Stigmergic Collaboration: A Framework for Understanding and Designing Mass Collaboration

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Mass Collaboration as Digital Stigmergic Collaboration

There are many opportunities for using mass collaboration in education (Cress et al., 2013). However, as an area that is still emerging, there are also many gaps in both understanding mass collaboration, as well as its effective design and delivery. This makes it challenging to conduct effective research, establish and manage mass collaboration in educational contexts or understand how they work in order to effectively engage pre-existing communities. This article aims to help address this challenge by outlining a framework for defining, understanding and, ultimately, designing mass collaboration.[1]

In the context of this paper and the framework presented here, mass collaboration is defined as digital stigmergic collaboration (collective creation of shared representations in digital media) where the membership is near or greater than 25 participants (Elliott, 2007). This definition is based upon an underlying understanding of collaboration as the process of a group collectively creating emergent, shared representations of a process and or outcome that reflects the input of the total body of contributors.

[1] The theory summarised here was developed and is described more fully in my doctoral thesis, Stigmergic Collaboration: A theoretical framework for mass collaboration (2007). This paper also draws on learning and insight gained from 7 years of industry experience following completion of my PhD. This has involved applying this framework to the design and delivery of mass collaborations focused on the creation of government policy, strategy and urban planning. While all these instances have required considerable strategic community building components, the core logic that stigmergic collaboration underpins scalable collaboration has held true and provided key design insights.

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The framework presented here also draws upon a concept known as 'stigmergy'. Stigmergy is a form of mediated communication where signs placed in the environment by agents serve as stimuli to other agents to further transform the environment, for example, the use of pheromones in ant colonies. Stigmergy as a concept was developed in the context of the study of social insects and has recently been expanded through application in fields such as artificial intelligence (AI) and robotics. In the present context, stigmergy helps explain how collaboration scales from small group settings to large online communities, thereby shattering the 'glass ceiling' of face-to-face collaboration (Elliott, 2007). Stigmergy is also a behavioural mechanism that equates to the externalisation of collaborative interactions and creative contributions that take place in collaborative learning situations. Therefore, linking stigmergy to the role of media in collaboration provides a means for tracing an evolution from the manipulation of materials for the augmentation of face-to-face collaborative processes to the emergence of digital workspaces and mass collaboration.

In the context of education, through its inherently distributed process and mechanisms, stigmergy enables a radically more distributed and decentralised mode of interaction, production, teaching and learning. It puts participants more in control over their choice of roles, contribution, learning activities and experience. As a specific type of social system, stigmergy also shifts interactions from person to person to a site-of-work focus. This lowers the barriers to participation by reducing the need for social negotiation (Elliott, 2007) while allowing individuals to self-select topics and activities of interests.

The ideas presented in this chapter are organised with the aim of illustrating how collaboration is a specific type of collective activity that can only scale beyond small face-to-face groups through stigmergy. After a brief introduction to the ideas, the sections of this chapter are:

- *Frameworks for understanding and designing collaboration*—which provides the rationale and underlying assumptions made about collaboration in general
- *Stigmergy—scaling social interaction through indirect communication*—a brief introduction to the origins and key elements and aspects of stigmergy
- *Stigmergic collaboration—how collaboration scales membership and reach*—which applies stigmergy directly to collaboration and shows how it is extended as a result
- *Defining and designing mass collaboration*—reflects on several other design considerations and implications of stigmergic collaborative systems

The chapter ends with suggestions for future research and how the connections between the present work and CSCL might be further explored.

Frameworks for Understanding and Designing Collaboration

An Etymological and Action Research Approach to Defining Collaboration

Central to the approach for the framework for mass collaboration is a grounded understanding and position regarding collaboration in any context and at any scale. Therefore, the following section provides in brief the research rationale behind this particular understanding of collaboration.

From an etymological perspective, collaboration as a term is relatively new to the English language. First appearing in print in 1802, the term, *collaborator*, was used throughout the nineteenth century to refer to scientific (co-authorship) and artistic (playwright) co-creation. A key insight that etymological review reveals is that most early mentions were in relation to the collective creation of literary content (Elliott, 2007). This is a form of collective activity which not only incorporates the creative process but that of stigmergy. Expanded below, stigmergy is a mode of communication where agents make changes to their environment and interpret these changes as messages, which cue specific behaviours. In his *Expert Assessment of Human-Human Stigmergy*, developed for the Canadian Government, Parunak confirms, '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' (Parunak, 2005).

That stigmergy is integral to the etymological origins of collaboration provides a critical insight into its material nature and process. Further, the involvement of creative production represents a primary distinction between collaboration and cooperation, where cooperation involves more transactional interactions often characterised by maintained divisions of labour (Dillenbourg, Baker, Blaye, & O'Malley, 1996; Stahl, Koschmann, & Suthers, 2006). That this more specific usage of the term 'to collaborate'—the involvement of media in collective creative production, e.g. co-authoring—has been lost or subsumed within a larger, more generalised usage of the term (e.g. to work in conjunction with another[2]) is interesting in its own right.

This general, more commonplace definition, means that definitions of collaboration can and do occur in a wide range of research contexts. These include fine art criticism (Green, 2001), IT, organisational theory (Black et al., 2003), network theory (Newman, 2001), educational theory (Gifford & Enyedy, 1999) and artificial intelligence (Grosz & Sarit, 1999). When reviewing these definitions, a key reflection is that the definition of collaboration tends to vary depending upon the contexts, interests and applications of those who are defining it. While this is to be expected, a goal of the present research has been to develop a generalised understanding applicable across disciplinary contexts.

[2] *Oxford English Dictionary, Second Edition,* (1989). (Eds.) J. A. Simpson & E. S. C. Weiner. Oxford: Oxford University Press

Although some have expressed the need for a general theory or framework of collaboration (Wood & Gray, 1991), no specific field of research has attempted such a formulation that is designed for application in all contexts and at all scales. Any such framework would need to account for the collective generation of ideas where agents are in some way synchronised during the creative process. While the cognitive sciences provide a body of knowledge to draw upon, approaches in this area tend to view cognition as information processing within individual minds, often excluding wider social and contextual factors (Hollan, Hutchins, & Kirsh, 2000).

However, a number of disciplines acknowledge and even emphasise the role that the wider social, cultural and material context plays in the formation of cognition, meaning, relevance and intelligence. These include activity theory (Engeström, 1987; Gifford & Enyedy, 1999; Leont'ev, 1979, 1981; Vygotsky, 1978), situated action (Suchman, 1987), distributed cognition (Hutchins, 2000; Susi & Ziemke, 2001) and actor-network theory (Latour, 2005; Law, 1992) and CSCL (Stahl et al., 2006). This more holistic perspective provides a platform for understanding collaborative production as a process that is simultaneously social, cultural and material. It also provides a link to stigmergy and its role in coordinating the creative contributions through the material environment—whether physical or virtual. In fact, Susi and Ziemke concluded that stigmergy offers a minimal common ground between activity theory and situated and distributed cognition (Susi & Ziemke, 2001).

Aligned with this lineage of thought, I developed the following definition, specifically to inform the design of collaborative processes and technologies in any context, at any scale.

> *Collaboration is the process of two or more people collectively creating emergent, shared representations of a process and or outcome that reflects the input of the total body of contributors.*

Another version of this definition, one that preferences the process or mode of co-creation, is:

> *Two or more people adding, editing or deleting a shared pool of content.*

The shared representations or pool of content being created can comprise physical or virtual media and materials or simply the ideas within each another's minds. Therefore, this definition can account for situations where collaboration is driven primarily by language exchanges (i.e. a discussion where new ideas are formed). I call this *discursive collaboration*. This definition also covers scenarios where the goal is to externalise these shared representation or content into the environment (e.g. coding a new software application or creating a public artwork sculpture). This second form I call *stigmergic collaboration* (described in detail below). While discursive and stigmergic collaboration can occur in their pure form individually, it is more common to see them integrated with one another and taking place together.

While this definition also stipulates that the output of collaboration may be an ongoing process (such as in the case of business partners) and or a final outcome (such as a co-authored paper), it is also necessary to recognise that for all participants whose activity is deemed collaborative, their input must be supported by the process

and represented in the outcome. Having said this, a collaborator's contribution may not be visible, having been incorporated at earlier stages and thus undetectable, but with its effects still affecting the overall process and outcome. Through the specification of unique, yet universally applicable processes and concepts, this definition aims to be applicable to collaboration in every field of human endeavour at any scale.

Collaboration, Cooperation and Coordination: So What's the Difference?

While the above definition provides a grounding to build upon for understanding *mass* collaboration, in order to develop a holistic and generalised understanding, it must be considered within and in relation to other collective activities where individuals come together to generate value together. Three broad collective processes are presented here, which are assigned to the commonplace terms, collaboration, cooperation and coordination.[3] This approach aims to bring higher resolution to these terms, while at the same time keeping their definitions simple enough to be used in a wide range of research and industry settings.

- Collaboration: two or more people collectively creating emergent, shared representations of a process and or outcome that reflects the input of the total body of contributors.
  - Examples: co-authorship of a single research article, jazz improvisation and wiki page collaboration (e.g. Wikipedia article)
- Cooperation: Separate and distinct, individualistic contributions are made, where the contributions are aggregated for overall gain, value or insight.
  - Examples: surveys; comments made on a research article or blog post, as opposed to editing it directly; and refuse recycling
- Coordination: Unrelated entities are drawn together or arranged within a space designed to align features and highlight patterns.
  - Examples: Web search returns, workplace environments and conferences and common protocols

While these definitions can be used individually in the analysis of existing situations, technologies and spaces, they can also be used to guide the design of new ones. Further, the distinctions drawn here between collaboration and cooperation are similar to those that have been made in other CSCL contexts (Dillenbourg et al., 1996; Roschelle & Teasley, 1995), where cooperation is related to apportioning

[3] Adapted from *Stigmergic Collaboration: A theoretical framework for mass collaboration* (Elliott, 2007)

discrete pieces of work to individuals and creating divisions of labour, while collaboration as linked to a coordinated effort of a group to problem solve together. The present framework extends this thinking, providing a basis for understanding how the two are supported by even deeper mechanisms and processes (e.g. coordination).

A Tool for Analysing and Designing Collaborative Process

While the above definition of collaboration and framework for collective activity provides insight regarding *what* collaboration can be considered to be, they are not focused directly on describing *how* collaboration gets done. And to reiterate, the goal of the present research is to develop approaches applicable at any scale, whether it is two people or two million. Therefore, the following statement is a theory of how collaboration gets done, in any context, at any scale, that is premised upon the above framework for collective activity:

Shared vision guides active contribution to a shared plan and outcome.

This statement is comprised of three components, with each component generalising for specific approaches and techniques used in differing contexts. The following figure shows the relationships of these different components (Fig. 1):

1. Shared vision
   - Shared vision must be based upon a platform of shared understanding, also referred to as 'grounding' (Dillenbourg, 1999).
   - Many methods exist for supporting this part of the process, e.g. workshopping, the MG Taylor method.[4]
   - Shared vision also includes the need to cultivate shared purpose, inspiration, motivation and alignment of goals and interests.

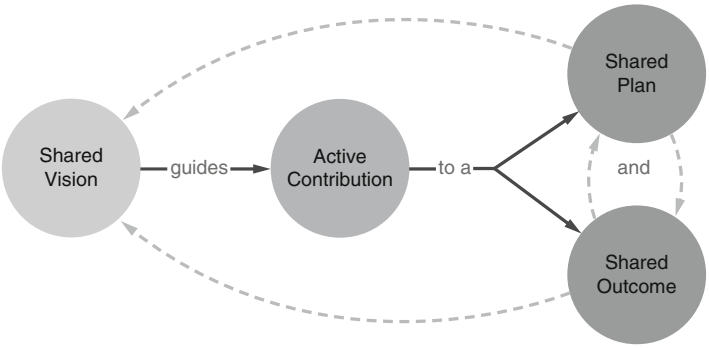

Fig. 1 Analysis and design tool for collaboration

[4] http://www.mgtaylor.com/public/2001/pat_pend.html

2. Active contribution

   - Contribution must be actively made by all participants.
   - For participants to make meaningful and substantial contributions, to 'add, edit or delete', they must be granted or enabled access to the shared content.
   - In order to cater to the interests, capabilities and capacities of participants, efforts should be made to support multiple modes and means of contribution.

3. Shared plan and outcome

   - Continued alignment of a group's shared vision is premised upon a collective understanding of what the group is doing now and in the future. Hence, a shared plan is often a key enabler.
   - A shared plan may exist as an explicit document or artefact or as an element of shared understanding.
   - If a collaborating group is to grow in membership, new participants must be onboarded. A shared plan is key to alleviating onboarding bottlenecks, with documentation of shared vision and journey to date often being included.
   - The ability to share in contributing to the outcome is imperative, which necessitates access to the outcome (whereas, in cooperative settings, outcomes may be the sole property of those responsible for the aggregation of individual contributions).
   - The necessity for continuous negotiation of the shared plan and outcome means that this overall process is cyclical, with active contribution to the plan and outcome leading to an ongoing redefinition of shared vision.

Like the framework for collective activity, this tool can be applied in an analytical capacity, as a health check, to determine if genuine collaboration (as defined above) is taking place. Or, it can be used as a design tool, to determine the requirements for a collaboration that is to take place.

Stigmergy: Scaling Social Interaction through Indirect Communication

The concept of stigmergy was originally developed in study of social insects such as ants and termites. While each individual agent in isolation appears to pursue their own agenda, somehow, the colony as a whole exhibits high levels of organisation (Theraulaz & Bonabeau, 1999). This became known at the time as the 'cooperation paradox', with early scientific concepts and technology being unable to identify how this organisation was coordinated. However, when pheromones were able to be detected and their role as a sign within the environment was understood, the theory of stigmergy could be substantively developed.

As a result, in 1959, Pierre-Paul Grassé coined the term stigmergy from the Greek words stigma 'sign' and ergon 'action' (1959) in order to capture the notion that signs left in the environment may produce action from agents. Not only do

individuals provide stimuli for other individuals through cues such as pheromones trails, but they can also provide cues by reorganising the environment in such a way which produces structures that also serve as stimuli. This allows highly complex structures to self-organise due to the collective input of large numbers of individuals performing extraordinarily simple actions in response to configurations of and encodings within their local environment. This total stigmergic system comprises three key components: agents, environment and the interactions between the two. Further, these interactions give rise to emergent, system-level dynamics.

Agents in the Stigmergic System

In order to make changes to their environment, agents must have the capacity to sense and assess the environment's state, as well as make changes to it in conjunction with their assessment. The ability to sense, assess and change the environment evolves over time in response to a given environment, giving rise to a set of dynamics unique to each stigmergic system. For example, termites have evolved the ability to sense punctures in their mounds, along with corresponding ability to assess repair the damage (Grassé, 1984; Kennedy, Eberhart, & Shi, 2001). Ants create piles of dead ants (cemeteries), by sensing existing piles and moving ants from smaller into larger piles (Bonabeau, Theraulaz, Fourcassié, & Deneubourg, 1998).

The Role and Characteristics of a Stigmergic Environment

The environment in a stigmergic system can be broadly characterised by the three components of topology, variables and processing dynamics.

Stigmergic systems may employ any form of topology, including graphs (networks), indices (catalogues) and Cartesian coordinates (space) (Elliott, 2007). While the environment's structure may vary, it is important that the agent's activities are situated within some form of spatial domain that provides for the agent's experience of localisation. This experience restricts their engagement and senses and limits the demands placed upon their interactive capacities (Parunak, 2005). This enables the system to scale no matter how large the environment grows since there is no centralised organisation or regulatory network needed to span it. Instead, the coordinative and information processing rules and dynamics are distributed throughout the environment and individual agents, forming emergent patterns relevant to the interaction of the agents and environment.

An environment's structure also lends itself to a certain set of state variables that agents may change. For example, in ant systems, variables supporting pheromone deposit include permeability of soil and vegetation, while in animal trail systems, obstacles, ground cover and terrain mutability contribute to the possibility of encoding trails. In human contexts (expanded below), online media lends itself to

variables related to document collaboration, where text and numerical variables are most broadly supported.

Finally, an environment's processing dynamics govern the evolution of variables through time, with the stigmergic system typically incorporating these dynamics to its advantage. This provides the function of additional information processing capacity to the agent-environment interactions. For example, the aggregation and evaporation of pheromones in insect systems have the effect of 'truth maintenance and discarding obsolete information' (Parunak, 2005). Similar effects can be observed in animal trail systems where trodden earth, erosion and dying vegetation produce the trails, while regrowth and continued erosion maximise fidelity through diminishing those which are unused. In human systems, such as textual wiki collaboration, the system's processing capabilities might include notifications of new contributions to other participants, alerts indicating number of +/- characters changed in an edited wiki page (e.g. Wikipedia's "Related changes" feature), or spelling correction suggestions.

Types of Stigmergic Interactions

Interactions in stigmergic systems can be classified into four primary categories:

1. Sematectonic stigmergy: Agents interpret certain configurations of their actual environmental or agent placements as signs.
2. Marker-based stigmergy: Agents interpret specialised markers deposited in the environment as signs (similar to the notion of 'metadata'; Parunak, 2005; Brueckner, 2000).
3. Quantitative signs: These are scalar and of a single type, representing varying intensities of cues.
4. Qualitative signs: These form a unique, discrete set of cues (Kramer, 2005; Parunak, 2005; Theraulaz & Bonabeau, 1999).

Both sematectonic and mark-based interpretations may be comprised of quantitative and or qualitative signs. These four types of interaction provide a means of discriminating and classifying stigmergic activity in a wide range of contexts. For instance, the stigmergic collaboration of co-authoring a Wikipedia article entails for the most part sematectonic/qualitative interpretation of the current state of the article's content (Parunak, 2005). However, common wiki tools such as 'recent changes' provide marker-based/quantitative feedback through positive and negative counts of characters added or deleted during past revisions.

System-Level Dynamics That Emerge as a Result of Stigmergy

The stigmergic system functioning as a whole (all agents plus the environment and its capabilities) produces emergent, system-level dynamics. These dynamics are a distinguishing factor of stigmergy and appear on a level above that of the local

interactions of agent and environment. For instance, regarding the above example of Wikipedia article co-authoring, the emergent system-level behaviour is the expression of a jointly held consciousness that leads to a uniform and holistic conception of an encyclopaedia (Parunak, 2005). In termite mound building (the placement of single, pheromone-impregnated mud balls upon one another), the system-level behaviour is the construction of complex nests and architectures such as arches and ventilation systems (Grassé, 1984; Kennedy et al., 2001; Theraulaz & Bonabeau, 1999).

The emergent capacities of stigmergy also mean that such systems are evolvable, adaptable and able to develop new behaviours (Kelly, 1994; Parunak, 2005). This is an ideal feature for collaborative groups seeking multiple solutions in a continually changing environment. It is also in many ways an excellent fit for learning communities who must constantly adapt to the integration of new knowledge, perspectives and experiences. This ability to adapt and develop new behaviours as an overall system is also closely linked to the notion of intelligence. In stigmergic systems, intelligence is understood to reside 'in the interactions among the agents and the shared dynamical environment' (Parunak, 2005). This raises interesting questions in the context of education with regard to where to locate learning and the outcomes it generates (Cress, 2013).

Human Applications and Adoption of Stigmergy

There are many examples of human-human stigmergy. These include trail and track formation (Helbing, Keltsch, & Molnár, 1997; Helbing, Schweitzer, Keltsch, & Molnár, 1997), graffiti and illegal garbage dumping, where an initial refuse pile attracts more dumping at the same location.[5] On the larger scale, applications comparable to nest building in social insects include the constraints and impositions placed upon development in urban areas by previous building works. However, many smaller-scale instances easily blend into our day to day without our notice, such as how we might place our cutlery on our plate to signal to a waiter that we are finished with our meal. All of these examples are of the sematectonic variety (configurations of the environment) with trail formation, garbage dumping and cutlery placement being quantitative (of a single scalar quantity), while graffiti and building works being largely qualitative (unique, discrete cues).

However, types of stigmergic interaction in human activity tend to be nested, reflecting the complexity of human culture and engagement. For instance, while graffiti might on the outset appear qualitative to those who engage in the art (a good work's techniques and or subject matter inspiring a response in a common location) from outside the graffiti community, it would seem to be an activity governed more

[5] Garbage dumping as stigmergy is mentioned by Dylan Shell on comment to Joe Gregorio's (2002) Stigmergy and the World Wide Web. *Bitworking* (web log): http://bitworking.org/news/Stigmergy, retrieved 20 December 2005

by quantitative means (the more works existing on one particular wall, regardless of merit, the more likely it is that more will be attracted). Of course, both are correct. Additionally, many applications of stigmergy mixes marker based with sematectonic mechanisms. For instance, when a editing a Wikipedia article, it is a common practice to make a revision note, explaining an edit made. Such notes place a marker outside of the content of the focus activity (i.e. improving an article), the equivalent of making a note in a document's margins when co-authoring.

Whether sematectonic, marker based, physical or virtual, the large extent of human-human stigmergy represents a significant area of further research in a wide range of fields, not the least of which CSCL.

Stigmergic Collaboration: How Collaboration Scales in Membership and Reach

While the examples provided above are of human-human stigmergy, they are not necessarily stigmergic *collaboration*. Stigmergic collaboration arises when two or more people utilise some form of material media for the encoding of their collective creative endeavour. For example, and drawing upon the framework for collective activity, graffiti 'canyons' (laneways and walls that attract graffiti) might be best classed as stigmergic coordination, whereas signalling to waiters with your cutlery would be considered stigmergic cooperation. However, drafting Wikipedia articles with other Wikipedians is a classic example of stigmergic collaboration.

The theory of stigmergic collaboration helps understand the role that the externalisation of shared representations plays in scaling and extending collaborative activity. Specifically, it describes how and why this is important. It is important because it extends participants' collaborative capabilities across four primary lines, space, time, mind and the process of emergence.

More Space for Collaboration

Stigmergic collaboration extends the space for collaboration beyond our minds, into the physical and virtual world around us. As we encode aspects of our media environment (e.g. a whiteboard), more surface area (conceptual, physical or virtual) provides for increased access.

More Time for Collaboration

Similarly, material representations of the collaborative output provides an increased level of permanence to contributions through time. This can expand the influence and presence of contributions to those beyond the participants immediately present.

This can be as immediate as emailing a picture of a whiteboard to those not able to attend a meeting or as extended as spanning thousands of years as is the case with cave paintings.

Increased Cognitive Ability for Collaboration

Stigmergic collaboration also allows us to better 'see what we think', providing an enhanced capacity to remember, review, reflect upon and learn from contributions (Cress, 2013; Flower & Hayes, 2008; Webb, 1982). By externalising our otherwise internal representations, we enable the possibility for our consciousness to subject these representations to the workings of components of the brain which are otherwise less connected internally (Baars, 1997; Cress & Kimmerle, 2008). In collaborative contexts, not only does this augment our individual minds but also helps better distribute cognitive load across the group by optimising for working capacities spread throughout the group that would also be otherwise less connected. Externalising into our media environment also opens up the possibility of taking advantage of any transformational dynamics this environment may possess or make possible. For example, calculating, correcting, reformatting, connecting, synthesising, visualising and distributing content—these all extend the mind's capacities and cognition into the wider environment.

Accelerating the Emergence of Collaborative Outcomes

The combination of extended space, time and cognition through stigmergy also extends one of the most important outcomes of collaboration, the process of emergence—larger patterns arising as a result of lower-level, individual contributions. The opportunity for more varied, detailed, persistent and meaningful contributions by more participants means more emergent outcomes are possible. The experience of witnessing this emergence can be both exciting and stimulating (as most with collaborative experience would likely attest). This can have the effect of contributing positive feedback back into the stigmergic system, catalysing even further emergent outcomes. Ultimately, the emergence of outcomes generated by the group above and beyond those generated by any one participating individual is the primary goal and value of collaboration.

Extending Stigmergic Collaboration Through Digital Networks

Extensions of collaborative capability through stigmergy enable numerous forms of collective creation which would otherwise be beyond the scope of our unassisted mental capacities, such as co-authoring books, research articles, plays and films or

the collective creation of sculptures, murals, dramatic performances and research projects. However, even greater potential is unleashed when stigmergic collaboration is amplified with networked digital media. Tools such as Google Docs are providing synchronous collaborative editing opportunities that were previously unavailable even several years ago. These types of tools (to take a simple example) provide the opportunity to shift co-authoring from being reliant upon digital stigmergic *cooperation* procedures (emailing a word processing document around to collaborators, whose contributions must be carefully managed and integrated so as to avoid revision conflicts) to much more genuinely collaborative processes (participants seeing each others' contributions being made in real time and thus being able to manage the integration of their own input). In addition, as outlined in the following section, when digital stigmergic collaboration has the requisite features to support scalability, mass collaboration may also become possible.

Opportunities for Stigmergic Coordination and Cooperation

While this present work is focused on stigmergic collaboration, it is important to note that stigmergy is present in applications of both coordination and cooperation as defined above. Much like collaboration, the encoding of media and especially in digital contexts, stigmergy can act as a powerful extension of cooperation and coordination. Whether it is in cases such as Google's search engine (digital stigmergic coordination), or eBay's online marketplace (digital stigmergic cooperation), the combination of stigmergy, coordination and cooperation, along with networked digital technologies, is transforming our society in significant ways.

Defining and Designing Mass Collaboration

Mass collaboration is defined in the current context as digital stigmergic collaboration (collective creation of shared representations in digital media) where the membership is near or greater than 25 participants. Further, mass collaboration is typically characterised by a number of features described below:

1. Social workspaces: a digital environment or platform that helps attract, coordinate and govern participation
2. Content negotiation: where content creation is the primary mode of interaction, as opposed to social negotiation in the case of face-to-face or smaller-scale collaboration
3. Emergent teaming: where group formation is based more on interest and meritocratic capability than existing relationships or functional roles

The Social Workspace: Where Stigmergic Collaboration Gets Done

Through the process of stigmergic activity, digital artefacts and their corresponding annotations tend to build up, forming a field of work or a social 'workspace' (Ricci, Omicini, Viroli, Gardelli, & Oliva, 2006). These artefacts and their supporting workspaces mediate interaction, providing the coordinative and cooperative functions that support collaboration. Artefacts (e.g. a Wikipedia article) may be linked to one another and/or shared across different workspaces. Workspaces themselves may overlap, sharing both participants and artefacts, and can be nested recursively.

Mass collaborative workspaces also tend to reflect the attributes of a 'boundary object' as identified by sociologist of science Leigh Star (1989). Boundary objects serve the function of coordinating the perspectives of multiple constituencies for some purpose or activity and traditionally may be conceptual or tangible artefacts, simple or complex in their structure (Star, 1989; Star & Griesemer, 1989). Star identifies four main features of the boundary object:

1. Modularity: Each perspective can attend to one specific portion of the boundary object.
2. Accommodation: The boundary object lends itself to various activities.
3. Abstraction: All perspectives are served at once by deletion of features that are specific to each perspective.
4. Standardisation: The information contained in a boundary object is in a pre-specified form so that each constituency knows how to deal with it locally (Star, 1989 as summarised by Wenger, 1998).

The below table provides several examples of these characteristics as represented in mass collaborative social workspaces (Table 1).

The specific technologies that underpin mass collaborative workspaces can vary greatly (as is evident by the above examples). However, their core, high-level functionality is the provision of a site of work accessible to a number of participants that enables one to work as if alone via the ability to add, edit and delete a shared pool of content. Another way of saying this is that the technology must provide for individual contributions to a larger unified work consisting of dynamic content. It must be stressed that this entails not just adding content but also editing and deleting pre-existing material contributed by other participants. This is necessary in order to enable the emergence of *shared* representations held by the total collaborative group.

How a Focus on Content over Social Relationships Supports Scalable Collaboration

The coordination of individuals working as if alone, but in relation to one another, has the effect of providing a site of collaborative work where activities do not have to be mediated by turn-taking social negotiation. Instead, focus is shifted to the

Table 1 Boundary object features associated with mass collaborative projects

Project	Modularity	Abstraction	Accommodation	Standardization
Wikipedia	Any number of people can edit any number of articles at any given time	Contributors can attend separately to issues of content, layout, technical infrastructure, community discussion etc.	Encyclopaedias are abstractions by nature, attempting to represent a 'neutral point of view', the 'no original research' rule	Community-defined standards for content layout, drafting procedures (no copyright material), neutral point of view
Minecraft	Many people may inhabit and build objects in many places	Many activities are open to participants: building objects and the environment, organising events, exploring, socialising	The environment's underlying rules (its 'laws of physics') provide a uniform and common experience by restricting all other possibilities	There is a single set of procedures, software code and licensing rules regarding the modification and adaptation of existing work which is uniform for all residents
Open-source repositories (e.g. GitHub, SourceForge)	Modular by nature, sections of code may be developed by any number of different participants	Various activities are open to participants: writing original functionality, bug fixes, testing	The objectives of the project (i.e. to provide software with 'x' functionality) unify perspectives by restricting and focusing possibilities	Specific coding languages and programming methods are agreed upon or are present as existing code, thereby standardising ongoing contributions[a]

[a]For example, see Apache HTTP Server style guide (online resource) <http://httpd.apache.org/dev/styleguide.html> retrieved 11 December 2014

immediate engagement with a shared site of work through indirect communicative exchanges. This streamlines the creative process, freeing up time and energy that participants would otherwise use in negotiation, while not closing off the options for social negotiation typically supported by workspaces' wider features (e.g. Wikipedia's talk pages or a wiki's related discussion forum or email list serve).

Significantly, this also enables the number of collaborative participants to scale from several dozen (at best) in face-to-face contexts (Lipnack & Stamps, 2000) towards tens and even hundreds of thousands. This is because the capacities of the individual participants are not overwhelmed by the high demands of maintaining social relations with numerous others across an ever-expanding domain and having to negotiate their contributions with them. This lowers the 'costs' of contribution by reducing the need to become acquainted with other participants and to maintain relationships and negotiate contributions with them as they are made. This exploits the potential inherent in digital stigmergic systems for the global coordination of local input, while supporting potentially unlimited scaling.

However, from a design and education perspective, it is important to remember that while social negotiation may be reduced, cultural aspects such as working methods, styles, language and various technological literacy still must be negotiated. Similarly, it is also critical to understand that social negotiation still takes place in mass collaborative contexts and may even be essential to growing and supporting the collaborative community. Most, if not all, mass collaborations have discussions associated with content creation. The key dynamic is here is that negotiation takes a back seat in the creative process as compared to content creation—it is possible to contribute to Wikipedia or Minecraft, for instance, without discussing what you are creating. In the case of Wikipedia, this manifests as encyclopaedic articles; for Minecraft it is the evolving digital landscape and constructions within it; and for open-source software projects, it is the software application.

One key outcome of mass collaborative content creation is that the site of work amounts to a 'single source of truth'. A single source of truth provides coordination effects for participants because everyone has access to the same information about the state and focus of the collaboration (the shared plan) as well as its outcomes. A single source of truth also drives a sense of equity in the creation, or shared ownership, because it is the same object of creation that everyone is contributing to. Therefore, in design contexts, consideration of these dynamics can be important through ensuring that participants can maintain relevant ownership of their contributions through licensing schemes such as Creative Commons.

Management-Free Teaming and Co-production

While a shift from social to content negotiation largely characterises the individual experience of mass collaboration, the collective experience has a corresponding change from interactions driven by more explicit social coordination to one of distributed decision-making and action. Specifically, the formation of teams without explicit member coordination or hierarchical management, what I call *emergent teaming*, is a feature of stigmergic activity. For example, signs in the workspace environment such as prominently placed links to interesting sites of work can guide groups of contributors to converge on locations of mutual interest. Like pheromones in ant colonies guiding teams to a food source for collection, participants create stigmergic cues in their workspace that rally and coordinate the contributions of subgroups.

This same dynamic of emergent teaming can be understood from the alternate perspective of 'group-forming networks' (GFNs). These are networks that support the formation of communicating groups within a larger network. These subgroups create value that scales exponentially with network size. This scaling occurs at a rate of 2 to the power of N where N is the number of nodes in the network (Reed, 1999). Value in this context is defined as 'the value of potential connectivity for transactions. That is, for any particular access point (user), what is the number of different access points (users) that can be connected or reached for a transaction when the need arises'. GFNs have therefore been identified in research as being one

of the more powerful drivers of network value which may have contributed significantly to the growth of giants such as eBay, the popularity of chat rooms and even the Internet itself (Reed, 1999). This effect is now generally referred to as 'Reed's law'. Therefore, mass collaboration can also be seen as a GFN, with emergent teaming as evidence of value being generated within a given network.

Conclusion

It is my belief that there is considerable scope for developing more nuanced and specific definitions for collaboration that improve our ability to analyse and design it. For example, collaboration is a form of collective production where a group has add, edit and delete rights to a shared pool of content and provides specific requirements for functionality that can be designed into software. The application of stigmergy further expands the understanding and definition of collaboration by showing how collective production can scale from small face-to-face teams to large, distributed groups who are not managed by any central function.

With regard to educational and learning contexts, further research should be undertaken to connect theories of stigmergy and collaboration presented in the CSCL literature to that presented here and in other contexts (such as AI, robotics, distributed cognition, etc.). There are likely many findings in CSCL that can be reinterpreted from the perspective of stigmergic systems and their dynamics. For example, stigmergic collaboration challenges notions of what synchronicity and its requirements for collaboration (Dillenbourg, 1999; Stahl et al., 2006).

Another area for further exploration in CSCL contexts is how stigmergy drives self-direction of engagement and interaction, requiring the participant to take more responsibility for their actions and activity than in more traditional working contexts. This creates an environment that the agent is able to independently traverse, exploring for own interests, while still enabling collective outputs and outcomes. This represents both opportunities and challenges in educational settings, enabling more 'self-directed' and 'student-owned learning outcomes', while at the same time requiring educators develop more nuanced understandings of how learning can and is already happening in mass collaboration contexts.

The effective application of mass collaboration to educational and learning situations also must address a key challenge: Collaboration is a capability that is shared between its participants and can only be cultivated through its application. Therefore, learning the skills of mass collaboration follows the same pattern as learning in CSCL contexts: The perspectives and practices are intersubjective and reside between the participants as much as within individuals (Stahl et al., 2006; Suthers, 2005). So in essence, to be able to build the skills needed to collaborate, as well as understand mass collaboration, one must do mass collaboration. In order to address this, I advocate an action research approach. This will allow researchers and educators alike to cultivate a more full and genuine understanding of mass collaboration, through engaging in the actual activity of mass collaboration.

This echoes Stahl's reflections on potential collaborative future for CSCL, 'CSCL may in its next phase collaboratively construct new theories, methodologies and technologies specific to the task of analyzing the social practices of intersubjective meaning making in order to support collaborative learning' (Stahl et al., 2006). In this context, the most logical and compelling idea may then be to establish a mass collaboration on mass collaboration in education.

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