Together we stand

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University culture stands at a critical crossroads: the era of team science is upon us functionally, but not yet structurally. Solutions to the problems this mismatch creates involve rethinking education — and giving credit where credit is due.

Over the past 70 years, scientific research has been transforming from a solitary operation into an endeavour characterized by ever-increasing team size[1]. The importance of this transformation cannot be overstated. As science undergoes this remarkable evolution, one might expect that the scientific community and its primary host — academia — would develop new norms that better serve its needs. But the academic career structure, originally conceived to reward self-sufficient independent researchers, continues to be implemented in a system now dominated by teams. To make matters worse, increasingly specialized education leaves academics ill-prepared to cope with this challenge. When, how and why did this problem arise, where will it lead and how can it be rectified?

Evolution of team science

Most historical paradigm shifts occur over a significant period of time, so it is difficult to delineate with accuracy the beginning of large-team science. Nevertheless, we can argue that the Manhattan Project was a landmark event[2]. For the first time, a large number of scientists — many of them physicists — came together to work for years towards a common goal. Robert Oppenheimer is widely recognized as the project's lead scientist — the principal investigator in today's terms. Yet little is known about the identities and roles of the other scientists involved.

Ever since the Manhattan Project, physics has been a leading force in the evolution of team science. Recently, this trend soared to new heights with the Higgs boson experiments at CERN. The two papers describing the results of these experiments featured a combined author list containing approximately 6,000 names[3,4].

Biology also follows the team-science model, largely driven by the demands of ambitious genetics research — the catalyst being the Human Genome Project[5]. Physics and biology are in the vanguard of a science system that seems to be moving towards large teams (Fig. 1a). Nobel prizes, long considered recognitions of the achievements of individuals, are now jointly awarded with increasing regularity[6]. These trends raise fundamental ethical considerations regarding the rights and responsibilities of individuals in teams and across the scientific community.

What is the reason behind this shift towards team science? There is no single answer to this question, but factors associated with the nature of modern scientific investigations and governments' involvement have a role.

At the start of the twentieth century, closed-form solutions based on first principles culminated in the formulation of the theory of relativity[7]. Since then, science has shifted away from rigorous deduction towards hypothesis-driven experimental investigation — often on a grand scale — supported by statistical testing[8]. In this framework, there are ever fewer opportunities for scientists to conduct independent research, marking the end of the solo-discoverer era[9]. Although the central idea in a project may belong to a single researcher, designing the experiment or study, developing the technology to execute it, mining the data and communicating the results are all distinct tasks that require significant training, time commitment and separate credit[10].

The changing nature of science has also been complemented by the increasing dominance of public funding in research projects, both small and large[11]. Public funding comes with ambitious goals, stressful term limits and requirements for broad inclusion and dissemination. In many cases, this converts the need for collaborative research efforts into a mandate. Globalization and the Internet have further amplified teaming behaviours in science by reducing political and communication barriers.

Challenges of team science

From the Manhattan Project to the Higgs boson experiments, team science has proven successful and important. As this model continues to spread, however, it incurs an increasing human and moral cost that needs to be addressed before it undermines its mission.

Scientific research critically depends on the abilities of the people that are engaged in it. Talented, ethical and well-prepared individuals, who trust that their hard-earned accomplishments will be rewarded, are fundamental to the well-being of the science system.

The problem is that both academic training and merit criteria are misaligned with the collaborative nature of modern research. Concomitant with increasing team sizes, graduate curricula have shed all vestiges of humanities education that were once part of a 'Doctor of Philosophy' programme. This change was effected in response to the need for specialization[12]. Ironically, one might argue that these elements of philosophical and historical wisdom are more essential to academics than ever before. A researcher working within a team is likely to run into conflicts of interest and needs to learn how to balance collaboration with competition.

Recently, responsible-conduct-of-research courses have been mandated in many doctoral programmes in the USA, reflecting an increased emphasis on regulation in response to repeated incidents of misconduct. The educational results are mixed[13], thus begging the question: is awareness of the rules sufficient to elicit ethical behaviour? Can a few hours of training replace the cultivation of values and attitudes that was once part of a doctoral education?

To make matters worse, the mentorship model in PhD programmes is weakening. The close interaction between adviser and advisee has long been the pillar of virtue ethics in academic life, much like the close interaction between parents and children has been the pillar of virtue ethics in society. As the ratio of principal investigators to students moves from 1:1 to 1:10 or 1:100, we witness the proliferation of 'academic orphans' — fledgling researchers who do not benefit from close interaction with a senior researcher. Treated largely as cogs in a huge machine, such academic orphans are likely to develop behavioural problems, further undermining their scientific output.

These rifts in graduate education are compounded by problems in the criteria set for academic career progression. The tenure system was developed during an era of independent researchers and was based on individual scholastic achievements. Such achievements were easier to recognize in the absence of team networks. As this model gave way to team science and public research funding became increasingly important, tenure and promotion criteria remained focused on the individual, largely ascribing scholastic merit to the status of principal investigator. Being a co-investigator in several grants but principal investigator in none can jeopardize faculty members' tenure in some universities, irrespective of the quality of their research.

In a system that idolizes only one team role, everybody tries to assume this role, having little incentive to share it. This is not only impossible, but also undermines productivity, as not everyone's talents fit the principal-investigator description. All the other team roles, such as modelling, performing measurements and analysing data, are viewed as a necessary chore on the path to principal-investigator coronation. These roles are typically assigned to PhD students, postdoctoral researchers and non-tenure-track research personnel.

This policy contributes to long-term imbalanced and unsustainable trends[14], which have manifested themselves in an unhealthy swelling and aging of the postdoctoral population (Fig. 1b) — many of whom end up in non-tenure-track careers (Fig. 1c). A steep pyramidal career structure characterized by limited upward mobility undermines the future of the research community, in much the same way as a similar trend affects society[15].

In such a highly skewed system, not only are rewards biased, but also the assignment of blame becomes nontrivial. What are the norms for sanctioning in teams?

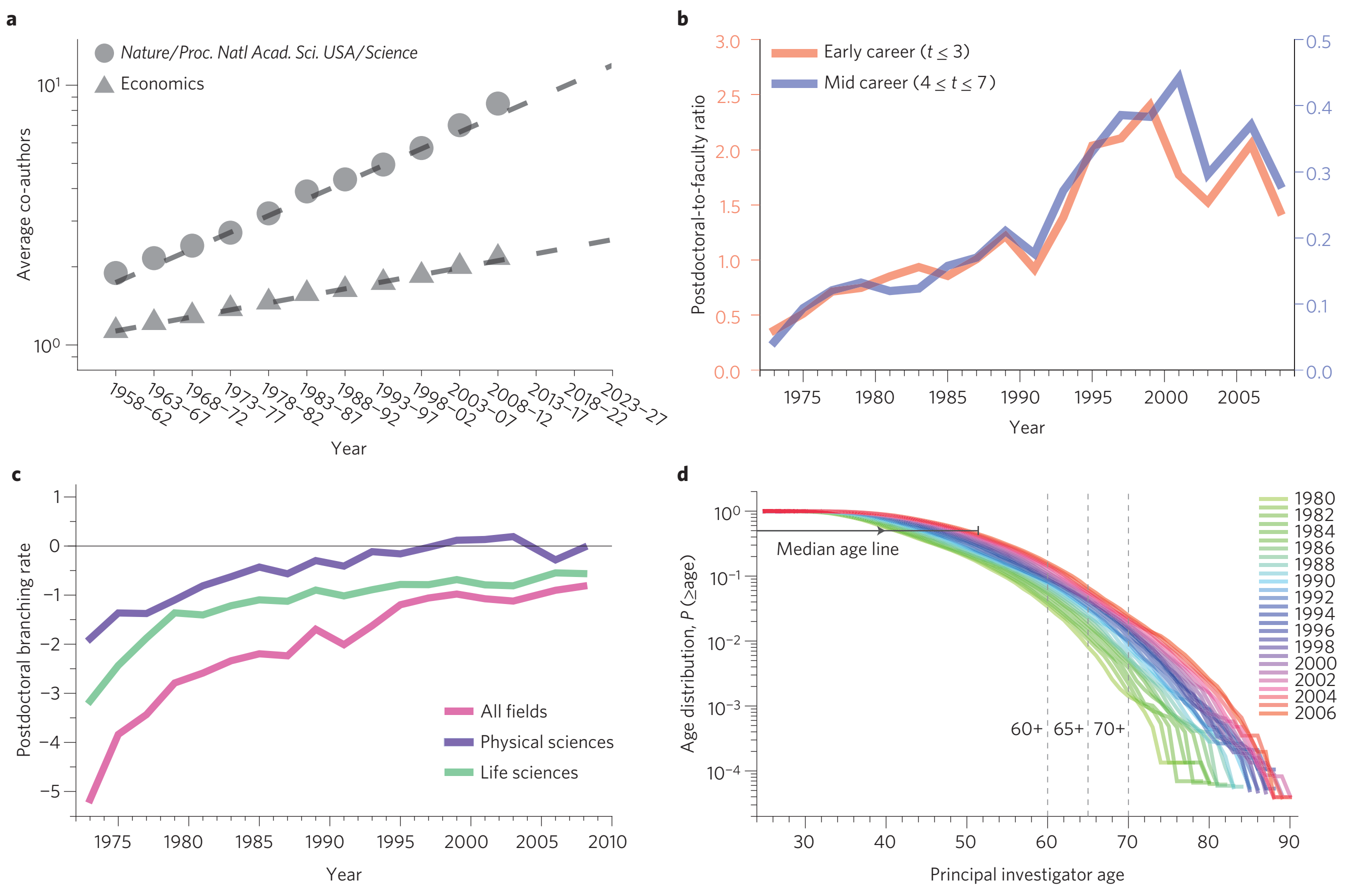

Figure 1 | a, The fast disappearance of the solo author. Mean authorship size in three multidisciplinary science journals (circles) shows persistent growth. If the trend continues, by 2040 there will be an average of 18.7 co-authors per paper, with 1% of papers having in excess of 113 authors. Even social sciences, such as economics (triangles, representing data aggregated from 14 high-impact economics journals), seem to be working their way towards team science at a slower but persistent pace. Data from Thomson Reuters Web of Science, excluding content types not classified as 'Articles'. More details can be found in ref. 6. **b**, The disappearing middle class in academia. Postdoctoral-to-faculty ratios in the early- and mid-career levels illustrate the swelling and unnatural longevity of postdoctoral appointments. t is the number of years since PhD completion. Data from the National Science Foundation, Science and Engineering Indicators 2012. **c**, The dramatic shift in the flow of postdoctoral careers towards non-tenure-track positions. The branching rate is defined as the relative difference in non-tenure-track to tenure-track population sizes normalized by the size of the postdoctoral population, $[S_{\text{other full-time}}(y) - S_{\text{junior faculty}}(y)] / S_{\text{postdoc}}(y)$, where $S(y)$ indicates the population size in year y. Data from the National Science Foundation, Science and Engineering Indicators 2012. **d**, Age and power imbalances in biomedical academics. Evolution of the cumulative age distribution for principal investigators in National Institutes of Health Research Project Grants. Data from National Institutes of Health.

Within the amorphous team structure, the only clearly identified individual is the principal investigator. But is the principal investigator responsible for every bad deed within a team? On the other hand, if the principal investigator passes the blame onto another team member, how credible is such an allegation given the monolithic power structure?

Candidate solutions

The systems on which academic training and awards are based need to evolve so that they meet the challenges posed by the collaborative nature of modern science.

Restructuring graduate education. Responsible-conduct-of-research training has all the characteristics of a band-aid solution and seems unlikely to effect the required behavioural changes in the research corps. We believe that humanities training should be reintroduced into doctoral programmes. Such a curriculum revision will be successful only if the chasm between the liberal arts and science communities is bridged. The humanities departments that will implement these programmes need to understand that teaching humanities to scientists is different from teaching humanities to humanists. At the same time, the science departments need to realize the strategic value of a broader graduate education — and embrace it.

Furthermore, the teaching model in graduate courses has to evolve to support group culture. Students should learn in groups, work in groups and be evaluated in groups. Requiring that the graduate curriculum be navigated independently, while academic and corporate research and development laboratories operate in an interactive team mode, is an exercise in futility. A collaborative education model may even prevent future tensions in the laboratory. Behavioural problems can often develop when people accustomed to working alone are suddenly made to work with others.

Last, but not least, performance in doctoral and postdoctoral mentorship should form part of the criteria for promotion and tenure[16]. In large-team settings, where the mentor does not have time to devote sufficient personal attention to each team member, a hierarchical system for offering practical help should be implemented. For the more challenging issue of socio-emotional help, a creative solution has to be found. Communal mentorship, where more than one collaborating mentor offers support, may provide such a solution.

Restructuring research. Academia needs to look for models in other creative communities that have embraced a team structure and used it to their advantage. Film-making may be one such paradigm. Unlike academia, the movie industry has been largely based on team efforts since its inception. The prizes awarded at film festivals are good examples of how a team reward system should be structured and operated. The workload is divided into key components that require specialized effort. Then, each of these components is separately recognized and rewarded. To the eyes of the world, some components weigh more than others: a film's audience typically pays more attention to the director and lead actors. Internally, however, the industry values every single contribution.

A good film editor has bargaining power. There are clear avenues for independent recognition (with, say, an Oscar in film editing) and, perhaps more importantly, the work is not simply a step along the path to directorship. The same applies for scriptwriters and sound engineers, as well as almost every role in the filmmaking process. Each speciality has an independent and sustainable career path.

By rewarding principal investigators only, the academic system takes the opposite approach, and in doing so, continues to undermine researchers' productivity. The most effective way to transform such a rigid system is through its funding. Multidisciplinary grants, which are a significant portion of new funding programmes, should identify distinct investigator roles. The principal investigator could be replaced by a crew structure, which includes, for example, a chief designer, a methods person, a technologist and a data analyst — each with equal standing. Depending on the topic, more distinct roles could be identified[10].

This new grant design would recognize all aspects of the modern scientific operation. And it would incentivize promotion and tenure committees to reform their merit criteria. Still, this grant model alone cannot fully solve the problem. The newly appointed investigators, drawn mostly from the postdoctoral and non-tenure-track ranks, would need to be included in the faculty structure.

The ultimate goal is to swell the middle ranks in academia, promoting a more equitable distribution of federal funding (Fig. 1d). Ideally, this would restore the power balance within research teams. Aristotle famously asserted that "the most perfect political community is one in which the middle class is in control, and outnumbers both of the other classes". Indeed, the beneficial effects of a sizeable middle class have been well documented[17]. The advantages for the scientific community are expected to be no different.

The question is how, in an era of shrinking budgets and spiralling education costs, universities can replace low-cost non-tenure-track positions with high-cost tenured roles. We believe the answer to this question is fourfold: we need to restructure the grant overhead, develop late-career options, rebalance teaching loads and capitalize on our researchers' productivity. Diverting grant resources to university administrations, allowing tenured positions to be overpopulated by faculty over 70 years of age (Fig. 1d) and exempting accomplished principal investigators from managing a full teaching load are all part of the problem.

The misalignment of academic policies and norms with the increasingly collaborative nature of science is real, and so are the tensions that it generates. Introducing an imaginative set of policies to fix the problem has its own risks, no matter how well thought out these policies are. However, the risk of inaction is even greater. After all, academia needs to practice the innovation it preaches. ❒

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