Staying in the Loop: Structure and Dynamics of Wikipedia's Breaking News Collaborations

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ABSTRACT

Despite the fact that Wikipedia articles about current events are more popular and attract more contributions than typical articles, canonical studies of Wikipedia have only analyzed articles about pre-existing information. We expect the co-authoring of articles about breaking news incidents to exhibit high-tempo coordination dynamics which are not found in articles about historical events and information. Using 1.03 million revisions made by 158,384 users to 3,233 English Wikipedia articles about disasters, catastrophes, and conflicts since 1990, we construct "article trajectories" of editor interactions as they coauthor an article. Examining a subset of this corpus, our analysis demonstrates that articles about current events exhibit structures and dynamics distinct from those observed among articles about non-breaking events. These findings have implications for how collective intelligence systems can be leveraged to process and make sense of complex information.

Categories and Subject Descriptors

K.4.3 [**Computers and Society**]: Organizational Impacts – *Computer-supported collaborative work.*

General Terms

Management, Design, Human Factors.

Keywords

Wikipedia, high-tempo collaboration, network analysis, breaking news, collaboration, multigraph

1. INTRODUCTION

As an encyclopedia that "anyone can edit", Wikipedia has attracted substantial scholarly interest in understanding the socio-technical processes that sustain motivated and coherent peer production of quality information. For example, some of the earliest research found that characteristics of the editorial group are associated with attributes of a Wikipedia article: more editors means higher-quality "featured" articles [29].

Kittur, Kraut and colleagues showed larger numbers of editors are associated with greater process loss when article requires interdependent editing [15, 16]. In such cases they suggested that concentrating the work among a small number of editors allows them to construct a shared model of the article structure that can later be exploited by larger numbers of editors. This suggests that concentrated activity by a small number of editors early in the life of an article, followed by contributions from a larger group of editors once the structure has been set, is a model arrangement for successful article creation.

However, we argue that this understanding of the relationship between the characteristics of editors, task attributes, and various outcome measures is incomplete, because it treats the development of all Wikipedia articles as identical. To highlight this we focus on a very important class of articles known as "breaking news articles", written as an incident (like an airplane crash) unfolds, and compare them with "non-breaking" articles about similar incidents that occurred in the past and are therefore already well documented in other sources. These breaking articles—which are all but ignored by previous research on editorial processes—attract more contributors [28], more unique edits [30], and more page views [18] in a given month than other article types.

Breaking news incidents are highly salient, and we argue that the behavior of users engaging in sensemaking, information seeking, the sources from which knowledge is being synthesized, and the contribution patterns associated with articles about these incidents operate under very different dynamics than those of other Wikipedia articles. Our research shows different article types yield different editorial revision practices, and a small set of coordinating editors working early on in the life of an article may not be appropriate for all article types. Thus, a disconnect may exist between the articles upon which our theoretical understanding has been established and the articles that are most prominently produced and consumed.

To demonstrate differences in editorial patterns, we adopt a structural approach and use network analysis methods to characterize the patterns of collaboration on Wikipedia articles. Using the revision histories of Wikipedia articles about commercial airline disasters, we construct "article trajectories" that capture the structure and temporal dynamics that emerge from the relationships among editors modifying other editors' contributions within an article. By capturing substantively different patterns of interaction as editors revise other users' contributions, this article trajectory method surfaces the ways in which editors remain involved in the joint monitoring and modification and captures different processes of interaction and peer production of Wikipedia content. Compared to non-breaking articles which lack these tight dependencies and motivations to contribute, we expect breaking news articles should exhibit close and dense co-authorship ties in our revision network approach, indicating the presence of heedful, coupled interactions.

Our findings demonstrate that article revision patterns immediately following unexpected, catastrophic incidents differ from the revision patterns of similar articles about historical events. Although these patterns of interaction on breaking news articles have intensified as Wikipedia has become more popular, the revision networks of breaking articles also "regress to the mean" as the event becomes more distant. We conclude by

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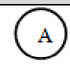
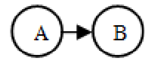
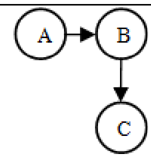
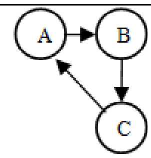
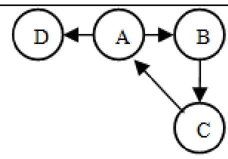
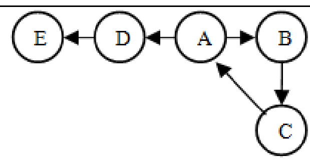
Revision number	Revision editor	Revision history chain graph
1	A	
2	B	
3	C	
4	A	
5	D	
6	E	

Figure 1: Article trajectory construction example

discussing the implications our findings have for analyzing and theorizing about the success of online communities when participation is intense, popular, and brief as well as recognizing that collective intelligence systems create very different types of information artifacts under various contexts for production.

2. RESEARCH QUESTIONS

Following a catastrophic incident, users are motivated to seek and monitor information about an event. This upsets the ability for a small, dedicated cohort to engage in concentrated structuring and synthesis. Little is currently known about how Wikipedia editors co-author content and contribute new information as it becomes rapidly available in current and breaking news articles. Social media spaces exhibit analogous processes as citizens and responders use mobile phones, text messaging, and micro-blogging to organize ad hoc responses, process and disseminate information, and provide social support [22]. However, most Wikipedia users are personally unaffected by the immediate consequences of a particular event and Wikipedia policy emphasizes the need for neutral and reliable sources for all encyclopedic content. These discrepancies motivate three central research questions about breaking news articles:

First, do breaking news articles exhibit different patterns of coauthorship and revision than non-breaking articles? Immediately following a breaking news event, collaboration should be characterized by intense interaction in which individuals iteratively read and modify each other’s contributions to construct a joint account of the event. The resulting structures of these articles’ article trajectories should manifest as highly centralized and dense interactions as early contributors and newer editors revise each other’s accounts and process information.

Second, how do interaction patterns for a single article change over the article’s lifecycle? As the article develops and more reliable and authoritative information is revealed about the incident, a breaking article’s content and style should stabilize and exhibit article trajectory properties more similar to non-breaking articles over time.

Third, what features of editors’ interactions with other editors predict their re-engagement on other articles? In particular, do editors interact on subsequent articles? Are highly central editors likely to participate in many collaborations? The re-emergence of interactions among editors and symmetries of arrival and departure from breaking collaborations would likewise suggest the coherence and similarity of action over time are instances of organizational regeneration [3, 19]. Repeated and central editorship across collaborations would suggest editors manage dependencies and self-organization in high-tempo collaboration by relying on social roles to constrain and enable action [8, 27].

3. OUR APPROACH

Traditional statistical approaches to group activity often omit complex patterns and dependencies which can emerge from aggregate interactions. For example, a Gini coefficient of edit distributions among editors cannot separate concentration of activity among isolated individuals from the concentration of activity among individuals within a cohesive subgroup. We employ a network analysis perspective to understand the structures and positions which emerge from dyadic interactions of users modifying revisions to a Wikipedia article. Unlike previous network analyses of Wikipedia that focus on the structure of links among articles [2], revert patterns [24], or changes in content as types of endorsement networks [4], we expand on previous work using event logs to discover networks [25] by representing articles’ revision histories as a network.

A “revision” is the state of a Wikipedia article at a given point in time, authored by an editor. An article revision history consists of a series of instances where an editor has “saved” or “committed” changes after revising the content of the article. We construct an “article trajectory” from the temporal sequence of commits in a single article’s revision history. The nodes in article trajectory are editors, and a directed edge between nodes represents a commit that transitions the article from one editor’s revision to the next. This approach captures a structural view of the revision history, which allows us to view and analyze complex relationships between editors and article versions.

In the example presented in Figure 1, editor A creates an article at time 1. Then, at time 2, editor B edits and saves the article, replacing editor A’s version. Thus, the A←B dyad can be interpreted as “editor B saved a new version after editor A”. At time 3, editor C’s revision could reflect changes to content added or modified by editor B, or the introduction or removal of entirely different content. We also begin to see the early stages of a “chain” forming: new editors modify prior editors’ revisions, but prior editors never revise subsequent edits.

At time 4, editor A returns to the article and commits a new revision after editor C. This additional commit by an editor who has previously contributed appears in the network representation as a “loop.” At time 5, editor D saves a revision after editor A’s *second* revision which indicates editor A has saved more than one article revision in this article's history, making her increasingly central in the network. At time 6, editor E modifies editor D's revision. Consider if editor A had not made her second contribution: editor D would have instead modified editor C's revision, and a "chain" of single editor revisions would have grown. Alternatively, an editor can modify her own revision in succession, creating a self-loop.

This example illustrates the construction of a single article's trajectory. A loop occurs when individual editors save multiple different revisions throughout the history of an article, contributing content or making other changes more than once. A chain appears when subsequent editors only commit one revision and never contribute to that article again.

While this approach does not assume user-to-user interactions are necessarily in response to one another or that these interactions occur around the same content, the aggregation of interactions will reveal structural patterns and positions as editors engage in implicit coordination [15, 16]. The article trajectory approach furthermore treats all revisions equally—major, minor, vandalism, reversion to previous states—because editors' activity in response to these incidents illustrates their investment in the article as well as the role they play vis-à-vis other editors' actions.

Using the Wikipedia API, we downloaded the content and revision history associated with each article in the corpus. To construct a article trajectory for each article, first we sorted the revisions in each article's history chronologically, and then transformed each revision into an edge in the network linking the editor who "saved" that revision, and the editor who saved the previous revision. Individual-level and global network statistics were calculated in NodeXL and NetworkX [9, 23].

4. STUDY 1: STRUCTURE & DYNAMICS

The first study is a sub-sample of 229 articles selected from Wikipedia's "List of accidents and incidents involving commercial aircraft". These articles were written about incidents that took place in a 20-year time window from January 4, 1990 to December 25, 2009. We excluded incidents attributable to hijacking or terrorism from the sample (like the flights involved in the 9/11 attacks), because these are outliers with respect to salience and visibility of the incident. Seventy-six articles in the second corpus were started within 96 hours of the incident which we categorized as "breaking" articles. We categorize the remaining 153 articles in the second corpus as "non-breaking". The non-breaking articles include 44 incidents that took place after Wikipedia was founded in January, 2001, and 109 incidents that occurred before Wikipedia was founded and thus could not have been authored as a breaking article.

4.1 Metrics

We calculated four network statistics that capture the structural characteristics of the article revision networks to identify "tighter" or "looser" patterns of editor activity. "Tight" patterns of editor activity exhibit many loops and few chains, as editors who have previously saved a revision return to the article later to contribute additional revisions. Conversely, "loose" patterns of activity exhibit few loops and many chains, as editors contribute single revisions and do not return.

The following network measures are dependent variables while incident and article attributes such as fatalities, location, incident date, and first edit timestamp are independent variables or controls in the regression models. The distributions for closeness, betweenness, clustering, creation lag, fatalities, and number of editors were all positively skewed and were log-transformed to generate quasi-normal distributions for the analysis.

- The *diameter* of a network is the length of the longest shortest path (geodesic) between any two nodes in the revision network. Articles with a "loose" revision history structure manifest greater final distance between editors' revisions than articles with a "tight" revision history structure. The longest geodesic on a breaking article such as Air France Flight 358 is 15 (Figure 2b) while the longest geodesic on a non-breaking article such as China Airlines Flight 611 (Figure 2f) is 33.
- The *average closeness* of a network captures the tendency for nodes on the network to be able to reach each other with short paths. Closeness is formally calculated as the inverse of the sum of the lengths of the geodesics to every other node on the network [26]. In a "tight" article revision network, editors' saved revisions have a higher average closeness than in a "loose" revision network. Therefore, we expect that breaking articles should have higher closeness centrality than non-breaking articles.
- The *average betweenness* of the network represents the tendency for a network to have many "brokers" or connecting nodes that would otherwise be unconnected [26]. Revision networks of articles like Air Philippines Flight 541 (Figure 2d) that exhibit a "loose" pattern of activity, should have high average betweenness centralities because removing any editor would make it impossible for others to connect since there are no loops (perhaps indicating a lack of central coordinating editors). Article revision networks with a "tight" pattern of activity like Air France Flight 358 have low average betweenness since there are several editors connecting the network. We expect that breaking articles should have lower betweenness centralities than non-breaking articles.
- The *average clustering* of the network captures the tendency of the immediate neighbors (alters) of an editor to edit each other's revisions as well. Article revision networks with a "tight" pattern of activity and more neighboring editors making revisions with each other have higher clustering coefficients than those with a "loose" pattern. Breaking articles should have higher clustering coefficients than non-breaking articles.

Specific attributes like the number of fatalities, location, and incident date were manually recorded for each of these articles.

- *Editors* is the number of unique contributors to the article—effectively the number of nodes in the network. We acknowledge that several of the dependent variables (network statistics) are affected by the number of vertices on the graph; this variable is included as a control rather than explanatory factor.
- *Creation lag* is the difference between the timestamp of the first contribution and the date of the incident. This captures how long after the incident occurred the article appeared in Wikipedia. Breaking articles have small creation lags and non-breaking articles have large lags.
- *Fatalities* is the number of individuals killed as a direct result of the incident. The severity of an incident may affect the amount of attention paid to that incident, leading to an

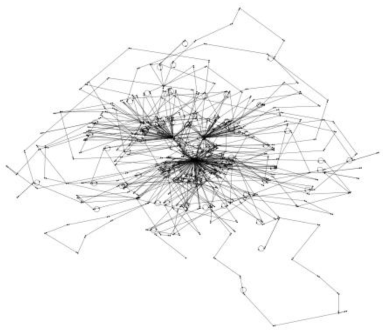


Figure 2a: Adam Air Flight 574 (Breaking article)

Figure 2b: Air France Flight 358 (Breaking article)

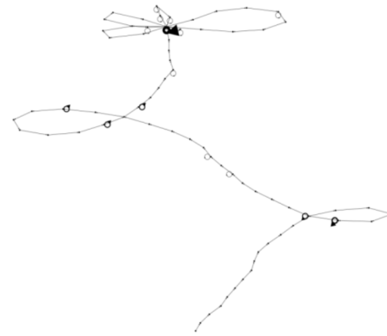


Figure 2c: Kam Air Flight 904 (Breaking article)

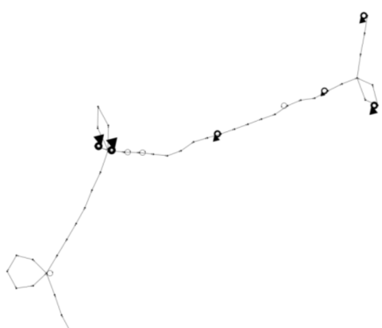


Figure 2d: Lufthansa Flight 2904 (Non-breaking article)

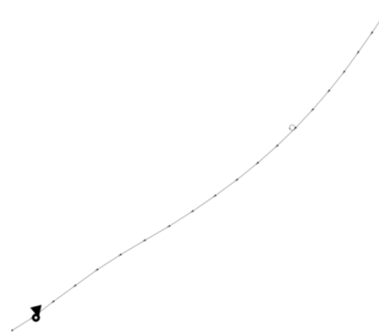


Figure 2e: Air Philippines Flight 541 (Non-breaking article)

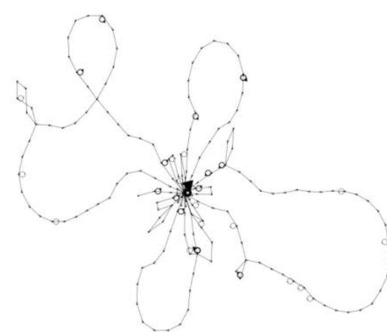


Figure 2f: China Airlines Flight 611 (Non-breaking article)

increase in editor contributions for incidents with more fatalities.

- *OECD* is a dummy variable that codes for whether the crash occurred in one of the 32 member nations of the Organization for Economic Cooperation and Development as of 2010. Because Wikipedia editors display a self-focus and local bias of article topics [11], events that occur outside of developed nations may receive different levels of attention.
- *Wiki-age* is the difference between the time and date of the first contribution and January 15, 2001, the date Wikipedia was launched. This variable captures how old Wikipedia was when the article was created and is a correlate for Wikipedia's popularity. Breaking articles that have occurred more recently have greater wiki-ages while breaking articles that occurred earlier in Wikipedia's history have smaller wiki-ages. This is an attribute of the article rather than individual revisions.
- *Breaking phase* is a categorical variable for the set of breaking articles that codes for whether the contribution occurred in the first phase of the article's existence (days 0-7), the second phase (days 7-187), or the third phase (after day 187).

4.2 Results

We examined the relationship between creation lag and article revision network structure (Table 1) and whether later phases of breaking article revision activity resembles patterns in revision activity on non-breaking articles (Table 2).

Figure 2 depicts six representative article revision networks; three for breaking articles and three for non-breaking articles. The thickness of the lines is proportional to the frequency of directed interaction between editors which is generally just a single interactions. In many cases, editors modified their own revisions in succession creating self-loops. By visual inspection, we observe that some breaking articles appear to have "tighter" patterns of revision activity, with fewer "chains" and more "loops". However, other breaking articles like Kam Air Flight 904 exhibit the "loose", chain-like structures we expect to find in non-breaking articles (see Figure 2c), and some non-breaking articles such as China Airlines Flight 611 exhibit the "tight" loop-like structures we expect to find in breaking articles (see Figure 2f). We therefore used linear regression models to analyze in a principled fashion the relationship between creation lag, fatalities, OECD location, number of editors and the four descriptive network statistics: diameter, closeness, betweenness, and clustering, across our entire corpus of articles.

4.2.1 Breaking Articles are More Coupled

The article revision networks exhibit strong relationships between creation lag and how "tight" or "loose" the pattern of revision activity is in each article's trajectory.

Model 1 reveals that revision networks for articles with greater elapsed time between the creation of the article and the incident date (creation lag) have significantly longer diameters, even after controlling for the number of editors in the network. Conversely, articles that are created immediately after an incident exhibit much "tighter" revision patterns, resulting in denser networks. In Model 2, we expected longer creation lags to result in revision networks with less closeness centrality. However, the effect was not significant and therefore we did not find support for this claim. Model 3 examines average betweenness centrality, and we observe again that articles with higher creation lags have fewer

	Model 1: Diameter	Model 2: Close‡	Model 3: Between‡	Model 4: Cluster‡
Creation lag‡	0.164* (2.47)	-0.045 (-0.75)	0.094*** (3.49)	-0.370*** (-4.99)
Deaths‡	0.017 (0.24)	0.164** (2.79)	-0.036 (-1.37)	0.027 (0.38)
OECD	-0.142* (-2.14)	0.097 (1.62)	-0.067* (-2.52)	0.051 (0.69)
Editors‡	0.585*** (8.58)	-0.690*** (-11.17)	0.990*** (36.06)	-0.084 (-1.10)
R^2	0.284	0.412	0.884	0.112

Table 1: Standardized beta regression coefficients (t statistics) for all articles (N=229); ‡ log-normalized * p<0.05, ** p<0.01, *** p<0.001

	M5: Diameter	M6: Close.‡	M7: Between.‡	M8: Cluster.‡
Wiki-age	-2.9e-3*** (-4.17)	1.26e-4* (2.16)	-2.18e-4** (-2.76)	2.26e-4 (0.44)
Deaths ‡	0.0170 (0.29)	-1.02e-3 (-0.20)	2.72e-3 (0.40)	7.66e-4 (0.02)
OECD	-1.46 (-1.53)	0.103 (1.27)	-0.086 (-0.78)	0.291 (0.41)
Editors‡	3.33*** (10.59)	-1.38*** (-57.78)	1.51*** (45.48)	2.17*** (8.43)
Phase 1 (days 0-7)	.	.	.	.
Phase 2 (days 7-187)	2.37** (2.98)	-2.68*** (-4.95)	0.358*** (4.65)	-1.78* (-2.41)
Phase 3 (days 187+)	6.23*** (8.15)	-0.45*** (-8.69)	0.603*** (8.18)	-4.36*** (-6.08)

Table 2: Regression coefficients (t statistics) for breaking articles (228 balanced obs. for 76 articles). Phase 1 is the base category; ‡ log-normalized; * p<0.05, ** p<0.01, *** p<0.001

ties based on revisions by editors who had previously contributed to that article. Higher betweenness scores suggest the presence of more and longer chains in the revision network. Finally, Model 4 suggests articles about incidents that occurred farther in the past exhibit lower average clustering coefficients. In other words, the groups of editors whose revisions are modified by a single editor are less likely to mutually modify others' revisions. In contrast, the breaking news editors exhibit a greater tendency to revise in groups or clusters when engaging Wikipedia's editorial process.

The number of fatalities in an commercial airline crash has little effect on the revision network statistics and was only significant for average closeness. This suggests the severity of a crash does not lead to editors exhibiting greater involvement in the collaboration. However, airline crashes that occurred in OECD nations had smaller diameters and smaller betweenness, suggesting that editorial engagement may differ depending on the socio-economic development of the region of the crash.

4.2.2 Unique Structures Regress to Mean

We investigate how the revision network structures of breaking news articles change over the lifecycle of the article. In particular, we address (1) what phases in breaking articles' histories contribute to the characteristic "tight" patterns, and (2) do the network structures found throughout these articles' revision histories "regress to the mean" by becoming "looser" over time and looking more like their non-breaking counterparts.

We examine the set of 76 articles authored within 96 hours of the incident, and construct three article revision networks for each article, one for each "breaking phase". *Breaking phase* is a categorical variable that codes each revision of a breaking article for whether it occurred in the first phase of the article's existence (days 0-7), the second phase (days 7-187), or the third phase (after day 187). This variable captures changes in the editor interaction patterns over the lifecycle of an article. Averages of 55.8% of all revisions are made in Phase 1, 17.3% in Phase 2, and 25.9% in Phase 3. These cutoffs were chosen to reduce left and right-censoring effects in breaking articles with highly skewed activity by distributing edits evenly across phases for all articles.

As before, to control for exogenous factors such as the severity of the event, systematic biases in editor attention based on geography or socio-economic status, and the number of contributors to the article, we incorporate control variables similar to those used in the previous analyses. However, a hierarchical approach is necessary to account for repeated observations for each article at different points in time (breaking phase).

Network statistics (diameter, closeness, betweenness, clustering, editors) change as the network changes over time, while variables at the article level (wiki-age, fatalities, OECD) remain constant. Thus, the primary effect we are measuring is differences in articles' diameter, closeness, betweenness, and clustering at each of the three points in time, controlling for the age of Wikipedia at article creation, fatalities, location, and number of editors. The regression coefficients for this multilevel model are reported in Table 2 and the changes across time for the corresponding dependent variables are shown in the "Phase" parameters. A Hausman test comparing a random intercept model to a random coefficient model (allowing the coefficients for phase to vary over time) caused neither significant changes in valence or significance nor showed a significant improvement in fit; we therefore report the results for the simpler random intercept model.

Examining the breaking phase coefficients, significant differences are observed within articles between the first phase of the collaboration and the second, and between the first and third phases. The diameters of breaking articles' revision networks are significantly larger in both the second and third phases than in the first phase, holding the other predictors in the model constant. Similarly, the average closeness centralities of the networks decrease for the later phases as compared with the initial collaboration. The article revision networks exhibit significantly higher average betweenness centralities in Phase 2 and Phase 3 as well. Finally, we also observe that the average clustering coefficients of breaking articles are significantly smaller in latter phases of the collaboration.

These results suggest breaking articles exhibit unique revision network patterns in the aftermath of an incident, but over time the activity of editors contributing to the revision network increasingly resembles the revision network patterns of non-breaking articles.

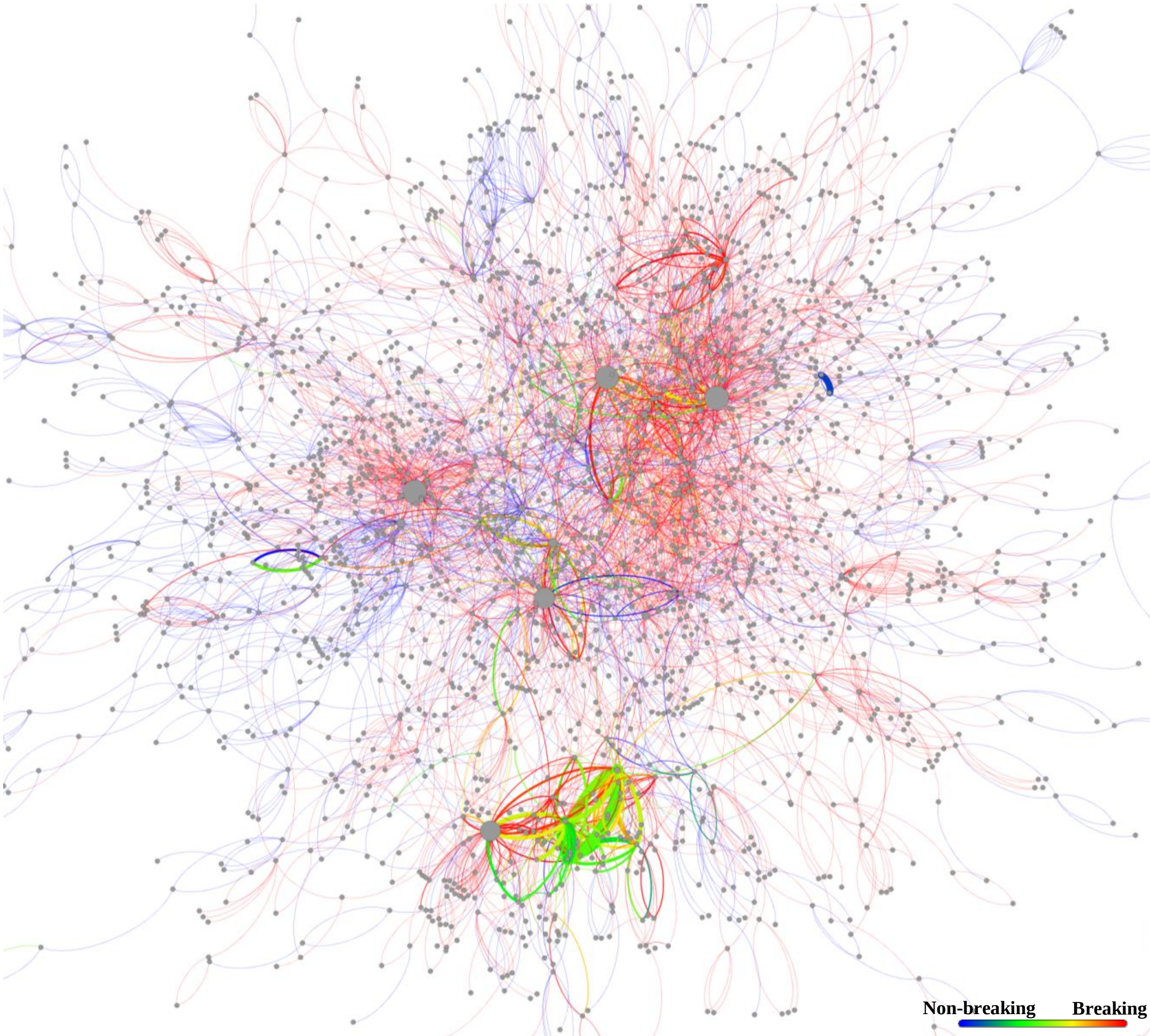


Figure 3: Largest component in repeat interaction multigraph. Editors (in grey, sized by degree) are linked with weighted edges if their interactions with another editor appear on two or more distinct articles. Bluer edges have greater fractions of non-breaking article interactions, redder edges have greater fractions of breaking article interactions.

5. STUDY 2: REPEAT COLLABORATION

The second study analyzes 1.03 million revisions made by 158,384 unique users to 3,233 English Wikipedia breaking articles (n = 1538) and non-breaking articles (n = 1695) about disasters, catastrophes, and conflicts from 1990 through 2011. These articles include conflicts (e.g., wars, battles, political unrest), crimes (e.g., murders, kidnappings, and terrorism), fires (e.g., building fires, wildfires, explosions), health disasters (e.g., disease outbreaks), industrial accidents (e.g., spills, mine collapses), natural disasters (e.g., hurricanes, earthquakes, tornadoes), and transportation accidents (e.g., airplane crashes, train collisions, road accidents). These categories are categorized by incident year such that the Deepwater Horizon oil spill will appear in the "2010 industrial accidents" category, reflecting the fact that the incident itself occurred in 2010 even if the first or subsequent revisions to the article occurred at subsequent times.

We conduct two analyses of article trajectories using this data. The first constructs a *repeat interaction multigraph* to assess the structure of editor interactions across all the articles. The second develops a statistical model of how a given article's revision history and chain influences editors to participate in many article collaborations.

5.1 Metrics

The revision history of each article as well as its article trajectory encodes several important attributes about the structure and dynamics of the collaboration. With the exception of *bytes added*, each of these metrics is log-transformed to correct for strong skews in distributions. For each editor in each article's trajectory, we record the following metrics:

- *Article Count* is the count of the unique articles an editor has revised within the sample. Editors who have made at least one change to only one article will have an article count of 1, while editors who have made at least one change to 10 articles will have a count of 10.

- *Degree* is the number of connections an editor has to other editors in the article trajectory. Because the article trajectory is directed, degree is the sum of an article's in-degree and out-degree and the value is normalized to the size of the graph. A normalized degree of 1 indicates the node is connected to every other node in the network.
- *Timestamp* records age of an article by measuring the time (in seconds) elapsed since the article was created. The first revision to an article necessarily has a timestamp of 0. For editors who have made several revisions, we use the minimum value of timestamp to capture how early editors join collaborations.
- *Edit lag* is the amount of time elapsed since the prior revision to the article was made. An edit lag of 1 reflects a revision made one second after the previous article was committed. Editors fully engaged in the collaboration will have smaller edit lags as they make changes immediately following others' revisions. For editors who made several revisions, we use the median value of edit lag to capture a central tendency of editors' engagement for skewed distributions.
- *Bytes added* is the change in the length of an article compared to the previous revision. Revisions which remove content add negative bytes. Editors who add large amounts of content to articles will have large positive bytes added. The median value of bytes added captures the central tendency in skewed distributions of positive and negative values.
- *Top editor* is a dummy variable coding whether the editor is among the top 10% of editors as measured by degree.
- *Fraction top neighbors* is the fraction of a node's neighbors who are among the top 10% of editors by degree. A fraction of 1 means all of a node's neighbors are in the top 10% of editors while a fraction of 0 means none of a ndoe's neighbors are in the top 10% of editors.
- *Average neighbor degree* is the average of an editor's neighbors' degrees. High values of average neighbor degree mean the editor it connected to other well-connected editors as observed in [13].

5.2 Results

5.2.1 Repeat Interaction Multigraph

We constructed article trajectories for each article and aggregated these into a directed multigraph where pairs of editors can have multiple edges, each edge corresponding to interactions between the same editors on different articles' revision chains. Figure 3 visualizes the largest component of this repeated interaction multigraph. The graph contains 3,314 editors and 6,451 edges where the dyad interacted the same way on two or more articles.

Several features of this article trajectory are notable. First, the largest component includes 92.3% of the nodes and 98.4% of edges in the total repeat interaction graph. Because editors' interactions across collaborations are highly connected and embedded rather than isolated and atomistic, it suggests interactions within an article trajectory are not spurious, but rather that many editors jointly monitor and edit articles with each other. Second, the vast majority of interactions between the same editors across different articles involve breaking articles (redder edges) rather than non-breaking articles (bluer edges). The dominance of repeat interactions on breaking articles in the repeat interaction

	M9: Breaking Article Count‡	**M10: Non-Breaking Article Count‡**
Degree‡	3.73 21.36***	2.79 17.44***
Min. Article Age‡	-0.125 -38.8***	-0.0544 -14.87***
Med. Edit Lag‡	0.130 39.36***	0.114 27.72***
Med. Bytes Added	-1.32E-05 -5.73***	1.07E-05 2.42**
Top Editor‡	0.450 13.15***	0.314 6.56***
Frac. Top Neigh.‡	-0.201 -8.21***	0.0233 0.68
Avg. Neigh. Degree‡	-0.0779 -5.77***	-0.258 -9.94
Intercept‡	-1.47 -33.22***	-2.19 -32.44

Table 3: Regression estimates (t statistics) for the normalized count of articles revised by editors in breaking (*n* = 173,292) and non-breaking (*n* = 81,682) contexts.
‡ log-normalized; * p<0.05, ** p<0.01, *** p<0.001

multigraph implies breaking articles are not one-off collaborations but involve repeated interactions among the same editors across different articles.

Third, there is a distinct cluster of thick, dense, and green interactions at approximately 6 o'clock in Figure 3 removed from (but still connected to) the larger collaboration. These editors' interactions reflect their specialization in a particular genre of articles; tropical storms and hurricanes, in this instance. The thick and yellow to green colors reflect these editors' repeated interactions as they attend to each other's revisions as they collaborate on a specific category of articles containing a mix of breaking and non-breaking articles. The article trajectory approach suggests a novel way to mine large-scale digital behavioral traces to surface interactions among collectives of individuals engaged in mutually shared practices.

5.2.2 Centrality Influences Repeat Participation

To test the extent to which contextual features of revision histories and their chain structure influences the how many articles editors revise, we specify a regression model for each of set of breaking and non-breaking articles. Each observation is a record of an editor's revision history behavior and chain structure in an article's trajectory. The dependent variable is a normalized count (effectively percentage) of the articles in each corpus to which the editor contributed.

We employ a generalized linear mixed model containing fixed and random effects with a negative binomial distribution to model both the count data and repeated observation of editors across different articles. Correlations of fixed effects were primarily concentrated in the intercept term. An ANOVA comparing models confirmed the model we report had a significantly better fit than models with mixed effects ordinary least squares regression, random intercept model with binomial distribution, or a random effects model with binomial distribution. The fixed effect estimates for the breaking and non-breaking models are summarized in Table 3.

Behavioral attributes such as when editors join collaborations, how intensively they edit, and how much content they change are examined before turning to the structural context of editors' participation such as the number of connections to other editors, whether an editor is among the most central, and the features of the other editors with whom an editor interacts.

The later an editor joins a collaboration (*Minimum Article Age*), the less likely he or she will contribute to many separate articles. Editors who join the collaboration after much of the early work shaping and framing the article has been done are potentially less engaged. This engagement deficit, in turn, manifests as a lack of participation revising other articles. This engagement interpretation is complicated by the estimates for median edit lag: positive coefficients suggest the presence of deliberative editors who wait longer to make a revision after previous revisions are in fact more likely to edit many articles. Editors who add more content to articles (*Median Bytes Added)* are, however, less likely to participate in many article collaborations. Alternatively, editors who remove content are more likely to participate in many collaborations.

These findings suggest editors engage in strategic behavior as well as the existence of distinct classes of editing behavior corresponding to social roles in these collaborations [8, 27]. Some editors participating in many collaborations potentially join newly-created articles but are not intensively revising the article by making immediate changes after other editors, avoid making major changes to the articles, or have a tendency to remove content from articles. There are also editors who are highly committed as they make major changes in content and intensively revise breaking articles following other editors' contributions, but do not participate in many collaborations. However, we urge caution in adopting this interpretation of distinct social roles as orthogonal behaviors because the direction of estimates for "bytes added" were not robust across modeling approaches.

Turning to the structural context of editors' interactions, in both breaking and non-breaking articles, the more distinct interactions an editor has with other editors (*Degree*) increases the number of distinct articles the editor ultimately revises. The most central editors (*Top Editor*) who interact with many other editors necessarily make many revisions over the course of an article but this behavior is also correlated with a tendency to edit many articles. Editors solely interacting with or otherwise being surrounded by many other top editors (*Fraction Top Neighbors*) are less likely to edit many breaking articles while a positive but non-significant effect is observed for non-breaking articles. Finally, breaking and non-breaking articles exhibit similar tendencies to reduce the number of articles edited as if an editor's neighbors are well-connected (*Average Neighbor Degree*).

Editors of breaking articles who interact with well-connected editors are likely to reduce the number of articles they edit. Determining the direction of this effect is difficult to disentangle with the model as it may be the case that editors' interactions with prolific editors are reversions, immediate modification, or other instances of "biting the newbies". This may lead these peripheral editors to become disheartened and discourage them from participating in other collaborations [10]. Alternatively, the causal direction may flow from prolific editors to interactions with peripheral editors: editors contributing to many articles fulfill specific brokerage roles like administration or copy-editing which leads them to interact with relatively inactive or novice users.

6. DISCUSSION

Unlike prior work which has looked at co-authorship patterns *across* Wikipedia articles [2, 4, 14], we introduced article trajectories as a method for capturing the collaboration structure *within* Wikipedia articles. We tested these article trajectories on Wikipedia articles about unexpected and breaking news events which have unique coordination demands. Study 1 found breaking articles' trajectories are initially characterized by highly clustered and centralized interactions with other editors but these features diminish over time and regress to structures found on non-breaking articles. Looking across different articles' trajectories in Study 2, we found a well-connected latent collaboration structure of editors interacting with each other across articles. Finally, we identified significant behavioral and structural features correlated with the tendency for editors to participate in many article collaborations.

Our results illustrate how breaking articles are a unique type of collaboration context which differs from traditional Wikipedia articles that center on activities, events or topics that can rely on pre-existing knowledge. Furthermore, we provide new insights into how the structures of high-tempo knowledge collaborations change over time. The characteristic "tight" revision patterns observed on breaking news articles may be attributable to different coordinative processes that are invoked following an incident but as the salience of the event fades and more information comes to light, the pattern of revisions begins to revert to the looser revision networks more typical of non-breaking articles. These structures may be an artifact of editors' joint attention and interrelating as they cope with the influx of new information and collaborators. As more accurate and consistent accounts of the event begin to surface in other reliable outlets, this impetus subsides and the editors can begin to focus more on the structuring that occurs with more typical article types.

As Study 2 demonstrates, breaking and non-breaking article collaborations are not isolated but embedded in a larger community or collectivity of practice [5, 17] where editors' interactions with each other occur repeatedly across breaking articles, in particular. Our article trajectory approach also identified editors mutually engaged in a shared practice of editing articles about hurricanes as distinct from the rest of the repeat interaction multigraph. Taken together, this suggests the possibility of leveraging large-scale behavioral data analysis methods like revision chain analysis to highlight individuals and groups for follow-on qualitative studies of their identities, motivations, and practices.

While these findings complicate the coordination models outlined by Kittur and colleagues [15, 16], they also reaffirm the importance of understanding the interdependence between task demands and coordination methods. Our article trajectory approach extends this work by allowing a more critical examination of the particular interaction patterns editors adopt in response to the coordination demands of high tempo collaborations. Mining real-time activity logs to construct article trajectories and computing the simple network statistics may offer metrics or other inputs to classifiers so that administrators and other community members can identify intense or trending activity which would be missed with simpler count statistics.

Because our approach using article commits to the revision histories did not capture changes in the content of the articles, we did not examine interactions between editor contributions and content [1, 4, 10, 21]. Contributions related to changes in punctuation or reverting vandalism are certainly less demanding tasks than authoring and integrating novel content but are nevertheless lumped together as equal revision processes in our approach. We also did not examine the success of these collaborations (*e.g.*, article length, rating, page views) which would allow us to separate out intense collaborations resulting from tendentious editing or controversial topics versus substantive coordination. Although prior work suggests Wikipedia editors prefer synchronous technologies like Internet Relay Chat (IRC) over discussion pages for explicitly coordinating on breaking news articles [12], our analysis did not examine the extent to which positions in article trajectories were reproduced within article discussions. Our approach likewise only examined the English Wikipedia whereas future work should also establish whether these temporal and structural correlates are also found in other genres, languages, and cultures.

Our network analysis likewise employed aggregated descriptive statistics rather than generative models to characterize the similarities and differences of networks. Future work should examine the variation across networks in constituent local network structures (such as triadic census) and employ exponential random graph techniques to evaluate multi-level, multi-theoretical processes like preferential attachment, closure, reciprocity, and homophily governing network evolution [6].

Nevertheless, our findings have substantial implications for theorizing about the motivations to contribute to online communities. Ensuring the stability of the community of contributors and motivating sustained contributions over time is paramount to the success of many online communities such as Wikipedia [20]. However, participation in online communities does not always occur under conditions of stasis. The case of breaking news articles on Wikipedia highlights how online communities need to have the flexibility to rapidly accommodate and socialize large influxes of participants attempting to make sense of unexpected events and engage in diverse forms of collective action in response to them. Instances of fluid, close coordination which occur under conditions of minimal self-disclosure and limited consensus are simultaneously high-risk but also potentially ecstatic experiences for individuals [7]. Breaking news articles on Wikipedia offer a compelling case to examine how online communities balance the competing interests to support openness, flexibility, and autonomy against institutional needs for structure, norms, and socialization over very different time scales. Scholars should thus examine how short-lived online communities can actually be instances of successful collaboration.

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