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Turbulent Stability of Emergent Roles: The Dualistic Nature of Self-Organizing Knowledge Coproduction

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Increasingly, new forms of organizing for knowledge production are built around self-organizing coproduction community models with ambiguous role definitions. Current theories struggle to explain how high-quality knowledge is developed in these settings and how participants self-organize in the absence of role definitions, traditional organizational controls, or formal coordination mechanisms. In this article, we engage the puzzle by investigating the temporal dynamics underlying emergent roles on individual and organizational levels. Comprised of a multilevel large-scale empirical study of Wikipedia stretching over a decade, our study investigates emergent roles in terms of prototypical activity patterns that organically emerge from individuals' knowledge production actions. Employing a stratified sample of 1,000 Wikipedia articles, we tracked 200,000 distinct participants and 700,000 coproduction activities, and recorded each activity's type. We found that participants' role-taking behavior is turbulent across roles, with substantial flow in and out of coproduction work. Our findings at the organizational level, however, show that work is organized around a highly stable set of emergent roles, despite the absence of traditional stabilizing mechanisms such as predefined work procedures or role expectations. This dualism in emergent work is conceptualized as "turbulent stability." We attribute the stabilizing factor to the artifact-centric production process and present evidence to illustrate the mutual adjustment of role taking according to the artifact's needs and stage. We discuss the importance of the affordances of Wikipedia in enabling such tacit coordination. This study advances our theoretical understanding of the nature of emergent roles and self-organizing knowledge coproduction. We discuss the implications for custodians of online communities as well as for managers of firms engaging in self-organized knowledge collaboration.

Keywords: online production communities; coproduction; Wikipedia; emergent roles; stability; mobility; artifact-centric; boundary infrastructure
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1. Introduction

Recent years have seen the rise of new forms of organizing for knowledge production, with a predominant one being open online coproduction communities such as Wikipedia and open-source software (Benkler 2006, von Krogh and von Hippel 2006). The distinct principles of these new forms are leading to a reinvestigation of traditional assumptions in organizational theory and a development of new theoretical understandings and constructs (Lakhani et al. 2013, Schreyögg and Sydow 2010, Zammuto et al. 2007, Lifshitz-Assaf 2016). One of the key guiding principles of these open coproduction knowledge communities is self-organizing, where participants themselves select how and when to work and what to work on (Lakhani and Panetta 2007, Benkler 2006, von Krogh and von Hippel 2006, O'Mahony and Lakhani 2011, Oreg and Nov 2008). This self-organizing is

incommensurate with the logic of traditional organizations, based on a Chandlerian logic (Chandler 1962) that emphasizes authority, centralized hierarchy, and control. This has led to an inquiry of how emergent (or "informal") knowledge work is developed in such new forms that, without utilizing clear role definitions, traditional organizational control, or coordination mechanisms, nevertheless result in a cumulative and high-quality knowledge-based product (Faraj et al. 2011, Kane et al. 2014, Okhuysen and Bechky 2009, Arazy et al. 2011, Ransbotham and Kane 2011, Arazy and Nov 2010).

To build a comprehensive conceptualization of the work process, such an inquiry requires a focus on the emergent roles that individuals enact based on the work itself (Orlikowski 2000) and the tasks that are performed as they emerge, to build a comprehensive conceptualization of the work process (Bechky 2006). This perspective on roles, that focuses on individuals' role behavior in relation to their work, is similar to the interactionalist view of roles (Goffman 1961, Turner 1986). This view is in contrast to the traditional structural perspective of roles that understands roles as based on social expectation, norms, and status positions (Katz and Kahn 1978). Recently, there has been a call to focus on the nature of these emergent roles and how knowledge coproduction work organically develops over time (Faraj et al. 2011, Kane et al. 2014, Majchrzak et al. 2013). The study of emergent roles in traditional organizations is well established, and scholars often refer to these as part of the "informal" aspects of work in organizations (Okhuysen and Bechky 2009). However, new forms of organizing for knowledge production, such as open online coproduction communities, introduce a novel area for theoretical exploration, as they rely heavily and almost exclusively on these emergent roles (Zammuto et al. 2007). Thus, the emergent becomes the center of knowledge production processes, rather than a component that complements formal roles.

The temporal view of the relationship between emergent roles and work has long been argued to be an important and missing perspective (Orlikowski and Yates 2002, Langley et al. 2013, Hernes 2014). In self-organizing knowledge coproduction, this perspective is particularly relevant, as the high level of fluidity in participation results in multiple tensions in the creation of a cumulative body of knowledge (Faraj et al. 2011, Kane et al. 2014). Therefore, in this study, we unpack the black box of the emergent roles in knowledge coproduction work over time. We suggest that addressing this research objective warrants a multilevel perspective combining the individual and the organizational levels. Theoretical advances in this area have been made in the past decade, calling for a more nuanced conceptualization of emergent roles and work at both the organizational (Schreyögg and Sydow 2010, Langley et al. 2013, Farjoun 2010) and individual level (Faraj et al. 2011, Preece and Shneiderman 2009). However, empirical studies have yet to follow through. This investigation is particularly warranted given conflicting views in the literature on the extent to which and how individuals change their emergent roles and behavior in online coproductions communities over time (Panciera et al. 2009, Kane et al. 2014).

To address these gaps, we investigated new forms of organizing to learn about knowledge production with minimal formal role definition and structuring of the knowledge production activities. Moreover, we sought an organization that had developed a large number of sustained coproduction efforts over extended periods and multiple knowledge-based products, thereby allowing us to study participants' role-taking behavior across such products. We therefore selected Wikipedia as the setting for our investigation. Wikipedia is one of the most notable examples of peer production (Benkler 2006). Roles in Wikipedia are largely informal and emergent, and are organized around practices (Faraj et al. 2011, Gleave et al. 2009). Thus, the richness of its participant behavior data, both in depth and breadth, makes it particularly suitable for conducting a multilevel investigation of emergent roles in online coproduction communities.

Our empirical investigation focuses on 1,000 representative Wikipedia articles from various topical domains and of varying maturity levels (in terms of the number of revisions they have gone through), and analyzes the editing activities in the coauthoring process of these articles. Our data collection and analysis procedure combined manual annotation processes (over 30,000 editing activities), machine learning algorithms (scaling up and automating the annotation process to 700,000 activities), and complex software scripts (to track the behavior of over 200,000 distinct participants over a period of 11 years). We recorded contributors' detailed profiles of wiki edit work and used statistical methods to identify behavioral regularities, or, more specifically, prototypical activity patterns, as a proxy for emergent roles (Liu and Ram 2011, Welser et al. 2011). Seeking to understand the temporal dynamics by which the organizational and individual levels interact, we compared role dynamics between the "forming" period (from January 2001 to the end of 2006) and the "establishing" period (from January 2007 to the end of 2012) in Wikipedia's evolutions (Halfaker et al. 2012).

We found that while there is turbulent and intense mobility at the individual level, where many participants often take and shed roles instantaneously, the global structure of work is highly stable over epochs in Wikipedia's life, despite fundamental changes in

its governance mechanisms. We conceptualize this dualistic interplay between individual-level mobility and organizational-level stability as "turbulent stability." A qualitative analysis of contributors' comments when editing articles, complemented with a quantitative analysis of role distribution across stages of articles' development, suggests that in enacting a particular role, contributors respond to the immediate needs of the coproduced artifact. We suggest the artifact-centric production as the critical enabling mechanism for the stability in emergent role behaviors across epochs in Wikipedia's evolution. Finally, we uncover the nature of emergent roles within Wikipedia, revealing some conceptualized yet not empirically recorded roles.

2. Theoretical Perspectives

In this section, we provide the theoretical perspectives for this work, by reviewing relevant streams in the literature. We first review prior works on emergent roles in knowledge coproduction communities (Section 2.1); next, we turn our attention to the literature on the dualistic nature of self-organizing knowledge coproduction (Section 2.2); and finally, we discuss the role of the artifact in facilitating coproduction (Section 2.3).

2.1. Emergent Roles in Knowledge Coproduction

In recent years, new forms of organizing for knowledge production have emerged, where one prominent form is open online coproduction communities such as Wikipedia and open-source software development (Benkler 2006, von Krogh and von Hippel 2006). Benkler (2006) defines this commons-based peer-production as a system of production, distribution, and consumption of information goods characterized by decentralized individual action carried out through widely distributed, nonmarket means that do not depend on market strategies, *autonomous, self-selected, decentralized action* (Benkler 2006, emphasis added). The distinct principles of these new forms call for a reinvestigation of traditional assumptions in organizational theory and a development of new theoretical models applicable to this setting (Baldwin and von Hippel 2011, Lakhani et al. 2013, Schreyögg and Sydow 2010, Zammuto et al. 2007, Lifshitz-Assaf 2016). Despite the absence of clear role definitions, or traditional organizational control and coordination mechanisms, the community-based model has been shown to be very effective, yielding high-quality knowledge products (Faraj et al. 2011, Kane et al. 2014, Okhuysen and Bechky 2009, Arazy et al. 2011).

To pursue this inquiry, we focused on the emergent roles of knowledge coproduction and their temporal dynamics. A theoretical focus on roles, as Turner (1986, p. 360) suggests, provides an "understanding of why different patterns of social organizations emerge, persist, change, and break down." Emergent roles organically materialize as work activities are enacted and are characterized by the tasks performed. The investigation of emergent roles can shed light on roles in action (Orlikowski 2000) and increase our understanding of labor division in the work process (Bechky 2006). Cohen (2013) stresses the importance of studying how tasks are assembled, bundled, and amalgamated into a job or a role. This perspective resonates with the interactionalist view of roles (Goffman 1961, Turner 1986) and stands in contrast to the traditional structural perspective of roles, which views them as based on social expectations, norms, and status positions (Katz and Kahn 1978). It is also important to note that the sociological and organizational literature have been investigating the existence of emergent roles, usually as associated with the "informal" aspects of work in organizations, vis-à-vis the formal aspects (for a review, see Okhuysen and Bechky 2009). However in self-organizing knowledge coproduction communities, using the "informal versus formal" dichotomy is less applicable, since the production aspects of these online communities are largely "informal" and rely heavily on emergent work.

So far, the majority of empirical studies of roles within online communities have paid particular attention to the more "formal" aspects of roles similar to those in traditional organizations. Prior studies in this area have investigated leadership roles (Butler et al. 2008); organizational roles that enable power, authority, and status (Arazy et al. 2014, Forte et al. 2009, Stvilia et al. 2008); and promotion processes from one formal role to another (Burke and Kraut 2008, Arazy et al. 2015). However, recent conceptualizations of self-organized knowledge coproduction call to shift the focus to emergent roles and to the ways in which they are enacted in the moment, on a transient basis (Faraj et al. 2011, Kane et al. 2014, Majchrzak et al. 2013). Faraj et al. (2011) theorize that in these generative organizations—characterized by fluid participants, boundaries, and norms, loose governance, and absence of deep social relationships—roles rapidly emerge and change. They describe knowledge collaboration as "the enactment of temporary sets of behaviors that are volitionally engaged in, self-defined, and inductively created for the purposes of the online community" (Faraj et al. 2011, p. 1231). Few empirical studies have followed this perspective and tried to characterize the emergent roles that are created in response to tensions (Faraj et al. 2011), such as those between knowledge, change, and retention (Kane et al. 2014). We build on these recent conceptualizations to define emergent roles based on the knowledge coproduction work itself and the sets of activities being enacted, and operationalize emergent

roles as prototypical activity patterns (Welser et al. 2011, Liu and Ram 2011).

2.2. The Dualistic Nature of Self-Organizing Knowledge Coproduction

To shed light on the broader puzzle of how emergent knowledge work is developed without clear role definitions, we need a comprehensive understanding of the nature of these roles and their development over time. The temporal view of emergent work has long been argued to be an important and missing one (Orlikowski and Yates 2002, Langley et al. 2013, Hernes 2014). In particular, there is a need to investigate the interplay between change and stability in organizations (Langley et al. 2013, Farjoun 2010, Faraj et al. 2011). In the context of our investigation of roles, it is not clear how individuals' mobility in and out of community coproduction work affects the characteristics of emergent roles (i.e., the extent to which emergent role behaviors persist over time). Traditional structural role theory (Katz and Kahn 1978) attributes the stability of role behaviors in traditional organizations (despite turnover in role occupants) primarily to norms and expectations held by role partners. Online coproduction communities, however, differ. Traditional mechanisms for sustaining stable role behaviors are absent in online coproduction communities, and the question of emergent role stability in such new forms of organizing remains open.

A review of the literature on knowledge coproduction reveals conflicting views regarding the question of mobility versus stability of emergent roles. On one hand, Faraj et al. (2011, p. 1231) suggest that in these fluid online communities, "role-making contributions do not appear to be part of a repeated pattern, but rather a reaction by a single participant to a perceived state of the community." Based on this perspective, we may postulate that the high levels of change and fluidity in individuals' role taking and shedding will translate into unstable role behaviors; that is, over time it will yield a high level of mobility on the individual level of taking and shedding roles, yet a low level of stability on the organizational level of these roles. Moreover, organizational theory perspective will also strengthen the prediction of a low level of stability over time since online coproduction communities' organizations change dramatically as they evolve (Halfaker et al. 2012).

Yet an alternative view suggests that participants do not change their role behavior significantly over time. For instance, Panciera et al. (2009, p. 59) argue that "Wikipedians are consistent. Wikipedians tend to maintain a high and constant level of participation for the majority of their lifespan." Other views suggest that changes in participants' behavior follow a particular trajectory, such as increasing the breadth and depth of their activities (Preece and Shneiderman 2009). We may therefore predict that individuals will keep to the same sets of tasks and enact the same emergent roles over time. Such a systematic activity pattern is likely to result in stable (emergent) role definitions, wherein the nature of emergent roles would remain constant over extended periods.

Many organizational theorists have discussed changes that "sustain and, at the same time, potentially corrode stability" in organizations (Tsoukas 2005, p. 183). Yet empirically, such changes have been challenging to validate and conceptualize. Online coproduction communities offer such an opportunity. These new forms enable an investigation that can both "zooming in and out" (Gaskin et al. 2014, p. 851) of the actual work to find patterns of both change and stability in the unfolding self-organizing coproduction. Despite these opportunities, research to date has tended to focus on only a single level: either exploring individuals' role dynamics (Preece and Shneiderman 2009) or characterizing the roles that emerge through collective action (Liu and Ram 2011). We therefore take a multilevel perspective, aiming to capture the tension between change and stability at both levels. As Aaltonen and Kallinikos (2013, p. 187) stress, for coproduction communities such as Wikipedia, to understand collective action, we need "knowledge making and learning that transcends methodological individualism."

2.3. Artifact-Centric Coproduction

Traditional role theories suggest that stability and change in roles are based on either role definitions and expectations (the structural perspective, see Katz and Kahn 1978) or social interactions and negotiation (the interactionalist perspective, see Goffman 1963, Turner 1986). However, in online coproduction communities, scholars argue that roles emerge based on tensions that arise in the coproduction of artifacts and require balancing (Faraj et al. 2011). This perspective highlights the role of the coproduced artifact as a central mechanism enabling tacit coordination in peer production (Howison and Crowston 2014). Our study advances this perspective. A focus on the artifact as a key factor facilitating emergent work highlights the role of materiality in organizational change (Leonardi and Barley 2008) and is aligned with the call for combining the social and material dimensions in studying organizations (Orlikowski and Scott 2008).

The organizational and sociological literatures have referred to transparent and accessible artifacts that serve as a common substrate of knowledge as "boundary infrastructure" (Bowker and Star 1999), arguing that this infrastructure facilitates shared work. Boundary infrastructures enable knowledge production between professionals with different epistemic

cultures (Cetina 1999) and in multiple organizations and professional communities (Bechky 2006, Carlile 2002). For instance, Tuertscher et al. (2014, p. 1588) investigated knowledge work around the development of a complex technological system (ATLAS) and suggested that "Undergirding . . . was the boundary infrastructure comprising objects and representations such as simulations that enabled common ground among the geographically distributed participants hailing from different epistemic communities." Kellogg et al. (2006) also conceptualized the coordination in temporary organizations using the notion of boundary objects that serve as a "trading zone" (Galison 1997) facilitating the dynamic and ongoing work accommodation among online advertising professionals and between them and their clients.

For coproduction communities, the boundary infrastructure is much more than a bridge connecting disparate individuals. Rather, it is a sine pro quo; the existence of an online community is based on and is shaped by the artifact and its affordances (Faraj and Azad 2012). Okhuysen and Bechky (2009) highlight the roles of objects and representations in creating a common understanding of the work process and in facilitating coordination. Other scholars refer to this coordination as "stigmergic," borrowing notions from natural collective intelligence systems: "In these virtual settings traditional coordination mechanisms (hierarchical direction, mutual adjustment in face to face meetings, etc.) face limitations and the artifact takes on a more important role" (Bolici et al. 2016, p. 15). They propose that stigmergic coordination plays a central role in coproduction communities of open-source software development, where "actors are leaving traces of their actions in the code and they are reading and reflecting on the code written by others in order to take coordinated action." Our study strengthens this line of research.

3. Research Methodology and Findings

In the sections above, we reviewed the literature on emergent roles and highlighted some of the gaps in this literature, namely, in terms of (a) the nature of emergent roles and the extent to which they are stable over time, (b) role-making dynamics, and (c) the way in which multiple levels (individual/organizational) and dynamic patterns (mobility/stability) interact. Our objective in this study is to fill these gaps in the literature and advance our understanding of emergent work in online coproduction communities. In what follows, we discuss the method employed for addressing this research objective.

The setting for our study is the online encyclopedia coproduction community Wikipedia. Wikipedia has been able to recruit thousands of volunteers to produce millions of encyclopedic entries in 287 languages and develop extensive policies and mechanisms for governing its collaborative authoring process. Wikipedia operates many different projects, defined as the coproduction of a particular knowledge-based product (i.e., authoring and editing of a particular encyclopedic article on a wiki page), where the project group is comprised of the set of volunteers that contributed to the wiki article. Wikipedia's success has attracted the attention of both organizational and information systems scholars (Arazy et al. 2011, Forte et al. 2009, Ransbotham and Kane 2011).

The availability of temporal data harvested from peer-production system logs could be employed in computational social science—the quantitative modeling of technology-mediated social participation systems—similar to how the capacity to collect and analyze massive amounts of data transformed the fields of biology and physics. Technology-mediated interactions in sociotechnical systems, such as online peer-production communities, capture the sequential contributions to a common artifact. Thus, analyzing these temporal sequences can reveal key insights regarding groups' collaboration patterns in their natural setting and allow us to identify emergent roles. In addition, we have employed a qualitative manual annotation procedure to interpret system log data. We have found that a multimethod approach is advantageous for studying emergent roles in online communities (Gleave et al. 2009, Welser et al. 2011).

We employed a sample of Wikipedia knowledge-based products (i.e., articles), tracking all editors and edit activities in each article in the sample from the article's creation until our cutoff date (January 4, 2012). After categorizing each activity, we created an activity profile for each contributor and then clustered contributors to identify prototypical activity profiles. Our goal is to investigate coproduction of knowledge artifacts, and thus the focal object of our analysis is a Wikipedia article. Given the dependencies between activities (i.e., each contribution is a response to earlier contributions; Kane et al. 2014), it is essential that the analysis of activities tracks complete coproduction sequences around a particular article, rather than tracking a set of participants and their contributions across many articles. Our primary strategy for capturing the complex role dynamics is temporal bracketing: recording a series of "snapshots" of the process over time (Langley et al. 2013). We apply this temporal bracketing strategy in our various analyses: (a) comparing two periods in Wikipedia's life (in analyzing the stability of emergent roles and individuals' role-taking dynamics), and (b) comparing four stages of articles' evolution (based on the number of revisions).

3.1. Sample

We employed a double-stratified sampling procedure, randomly selecting 1,000 articles from the January 2012 dump of the English Wikipedia. Our strata were based on (a) the maturity of articles (in terms of the number of revisions) and (b) the articles' topical domains. This is important given that collaboration patterns could differ across articles in different stages of their life cycles (Hallerstede 2013) and across topical domains (Arazy et al. 2011, Kittur et al. 2009). This sampling approach is in line with prior studies of Wikipedia (Arazy et al. 2011). Given the power law distributions in the number of articles' revisions (Ortega et al. 2008), we used the following four maturity strata: (a) 1–10 revisions, (b) 11–100 revisions, (c) 101–1,000 revisions, and (d) more than 1,000 revisions. We refer to these stages as *inception*, *creation*, *growth*, and *maturity*, respectively (Hallerstede 2013). The topical strata were based on Wikipedia's categorization system, using the main topics scheme.[1] The 25 topical categories are agriculture, arts, business, chronology, concepts, culture, education, environment, geography, health, history, humanities, humans, language, law, life, mathematics, medicine, nature, people, politics, science, society, sports, and technology. With four maturity strata and 25 topical categories, we have 100 cells with 10 randomly selected articles in each (i.e., 250 articles in each maturity stratum and 40 articles in each topical category). Altogether, our sample contains 721,806 activities (i.e., article revisions), authored by 222,119 contributors.

3.2. Categorizing Activities

To create activity profiles of contributors, we needed to first determine the categories of edit activities. The categorization of activities was based on a two-step approach: first, we manually annotated a data sample; second, by employing the manual annotation as a training set, we applied a machine learning algorithm to categorize all 721,806 revisions in our sample set of 1,000 articles. By contrast to prior studies that have focused on active contributors (Liu and Ram 2011), we included all contributors, even those with very few editing activities, assuming that such activities were intentional (rather than random). This inclusive approach enabled us to model vandals and other types of occasional contributors. (Note that contributors with only one activity make up more than half of all contributors in our sample.) We tested the sensitivity of the clustering solution to this decision and found that the solution is relatively insensitive to the choice of including low-activity contributors (for details on this, see Appendix B.1).

[1] The English Wikipedia main topic categorization scheme is developed by the community and is subject to frequent changes; see http://en.wikipedia.org/wiki/Category:Main_topic_classifications.

The annotation of revisions was based on the taxonomy of wiki work developed in prior works (Kriplean et al. 2008, Arazy et al. 2010), which was already employed as a basis for the large-scale manual annotation task in Antin et al. (2012). The original taxonomy by Kriplean et al. (2008) included 10 edit categories, which were refined by Antin et al. (2012) after some pilot testing. We further refined this taxonomy through pilot testing until we generated a comprehensive list of 12 meaningful editorial work types that could be understood and identified by coders, as described in Table 1. The unit of analysis for our annotation was at the revision level, and each revision could contain multiple types of "editing work"; in other words, we allowed for multilabeling. For example, a revision could be annotated as both *delete substantive content* and *hyperlinks*. Appendix A.1 provides details on the process of manual annotation study.

Once the training set was created, we used a machine learning algorithm to classify all revisions in our 1,000 article set. Machine learning algorithms build a model based on labeled input and then make predictions; they are useful in tasks that do not lend themselves to the explicit programming of rule-based algorithms. A machine learning algorithm typically employs a set of features—in this case, features of the Wikipedia revision—for making the classification. Through an extensive set of experiments, Daxenberger and Gurevych (2013) identified the most important features for this task, including features based on metadata (information extracted from the revision comment, author name, time stamp, or other flags), textual features, wiki markup, and language features. We built on this approach, with some modifications. In particular, our unit of analysis was the wiki revision, whereas in the prior work each revision is decomposed into several "edits" (representing distinct local changes to the wiki page). To verify that the features are well suited for our task, we tested their performance on the manually classified data set, using a Random k-Labelsets (RAKEL) classifier. Overall, the performance of this classifier is satisfying with a micro-F1 score of 0.78. The classifier performs close to human agreement, as shown by the macro-F1 score of 0.68 (compared to human agreement of 0.73). Appendix A.2 provides more detail on the automatic classification procedure.

After verifying that our classifier performs well on test data, we employed it to classify all revisions in our 1,000 article set. This resulted in 689,514 revisions classified with a valid category, contributed by 222,119 distinct participants. Our analysis showed that the distribution of contributors' activity follows a power law, whereby more than half of the contributors in our sample performed only a single activity, and the most active contributor performed 3,815 activities across the

Table 1 The 12 Edit Categories Used to Annotate the Revisions in Our Data Sample

Category	Description
Move or create new article	An article is created or moved
Add substantive new content	New information is added, changing the meaning of the article
Delete substantive content	Existing information is removed, changing the meaning of the article
Fix typos and grammatical errors	Grammatical, spelling, and/or minor formatting errors are corrected
Rephrase existing text	Sentences are restructured for clarity, not changing the article's meaning
Hyperlinks (to other Wikipedia pages)	A link target is changed; a link is added; an existing link is deleted
References (to external sources)	References to external sources are added, deleted, or changed
Add or change Wiki markup	A text body containing wiki markup is added, deleted, or changed
Reorganize existing text	One or more text bodies are moved; headings or categories are added or deleted, changing the articles' overall structure
Insert vandalism	Malicious content is added; text is deleted without any obvious reason
Remove vandalism	Damage done by a vandal is reverted
Miscellaneous	A change which does not fall under any of the other categories is performed

1,000 article set. Roughly 12% of all contributors in our sample were active four times or more, and 10% of all contributors were active in more than one article. The contributors in our sample performed various types of activities, where often an activity was associated with several categories from our taxonomy. The most frequent category was the *add or change wiki markup* category (43% of activities), followed by the *add substantive new content* category (30%); the least frequent were *hyperlinks* (*to other Wikipedia pages*) (2%), *miscellaneous* (2%), and *move or create new article* (less than 1% of activities). Please see details in Appendix A.2.

3.3. Identifying Prototypical Activity Profiles

Each of the contributors in our sample was represented through a vector listing the number of activities he performed as well as the activities' categories. We assumed that a contributor may enact different roles in different article coauthoring projects (Gleave et al. 2009), and we created several activity profiles for each contributor, one for each article he contributed to.[2] In total, we created 325,417 activity vectors. For example, a contributor working on a particular article can perform 17 activities with category *add substantive new content*, 13 *delete substantive content* activities, and so on. Given our goal of modeling roles (rather than individual contributors), we normalized the activity profiles, dividing the count of revisions in each category by the overall number of activities made by the particular contributor on the article at hand. Thus, we eliminated distinctions between contributors with varying activity levels.

We then employed a clustering algorithm to group contributors' activity profiles, referring to each cluster's centroid as the prototypical activity profiles. These prototypical profiles are interpreted as emergent roles (Gleave et al. 2009, Liu and Ram 2011).

[2] Please see Appendix B.2 for details regarding the verification of the assumption of individual profiles per articles.

The input to clustering is contributors' activity profiles, one profile for each article $p_i \in P$ the contributor was active on. Let $e^1_{u_m,p_i}, e^2_{u_m,p_i}, \ldots, e^{12}_{u_m,p_i}$ denote the number of each of our 12 edit categories performed by contributor u_m to the article p_i, where $e^T_{u_m,p_i}$ denotes the total number of edits by contributor u_m to article p_i. Then, we defined the activity profile vector of contributor u_m to article p_i as $\overrightarrow{prof}_{u_m,p_i} = \langle e^1_{u_m,p_i}/e^T_{u_m,p_i}, e^2_{u_m,p_i}/e^T_{u_m,p_i}, \ldots, e^{12}_{u_m,p_i}/e^T_{u_m,p_i}\rangle$.

We employed the K-means clustering algorithm with the Euclidean distance measure, which aims to partition a set of observations (in our case, a contributor's activity profile) into k clusters; a cluster's centroid serves as a prototype of the cluster, and each observation belongs to the cluster with the nearest centroid (Jain et al. 1999). We iteratively tested K-means for k clusters, where $k \in [2, 10]$ (a larger number of clusters would be difficult to interpret intuitively). To determine the optimal number of clusters, for each value of k, we calculated the cluster *Compactness* and *Separation* metrics for the results of K-means clustering (Liu and Ram 2011, He et al. 2004). *Compactness* is based on the homogeneity of vectors in each cluster (smaller values indicate higher average compactness). *Separation* measures the overall dissimilarity between the clusters (smaller values indicate higher average separation). We combined the two metrics using the *optimal cluster quality* (*OCQ*) measure (He et al. 2004), giving *Compactness* and *Separation* equal weight. Given that clustering results depend on the selection of initial random seeds, we instantiated the seeds using the K-means++ method (Arthur and Vassilvitskii 2007) and iteratively tested a range of values for the initial seed. The lowest *OCQ* score (indicating the best clustering quality) was obtained for $k = 7$. A plot with the *OCQ* values for different k values can be found in Appendix B. Additionally, we qualitatively compared clustering solutions across values of k by trying to interpret the vectors describing the cluster centroids. This manual analysis

Table 2 Emergent Roles as Prototypical Activity Patterns

	Emergent role						
Edit category	All-round contr.	Quick-and-dirty eds.	Copy editors	Content shapers	Layout shapers	Watchdogs	Vandals
Move or create new article	0	0	0	0	0	0	0
Add substantive new content	**24**	**77**	0	**9**	0	0	2
Delete substantive content	**7**	5	0	1	0	1	1
Fix typos and grammatical errors	4	2	**95**	4	1	1	0
Rephrase existing text	**9**	2	2	1	0	0	2
Hyperlinks (to other Wikipedia pages)	3	0	0	0	1	0	0
References (to external sources)	**7**	0	0	1	1	0	0
Add or change Wiki markup	**39**	2	0	**29**	**97**	1	1
Reorganize existing text	1	0	0	**53**	0	0	0
Insert vandalism	3	**12**	2	1	0	2	**95**
Remove vandalism	2	1	0	1	0	**94**	0
Miscellaneous	2	0	0	1	0	0	0

Notes. Values are percentages, and bold values are values above 5%.

confirmed that the clustering solution with $k = 7$ produced centroids that could be interpreted intuitively as emergent roles.

Our findings illustrate the nature of emergent roles, as represented through the activity profiles of clusters' centroids (see Table 2). Each cluster was given a representative title, as follows: *all-round contributors*, *quick-and-dirty editors*, *copy editors*, *content shapers*, *layout shapers*, *watchdogs*, and *vandals*. The *all-round contributors* cluster has the highest percentage of contributors; 41% of all contributors' profiles in our sample are assigned to this cluster. As shown by its centroid, contributors with this role are active in many edit categories, with a slight tendency toward adding content and wiki markup. The *quick-and-dirty editors* cluster (11%) represents contributors with a relatively clear focus on adding new content. However, some of their contributions were labeled as vandalism. Different from the vandalism cluster, which has a clear focus on vandalism activities, here, vandalism activities are coupled with the addition of new content. We assumed that, unlike the activities of vandals, these are contributions made in good faith that were often reverted because they were not done properly and did not comply with Wikipedia's policies (e.g., neutral point of view, supporting claims by references, etc.). *Copy editors* show a clear tendency toward one activity category, namely, fixing grammar and spelling errors. The two clusters representing "shaping" activities contain relatively few profiles: *content shapers* (4%) concentrate on activities associated with the (re)organization of content, whereas *layout shapers* (6%) focus almost entirely on adding markup to an article. The *watchdogs* and *vandals* clusters have equal size (13% of profiles) and contain contributors with a clear focus on a single edit category, namely, inserting or removing vandalism, respectively.

3.4. The Organization of Work: Stability of Prototypical Activity Profiles

The clustering procedure described above aggregates contributors' activity profiles, and the resulting solution describes the organization of work in Wikipedia. Here, each cluster corresponds to a particular prototypical activity pattern, which corresponds to an emergent role. When using such automatic clustering techniques, we need to ensure that space defined by contributors' activity vectors naturally organizes into clusters, and thus we performed an analysis of clustering reproducibility. Clustering results may be of low quality in the sense that different clustering approaches may claim to summarize a given data set equally well, and we cannot tell which ones better reflect the intrinsic structure of the data (Bayá and Granitto 2013). The metrics described above (*Compactness*, *Separation*, and *OCQ*) are useful in determining the best clustering solution for a *K*-means algorithm on a given solution space, but cannot generalize to compare clustering solutions across algorithms and different data spaces. Thus, to assess clustering quality, a much more general approach is required. Lange et al. (2004) devised a validation method for detecting the number of arbitrary shaped clusters. They trained a classifier that learned the structure that was found by a clustering algorithm using the "natural groups" produced by the clustering algorithm as labels of the input to the classifier. *Cluster reproducibility*[3] measures the classification risk of the labels produced by the clustering.

Following Lange et al. (2004), we calculated the cluster reproducibility, $\bar{S}(A_k)$, where A is the clustering algorithm and k is the number of clusters. In several rounds, we split the full data sample randomly in two halves, X and Y. The average 0-1 loss between $A_k(Y)$

[3] Please note that Lange et al. (2004), whose approach we adopted, referred to clustering reproducibility as "stability." To avoid confusion with our analysis of stability across time, we chose to refer here to "clustering reproducibility."

and a classifier prediction $\phi(Y)$ (ϕ is trained on $A_k(X)$) corresponds to the average dissimilarity of clustering solutions. After normalizing this value by the misclassification rate of a random labeling, we arrived at the cluster stability value, $\bar{S}(A_k)$. Smaller values of $\bar{S}(A_k)$ signify a lower misclassification risk and, thus, a higher reproducibility of the clustering solution. Our analysis indicated that cluster reproducibility $\bar{S}(A_k)$, for values of $k \in [2, 10]$, reached a local minimum at $k = 7$, corroborating our earlier findings regarding the optimal number of clusters. The clustering reproducibility value $\bar{S}(A_7)$ was 0.31, and the average 0-1 loss between our clustering solution $A_7(Y)$ and a classifier prediction $\phi(Y)$ was 0.27,[4] indicating that the risk of irreproducible clusters in our solution is not high. For $k < 7$, reproducibility values were consistently worse compared to $\bar{S}(A_7)$. For values of $k > 7$, only $k = 9$ and $k = 10$ yielded slightly lower values of $\bar{S}(A_k)$. The classifiers we tested for ϕ were Sequential Minimal Optimization (SMO) (Platt 1998) and C4.5 (Quinlan 1993).

3.5. The Organization of Work: Stability Across Periods in Wikipedia's Evolution

Wikipedia has gone through two major periods in its evolution: (I) "forming" (from the beginning of 2001 to the end of 2006) and (II) "establishing" (from January 2007 to 2012) (Halfaker et al. 2012). The first period is characterized by the establishment of the technical infrastructure, the introduction of basic procedures and policies around the organization of work, and rapid growth in the size of the community. The second period is exemplified by the development of a bureaucratic structure (Butler et al. 2008); a greater emphasis on policies, norms, and procedures (Kittur and Kraut 2010); and the formation of a complex organizational structure (Arazy et al. 2014).

To test whether the clustering solution describing the organization of work in Wikipedia is stable over time, we split our data for the two periods (2001–2006 and 2007–2012), and for each period we created profiles of contributors' activities. We applied the same clustering procedure described earlier. There were 96,757 contributors' activity vectors in the "forming" period and 233,687 in the "establishing" period, where only 5,027 contributors remained active in a particular article across both periods (this translates into an outflow of 95% at the end of the first period and an inflow of 98% entering the second period). Based on the Euclidean distance between centroids, we were able to align the two clustering solutions, mapping each centroid in one solution to the cluster centroid in the other.

[4] Further parameters are as listed in Lange et al. (2004): $r = s = 20$ (number of splits/iterations).

Comparing the clustering solutions for the two periods shows that the prototypical activity profiles are stable across the two periods in Wikipedia's evolution, as the two clustering solutions are highly similar and align well. The analysis of the distances between clusters' centroids shows that the average distance is 0.12 (11% of the average centroid distance in the clustering solution on the entire data), indicating that the nature of emergent roles (defined in terms of centroids' activity profile) changed very little between the two periods.[5] Figure 1 visualizes the alignment between the clustering solutions for the two periods. We were surprised to find such a high stability in the characteristics of emergent roles, despite fundamental changes in Wikipedia's governance mechanisms.

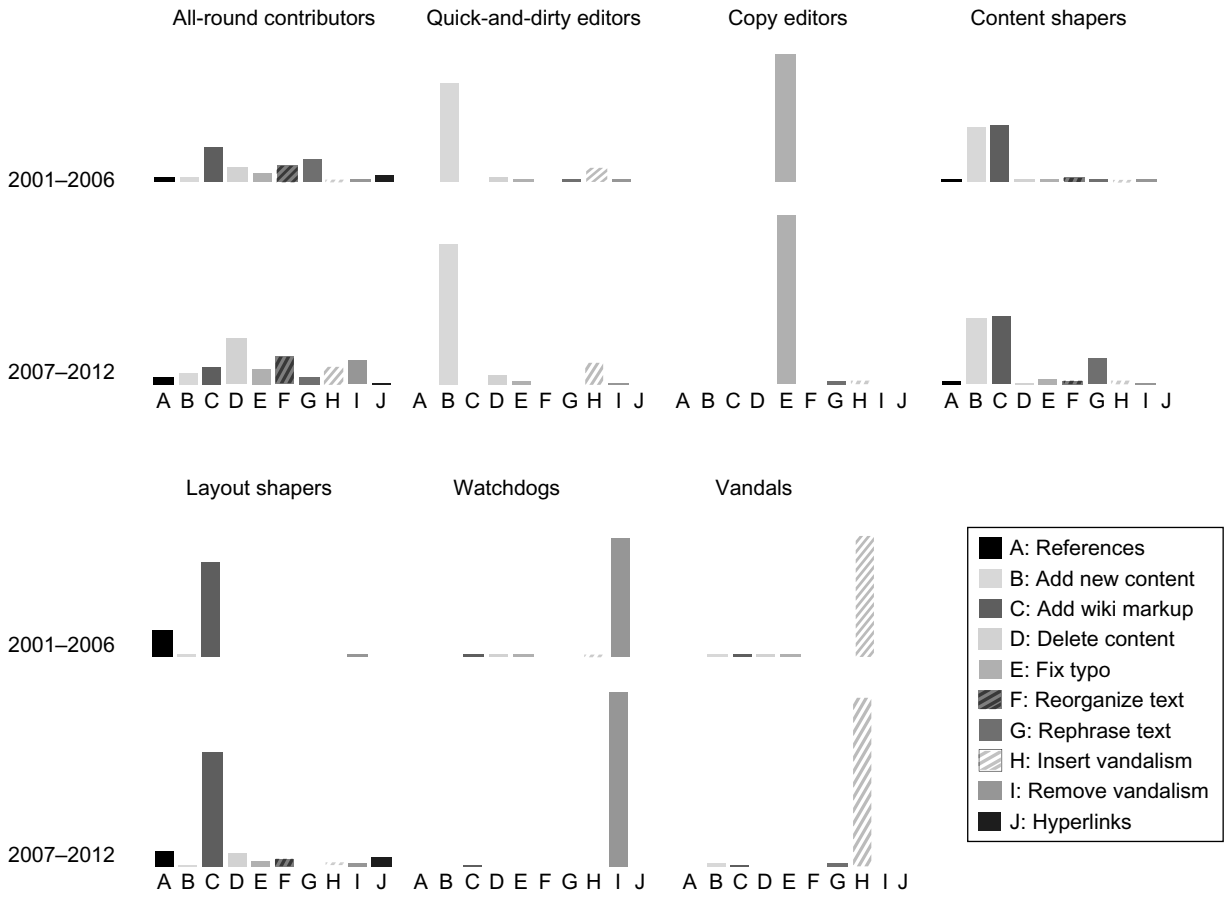
3.6. Individual-Level Analysis: Contributors' Dynamics

We based our analysis of individuals' dynamics on the comparison between the two periods of Wikipedia's life (2001–2006 and 2007–2012). First, we found evidence for massive fluidity, illustrating the high level of in- and outflows from the knowledge production process (Faraj et al. 2011). Our results show that 95% of those active in the "forming" period did not continue to the next period, and 98% of those active in the "establishing" period were newcomers. A closer look at the year-by-year attrition revealed that in the early years (2001–2006), 20%–25% continued their participation at the end of the year, and those numbers dropped to approximately 10% in later years (i.e., an outflow of 75%–80% in early years and roughly 90% yearly outflow after 2006). In terms of inflow, in the early years, 92%–94% of the users active in every calendar year were new (i.e., 6%–8% sustained their participation), and the inflow values dropped to roughly 90% in later years.

Building on our previous analyses, and after verifying that the nature of emergent roles is stable over time (i.e., clustering solutions for the two periods are almost identical), we were able to zoom in on individual contributors and investigate how they transition between roles across the two time periods. We found that among the 5,027 contributors active within an article at both periods, more than 50% changed their role over time. A detailed analysis of role transitions reveals that contributors tend to move toward the layout shaper role (incoming: 956; leaving: 346) and, to a lesser extent, to the watchdog role (incoming: 482; leaving: 187). By contrast, contributors tend to leave

[5] The reported alignment of clustering solutions used the Euclidean distance measure. To verify the robustness of this alignment between the clustering solutions for the two periods, we confirmed the analysis with the help of the Manhattan distance metric. Using both metrics, we arrived at the same alignment between clustering solutions.

Figure 1 The Characteristics of Emergent Roles Compared for Two Time Periods



the all-round contributor role (incoming: 378; leaving: 1,236). These role transitions suggest that while the nature of roles is quite stable across time, contributors do change their roles within the same article, often taking on more complex coauthoring roles (e.g., shapers or watchdogs). Table 3 presents the between-periods role transitions.

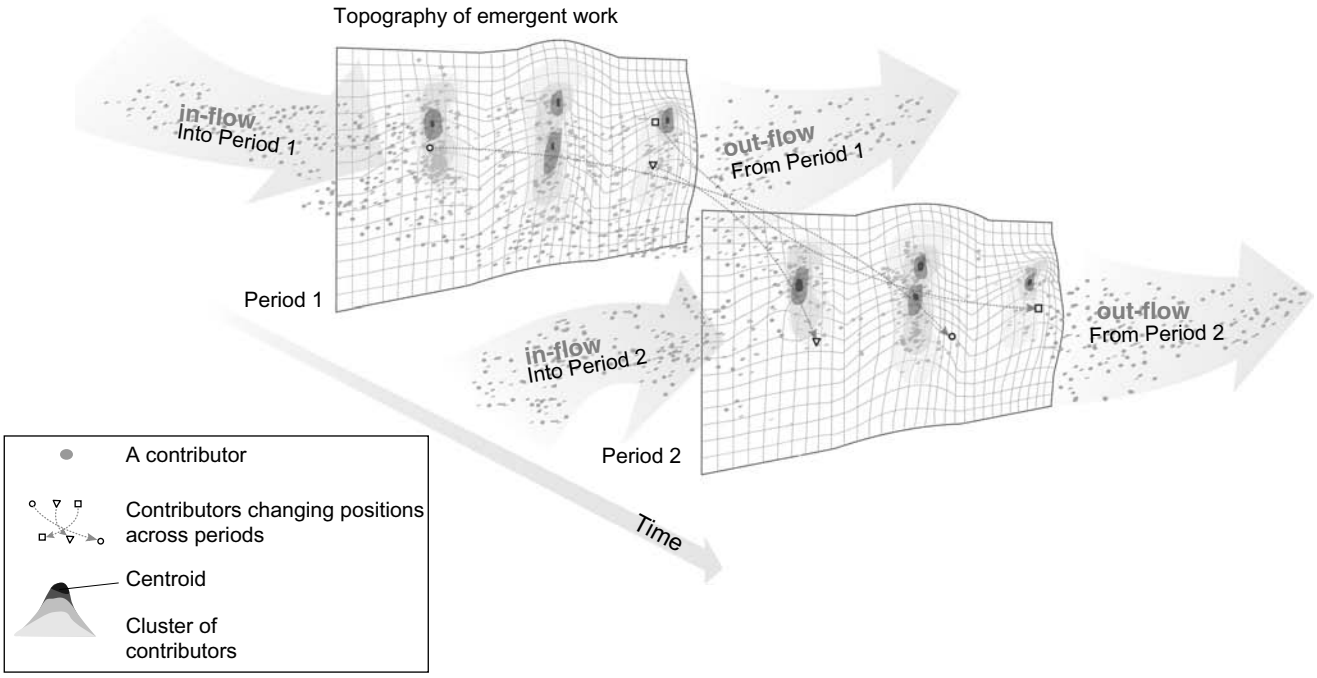
In sum, the series of analyses we performed sheds light on the nature of emergent roles as well as on participants' role-taking dynamics. First, we described the nature of emergent roles and validated the stability and robustness of our results (Sections 3.3 and 3.4; Appendix B). Our analysis of participants' role-taking behaviors shows massive in- and outflows, indicating that on a year-by-year basis, the vast majority of participants flow into and out of the coproduction process. Moreover, those continuing their participation across the two periods of Wikipedia's life are likely to change the role they play in the production of a particular article. In the face of this high mobility—as well as the fundamental changes the Wikipedia organization has gone through between the "forming" and "establishing" periods—one could expect that the patterns of contributors' activities would also change

Table 3 Role Transitions for the Set of 5,027 Contributors Active in Both Periods

	To Period B							
From Period A	All-round contr.	Quick-and-dirty ed.	Copy editors	Content shapers	Layout shapers	Watchdogs	Vandals	Sums
All-round contr.	**350**	40	93	387	476	231	9	1,586
Quick-and-dirty editors	17	**25**	5	48	15	11	9	130
Copy editors	47	8	**86**	67	123	41	1	373
Content shapers	172	54	84	**674**	258	119	20	1,381
Layout shapers	80	12	47	125	**240**	79	3	586
Watchdogs	57	2	20	31	76	**721**	1	908
Vandals	5	4	3	18	8	1	**24**	63
Sums	728	145	338	1,350	1,196	1,203	67	5,027

Note. Values on the diagonal (in bold) represent contributors maintaining the same emergent role.

Figure 2 Illustration of Our Concept of "Turbulent Stability" (Based on Fictional Data): System-Level Stability in the Face of Individual-Level Mobility



Notes. The grids reflect the activity spaces at two points in time. Darker regions ("mountain tops") represent cluster centroids corresponding to emergent roles.

across periods. Surprisingly, our results (Section 3.5) indicate that the nature of emergent roles remained highly stable across the two time periods. We refer to this interplay between individual-level mobility and organizational-level stability (in terms of the nature of emergent roles) as "turbulent stability" in knowledge coproduction, and perceive the introduction of this construct as an important theoretical contribution of this study. Please see Figure 2 for an illustration.

3.7. Investigating Artifact-Centric Coordination

A core question of this work is about how contributors self-organize around a stable set of emergent roles. Prior research points to formal control mechanisms, norms, and policies as key coordinating mechanisms. However, our results regarding the stability of emergent roles across periods where Wikipedia's organization differed greatly suggest that an alternative coordination mechanism is possibly at play. Following the artifact-centric line of reasoning (Bolici et al. 2016), we sought to explore the role played by the artifact and its affordances in facilitating coordination. We performed two types of analyses toward this goal. First, we conducted a limited-scope qualitative analysis of the traces left by participants, in terms of the actual activities they performed and the comments they left, shedding light on the rationale behind their activities. Second, we performed a statistical analysis of articles' evolution, comparing role distribution across these stages in articles' development. Given that knowledge products call for different types of work at different stages of their evolution (Benkler 2006), we conjectured that if contributors indeed responded to the needs of the evolving article, they would enact relevant emergent roles at particular stages.

Our qualitative analysis of a random selection of articles in our sample investigated the history of the articles' coproduction process. Wikipedia maintains a history page for each article, tracking its revisions. This page not only allows tracing the detailed activities performed by contributors; it also records their comments. Although these comments are intended to help others understand the nature of the changes made, they also shed light on the contributor's motivation and rationale for making the changes.[6] Our findings provide evidence that contributors choose to enact a particular role as a response to the work required at a particular point in time. Below, we provide a few examples.

Our first example includes a set of consecutive edits made by the same contributor working on the "Benito Mussolini" article. The series of edits include a variety of actions: the insertion and removal of hyperlinks, copyediting, and the addition and deletion of content, an activity profile typical of an all-round contributor. The comments made by this contributor, as presented in Figure 3, demonstrate the responsive

[6] Note that these comments were also used by our automatic revision classification algorithm to help determine the revision category.

Figure 3 A Set of Actions Performed by a Typical All-Round Contributor, Interrupted by One Different Contributor

06:42, 14 October 2012 Brothernight (talk I contribs) . . (143,589 bytes) (+37) . . (→ *Expulsion from the Italian Socialist Party*: *Added citaion needed tag.* -- ~~~~)
05:22, 14 October 2012 Brothernight (talk I contribs) . . (143,552 bytes) (+128) . . (→ *In popular culture*: *Corrected the spelling of the insult chiseler and explained why it is written that way.* -- ~~~~)
05:12, 14 October 2012 Brothernight (talk I contribs) . . (143,424 bytes) (+300)
04:33, 14 October 2012 Brothernight (talk I contribs) m . . (143,124 bytes) (+61)
04:30, 14 October 2012 Brothernight (talk I contribs) . . (143,063 bytes) (–110) . . (*Made several changes, one of which was a repeat.* -- ~~~~)
03:54, 14 October 2012 Brothernight (talk I contribs) . . (143,173 bytes) (+66) . . (*Added an appropriate link.* -- ~~~)
03:18, 14 October 2012 852derek852 (talk I contribs) . . (143,107 bytes) (+101) . . (*Removed vandalism*)
03:10, 14 October 2012 Brothernight (talk I contribs) m . . (143,006 bytes) (+7)
03:01, 14 October 2012 Brothernight (talk I contribs) . . (142,999 bytes) (+73) . . (*Added a link to what really happened with Mussolini's futile attempt to deal with the Pontine Marshes.* -- ~~~~)
02:11, 14 October 2012 Brothernight (talk I contribs) . . (142,926 bytes) (–84) . . (*Made a heartfelt attempt to explain what Italian Fascism was all about.* -- ~~~~)
01:17, 14 October 2012 Brothernight (talk I contribs) . . (143,010 bytes) (–17) . . (*Removed the linked word "corporatism" as it is meaningless to most speakers of English in this particular context.* -- ~~~~)

nature of actions, where the contributor chooses to fix flaws and refine the articulation.

Next, we provide indirect evidence for the action of a quick-and-dirty editor. These editors are characterized by additions of content, often including mistakes (and thus occasionally tagged as vandalism). They are content oriented and care less for Wikipedia's standards and norms (Arazy et al. 2011); thus, they are not likely to exert extra effort in adding comments. Nonetheless, a comment by a contributor correcting a posting by a quick-and-dirty editor in the "Bianca Jackson" article illustrates the nature of this emergent role and provides evidence for how editors are responding to the state of the artifact:

> Reverted good faith edits by 146.199.244.239 (talk): Lorraine not her stepmother, she was grown up before she knew Lorraine existed.

Copy editors often make small changes at the word level, correcting small errors. Below are examples of editors acting as copy editors in the "Avro Canada CF-105 Arrow" and "Newcastle upon Tyne" articles, respectively:

> Delete double period.

> Took kilometres out of ( ) and put miles in. Since it is located in the United Kingdom, kilometres should be the default measurement.

Content shapers are mostly involved in improving the organization of content on the wiki page, moving sections around, removing duplications, and often categorizing articles. The comments below illustrate the actions of two content shapers reorganizing the order of content in the "Kurdistan Workers' Party" article:

> Moved into chrono[logical] order.

> Rv. it was in chronological order (a reverse one, to be precise), before this edit.

Layout shapers are mostly involved in changing wiki markup: formatting lists, tables, links, section headers, etc. Below is an example for an action of a typical layout shaper working on the "Benito Mussolini" article:

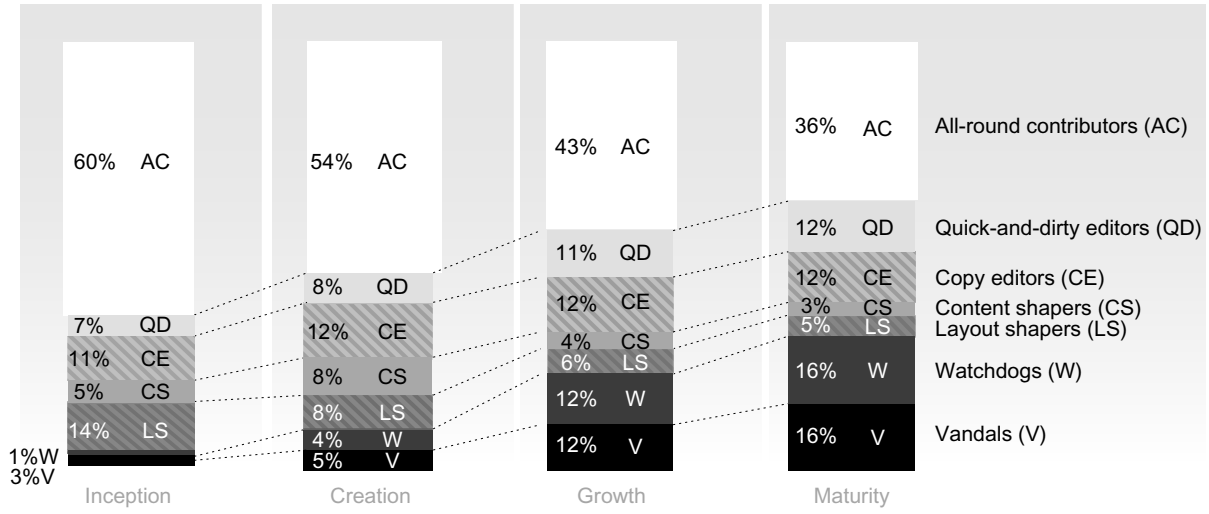
> [A]dded list formatting, removed flash movie.

Finally, watchdogs are involved in the correction of vandalism. Thus, by definition, their work is responsive in nature and involves close monitoring of the artifact. While vandals are not likely to leave comments describing their actions, watchdogs often do leave comments, as exemplified by the comment to the "Bianca Jackson" article above as well as by the following comment by an editor working on the "Economy of Angola" article:

> Reverting possible vandalism by 2605:6000:8281:BA00:3C5A:1B48:EB81:29DC to version by 2001:4C50:21D:F400:B565:F3EB:735B:522. False positive? Report it....

In addition to the evidence for artifact-centric coordination derived from our qualitative analysis, we sought quantitative evidence for the relationship between an article's state and a contributor's decision to enact a particular role. Our next analysis thus investigated the distribution of emergent roles at different stages in an article's evolution. We focused our analysis on the 250 articles from our sample that had passed through all stages in an article's life to reach maturity (more than 1,000 revisions). We portioned each article in our subsample into these stages. For example, an article with 1,253 revisions was partitioned into: 1–10 revisions, 11–100 revisions, 101–1,000 revisions, and 1,001–1,253 revisions. We then created contributor–article–partition activity vectors for each article partition and associated each vector with a cluster centroid (i.e., emergent role). Next, for each article in a partition, we listed the percentage of contributors playing each role. We then aggregated the data for each of the partitions, averaging each role's percentages. Comparing the means for each role across the four partitions shows whether an emergent

Figure 4 **The Distribution of Emergent Roles Across the Four Stages of Articles' Life Cycle**



role changed its relative concentration between the stages of an article's life.

Findings from our analysis reveal some significant differences between the four stages, as illustrated in Figure 4. To better assess those variations, we applied an analysis of variance (ANOVA) model (Edwards 1979) and found that the differences between stages are statistically significant ($p < 0.001$) for all of the roles. Three roles—all-round contributors, content shapers, and layout shapers—start at relatively high proportions and then generally decline with an article's maturity, whereas three other roles—quick-and-dirty editors, vandals, and watchdogs—show a constant increase in proportion. A least significant difference post hoc analysis (Williams and Abdi 2010) shows that these increase/decrease trends are to a large extent consistent, such that pairwise differences for consecutive life-cycle stages are statistically significant (for all roles across most stage transitions; $p < 0.001$). However, for most roles, the relative proportions stabilize at the growth stage, such that the differences between the growth and maturity stages are statistically insignificant (except for the roles of all-round contributors and watchdogs, where the trend continues into the maturity stage; $p < 0.001$).[7] The relative proportion of all-round contributors is highest across all life-cycle stages, yet this proportion decreases as articles mature (starting with 60% at the inception stage and ending at 36% at the maturity stage). This suggests that articles at more mature stages require more specialized work. The shaping roles (content shapers and layout shapers) start at moderately high proportions (together, 20% at the inception stage) and end low (together, 8% at the maturity stage), indicating that delineating the article's structure is more important in the early stages of an article's life cycle. The quick-and-dirty editor role takes the opposite trajectory: 7% at inception and growing constantly to 12% at maturity. This could possibly be explained by the fact that more mature articles attract a broader readership, and consequently invite one-time editors. The constant rise in the proportion of watchdogs (1% to 4% to 12% to 16%) follows closely the increase in the vandal population, suggesting that watchdogs react to the rising concern of vandalism. Together, these results—described in Figure 4—provide indirect quantitative evidence for the role of the artifact in determining the types of emergent roles that contributors choose to enact.

4. Discussion

While scholars investigating online coproduction communities are beginning to uncover the nature of emergent work, much is still unknown. At the organizational level, there have been attempts to characterize the bundles of tasks that make up emergent roles (Fisher et al. 2006, Gleave et al. 2009, Liu and Ram 2011, Welser et al. 2011), yet we lack an understanding about the extent to which these roles are robust and stable over time. At the individual level, not only do existing conceptualizations disagree on the extent to which emergent roles are fluid and transient, but there has also been a scarcity of empirical investigations validating these conceptualizations (Faraj et al. 2011, Kane et al. 2014, Panciera et al. 2009). Scholars have suggested that new organizational forms combine both stable and dynamic elements (Schreyögg and Sydow 2010, Langley et al. 2013, Farjoun 2010), and have called for a multilevel analysis that would

[7] The one exception was for copy editors, where the proportion remained constant (at 12%) through the creation, growth, and maturity stages.

explore these tensions (Gaskin et al. 2014). Yet empirical validations have been slow to follow. Our study has made inroads toward filling in these gaps. In Sections 4.1–4.4, we argue our study's contributions to the various literatures we drew on.

4.1. Emergent Roles in Knowledge Coproduction

While role theorists allude to the notion of emergent roles, to date, the theoretical understanding of the temporal dynamics of emergent roles is far from comprehensive. Turner (1978, p. 1) describes roles that are "put on and taken off like clothing" without lasting effect on personality. Faraj et al. (2011, p. 1231) call for "the enactment of temporary sets of behaviors that are volitionally engaged in, self-defined, and inductively created for the purposes of the online community." Others (Gleave et al. 2009, Welser et al. 2011) advocate for a broader understanding of "role ecologies," stating that "we should aim for systems that can assess degree of role performance, and, ideally, to track assessment across time to monitor role change" (Welser et al. 2011, p. 128). Our empirical study represents a preliminary step toward this aim.

Extant conceptualizations of online production communities have pointed to two prototypical role behaviors: (a) those adding new content and (b) those "shaping" existing content (Kane et al. 2014, Majchrzak et al. 2013, Yates et al. 2010). Such roles were operationalized using surveys of contributors' perceptions. However, these operationalizations are divorced from taxonomies of wiki work (Antin et al. 2012, Kriplean et al. 2008) and fail to account for a variety of disparate activities (e.g., copyediting, adding hyperlinks). Our study's findings point to seven emergent roles as they are practiced in Wikipedia: *all-round contributors*, *quick-and-dirty editors*, *copyeditors*, *content shapers*, *layout shapers*, *watchdogs*, and *vandals*. While the majority of these roles map well to those identified in earlier studies that employed bottom-up approaches (Liu and Ram 2011), we were also able to identify previously unnoticed prototypical behaviors that correspond to roles in conceptual frameworks (Majchrzak et al. 2013, Yates et al. 2010). Our findings thus help to bridge these two literatures. In particular, our results indicate that there are two distinct forms of shapers. The first, content shapers, concentrate on activities associated with the reorganization of text (and, to a lesser extent, adding wiki markup), while the second, layout shapers, are almost entirely about adding wiki markup. Majchrzak et al. (2013, p. 455) argue that "recognizing and clarifying the role of shaping allows us to theorize new ways in which knowledge resources affect knowledge reuse," and our empirical findings contribute toward this goal.

We also make a methodological contribution by introducing techniques that have not been used previously in the study of online production communities: studies in the area rarely examine clustering reproducibility (Lange et al. 2004) and assume, rather than validate, that clustering results represent natural groupings in the data. In addition, our method for profiling participants' activities employed machine learning, which has some unique advantages over the previously used rule-based approach (Liu and Ram 2011).

4.2. The Dualistic Nature of Self-Organizing Knowledge Coproduction

The main contribution of this study is in discovering the "turbulent stability" of emergent roles and unraveling the dualistic nature of self-organized knowledge coproduction. This duality between individual-level turbulence and organization-level stability in emergent role behaviors contributes to our understanding of new forms of organizing for knowledge production. Scholars have called for research on the emergent nature of work in postindustrial production that takes place outside traditional boundaries and requires "assembling specialized knowledge in ways that we have not done before while facing new task environments" (Okhuysen and Bechky 2009, p. 496). Schreyögg and Sydow (2010, p. 1256), for instance, call for developing theoretical frameworks that "overcome the one-sided ideals of organizational fluidity and full flexibility on the one hand and the advantages of bureaucratic replication on the other hand." Instead, they suggest conceiving contemporary organizations in terms of dual, dialectic, or paradoxical processes.

Organizational theorists have highlighted the need to develop refined theoretical understandings of the processes underlying, enabling, and sustaining emergent work (Orlikowski 2000, Hernes 2014, Farjoun 2010). To date, the literature on online production communities has paid particular attention to the role of community-based governance mechanisms, such as norms and policies (Forte et al. 2009, Kittur et al. 2007), coordination processes (Shah 2006, Demil and Lecocq 2006), and quality control procedures (Stvilia et al. 2008). What seems to be missing from this scholarly discourse is attention to the emergent nature of coproduction work itself (Faraj et al. 2011, Kane et al. 2014, Majchrzak et al. 2013, Choi et al. 2010, Panciera et al. 2009). We note that while some scholars have previously questioned the ability of the "crowd" to self-select and replenish its role players (Goldman 2009), this study illustrates that massive amounts of distinct contributors *can* enact emergent roles, shed them, and sometimes transition to new roles, and yet, at the organizational level, these roles remain stable and well defined over time.

Results from our study showing the persistence of emergent roles reveal that stability in knowledge coproduction work can emerge independent of formal organizational structures. In particular, we find evidence for the rise of stability at the system level (i.e., emergent role behaviors) in the face of high levels of role mobility at the individual level (i.e., transitions in and out of coproduction, as well as between emergent roles). Given the high level of fluidity and mobility in participants' role enactment during knowledge coproduction (Faraj et al. 2011, Kane et al. 2014), one might expect that these high levels of change in individual's role taking and shedding will translate into unstable role behaviors. This is especially true when the organization goes through fundamental changes in structure and governance procedures (as was the case for Wikipedia; Halfaker et al. 2012). Hence, our results about the stability in emergent roles behavior are quite surprising, and are of particular importance.

Our findings regarding the turbulent stability of emergent roles also contribute to the discussion in the literature on new forms of organizing. In particular, our results inform the debate between the bureaucratic and "open" perspectives, suggesting a more nuanced synthesis of the two approaches. To date, the literature on new forms of organizations moves between two extremes: on one hand, scholars claim that such coproduction communities are built on unprecedented freedom and very little structure, and thus represent a new form of organization; on the other hand, scholars focus on how formal structures rise in such settings, transforming the organization into familiar bureaucracies (Shaw and Hill 2014, Puranam et al. 2014). We note that even in periods when the organization has become more formal and institutionalized (i.e., Wikipedia in the period between 2007 and 2012), it kept "production" work free from workflow constraints associated with traditional knowledge production. Strikingly, the way in which work organically self-organizes into emergent role behaviors has remained consistent over the two distinct periods in Wikipedia's evolution. Thus, our study stresses the value of a more hybrid and nuanced approach to the understanding of the dynamic processes underlying online production communities (Schreyögg and Sydow 2010).

4.3. Artifact-Centric Production

We argue that the enabling means for the turbulent stability in emergent roles is artifact-centric coproduction. Our finding that emergent role behaviors remain stable over two distinct periods in Wikipedia's life, despite fundamental organizational changes in governance structure and norms, rules out the explanation of traditional role theories that the mechanisms stabilizing role behaviors are persistent norms, policies, or social interactions. The artifact-centric perspective highlights the role of the coproduced artifact as a central mechanism facilitating tacit coordination in peer production (Howison and Crowston 2014) and supporting "mutual adjustment" (Mintzberg 1992). We maintain that the artifact and its affordances served as a stabilizing factor amid the turbulence of individuals' role mobility.

Orlikowski and Scott (2008) called for the development of a unified conceptualization that encompasses the social and the material under the label of sociomateriality. In this study, we provide empirical evidence in support of this perspective. More specifically, we find support for the conceptualization introduced by Faraj et al. (2011), describing emergent role-taking as a response to rising tensions around the coproduction of an artifact. We use evidence from contributors' comments indicating that, when enacting a particular emergent role, they respond to the current state and needs of the artifact. A contributor enacting the emergent role of content shaper in response to tension fluctuations commented, "It was in chronological order (a reverse one, to be precise), before this edit," bringing empirical evidence to the ideas postulated by Faraj et al. (2011, p. 1231): "When convergence is so incomplete and temporary that ideas become disorganized, a participant may create an organizer role for herself by organizing ideas that others have posted." Moreover, our study explores whether a product's maturity level influences participants' role-taking behaviors (Kane et al. 2014). Faraj and Azad (2012) emphasized the temporal dimension of the artifact-centric perspective, viewing the artifact not as a static object to which the "social" responds, but rather as an evolving relational construct. Our findings imply that when enacting a particular emergent role, participants consider the maturity level of the product. Our study thus provides corroboration for the artifact-centric perspective and demonstrates the importance of the artifact in directing emergent work.

Our findings also have implications for role theories. Traditional theories of organizational roles assume a "stage" (Goffman 1963) where roles are performed, viewed, monitored, and negotiated with others. Coproduction communities offer a novel interplay between "front stage" and "back stage": at the front stage is the visible artifact-centric coproduction work, whereas at the back stage are workers, often anonymous, and their emergent roles (Zammuto et al. 2007). Such settings create a unique dynamic of choices, where role-taking decisions are less susceptible to social comparison or herding considerations (Faraj et al. 2011).

We argue that the affordances provided by the sociotechnical system underlying the online community are a central factor facilitating artifact-centric

coproduction. The past decade has seen a growth in the investigation of these affordances (Zammuto et al. 2007, Majchrzak and Markus 2016), specifically of social media and wikis (Treem and Leonardi 2012, Majchrzak et al. 2013). These studies have tried to identify the specific features that enable (Ziaie 2015) or forestall (Majchrzak 2009, Yeo and Arazy 2012) online knowledge collaboration. We suggest that the key enabling affordances for turbulent stability of emergent roles are work process visibility (Treem and Leonardi 2012, Wagner 2004), unconstrained workflow (Wagner 2004), choice of anonymity (Gabrielle 2012), task decomposability (Lakhani et al. 2013, Baldwin and von Hippel 2011), and open boundaries (Zammuto et al. 2007). To validate the boundary conditions of this study's findings, we call for future research into other coproduction communities (e.g., the GitHub platform supporting open-source software development).

Finally, we propose that in addition to affordances, the clear definition of the nature of the end product is key to enabling artifact-centric production (Zhu et al. 2012). The "five pillars" of Wikipedia make the nature of the coproduced artifact clear: it is an encyclopedic entry that should provide a brief overview of a topic, state facts rather than opinions, provide support for these statements, and include only copyright-free material. In fact, scholars have attributed Wikipedia's success to this clarity in artifact requirements (Hill 2013). This high level of clarity serves as a "boundary infrastructure" (Bowker and Star 1999) that stabilizes and facilitates tacit coordination. While Wikipedia hosts millions of coproduced artifacts, the understanding of artifact requirements is shared between all participants, over a decade of coproduction work. We note that by and large, prior studies on "boundary infrastructure" and "boundary objects" were able to demonstrate their effect in enabling communication and coordination only within a restricted setting, during a relatively short period, and with a small number of participants (Carlile 2002, Kellogg et al. 2006). Our study enriches this literature by demonstrating the effects of "boundary infrastructure" in a much broader and dynamic setting.

4.4. Practical and Managerial Implications

Recent years have witnessed an increase in the types of knowledge-based products cocreated in self-organizing online communities, such as open-source software, community-based maps, product designs, and the development of scientific knowledge through the aggregation of citizen's contributions. Our findings have important practical implications for designers and administrators of these online communities. Many coproduction communities struggle with the decisions of how much structure to impose on the coproduction process and whether or not to formalize roles. Our findings demonstrate that it is possible to achieve stability in the overall organization of knowledge work while avoiding explicit role prescriptions in the production space and allowing community members freedom in self-selecting their level and form of participation. It is essential for platform designers to build into the information technology (IT) platform affordances that enable this turbulent stability. For instance, guiding participants to tasks without imposing restrictions on coproduction workflows requires making the evolving requirements of the artifact more visible.

More specific practical implications of our study relate to the "statistical machinery" developed for identifying participants' emergent roles. In particular, our methods can be employed to develop tools that track contributors' activities, identify for them tasks of interest (Zhang et al. 2014), and offer them "career guidance"; that is, rather than simply encouraging participants to become more involved—which is implied by extant frameworks such as "Legitimate Peripheral Participation" (Lave and Wenger 1991) or "Reader-to-Leader" (Preece and Shneiderman 2009)—we propose that participants be offered specific, personalized, nonbinding guidance regarding the nature of tasks most relevant for them.

Beyond online communities, key principles from the community-based peer-production model have recently begun "spilling over" into traditional organizations (Lifshitz-Assaf 2016). Many companies use wikis as a knowledge management tool (Majchrzak et al. 2013, Arazy and Nov 2010), particularly for developing organizational encyclopedias and knowledge-sharing tools (Arazy and Gellatly 2013, Arazy et al. 2016), adopting in part the organic processes that typify wiki-based collaboration. Similarly, some technology companies participate in open-source software development.

However, only a few have gone through the transformation needed to truly adopt the principles of peer production for their internal research and development processes (Lifshitz-Assaf 2016, Levina et al. 2014) or for their organizational design (Puranam and Håkonsson 2015, Van De Kamp 2014).

5. Conclusion

Following a call to investigate the temporal dimension in complex and evolving sociotechnical systems (Orlikowski and Yates 2002), our study explores the temporal dynamics of emergent roles. We investigated a large number of coproduction projects within one setting (i.e., Wikipedia). The advantage of this research method is that it allowed for substantial variation and at the same time controlled for

exogenous factors that might have hindered a cross-organizational study. However, we do acknowledge potential concerns regarding generalizability. Our findings suggest several theoretical contributions to our understanding of (I) the nature of emergent roles, (II) the dualistic nature of self-organizing knowledge coproduction, and (III) artifact-centric coproduction. Notwithstanding our study's contribution, it represents only a preliminary investigation of emergent roles in online coproduction communities, and thus leaves much room for future research. We investigated a large number of coproduction projects within one setting (i.e., Wikipedia). The advantage of this research method is that it allowed for substantial variation and at the same time controlled for exogenous factors that might have hindered a cross-organizational study. However, we do acknowledge the potential concerns regarding generalizability to other settings and stress the need to extend the investigation of emergent roles to other online communities. In addition, while our study does show that individuals transition between roles, future research is warranted to reveal the intricacies of contributors' temporal dynamics between emergent roles and across knowledge-based products. From a methodological perspective, we propose that additional approaches may complement the statistical methods applied in this study to offer a more comprehensive description of emergent work dynamics. For example, scholars have suggested that sequencing techniques from bioinformatics and related fields could be applied to the investigation of the temporal dynamics of sociotechnical systems (Gaskin et al. 2014), and in particular to the study of Wikipedia (Keegan et al. 2016). We thus call for future research that will use sequencing methods to reveal emergent patterns of work (i.e., the "DNA" of coproduction).

Whereas our study has focused on work patterns that emerge organically, we do acknowledge that formal organizational structures may also affect the way in which self-organized work emerges. For example, the relationship between a participant's formal role in the community (namely, her position on the periphery–core continuum, power, status) and the set of behaviors she enacts is a potential additional important factor. Whereas some empirical studies have demonstrated that a participant's position in the organization is not directly linked to the set of behaviors he enacts (Yates et al. 2010), other scholars have argued that there is a strong connection between formal and emergent roles (Levina and Arriaga 2014). We thus call for future research to explore the extent to which the temporal dynamics of formal and emergent roles are interconnected.

We also recognize that other potential explanations are plausible, and alternative theoretical perspectives could be employed to shed light on the nature of emergent coproduction work; namely, this study's findings regarding the spontaneous emergence of system-level order (or stability) from complex dynamic interactions between self-organizing agents imply that Wikipedia could be viewed as a complex adaptive system. Complexity theory has been applied to explain a host of organizational phenomena (Chiles et al. 2004, McKelvey 2008), and in particular, IT-mediated social participation (Nan and Lu 2014). We believe that novel insights could be gained by viewing knowledge coproduction through the lens of complexity theory, and we call for future research that will employ this conceptualization for understanding emergent work within peer production.

In conclusion, we believe that online coproduction communities represent a fascinating research area. Understanding how emergent roles are enacted in response to the needs of the artifact as well as the mechanisms enabling such artifact-centric coproduction are key to theorizing online knowledge collaboration. Practitioners interested in leveraging the potential of emergent work within corporate walls are encouraged to take note of our findings regarding the mechanisms for balancing openness and control.

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Appendix A. Categorizing Wiki Editing Activities

A.1. Manual Annotation of Training Set

The training set (for the machine learning algorithm) was created through manual annotation of a smaller set of English Wikipedia articles. We employed the sample of 93 articles used in Arazy et al. (2011, 2013), which was created using a stratified sampling approach and covers Wikipedia's various topical categories. Four undergraduate research assistants were recruited to categorize the revisions. To ensure shared understanding of the activity taxonomy, we created a document defining and explaining the various categories as well as a document providing examples and explaining how to resolve ambiguities. Prior to beginning the manual annotation procedure, the four

coders went through a training session in which they learned the categories' definitions, practiced classifying "dummy" articles independently, and then sat together to discuss their classifications and worked to arrive at a consensus. Throughout this training procedure, the definition and example documents were refined, and then later used as key resources during the annotation process.

Once a shared understanding was reached, coders began working on articles in the training set, where two coders were randomly assigned to each article in the set, processing its revisions in sequence, beginning with the article's first revision. The annotation process was aided by a software tool, which compared revisions, allowed easy selection of categories, and simplified the progression from one revision to the next. On average, coders spent 90 seconds on each revision and, collectively, hundreds of hours annotating all revisions in this set. This substantial effort resulted in a comprehensive data set, making it an excellent training set for machine learning and automated annotation. For each revision in our set, we compared the annotations of the two coders. We calculated interrater agreement using Krippendorf's alpha (Krippendorff 2004), employing the Measuring Agreement Set-Valued Items (MASI) function for computing distance in multilabeled data (Passonneau 2006). Interrater agreement was 0.71, reflecting substantial agreement (Landis and Koch 1977). Taking a conservative approach, we excluded all revisions where a full consensus was not reached (including partial matches),[8] leaving us with 13,592 categorized revisions with, on average, 1.5 categories per revision.

A.2. Automatic Categorization of the Study's Sample

For the machine learning model, we employed the same set of features as reported in Daxenberger and Gurevych (2013) with several minor changes (beyond stepping from edit level to revision level): for the "metadata" class, we do not use the "number of edits" feature; from the "textual features" class, we used all but "diff repeated tokens" and "ratio diff to revision tokens," and made a small modification to the "simple edit type" feature; for the markup and language classes, we exclude the "diff type pos" tags. The parameters of all features were set as suggested by Daxenberger and Gurevych (2013).

We used the Random *k*-Labelsets (RAKEL) algorithm (Tsoumakas et al. 2011), as this method yields the best performance for the particular task of this study (Daxenberger and Gurevych 2013). RAKEL learns its model on ensembles of classifiers trained on random label subsets. The subsets are created by transforming the multilabeled data into single-labeled data using the label powerset transformation (Trohidis et al. 2008). The single-labeled subsets can then be classified with single-label (base) classifiers. To verify that the features are well suited for our task, we tested their performance on the manually classified training set[9] (with a 80/20 split between learning and test subsets), comparing two base classifiers: the C4.5 decision tree classifier (Quinlan 1993) and the popular random forest classifier (Breiman 2001). The experiments were carried out with the help of the automatic text classification system DKPro TC (Daxenberger et al. 2014). Results of these experiments are described in Table A.1, panels (a) and (b).

Table A.1 Performance of Classifiers (RAKEL with Random Forest and C4.5 Base Classifiers), Trained and Tested on Subsets of the Annotated Data

(a) Several performance scores, measured across all categories

Score	RF	C4.5
Exact match	0.66	0.60
Example-based F1	0.75	0.73
Macro-F1	0.68	0.68
Micro-F1	0.78	0.77
One error	0.22	0.22
Human agreement (macro-F1)	0.73	

(b) F1 scores per category, compared to human agreement

Category	RF	C4.5	Human
Move or create new article	0.81	0.85	0.90
Remove vandalism	0.78	0.78	0.85
Insert vandalism	0.64	0.59	0.81
Add substantive new content	0.81	0.79	0.80
Add or change Wiki markup	0.92	0.92	0.80
Reorganize existing text	0.70	0.69	0.79
Fix typos and grammatical errors	0.73	0.72	0.69
Delete substantive content	0.57	0.56	0.68
References (to external sources)	0.78	0.81	0.66
Hyperlinks (to other Wikipedia pages)	0.56	0.59	0.64
Rephrase existing text	0.38	0.35	0.61
Miscellaneous	0.49	0.51	0.52

Overall, the performance of the RAKEL classifier with a random forest base classifier is satisfying with a micro-F1 score of 0.78. The classifier performs close to human agreement, as shown by the macro-F1 score of 0.68 (as compared to human agreement of 0.73). For two-thirds of all revisions in the test data, our model found the exact set of categories. As indicated by the "one error" measure, for 22% of the revisions, the algorithm's highest confidence prediction (i.e., category) was not in the set of true categories. We note that there are substantial differences in the algorithm's performance across categories, similar to what was reported in earlier studies (Daxenberger and Gurevych 2013). In particular, our classifier had difficulties with the categories[10] *rephrase existing text* and *miscellaneous* (and, to a lesser extent, with the categories *hyperlinks*, *delete substantive content*, and *insert vandalism*).

After applying the classifier to the 1,000 article sample, roughly 4% of the revisions from our article set remained unclassified (the classifier had a confidence lower than the threshold for each of the revision categories), leaving us with 689,514 revisions with a valid category, contributed by

[8] We also excluded partial matches, for example, cases where the first coder categorized the revision with the multiple labels A, B, and C and the second coder categorized it with A, B, and D.

[9] We optimized our classifier's hyperparameters (including the threshold that creates bipartitions from the ranked classifier output) according to the micro-F1 score.

[10] The performance of the human raters also suffered in these categories.

Table A.2 Number and Percentage of Revisions in the 1,000 Article Sample Labeled with a Certain Edit Category, After Automatic Classification

Category label	Revisions	Percent.
Add or change Wiki markup	294,444	42.70
Add substantive new content	203,501	29.50
Remove vandalism	110,960	16.10
Insert vandalism	98,445	14.30
Fix typos and grammatical errors	95,182	13.80
Delete substantive content	51,304	7.40
References (to external sources)	44,247	6.40
Reorganize existing text	40,845	5.90
Rephrase existing text	39,219	5.70
Hyperlinks (to other Wikipedia pages)	12,435	1.80
Miscellaneous	11,533	1.70
Move or create new article	1,126	0.20

222,119 distinct participants.[11] Table A.2 lists the absolute and relative numbers of revision categories in the 1,000 article sample after automatic classification.

Appendix B: Robustness Analysis for Clustering Solution

This appendix describes two robustness analyses we performed for the global clustering solution. Figure B.1 presents the *Compactness*, *Separation*, and *OCQ* metrics for the various values of k, i.e., numbers of clusters.

B.1. Sensitivity to Little-Activity Profiles

To test whether the fact that many of the contributor–article vectors are based on only a few activities impacts our results, we repeated the clustering analysis after excluding all vectors of fewer than four editing activities (excluding 64% of the data; leaving 118,208 vectors). We found that this restricted solution setting, $A'_7(Y)$, was very similar to the original global (and inclusive) clustering solution, $A_7(Y)$: the average distance between centroids for the two clustering solutions was 0.24, which corresponds to roughly a fifth (22%) of the average pairwise cluster distance in the global clustering solutions. This suggests that the clustering result is relatively insensitive to whether few-activity vectors are included or not.

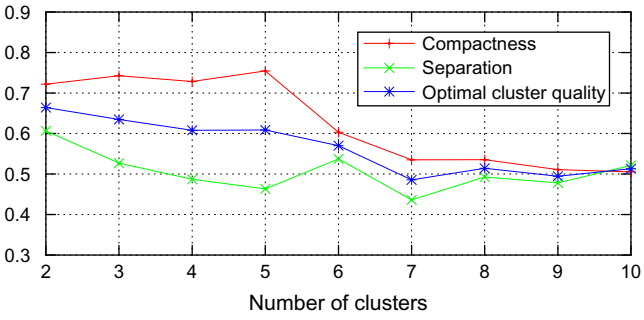
B.2. Sensitivity to the Article-Dependent Assumption

We also tested the validity of our assumption that contributors' activity profiles are article dependent (i.e., contributors play different roles at distinct articles). For this test, we generated an alternative set of contributors' profiles, where each contributor is associated with only a single profile (summing up all of his activity across articles; altogether 222,119 such profiles), and reran clustering on these new profiles. We performed the same clustering optimization process as reported earlier.

We found that the clustering solution when violating the article-dependent assumption (i.e., assuming that a contributor's profile is article independent, such that he has a single activity profile for his activity across all articles), $A''_7(Y)$, was very similar to our global clustering solution, $A_7(Y)$: the average centroid distance between the two solutions was 0.19 (corresponding to 17% of the average centroid distance in the global clustering solution), demonstrating that our clustering solution is largely insensitive to the article-dependent assumption.

[11] Our sample comprised all types of contributors, including unregistered anonymous participants (identified through their IP address), registered members, and software robots (or bots). We acknowledge that participants may not fully correspond to IP addresses. However, this has a negligible impact, and it is common practice for studies of Wikipedia to associate an IP address with a contributor (Arazy et al. 2011).

Figure B.1 (Color online) Compactness, Separation, and Optimal Cluster Quality for $k \in [2, 10]$ (K-Means Clustering)



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