The wisdom of polarized crowds

Feng Shi[1,2,7], Misha Teplitskiy [2,3,7]*, Eamon Duede[2,4] and James A. Evans [2,5,6]*

As political polarization in the United States continues to rise[1-3], the question of whether polarized individuals can fruitfully cooperate becomes pressing. Although diverse perspectives typically lead to superior team performance on complex tasks[4,5], strong political perspectives have been associated with conflict, misinformation and a reluctance to engage with people and ideas beyond one's echo chamber[6-8]. Here, we explore the effect of ideological composition on team performance by analysing millions of edits to Wikipedia's political, social issues and science articles. We measure editors' online ideological preferences by how much they contribute to conservative versus liberal articles. Editor surveys suggest that online contributions associate with offline political party affiliation and ideological self-identity. Our analysis reveals that polarized teams consisting of a balanced set of ideologically diverse editors produce articles of a higher quality than homogeneous teams. The effect is most clearly seen in Wikipedia's political articles, but also in social issues and even science articles. Analysis of article 'talk pages' reveals that ideologically polarized teams engage in longer, more constructive, competitive and substantively focused but linguistically diverse debates than teams of ideological moderates. More intense use of Wikipedia policies by ideologically diverse teams suggests institutional design principles to help unleash the power of polarization.

Recent political events, including the 2016 presidential election, have underscored growing political divisions in US society. Political speech has become markedly more polarized in recent years[1], tracing a growing divergence between the platforms of the major political parties[2] and leading to a state of political hyper-partisanship[3]. However, the effects of political difference are not confined to the domain of politics alone. A growing literature documents how individual political alignments shape personal consumption of ostensibly non-political products, news and cultural and scientific information[9-13]. This literature has converged on an alarming narrative: despite the early promise of the World Wide Web to democratize access to diverse information[14], increased media choice and social networking platforms have led to the converse. Collaborative filtering allows individuals to passively enter echo chambers that limit the variety of information they observe and trust[15-17]. These can degrade the quality of individual decisions, including those that undergird basic democratic institutions[6-8]. Psychological mechanisms such as motivated reasoning[18,19] and a tendency to discount identity-incongruent opinions[7,20] stimulate and reinforce polarizing information. Opposing social identities can foment conflict and even make communication counter-productive[21].

Nevertheless, a large literature documents the predominantly positive effect that social differences can exert on the collaborative production of information, goods and services[4,5]. Research demonstrates that individuals from socially distinct groups embody diverse cognitive resources and perspectives that, when cooperatively combined in complex or creative tasks, produce ideas, solutions and designs that outperform those from homogeneous groups[22-25]. Collaborations between inventors from distinct social groups result in more creative patents[26], scientific teams representing distinct disciplines produce more highly cited papers[27] and gender diversity broadens the range of questions that scientists ask[28].

However, the effect of political diversity on the collective production of knowledge remains unclear. Insights from cognitive diversity research suggest that political diversity, like other forms of diversity, should positively impact the quality of group production because different perspectives, in the words of John Stuart Mill, "instead of being one true and the other false, share the truth between them"[29]. Literature on echo chambers, by contrast, suggests that political diversity may hamper productive cooperation as partisans perceive information held by opponents as not simply different, but wrong. In short, political diversity should increase access to fresh perspectives and information but may also undermine the quality of discourse and engagement required to enjoy the performance benefits typically obtained by diverse groups.

To assess the effect of political diversity on team performance, we studied the effect of political polarization on the performance of approximately 400,000 online teams. We focused on teams or communities of Wikipedia editors who worked on English-language articles in three large domains: politics, social issues and science. Whether online editors collaborating on a Wikipedia article should be considered a team or community is an empirical question relating to the temporal and topical proximity of editor discussion and contribution. For clarity, we use the term 'team' to refer to all such editing collectives and 'community' to characterize Wikipedia editors as a whole.

We measure editors' online ideological alignments by their contributions to conservative (red) versus liberal (blue) articles on the English-language Wikipedia, using a Bayesian framework to account for limited or random edits (see Methods and Supplementary Methods 1 for details). We observe a wide distribution of measured ideological alignments for Wikipedia editors (Fig. 1a). The peak at the centre of the distribution comports with our observation that a large number of people only contributed minor edits to Wikipedia, such as correcting a typo. There are also two lower but substantial peaks at the tails of the distribution, which identify editors who contribute substantial content to either liberal or conservative articles. The relative equality of these two divided populations suggests substantial polarization on Wikipedia. The variance of alignments across all editors of political articles is 0.04. This observed variance was significantly higher than those obtained in random simulations that assume editors allocate their effort at random with ideological alignments of 0 (the bootstrapped P value for the observed variance is less than 0.001, which is the empirical

[1]Odum Institute for Research in Social Science, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA. [2]Knowledge Lab, University of Chicago, Chicago, IL, USA. [3]Laboratory for Innovation Science, Harvard University, Boston, MA, USA. [4]Committee on the Conceptual and Historical Studies of Science, University of Chicago, Chicago, IL, USA. [5]Department of Sociology, University of Chicago, Chicago, IL, USA. [6]Santa Fe Institute, Santa Fe, NM, USA. [7]These authors contributed equally: Feng Shi, Misha Teplitskiy. *e-mail: mteplitskiy@fas.harvard.edu; jevans@uchicago.edu
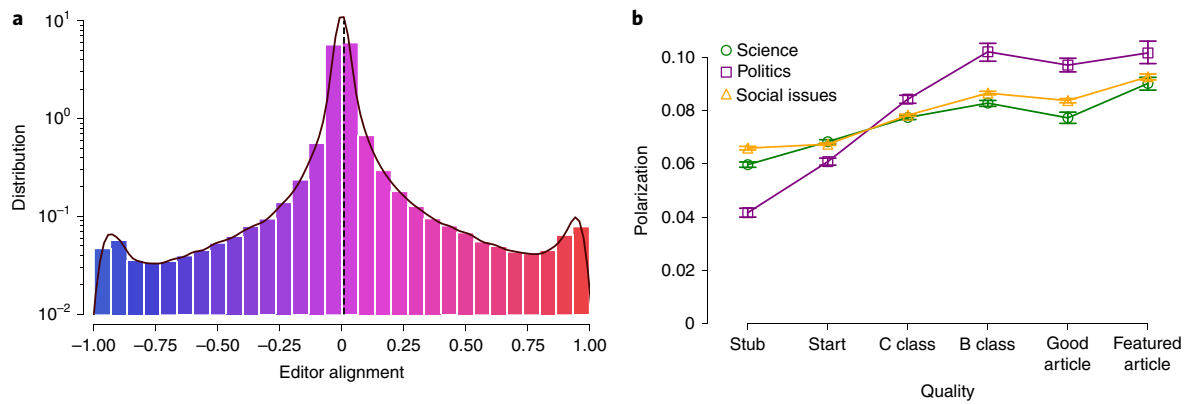
Fig. 1 | Political alignment and the relationship between political polarization and article quality. a, The distribution of editors' computationally measured ideological alignments, ranging from −1 (most liberal, where editors make intensive and exclusive contributions to liberal articles) to +1 (most conservative, where editors make intensive and exclusive contributions to conservative articles). **b**, The average polarization score for teams in each article quality level (Stub, lowest; Featured article, highest) for politics, social issues and science articles. Error bars around the mean denote the 95% confidence interval (CI). The actual numbers for the means and their CIs are included in Supplementary Table 3.

probability of observing a variance larger than 0.04 in 100 random simulations; see Supplementary Methods 3 for details of the simulations). We then measure the polarization of any given group of editors by the variance of their alignment scores.

As the number of editors for an article increases, their average political alignment decreases (Fig. 2). This phenomenon is sometimes referred to as Linus's law: "with enough eyeballs, all bugs are shallow"[30]. Articles attracting more attention tend to have a more balanced engagement from editors along the conservative–liberal spectrum. This finding replicates those reported by Greenstein and Zhu[31,32] in their studies of bias regarding Wikipedia's US political coverage, showing that increased editor interaction reduced individual biases and yielded greater content neutrality. However, this pattern raises a concern regarding the ideological alignment measure: if a popular political article, whether liberal or conservative, attracts more balanced engagement from liberal and conservative editors, then it should contribute less information to our inferred ideological alignment for those editors. We checked the robustness of our results after relaxing our dichotomous classification of politics pages (see Supplementary Methods 2). Specifically, we adapted our Bayesian framework to update the alignment of liberal and conservative pages as a function of the balance of liberal and conservative editors who edit them. We recursively calculated the alignment of editors based on this updated alignment of pages and found that this measure produced results qualitatively the same as those shown below for our simple dichotomous measure (see Supplementary Methods 2 and Supplementary Table 5).

The six-category quality scale for Wikipedia articles ranges from Featured article (highest quality) to Stub (lowest quality). Figure 1b plots the relationship between average team polarization (that is, average variance of alignments) and quality for political, social issues and science articles.

In political, social issues and science articles, higher polarization is associated with higher quality. To establish this relationship statistically, we estimated an ordinal logistic regression model at the article level with article quality as the outcome and polarization as the main independent variable. We controlled for the absolute value of average team alignment and article and editor features that may plausibly confound the relationship between polarization and quality. These article features include length, number of edits and number of editors for each article. We specifically controlled for editors' editing experience by adding the average number of previous edits for each team.

As expected, the number of edits, the length of the article and the number of editors significantly predict article quality (see Table 1 for regression results). The coefficient for the |alignment| term suggests that quality decreases when editors are biased, on average, in either direction. Most critical is that polarization, the variance of political alignments, is positively and substantially associated with quality: a 1 unit increase in polarization multiplies the odds of moving from lower- to higher-quality categories by a factor of 18.57 for political articles, 2.06 for social issues articles and 1.90 for science articles. See Supplementary Methods 2 for an analysis that insures attentuation bias is not responsible for the effect size of polarization across corpora.

To explore the mechanisms by which ideologically polarized teams outperform homogeneous teams, we examine the Wikipedia talk pages. Each Wikipedia article has an associated talk page where 'backstage' knowledge assemblage occurs. Here, editors debate proposed additions and deletions, identify shortcomings and attempt to persuade their fellow editors regarding content for the public facing 'frontstage' Wikipedia article[33]. Using text from these talk pages, we examine the relationships between political polarization and the following aspects of debate: debate intensity, information diversity and use of Wikipedia institutions—policies and guidelines—to discipline discussion. We investigate pairwise correlations between polarization and these debate mechanisms and then estimate regression models to test the effect of polarization on these mechanisms separately. Finally, we assemble them into a structural equation model that allows us to identify their relative influence on article quality. All statistical analyses yield consistent results regarding mechanisms of collaboration, as discussed below and detailed in Supplementary Methods 6 and 7.

Studies of team diversity and performance provide evidence that the diversity of information held by individuals is the key driver of superior performance[5]. Nevertheless, information diversity is almost never measured directly, particularly in non-laboratory settings. The concept of information diversity confounds the substance and form of information, which are independently critical in ideological conflicts where interlocutors holding different beliefs frame the same issues in distinct language with distinct meanings. To address this challenge, we decompose information diversity into two measurable dimensions: lexical and semantic diversity. Semantic diversity captures distinct issues discussed on a talk page, whereas lexical diversity captures the number of ways in which editors discuss those issues. Because political polarization is predictably
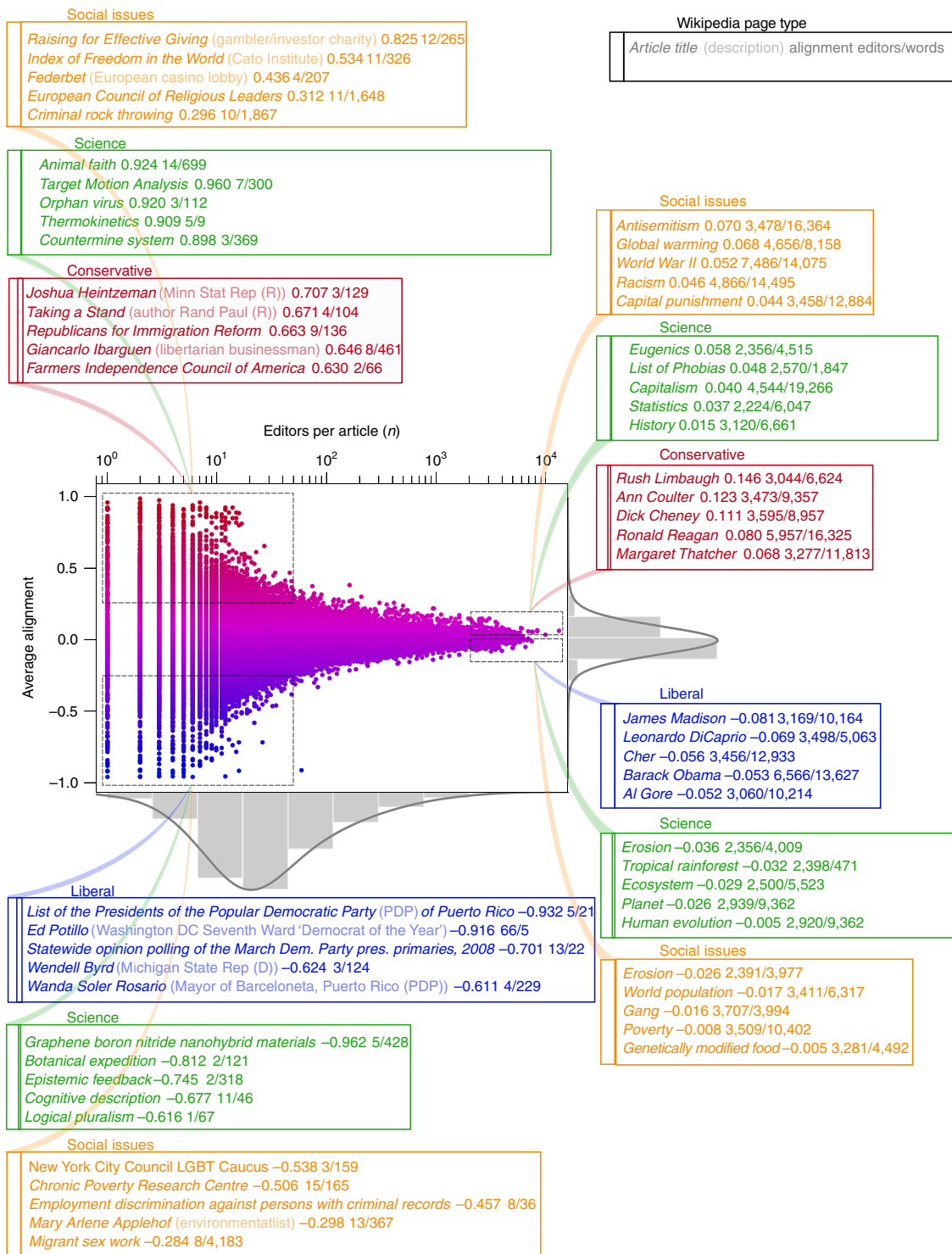
Fig. 2 | Scatter plot with each article's average editor alignment by number of editors. Average political alignment shrinks as the number of editors increases, demonstrating the Linus effect. Histograms on the *x* and *y* axes reveal the density of articles at each level of editorial attention and average political alignment, respectively. Gray curves over the histograms are Gaussian kernal density estimates from the data. Those curves are plotted on the same scales as the corresponding histograms. Call-out boxes list five of the most liberal and most conservative pages for articles receiving the most and least editorial attention, featuring article titles followed by an optional description, mean political alignment, number of editors and article length in bytes. In the examples, "Minn Stat Rep (R)" denotes Minnesota House of Representatives (Republican), "Michigan State Rep (D)" denotes Michigan House of Representatives (Democratic), and "Dem. Party pres. primaries" denotes Democratic Party presidential primaries. The "R" appearing after Rand Paul stands for Republican. LGBT stands for lesbian, gay, bisexual and transgender. These examples illustrate a meaningful association between the political preferences of right- and left-leaning Wikipedia editors and the pages they edit (for example, *Capitalism* and *History* versus *Planet* and *Human evolution*).

Table 1 | Odds ratios from ordinal logistic regression models predicting article quality

Independent variable	Politics	P	Social issues	P	Science	P
Polarization	18.88	<0.001	2.06	<0.001	1.79	0.006
|alignment|	0.30	<0.001	0.49	<0.001	0.65	0.002
Editing experience	1.05	0.02	1.06	<0.001	1.01	0.30
Number of editors	0.41	<0.001	0.51	<0.001	0.56	<0.001
Article length	33.55	<0.001	47.83	<0.001	56.54	<0.001
Number of edits	3.26	<0.001	1.71	<0.001	1.69	<0.001
N	12,570		161,070		49,995	

Statistical significance levels (P values) are derived from two-sided Wald tests. The columns present odds ratios estimated on political, social issues and science articles, separately. N denotes sample size.
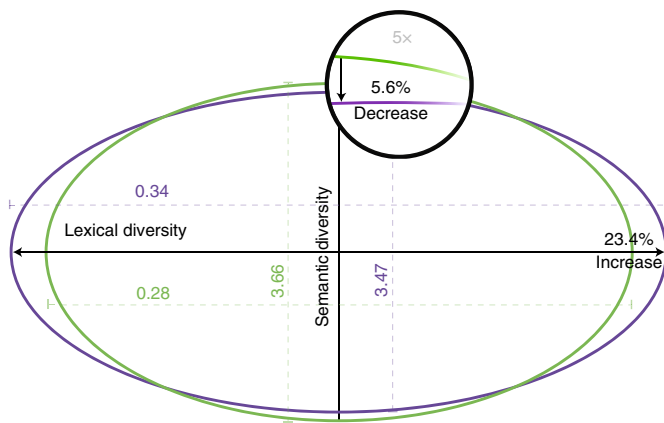
Fig. 3 | An illustration of the shift in talk page debate activity between teams in the bottom and top thirds of the political polarization distribution. Compared with the least polarized third of teams (green), the most polarized third (purple) semantically contract by 5.6% and lexically expand by 23.4%: they talk more about less, focusing on core politically contested subjects, but framing them in distinctive ways.

related to political content, we expect that political polarization among Wikipedia editors will focus the debate on the subset of politically relevant topics within their article, but frame those issues in diverse and conflicting ways. If we are correct, greater political polarization among editors will yield lower semantic diversity and higher lexical diversity on their talk pages. We measure the lexical diversity of each talk page as a function of its distinct and distinguishing words. We measure the semantic diversity of a page as a function of the dispersion of words on that page in a latent semantic space defined by all Wikipedia articles, such that higher semantic diversity indicates that more Wikipedia topics were debated. (See Supplementary Methods 4 for details of the two diversity measures.) We find that high political polarization narrows debate by reducing talk page semantic diversity but generates alternative framings traced by greater lexical diversity, as illustrated in Fig. 3.

Diverse information should be more difficult to integrate, particularly if contested. We measure two core aspects of debate intensity including volume and temperature. Following previous research that found talk page length to be associated with article quality[34,35], we measure debate volume as a function of talk page length and distinct edits. Polarized teams may attempt to integrate more diverse information, requiring more talk, which yields greater article quality. Integrating diverse perspectives on contested and value-laden topics could be acrimonious, but a balance of liberals and conservatives could lower the temperature of potentially volatile

collaborations, following research that links competitive imbalance to emotional aggression and violence[36]. We measure debate temperature using the `Detox` tool, developed by Wikimedia to identify harassment in the Wiki community. `Detox` detects toxic comments using a sophisticated machine learning classifier[37], which we apply to all talk page edits. We find that polarized teams generate a larger volume of debate (polarization coefficient $\beta = 0.37$; CI = (0.33, 0.40); $z(86) = 20.20$; $P < 0.001$; two-sided Wald z-test, in the structural equation model discussed below and in Supplementary Methods 7) and their balance of political perspectives reduces flare-ups in debate temperature (|alignment| coefficient $\beta = 0.08$; CI = (0.04, 0.13); $t(205,737) = 3.67$; $P < 0.001$; two-sided Student's t-test, in the linear regression model that predicts debate temperature using |alignment|, polarization, number of editors, number of edits and page lengths).

Finally, we explore the self-governance of contested knowledge through the use of Wikipedia policies and guidelines. Policies and guidelines are invoked so frequently that they have a standard nomenclature[38]. For example, an editor who believes that part of an article is biased may invoke the neutral point of view (NPOV) policy in the article's talk page. The NPOV policy requires claims made on Wikipedia to be free from editorial bias and inclusive of all significant views reported in reliable sources. Wikipedia also relies on a collection of less binding guidelines that refer to desired qualities of Wikipedia pages and the editorial process. These include that articles should cite sources (CITE) and avoid or disclose any conflicts of interest (COI). We expect editors within polarized teams to encounter differences not easily resolved and, when debate fails, to discipline or challenge collaborators by invoking Wikipedia's policies and guidelines. Indeed, the number of policy and guideline mentions are found to increase with polarization. When disaggregated, we find that NPOV and OR (no Original Research) are the most frequently cited policies, and each significantly correlates with polarization (for NPOV, Pearson correlation $\rho = 0.10$; $t(4671) = 6.87$; $P < 0.001$; CI = (0.072, 0.128); and for OR, $\rho = 0.08$; $t(6498) = 6.47$; $P < 0.001$; CI = (0.056, 0.104); both for two-sided t-tests).

Correlations between all modelled variables are presented in Supplementary Fig. 3 and are consistent with the regressions and structural equation model described below (and in Supplementary Methods 6 and 7). We also note interesting associations between talk page measures, suggesting micromechanisms of conflict and coordination, such as the negative correlation between debate temperature and talk page length ($\rho = -0.08$; $n = 205,744$; $P < 0.001$ in two-sided t-tests). This is relevant to the growing literature about online 'trolling' behaviour[39,40], suggesting that interactional toxicity is associated with foreshortened debate and a decreased collective capacity to construct quality Wikipedia pages.

We present results from a structural equation model in Fig. 4, which allowed us to evaluate the combined impact of political polarization on article quality through mechanisms of collaboration.
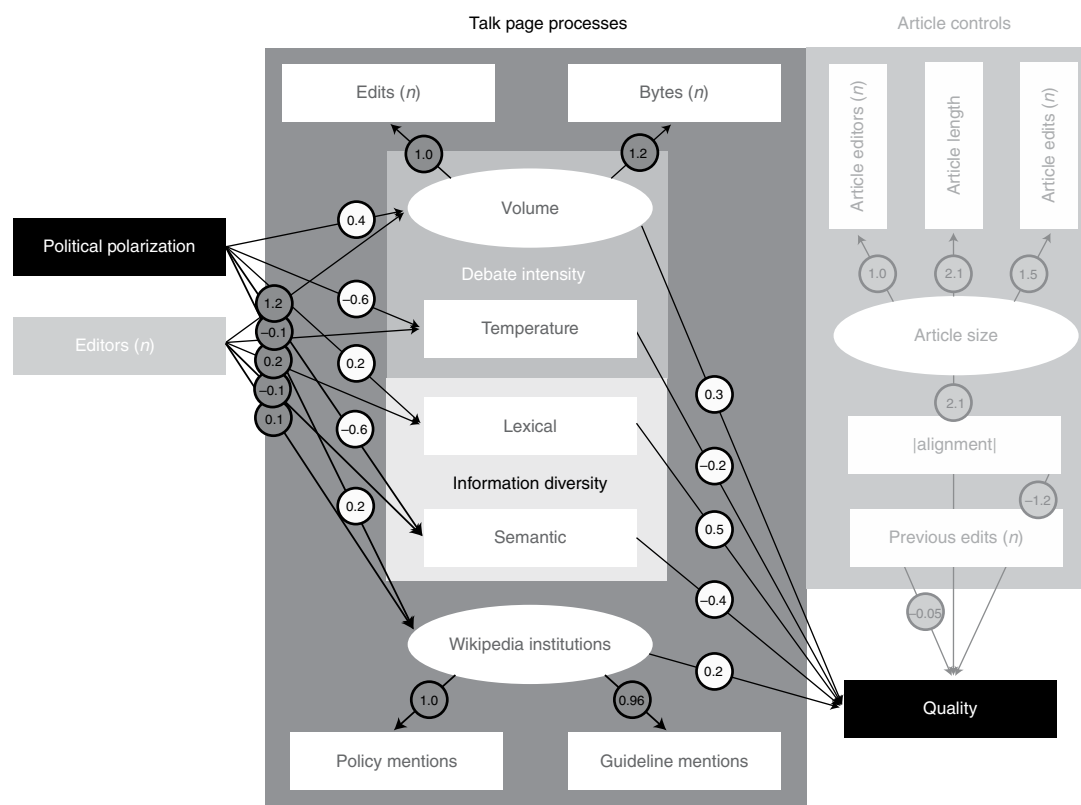
Fig. 4 | Estimated structural equation model linking political polarization with article quality through talk page activity. The model includes control variables associated with features of the articles themselves. Values in circles represent coefficients, rectangles represent measured variables, and ovals indicate latent variables. All coefficients are significant at the $P < 0.001$ level, agreeing with individual models and bivariate correlations. See Supplementary Methods 7 for more details about the model and results.

We summarize the model estimates here. (See Supplementary Methods 7 for additional details.) The model is fitted to 205,744 pages. Compared with ideologically homogeneous or skewed teams, polarized teams debate (1) fewer topics ($\beta = -0.65$; $z(86) = -37.28$; $P < 0.001$; CI = $(-0.68, -0.61)$; two-sided z-test), (2) with more competing terminology and framings ($\beta = 0.20$; $z(86) = 13.82$; $P < 0.001$; CI = $(0.17, 0.23)$; two-sided z-test). They engage in more debate (3) ($\beta = 0.37$; $z(86) = 20.20$; $P < 0.001$; CI = $(0.33, 0.40)$; two-sided z-test), (4) which is less acrimonious ($\beta = -0.60$; $z(86) = -18.28$; $P < 0.001$; CI = $(-0.656, -0.53)$; two-sided z-test). They also (5) more frequently appeal to Wikipedia policies and guidelines to govern these interactions ($\beta = 0.20$; $z(86) = 8.20$; $P < 0.001$; CI = $(0.14, 0.24)$; two-sided z-test).

Lastly, to assess whether editors' ideological preferences measured on Wikipedia correspond to their ideological preferences offline, we fielded two surveys, focusing on editors' political party affiliation and ideological self-identity (see Supplementary Discussion 1 for details). In both surveys, approximately 45% of the contacted editors reported living in the United States, and we report results from their answers here. Our computational ideological alignment measure correlates moderately well, and significantly predicts self-reported party affiliation on the Democrat−Republican spectrum ($\rho = 0.35$; $P = 0.035$; $n = 28$; one-tailed permutation test, performed because the correlation is predicted to be positive; area under the receiver operating characteristic curve (AUC) = 0.71). Associations between computational and self-reported ideology (on the liberal−conservative scale) are slightly weaker, with $\rho = 0.25$ ($P = 0.06$; $n = 41$ in a one-tailed permutation test) and a predictive AUC of 0.65. The lower associations with self-identified ideology are not surprising, considering that self-identity may be constructed in reference to one's peers rather than being anchored along a global

spectrum. Moreover, the ideology survey was fielded after the inauguration of Donald Trump as president, which may have influenced individuals' political self-identities or willingness to report them in surveys. Finally, responses to this second survey were highly imbalanced, with seven individuals self-identifying as 'extremely liberal' and zero self-identifying as 'extremely conservative'.

Taken together, the survey results provide some evidence that editing preferences measured online are correlated with, and predictive of, party affiliations and ideological preferences offline. Further research, including lab and field experiments, is necessary to establish these suggestive relationships with causal certainty.

Mechanisms of polarized collaboration are echoed by editors in their survey responses. One-third of respondents indicated awareness of politically motivated conflicts, and two-thirds of those described them in detail. Conflicts typically entailed the encounter of biased content (for example, 'The page read like anti-Russian propaganda') or having one's own content revised by editors perceived as biased (for example, 'My neutral edits regarding a particular political group were moved lower in the article to show negative opinions of this group first'). Many such conflicts were resolved through debate. One respondent recalled a conflict over the meaning of the word 'refugee' that was resolved 'by legal arguments that would convince an impartial observer'. Another related an intense conflict on a page about homosexuality, but admitted that as a result 'the article is in a better state'. Other conflicts were resolved through administrator intervention. One respondent reported editing a page about a far-right politician that other editors would repeatedly vandalize; administrators intervened and protected the page from further edits. Unbalanced political competition, however, where lone editors sought to de-bias articles maintained by politically like-minded communities (for example, with a perceived 'right

wing slant' or 'anti-Russian bias') led to more acrimonious conflict that often resulted in editor bans. Editing contested topics required toughness and endurance, which was ameliorated by balanced conflict. It is precisely these engagements that are missing from segregated echo chamber platforms, and channel Wikipedia editors' diverse perspectives into articles of superior quality.

This study provides empirical, real-world evidence that ideological polarization can lead to productive, high-quality collaboration. Wikipedia teams comprising a balance of ideologically polarized individuals perform better than groups consisting of political partisans and even moderates. Positive effects from polarization are observed in political, social issues and even science articles. The intensified effect of ideological polarization on pages with greater political content suggests that diversity is not universally beneficial, but assists when directly or indirectly relevant to the topics considered. We demonstrate how frequent, intense disagreement within ideologically polarized teams foments focused debate[41] and, as a consequence, higher-quality edits that are more robust and comprehensive.

While our study revealed a statistically significant relationship between polarization and collaborative outcomes, we note several limitations of our analysis. First, our passive, computational assessment of editors' political alignments, on which our focal polarization measure relies, is fundamentally indirect. It captures political interest through engaged editorial participation, which modestly predicts and correlates with both political party affiliation and self-described ideology. A direct measure of political ideology or one containing a greater signal of ideology and/or affiliation, however, would tighten our inferences linking polarization to productive collaboration.

Second, although we have controlled statistically for many factors known to influence article quality in our models, confounding factors that we did not consider may remain. For example, most contentious articles have been protected at some point and can only be edited by administrators or senior editors while protected. It is possible that the effect of polarization that we observed is driven by this protection mechanism. We ruled out this possibility by controlling for protection status in our models (see Supplementary Discussion 2 for details), but it is beyond our capacity to exhaust all possible factors. We anticipate this to be an important area for future research.

Third, the observational nature of this study places constraints on interpreting the relationship between ideological polarization and quality as causal. We observed only the behaviour of those editors who voluntarily cooperated with others of contrary politics to produce articles of higher quality, or those who avoided such collaborations and produced lower-quality articles. It is possible that these are different kinds of people, and so we cannot rule out the possibility that randomly assigned ideologically polarized teams may not outperform more homogeneous ones. Causal identification of this relationship between Wikipedia's design and productive collaboration will demand laboratory and field experiments that enable both randomization and control. Nevertheless, concerns of extreme self-selection on Wikipedia are allayed by its 'encyclopaedic monopoly'. As the fifth most visited website in the world with more than 5 million articles on a wide range of topics, Wikipedia represents an effective monopoly of reference attention. Efforts have been made to produce politically skewed alternatives[42], but no viable substitutes exist. More importantly, Wikipedia contains only a single version of an article for a given topic. Consequently, if someone wishes to influence public knowledge on topics such as 'Climate change' or 'Free market' through Wikipedia, they must collaborate with existing editors who hold differing views but equal motivation. This is particularly salient for articles on contested topics, and frames a dramatic contrast with segregated echo chambers in the blogosphere. Previous research on Wikipedia also suggests that cross-party collaboration is the norm rather than the exception[43].

Ideologically diverse collaborations are not without costs. One major obstacle to creating well-functioning, diverse teams is that such teams produce outputs that may appear worse to the team members themselves[44]. Membership in homogeneous teams also feels better as participation affirms prior beliefs[45] and shelters contributors from aggressive interaction. Respondents to our survey echoed this sentiment by reporting pervasive displeasure in having to convince obstinate, competing partisans of points that they took to be self-evident. However, balanced competition softened the emotional edge of ideological conflict by allowing members to police tone and content with the omnipresent policies and norms of Wikipedia[46]. Use of these named/acronymed norms and policies was woven into the practice of Wikipedia conversation, signalled membership in the overarching Wikipedia project and probably helped compensate for a reduced vocabulary of norm enforcement available in online, as opposed to face-to-face, interaction[47]. Unlike many online settings, when norms and policies break down, powerful moderators may step in and revert edits, lock pages and execute bans, but it is the success and not the failure of Wikipedia norms that predicts quality. Excluding the crowd by restricting pages to senior editor contributions had a strong negative association with content quality (see Supplementary Discussion 2 for details).

Previous research suggests that very high levels of diversity in teams may deteriorate the quality of teamwork. To explore whether political diversity has an upper bound beyond which polarization hampers performance, we re-estimated the regression models of quality with a quadratic polarization term. A negative coefficient on the quadratic polarization term would suggest that very high polarization degrades article quality. We find that the coefficient is indeed negative ($\beta = -12.66$; $t(223,151) = -11.64$; $P < 0.001$; in a two-sided t-test). Nevertheless, the polarization level at which the association between polarization and quality becomes negative is very high, and is not realized by 95% of the teams in this study. Furthermore, a regression of quality on polarization estimated on only the 5% most polarized teams shows no statistically significant pattern between polarization and quality ($\beta = 0.12$; $t(11,152) = 0.23$; $P = 0.81$; in a two-sided t-test). Overall, we do not find evidence that very high levels of political polarization hamper Wikipedia performance.

This study raises the possibility that, in crowd-sourcing contested knowledge, the most motivated contributors are those with a biased perspective—an idiosyncratic take or angle on the disagreement at hand. Conducting debates on platforms such as Wikipedia can demand high levels of motivation and patience. For example, the top editor of Hillary Clinton's Wikipedia page estimated spending 15 hours per week on protecting it from vandals[48]. Neutral users lacking partisan motivation may choose to allocate their time elsewhere. It is plausible that for voluntary crowd-sourcing platforms there exists an optimal, non-zero amount of user bias. Platforms that discourage all user bias may be inefficient or unsustainable.

To the extent that ideological diversity can improve the quality of politically relevant crowd-sourced knowledge, it is important to consider whether platforms should intervene to promote or even impose such diversity where it is missing. Our work suggests that for contested knowledge, platforms should seek not only high numbers of experts but those with balanced, diverse perspectives to construct an environment through which motivated conflicts can be disciplined by enforceable policies and guidelines. Just as institutional designs to promote gender diversity have proved valuable for fairness and performance in a variety of domains[49–51], designing for political diversity may become an increasingly important priority. Our study suggests that designing for political diversity may allow the digital age to grapple with John Stuart Mill's admonition that "not the violent conflict between parts of the truth, but the quiet suppression of half of it, is the formidable evil; there is always hope when people are forced to listen to both sides…"[29].

Methods

Overview. Using edit histories, we measured the online political preferences—ideological alignment—of 605,359 Wikipedia editors by the relative quantity of content they contributed to conservative versus liberal political articles. In addition, two surveys were conducted with $n = 500$ and $n = 327$ random samples of Wikipedia editors for whom we had calculated the index. We then used a machine learning algorithm developed by Wikimedia's internal researchers to measure the quality of Wikipedia articles[52] and related article quality to the political diversity of teams. Finally, we sought insight regarding mechanisms of collaboration among polarized teams by computationally exploring characteristics of article talk pages where the work of editing, debate and persuasion occurs.

Data collection. We extracted data from a complete English Wikipedia database dump on 1 December 2016. The data include all edits made to all English Wikipedia articles since its start until 1 December 2016. Within this dump, we focused on three sets of articles: politics (20,947 articles), social issues (162,085 articles) and science (49,530 articles), which represent approximately 5% of all English Wikipedia articles. Summary statistics of the three corpora may be found in Supplementary Table 1. Users' total numbers of edits ever made to Wikipedia were collected through Wikipedia's online application programming interface (http://en.wikipedia.org/w/api.php).

The corpus of political articles consists of two sub-corpora, liberal and conservative articles. The liberal sub-corpus consists of all articles categorized under the 'Liberalism in the United States' category[53] and its subcategories. For instance, the article *New Deal coalition* is directly under the root category, while *The New Republic* is located under the subcategory 'Liberalism in the United States > Modern liberal American magazines'. The conservative sub-corpus was collected in a similar fashion starting with the 'Conservatism in the United States' category[54]. For instance, *Conservatism in the United States* links to *Economic liberalism*, which links to *Market economy*, and all three articles are in the conservative subcorpus. A total of 406 articles (approximately 4%) appear in both corpora and were removed.

The titles of social issues articles were collected starting from the page 'Category:Social issues'[55]. We collected all the articles and subcategories linked to from the page, repeating this process in every subcategory of social issues and stopping four levels down from the root. Social issues include articles relating to human welfare and justice, including *Homelessness*, *Teenage pregnancy* and *Social services*. These articles tend to be relatively controversial and politically salient. Titles of science articles were collected similarly, following the category structure of scientific disciplines in Wikipedia, starting from the page 'Category:Scientific disciplines'[56] and following the iterative procedure pursued for social issues articles.

Measurement of article quality. We measured the quality of Wikipedia articles algorithmically using a prominent approach that draws on features derived from article content alone, and not information about editors or their collaboration patterns[57]. Wikipedia editors have scored hundreds of articles on quality, but human-generated ratings for most of Wikipedia's millions of articles do not exist and necessitate an algorithmic approach. In particular, we used the `wikiclass` algorithm, developed by Wikimedia research staff[52] and trained on Wikipedia articles scored by active editors for quality using a six-class scale, which ranges from Featured Article (highest quality) to Stub (lowest quality). The `wikiclass` algorithm predicts the correct quality class in 62.9% of cases and is off by at most one quality class in 90.7% of cases[52].

Measurement of ideological preferences. We measure editors' online ideological preferences or alignments by the fraction of bytes they choose to contribute to conservative (red) versus liberal (blue) articles on the English-language Wikipedia, with a Bayesian framework to account for limited or random edits. The corpus of conservative articles consists of all articles categorized under 'Conservatism in the United States', and similarly for 'Liberalism in the United States'. (See Data collection above.) This procedure scores editors as ideologically neutral (~0) if they contribute equally to both sets of articles or little to either set, and closer to −1 or +1 the more exclusively they contribute to liberal or conservative articles, respectively.

Specifically, we model the total bytes an editor contributed to red articles (X) as a random variable satisfying a binomial distribution $X \approx \text{binomial}(K, p)$, where K is the total number of bytes contributed to political articles (red or blue) and p is the probability of contributing to red articles. This probability p represents our measure of ideological alignment for the editor, after rescaling it to the range −1 (most liberal) to +1 (most conservative). The parameter p is an unknown quantity to be estimated from observations X and K. We estimated it through a conservative, Bayesian framework described in Supplementary Methods 1.

The quantity of primary interest is the variance of alignments among a group of editors, which quantifies the spread of editors across the liberal−conservative spectrum. We used the variance in ideological alignments as a measure of polarization for any group of editors editing the same Wikipedia page. Previous research has found that this measure most directly captures the polarization of a group along a continuous cognitive dimension[58].

Surveys of editors. To assess the extent to which our measure of online ideological preferences corresponds to individuals' offline preferences and self-identities,

we conducted two surveys on $n = 500$ and $n = 327$ random samples from the set of editors for whom we had estimated alignment scores. The first survey focused on political party affiliation, while the second focused on ideological self-identity. Both surveys allow us to explore the mechanisms of collaborations within polarized groups by asking editors about relevant editing experiences. We worked directly with the Wikipedia community and Wikimedia staff to carry out the surveys, including the development of a research page on the Wikimedia Meta-Wiki site and direct engagement with those expressing concerns therein[59]. The arrived-on process required a single member of our team (E.D.) to personally post the survey link on each of the randomly selected editors' pages along with an explanation. The number of solicitations we could make per day (and the total number) was capped. In the end, we posted 500 solicitations in November 2017 for the first survey and received 118 responses. For the second survey, we posted 327 solicitations in April 2018 and received 100 responses. We did not record any demographic data on our respondents beyond whether their residence was inside or outside of the United States. Participants were shown a consent script prior to any questions. All questions on the survey were optional. The surveys' methods were approved by the University of Chicago's Institutional Review Board (IRB17-0679). More information may be found in Supplementary Discussion 1.

Code availability

Code used to gather, process and analyse the data is available at https://github.com/KnowledgeLab/wisdom-of-polarized-crowds.

Data availability

Data used in the study are available at https://github.com/KnowledgeLab/wisdom-of-polarized-crowds.

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Acknowledgements

Author contributions

All authors designed the research, interpreted the results and drafted the paper. F.S., M.T. and E.D. gathered the data. F.S. designed the code and F.S. and M.T. analysed the data.

Competing interests

The authors declare no competing interests.

Additional information

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Corresponding author(s):	James A. Evans
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Software and code

Policy information about availability of computer code

Data collection	The main data set consists of the 2016-12-01 Wikipedia database dump publicly provided by Wikimedia (https://dumps.wikimedia.org/backup-index.html. Accessed 2017-12-15). We used a publicly available database of word embeddings called fastText (https://fasttext.cc/docs/en/pretrained-vectors.html. Accessed 2017-07-01). Survey data was collected using Google Forms (Survey 1) and Qualtrics (Survey 2).
Data analysis	Analysis was conducted using Python 3.6 and R3.5. Natural language processing was done primarily using the Python package "NLTK" Version 3.4. Structural equation modeling was performed using R package "lavaan" 0.6-3. Article quality was assessed with Python package wikiclass.

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The study consists primarily of a quantitative analysis of observational, publicly available data from Wikipedia. A small survey was conducted with Wikipedia users to validate quantitative measures.
Research sample	The editing activity on Wikipedia is recorded using users' usernames or, for unregistered users, their IP addresses.
Sampling strategy	The bulk of the analysis used observational data. For the survey of editors, we created random samples of n=500 from the set of editors for whom we had calculated ideological alignment scores (those editing at least one page in our Politics corpus). For the first survey, a survey link was posted to the public user page for each of the 500 individuals; for the second survey, only n=327 such links were posted, due to the labor-intensity of the posting procedure.
Data collection	*Provide details about the data collection procedure, including the instruments or devices used to record the data (e.g. pen and paper, computer, eye tracker, video or audio equipment) whether anyone was present besides the participant(s) and the researcher, and whether the researcher was blind to experimental condition and/or the study hypothesis during data collection.*
Timing	The observational data came from the 2016-12-01 Wikipedia database dump. The surveys were conducted in November 2017 and April 2018.
Data exclusions	Unregistered users (whose usernames are IP addresses) were excluded from the observational dataset, because IP addresses are not reliable as identity. Survey responses from respondents who reported living outside of the USA were dropped, as the political culture we focus on is USA-specific.
Non-participation	n/a
Randomization	n/a

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Policy information about studies involving human research participants

Population characteristics	Demographic characteristics of Wikipedia users are not available in the observational data. Regarding the surveys, we did not collect demographic characteristics beyond location (see above)
Recruitment	Observational data included the entirety of Wikipedia editors. Regarding surveys, see above.
Ethics oversight	University of Chicago's Institutional Review Board (IRB17-0679)

Note that full information on the approval of the study protocol must also be provided in the manuscript.