A Game-Theoretic Analysis of Competitive Editing in Wikipedia: Contributors’ Effort to Influence Articles and the Community’s Attempt to Ensure Neutrality

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Abstract

Peer production, such as the collaborative authoring of Wikipedia articles, involves both cooperation and competition between contributors, and we focus on the latter. As individuals, contributors compete to align Wikipedia articles with their personal perspectives. As a community, they work collectively to ensure a neutral point of view (NPOV). We study the interplay between individuals’ competition and the community’s endeavor to ensure neutrality. We develop a two-level game-theoretic model, modeling the interactions of ownership-motivated individuals and neutrality-seeking communal mechanisms as a Stackelberg game. We present our model’s predictions regarding the relation between contributors’ effort (i.e. typical size of edit) and benefits (i.e. the portion of the article they eventually “own”). We validate the model’s prediction through an empirical analysis, by studying the interactions of 219,811 distinct contributors that co-produced 864 Wikipedia articles over a decade. The analysis and empirical results suggest that contributors who make large edits (“creators”) eventually lose the article’s ownership to those who refine the articles and typically make smaller edits (“curators”). Whereas neutrality-seeking mechanisms are essential for ensuring that ownership is not concentrated within a small number of contributors, our findings suggest that the burden of excessive governance may deter contributors from participating.

KEYWORDS: Peer-production, Wikipedia, Content Creation, Competition, Governance, Game Theory.

I. INTRODUCTION

Over the past two decades online information goods created and used by millions of people, such as open source software and Wikipedia, have captured the attention of researchers in a variety of disciplines. Research in the area has studied communities’ ability to facilitate the creation of high-quality information goods and govern large-scale collaboration (Benkler 2006, Michelucci and Dickinson 2016, Giles 2005, Gavalda-Miralles et al. 2014, Sauermann and Franzoni 2015). Our focus is Wikipedia, one of the most prominent examples of peer-production. Wikipedia recruited over 23 million volunteers to produce hundreds of millions of encyclopedic entries in 287 languages. As Wikipedia has become one of the most popular information sources on the web and the destination most internet users turn to when...
they seek information (Halfaker et al. 2012), the quality of its articles has been the topic of public debate. Wikipedia is based on wiki technology: a web-based collaborative authoring tool that allows contributors to add new content, append existing content, and delete or overwrite prior contributions (Leuf and Cunningham 2001). Wikipedia articles evolve through the continuous additions, deletions, and shaping existing content (rewriting, reorganizing, and integrating). Wikipedia has developed a complex organizational structure, where some contributors tend to focus on adding new content (i.e., “builders”), others are more involved in the reorganization and “refactoring” of others’ contributions (i.e., “fixers”), while others take responsibility for quality assurance and fighting vandalism (Butler et al. 2007).

Given their reliance on volunteers, peer production projects such as Wikipedia need to attract and retain participants with various interests and skill-sets. One of the key motivating factors is contributors’ desire to express their knowledge and perspective on the topic by shaping articles’ contents. Prior studies have shown that often indirect personal benefits underlie such contributions. For example, a contributor may be motivated by the desire to increase her own status and reputation within the community or promote her own worldview in published articles (Edwards 2013, Richards 2014). Consequently, when many contributors participating in a collective authoring effort attempt to promote their perspectives, competition between viewpoints is inevitable, and is likely to result in biases (Greenstein and Zhu 2016).

Whereas most research in the area emphasized the cooperative aspects in Wikipedia’s co-production, answering the call to shift the focus in online collaboration research to issues of scarcity and competition (Wang et al. 2013), the current study focuses on contributors’ competition over the content in Wikipedia articles. Building on the theory of psychological ownership (Pierce et al. 2001), we use the terms “ownership of articles” and the attempt to “own articles” to refer to the way in which contributors imbue articles with their personal viewpoints. In developing our conceptualization, we build on prior studies in the area, which demonstrate that competition and struggle over the views expressed in articles is a salient feature of Wikipedia’s co-production (Kane et al. 2014, Arazy et al. 2020, Bidar and Asindhgatta 2020, Young et al. 2020). These prior studies have discussed individual contributors’ attempt to influence articles’ contents. However, in a large system such as Wikipedia, where participants’ contributions tend to be in reference to some existing content (contributed by others), knowing the effects of contributors’

1“Refactoring” is a term borrowed from software development and entails the restructuring of existing computer code: changing the organization without changing its external behavior.
actions on others is essential for understanding the system’s dynamics. We, thus, extend prior research by investigating the effects of collaborators’ behavior on others’ actions and studying the system’s dynamics. Contributors’ dynamics does not happen in a void. Instead, the community works to facilitate and govern the collaborative production process. Wikipedia’s governance mechanisms were investigated in detail, e.g. (Schroeder and Wagner 2012, Aaltonen and Lanzara 2015, Auray 2012). Wikipedia has extensive mechanisms to ensure that the co-produced content is of high quality, including norms, policies, and technical tools for facilitating collaboration, resolving conflicts and fighting vandalism (Forte et al. 2009). In particular, Wikipedia emphasizes objectivity (Neutral Point of View; NPOV) as a central pillar of the community and lists “susceptibility to editorial and systemic bias” as one of the key aspects of its quality assurance work (Greenstein and Zhu 2012, 2016, 2017, 2018). Of particular relevance to our investigation are studies of governance mechanisms intended to ensure neutrality and counter attempts to bias Wikipedia articles (Hassine 2005, Young et al. 2020). To date, these studies have fallen short of linking governance mechanisms to individuals’ behavior.

The overarching objective of our study is to investigate the interplay between governance and contributors’ competition in peer-production (and specifically, in Wikipedia). Game theory, “the study of mathematical models of conflict and cooperation between intelligent rational decision-makers” (Myerson 1991), is well suited for studying competitive dynamics and thus may reveal insights into peer production. Despite its demonstrated utility in studying cooperation and competition, the use of game theory in peer production research has been rather limited (Jain and Parkes 2009). In this study, we develop a two-step game-theoretic model that captures both competition between contributors over content ownership and the community’s governance efforts to maintain neutrality. Contributors in this game theoretic analysis balance the costs of participating in Wikipedia’s collaborative-authoring process (including the costs of editing articles, coordinating work, and complying with the community’s governance) with the benefits (i.e. “owning” portions of an article such that it reflects the contributor’s viewpoint or agenda). We estimate the effort of editing articles through edits’ size, and for convenience we refer to those who regularly make large-size edits as “creators” and to those who typically make small-size edits as “curators” (Kim...
et al. 2017, Rinie et al. 2012, Hill and Monroy-Herandez 2017, Hull and Scott 2013) (these labels are inconsequential to our modeling and empirical analysis). We employ a “content ownership” algorithm from a prior study (Arazy et al. 2010), and operationalize the community’s goal of ensuring neutrality in terms of reducing contributors’ concentration - i.e. maximizing entropy of content ownership. We report on a computationally-heavy empirical analysis of 219,811 distinct contributors co-producing 864 articles that provides support for our model’s predictions. Processing the seven-hundred-thousand revisions for measuring effort and contributor's content ownership demanded that we employ a powerful computational infrastructure.

Intuitively, we expect that the “creators” who add much content would retain ownership of the articles. However, surprisingly, the key results of our game-theoretic analysis are:

- Analytically, we find that under the governance mechanisms, the fractional content owned by a contributor within a focal article is negatively correlated with the average size of her edits. In essence, those who regularly make large-size edits (i.e. “creators”) loose ownership of the article to those who typically exert little effort and make small edits (i.e. “curators”). As a consequence, when the competition over ownership unfolds, i.e., the number contributors in an article is significant, only content added by those whose standard edit size is below the group’s average survives Wikipedia’s refactoring process. Empirically, we corroborate this result.

- Analytically, we show that governance should be curtailed to a maximum limit, beyond which it discourages contributors from making contributions to an article, bringing the co-production process to a halt.

II. RELATED WORK

Scholarly accounts of peer-production initiatives such as Wikipedia tend to emphasize the collaborative aspects (Arazy et al. 2011, Benkler 2006, Kittur and Kraut 2010, Kittur et al. 2007, Ransbotham and Kane 2011). However, competition between collaborators cannot be overlooked (Lasfer and Vaast 2019). Given that Wikipedia has become the primary entry point for those seeking information on the web
(Halfaker et al. 2012), the impact, and thus the associated benefit, of shaping an article’s contents can be high (Das et al. 2013), as demonstrated by commercially sponsored attempts to bias Wikipedia’s content (Edwards 2013, Richards 2014). Recent news stories reveal that commercial entities - often through agents, such as PR agencies or political operatives - have been attempting to manipulate Wikipedia articles’ content (McKenzie et al. 2012, Columbia 2013, Richards 2014). Such manipulations attempt to portray the interested parties favorably, and have been carried out over years, often employing sophisticated methods (e.g. using multiple accounts, building trust in the community and gaining access to special privileges) (Oppong 2014). Wikipedia fights these manipulations through social, technical and legal means (Edwards 2013).

Additionally, competitions over content can also originate from well-intentioned contributors. Prior studies have looked at conflicts of opinions between contributors (Arazy et al. 2011), focusing on conflict resolution mechanisms and the impact of conflicts on the article’s quality. More recently, several research works explicitly discuss contributors’ attempt to influence articles. For example, Umarova and Mustafaraj (2019), Hube (2017) and Hube and Fatahu (2018) describe various forms of biases and violations of Wikipedia’s NPOV policy, and propose automatic methods for detecting these biases. Additional very recent studies empirically demonstrated that Wikipedia contributors often shape an article in a way that is aligned with their worldview, such the articles often evolve through the “pulling” of the article towards the direction that represents the editor’s perspective. Arazy et al. (2020) state that “contributors to a focal artifact manipulate the article according to their particular viewpoints, thus pulling the artifact’s trajectory in different directions” (p. 2014) and then suggest that such “pulls” may possibly stem from “··· a more deliberate attempt to shape the artifact according to the contributor’s personal vision.” (p. 2016). Together, these studies demonstrate that competition and struggle over the views expressed in articles is a salient feature of Wikipedia’s co-production.

Psychological ownership theory (Pierce et al. 2001) may provide a potential explanation for why compete to own pieces of an article. According to this theoretical framework, actors that occupy a shared social space can easily form an ownership feeling over a target (in this case, a Wikipedia article) if they invest much time or energy on it, are familiar with it, or have control over it. This is particularly pertinent in cases where the individual is the originator of the target (or portion of that target), as in the case of
contributing content to a Wikipedia article. A contributor of content to the article will feel the content is her personal psychological property, and subsequently will be unwilling to share the target of ownership with others or lose control over it (Pierce et al. 2003).

Territoriality theory (Brown and Robinson 2005) may further explain how psychological ownership could result in competition over an article’s contents. According to this theory, the stronger an individual’s psychological ownership of an object, the greater the likelihood he or she will treat that object as his or her territory. Territoriality behavior is likely to emerge as community members work together to accomplish a common goal. It serves a communicative function, by signaling to others one’s stake to a territory or an object. Consequently, territoriality may be expressed through the defense of one’s turf from perceived invasions (Brown and Robinson 2005). From such a viewpoint, if an individual experiences a strong feeling of ownership for the content that she has contributed, she may exhibit territorial behavior over that section of the article, which subsequently leads her to defend the “owned” content from others’ attempt to change or overwrite it (Halfaker et al. 2009, Kriplean et al. 2007, Scott et al. 2004, Thom-Santelli et al. 2009). Kane et al. (2014) report that roughly two-thirds of the collaborative-authoring patterns in the Wikipedia article they had investigated entailed “defensive filtering”. They explain that in the defensive filtering pattern “The focus of production was on protecting the content that has been created by the co-production community” and that the nature of interaction is defensive and combative. Contributors may become committed to stabilizing knowledge already co-produced. When assessing whether a change to the article fits with the article’s current articulation and ensuring that it does not “violate organizational and content decisions already made” (Kane et al. 2014), Bidar and Asindhgatta (2020) describe power dynamics in Wikipedia whereby certain contributors may attempt to dominate an article, and block alternative viewpoints. Young et al. (2020) describe such a domination dynamic that is related to gender bias, where core contributors wrestle against peripheral contributors to shape articles according to their viewpoints.

While territoriality may be linked to positive behaviors, such as increased motivation and commitment and could help in the organization of work, it raises concerns for competitive tensions and for potential for biases in the co-produced knowledge-based goods. For example, Halfaker et al. (2009) show that territorial behavior is directly linked to turf wars (namely, the revert of a Wikipedia article to its previous

5Please note that contributors may also try to protect a particular version of the article and exhibit territorial behavior even if they did not edit the article, for example in protecting the content of like-minded contributors.
version). Furthermore, territorial behavior may deter members’ participation (Thom-Santelli et al. 2009).

Distributed collaborative communities often employ policy and community norms in order to prevent the expressions of such behavior. The Wikipedia community explicitly discourages contributors from taking ownership of their work and the “Ownership of Content” policy specifically points out that being a primary contributor is not grounds for asserting possession of an article:

“All Wikipedia content – articles, categories, templates, and other types of pages – is edited collaboratively. **No one** [emphasis in source], no matter how skilled, or how high standing in the community, has the right to act as though they are the **owner** [originally emphasized in italics] of a particular page. … Some contributors feel possessive about material they have contributed to Wikipedia. …

**Believing that an article has an owner of this sort is a common mistake people make on Wikipedia**”

How are socio-technical governance mechanisms used to mitigate the effects of territoriality? Large-scale social production systems, such as Wikipedia, require governance mechanisms in order to direct the integration of dispersed knowledge resources in the process of value creation. Without such mechanisms, coordinating the work of assessing, selecting, shaping, integrating and oftentimes rejecting contributors’ postings would be impossible (Aaltonen and Lanzara 2015). Wikipedia employs a community-based governance model that is based on egalitarian principles, rather than on formal contracts and hierarchies (Arazy et al. 2020). Over the years, Wikipedia has developed an extensive set of mechanisms to ensure that the co-produced content is of high quality, including norms, policies, and technical tools for facilitating collaboration, resolving conflicts and fighting vandalism (Schroeder and Wagner 2012, Forte et al. 2009, Auray 2012). What is unique to Wikipedia governance model is that it is collective and dynamic. That is, the community organically develops policies and procedures, and these continuously undergo changes by community members (Aaltonen and Lanzara 2015). Thus, governance is collective in the sense that it does not depend on any particular individual or a group of individuals within the system.

Central to Wikipedia’s governance is the Neutral Point of View (NPOV) principle (Hassine 2005, Greenstein and Zhu 2012, 2016, 2017, 2018, Young et al. 2020), which promotes objectivity and acts to ensure that no one particular viewpoint dominates an article. NPOV is one of the five fundamental

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6Wikipedia founder, Jimmy Wales, speaks openly against the notion of ownership. For example, see a talk in the 21st Chaos Communication Congress in December 2004 (talk titled “Wikipedia Sociographics”): http://ccc.de/congress/2004/fahrplan/event/59.en.html.

7https://en.wikipedia.org/wiki/Wikipedia:Ownership_of_content retrieved February 8, 2021.
principles (or pillars) of Wikipedia. The principles states that:

“We strive for articles that document and explain major points of view, giving due weight with respect to their prominence in an impartial tone. We avoid advocacy and we characterize information and issues rather than debate them. In some areas there may be just one well-recognized point of view; in others, we describe multiple points of view, presenting each accurately and in context · · · Editors’ personal experiences, interpretations, or opinions do not belong.”

Contributors to Wikipedia are requested to edit articles with a neutral perspective, representing views fairly and trying to avoid bias. However, biases, the opposite of NPOV, may arise when a subjective information is too difficult to verify, when an issue is too complex to be fully represented (whereby generating a consensus requires considerable effort and expertise), or in cases when contributors intentionally try to impose their own ideology in an attempt to influence readers’ viewpoints (Greenstein and Zhu 2016, Arazy et al. 2020, Young et al. 2020). Enforcing NPOV has become a central concern for Wikipedians, and many of the discussions on articles’ coordination spaces (i.e. ‘talkpages’) (Arazy et al. 2011) and dedicated Internet Relay Chat (IRC) channels (Greenstein and Zhu 2016) concern whether particular section of an article reflects the NPOV principle. Editorial activity is often not distributed evenly within a Wikipedia article, such that a small share of the contributors makes a substantial share of the revisions. Thus, in enforcing neutrality, the community tries to ensure that the “ownership” of an article’s content is not concentrated in the hands of few contributors.

III. RESEARCH QUESTION

The scholarly literature on peer production has not investigated the interplay between individuals’ competitive dynamics and the socio-technical governance mechanisms. Our goal in this paper is, thus, to investigate Wikipedians’ competition over content ownership and to explore the way in which this competitive dynamic is shaped by the community’s effort to ensure neutrality. While we acknowledge that contributors to Wikipedia also exhibit cooperative behavior, our focus here is the competitive dynamics. We see two potential mechanisms by which NPOV enforcement could...
affect the competitive dynamics. First, the efforts to ensure neutrality could curtail excessive one-sided ownership of an article, and consequently directly impact contributors’ attempts to own article fractions. Second, adhering to norms, policies and procedures may tax contributors, increasing the effort associated with participation in co-production. We, thus, pose the following two research questions:

*RQ1: How do contributors balance and costs and benefits of peer-production? More specifically, what is the relation between the efforts that contributors regularly exert when editing an article and their fractional ownership of that article?*

*RQ2: How do governance mechanisms affect the competitive dynamics underlying Wikipedia’s co-production process? In particular, how does the community’s attempt to ensure a neutral point of view affect the relationship between contributors’ efforts in editing articles (i.e. whether they are characterized as “creators” or as “curators”) and the amount of content that they “own” within a particular article?*

### IV. A Game Theoretic Model for Competition and Governance

A game-theoretic model should capture essential features of the modeled system. Whereas we acknowledge that socio-technical systems such as Wikipedia are complex and exhibit both cooperative and competitive dynamics, here we attempt to only capture Wikipedia’s competitive dynamics. Specifically, our game-theoretic model aims at representing (a) contributors’ competition to “own” articles’ contents and (b) the community’s attempt to ensure that articles present a neutral and balanced perspective. Our model assumes that a contributor’s goal is to maximize ownership of article sections, such that content “owned” by that contributor survives multiple rounds of revisions of the article. Our model also assumes that the objective of Wikipedia’s governance mechanisms enacted by the community is to ensure the neutrality of content, such that no single contributor takes ownership of large portions of an article (please refer to Appendix B for an empirical validation of this assumption). We acknowledge that Wikipedia’s governance has the broader goal of assuring content quality and reliability, by ensuring articles’ accuracy and completeness. Our focus here is on one important dimension of content quality: objectivity or lack of bias ([Arazy et al., 2011](#)). Beyond the importance of this particular dimension of articles’ quality (as evident by the NPOV pillar), objectivity is directly impacted by contributors’ effort to “own” content. We model
the interactions between the governance mechanisms and contributors as a Stackelberg (leader-follower) game (Vonstackelberg 1952, Simaan and Cruz 1973), where the community is the leader who determines a level of governance that increases the neutrality of an article. Given a set level of governance, contributors’ interactions are modeled as a non-cooperative game, where each contributor’s objective is to maximize her content ownership. A high level schematic of the interactive model between the community’s goal of ensuring neutrality and contributors’ competition over content ownership is shown in Figure 1.

Peer-production on Wikipedia is a complex socio-technical process and contributions occur asynchronously over time. Our strategy for capturing these dynamics is temporal bracketing: recording a series of yearly “snapshots” of the process over a finite time horizon (Langley 1999). We use a static game-theoretic model to study these interactions, and test the model against empirical data for each of the yearly snapshots. Please note that modeling such a complex process requires some simplifying assumptions. We assume that Wikipedia’s governance structure, and in particular the goals of ensuring neutrality, are stable over time (as changes in policies are relatively infrequent). As a first-cut approximation, we don’t distinguish between the different contributors’ goals, knowledge or roles, as well as assume that no learning occurs. It should be stressed that although our model provides an approximation to the
complexities of peer-production, the model was empirically validated with data that captures Wikipedia’s actual collaborative-authoring dynamics.

As mentioned above, our model assumes self-interest driven actions of contributors, where the goal of individual contributors is to advance their personal point of view and “own” contents of an article. We model the utility of each contributor in the non-cooperative game as her fractional ownership in the article. Each contributor incurs a cost in making the contribution, modeled as the sum total of: (a) the effort expended in producing content and editing an article (this cost element is specific to each contributor); (b) the effort associated with participation in coordination and governance work, such as writing policies or sitting on various committees (this cost, too, is contributor-specific and is independent of her content production activity); and (c) the effort associated with complying with governance (similar for all contributors). Our objective is then to determine for each contributor the optimal levels of activity, so that her net utility is maximized. We model the net utility as the difference between the utility (the contributor’s fractional ownership) and the cost (a measure of all efforts she expended). The optimal strategies are determined through the Nash equilibrium of the non-cooperative game that models the interactions between contributors. We analyze the conditions for the existence and uniqueness of a Nash equilibrium for the game and discuss its implications.

We model the interactions between the governance mechanism - namely, enforcing a neutral point of view- and contributors as a Stackelberg (leader-follower) game. The role of the neutrality mechanism is to choose the optimal level of enforcement, \( t \), defined in our model in terms of the effort imposed on contributors to make a single unit of contribution (i.e. edit an article). The response of the \( N \) contributors in the particular article is to make unilateral contributions that yield content ownership, \( x_1, x_2, \ldots, x_N \), for them, respectively. Please refer to Table I for the list of notations that are used in our analysis.

We report on an empirical analysis of 219,811 distinct contributors co-producing 864 articles (lifespan ranges from 129 to 4078 days; mean = 2681 days) that validates our model’s predictions. We perform the empirical validation for the entire period covered by our data set (2001-2012), as well as for each yearly interval independently. The key results of our game-theoretic analysis validated by data, include:

\[ \text{Using the fractional ownership metric - i.e., the percentage of an article contents owned by a particular contributor- we are able to account for differences in length between articles. As an example, knowing that one contributed 15\% of an article’s contents is more informative that knowing that she contributed 8 sentences.} \]
• The neutrality mechanisms that act to avoid uneven distribution in content ownership have to be constrained, such that a contributor’s effort in complying with governance would not exceed a threshold.
• Under the neutrality mechanisms, the fractional content owned by a contributor is negatively correlated with the effort she expends. In particular, the “creators” that add large pieces of content loose ownership of the article to the “curators” who typically engage in small adjustments that require little effort. As a consequence, when the competition over ownership unfolds, i.e., the number contributors in an article is significant, only content added by those whose standard edit requires effort below the group’s average (i.e. “curators”) survives the ongoing refinement and refactoring.

A. Co-Production: Contributors’ Competition

We model the interactions of the \( N \) content contributors\(^{11} \) to a particular Wikipedia article as a non-cooperative game. The strategy set is the content added to the article by each contributor \( x_1, x_2, \ldots, x_N \). Contributors’ actions are aimed at maximizing their content owned. Specifically, the actions of contributors are changes to the co-created artifact (i.e. “edits”), whereby each contributor “owns” the content she added, and indirectly reducing others’ fractional ownership.

The \( i^{th} \) contributor has fractional content ownership,

\[
c_i = \frac{x_i}{\sum_{j=1}^{N} x_j}.
\]

Contributors’ editing actions incur a cost (i.e. the effort in explicating knowledge and modifying an article). Contributors are characterized by their activity profile within Wikipedia. In particular, the \( i^{th} \) contributor is characterized by the average size of his edits to Wikipedia articles, \( \beta_i \). Building on work in the area of software development which approximated coding effort based on the quantity of code produced (i.e. lines of code) (Shihab et al., 2013; Mendes et al., 2006), we assume that effort is a linear function of edit size, such that the contributor’s average effort per content contribution is \( L\beta_i \). Hence, the effort contributor \( i \) makes to the focal article is a function of his regular effort expenditure per edit, a constant, and the amount of content he contributed to the focal article i.e., the effort invested in contributing content to an article is \( L\beta_i x_i \).

\(^{11}\)Please note that while our model assumes a given number of contributors, it does allow for contributors to make a choice regarding their participation. Namely, by deciding to own zero content contributors are actually deciding not to join the game.
In addition, the $i^{th}$ contributor needs to expend additional effort to overcome the attempt by Wikipedia’s governance to ensure neutrality of an article (e.g., in learning and complying with Wikipedia’s rules and policies), and yet maintain every unit of her ownership. Therefore, the $i^{th}$ contributor owning $x_i$ amount of content also expends an effort $tx_i$ to overcome the level of neutrality enforcement, $t$, (in addition to the effort in editing the article, $\beta_i x_i$). A contributor also expends efforts and incurs a cost by participating in coordination and administrative work. This cost element is user specific but fixed for a user (i.e., independent of the size of the edits they make) and we model this fixed cost as $f_i$, for user $i$. The net utility experienced by the $i^{th}$ contributor, $u_i$, can be written as the difference between utility of contributor $i$, given by Equation (1) and the total effort expended by contributor $i$. Formally stated:

$$u_i = c_i - (L/\beta_i + t)x_i - f_i = \frac{x_i}{\sum_{j=1}^{N} x_j} - (L/\beta_i + t)x_i - f_i.$$ (2)

Note that in general, a convex function of $x_i$ would be the most comprehensive model for the cost incurred by each contributor, to own $x_i$ amount of content. We consider a linear cost model, which is a special case of a convex cost function [Luenberger 1984], which we use in Equation (2).

Each contributor then determines her optimal amount of contribution, $x_i^*$, that maximizes, her net utility, $u_i$ when the contributions made by all other contributors, $x_j$, $j \neq i$ are fixed. It is therefore observed that the net utility obtained by the $i^{th}$ contributor not only depends on the strategy of the $i^{th}$ contributor (i.e., $x_i$), but also on the strategies of all the other contributors (i.e., $x_j$, $j \neq i$)\(^{12}\). This results in the non-cooperative game of complete information [Neumann and Morgenstern 1944] between the contributors. The optimal $x_i$, $\forall i$ (denoted as $x_i^*$), which is determined by maximizing $u_i$ in Equation (2)\(^{13}\), is then the Nash equilibrium of the non-cooperative game where no contributor can make a unilateral change.

The unique Nash equilibrium, $x^* = [x_1^* \ x_2^* \ \cdots \ x_N^*]^T$, can be obtained in closed-form as follows. $x^*$ is obtained by determining the best response for contributor $i$, $x_i^*$ which maximizes its net utility, $u_i$ (given by Equation (2)) when the contributions made by all other contributors, i.e., $x_j$, $j \neq i$ are known. However, it is noted that every contributor attempts to do the same. In other words, the unique Nash equilibrium, $x^* = [x_1^* \ x_2^* \ \cdots \ x_N^*]^T$, is the vector that maximizes the net utility, $u_i$, in Equation (2),

\(^{12}\)Therefore, $u_i$ is also sometimes denoted as $u_i(x_i, x_{-i})$ where $x_{-i}$ represents the vector, $[x_1 \ x_2 \ \cdots \ x_{i-1} \ x_{i+1} \ \cdots \ x_N]^T$, i.e., all elements of the vector, $x = [x_1 \ x_2 \ \cdots \ x_N]^T$ except the $i^{th}$ element.

\(^{13}\)when all other $x_j$’s, $j \neq i$ are fixed, i.e., the vector, $x_{-i}$ is fixed.
∀ i. Applying the first order necessary condition to Equation (2), \( x_i^* \) is obtained as the solution to
\[
\frac{\partial u_i}{\partial x_i} \bigg|_{x_i=x_i^*} = \frac{\sum_{k=1 \atop k \neq i}^N x_k^*}{\left(\sum_{j=1}^N x_j^*\right)^2} - (L\beta_i + t) = 0, \quad \forall i
\] (3)
subject to the constraints \( x_i^* \geq 0, \forall i \).

From Equation (3), we obtain
\[
\frac{\partial^2 u_i}{\partial x_i^2} = -\frac{2 \sum_{k=1 \atop k \neq i}^N x_k^*}{\left(\sum_{j=1}^N x_j^*\right)^2} < 0, \quad \forall i, \text{ when } x_i \geq 0.
\]
Thus, \( u_i \) is a concave function of \( x_i \) and \( x_i^* \), which solves Equation (3) subject to \( x_i^* \geq 0, \forall i \), is a local as well as a global maximum point. In other words, the non-cooperative game has a unique Nash equilibrium. The vector of contributions, \( x^* = [x_1^*, x_2^*, \ldots, x_N^*]^T \), can be obtained by numerically solving the system of \( N \) non-linear equations specified by Equation (3). However, to study the effect of the contributors’ type (i.e. their \( \beta_i \)'s) and the level of neutrality enforcement, \( t \), on contributors’ strategies, it is desirable to obtain an expression that relates the vectors, \( x^*, x = [x_1, x_2, \ldots, x_N] \), \( \beta = [\beta_1, \beta_2, \ldots, \beta_N] \), and \( t \).

Solving Equation (3), the unique Nash equilibrium of the non-cooperative game can be obtained as
\[
x_i^* = \frac{\sum_{j=1}^N L\beta_j - (N-1)L\beta_i + t}{\left(\sum_{j=1}^N (L\beta_j + t)\right)^2}
\] (4)
Note that the unique Nash equilibrium \( x^* \), is feasible, i.e., \( x_i^* > 0, \forall i \) if and only if
\[
(N-1)L\beta_i < \sum_{j=1}^N L\beta_j + t \quad \text{or} \quad (N-2)L\beta_i < \sum_{j=1 \atop j \neq i}^N L\beta_j + t.
\] (5)
Intuitively, Equation (5) implies the following. Let all the other contributors as well as the neutrality enforcement represent “adversaries” of contributor \( i \). The right hand side shows the total adversarial activity level against contributor \( i \). The left hand side shows a term similar to the total activity level in the favor of contributor \( i \) if contributor \( i \) were to duplicate herself against each individual adversary. Equation (5) then says that a contributor makes a positive contribution to an article only if the contributor has to expend effort in his/her favor, that is less that the effort or activity level of the adversaries.

The fractional content ownership of contributor \( i \) at the Nash equilibrium, \( c_i^* \), can then be obtained from Equation (1) and Equation (4) as
\[
c_i^* = \left(\frac{x_i^*}{\sum_{j=1}^N x_j^*}\right)^+ = \left[1 - \left(\frac{(N-1)(L\beta_i + t)}{\sum_{j=1}^N (L\beta_j + t)}\right)\right]^+.
\] (6)

\(^{14}\)See Appendix B for details.
where for any, $\theta$, $\theta^+ = \max(\theta, 0)$\textsuperscript{15}. It is observed that the ownership $c^*_i$ is non-zero only if Equation (5) is satisfied, i.e., if the Nash equilibrium is feasible.

Note that the optimal $x^*_i$ in Equation (4) and the optimal fractional ownership, $c^*_i$ in Equation (6), do not depend on the fixed cost, $f_i$. This is because, the fixed cost does not change with changing $x_i$ (from Equation (2)) and hence has no bearing on the optimal $x^*_i$. Similarly, from Equation (1), the fractional ownership, $c_i$, is independent of $f_i$ and therefore, $c^*_i$ in Equation (6) is also independent of $f_i$. The condition in Equation (5) and the expression in Equation (6) have the following interesting implications.

- From Equation (6), the ownership of contributors depend on the $\beta_j$ of all the contributors. This is intuitively correct in a peer production project like Wikipedia because changes to the produced artifact are made by multiple contributors and the ownership held by a contributor will depend on the activity tendencies of all the contributors co-producing the artifact.

- The expression in Equation (6) indicates that contributors who tend to make small changes to articles (i.e. “curators”) are left with larger fractional ownership and those who regularly make large edits (i.e. “creators”) remain with smaller fractional ownership, i.e., the fractional content ownership is a decreasing function of the typical size of one’s edits.

- In Equation (4), the level of neutrality enforcement, $t$, appears as a linear factor in the numerator and as a second order quadratic factor (power of 2) in the denominator. Therefore, when neutrality enforcement, $t$ increases, the overall content owned by a contributor decreases. This implies that when the “tax” imposed on contributors in terms of complying with NPOV norms, policies and procedures is too high it outweighs the benefits associated with content ownership, such that contributors stop competing for ownership (and in effect, co-production is stalled).

- Equation (6) can be re-written as

\[
c^*_i = \left[ 1 - \left( \frac{L\beta_i + t}{\frac{1}{N-1} \sum_{j=1}^{N} L\beta_j + \frac{N}{N-1} t} \right) \right]^+. \tag{7}
\]

Asymptotically, i.e., as the number of contributors, $N$, becomes large $c^*_i$ is evaluated by taking $\lim_{N \to \infty}$.

\textsuperscript{15}In other words, if the term $\theta$ is positive or zero, then use it as it is. If $\theta$ is negative, then take it to be 0.
in Equation (7), to obtain
\[ c_i^* = \left[ 1 - \left( \frac{L\beta_i + t}{LE[\beta] + t} \right) \right]^+ \]
\[ = \left( \frac{LE[\beta] - L\beta_i}{LE[\beta] + t} \right)^+ , \tag{8} \]
where \( E[\beta] \triangleq \frac{1}{N} \sum_{j=1}^{N} \beta_j \), is the average size of edits of all contributors making changes to the focal Wikipedia article. It is observed from Equation (8) that \( c_i^* > 0 \) for only those contributors for whom \( \beta_i < E[\beta] \). Therefore, only those contributors whose edit size (and thus, edit cost) in making a unit contribution is below the average edit cost by contributors working on the focal article, end up with non-zero ownership, when the number contributors in an article is significant.

- The \( c_i^* \) given by Equations (6) and (7) are the exact expressions for the content ownership. The asymptotic behavior in Equation (8) is used only to reach the conclusion that when the number contributors in an article is significant, only those contributors whose edit sizes are less than the average edit size, survive the competition and end up owning non-zero percentage of content in the article. For all the numerical analysis, only Equation (6) is used.

While the above result seems counter-intuitive, it is in fact a result of the governance mechanisms and its desire to increase neutrality. One might expect that the creators who contribute more content (and in the process exert more effort) would end up owning much of an article’s contents. In contrast, the results of our game-theoretic analysis implies that when competing over content ownership in the presence of Wikipedia’s governance to ensure neutrality, those contributors making on average large contributions (i.e. creators) would eventually not own any content. Please refer to Appendix A for a summary of the notations we use and to Appendix B for details of the Nash equilibrium of the non-cooperative game between contributors.

B. Neutrality Enforcement and its Effect on Co-Production

The community governance factor in our model is the result of contributors’ aggregate governance effort. The level of governance, \( t \), should be chosen so as to maximize the effectiveness of peer production. The main objective of Wikipedia’s governance is to reduce bias and ensure that all points of view are reflected in an article. Wikipedia policies define Neutral Point of View as a central pillar of the community and its quality assurance procedures pay particular attention to the elimination of biases. Prior studies in the area
have stressed the importance of the Neutral Point of View norm in Wikipedia’s governance (Forte et al. 2009, Greenstein and Zhu 2016). Biases occur when a single viewpoint dominates the deliberation, or in the case of Wikipedia, the article gives more weight to one point of view over another. Often, such biases are the result of one contributor taking substantial ownership of an article; in contrast, when multiple contributors own sections of the article, a more neutral point of view is expected. Thus, our notion of article neutrality reflects equal ownership of an article’s contents (and we are less interested here in the particular biases that may be present in the content added by each contributor).

Building on information theory (Shannon 1948), we use the metric of entropy to estimate the amount of bias in the distribution of content ownership. We note that the entropy metric was employed in prior studies in organization science (Ancona and Caldwell 1992), and in particular in estimating the distribution of work in Wikipedia (Arazy et al. 2011). In information theoretical terms, if a source emits $N$ possible symbols, $s = \begin{bmatrix} W_1 & W_2 & W_3 & \ldots & W_N \end{bmatrix}^T$ with probability distribution, $p_i$, i.e., the source emits symbol, $W_i$, with probability, $p_i \geq 0$, $\sum_{i=1}^{N} p_i = 1$, then the entropy of the source, $H$ is defined as (Cover and Thomas 2006)

$$H = \sum_{i=1}^{N} p_i \ln \frac{1}{p_i} = - \sum_{i=1}^{N} p_i \ln p_i.$$  

(9)

In any Wikipedia article, the fractional ownership of each contributor, $c_i^*$ are all non-negative and satisfy the condition, $\sum_{i=1}^{N} c_i^* = 1$. Therefore, page can be viewed as as information source, the $N$ contributors play the role of the $N$ possible symbols and the fractional content ownership of each contributor, $c_i^*$, plays the role of $p_i$. The entropy of the page can then be written as

$$H(t) = \sum_{i=1}^{N} c_i^* \ln \frac{1}{c_i^*} = - \sum_{i=1}^{N} c_i^* \ln c_i^*.$$ 

(10)

In Equation (10), the entropy, $H(t)$, may depend on other factors, e.g., the optimal contributions, $x_i^*$, $1 \leq i \leq N$, obtained from Equation (4), which in turn, depend on $\beta$. However, we represent the entropy as $H(t)$ because the neutrality enforcement, $t$, is the the only parameter in $H$ that represents the action taken by Wikipedia’s governance mechanisms. Our model’s optimization function for neutrality enforcement (maximizing entropy in contributors’ ownership) is normalized (each article’s entropy is calculated in relation to the maximum entropy of any article, which is 1).
It was shown in information theory (Cover and Thomas 2006) that the expression of entropy, \( H(t) \), in Equation (10) is maximized when \( c_i^* = \frac{1}{N}, \forall i \), i.e., when all contributors make equal contribution, which corresponds to the scenario when there is complete neutrality. Therefore, we use the entropy in Equation (10) as the objective function for determining the optimal level of neutrality enforcement for the Stackelberg game. Namely, the objective function for neutrality enforcement in our model is to minimize the bias or maximize the entropy in content ownership within an article\(^16\). The optimal level of neutrality enforcement, \( t \), is the value of \( z \) that maximizes \( H(z) \) in Equation (10), which is obtained by replacing \( t \) by \( z \) in Equation (6). Then,

\[
t = \arg \max_z H(z), \text{ i.e., } \left. \frac{\partial H}{\partial z} \right|_{z=t} = 0.
\]  

(11)

From Equations (6), (10) and (11), the optimal value of \( t \) that maximizes the entropy is the value of \( t \) that makes \( c_i^* = 0, \forall i \), i.e., \( t \rightarrow \infty \).\(^17\) Our analysis indicates that while neutrality enforcement levels remain moderate, our prior results from the non-cooperative game remain unchanged, such that those making above-average contributions end up not owning content. However, when neutrality enforcement levels exceed a certain threshold the non-cooperative model collapses, ownership becomes a direct function of neutrality enforcement (rather than contributors’ efforts). Namely, from Equation (6), when \( t >> NE(\beta) \) (i.e. when the amount of effort a contributor has to exert to overcome neutrality enforcement is significantly- typically one order of magnitude- larger than the aggregate effort of all contributors exert in making unit contributions to the article), \( c_i^* \approx \frac{1}{t} \rightarrow 0 \). In other words, ALL contributors end up owning an insignificant but equal portion of the article’s contents. Therefore, the optimal value of \( t \) is obtained by solving

\[
t = \arg \max_z H(z), \text{ i.e., } \left. \frac{\partial H}{\partial z} \right|_{z=t} = 0,
\]  

subject to the constraint

\[
t \leq z^*,
\]  

(12)

where \( z^* \) represents the maximum level of neutrality enforcement allowed in order to maintain the neutrality of an article above a required threshold. The resulting Stackelberg game model is depicted

\(^{16}\)In Appendix C, we show empirical evidence that there is strong positive correlation between the entropy of an article and its quality (and hence, its neutrality), thus justifying the objective function in Equation (11).

\(^{17}\)See Appendix D for details.
Fig. 2. The comprehensive Stackelberg game depicting the complete interaction between Wikipedia’s governance to ensure neutrality and competition between contributors to maximize content ownership.

The complete model for the principal agent (leader-follower) game between the governance mechanism and the competitive self-interested contributors suggests that at the Stackelberg equilibrium, governance mechanism operates in such a manner to result in an implicit outcome that the entropy is kept high, i.e., the difference between maximum and minimum fractional content ownership is kept low, therefore ensuring article’s objectivity. Further, our model limits governance levels to an upper threshold.

V. VERIFICATION OF THE ANALYSIS WITH EMPIRICAL DATA

To verify the game theoretic analysis, we compared its predictions against data from Wikipedia. In line with recent studies in the area (Arazy et al. 2016), we employed a double-stratified sampling procedure, randomly selecting 1000 articles from the January 2012 dump of the English Wikipedia. Our strata were based on: (I) the number of revisions the article has gone through (i.e., article maturity) and (II) the article’s topical domains. This sampling strategy is important given that collaboration patterns could differ across articles in different phases of their life cycle across topical domains. Given the power law distributions in the number of articles’ revision (Ortega et al. 2008), we used the following four maturity strata: (a) 1-10 revisions; (b) 11-100; (c) 101-1000; and (d) more than 1000 revisions. The topical strata
were based on Wikipedia’s categorization system, using the main topics scheme. With 4 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, this sample contained: 1000 articles and 721,806 editing activities (i.e. article revisions), made by 222,119 contributors. After excluding articles with a single contributor, we were left with 864 multi-contributor articles, which make up the sample for our analysis.

We measured contributors’ benefit (i.e. ownership of articles’ contents) and costs (namely, the effort in making an edit) by calculating the fractional ownership for each contributor in each article of our sample using the algorithm in (Arazy et al. 2010). The content ownership algorithm tracks the evolution of content, recording the number of sentences owned by each contributor at each revision, until the study’s end date. The algorithm uses a sentence as the unit of analysis, where each full sentence is initially owned by the contributor who first added it; as content on a wiki page evolves, a contributor loses a sentence when more than 50% of that sentence’s content (i.e. the words in the original sentence) is deleted or revised by others (thus, a contributor making a major revision to an existing sentence can take ownership of that sentence). If no single contributor “owns” more than 50% of a sentence, that sentence becomes ownerless. The output of the algorithm is, for each contributor, the number of sentences (and the fraction of sentences within the focal Wikipedia article) originated by her that persisted in the most recent version of the article.

We defined $s_i$ as the number of sentences owned by contributor $i$. A contributor’s fractional ownership in a particular article is obtained as $\frac{s_i}{\sum_{j=1}^{N} s_j}$. Next, we calculated the effort expended by the contributor. A contributor’s average edit size, $\beta_i$, was calculated based on his activity profile across all articles within the sample to which he contributed. The size of edits was calculated using the Levenshtein distance (Levenshtein 1966). The Levenshtein distance is a string metric used in information theory and computer science for measuring the difference between two sequences (or between two text segments) and is defined as the minimum number of single-character edits (i.e. insertions, deletions or substitutions) required to change one word into the other (Ristad and Yianilos 1998). This metric has been commonly used in the

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18 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](http://en.wikipedia.org/wiki/Category:Main_topic_classifications).

19 In line with prior works in the area (Arazy et al. 2011), we assume that for non-registered contributors, a unique IP address corresponds to a distinct contributor. About half of the contributors in our sample are non-registered.
study of Wikipedia to estimate the scope of editing activities (Keith et al. 2007). Based on this data, we were able to calculate the following parameters for each of the 864 articles in our sample:

- The number of distinct contributors ($N$)
- The total number of edits made by the $i^{th}$ contributor ($1 \leq i \leq N$), $\zeta_i$, across all of the articles in our sample
- The size of all edits made by the $i^{th}$ contributor ($1 \leq i \leq N$), $e_i$, to all articles in our sample (summing up the Levenshtein distance of all edits made by that contributor).

Using these set of parameters, we compute the average edit size of contributor $i$ for unit contribution, $\beta_i$,

$$\beta_i = \frac{e_i}{\zeta_i}.$$  

Note that $\beta_i$ is a trait of the contributor, such that it remains the same for every article that we analyze.

The number of contributors in the 864–article sample was found to follow a uniform distribution with average number of contributors being 124.6 and a standard deviation, 71.9. We also found that contributors are more likely to make smaller edits than larger edits, with the distribution of $\beta_i$ resembling an exponential probability density function. The average $\beta_i$ was 8.4 (measured in Levenshtein distance) and the standard deviation was 2.9. The average content ownership in an article for users, $c_i^*$, was found to have a mean of 8% and a standard deviation of 0.55.

Employing the $\beta_i$’s thus obtained, we use the expression in Equation (6) to determine our model’s prediction for a contributor’s fractional ownership in a particular Wikipedia page. Equation (6) provides us with a contributor’s expected fractional ownership. We repeated this analysis for all Wikipedia articles in our sample and for all contributors in each article.

We empirically tested our model’s predictions regarding the relation between contributors’ average edit size (i.e. a proxy for the effort typically exerted by a contributor when making an edit) and their resulting content ownership, and their resulting content ownership. In trying to get a better understanding of the temporal dynamics underlying the co-production competition over an article’s content, we applied a temporal bracketing technique by breaking each article into yearly brackets (i.e. Year 1 since inception, Year 2, etc.). We then created subsets by yearly periods, capturing the states of all articles after their first year of operation, second year etc., and calculated contributors effort and fractional ownership at the end of each year in an article’s life. Next, for each of these yearly subsets, we repeated the analysis described
Our findings show that the model’s prediction regarding contributors’ fractional ownership are almost identical to the empirical findings. Please see Figure 3(a) for the results for the entire study’s period. Looking at the temporal brackets, we observe that already at the end of the year of inception (Year 1), the process converges and our model’s predictions closely match the empirical data (see Figure 3(b)). Figure 3(c) shows that from Year 2 onward, the results are almost identical to the findings for the entire period. These results suggest that as articles mature and the co-production process stabilizes, our empirical results above, comparing the model’s prediction to actual fractional ownership.
become more aligned with the model’s prediction. In order to further test for the effect of articles’ maturity, we analyzed the alignment between model’s prediction and empirics by the number of contributors per article. We found that the alignment increases as the number of contributors per article grows (stabilizing at roughly 30 contributors per article). We measured the Pearson’s correlation coefficient value between the fractional ownership obtained by the game theoretic analysis and that obtained from the measured data (2 years from inception, and onward), and found it to be 0.873, thus demonstrating, that the data closely follows our model’s predictions. The stability of our findings across various stages of an article’s life cycle solidifies the validity of our model, demonstrating that despite simplifying assumptions and use of a static model, we are able to capture the temporal dynamic underlying competition of an article’s contents. In order to verify the robustness of our model, we have re-ran our analysis, this time when excluding non-human editors (i.e. “bots”). Our findings indicate that the pattern of results - for both the entire-period and temporal bracketing analyses - remains the same.

Trying to get a better sense of the (small) discrepancies in ownership values between the model’s prediction and empirical data, we explored whether the differences could be offset by establishing a linear fit function mapping. Let \( a \triangleq [ a_1 \ a_2 \ a_3 \ \cdots \ a_N ] \) (representing the ownership of the contributors obtained by the game theoretic analysis) and \( d \triangleq [ d_1 \ d_2 \ d_3 \ \cdots \ d_N ] \) (representing the ownership of the contributors obtained from the empirical data). For each Wikipedia article, we fit a function

\[
\hat{d}_i = \rho a_i + \delta, \quad 1 \leq i \leq N, \tag{13}
\]

where the parameters, \( \rho \) and \( \delta \), are obtained by the method of least squares \( [\text{Meyer} \ 2000] \). We randomly selected 300 articles as training data in supervised learning to determine the linear regression coefficients, repeating the training/testing split 1000 times. The average error for the training data was 8%. We then ran a linear regression on the remaining 564 pages and tested the linear fit as well as its significance by measuring the \( p \)-value. The error was found to be between 11-16% and the linear regression was statistically significant at \( p < 0.05 \). The implication of this result is that the game theoretic analysis models the contributors’ interactions in Wikipedia accurately up to a linear scaling factor.
VI. DISCUSSION AND CONCLUSION

In this paper we developed a game-theoretic model of competition and governance in Wikipedia and corroborated the model through an empirical study. We stress that we did not intend our game-theoretic model to be comprehensive; socio-technical systems such as Wikipedia are much too complex to be fully captured through a game-theoretic model. Instead, we attempted to model few essential features of Wikipedia’s co-production process, namely contributors’ competition over content ownership and the community’s strive to ensure a balanced position. The results of our model, supported by findings from an analysis of 219,811 distinct contributors co-producing 864 representative articles over an eleven-year period, seem counter-intuitive. Namely, our findings indicate that under the conditions of the community’s strive to ensure neutrality, the “creators” who on average make large contributions (and thus exert high effort per editing activity) end up owning relatively little of the article’s contents. Furthermore, asymptotically, only contributions made by “curators”, whose edit sizes (and effort) are below that expended on average by the group of contributors working on the article, survive the on-going changes to the article’s content.

How could this result be explained? One line of explanation for this points to community’s effort to ensure neutrality (Greenstein and Zhu 2016, 2017, Young et al. 2020). The “creators” making large contributions and taking ownership of large portions of the article may potentially pose a threat to the article’s neutrality. In response, the community works collectively to fight such manipulations and restores neutrality. In the long run, the result is a more neutral content (Stvilia et al. 2008, Greenstein and Zhu 2012). Not withstanding the role of community efforts to ensure neutrality, our results may also be explained by paying attention to the profile of those making the large contributions. Prior studies have identified the “creators” (Kim et al. 2017, Rinie et al. 2012, Roque et al. 2016, Hull and Scott 2013, Hill and Monroy-Herandez 2017) or “content-oriented” contributors as those mainly interested in explicating their knowledge of the topic, and much less in Wikipedia’s internal processes. In contrast, the “curators” (also referred to as “community-oriented” contributors (Arazy et al. 2011)), who engage in refining, shaping, and refactoring of content (Butler et al. 2007) and act as “janitors of knowledge” (Niederer and Dijck 2010) own larger portions of articles. Both these lines of explanation highlight the effectiveness of Wikipedia’s governance.
A second powerful result of this study is in demonstrating that the community’s efforts to govern content creation and ensure neutrality, although essential for maintaining a balanced position, should be curtailed. The reason is that when the “tax” imposed on contributors in terms of complying with NPOV norms, policies and procedures is too high it outweighs the benefits associated with content ownership, such that contributors stop competing for ownership (and in effect, co-production is stalled). Prior studies have documented the growing bureaucracy of Wikipedia (Butler et al. 2008), and have suggested that the increasing complexity of Wikipedia’s governance structure is deterring newcomers and may eventually lead to the decline of Wikipedia (Halfaker et al. 2012). Our results provide an analytical proof for the risk associated with increased governance cost and highlight the need to balance the cost and benefits associated with the governance of online production communities.

In sum, our study makes important contributions to research on peer production. First we shed light on the competitive dynamics underlying peer production. Second, we show how Wikipedia’s governance and in particular, the community’s efforts to maintain neutrality, affect contributors’ behavior and consequently, the quality of the co-produced articles. Although there have been studies using game theory and network ties to study collaboration in social networks in general (Hanaki et al. 2007) and applied to Wikipedia in particular (Zhang and Wang 2012), we are not aware of prior research in this area that linked governance to individuals’ actions.

Notwithstanding these contributions, our work could be extended in several directions, for example by employing alternative measures for our model’s constructs (e.g. alternative measures of articles’ objectivity, for example through an analysis of Wikipedia’s discussion pages) and extending the model to include additional constructs related to contributors (for example: contributors’ intent and their psychological ownership, their compliance with Wikipedia’s policies, or the phase in an article’s life when they concentrate their edits) and related to the articles (the extent to which articles are controversial or the importance of the knowledge-based product). Future research could also attempt to empirically validate our model’s prediction that excessive levels of governance impede peer-production.

An additional important contribution of this study is in applying game theory to investigate peer production in Wikipedia. Prior studies have called for the development of new economic models (Lerner and Tirole 2002) and in particular, the application of game theory to investigate emerging socio-technical
systems such as Wikipedia (Conte et al. 2012). Few studies have used game-theoretic models to compare the efficiency of closed- and open-source software development regimes (Baldwin and Clark 2006), investigate the competitive dynamics of the process by which participants provide feedback on each other’s work (i.e. rating and reputation systems) (Dellarocas 2003), and to study co-production in user generated content (Ghosh and McAfee 2011), crowd sourcing (Horton and Chilton 2010) and Wikipedia (Anand et al. 2013). Our study extends prior work in the area by using game theory to shed light on the role governance mechanisms play in moderating the competition between contributors to peer production. Our game-theoretic model provides insights into the complexities of cooperation and competition in peer-production, making several simplifying assumptions.

Whereas our empirical analysis corroborated the game-theoretic model, we did observe small discrepancies between the model’s predictions and the empirical data. One possible explanation for these differences is that our model provided only an approximation of Wikipedia’s complexities. Future research could help make progress: such work could relax some of our model’s assumptions, for example model learning effects, capture other important qualities of articles such as accuracy or completeness, explore multi-stage games, and consider various classes of contributors that differ in their roles and goals.

In particular, we foresee three avenues for extending our study. First, in our model a contributor owns his newly-added content thus impacting others’ relative ownership. A more sophisticated model could also account for overwriting (or deleting) another contributor’s content, thus directly impacting the ownership of a specific other. A challenge for such a model would be to handle the complexity associated with numerous pair-wise relationships. Second, our model could possibly be extended to capture a tighter linkage between the leader-follower game (community governance) and the non-cooperative game (competition over content ownership), for example by linking the effectiveness of the community’s governance to the aggregate of contributors’ governance effort. Third, future work could represent cooperative dynamics within Wikipedia. Although our model indirectly accounts for cooperation in that each player in the game could be seen to represent a group of collaborative similar-minded contributors, a more complete model could directly model cooperative behavior.

In conclusion, we believe that game theory can reveal deep insights into the complex dynamics underlying peer production. While game theory, and in particular leader-follower game, has already
been employed in the context of allocation of divisible resources (Maheswaran and Basar 2006), the application of such techniques to community-based peer production is novel. Future research directions for game theory in this area include: the use of cooperative game theory (Branzei et al. 2008) to study the stability of the production process; applying coalitional game models (Ray and Vohra 1999) to analyze how competing coalitions of contributors emerge, applying resilience and immunity models (Halpern 2008) to investigate how the peer production process performs in cases of deviations from expected behavior; using evolutionary game theory (Weibull 1997) to study how unexpected behaviors emerge as a result of sequential actions by different contributors; to develop models that would account for the relationship between individual’s governance work and the community’s overall governance level and using algorithm and mechanism design (Jackson 2000) to determine the most effective community governance structures.

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### APPENDIX A

**NOTATIONS USED IN THE ANALYSIS OF THIS RESEARCH**

| Notation | Description |
|----------|-------------|
| $N$      | Number of contributors for a focal Wikipedia article |
| $x_i$    | Amount of contribution by the $i^{th}$ contributor to the focal article |
| $c_i$    | Fractional (content) ownership of the $i^{th}$ contributor in the focal article |
| $f_i$    | Fixed cost incurred by the $i^{th}$ contributor (by participation in peer production and governance work) |
| $t$      | Level of neutrality enforcement |
| $\beta_i$ | Average size of the $i^{th}$ contributor's edits (across all articles he contributed to) |
| $E(\beta) = \frac{1}{N} \sum_{i=1}^{N} \beta_i$ | Average size of edits for all those contributing to the focal article |
| $u_i = c_i - (L\beta_i^i + t)x_i - f_i$ | Utility of the $i^{th}$ contributor in the focal article |
| $x_i^*$ | Optimal amount of contribution by the $i^{th}$ contributor in the focal article which maximizes $u_i$ with respect to $x_i$ |
| $c_i^*$ | Fractional content ownership of the $i^{th}$ contributor within the focal article when she makes the optimal contribution, $x_i^*$ |
| $\alpha_i$ | A simplified notation to represent $\frac{1}{L\beta_i + t}$ |
| $D$ | An $N \times N$ diagonal matrix with $N, 0, \ldots, 0$ along the diagonal |
| $D_\alpha$ | A diagonal matrix with $\alpha_1, \alpha_2, \ldots, \alpha_N$ along the diagonal |
| $\mathbf{1}$ | A column vector in which all entries are 1, whose transpose is $\mathbf{1}^T$ |
| $P$ | A matrix whose columns are orthonormal eigen vectors of $\mathbf{1}\mathbf{1}^T$ |
| $H(t)$ | Entropy of an article with governance level, $t$ |
| $s_i$ | Total number of sentences owned by the $i^{th}$ contributor in the focal article |
| $\zeta_i$ | Total number of edits made by the $i^{th}$ contributor over all articles in our sample |
APPENDIX B

NASH EQUILIBRIUM OF THE NON-COOPERATIVE GAME BETWEEN THE CONTRIBUTORS

In this section, we detail the steps in obtaining the optimal contributions Re-writing Equation \((3)\),
\[
\left(\sum_{j=1}^{N} x_j^*\right)^2 - \alpha_i \sum_{j \neq i}^{N} x_j^* = 0, \quad \forall N, \tag{14}
\]
where \(\alpha_i \triangleq \frac{1}{t+L_j} \). Equation \((14)\) can be written as
\[
(x^*)^T 11^T x^* - D_\alpha (11^T - I) x^* = 0, \tag{15}
\]
where \((.)^T\) represents the transpose of a vector or a matrix, \(D_\alpha\) is the diagonal matrix \(\text{diag}(\alpha_1, \alpha_2, \cdots, \alpha_N)\), \(1\) is the column vector in which all entries are one, \(0\) is the column vector in which all entries are zero and \(I\) is the identity matrix.

It can be easily verified the vectors, \(y_1 = \frac{1}{\sqrt{N}} 1\) and for \(j = 2, 3, \cdots, N\), \(y_j = [y_{kj}]_{1 \leq k \leq N}\), where
\[
y_{kj} = \begin{cases} 
-\frac{1}{\sqrt{j(j-1)}} & k < j \\
\frac{j-1}{\sqrt{j(j-1)}} & k = j \\
0 & k > j
\end{cases}
\tag{16}
\]
form a set of orthonormal eigen vectors to the matrix, \(11^T\). The eigen value corresponding to \(y_1\) is \(N\) and those corresponding to \(y_2, \cdots, y_N\) are 0s. Let
\[
P = [y_1 | y_2 | \cdots | y_N]. \tag{17}
\]
Then, \(P\) is an orthogonal matrix and by orthogonality transformation \([\text{Meyer}2000]\),
\[
P^T 11^T P = D = \text{diag}(N, 0, 0, \cdots, 0). \tag{18}
\]
Let \(z = [z_1 \ z_2 \ z_3 \ \cdots \ z_{N-1} \ z_N]^T\). Since the eigen vectors of a matrix form a basis for the \(N\)-dimensional sub-space \([\text{Meyer}2000]\), the vector, \(x^*\), can be written as \(x^* = Pz\). In other words, from Equations \((16)\) and \((17)\),
\[
x_1^* = \frac{z_1}{\sqrt{N}} - \sum_{j=2}^{N} \frac{z_j}{\sqrt{j(j-1)}}, \tag{19}
\]
\[
x_k^* = \frac{z_1}{\sqrt{N}} + \frac{(k-1)z_k}{\sqrt{k(k-1)}} - \sum_{j=k+1}^{N} \frac{x_j}{\sqrt{j(j-1)}}, \quad 2 \leq k \leq N - 1, \tag{20}
\]
\[
x_N^* = \frac{z_1}{\sqrt{N}} + \frac{(N-1)z_N}{\sqrt{N(N-1)}}. \tag{21}
\]
Intuitively, the vector, $z$, is a linear transformation of the set of variables in the vector, $x^*$, which enable solving the set of Equations characterized by (15), using an approach similar to that outlined in (Anand et al. 2014), described by the following steps.

- Using $x^* = Pz$ in Eqn. (15) and Equation (18), we obtain

$$z^T Dz_1 - D_0 (11^T - I) Pz = 0.$$  \hspace{1cm} (22)

- The above is a set of non-linear equations in $z$, in which the $k^{th}$ equation depends on $z_1$ and $z_j$, $k \leq j \leq N$. Solving the non-linear equations by backward substitution (Meyer 2000), $z_k$, $2 \leq k \leq N$ can be written in terms of $z_1$ as

$$\frac{z_k}{\sqrt{k(k-1)}} = \frac{Nz_1^2}{k(k-1)} \left[ \frac{k}{\alpha_k} + \sum_{j=k+1}^{N} \frac{1}{\alpha_j} \right] - z_1 \frac{N(N-1)}{\sqrt{N} k(k-1)}.$$  \hspace{1cm} (23)

- Using Equation (23) to replace all $z_k$’s in terms of $z_1$ in the set of non-linear equations in Eqn. (22), $z_1$ can be obtained as

$$z_1 = \frac{N-1}{\sqrt{N}} \left( \frac{1}{G} \right),$$  \hspace{1cm} (24)

where

$$G \triangleq \sum_{j=1}^{N} \frac{1}{\alpha_j}.$$  \hspace{1cm} (25)

- Combining Equations (23) and (24), for $2 \leq k \leq N$,

$$\frac{z_k}{\sqrt{k(k-1)}} = \frac{(N-1)^2}{k(k-1)} G^{-1} \left[ G^{-1} \left( \frac{k}{\alpha_k} + \sum_{j=k+1}^{N} \frac{1}{\alpha_j} \right) - 1 \right]$$  \hspace{1cm} (26)

- Using Equations (19)-(21) and $\alpha_i = \frac{1}{\rho_{ij} + L_{ij}}$ in Equation (24) and Equation (26), the unique Nash equilibrium, $x^*$ can be obtained as given by Equation (4).
We sought to validate reasoning underlying the objective function. Namely, we sought evidence that the goal of the Wikipedia community is indeed to maximize neutrality (i.e. entropy) in content ownership. Optimally, we would have been able to compare the entropy in content ownership to article’s objectivity. However, such a metric of objectivity is not available for our dataset, especially when we consider that our empirical validation requires this metric for each article revision. Instead, we employed a more general metric of content quality, recognizing the limitation that objectivity is but only one dimension of content quality. We, thus, compared the entropy in content ownership for all articles in our sample with article’s quality at the cut-off date of our study. Our entropy measure is normalized (i.e. each article’s entropy is calculated in relation to the maximum entropy of any article, which is 1), so as to control in variations in the number of contributors per article.

Deriving such a content quality metric is not an easy task. Although the Wikipedia community rank article’s quality, content on articles in a continuous flux, and the community is not able to rank re-visit the quality of each article revision. Furthermore, only a small portion of the articles in our sample have been ranked by the Wikipedia community. Consequently, we chose an alternative method for estimating articles’ quality, building on the recent work of the Wikipedia Foundation to develop an automated tool for estimating articles’ quality. The ORES (Objective Revision Evaluation Service) service is intended to be scalable, easily extensible and responsive (Dang and Ignat 2016, Sarabadani et al. 2017). ORES uses automatic machine-learning methods. ORES is trained on Wikipedia’s community-based article scoring procedure, which stresses the goals of content reliability, verifiability, objectivity, and importance, and assigns articles with quality grades (from lowest to highest: Stub, Start, C grade, B grade, Good Article (GA), and Featured Article (FA)). We used the ORES API to extract quality estimates for each Wikipedia article in our sample of 864 articles at the date of our study’s cut-off. The ORES API outputs probabilities for having the article associated with each of the quality grades. Finally, the probabilities were weighted using the scheme of [Stub = 0, Start = 1, C = 2, B = 3, GA = 4, FA = 5] to produce a score between 0 and 5. As shown in Figure 4, we found a strong correlation (Pearson correlation coefficient ≈ 0.82) between articles’ quality and the entropy in content ownership, suggesting that maximizing entropy is a
reasonable objective function to maximize.

![Normalized Entropy vs. ORES Quality Index](image)

Fig. 4. The quality index for the 864 articles analyzed in this study as a function of the entropy in articles’ content ownership. There is a strong positive correlation (Pearson correlation co-efficient ≈ 0.82) between the entropy of an article and its quality.

In order to provide an additional verification for our objective function (i.e. maximizing entropy for determining the optimal level of governance, \( t \)), we sought additional evidence that the goal of the Wikipedia community is indeed to maximize neutrality (i.e. entropy) in content ownership. We employed a set of 96 Wikipedia articles used in [Arazy et al., 2011][20], which sampled articles from Wikipedia’s various topical categories. On average an article in this set was edited by 49 contributors and went through 91 revisions. This data set provides a robust metric of objectivity, along with additional metrics of information quality along the dimensions of: accuracy, completeness, and representation (on a 7–point Likert scale). These metrics were determined through a three-phased approach: (1) manual analysis by student assessors as part of a course assignment (multiple assessors per article); (2) independent manual analysis by senior university librarians comparing the articles to external sources (three assessors per article); and (3) consensus between the three librarians using a Delphi approach. The outcome variable for this data set was the average of consensus score for the various quality metrics, on a 1 – 7 scale. Using the same method applied to our study’s primary sample, we calculated the ownership of each article and the entropy in contributors’ content ownership. Results from our analysis show a strong correlation between entropy in ownership and article quality (Pearson coefficient ≈ 0.78), further supporting our

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[20] This data set with articles’ quality metrics was obtained through direct correspondence with the authors.
definition of the objective function (for determining optimal governance level, t) as the maximization of articles’ entropy (in terms of contributors’ content ownership).
We now present the detailed analysis to show the fact that the optimal value of \( t \) that maximizes the entropy of a page is \( t \to \infty \). From Equation
\[
\frac{\partial H}{\partial z} = -\sum_{i=1}^{N} \frac{\partial c_i^*}{\partial z} (1 + \ln c_i^*). \tag{27}
\]
Therefore, the condition \( \frac{\partial H}{\partial z} = 0 \) yields the condition,
\[
\sum_{i=1}^{N} \frac{\partial c_i^*}{\partial t} \ln c_i^* = -\sum_{i=1}^{N} \frac{\partial c_i^*}{\partial t} \ln c_i^*. \tag{28}
\]
From Equation (6),
\[
\frac{\partial c_i^*}{\partial z} = \frac{(N - 1) \left( NL\beta_i - \sum_{j=1}^{N} L\beta_j \right)}{(Nz + \sum_{j=1}^{N} L\beta_j)^2} = \frac{N(N - 1) (L\beta_i - LE[\beta])}{(Nz + \sum_{j=1}^{N} L\beta_j)^2}, \tag{29}
\]
i.e., \( \frac{\partial H}{\partial z} = 0 \Rightarrow \sum_{i=1}^{N} \frac{\partial c_i^*}{\partial z} = 0. \tag{30} \]
Putting Equation (30) in Equation (28) and simplifying, the optimal neutrality enforcement, \( t \) is obtained as the value of \( z \) that solves
\[
\sum_{i=1}^{N} [(\beta_i - E(\beta)] \ln c_i^*(z) = 0. \tag{31}
\]
From the observations listed in Section IV-A, if \( \beta_i > E(\beta) \), then \( c_i^* = 0 \), i.e., \( \ln c_i^* \to -\infty \). \( 0 < c_i^* < 1 \) when \( \beta_i < E(\beta) \), i.e., \( \ln c_i^* < 0 \). Therefore, the value of \( t \) that satisfies Equation (31) is the value that makes \( \ln c_i^* \) go to \( -\infty \), i.e., make \( c_i^* \to 0 \), i.e., \( t = \infty \), from Equation (6). Therefore, the value of \( t \) that maximizes \( H(t) \) is \( t \to \infty \).