Academic Authorship and STEM Diversity

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3 attachments (1 MB)

What can be done to resolve academic authorship disputes, THE 2020.pdf; The increasing dominance of teams in the production of knowledge, Science 2007.pdf; ATT00001.txt;

Dear Colleagues,

In late January, I attended three events that had a large impact on me – UArizona/National Academies of Sciences, Engineering & Medicine Townhall on Advancing STEM Equity at Minority Serving Institutions, Women in Science and Engineering Excellence Banquet, and the Norton School's opening reception for the *Work x Family* exhibit. I was impressed, enthralled and also appalled by things I heard at each event.

I want to share with you the attached *Times Higher Education* article. Clearly there are discipline differences in publishing mores, but our society expects minimum standards of equity and fairness as well as compliance with equality laws. The article resonated with me as I have experienced an incident like those described. When at another institution, I observed a senior administrator's poor handling of a scientific integrity issue stemming from intellectual contribution and authorship. I believe senior and experienced people with the power of position and experience owe a duty of care to the less empowered.

For most papers in my CV, first and/or senior authors are marked as joint. "Rules of engagement" were clear from the start. However, my CV also has papers during my PhD work that did not recognize my contribution as I chose to recognize people as a PI. My CV also doesn't have papers that should be there, as the article describes. I also have seen practices in colleagues that I believe do not meet the standards of equity, fairness and inclusion our society expects today, let alone our own moral and ethical compasses.

Also attached: what I consider a seminal paper – why teams in science are good for us and the society funding our work.

I believe our enterprise leads the university in STEM diversity. We're the most connected to the Nations, with the greatest connection to all parts of the state, and we can improve. Our diversity obliges us to set the standard as leaders in STEM equity, fairness and inclusion. I encourage everyone leading research to have a discussion with their team about the authorship issue. For some it may be short. I ask CALS unit heads and Cooperative Extension county directors to proactively ensure equity, fairness and inclusion in publications.

Please contact Parker Antin, Kirsten Limesand, Jeff Silvertooth, Jeannie McLain or me if you feel you may not be being, or have not been, treated appropriately.

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Regards,
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The University of Arizona is located statewide on the ancestral homelands of indigenous peoples.

What can be done to resolve academic authorship disputes?

With careers riding on young scientists' position in author lists, friction is all too common. A snowballing initiative to list authors' contributions aims to make sure credit is always given where it is due. But will it be enough to ease the angst? Jack Grove is first author

January 30, 2020

By Jack Grove (/content/jack-grove-0)

Twitter: @jgro_the (https://twitter.com/jgro_the)

"I knew something strange was happening when my colleagues stopped responding to my emails," says Sarah, recalling the moment she suspected something unusual was happening with a forthcoming journal paper.

"I'd spent a couple of weeks doing mathematical modelling work for the theoretical paper we were writing and, while I wasn't the main contributor to the paper, I established some conditions for the project and helped to make sense of the results," the physicist explains. Sarah (not her real name) soon learned, however, that her fellow authors had removed her name from the paper without informing her – a move, she believes, that was linked to her decision to leave her postdoctoral position a few months earlier. "I was now in a faraway country – without an academic job and having a tough time personally – so they thought they could get away with it," she says.

Source: Getty

Happily, Sarah was eventually able to convince her collaborators of the value of her contributions, even if she was listed as having made the smallest contribution. "Having my name on the paper was important because it recognised what I'd done," she reflects.

READ MORE
Scientists quit Nobel-winning project over authorship dispute (/news/scientists-quit-nobel-winning-project-over-authorship-dispute)

Nevertheless, her case is illustrative of the very fraught, distinctly unscientific process by which the authorship of academic papers is determined. Some disciplines – particularly those involving large teams, such as high-energy physics – simply list authors in alphabetical order, but a 2012 analysis (https://arxiv.org/ftp/arxiv/papers/1206/1206.4863.pdf) by Ludo Waltman, professor of quantitative science at Leiden University (https://www.timeshighereducation.com/world-university-rankings/leiden-university), suggests that this practice is in decline and accounted for less than 4 per cent of all papers published in 2011.

The vast majority of disciplines instead list authors in order of the perceived significance of their contribution to the published work. And an early career researcher's position in that order is particularly crucial given that, in an era of intense competition for permanent academic positions, landing first- or even second-author status on a highly rated paper can make the difference between staying in academia or not. The era when young scientists might amicably settle authorship order with a series of croquet matches on the lawns at Imperial College London (https://www.timeshighereducation.com/world-university-rankings/imperial-college-london) – as British ecologists Michael Hassell and Robert May did (https://twitter.com/VolkerNehring/status/917384523599568901) in 1973 – seems a long way off.

Even with the best will in the world, it has never been easy to compare the relative values of intellectual and practical contributions to papers. Is coming up with the idea for the key experiment more worthy of recognition than carrying out the bulk of the experiments, for instance? What about the contribution of someone who did a lot of experiments, most of which threw up negative results through no fault of their own, compared with that of someone who did much less experimental work but got lucky with their results? And with research increasingly being carried out by large, interdisciplinary teams, sometimes involving multiple principal investigators, the judgements involved in determining authorship order have only become harder, even disregarding the inter-lab power struggles that inevitably come into play in these cases.

A further consideration for early career researchers is whether it is worth disputing authorship at all, given the risk of creating enemies of those with the power to make or break careers. One PhD student – who also wishes to remain anonymous – tells *Times Higher Education* that she was removed as first author from a paper she had written while interning at a research institution. She submitted the paper to the journal, but was told by her supervisor that since she “wouldn't be able to answer the reviewers' comments when the time came”, she was being demoted to a lower authorship position.

“I am starting out in my career, so I didn't start a formal dispute…because my research space is a very small one,” she explains. “I now keep a paper trail and never send any documents out without my name on them in case it happens again.”

Sarah, too, is worried that speaking about her experience could attract criticism from her former collaborators, including her former mentor (hence her request for *THE* not to use her real name). However, she had no choice but to risk a falling-out with them to retrieve her credit for her postdoctoral work.

“My PhD supervisor had refused to help me publish, so my profile was not looking very attractive to academia,” she explains. But letting the situation lie was not an option given the sacrifices she had made to gain her postdoc position and the chance to publish: “I have moved around the world, said goodbye to friends and relationships and worked long hours, including New Year’s Day. Research does literally become your life. You are also told that you’re worthless unless you publish.”

Fighting your corner on authorship is essential, agrees Philip Moriarty, professor of physics at the University of Nottingham (https://www.timeshighereducation.com/world-university-rankings/university-nottingham), given the need for solid publications when applying for academic jobs.

“What once might have been considered a little bit of a squabble between academics can now be career-defining,” says Moriarty, reflecting that the CV that won him a lectureship in condensed matter physics at Nottingham in 1997 would “not get me within sniffing distance of a shortlist today”.

But Moriarty also agrees on the need for early career researchers to be cautious when challenging their position in the authorship order of a paper. The PI overseeing the paper as senior author (typically listed last in the author order) “will be writing you references for years and you are going up against their judgement”, he notes, adding that the outcome of any such appeal will “depend on the personality of the supervisor, your relationship with them and whether you can raise issues like this without them going ballistic”.

Such disputes typically arise within the context of a wider breakdown in the relationship between early career researchers and their supervisors, Moriarty adds, so approaching a trusted third party to intervene can help. However, he notes that even this approach is not risk-free: “At a PhD supervision conference, this suggestion was raised and one participant was adamant that you should ‘keep your head down’ as you would never get anywhere if you irritated your supervisor.”

Nevertheless, when the stakes are high, passions run high too, and pragmatism can take a back seat.

“You do see papers being retracted (https://twitter.com/VolkerNehring/status/917384523599568901) over authorship order, where people would rather see the work leave the scientific literature altogether than concede the argument,” notes Matt Hodgkinson, who oversees publishing ethics for Hindawi, an open-access publisher that runs about 230 peer-reviewed journals. “Someone who has been left off the authorship list might choose to let it lie for a while, but then thinks better of it and contacts the journal. When several PhDs or postdocs are on a paper, we also see more than one claiming first authorship," adds Hodgkinson, noting that settling scientific contributions to a paper is "often mixed up with lab politics".

One dispute involving a Hindawi title ran for almost four years after a Turkish medic argued, ultimately successfully, that he deserved to be listed on a paper published in *Case Reports in Emergency Medicine* in August 2015. It was settled by a ruling (https://retractionwatch.com/2019/07/16/no-delight-for-turkish-surgeon-in-authorship-dispute-over-case-study/%20)from Turkey's intellectual property rights court, amid unsubstantiated claims that the author's omission had been motivated by religious and political considerations. "Without doing a raid on the lab, it was not really possible for us to say who had done what, so it went to the institution and then to the court," says Hodgkinson. The journal published an expression of concern over the paper in July 2019 highlighting the court's decision.

"It's rare that we see court cases about articles submitted to us, but the significant ones we've seen relate to authorship," Hodgkinson says. And, more generally, bust-ups over authorship are becoming a growing headache for publishers, with a quarter of anonymised case reviews listed by the Council on Publication Ethics relating to such disputes, according to Hodgkinson. This month, a Wellcome Trust report (https://www.timeshighereducation.com/news/half-researchers-seek-or-desire-counselling-says-wellcome-trust-poll%20), based on a poll of 4,065 respondents, found that 40 per cent of researchers had experienced issues with others taking credit for their work, with those on short or fixed-term contracts feeling "particularly vulnerable" to this kind of exploitation by senior colleagues.

That tallies with similar studies, which indicate that between a third and two-thirds of researchers report having been involved in an authorship dispute, according to a 2018 paper by Zen Faulkes, professor of biology at the University of Texas Rio Grande Valley (https://www.timeshighereducation.com/world-university-rankings/university-texas-rio-grande-valley-0), published (https://researchintegrityjournal.biomedcentral.com/articles/10.1186/s41073-018-0057-z) in the journal *Research Integrity and Peer Review*.

At present, the best-known template for deciding authorial credit is the so-called Vancouver Convention (http://www.icmje.org/icmje-recommendations.pdf), created by the International Council of Medical Journal Editors in 1978 and revised most recently in 2014. But these rules are largely unhelpful in resolving disputes, Faulkes believes, because they were "created from the top down, so they don't have buy-in from most scientists". Moreover, too many medical journal editors "don't seem to enforce their own guidelines", he adds.

In Faulkes' view, the current level of disharmony suggests that a new model of credit allocation is needed. One solution that is proving popular is to give joint first authorship to numerous collaborators. This phenomenon was seen in just 1 per cent of publications in 2000, but that had risen to 8.6 per cent in 2009, according to a study (https://elifesciences.org/articles/36399) by Nichole Broderick and Arturo Casadevall published in January 2019.

By 2019, the majority of papers published in some journals used joint first authorship – with 11 joint first authors listed in two papers, according to the paper, "Meta-research: gender inequalities among authors who contributed equally", published in *eLife.* Of the 28 papers published in the first three issues of the *Journal of Clinical Investigation* in 2019, for instance, 12 listed three or more authors as co-first authors, while one paper listed nine.

However, not everyone is convinced by the merits of this approach. Some view it as an unethical cop-out, via which some demonstrably lesser contributions can receive undue credit. Moreover, female scientists are more likely to be listed second to male co-authors even in cases of apparently equal contributions, Broderick and Casadevall found (https://retractionwatch.com/2019/05/16/sharing-the-coin-of-the-realm-how-one-journal-hopes-new-authorship-rules-will-cut-down-on-bias/).

Indeed, "even when there is joint first authorship, it seems the person who is credited first benefits the most as this is still the currency used by science", observes Hindawi's Hodgkinson. Hence, since joint first authors are likely to be listed in alphabetical order, those with surnames beginning with letters near the beginning of the alphabet are likely to benefit most; previous studies (https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2803164) of alphabetical ordering have revealed that researchers with surnames beginning with letters later in the alphabet are aware of the phenomenon and react by collaborating less. Worse, there is evidence (https://www.liebertpub.com/doi/10.1089/elj.2013.0226) that such “alphabetism” disadvantages certain ethnic groups, such as East Asians, more than others.

For his part, Faulkes advocates “a credit system like movies and television, where contributions are listed by the tasks performed”. For him, a list of authors with no further indication of what they actually did is next to useless.

“If the new *Star Wars* movie was a scientific paper, you'd see [lead actor] Daisy Ridley, [director] J. J. Abrams, [music composer] John Williams, and [set designer] Rosemary Brandenburg all mixed together in a list, with no indication of what each did: it would be absurd,” he believes.

Faulkes is pessimistic about the prospects of a movie-style credit system catching on, given “how slowly innovations in scientific publishing are adopted”. However, substantial movements in that direction are already happening. Some journals explicitly list what each author’s contribution to the paper was. And these include many journals published by Elsevier, the world’s largest science, technology, engineering and mathematics publisher.

The journals have adopted the “Contributor Roles Taxonomy (https://casrai.org/credit/)” (CRediT) system, which requires lead authors to provide an accurate summary of each author’s contribution to 14 distinct areas deemed relevant to authorship: conceptualisation, data curation, formal analysis; funding acquisition; investigation; devising methodology; project administration; contribution of resources; development of software; supervision; validation; visualisation; writing; and reviewing and editing.

The initiative originates from a 2012 workshop of researchers, publishers and others led by Harvard University (https://www.timeshighereducation.com/world-university-rankings/harvard-university) and the Wellcome Trust, and has been piloted in 150 Elsevier journals. The reception from both authors and editors was “very positive”, according to a December press release (https://www.elsevier.com/about/press-releases/corporate/elsevier-expands-credit-approach-to-authorship#https%3A%2F%2Fwww.elsevier.com%3A443) announcing the expansion of the scheme to 1,200 of Elsevier’s 2,500 journals, with “hundreds” more to be added to the list through 2020.

According to the website (https://casrai.org/credit/) of the Consortia Advancing Standards in Research Administration Information (CASRAI), which facilitated the workshop, a total of 30 publishers have so far adopted the system, including Springer, Wiley and Oxford University Press, although not all mandate it.

However, authors in this system continue to be listed in order of perceived contribution. Hence, even if such innovations were universally adopted, it seems unlikely that disputes over that order will disappear. So how *should* the different contributions to papers be weighed? Most crucially, how should inspiration be weighed against perspiration?

For Faulkes, “ideas are cheap in this business, so I tend to put more value on data collection and execution”. Others, however, are wary of establishing the notion that long hours spent on a project should immediately entitle someone to an authorial credit, let alone a substantial one.

“I have a bunch of students working with me all the time, but doing data entry or scanning does not qualify [them] for authorship,” explains Michael E. Smith, director of Arizona State University (https://www.timeshighereducation.com/world-university-rankings/arizona-state-university)’s Teotihuacan Research Laboratory, whose archaeological projects focus on the Aztec civilisations of Mexico and central America.

Smith regrets being too generous in extending authorial credits to minor players on projects earlier in his career – an act that devalued the bona-fide credits won by other co-authors, he now feels. “It made me feel good at the time to include people, but I’m not so sure I was right to do this. It’s a question of drawing the line somewhere,” he reflects, pointing out that the hired hands used on digs in Mexico could be considered co-authors if their number of hours worked was considered a key consideration. On the other hand, “when a student makes a genuine creative contribution or finds something I could not have come up with, this should be recognised”.

Deciding who should be listed as first author is a particularly “big responsibility”, according to Lynn Kamerlin, professor of structural biology at Uppsala University (https://www.timeshighereducation.com/world-university-rankings/uppsala-university) in Sweden, and it is often far from straightforward. Particularly difficult to call are situations in which a project’s initiator has moved on before it is complete, leaving others to complete the work, she suggests.

For Faulkes, the “amount of work done on a project [should weigh] more heavily than a sense of ownership because ‘I started a project’. The latter is mainly ego talking”. Kamerlin agrees with that principle, but she still finds it hard to adjudicate between competing claims in certain cases.

“If someone has left but done the majority of the work, it is easier to make a call, but I’ve also had the opposite,” she says. “You can have someone whose successor finds serious problems with the things that the project’s initiator has done, requiring repeat experiments and a lot of work, so the new person should obviously be first author. This wasn’t very popular with the person who had left, but passions also ran high with the individual who ultimately became first author.”

Kamerlin is also in favour of more detailed descriptions of what co-authors have done, but dismisses the idea that it is a silver bullet to solve disputes. “It’s very much based on the idea of five to 10 people in a laboratory working on a paper, when today’s research sometimes involves hundreds of researchers,” she says, suggesting that, in such cases, “primary authors who drove the work” should instead be listed ahead of less significant collaborators.

As for movie-style credits, this “assumes everyone is telling the truth” about their contributions, Kamerlin adds. “And people sometimes have some very strange ideas about what constitutes authorship – with some thinking a comment here or there is enough.”

That issue is particularly pertinent when it comes to senior scientists who insert themselves as authors on papers to which they had little to no input. This practice allows some leaders of large teams to publish hundreds (https://www.timeshighereducation.com/news/restrict-researchers-one-paper-ayear-says-ucl-professor) of papers every year, leading to stellar research metrics and the career rewards that come with them. However, if errors or wrongdoing are exposed later on, they typically escape blame by citing their lack of involvement in the hands-on experiments undertaken by junior researchers.

For his part, Moriarty thinks it is “very unethical to put your name to a paper just because you are the group leader”, and he wonders how the world’s most prolific scientists find time even to read their output, let alone oversee, revise and submit it to journals.

“If they are working 80 to 100 hours a week in the lab, there might be some justification”, Moriarty concedes, but, in practice, he believes that such a prolific output is only possible in labs where “postdocs are supervising PhD students on a day-to-day basis, and that is where the intellectual heft is really coming from”. But, in such cases, it is the postdocs who should be the senior authors, he believes.

Kamerlin is likewise sceptical of the tendency for principal investigators to be listed by default as the last author – usually justified by the fact that they “provided the infrastructure” for the research to take place. “It is really unfair on younger people doing the research,” says Kamerlin.

As for the theory that including more well known scientists helps a paper to get noticed by editors and readers, she says the consequence is that the junior researchers who actually did the work can be overlooked by funders or hiring panels. “I recently heard about a supervisor who asked to be removed from a PhD student’s paper for this reason, which was a classy move,” she adds.

However, Faulkes is less convinced that senior scientists are gaining unwarranted authorship credit. Many PIs quietly do a significant amount of unseen work to allow others the chance to publish, he explains. “I hear lots of cases of people saying: ‘This person did nothing!’ But I rarely hear PIs saying: ‘Yes, I did, and here's why I deserve authorship,’” he notes. But that doesn’t mean that the PIs’ case can’t be made.

“A long time ago, I submitted a paper – never published – without my supervisor's name on it, which was badly wrong of me,” he recalls. “I undervalued what my supervisor did to make the project possible, but, with the benefit of experience, I can see how much that individual deserved to be an author on the submission. As a student, I didn't know how important authorship was, and didn't realise the implications of someone’s not being on that title page.”

One important reason that disputes arise is that colleagues rarely have frank discussions about their expectations regarding the authorship of future papers arising out of the projects they are working on, leaving everyone on tenterhooks until the very last minute. But with technological innovations such as pre-print servers shrinking the time between submission and publication, the time and space for disputes to be ironed out post-submission is also being squeezed.

Yet the lack of agreement over how contributions should be assessed and ranked arguably remains the biggest source of conflict. And, unlike the Writers Guild of America, which has established rules (https://www.wga.org/uploadedfiles/credits/manuals/screenscredits_manual18.pdf) over what merits “substantial” credit in film and television work, there is no final arbiter for authorship disputes in science. In the absence of that, the best hope is for colleagues to engage in earlier, more honest conversations about authorship, Faulkes believes.

“I made my mistake because authorship is part of the ‘hidden curriculum’,” he says. “I doubt many people get explicit training on authorship conventions until they are in the advanced stages of graduate school or are about to submit a paper.”

Yet conventions are one thing and interpretation of them is quite another. Academics are only human, and with whole careers and identities hanging on publication success, is it hard to imagine any set of rules so watertight that their application to particular cases could never be disputed. As with many of the disputes and foul play associated with academic publishing, reducing that pressure may be the only way to get back from blood on the carpet to chats on the croquet lawn.

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POSTSCRIPT:

Print headline: *Order, order*

The Increasing Dominance of Teams in Production of Knowledge

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The Increasing Dominance of Teams in Production of Knowledge

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Figs. S1 to S3
References

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The Increasing Dominance of Teams in Production of Knowledge

Stefan Wuchty,[1]* Benjamin F. Jones,[2]* Brian Uzzi[1,2]*†

We have used 19.9 million papers over 5 decades and 2.1 million patents to demonstrate that teams increasingly dominate solo authors in the production of knowledge. Research is increasingly done in teams across nearly all fields. Teams typically produce more frequently cited research than individuals do, and this advantage has been increasing over time. Teams now also produce the exceptionally high-impact research, even where that distinction was once the domain of solo authors. These results are detailed for sciences and engineering, social sciences, arts and humanities, and patents, suggesting that the process of knowledge creation has fundamentally changed.

An acclaimed tradition in the history and sociology of science emphasizes the role of the individual genius in scientific discovery (*1*, *2*). This tradition focuses on guiding contributions of solitary authors, such as Newton and Einstein, and can be seen broadly in the tendency to equate great ideas with particular names, such as the Heisenberg uncertainty principle, Euclidean geometry, Nash equilibrium, and Kantian ethics. The role of individual contributions is also celebrated through science's award-granting institutions, like the Nobel Prize Foundation (*3*).

Several studies, however, have explored an apparent shift in science from this individual-based model of scientific advance to a teamwork model. Building on classic work by Zuckerman and Merton, many authors have established a rising propensity for teamwork in samples of research fields, with some studies going back a century (*4*–*7*). For example, de Solla Price examined the change in team size in chemistry from 1910 to 1960, forecasting that in 1980 zero percent of the papers would be written by solo authors (*8*). Recently, Adams *et al.* established that over time, teamwork had increased across broader sets of fields among elite U.S. research universities (*9*). Nevertheless, the breadth and depth of this projected shift in manpower remains indefinite, particularly in fields where the size of experiments and capital investments remain small, raising the question as to whether the projected growth in teams is universal or cloistered in specialized fields.

A shift toward teams also raises new questions of whether teams produce better science. Teams may bring greater collective knowledge and effort, but they are known to experience social network and coordination losses that make them underperform individuals even in highly complex tasks (*10*–*12*), as F. Scott Fitzgerald concisely observed when he stated that "no grand idea was ever born in a conference" (*13*). From this viewpoint, a shift to teamwork may be a costly phenomenon or one that promotes low-impact science, whereas the highest-impact ideas remain the domain of great minds working alone.

We studied 19.9 million research articles in the Institute for Scientific Information (ISI) Web of Science database and an additional 2.1 million patent records. The Web of Science data covers research publications in science and engineering since 1955, social sciences since 1956, and arts and humanities since 1975. The patent data cover all U.S. registered patents since 1975 (*14*). A team was defined as having more than one listed author (publications) or inventor (patents). Following the ISI classification system, the universe of scientific publications is divided into three main branches and their constituent subfields: science and engineering (with 171 subfields), social sciences (with 54 subfields), and arts and humanities (with 27 subfields). The universe of U.S. patents was treated as a separate category (with 36 subfields). See the Supporting Online Material (SOM) text for details on these classifications.

For science and engineering, social sciences, and patents, there has been a substantial shift toward collective research. In the sciences, team size has grown steadily each year and nearly

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Table 1. Patterns by subfield. For the three broad ISI categories and for patents, we counted the number (*N*) and percentage (%) of subfields that show (i) larger team sizes in the last 5 years compared to the first 5 years and (ii) RTI measures larger than 1 in the last 5 years. We show RTI measures both with and without self-citations removed in calculating the citations received. Dash entries indicate data not applicable.

		Increasing team size		RTI > 1 (with self-citations)		RTI > 1 (no self-citations)	
	N_{fields}	N_{fields}	%	N_{fields}	%	N_{fields}	%
Science and engineering	171	170	99.4	167	97.7	159	92.4
Social sciences	54	54	100.0	54	100.0	51	94.4
Arts and humanities	27	24	88.9	23	85.2	18	66.7
Patents	36	36	100.0	32	88.9	–	–

doubled, from 1.9 to 3.5 authors per paper, over 45 years.

Shifts toward teamwork in science and engineering have been suggested to follow from the increasing scale, complexity, and costs of big science. Surprisingly then, we find an equally strong trend toward teamwork in the social sciences, where these drivers are much less notable. Although social scientists in 1955 wrote 17.5% of their papers in teams, by 2000 they wrote 51.5% of their papers in teams, an increase similar to that in sciences and engineering. Mean team size has also grown each year. On average, today's social sciences papers are written in pairs, with a continuing, positive trend toward larger teams. Unlike the other areas of research, single authors still produce over 90% of the papers in the arts and humanities. Nevertheless, there is a positive trend toward teams in arts and humanities ($P < 0.001$). Lastly, patents also show a rising dominance of teams. Although these data are on a shorter time scale (1975–2000), there was a similar annualized increase in the propensity for teamwork. Average team size has risen from 1.7 to 2.3 inventors per patent, with the positive trend toward larger teams continuing.

The generality of the shift to teamwork is captured in Table 1. In sciences and engineering, 99.4% of the 171 subfields have seen increased teamwork. Meanwhile, 100% of the 54 subfields in the social sciences, 88.9% of the 27 subfields in the humanities, and 100% of the 36 subfields in patenting have seen increased teamwork.

Trends for individual fields are presented in table S1. In the sciences, areas like medicine, biology, and physics have seen at least a doubling in mean team size over the 45-year period. Surprisingly, even mathematics, long thought the domain of the loner scientist and least dependent of the hard sciences on lab scale and capital-intensive equipment, showed a marked increase in the fraction of work done in teams, from 19% to 57%, with mean team size rising from 1.22 to 1.84. In the social sciences, psychology, economics, and political science show enormous shifts toward teamwork, sometimes doubling or tripling the propensity for teamwork. With regard to average team size, psychology, the closest of the social sciences to a lab science, has the highest growth (75.1%), whereas political science has the lowest (16.6%). As reflected in Fig. 1A, the humanities show lower growth rates in the fraction of publications done in teams, yet a tendency toward increased teamwork is still observed. All areas of patents showed a positive change in both the fraction of papers done by teams and the team size, with only small variations across the areas of patenting, suggesting that the conditions favoring teamwork in patenting are largely similar across subfields.

Our measure of impact was the number of citations each paper and patent receives, which has been shown to correlate with research quality (*15–17*) and is frequently used in promotion and funding reviews (*18*). Highly cited work was defined as receiving more than the mean number of citations for a given field and year (*19*). Teams produced more highly cited work in each broad area of research and at each point in time.

To explore the relationship between teamwork and impact in more detail, we defined the relative team impact (RTI) for a given time period and field. RTI is the mean number of citations received by team-authored work divided by the mean number of citations received by solo-authored work. A RTI greater than 1 indicates that teams produce more highly cited papers than solo authors and vice versa for RTI less than 1. When RTI is equal to 1, there is no difference in citation rates for team- and solo-authored papers. In our data set, the average RTI was greater than 1 at all points in time and in all broad research areas: sciences and engineering, social sciences, humanities, and patents. In other words, there is a broad tendency for teams to produce more highly cited work than individual authors. Further, RTI is rising with time. For example, in sciences and engineering, team-authored papers received 1.7 times as many citations as solo-authored papers in 1955 but 2.1 times the citations by 2000. Similar upward trends in relative team impact appear in sciences and engineering, social science, and arts and humanities and more weakly in patents, although the trend is still upward (*20*). During the early periods, solo authors received substantially more citations on average than teams in many subfields, especially within sciences and engineering (Fig. 2E) and social sciences (Fig. 2F). By the end of the period, however, there are almost no subfields in sciences and engineering and social sciences in which solo authors typically receive more citations than teams. Table S1 details RTIs for major individual research areas, indicating that teams currently have a nearly universal impact advantage. In a minority of cases, RTIs declined with time (e.g., –34.4% in mathematics and –25.7% in education), although even here teams currently have a large advantage in citations received (e.g., 67% more average citations in mathematics and 105% in education).

The citation advantage of teams has also been increasing with time when teams of fixed size are compared with solo authors. In science and engineering, for example, papers with two authors received 1.30 times more citations than solo authors in the 1950s but 1.74 times more citations in the 1990s. In general, this pattern prevails for comparisons between teams of any fixed size versus solo authors (table S4).

A possible challenge to the validity of these observations is the presence of self-citations, given that teams have opportunities to self-cite their work more frequently than a single author. To address this, we reran the analysis with all self-citations removed from the data set (*21*). We found that removing self-citations can produce modest decreases in the RTI measure in some fields; for example, RTIs fell from 3.10 to 2.87 in medicine and 2.30 to 2.13 in biology (table S1). Thus, removing self-citations can reduce the RTI by 5 to 10%, but the relative citation advantage of teams remains essentially intact.

Because the progress of knowledge may be driven by a small number of key insights (*22*), we further test whether the most extraordinary concepts, results, and technologies are the province of solitary scientists or teams. Pooling all papers and patents within the four research areas, we calculated the frequency distribution of citations to solo-authored and team-authored work, comparing the first 5 years and last 5 years of our data. If these distributions overlap in their right-hand tails, then a solo-authored paper or patent is just as likely as a team-authored paper or patent to be extraordinarily highly cited.

Our results show that teams now dominate the top of the citation distribution in all four research domains (Fig. 3, A to D). In the early years, a solo author in science and engineering or the social sciences was more likely than a team to receive no citations, but a solo author was also more likely to garner the highest number of citations, that is, to have a paper that was singularly influential. However, by the most recent period, a team-authored paper has a higher probability of being extremely highly cited. For example, a team-authored paper in science and engineering is currently 6.3 times more likely than a solo-authored paper to receive at least 1000 citations. Lastly, in arts and humanities and in patents, individuals were never more likely than teams to produce more-influential work. These patterns also hold when self-citations are removed (fig. S5).

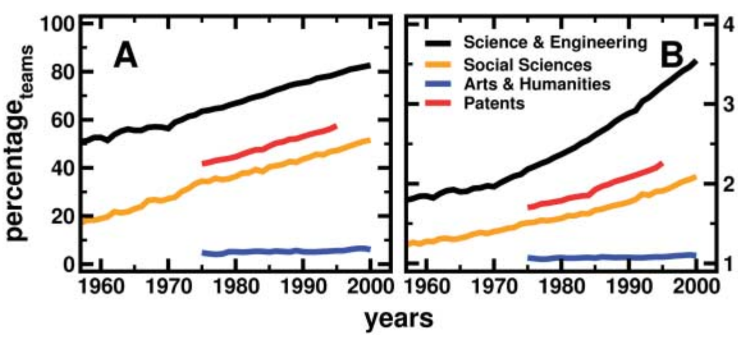

Fig. 1. The growth of teams. These plots present changes over time in the fraction of papers and patents written in teams (**A**) and in mean team size (**B**). Each line represents the arithmetic average taken over all subfields in each year.

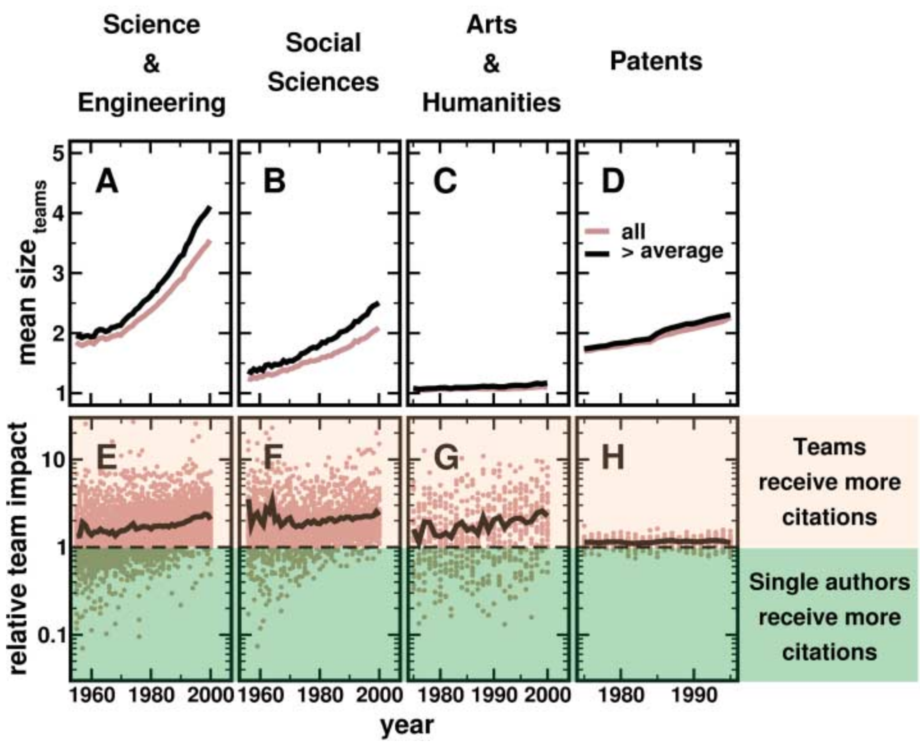

Fig. 2. The relative impact of teams. (**A** to **D**) Mean team size comparing all papers and patents with those that received more citations than average in the relevant subfield. (**E** to **H**) The RTI, which is the mean number of citations received by team-authored work divided by the mean number of citations received by solo-authored work. A ratio of 1 indicates that team- and solo-authored work have equivalent impact on average. Each point represents the RTI for a given subfield and year, whereas the black lines present the arithmetic average in a given year.

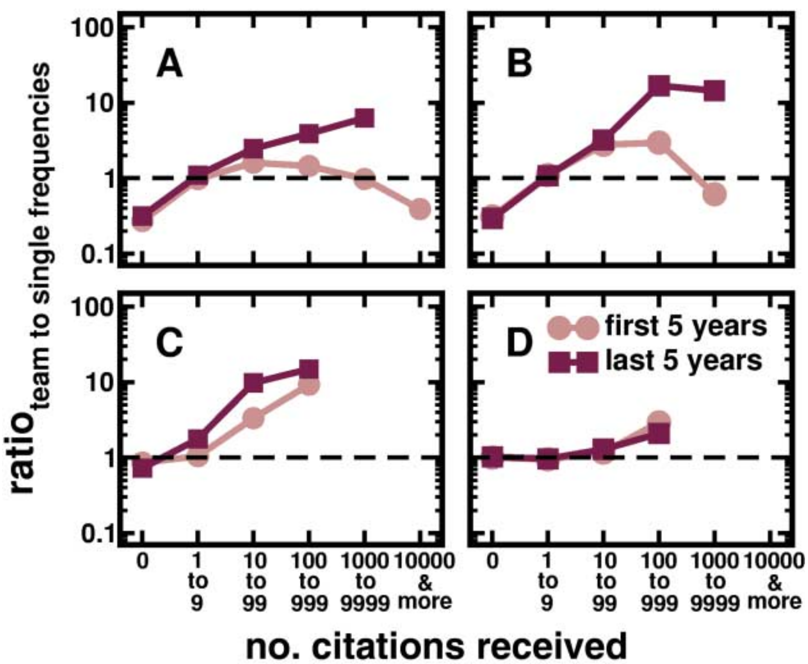

Fig. 3. Exceptional research. Pooling all publications and patents within the four research categories, we calculated frequency distributions of citations received. Separate distributions are calculated for single authors and for teams, and the ratio is plotted. A ratio greater than 1 indicates that a team-authored paper had a higher probability of producing the given range of citations than a solo-authored paper. Ratios are compared for the early period (first 5 years of available data) and late period (last 5 years of available data) for each research category, sciences and engineering (**A**), social sciences (**B**), arts and humanities (**C**), and patents (**D**).

Taken together, these results suggest two important facts about preeminent work in our observational periods. First, it never appeared to be the domain of solo authors in arts and humanities and in patents. Second, solo authors did produce the papers of singular distinction in science and engineering and social science in the 1950s, but the mantle of extraordinarily cited work has passed to teams by 2000.

Over our 5-decade sample period, the increasing capital intensity of research may have been a key force in laboratory sciences where the growth in teamwork has been intensive (*8*), but it is unlikely to explain similar patterns in mathematics, economics, and sociology, where we found that growth rates in team size have been nearly as large. Since the 1950s, the number of researchers has grown as well, which could promote finer divisions of labor and more collaboration. Similarly, steady growth in knowledge may have driven scholars toward more specialization, prompting larger and more diverse teams (*7*, *10*). However, we found that teamwork is growing nearly as fast in fields where the number of researchers has grown relatively slowly (see Supporting Online Material). Declines in communication costs could make teamwork less costly as well (*9*, *23*). Shifting authorship norms may have influenced coauthorship trends in fields with extremely large teams, such as biomedicine and high-energy physics (*24*, *25*), and yet our results hold across diverse fields in which norms for order of authorship, existence of postdoctorates, and prevalence of grant-based research differ substantially.

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19. Citations received were counted from publication year to 2006. Recent publications have smaller citation counts because they have had less time to be cited, but this effect is standardized when comparing team versus solo publications within a given year.
20. In patenting, we may observe weaker trends because (i) citing earlier work can limit a patent's scope, so that applicants may avoid citations, and (ii) patent examiners typically add the majority of citations, which makes patent citations different from paper citations (*26*, *27*).
21. A self-citation is defined as any citation where a common name exists in the authorship of both the cited and the citing papers. All citations were removed in which a citing and cited author's first initial and last name matched. This method can also eliminate citations where the authors are different people but share the same name. However, performing Monte Carlo simulations on the data, we find that such errors occur in less than 1 of every 2000 citations. Thus, any errors introduced by this method appear negligible. We did not remove self-citations from patents because citations to previous work in the patent literature are primarily assigned by the patent examiner (*27*), who independently assigns citations to earlier work based on the relevance of previous patents' content.
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SOM Text
Figs. S1 to S5
Tables S1 to S5
References

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MET Amplification Leads to Gefitinib Resistance in Lung Cancer by Activating ERBB3 Signaling

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The epidermal growth factor receptor (EGFR) kinase inhibitors gefitinib and erlotinib are effective treatments for lung cancers with *EGFR* activating mutations, but these tumors invariably develop drug resistance. Here, we describe a gefitinib-sensitive lung cancer cell line that developed resistance to gefitinib as a result of focal amplification of the *MET* proto-oncogene. inhibition of MET signaling in these cells restored their sensitivity to gefitinib. *MET* amplification was detected in 4 of 18 (22%) lung cancer specimens that had developed resistance to gefitinib or erlotinib. We find that amplification of *MET* causes gefitinib resistance by driving ERBB3 (HER3)–dependent activation of PI3K, a pathway thought to be specific to EGFR/ERBB family receptors. Thus, we propose that *MET* amplification may promote drug resistance in other ERBB-driven cancers as well.

Tyrosine kinase inhibitors (TKIs) are an emerging class of anticancer therapies that have shown promising clinical activity. Gefitinib (Iressa) and erlotinib (Tarceva) inhibit the epidermal growth factor receptor (EGFR) kinase and are used to treat non–small cell lung cancers (NSCLCs) that have activating mutations in the *EGFR* gene (*1*–*4*). Although most *EGFR* mutant NSCLCs initially respond to EGFR inhibitors, the vast majority of these tumors ultimately become resistant to the drug treatment. In about 50% of these cases, resistance is due to the occurrence of a secondary mutation in *EGFR* (T790M) (*5*, *6*). The mechanisms that contribute to resistance in the remaining tumors are unknown.

To explore additional mechanisms of gefitinib resistance, we generated resistant clones of the gefitinib hypersensitive *EGFR* exon 19 mutant NSCLC cell line, HCC827, by exposing these cells to increasing concentrations of gefitinib for 6 months. The resultant cell line, HCC827 GR (gefitinib resistant), and six clones isolated from single cells were resistant to gefitinib in vitro ($IC_{50} > 10$ μM) (Fig. 1A). Unlike in the parental HCC827 cells, phosphorylation of ERBB3 and Akt in the HCC827 GR cells was maintained in the presence of gefitinib (Fig. 1B).

We previously observed that *EGFR* mutant tumors activate phosphoinositide 3-kinase (PI3K)/Akt signaling through ERBB3 and that down-regulation of the ERBB3/PI3K/Akt signaling pathway is required for gefitinib to induce apoptosis in *EGFR* mutant cells (*7*, *8*). In addition, persistent ERBB3 phosphorylation has also been associated with gefitinib resistance in ERBB2-amplified breast cancer cells (*9*). We therefore hypothesized that gefitinib resistance in *EGFR* mutant NSCLCs might involve sustained signaling via ERBB3. After excluding the presence of a secondary resistance mutation in *EGFR* (*10*), we investigated whether aberrant activation of another receptor might be mediating the resistance. We used a phospho–receptor tyrosine kinase (phospho-RTK) array to compare the effects of gefitinib on 42 phosphorylated RTKs in HCC827 and HCC827 GR5 cells (Fig. 1C). In the parental cell line, EGFR, ERBB3, ERBB2, and MET were all phosphorylated, and this phosphorylation was either completely or markedly reduced upon gefitinib treatment. In contrast, in the resistant cells, phosphorylation of MET, ERBB3, and EGFR persisted at higher levels in the presence of gefitinib (Fig. 1C).

We next performed genome-wide copy number analyses and mRNA expression profiling of the HCC827 GR cell lines and compared them with the parental HCC827 cells (fig. S1 and table S1). The resistant but not parental cell lines showed a marked focal amplification within chromosome 7q31.1 to 7q33.3, which contains the *MET* proto-oncogene (Fig. 1D). *MET* encodes a transmembrane tyrosine kinase receptor for the hepatocyte growth factor (scatter factor), and *MET* amplification has been detected in gastric and esophageal cancers (*11*, *12*). Analysis by quantitative polymerase chain reaction (PCR) confirmed that *MET* was amplified by a factor of 5 to 10 in the resistant cells (fig. S2), and sequence analysis provided no evidence of mutations in *MET*.

To determine whether increased MET signaling underlies the acquired resistance to gefitinib, we examined whether MET inhibition suppressed growth of the resistant cells. HCC827 GR cells were exposed to PHA-665752, a MET tyrosine kinase inhibitor, alone or in combination with gefitinib (*13*). Although the HCC827 GR5 cells were resistant to both gefitinib alone and PHA-665752 alone, combined treatment resulted

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