit). The interesting situation is when the second contribution is a non-minor edit. Coming after a damaging edit, we consider this some kind of repair; after a minor edit, the editor's own contribution to the article; and after a non-minor edit, an interesting level of cooperation between the editors, each in turn making a substantive contribution to the same part of an article.

Data collection and analysis

We used the Wikipedia API to collect the data for our study because it provides precise information about the edits that can be easily connected to other data, such as the edit quality from

[3]http://ores.wmflabs.org/

[4]https://en.wikipedia.org/wiki/Help:Minor_edit

ORES score. We wrote a program to extract data using the API and to parse the revision history for each article and the associated Talk page to identify the individual edits. For each edit, the program retrieved the edit quality from the ORES Web service. Finally, the program built the *Edit* and *Talk* networks by identifying the consecutive edits made in the same line. To analyze the network structure, we used the Python package Networkx.

RESULTS

In this section, we present our results, discussing in turn the networks, network properties and contribution quality.

Constructed networks

Figure 5 shows the different network that we constructed from the edit history for a Wikipedia article and associated Talk page. Figure 5a and Figure 5b show respectively the *Edit* networks for the *Abraham Lincoln* article and the *Business* article. Note that the network for the *Abraham Lincoln* article shows a larger number of edits. Both show signs of more central editors, though this phenomenon is more visible in the less dense network for the *Business* article. Figures 5c and 5d show respectively the *Talk* networks for the *Abraham Lincoln* article and the *Business* article. Again, the network for the *Abraham Lincoln* article is larger, and more centralized. Finally, we propose a third kind of network, a stigmergic editing network. We formed this network by subtracting the *Talk* network from the *Edit* network. The respective networks are shown in Figures 5e and 5f. This procedure is conservative, as it removes any edit where an editor ever replied in Talk to the previous editor. Tables 2 and 3 provide basic statistics about each network. Note that there are more relations than edges because editors can be connected multiple times.

	edit	talk	talk+edit	stigmergic
#nodes	4600	1787	112	4598
#relations	19534	6790	3469	16065
#edges	13511	4667	321	13190
density	0.00119	0.0028	0.03	0.00117

Table 2: Descriptive statistics of different network properties of Abraham Lincoln

	edit	talk	talk+edit	stigmergic
#nodes	2444	72	4	2444
#relations	5248	87	39	5209
#edges	4648	78	3	4645
density	0.0015	0.030	0.5	0.015

Table 3: Descriptive statistics of different network properties of Business

Cooperation quality

We next present results on the nature of editors' contributions. As noted above, editors may be triggered to edit without explicit coordination by both positive and negative changes to an article. To understand the nature of the collaboration, we sorted the edits into the five categories defined in Table 1. As a comparison, we did the same for non-stigmergic edits, those for which there was also a contribution to the article's Talk page (computed as the intersection of the *Edit* and *Talk* networks).

Table 4 gives the counts of the edits in the different categories. Figure 6 and Figure 7 show the distribution of edits for the *Abraham Lincoln* and *Business* articles respectively. As shown in Figure 6a, about 4/5ths of contribution to the *Abraham Lincoln* article are done in a stigmergic way; the remaining 1/5th are made with contribution to the Talk page. Figure 6b shows the breakdown of edits among the different categories overall, while Figures 6c and 6d show the breakdown for the non-stigmergic and stigmergic edits respectively.

Collaboration quality and article quality

The analysis presented above of the kinds of edits made to the two pages suggest a relationship between the distribution of the kinds of edits and article quality. To further explore this relationship, we counted the number of different kinds of edits in a larger sample of articles. To do so, we randomly selected 61 articles from the English-language Wikipedia stratified by quality: 17 Featured articles (the top quality level), 21 Good articles and 23 C-class articles. We followed the same definitions as above to sort edits first into stigmergic and non-stigmergic edits and then into the five categories.

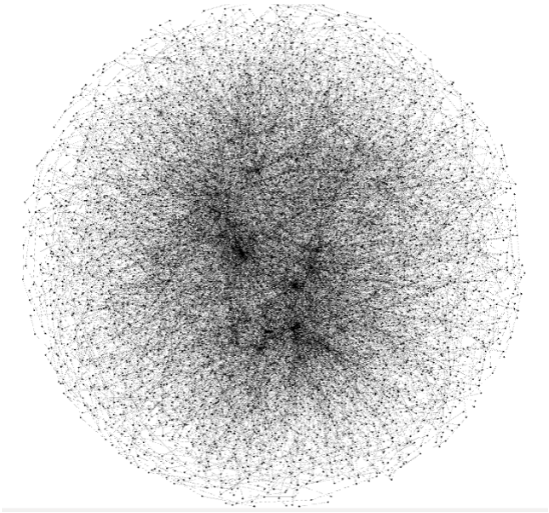
The distributions of these counts are shown as box plots in Figure 8 (note that the scale of the y-axes are different for the different plots). Overall there is a clear pattern that higher quality articles have more edits of all categories. Interestingly, stigmergic edits are distributed across all of the categories of edits for all qualities of articles. The data confirm that vandalism and vandalism fixing is generally stigmergic. In contrast, the non-stigmergic edits show a skew towards "interesting cooperation" for the higher-quality articles. And the C-class articles show a general dearth of non-stigmergic coordination.

CONCLUSION

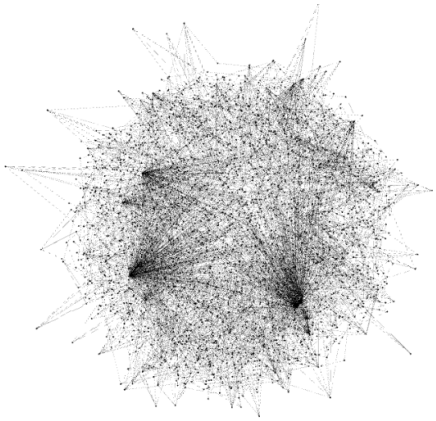
In summary, the data presented in this paper suggest that a substantial fraction of the edits made on Wikipedia are coordinated without explicit discussion on the Talk pages. (Indeed, because we adopted an overly strict operationalization, the data we present may be underestimates.) We hypothesize that these edits represent stigmergic coordination, namely, the prior edit itself sparks the following action. This interpretation seems most appropriate for the cases of "minor fixes" and "repairing vandalism", which would not seem to require much discussion. But even more substantive contributions seem often to be made without the need for discussion.

This paper contributes to research on coordination and on Wikipedia. Methodologically, the paper proposes a more refined approach to relating the contributions of Wikipedia editors by tracking edits line-by-line rather than article by article. We argue that this approach to building a network is a better reflection of how the work of one editor might influence another.

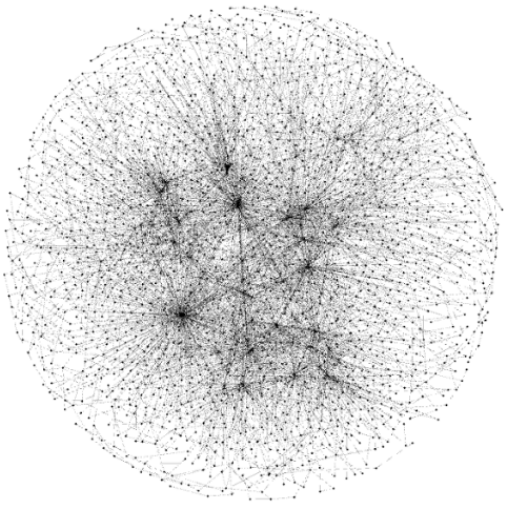
Theoretically, the paper demonstrates the potentially important role that stigmergy plays in coordinating the work of members



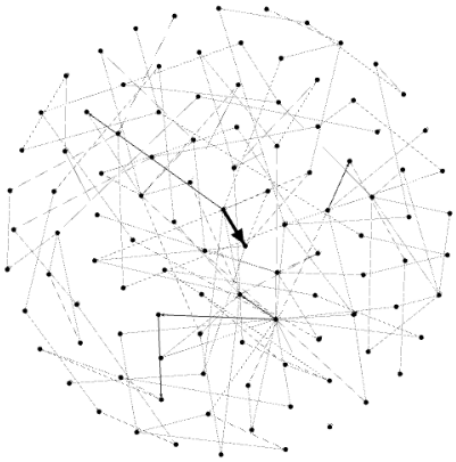
(a) Edit network *Abraham Lincoln*



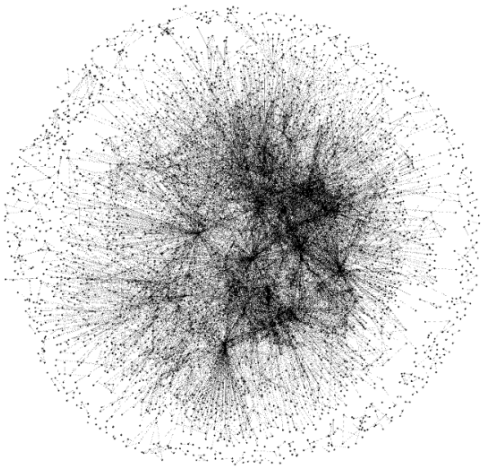
(b) Edit network *Business*



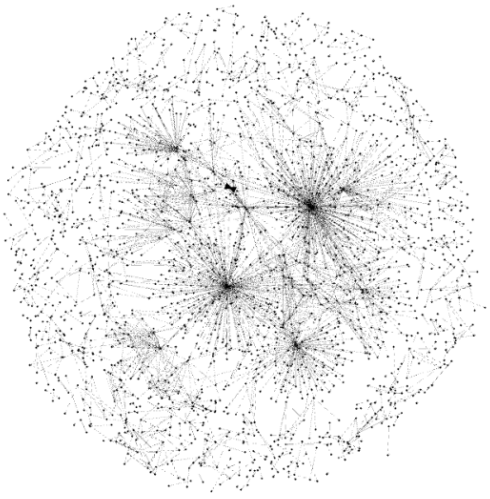
(c) Talk network *Abraham Lincoln*



(d) Talk network *Business*



(e) Stigmergic network *Abraham Lincoln*

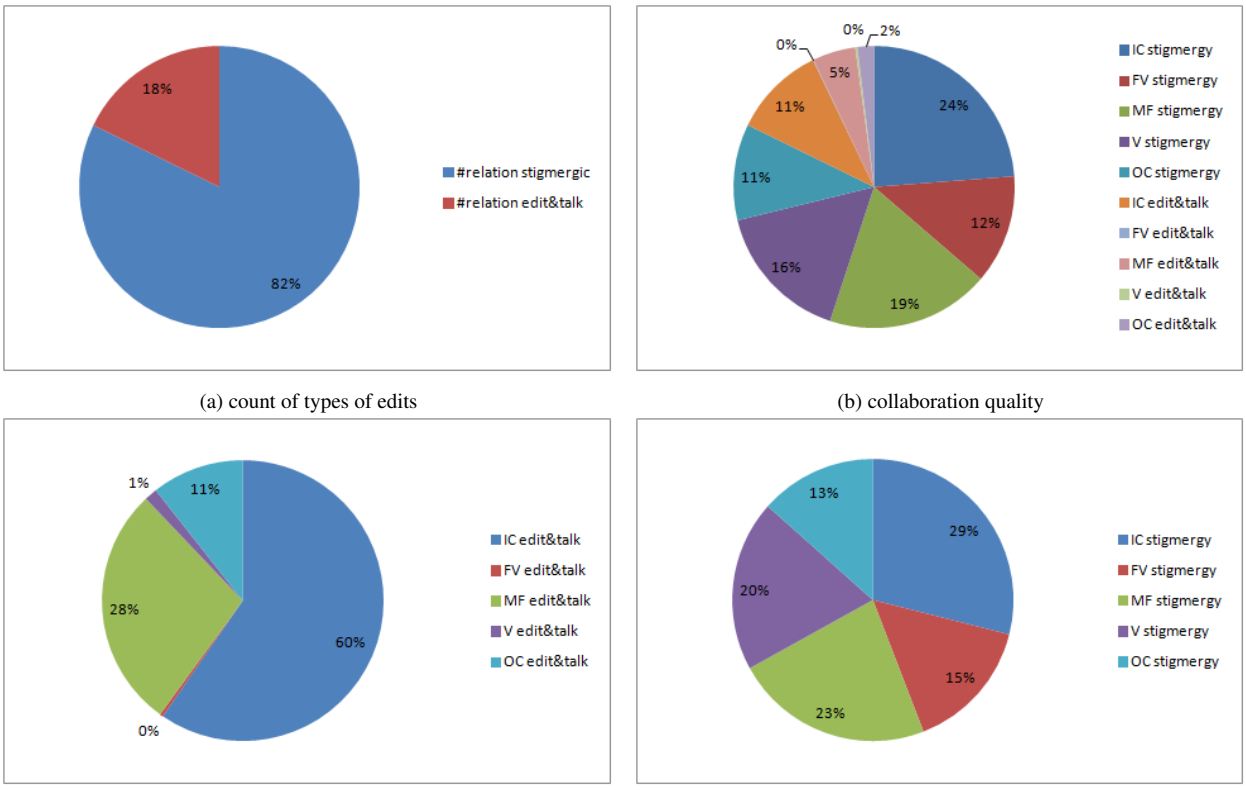


(f) Stigmergic network *Business*

Figure 5: Visualizations of the networks for two articles

	Abraham Lincoln		Business	
	Stigmergic	talk and edit	Stigmergic	talk and edit
#Contributions	16065	3469	5209	39
Vandalism (V)	3150	51	2088	1
Fixing Vandalism (FV)	2443	13	1437	0
Minor Fixes (MF)	3669	967	690	7
Own contribution (OC)	2156	369	324	12
Interesting Cooperation (IC)	4674	2069	670	19

Table 4: Descriptive statistics for collaboration quality



(a) count of types of edits

(b) collaboration quality

(c) collaboration quality in edit+talk network (non-stigmergic)

(d) collaboration quality in stigmergic network

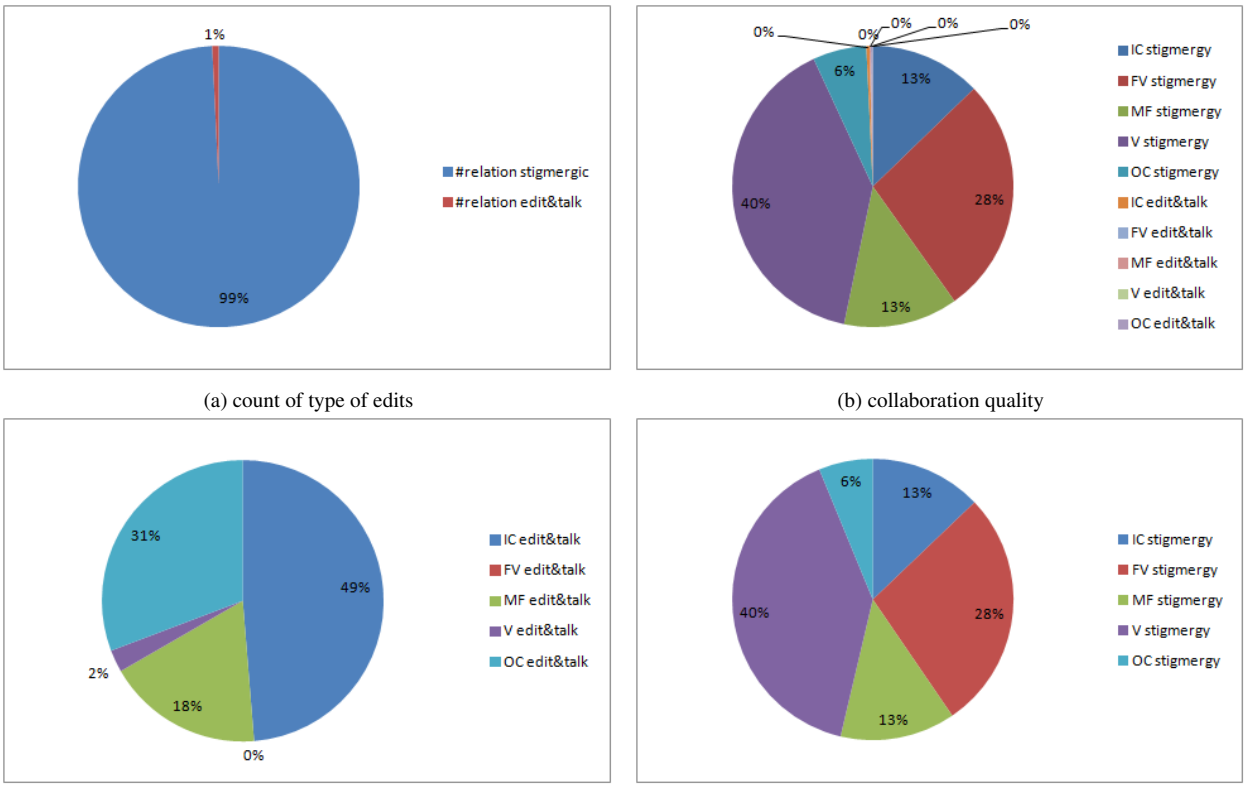
Figure 6: Breakdown of collaboration quality in the *Abraham Lincoln* article

of a distributed group. The data show how stigmergic coordination can support both for fixing problems and for making substantive contributions to the article.

Our preliminary results suggest multiple opportunities for further research. First, as noted above, our operationalization of stigmergic coordination (the *Edit* network minus the *Talk* network) is too stringent, since it eliminates any edit where the editor ever replied to the previous editor, which does not consider the order of edits. A different procedure to building the networks could take those ordering effects into account, identifying as non-stigmergic only edits that are temporally close to discussion. A further question is if the role of stigmergic vs. explicit coordination changes through the life of an article.

Second, while our current analysis rules out explicit coordination of most edits, it is not sufficient to distinguish between implicit and stigmergic coordination. It could be that editors find the Talk discussions useful in guiding their own behaviors without having to contribute themselves (though this mode of working is itself a form of stigmergic coordination). Future research using these data could examine in more detail how Talk contributions are related to editing.

Of particular interest is whether participation in Talk helps novice editors. On many occasions, editors have discussions



(a) count of type of edits

(b) collaboration quality

(c) collaboration quality edit+talk network (non-stigmergic)

(d) collaboration quality in stigmergic network

Figure 7: Breakdown of collaboration quality in the *Business* article

on the Talk pages or ask how to make contributions, thus improving through interaction with experienced editors. Passive reading of the Talk pages may provide a form of social learning. From such interactions, new editors can learn discipline and the rules and regulations about Wikipedia. But in communities like Wikipedia where participation is open, editors are not obliged to discuss for learning. They can instead learn directly by observing edits and by practicing. If they do not face difficulties and need help from other editors, they can directly contribute and making their own decision by following others.

Finally, more work is needed to understand how editors interpret the signals from the Wikimedia system regarding the activities of others and use those as guides for their own contributions, thus enabling stigmergic coordination. In particular, our analysis has considered only the metadata for edits and only coordination of allocation of effort. Examining the content of the edits, while much more challenging, could yield more insight into how the distributed group of Wikipedia editors achieve coordination in creating quality articles. For example, it is possible to insert comments in the body of an article: future research could examine how these guide editors.

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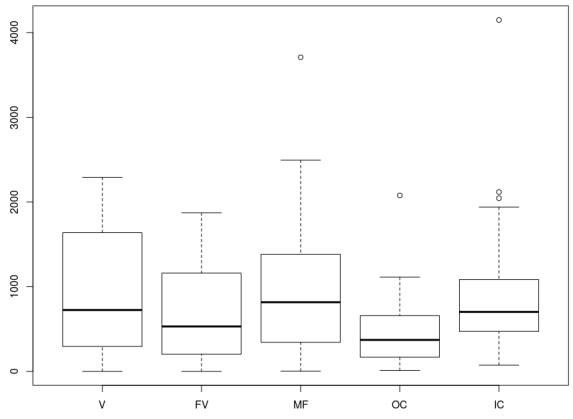
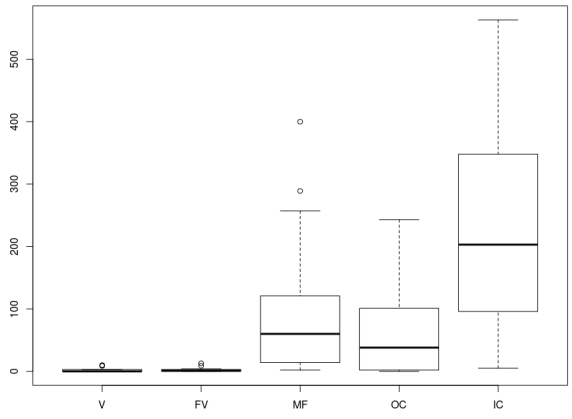
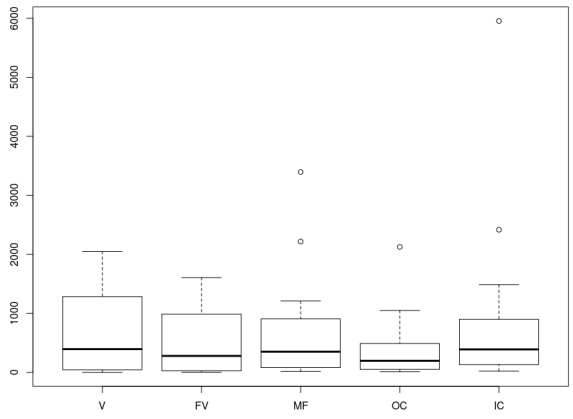


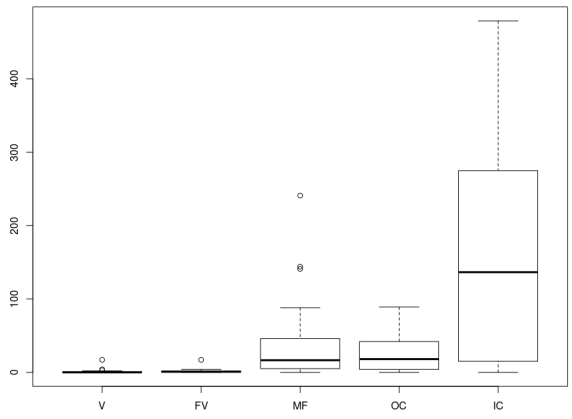
(a) FA-class in stigmergic network



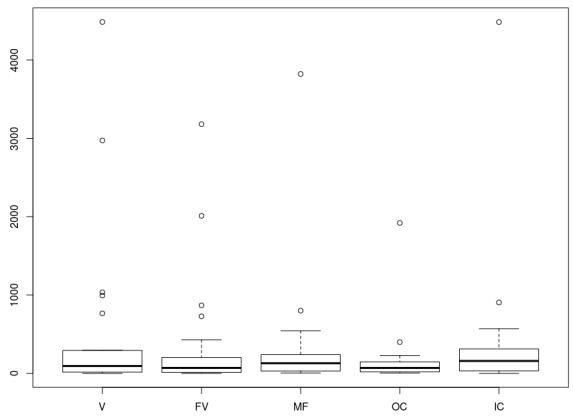
(b) FA-class in non-stigmergic



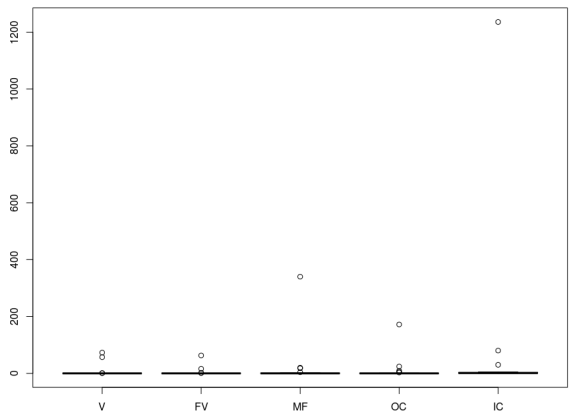
(c) GA-class in stigmergic network



(d) GA-class in non-stigmergic



(e) C-class in stigmergic network



(f) C-class in non-stigmergic

Figure 8: Cooperation quality in stigmergic network vs non-stigmergic network by article quality class. NB. plots have different y-axes.

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